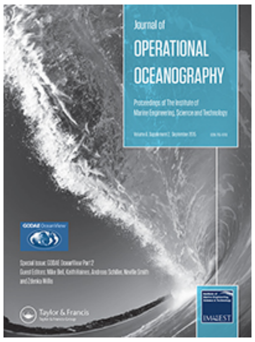

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Status and future of global and regional ocean prediction systems

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Operational evolution of global and regional ocean forecasting systems has been extremely significant in recent years. Global Ocean Data Assimilation Experiment (GODAE) Oceanview supports the national research groups providing them with coordination and sharing expertise among the partners. Several systems have been set up and developed pre-operationally, and the majority of these are now fully operational; at the present time, they provide medium- and long-term forecasts of the most relevant ocean physical variables. These systems are based on ocean general circulation models and data-assimilation techniques that are able to correct the model with the information inferred from different types of observations. A few systems also incorporate a biogeochemical component coupled with the physical system, while others are based on coupled ocean–wave–ice–atmosphere models. The products are routinely validated with observations in order to assess their quality. Data and product implementation and organization, as well as service, for users have been well tried and tested, and most of the products are now available to users. The interaction with different users is an important factor in the development process. This paper provides a synthetic overview of the GODAE OceanView prediction systems.

1. Introduction

Operational evolution of global and regional ocean forecasting systems has been extremely significant during the last 10 years. Several systems have been set up and developed pre-operationally, and the majority of these are now fully operational, providing medium- and long-term forecasts of the most relevant ocean physical variables. Following the GODAE Strategic Plan (2000), here we use 'operational' whenever the processing is done in a routine and regular way, with a pre-determined systematic approach and constant monitoring of performance. With this terminology, regular re-analyses may be considered as operational systems, as may be organized analyses and assessment of climate data.

The development of ocean forecasting systems is generally a national effort focused on regional requirements. Global Ocean Data Assimilation Experiment (GODAE) has given national groups the opportunity to collaborate and has provided a firm base for the development of a global ocean forecasting system. GODAE aimed to develop a global system of observations, communications, modelling and assimilation to deliver regular, comprehensive information on the state of the oceans in a way that would promote and engender wide utility and availability of this resource for maximum benefit to society (Smith 2006).

At the end of the 10-year GODAE project (Smith 2006; Bell et al. 2009), GODAE evolved into GODAE OceanView (Bell, this issue), https://www.godae-oceanview.org, which continues to foster the development and operation of global and regional ocean forecasting systems providing coordination and leadership in consolidating and improving ocean analysis and forecasting systems.

This paper describes the characteristics and evolution of the global and regional ocean forecasting systems represented in GODAE OceanView.

The paper is organized as follows: section 2 provides a general description of the GODAE Science Team; section 3 describes the evolution of the ocean prediction systems; section 4 describes the data and product service; section 5

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Figure 1. Geographical distribution of centres with ocean forecasting systems developed in GODAE and GODAE OceanView.

describes the future evolution of the systems, and section 6 has some concluding remarks.

2. GODAE OceanView Science Team

The global and regional systems described in this paper have been developed and are operated by several institutions from different countries, France, UK, Norway, Italy, USA, Australia, Canada, Japan, Brazil, China and India (see Figure 1). All these systems are represented in GODAE OceanView by their National Representatives in the GOVST (GODAE OceanView Science Team). GOVST was established in 2009 and, together with the ET-OOF group (Expert Team on Operational Forecasting System) from JCOMM (Joint Technical Commission for Oceanography and Marine Meteorology from WMO-IOC, World Meteorological Organization; Intergovernmental Oceanographic Commission), takes on the ongoing improvements in operational oceanography systems.

The vision and objectives of the GOVST is defined in the Terms of Reference, 2010 (www.godae-oceanview.org/about/terms-of-reference/), an extract of which is reproduced here as an aid for the reader.

> The GOVST is created with the mission to define, monitor and promote actions aimed at coordinating and integrating research associated with multiscale and multi-disciplinary ocean analysis and forecasting systems, thus enhancing the value of GODAE OceanView outputs for research and applications. Over the next decade, the science team will provide international coordination and leadership in:
>
> - The consolidation and improvement of global and regional analysis and forecasting systems;
> - The progressive development and scientific testing of the next generation of systems covering biogeochemical and ecosystems and extending from the open ocean into shelf sea and coastal waters;
> - The exploitation of the capability in other applications (weather forecasting, seasonal and decadal prediction, climate change detection and its coastal impacts, etc.);
> - The assessment of the contribution of the various components of the observing system and the scientific guidance for improved design and implementation of the ocean observing system.
>
> It is envisaged that the GODAE OceanView Science Team will coordinate a programme of activities implemented through the nationally funded activities of its members. The GOVST will provide a forum where the main operational and research institutions (national groups) involved in global ocean analysis and forecasting develop collaborations and international coordination of their activities. The primary purpose of the team is to accelerate the improvement and exploitation of these systems through exchange of information and expertise and the coordination of joint assessments. The science team consists of scientists leading the scientific development of the major national ocean analysis and forecasting systems, those implementing and improving the system (expertise for this area includes observation, modelling and data assimilation) as well as representatives of key observing systems (e.g. Argo, GHRSST and OST science teams).

The national representatives, members of GOVST, are responsible for reporting on national activities related to GODAE OceanView. They maintain an up-to-date description of national capabilities related to ocean analysis and forecasting (national reports). Every year, all the national representatives provide GODAE OceanView with an updated version of the national reports, detailing the most important characteristics of their systems. These reports are available at the GODAE OceanView website https://www.godae-oceanview.org/documents/q/category/govst/.

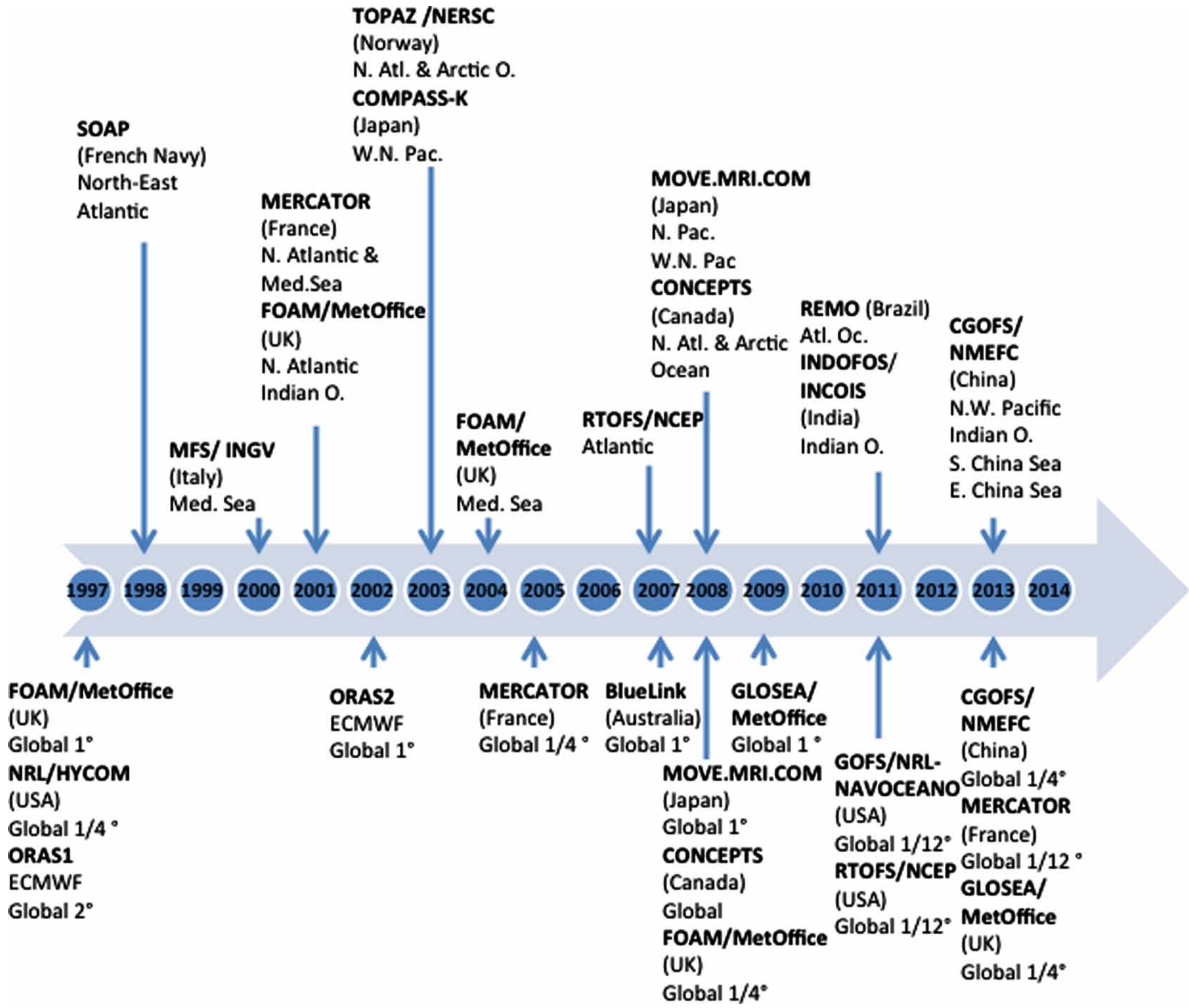


Figure 2. Chronological evolution of the development of the Ocean forecasting systems in operation in the different countries.

Since the inception of GODAE OceanView, the structure of these documents has evolved, and now there is a good level of harmonization among the reports provided for the different systems. This is a direct result of the effort done to encourage the exchange of information and the collaboration among the different National Systems.

3. Evolution of the ocean prediction systems

Since the beginning of the 1990s, more and more systems have been developed in different countries. The most relevant steps of evolution of the ocean forecasting systems are shown in Figure 2, which shows the year in which various prediction systems became operational. The first systems were developed at The Met Office, NRL/NAVOCEANO and ECMWF in 1997 and by the French Navy in 1998. Many other systems on a global and/or regional scale have been developed later, at the beginning of the year 2000, by other countries such as France, Italy, Japan and Norway. Australia and Canada developed their systems in the second half of years 2000. In the last few years also, China, Brazil and India have developed operational ocean forecasting systems. All the forecasting systems are continuously evolving in an attempt to provide increasingly more accurate products. A review of the GODAE regional and global systems that were operational at the end of the GODAE project (2007) can be found in Dombrowsky et al. (2009). This paper provides an overview of the systems as they are now, 5 years on from the inception of GODAE OceanView, how they have evolved and how they will evolve in future years.

To understand what requirements these forecasting systems should fulfil, we refer to the definition of operational oceanography given by Fleming (2002):

> Operational oceanography is the provision of scientifically based information and forecasts about the state of the sea (including its chemical and biogeochemical components) on a routine basis, and with sufficient speed, such that users can act on the information and make decisions before the relevant conditions have changed significantly, or became unpredictable.

From this definition, it is clear that the development/implementation/operation of a forecasting system is the result of a balance between science and technology. The evolution of these two aspects together with the funding strategies, at national and international levels, and the consideration of user needs, can explain the evolution shown in Figure 2.

A forecasting system is based on numerical modelling of the ocean dynamic and data-assimilation schemes for the blending of the observations into the model in order to provide the most accurate description of the past and the best initial condition for the forecast.

Therefore, ocean general circulation models (OGCMs) that are able to reproduce the fields that the forecasting system aims to predict are needed together with an adequate number of observations to be assimilated into the systems and to be used for the validation of the products. The OGCMs with all their components and the data-assimilation schemes are highly demanding in terms of computational resources. Computer power is therefore a limiting factor for the horizontal and vertical grid resolution. The performance of the more powerful supercomputers at the end of the 1990s was less than 1 teraFLOPS (TFLOPS = 10^{12} floating-point operations per second), while, at the time of writing, performances are typically around 100 TFLOPS to 1 petaFLOPS (PFLOPS = 10^{15} floating-point operations per second), and there are already some computers capable of 100 PFlops (www.top500.org). The supercomputing power available to the national agencies is constantly increasing, which facilitates the development of higher-resolution forecasting systems. For the same reason, more sophisticated assimilation schemes can be run with the simultaneous assimilation of observations from different platforms and for different ocean parameters. With these advances in computing power, it is therefore possible to operate high-resolution ocean forecasting systems, at regional and global scales, operationally in near real time.

The OGCMs are also continuously developed by the scientific community in order to be able to include different parameterizations, more accurate advection schemes, more complex vertical mixing parameterizations or new vertical coordinate schemes. Almost all the OGCM codes are now able to explicitly resolve the barotropic component, and so the tidal signal can be introduced.

An ocean monitoring network in near real time for *in situ* and satellite observations is needed in order to correct the model via data-assimilation techniques and to validate the model and the forecast products. The number of *in situ* observations at the global level, especially for temperature and salinity, is increased significantly during the most recent period (2000–2013), which is mostly due to the Argo profiles (http://www.argo.ucsd.edu). The number of Argo profiles collected per year has increased from 50 000 in 2003 to more than 150 000 in 2013 with a steep increment from year 2003 to 2006 (from Histogram of profiles on Argo GDAC, http://www.argodatamgt.org/Monitoring-at-GDAC/Active-floats-statistics). The number of available salinity observations has greatly increased because, before Argo, there were far fewer salinity observations compared with temperature, meaning that Argo data comprise a much higher proportion of available salinity observations. Moreover, datasets suited to the needs of operational forecasting systems (Cabanes et al. 2013, Legler et al. 2015) have been developed and, owing to the technological evolution of the instruments, i.e. their transmission components and the communication system, these are able to provide an increasing number of observations in near real time. The timeliness of the observations delivery is a crucial point for setting up the production cycle of a forecasting system because it will determine how much data you can assimilate and how far back you have to perform your analysis.

The satellite observations available for the forecasting systems are Sea Level Anomaly, Sea Surface Temperature, Sea Ice, Wind and Ocean Colour (Le Traon et al. 2015). The number of satellite measurements depends on several factors such as the type and number of sensors, sensor resolution, coverage of each sensor and revisit time. In the last few years, the number of satellite products available for operational oceanography has increased in number, quality and timeliness (i.e. availability in near real time). All these factors have influenced the evolution of the forecasting systems possible together with the technological development of data and product service for the users.

At present, there are many well-consolidated global and regional systems developed by different centres using ocean models with increased complexity and data-assimilation techniques that are able to properly predict the main ocean variability at different spatial and temporal scales. All the systems described here are producing real-time forecast/analysis products, delivered to different types of users. Most of the systems are also producing reanalyses, but these are not considered in this work, which is focused purely on the real-time forecasting systems.

3.1. *Global systems*

Several systems developed by different countries are covering the global ocean, and there are now 12 forecasting systems, 30% more than in 2009 when there were only seven systems. These prediction systems are able to provide a global analyses and medium and extended range forecasts, 7–18 days depending on the system, and long-range forecasts of 7 months. Following the WMO (World Meteorological Organization) definition,[1] http://www.wmo.int/pages/prog/www/DPS/GDPS-Supplement5-AppI-4.html:

- medium-range forecast: 3–10 days;
- extended-range forecast: 10–30 days;
- long-range forecast: 30 days to 2 years.

New systems are continuously being developed, and the existing systems updated in order to better meet the needs of the users. The resolution, in terms of horizontal and vertical grid discretization, plays an important role in the definition of the processes that a system is able to resolve. Usually the resolution of the model is referred to the capability to resolve (eddy resolving) or not (coarse resolution and eddy permitting) mesoscale eddies, which plays an important role in the dynamics of the ocean. The definitions of eddy-permitting and eddy-resolving models are referred to the Rossby radius, which varies from a few kilometres to several hundred kilometres in different areas of the globe. Around the equator, the Rossby radius reaches its maximum at 230 km, while at high latitudes and on the continental shelves area, this decreases to a value below 10 km (Chelton et al. 1998). Studies have been performed in order to define the horizontal resolution needed to resolve the first baroclinic deformation radius with two grid points (Hallberg 2013). From this study, it is clear that, while in equatorial regions a model resolution of 1/4° is sufficient to resolve the mesoscale processes, at high latitude and on the continental shelves a much higher resolution (at least more than 1/12°) is needed. Therefore, it is not straightforward to apply the commonly used definition of eddy permitting/resolving model to global models because this definition depends on the geographical area in which we are interested. Therefore, with all the approximation related to this definition, we can summarize (see Table 1) that five systems are eddy permitting with a resolution of 1/4° (NMEFC, CONCEPTS, FOAM, GLOSEA, MERCATOR). Three of them are eddy resolving with a horizontal resolution of 1/12–1/12.5°, which is the resolution required to be eddy resolving in mid latitudes (MERCATOR-OCEAN, GOFS, RTOFS). Three systems have coarse resolution (ECCO-NR, MOVE/MRI.COM-G, ECMWF) and the Bluelink/OceanMAPS has a coarse resolution of 1° everywhere except around Australia where the resolution is increased to 1/10°. This system is therefore eddy resolving around Australia and coarse resolution in all other areas. With respect to the systems operational in 2009, the horizontal resolution has increased, as would be expected in line with available computational resources.

Regarding the vertical resolution, as shown in Table 1, most of the systems have a z-vertical coordinate system, while only three have hybrid coordinate systems (MOVE/MRI.COM-G, GOFTS and RTOFS). The number of vertical levels among the z-coordinated system models is less than 50 for the coarse resolution systems and 50 or higher for

Table 1. Global forecasting systems considered in this work and their description in terms of horizontal and vertical resolution, and the model and data-assimilation components employed.

	Grid resolution		Model			
System	Horizontal	No. of vertical levels	OGCM	ICE	Data assimilation	Additional info/other components
ECCO-NRT (ECCO)	0.3-1°	46 z	MITgcm		Kalman filter & RTS smoother	
MOVE/MRI.COM-G (JMA/MRI)	0.3-1°	50 hybrid	MRI. COM2	Monthly Climatology	MOVE(3DVAR)	
ECMWF (ECMWF)	1°	42 z	NEMO		NEMOVAR (3DVAR)	Wave model (WAM)
BlueLink/OceanMAPS (Bureu of Meteorology)	1° (1/10°)	47 z	OFAM2 (MOM4)		BODAS (ensenble OI)	
FOAM (MetOffice) GLOSEA (MetOffice)	1/4° 1/4°	75 z 75 z	NEMO 3.2 NEMO 3.2	CICE CICE	NEMOVAR (3DVAR)	Coupled ocean-atm-ice (GloSEA)
CONCEPT (Canada)	1/4°	50 z	NEMO 3.1	CICE	SAM2-ice 3DVAR	
CGOFS (NMEFC)	1/4°	50 z	MOM4		3DVar	Wave model (NWW3)
PSY3 (Mercator-Ocean) PSY4 (Mercator –Ocean)	1/4° 1/12°	50 z partial step	NEMO 3.1	LIM2_EVP	SAM2V1-3DVAR large-scale T&S bias correction	BioGeoChemical (PISCES ¼)
GOFS (NRL/NAVOCEANO)	1/12.5°	32 hybrid	HYCOM		NCODA(3DVAR)	
RTOFS (NCEP)	1/12°	32 hybrid	HYCOM	Energy Loan	NCODA(3DVAR)	

the other systems. The z-vertical level distribution varies considerably from system to system, with the depth of the first level ranging from 1 m to 10 m. The FOAM and GloSea systems from the Met Office have the highest z-level resolution with 75 levels and a 1 m surface box.

Usually, the available computational resource is one of the major constraints for the increase in horizontal and vertical resolution. The forecast production time has to be short enough to provide the forecast products to the users before the relevant conditions have changed significantly. The choice of resolution should therefore be a compromise between the resolution required to resolve the relevant ocean dynamic processes and the capability to release the products in near real time.

Table 1 shows the principal components in terms of models and data-assimilation schemes for all of the systems. Most of the European systems plus Canada use NEMO (Nucleus for European Modelling of the Ocean) as the OGCM. The other models are community models such as HYCOM (Hybrid Coordinate Ocean Model) for the US systems or MOM4 (Modular Ocean Model) for the Australian and Chinese systems. Japan and ECCO have their own OGCMs – the MRI.COM and MITgcm (MIT General Circulation Model) codes respectively.

Six systems out of 12 also include an ice component. The inclusion and/or the increase in complexity of the ice component is yet another step in the evolution of the systems with respect to Dombrowsky et al. (2009).

The ice models differ from system to system. PSY3–PSY4 from Mercator use the LIM2 (Louvain-la-Neuve Sea Ice Model) code with the assumption that the ice dynamics are simulated by assuming that sea ice behaves as an elastic–viscous–plastic (EVP) continuum in dynamical interaction with atmosphere and ocean. The MOVE/MRI.COM-G also has an EVP sea-ice model. The CONCEPTS and MetOffice (FOAM and GloSea) systems use the CICE (Los Alamos sea ice model), which is also EVP as well as having multi-thickness categories. RTOFS instead has the Energy Loan model to manage the energetics of water phase changes in a consistent yet simple manner. Figure 3 shows an example of the improvement in the FOAM sea ice fields with the new version (v12), which includes, among other improvements, the change from the LIM2 single category ice model to CICE with five thickness categories. The forecast and analysis of the new system (v12 red lines in the figure) perform better than the old system (v11 blue line). The forecast ice extent (the area of the ocean where the ice concentration is above 15%) is further from the observed extent (grey dashed lines) than the analyses, but forecasts are better at v12 because they deviate less from the corresponding analyses and are simultaneously closer to the observed OSTIA (Operational Sea Surface Temperature and sea Ice Analysis) ice extent.

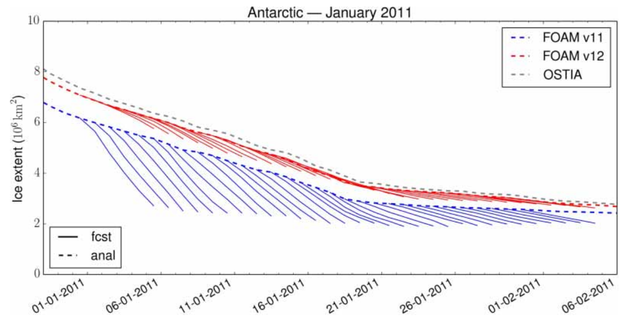


Figure 3. Time series of Antarctic sea ice extent (10^6 km^2) for the FOAM v12 (red), FOAM v11 (blue) and OSTIA systems (grey). Dashed lines show extents calculated from an analysis of ice concentration fields, while solid lines show the evolution of the ice extent over a series of 5-day hindcasts performed during January 2011.

Only the PSY3–Mercator system includes a biogeochemical component, which is an important step in the evolution of the forecasting systems. Biogeochemical forecasting remains an active area of development, and so the introduction of such a component will most likely feature in the future plans of some of the other GOV systems.

The ECMWF system is the only one that is an ocean–atmosphere–wave coupled system. The GloSea system from the Met Office and the MRI.COM-G are the only other ocean–atmosphere coupled systems. The coupled systems are an important step in the model developments and will play a very important role in the design of the future systems; therefore, GODAE OceanView has a dedicated Task Team on the 'Short- to Medium-Range Coupled Prediction' (Brassington et al. 2015). All the other global systems are forced at the surface by analysis/forecast products from Numerical Weather Prediction systems.

All the systems have a data-assimilation scheme [see Martin et al. (2015), for a detailed description of the different data-assimilation schemes implemented by these forecasting systems] that, for many, is based on a variational method (3D-Var). Mercator for both the systems instead uses a method based on a reduced-order Kalman filter based on the SEEK (Singular Evolutive Extended Kalman filter) formulation with a 3D-Var bias correction. The Australian system has a scheme based on the Ensemble Optimal Interpolation (OI) techniques, and the ECCO system uses a Kalman filter with a Rauch–Tung–Striebel (RTS) smoother. The level of complexity of the data-assimilation schemes has increased with respect to 2009 as the systems evolve towards more sophisticated techniques. An example is the FOAM system that has changed the data-assimilation scheme from the Analysis Correction scheme (Storkey et al. 2010; Martin et al. 2007) to the 3D-Var NEMOVAR system. The number and type of observations assimilated have increased together with the increased complexity of the data-assimilation schemes.

All the systems assimilate satellite along track data from altimetry using all the available satellites; Sea Surface Temperature (SST) data from satellites (some also from surface ship measurements, moored and drifting buys); vertical profiles of temperature and salinity from different platforms (CTD, XBT, Argo and drifters) and ice observations (both satellite and *in situ*).

The increment of the number and type of observations available for data assimilation and validation has increased the quality of the prediction system products. The impact of the data assimilation on these systems, at least for some, is described in Oke et al. (2015).

As previously mentioned, only a few of the GODAE systems are coupled atmosphere–ocean systems. All the other systems are therefore forced by Numerical Weather Prediction (NWP) analysis and forecast products by restoring terms, fluxes parameterization or bulk formulae in order to parameterize the air–sea interactions. There are several different NWP products used by all of these systems. The temporal resolution of these products can vary from 1 h, as for the CONCEPTS and for winds used in the FOAM system, or 3–6 h. Only MOVE/MRI.COM-G has an atmospheric forcing with 1 day of temporal resolution, and this is due to the design of this system, which aims to produce seasonal, rather than medium-range, forecast products.

Some of the systems, like PSY3 and PSY4 from Mercator-Ocean, have increased the temporal resolution of the NWP analysis/forecast products in the last 5 years. Other systems, such as GOFS, have recently updated their system by changing the NWP inputs used to force the ocean surface. They have moved from NOGAPS (Navy's Operational Global Atmospheric Prediction System) to NAVGEM 1.1 (NAVy Global Environmental Model) after some experiments were performed to assess the impact of this modification. Comparisons made between NOGAPS and NAVGEM showed that their surface differences were large enough, in surface heat flux and wind, such that great care has been taken in switching from NOGAPS to NAVGEM (Metzger et al. 2013).

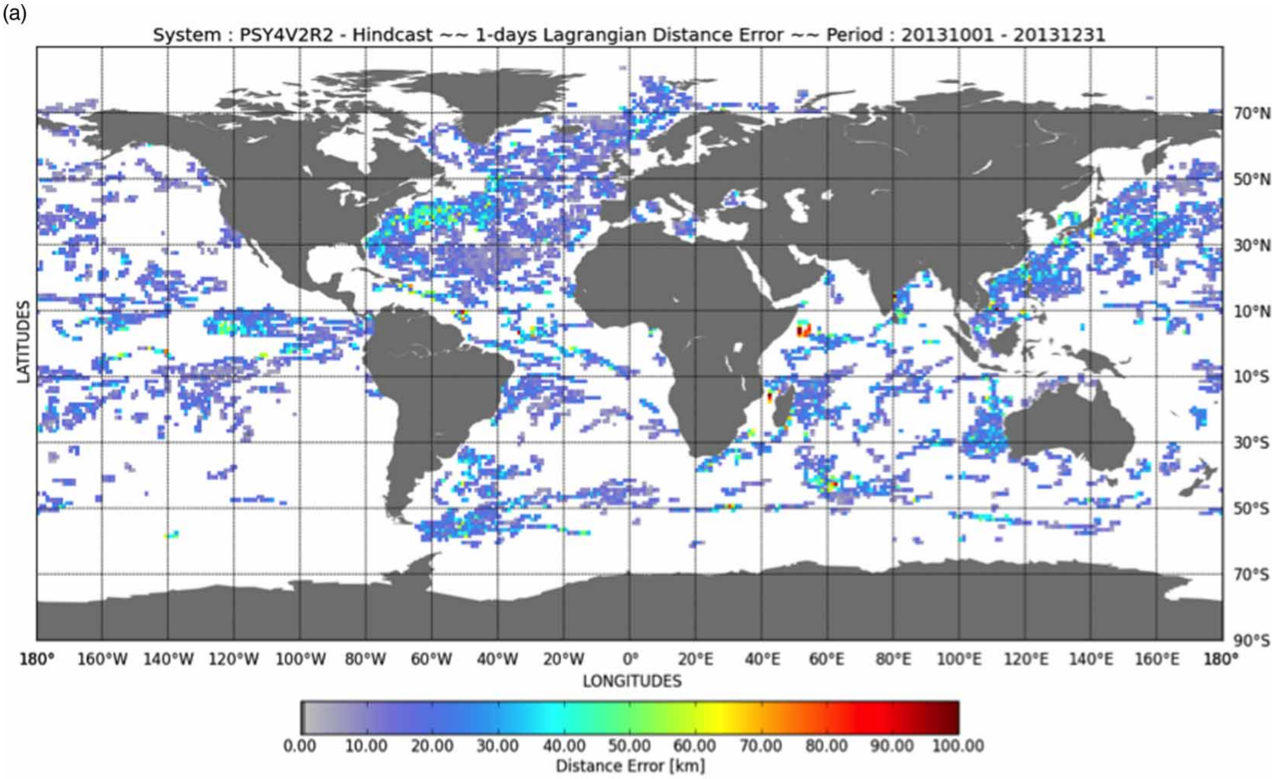
The products are evaluated with validation procedures in order to be able to assess the quality of the analysis and forecast fields. The observations are therefore very important not only for the data assimilation but also for the evaluation. All the systems have developed their own metrics, and some of them participate in an inter-comparison activity within the GODAE OceanView framework, which follows the standard provided by the Inter-comparison and Validation Task Team, IV-TT (https://www.godae-oceanview.org/science/task-teams/intercomparison-and-validation-tt/), Hernandez this issue. Figure 4 shows an example of an evaluation study done to assess the model current fields using the trajectories from drifting buoys. The positions of the AOML (Atlantic Oceanographic and Meteorological Laboratory from NOAA) surface drifting buoys are systematically used to initialize in the model Lagrangian particles, which are advected with the forecast velocities from the global 1/12° Mercator–Ocean PSY4 system. On the top panel, we can see that the 1-day distance error is smaller than 10 km in many places, but this error increases to 30–40 km in the main energetic areas such as the Gulf Stream, the Kuroshio, the equatorial currents and the Antarctic circumpolar current. The 1-day error can reach 80–100 km in specific places associated with mesoscale structures or confluence zones. Comparison between the top and bottom panel reveals an increase in distance error from a 1-day to 4-day forecast. In the main energetic areas, the error reaches 100 km after 4 days of advection and remains at around 30–40 km in the low energetic area as in the centre of the gyres. This is only one of many examples of evaluation of the products.

3.2. *Regional systems*

Several forecasting system have been developed in past years and are now operational in many different regions of the ocean. The regional systems are designed to provide detailed information in specific areas of interest. These systems differ from the global systems in the model domain and the grid resolution. Moreover, their model parameterization is tuned to simulate the characteristic processes of that region, such as ocean dynamics, mesoscale circulation, fronts, air–sea interaction processes, exchange at straits and so on. The model horizontal and vertical grid resolution can be specifically defined in order to take into account the mesoscale structures and fronts characteristic of that area and the typical properties of the water masses. The regional systems resolved processes at the basin scale and often have developed downscaling capacities in coastal and shelf regions where small-scale processes and coastal dynamic structures are important and need to be resolved with coastal models. The GODAE OceanView coastal models are described in Kourafalou et al. (2015). Figure 5 shows the geographical domain of all the regional systems considered in this work. The detailed definition of each domain is described also in Table 2. Most of the regional systems are nested into a global system through open boundary exchange of data.

These systems cover almost all the sub-domains of the global ocean with a higher coverage in the northern hemisphere. There are several overlapping areas among the different systems in particular in the Atlantic and the West Pacific area. The precise definition and characteristics of the regional systems depends on the phenomena to be investigated. The Japan Meteorological Agency (JMA) for example has developed regional forecasting systems in the western North Pacific including seas near the south coast of Japan where the Kuroshio, a strong western boundary current in the North Pacific Subtropical Gyre, sometimes changes its path (Fujii and Kamachi 2003;

(a)



(b)

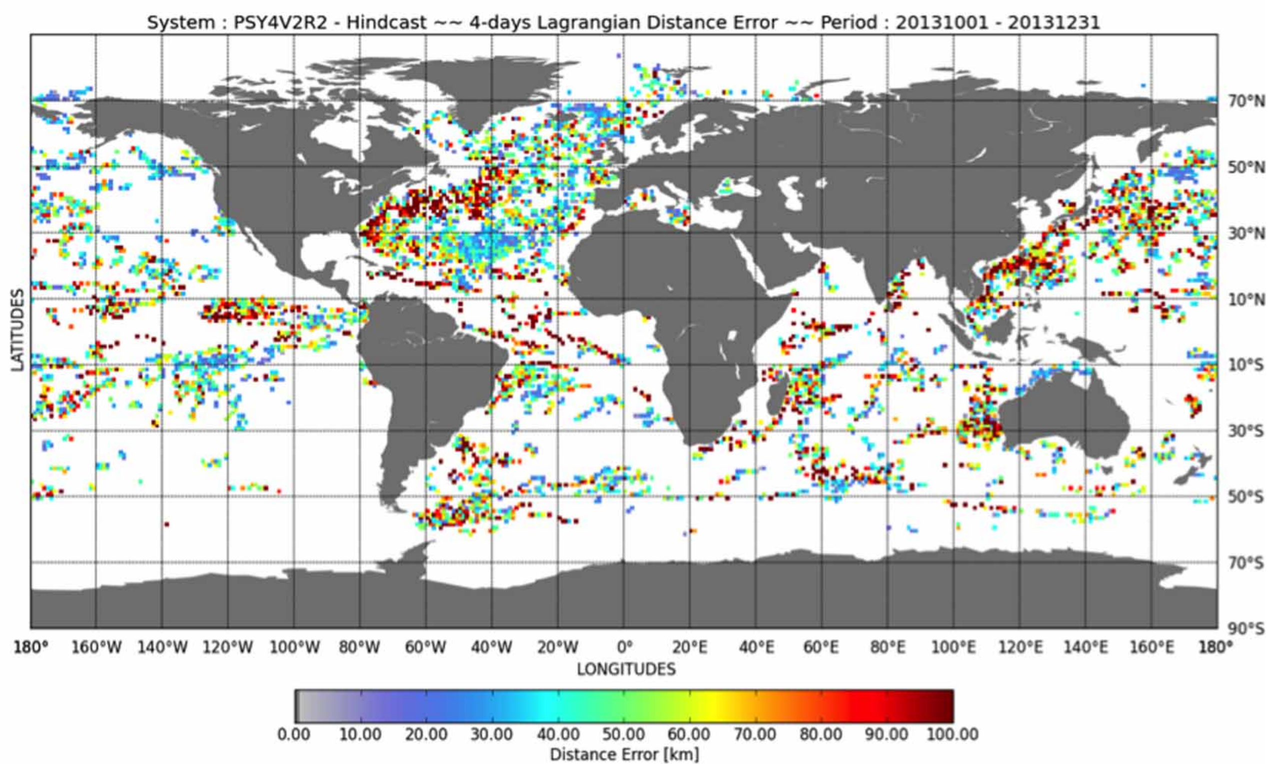


Figure 4. Comparison of the mean distance error in 1° × 1° boxes after a 1-day (top) and 4-day (bottom) drift between AOML (http://www.aoml.noaa.gov/phod/dac/gdp_doc.php) drifters' trajectories and the global 1/12° system (period: October–December 2013).

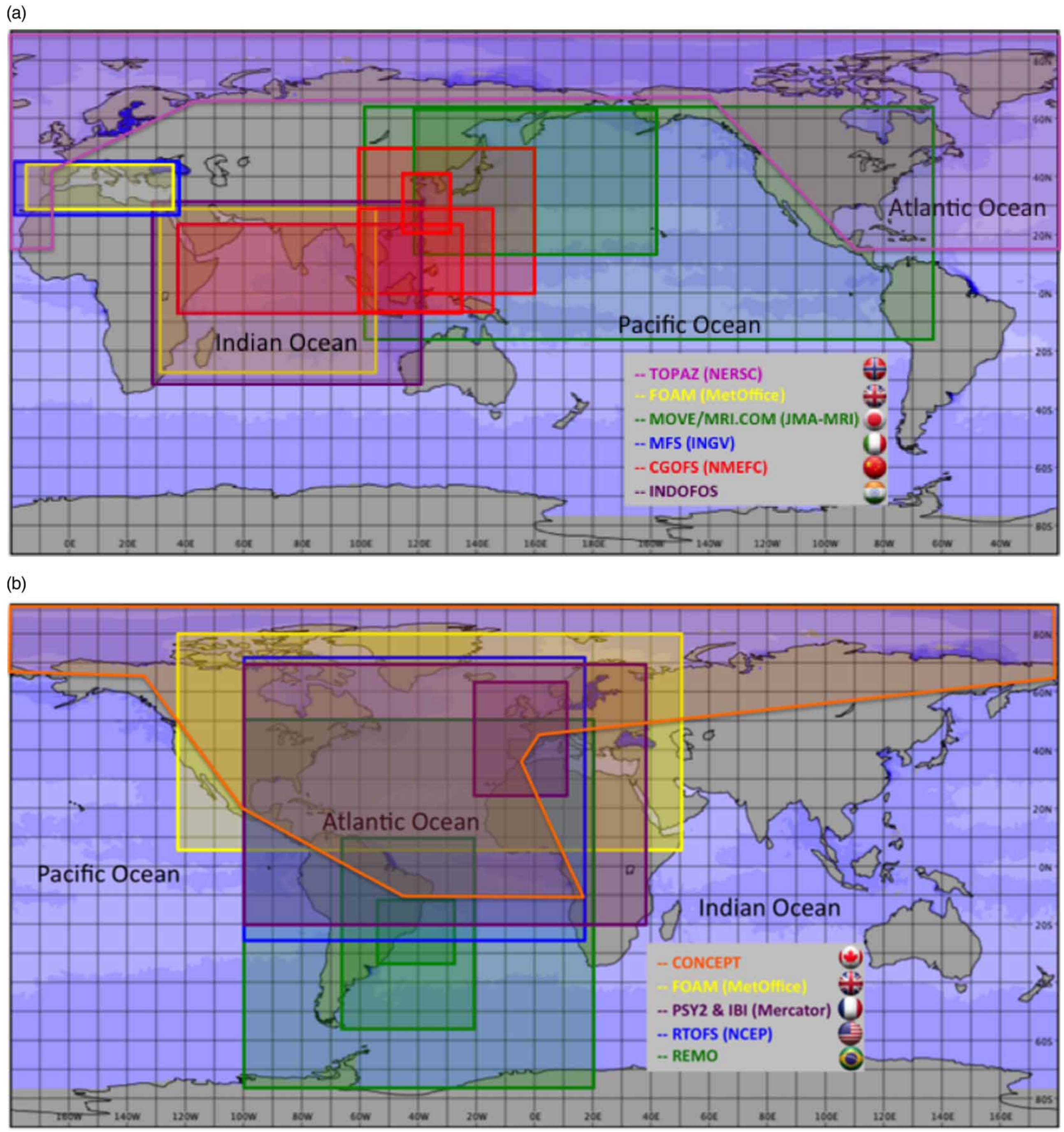


Figure 5. Spatial domains of the regional forecasting systems.

Kamachi et al. 2004). This phenomenon affects ships navigation and causes abnormally high coastal tides (see Figure 6) and rapid coastal currents (Kyucho). Located between Kuroshio warm water and Oyashio cold water, the sea around Japan represents good fishery grounds. In contrast, anomalous intrusion of Oyashio water to the east of Japan causes a cool northern easterly wind in the Tohoku area, affecting rice production. More recently, the Indian National Centre for Ocean Information Services (INCOIS) has set up an operational forecasting system based on several different regional models in order to be able to provide adequate information on all the different oceans/seas surrounding the India subcontinent. The demand for ocean forecast products is high due to the different maritime activities in the area such as traditional fisheries, high tech oil and gas exploitation, on-shore and off-shore port activities, recreational tourism and maritime traffic. The Japanese and Indian systems are two examples

Table 2. Regional forecasting systems considered in this work and their descriptions in terms of geographical domain, horizontal and vertical resolution and the model- and data-assimilation components.

		Grid resolution		Model			
System	Domain	Horizontal	No. of vertical levels	OGCM	ICE	Data assimilation	Additional info/other components
CONCEPTS (Canada)	Arctic & N. Atl.	1/12°	50 z	NEMO3.1	CICE	Downscaling from global SAM2 ocean analysis blended with regional 3DVAR ice analysis	
FOAM (MetOffice)	Mediterranean Sea	1/12°	50 z	NEMO3.2		NemoVAR (3DVAR FGAT)	
	Indian Ocean	1/12°	50 z	NEMO3.2		NemoVAR (3DVAR FGAT)	
	North Atlantic	1/12°	50 z	NEMO3.2	CICE	NemoVAR (3DVAR FGAT)	
TOPAZ (NERSC)	Atlantic & Arctic	1/8°-1/6°	28 hybrid	HYCOM	NERSC 1cat/EVP	DEnKF	BioGeoChemical component (NORWECOM)
PSY2 (Mercator) BI36 (Mercator)	Atlantic + Med	1/12°	50 z (partial step)	NEMO3.1	LIM2_EVP	SAM2V1 and 3Dvar large-scale bias correction for T and S	
	Iberia Biscay Irish Sea	1/36°	50 z (partial step)	NEMO3.4		NO. Initialized with PSY2 analysis	Tide
MOVE/MRI. COM (JMA-MRI)	North Pacific	1/2°	54 hybrid	MRI. COM	Based on CICE	MOVE (3DVAR)	
	West North Pacific	1/10°	26 hybrid	MRI. COM	Based on CICE	MOVE (3DVAR)	
MFS (INGV)	Mediterranean Sea	1/16°	72 z (partial step)	NEMO3.4		OceanVAR (3dVAR)	Wave model (WW-III) and BioGeoChemical component (OPATM-BFM from OGS)
RTOFS (NCEP)	N Atlantic	1/12°	26 hybrid	HYCOM		2DVAR (horizontal) + 1DVAR (vertical)	
CGOFS (NMEFEC)	NW Pacific	1/20°	22 sigma	ROMS		Ensemble OI	
	Indian Ocean	1/12°	20 sigma	ROMS		Ensemble OI	
	South China Sea	1/30°	36 sigma	ROMS		Ensemble OI	
	East China Sea	1/30°	30 sigma	ROMS		Ensemble OI	
REMO	Atlantic	1/4°	21 hybrid	HYCOM		Ensemble OI	
	Atlantic Metarea V	1/12°	21 hybrid	HYCOM		Ensemble OI	
	SW Atlantic	1/24°	21 hybrid	HYCOM		Ensemble OI	
INDOFOS	Indian Ocean	1/12°	40 sigma	ROMS		no	

of how different users needs and regional ocean characteristics require the development of an *ad hoc* ocean forecasting system.

There are at present 19 regional systems running operationally in the areas described in Figure 5. The area extension and the horizontal/vertical resolution vary considerably from system to system (see Table 2). The OGCM codes used are NEMO for the CONCEPTS, FOAM, MFS and Mercator-Ocean systems; HYCOM for the NERSC, the NCEP and the REMO systems; ROMS (Regional Ocean Modelling System) for CGOFS and INDOFOS; and MRI.COM for all the MOVE/MRI.COM systems.

All the systems implemented in the Arctic and in the north Atlantic or Pacific have ice model components based on the CICE, LIM2 or NERSC_EVP models. Few systems (MOVE/MRI.COM-NP and REMO-Atlantic)

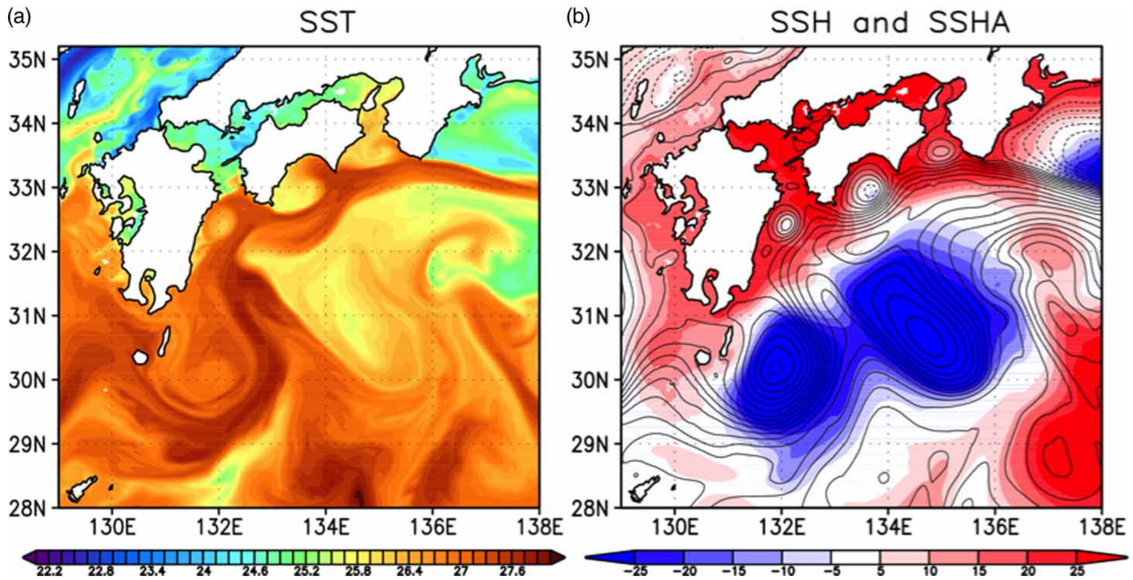


Figure 6. Sea surface temperature (a) and sea surface height (b) obtained using a 2-km high-resolution model. The case is when the Kuroshio warm water approaches the Seto Inland Sea causing an abnormal high tide there on 26 October 2011. Units are °C for (a) and cm for (b), where the sea surface height is shown by contours at 1 cm intervals and sea surface height anomaly by colour shading.

have a coarse resolution of 1/2–1/4°, and most of the systems have a horizontal resolution of at least 1/10°. The vertical levels can be Z-levels, hybrid or sigma, depending on the model code used. As for the global systems, the systems that use NEMO are z-level; the systems that use HYCOM have hybrid vertical levels, and the systems based on ROMS have sigma vertical coordinates. All the systems with z-level have at least 50 levels, and all of them use the partial step parameterization (NEMO_book_v3_3.pdf, page 90) to better resolve the bathymetry. The maximum number of vertical z levels is 72 for the MFS system implemented in the Mediterranean Sea. The number of levels in the hybrid coordinates ranges from 21 in the REMO systems to 54 in the MOVE/MRI.COM-NP. The systems based on the ROMS code have a number of sigma levels that vary from 20 to 40, depending on the system.

Clearly, the vertical resolution can vary considerably according to how the vertical discretization has been applied to each model and to the specific characteristics of each area.

All the systems, except for the IBI and INDOFOS systems, have a data-assimilation scheme (Martin et al. 2015). The FOAM, MFS, MOVE/MRI.COM and CONCEPTS (only for ice observations for CONCEPTS) regional systems use a 3D-Var scheme. The TOPAZ system uses instead a scheme based on the Ensemble Kalman Filter, while the PSY2 from Mercator uses the same scheme described for the global system based on the SEEK filter. All the other systems (CGOFS and REMO) use an Ensemble OI scheme.

All the systems with a data-assimilation scheme based on 3D-Var and Kalman Filter assimilate the same type of observations described for the global systems in Section 2.1 (see also Martin et al., 2015). The regional systems with an Ensemble OI system assimilate only SLA and SST observations. The impact of observations via data assimilation into these systems is described in Oke et al., (2015).

Several systems have improved their data-assimilation scheme in the last 5 years. The Brazilian REMO system (Lima et al. 2013) for example has substituted a simplified OI scheme with the Ensemble OI scheme (EnOI) for the assimilation of satellite SST and SLA. The skills of the 24 h forecast of this system were comparable with some of the GODAE OceanView systems, as shown by the Taylor diagrams (Taylor 2000) in Figure 7. The diagrams in Figure 7(a) and (b) were prepared with respect to the Argo temperature and salinity data, respectively, so that the data have a centred root-mean-square deviation (RMSD) equal to zero and a perfect correlation. The standard deviation of the temperature data is well captured by all systems, but the REMO system yields a smaller standard deviation for salinity than the observations and the analyses of the other systems. The REMO RMSDs of temperature and salinity are larger than the other systems, and the correlation smaller. It is expected that the REMO system will improve its skills when Argo data are assimilated.

Two systems, TOPAZ in the Arctic and the north Atlantic and the Mediterranean Forecasting System, also have a biogeochemical component (NORWECOM and OGS OPA-BTM, respectively; Skogen 1998; Teruzzi et al. 2014) coupled with the physical system. The integration of the physical and biogeochemical models is very important, especially at regional and coastal levels. The

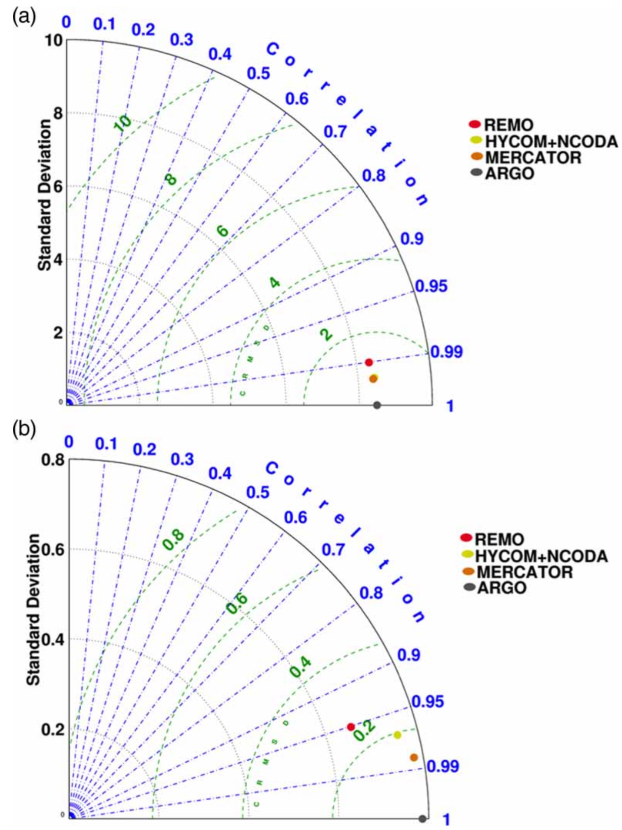


Figure 7. Taylor diagram for (a) temperature and (b) salinity for a REMO 24-h forecast (red), the HYCOM+NCODA analysis (yellow) and the Mercator-Ocean analysis (orange) considering Argo T/S data as reference from 1 April 2011 to 31 March 2012.

importance of this link is clear, for example, in Figure 8, where the gross primary production of carbon is shown from the Topaz4-NORWECOM system. The productivity is intense near the ice edge, and so its correct constraint is very important.

The Mediterranean Forecasting System, MFS (Tonani et al. 2008; Oddo et al. 2009) includes a wave component (based on WaveWatch-III) lightly coupled with the OGCM (NEMO) in order to improve the representation of the wave and oceanographic parameters (Clementi et al. 2013). The coupling between wave and circulation models is achieved through an hourly exchange of sea surface current and temperature fields from NEMO to WaveWatch-III; at the same time WaveWatch-III passes the neutral component of the drag coefficient to NEMO. This upgrade of the MFS system was developed within the EU-MyOcean and MyOcean2 projects (http://marine.copernicus.eu). This coupled system is able to provide users with the Stokes drift, which, in the case of an intense wind event, can be a strong signal in the current surface field (see Figure 9).

The tidal signal is resolved only by the RTOFS Atlantic system (NOAA/NWS/NCEP) and the Mercator-Ocean IBI (Iberian Biscay Irish seas). The IBI system was developed in 2011 in the context of the EU-founded project MyOcean in collaboration with Puertos del Estado (Spain). This system is characterized not only by the inclusion of the tidal signal in the OGCM (NEMO) model but also by an improved mixed layer scheme (Dombrowsky et al. 2012).

From this short overview of the regional systems, it is clear that, as expected, these systems differ not only for the geographical domain and the grid resolution but also for the processes resolved by their model configuration.

4. Data and product service

All the prediction systems produce data on global or regional scales, providing real-time forecast, analysis and hindcast fields on the model grid (native grid) or on an interpolated regular grid. The amount of data generated is very large and needs to be managed by data-services systems that will facilitate the user's ability to discover, evaluate, visualize, download and analyse all the available products (Blower et al. 2009).

The capability to discover, visualize and download the forecasting products is fundamental to reaching the oceanographic community and in general the users.

A great deal of progress from this point of view has been made in the last 5 years. All the systems described in this paper have a web page for the data discovery, and from most of them, the users can download and visualize data products (see Table 3).

The products from all the systems (except the Japanese products) are distributed in the same format, NetCDF, a standard for encoding oceanographic data. The data policy is different from centre to centre: in some cases, the access to the data is free, and in others some restrictions are applied.

Most of the centres developed dedicated catalogues in order to aid the users to discover the dataset they need. The structure, flexibility and performances of these informatics tools have increased significantly in recent years and have helped to serve products not only to the scientific research community but also to a wider community of users.

Depending on the system characteristics, all the GODAE systems deliver forecast products for the next 7–18 days, or for the next 7 months, as in the case of the MOVE/MRI.COM system. The ECCO system is the only one that does not produce forecasts but only analyses that are updated monthly. ECMWF instead does not disseminate the ocean analysis/forecast products. Most of these systems retain and distribute a long time series of analysis fields, ranging from 1 to 2 years or longer.

The development of the product service to the users has evolved differently in each country and for each system, even if there are several common tools used by most of the systems.

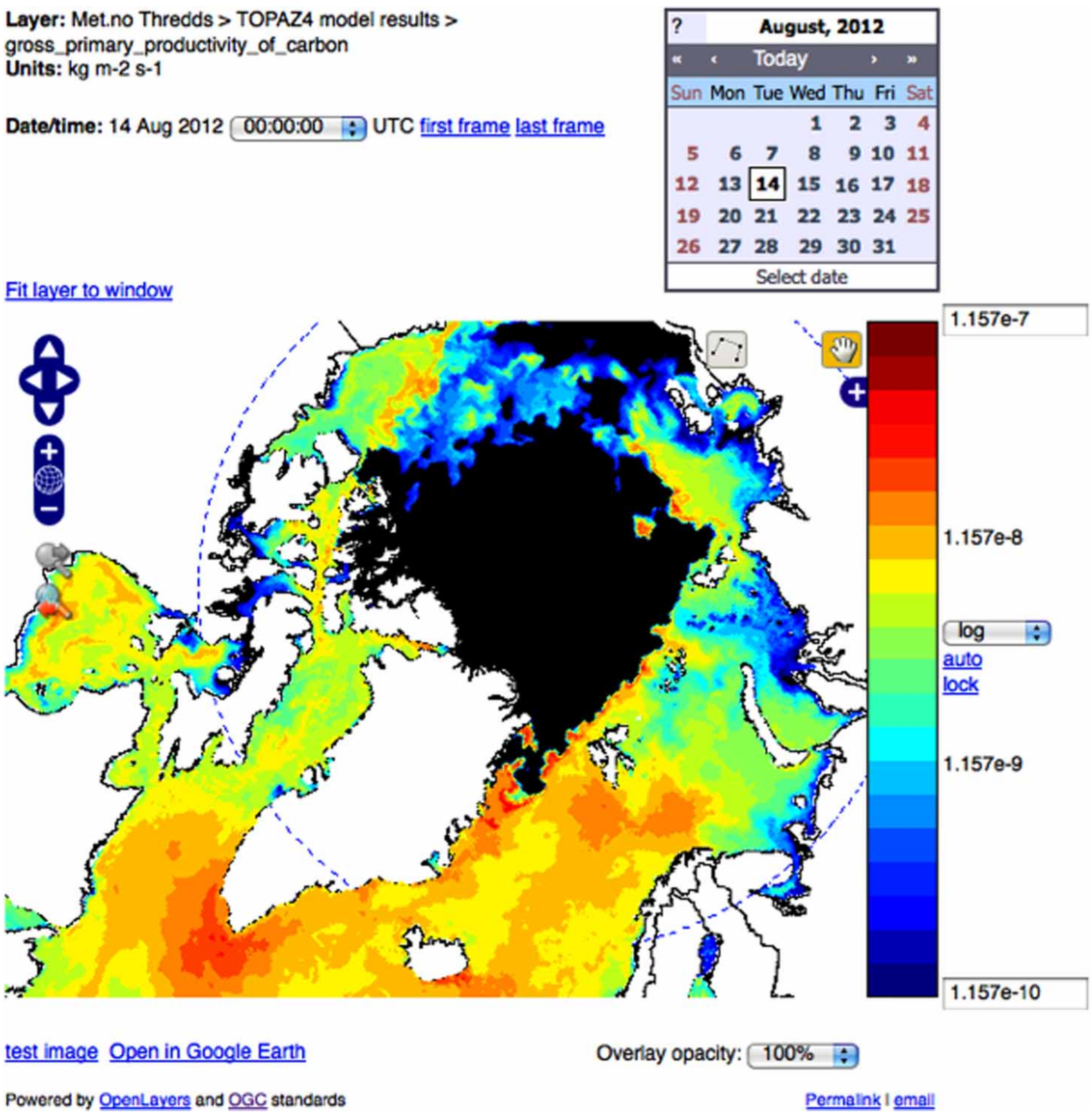


Figure 8. Gross primary production of carbon as forecast from the TOPAZ4-NORWECOM system in summer 2012. Note the intense productivity near the ice edge and thus the importance of its correct constrain by assimilation. The Godiva2 web map service provided by MyOcean has been used.

An example of this service evolution is the development of a European marine service. Most of the European systems described in this work are components of this system. A centralized catalogue has been generated for the dissemination of the products of the different forecasting centres. This initiative has been made in the frame of two projects, MyOcean (2009–2012) and MyOcean2 (2012–2014), http://marine.copernicus.eu, which developed the pre-operational European Copernicus marine service.

The operational products of the prediction systems are therefore available for different types of users and not only for the research community. The management of many emergencies in the last 4 years has relied on these products, including the Deepwater Horizon Oil Spill accident in the Gulf of Mexico on 20 April 2010 (Liu et al. 2011), the accident at the Fukushima Daichii nuclear power plant on 11 March 2011 (Masumoto et al., 2012; Garraffo et al. 2014) and the grounding of the Costa Concordia cruise ship on 13 January 2012 (De Dominicis et al. 2014).

These products have been used to initialize and provide lateral boundary information to the high-resolution ocean models implemented in the area of these incidents. In some cases, the systems also provided the current fields to force the oil spill or the radioactive dispersion modelling. More than one prediction system has been used in all of these examples enabling the development of ensemble products than were proved to be very useful for the assessment of the uncertainties.

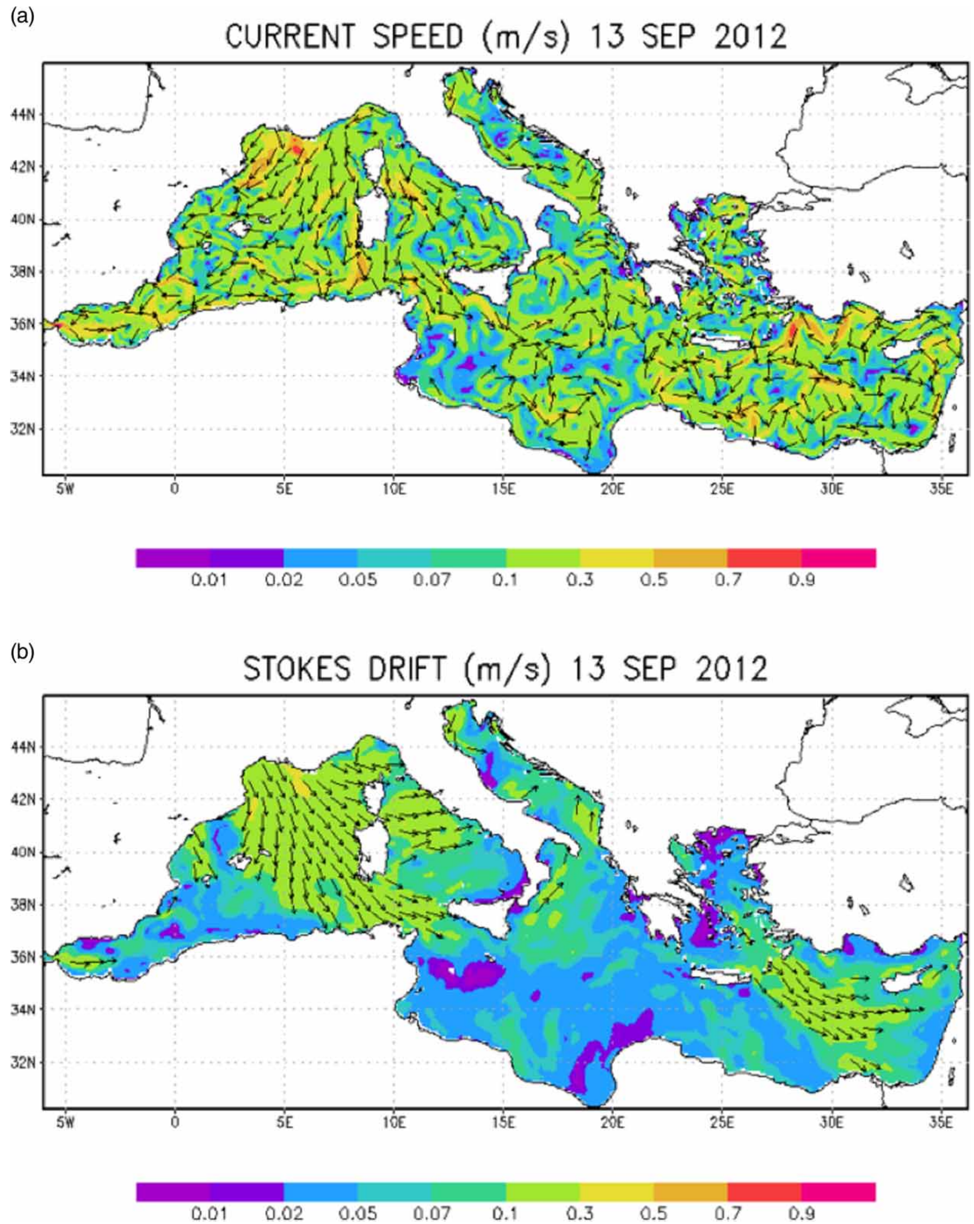


Figure 9. MFS forecast surface current field for 13 September 2012 (upper) and MFS surface Stokes drift forecast for the same day (lower). In the area of the Gulf of Lion (west basin), the Stokes drift currents have a higher intensity than the current speed forecast by the OGCM.

These examples underline the importance of using multiple systems with different characteristics implemented in the same area. Moreover, the high resolution of these products is very important, in both space and time in order to solve the ocean dynamics in areas of high variability.

These few examples prove that the important step to reach the users has been accomplished.

The interaction with the users for operational oceanography products is extremely important because users' feedback and requirements can provide a unique contribution to the development of new systems and new products that better suit the users' needs.

5. Future developments

All the systems have planned several improvements/developments for the next few years that affect all the components of the ocean forecasting systems:

- higher model grid resolution (horizontal and/or vertical);
- development of a biogeochemical model coupled with the physical system;
- implementation of coupled ocean–wave–ice–atmosphere forecasting systems;
- improvement of the data-assimilation scheme in order to adapt to the new forecasting systems characteristics;

Table 3. Data discovery, viewing and download services of the Global and regional prediction systems.

System	Website (data discovery)	Viewing service	Data download	Data format
ECCO-NRT (ECCO)	http://ecco.jpl.nasa.gov	X	OpenDAp Server/FTP	NetDF
MOVE/MRI.COM-G (JMA/MRI)	http://www.jma.go.jp/jma/indexe.html	NO	NO	TXT
MOVE/MRI.COM-WPN (JMA/MRI)	http://goos.kishou.go.jp/rrtdb/jmapro_new.html	X	NEARGOOS	
ECMWF (ECMWF)	http://www.ecmwf.int		ECMWF does not disseminate ocean forecast	
BlueLink/OceanMAPS (Bureu of Meteorology)	www.bom.gov.au/oceanography/forecasts (description) http://oceancurrent.imos.org.au (products download)	X	FTP	NetCDF
FOAM (MetOffice) GLOSEA (MetOffice)	http://marine.copernicus.eu http://www.ncof.co.uk/Deep-Ocean-Modelling.html	X	MyOcean download systems & FTP	NetCDF
CONCEPT (Canada)	Available soon	NO	NO	NetCDF
CGOFS (NMEFC)	http://www.nmefc.gov.cn/cgofs_en/index.aspx	X	NO	
PSY3/4 (Mercator-Ocean)	www.myocea.eu	X	MyOcean download systems & FTP	NetCDF
GOFS (NRL/ NAVOCEANO)	http://www7320.nrlssc.navy.mil/GLBhycom1-12/ (viewing and description) http://hycom.org (products download)	X	OpenDAP or FTP	NetCDF
RTOFS (NCEP)	http://polar.ncep.noaa.gov/global/	X	OpenDAP or FTP	NetCDF
TOPAZ	http://marine.copernicus.eu	X	MyOcean download systems & FTP	NetCDF
INDOFOOS	http://www.incois.gov.in/Incois/indofos_main.jsp	X	THREDDS/OpenDAP	NetCDF
MFS	http://marine.copernicus.eu http://medforecast.bo.ingv.it	X	MyOcean download systems & FTP	NetCDF
REMO	http://www.rederemo.org	X	OPenDAP	NetCDF

- assimilation of new types of observations;
- introduction of the ice component into the systems that do not have it yet;
- resolution of the tidal signal;
- better diagnostic protocols.

Even if each system has its own development plan, GODAE Ocean View provides guidance and an overview in order to share the expertise and to try and answer to users' needs.

Next there will be a short description of the near-future improvements for all the systems considered in this paper.

5.1. *MOVE/MRI.COM (JMA/MRI, Japan)*

The global model does not involve the Arctic area north of 75°N and adopts climatological ocean and sea ice condition for the area currently. In order to improve the representation of the tropical oceans and the Arctic area in the system, the ocean model will be replaced in early 2015 with a higher-resolution model with tripolar grid coordinate in which a sea ice model is incorporated.

The coastal system, MOVE/MRI.COM-SETO, is currently being developed (Figure 6) in order to predict abnormal coastal high tides owing to oceanic variations such as changes in the Kuroshio current. The system uses a 2-km high-resolution ocean model for south of the western Japan including the Seto Inland Sea nested in the lower-resolution western North Pacific model. The incremental 4DVAR method is adopted for the initialization. The system started operating in early 2015, and the area of the high-resolution model will be extended to cover the whole Japan by 2018.

5.2. *FOAM (MetOffice, UK)*

Over the next 5 years, there are plans to transition the Met Office short-range ocean forecasting systems to use a coupled ocean–ice–wave–atmosphere system with a 1/12° resolution ORCA12 ocean and an N1024 (~10 km) resolution atmosphere. This system will continue to use the NEMO, CICE and UM models, which will be coupled to the WAVEWATCH-III wave model (Tolman 2007).

The data-assimilation systems used at the Met Office are also being developed within the coupled framework to increase the consistency of the ocean and atmosphere analyses, and minimize coupled model initialization shock. This will initially involve the implementation of a weakly coupled assimilation scheme (Mirouze et al. 2013), which uses consistent coupled model background fields but performs separate analyses for the ocean/ice and the atmosphere/land – for which a prototype system is in the final stages of development. Further development work is planned to transition this scheme towards a fully coupled data-assimilation system.

5.3. *CGOFS (NMEFC, China)*

In the next 5 years, the planned developments of CGOFS mainly include: (1) replacing the MOM4-based global forecasting system with a new NEMO-based system; (2) increasing global model resolution from 1/4° to 1/12°; (3) developing downscaling schemes to drive ROMS-based regional systems by the NEMO-based global system; (4) further validating the EnOI data-assimilation system currently used for regional systems and assimilating more observations into the system; and (5) assimilating more observations, such as satellite chlorophyll data, into a marine ecosystem forecasting system.

5.4. *RTOFS (NOAAA/NCEP, USA)*

5.4.1. Global system

Plans for 2015 include an upgrade to 41 vertical levels with enhanced vertical resolution in the mixed layer and upper coastal oceans. This upgrade in close collaboration with US Navy (Metzger et al. 2014) would also couple HYCOM with CICE model using the ESMF (Earth System Modeling Framework). Plans have also begun for in-house analysis and initialization of this system at NCEP using a 3DVAR data assimilation, which is being developed in time for the next machine (hardware) upgrade expected in 2016. RTOFS is also serving as the ocean component for major coupling efforts at NWS/NCEP. HYCOM (the numerical engine for RTOFS) has been coupled successfully to the HWRF (Hurricane Weather Research and Forecasting) model for an improved hurricane prediction capability. This coupling is in the advanced stages of development and transition to operations. In addition, in close collaboration with US Navy, UCAR, ESRL and GFDL, efforts are under way to couple HYCOM with GFS and other earth system components within NEMS (NCEP's Environmental Modeling System) using tools provided by ESMF.

5.4.2. Regional system

This fiscal year, RTOFS Atlantic will undergo an upgrade to a recent version of HYCOM, which conforms to the community standards and provides for an efficient nesting within the Global RTOFS for more accurate representation of boundaries. Other near-future applications of this forecast system include coupled atmosphere–ocean hurricane forecasts and coupled circulation–wave ocean models with one-way and two-way interactions. Long-term plans involve using an ensemble-based modelling and data-assimilation system to improve forecast skill.

5.5. *MERCATOR-OCEAN (France)*

The main improvements in the next versions of the global systems will concern assimilation of new observations such as the surface velocity and the sea-ice concentration, and a new mean dynamic topography including new available observations from GRACE and global ocean reanalyses. An improved process for taking into account available observations in the assimilation scheme will also be developed thanks to a tuning of the observation errors based on Desroziers criteria (Desroziers et al. 2005) and with an optimization of the assimilation window to improve the initial state and consequently the forecast. Previous studies have shown improvements in forecasting with a shorter assimilation window from 7 to 5 days, for example (Drévillon et al. 2013), or with a time window depending on the type of observation (Martin et al. 2015).

From a more long-term perspective, the horizontal and vertical resolution will be improved, and the assimilation scheme will be updated to take into account satellite ocean colour observations, which are already available in real time with a good global coverage and a high resolution.

5.6. *TOPAZ (NERSC, Norway)*

In the next 5 years, we expect further improvements in the physical forecast accuracy by doubling the horizontal resolution of the ocean model, which should improve the resolution of narrow currents along the Arctic shelves. The ocean circulation should also benefit from new estimations of the mean dynamic topography from space. Further improvements in sea-ice drift and sea-ice thickness are expected from the sea-ice models: the EnKF supports the online estimation of uncertain model parameters (Massonnet et al. 2014). The assimilation system will also take advantage of new satellite measurements of ice thickness from SMOS and CryoSAT (Lisæter et al. 2007). In the years to come, the coverage of SAR images will become denser in the Arctic, which will boost ground-breaking developments of new sea-ice models accounting for the effect of waves (Williams et al. 2013), and using an elastic–brittle rheology based on solid mechanics rather than fluid mechanics (Girard et al. 2009). The ecosystem model will be gradually adapted to the particular light conditions and the plankton species dominating at high latitudes. The assimilation of ocean colour data and *in situ* data is also expected to improve the estimation of uncertain parameters (Simon et al. 2012).

5.7. *MFS (INGV, Italy)*

The current–wave (NEMO-WWW-III) interaction will be further developed, and the tidal signal will be introduced. The system resolution will be increased, and more data will be assimilated with the variational assimilation scheme (OceanVAR, Dobricic and Pinardi 2008). In particular, the satellite SST and the floats trajectories (Nilsson et al. 2011) will be introduced in the pool of the data assimilated. The real-time validation suite of the system will be further developed in order to provide a more accurate validation at a sub-basin scale.

5.8. *BlueLink/oceanMAPS (Bureau of Meteorology, Australia)*

OceanMAPS system will be upgraded to OceanMAPS3. The model horizontal resolution will be increased to 1/10 in all the model domains (the resolution is now 1/10 around Australia and 1 everywhere else) from 76°S to 76°N longitude.

The data-assimilation system, BODAS3 will have an extensive suite of new assimilation diagnostics to evaluate the quality of the products in near real time. This diagnostic tool will be based on standard metrics for the comparison of model/observation.

5.9. *GOFS (NRL/NAVOCEANO, USA)*

The ice model (CICE) will be added to the system and the number of the vertical level will be increased. The Improved Synthetic Ocean Profiles (ISPO) will be inserted into the new version of GOFS. ISPO is a technique developed by the US Navy to construct synthetic vertical profiles projecting remotely observed SSH and SST downward from the surface using a global database of statistical relationship (Helber et al. 2013).

The horizontal resolution of the system will be increased to 1/25 with the addition of the tides being planned for year 2016. A coupled GOFS3.5-WWW-III system is planned to be operational in 2018.

5.10. *CONCEPTS (Canada)*

A regional coupled atmosphere–ice–ocean–wave–snow model will be developed. The atmospheric model, GEM, will have a resolution of 15 km. The ocean models, NEMO-CICE_WW3 resolution will be 3–8 km with the introduction of tides, semi-Lagrangian scheme, Jacobian-free Newton–Krylov (JFKN) solver for sea-ice momentum eq. (CICE) and wave–ice coupling. This system, planned for 2015, will provide 3–5 days of ensemble forecast.

5.11. *INDOFOS (INCOIS, India)*

The development of fine-resolution ocean prediction systems will cover the entire coastal water of the country initially, and then the Indian Ocean rim countries subsequently.

5.12. *REMO (Brazil)*

The data-assimilation scheme used in all the systems will be further improved and validated.

6. Conclusions

In the last 5 years, the prediction systems of global and regional ocean forecasting were significantly improved from several points of view. The global systems have sensibly increased their resolution while the regional systems were applied on new areas. The complexity of the models has been increased: the models are now able to resolve more processes such as tides and waves, and are associated with more accurate data-assimilation schemes. Product services have been developed, and now the products of almost all the systems are available in near real time.

Some centres have started developing coupled systems that look very promising. Further scientific work is needed to understand better the processes that connect the different models (ocean–wave–atmosphere–ice).

The importance of coupling biogeochemical with physical systems has been stressed since the beginning. Given the complexity of developing these systems and the few real-time observational data for the biogeochemical systems, at present only a few systems offer this option. Many have now invested resources to be able to have this option in their systems in the future.

Examples of ensembles have been provided, but this line of research needs to be investigated further. The products should be delivered to the users efficiently and should be provided with an adequate spatial and temporal resolution.

The user/production interaction has to be taken into account as leading criteria for the future developments.

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Disclosure statement

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Note

1. These definitions have been developed specifically for numerical weather prediction and then extended to climate prediction. There are no such official definitions for the ocean prediction systems; therefore, this nomenclature has been adopted in this work even if the time-scales of ocean predictability are longer than for the atmosphere.

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Appendix 1. List of acronyms

3D-Var	Three-Dimensional VAriational assimilation
4D-Var	Four-Dimensional VARiational assimilation
AOML	Atlantic Oceanographic and Meteorological Laboratory from NOAA
BlueLink/ OceanMAPS	OCEAN Model Analysis and Prediction System
BODAS	BlueLink Ocean Data Assimilation System
CICE	Los Alamos Sea Ice Model
CONCEPTS	Canadian Operational Network of Coupled Environmental Prediction Systems
CryoSAT	Europe's first spacecraft dedicated to the study of ice
CTD	Conductivity Temperature and Depth (instrument for determining essential physical properties of sea water)
ECCO	Estimating the Circulation & Climate of the Ocean
ECMWF	European Centre for Medium-Range Weather Forecast
EnKF	Ensemble Kalman Filter

ESMF	Earth System Modeling Framework from NOAA
ESRL	Earth System Research Laboratory from NOAA
ET-OOF	Expert Team on Operational Forecasting System
EVP	Elastic–Viscous–Plastic
FLOPS	Floating Point Operation per Second
FOAM	Forecasting Ocean Assimilation Model (from the UK Met Office)
GDAC	Global Data Assembly Center
GEM	Global Environmental Multiscale (Canadian NWP model)
GFS	Global Forecast System
GFDL	Geophysical Fluid Dynamics Laboratory
GHRSST	Group for High-Resolution Sea Surface Temperature
GLOSEA	GLObal SEAsonal (coupled ocean–atmosphere modelling system from UK MetOffice)
GODAE	Global Ocean Data Assimilation Experiment
GOFS	Global Ocean Forecast System (from US NRL)
GOVST	GODAE Ocean View Science Team
GRACE	Gravity Recovery and Climate Experiment
HWRF	Hurricane Weather Research and Forecasting
HYCOM	HY brid Coordinate Ocean Model
IBI	Iberian Biscay Irish sea
INCOIS	Indian National Centre for Ocean Information Services
INDOFOS	INdian Ocean Forecasting System
IOC	Intergovernmental Oceanographic Commission
ISPO	Improved Synthetic Ocean Profiles
IV-TT	Intercomparison and Validation Task Team
JCOMM	Joint Technical Commission for Oceanography and Marine Meteorology
JFKN	Jacobian-free Newton–Krylov
JMA	Japan Meteorological Agency
LIM	Louvain-la-Neuve Sea Ice Model
MFS	Mediterranean sea Forecasting System
MIT	Massacgusetts Institute of Technology
MOM	Modular Ocean Model
MOVE/MRI.COM	Ocean Data Assimilation System (from JMA/MRI)
NAVGEM	Navy Global Environmental Model
NCEP	National Centers for Environmental Prediction
NEMO	Nucleus for European Modelling of the Ocean
NEMS	NCEP's Environmental Modeling System
NERSC	Nansen Environmental and Remote Sensing Center (Norway)
NetCDF	Network Common Data Format
NMEFC	National Marine Environment Forecasting Center (China)
NOAA	National Oceanic and Atmospheric Administration (US)
NOGAPS	Navy's Operational Global Atmospheric Prediction System (US)
NORWECOM	model for lower trophic levels and nutrient cycling
NRL	US Naval Research Laboratory
NWP	Numerical Weather Prediction
OGCM	Ocean General Circulation Model
OI	Optimal Interpolation
OPA-BTM	Ocean Parallelize – Biological Flux Model
OSTIA	Operational Sea Surface Temperature and sea Ice Analysis
REMO	Oceanographic Modeling and Observation Network (from Brazil)
RMSD	root-mean-square difference
ROMS	Regional Ocean Modeling System
RTOFS	Real Time Ocean Forecast System (from US NCEP/NOAA)
RTS	Rauch–Tung–Striebel
SEEK	Singular Evolutive Extended Kalman filter
SLA	Sea Level Anomaly
SMOS	Soil Moisture Ocean Salinity (Earth Explorer mission)
SSH	Sea Surface Height
SST	Sea Surface Temperature
TOPAZ	Toward an Operational Prediction system for the North Atlantic European coastal Zones
UCAR	University Corporation for Atmospheric Research
UM	Unified Model (SW suite)
WMO	World Meteorological Organization
XBT	eXpandable BathyThermograph