THE COPERNICUS MARINE ENVIRONMENTAL MONITORING SERVICE: MAIN SCIENTIFIC ACHIEVEMENTS AND FUTURE PROSPECTS

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THE COPERNICUS MARINE ENVIRONMENTAL MONITORING SERVICE: MAIN SCIENTIFIC ACHIEVEMENTS AND FUTURE PROSPECTS

BY

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ABSTRACT

The Copernicus Marine Environment Monitoring Service (CMEMS) provides regular and systematic reference information on the physical state, variability and dynamics of the ocean, ice and marine ecosystems for the global ocean and the European regional seas. CMEMS includes both satellite and *in-situ* high level products prepared by Thematic Assembly Centres (TACs) and modelling and data assimilation products prepared by Monitoring and Forecasting Centres (MFCs). The paper presents the CMEMS service evolution strategy and provides an overview of the main R&D activities and achievements carried out by CMEMS TACs and MFCs over the past three years. Future prospects are summarized in the conclusions.

Keywords: ocean, analysis, forecasting, research, physics, biogeochemistry, applications

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INTRODUCTION

The Copernicus Marine Environment Monitoring Service (CMEMS) is one of the six pillar services of the Copernicus program. Mercator Ocean was tasked in 2014 by the EU under a delegation agreement to implement the operational phase of the service from 2015 to 2021. CMEMS is the culmination of a line of activities aimed at the provision of operational marine services, beginning with MERSEA (2004-2008), and followed by MyOcean (2009-2012) under FP7, and MyOcean2 (and its follow-on) from 2012 through 2015. The development of CMEMS has required collaboration and innovation across research and technology, in observations, modelling, assimilation, and product and service delivery. Cooperation has extended across Europe and into the international community, in support of Blue Growth and the Blue Economy.

The CMEMS now provides regular and systematic reference information on the physical state, variability and dynamics of the ocean, ice and marine ecosystems for the global ocean and the European regional seas. This capacity encompasses the description of the current situation (analysis), the variability at different spatial and temporal scales, the prediction of the situation 10 days ahead (forecast), and the provision of consistent retrospective data records for recent years (reprocessing and reanalysis). CMEMS provides a sustainable response to European user needs in four areas of benefits: (i) maritime safety, (ii) marine resources, (iii) coastal and marine environment, and (iv) weather, seasonal forecast and climate. A major objective of the CMEMS is to deliver and maintain a state-of-the-art European service responding to public and private intermediate user needs, and thus involving explicitly and transparently these users in the service delivery definition.

The CMEMS mission includes:

- Provision of short-term forecasts and outlooks for marine state conditions and, as appropriate, to downstream services for warnings of and/or rapid responses to extreme or hazardous events;
- Provision of detailed descriptions of the ocean state to initialize coupled ocean/atmosphere models to predict changes in the atmosphere/climate;
- Monitoring and reporting on past and present marine environmental conditions (physics and biogeochemistry), in particular, the response of the oceans to climate change and other stressors;
- Analysing and interpreting changes and trends of the marine environment;
- Providing an easy, efficient and timely information delivery service to users.

CMEMS products include high level data sets derived from satellite and in-situ observations (through Thematic Assembly Centres, TACs) and model reanalyses, analyses and forecasts (Monitoring and Forecasting Centres, MFCs). They are based on near real-time (NRT) data transmission, state-of-the-art data processing and advanced modelling and data assimilation techniques. The product uncertainties are assessed through rigorous internationally recognized quality assessment methods.

CMEMS information delivery service and its service desk provide an easy, efficient and timely access to CMEMS data and products and related information. Users are able to discover, gain experience and access CMEMS operational data, products and associated services. Moreover, they express their requirements and provide feedback to drive the service evolution.

In this paper, the initial R&D achievements of CMEMS over the past 3 years are reviewed. This covers the different elements of CMEMS production centres. The objective is to illustrate the essential role of R&D activities to improve CMEMS products and services. These activities cover the different service lines of CMEMS: ocean physics, sea ice and biogeochemistry, real time monitoring and forecasting, delayed mode reprocessing and reanalysis.

The paper is structured as follows. Section 2 presents CMEMS architecture and the overall CMEMS strategy for service evolution and associated R&D activities. Product quality and multi-year product cross-cutting (i.e. common to all TACs and MFCs) issues are discussed in Sections 3 and 4. R&D activities including impact on applications are described in Section 5 for observation components (TACs) and in Section 6 for monitoring and forecasting components (MFCs). Main conclusions and future prospects are given in Section 7.

CMEMS ARCHITECTURE AND SERVICE EVOLUTION R&D ACTIVITIES

The backbone of the CMEMS relies on an architecture of production centres both for observations (Thematic Assembly Centres – TACs) and modelling/assimilation (Monitoring and Forecasting Centres – MFCs) and a Central Information System (CIS) (Figure 1).

- Four TACs, including three "space" TACs organized by ocean variables (sea surface topography, ocean colour, and sea surface temperature, sea ice and winds) and one for *in-situ* observations, gathering observational data and generating elaborated products, e.g. multi-sensor data products, derived from these observations. The TACs are fed by operators of space and in-situ observation infrastructure.
- Seven MFCs, distributed according to the marine area covered (including Global Ocean, Arctic Ocean, Baltic Sea, North-West European Shelf area, Iberia-Biscay-Ireland area, Mediterranean Sea and Black Sea), and generating model-based products on the ocean physical state and biogeochemical characteristics, including forecasts, hindcasts and reanalyses.
- A CIS, encompassing the management and organization of the CMEMS information and products, as well as a unique User Interface.

CMEMS evolves based on requirements from its users accounting for both existing and future needs. The CMEMS

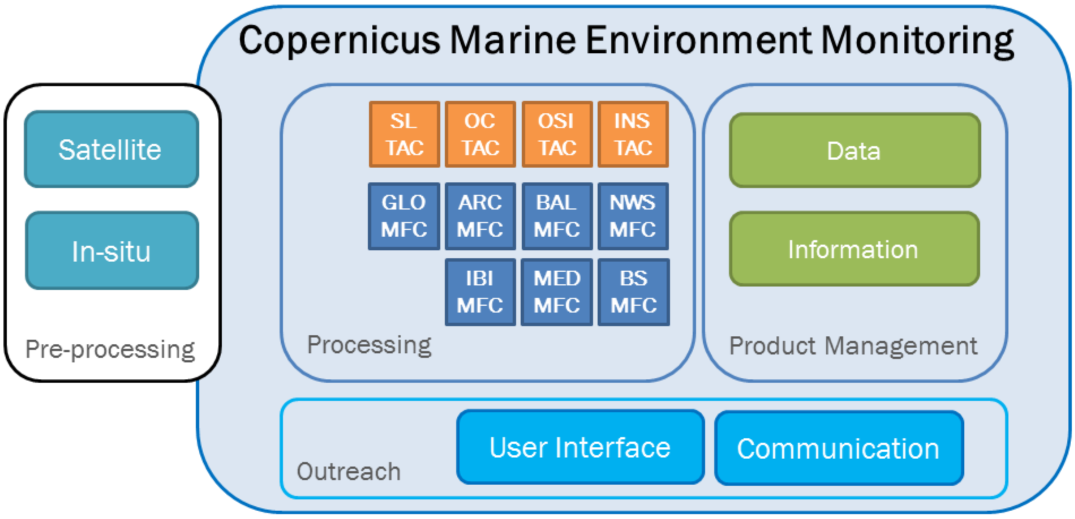


FIGURE 1

System overview of the Copernicus Marine Environment Monitoring Service chain. This schematic shows the main elements of the architecture. All these building blocks (processing, product management, outreach) will evolve over the coming years in response to user needs and science/technology advances.

evolution also takes into account new scientific and technological achievements and opportunities regarding both satellite and *in-situ* observations, modelling and assimilation capabilities, new communication and data processing technologies and the need to maintain competitiveness with respect to international players. CMEMS evolution is, in particular, driven by an increasing need for ocean and marine ecosystem monitoring and forecasting. This is imperative to understanding and predicting the evolution of weather and climate. This is also essential for a better and sustainable management of the oceans and seas to support the development of the blue economy that is expected to grow by a factor of at least 2 by 2030 (e.g. OECD 2016 study). As such, the capability of CMEMS to provide relevant answers to existing and future needs is highly dependent on the improvement of the service offered.

The CMEMS Service Evolution high-level Strategy and its associated R&D priorities (Mercator Ocean, 2016a; CMEMS STAC, 2017) introduce a set of over-arching goals and associated actions and R&D priorities for evolving the service from its initial state towards a mature, state of the art, leading to an innovative Copernicus Service. The CMEMS R&D roadmap identifies short-term (<1 year – Tier 1), mid-term (1 to 3 years – Tier 2) and long-term (3 to 10 years – Tier 3) R&D activities. Short-term R&D and part of the mid-term R&D are carried out by CMEMS production centres. Mid- and long-term R&D activities are mainly addressed through calls for tenders for CMEMS Service Evolution and through external (e.g. Horizon 2020 and national R&D programs). It should be emphasized that long-term R&D activities, although implemented in a different framework, are as crucial as short- and mid-term activities for the sustainable evolution of the service.

Continuous service improvement demands a well-designed and robust architecture. It provides a consistent approach to guide and organise the service evolution. System and product evolution are managed by a rigorous change management process and a transition management process is applied to minimise the impacts of the evolutions for the users. Every year in April a new version of the CMEMS system of systems is thus set into operation following a carefully managed development process (from design, to implementation, integration and operation). A formal review process is in place to manage the development and entry into service. Following the V1 CMEMS version that started the initial service, V2 and V3 versions were set up in April 2016 and April 2017 and V4 will enter into service in April 2018. The main developments of CMEMS TACs and MFCs from V1 to V4 are summarized in Annex 1.

In the following sections, cross-cutting issues related to product quality assessment and multi-year product developments are first described. The main R&D activities carried out by TACs and MFCs over the past 3 years are then detailed and main improvements of the service are summarized.

PRODUCT QUALITY ASSESSMENT

OVERVIEW

In order to deliver generic and reliable information in a consistent way for all CMEMS products, a dedicated Product Quality cross-cutting activity has been set-up at the start of CMEMS, bridging top level management by Mercator Ocean to routine and operational scientific validation in production centres. The activity aims at providing high-quality verified state-of-the-art ocean products, thus the information on the quality has to be scientifically sound and consistent, useful and communicated effectively to users. The Product Quality assessment activity also intends to take into account users' requirements and feedback.

Consequently, the CMEMS Product Quality framework is developed based on/using state-of-the-art scientific and technical validation/verification methodologies. The framework aims to mobilise newly developing ideas and associated capabilities from all relevant existing expertise across the involved European scientific community, making the link with best practices developed at the international level (e.g. the GODAE OceanView community). In particular, the CMEMS Product Quality starting framework is a heritage of the MERSEA/GODAE methodology (Hernandez *et al.*, 2015), focusing on four issues of increasing interest: 1) Consistency with existing knowledge of the ocean; 2) Accuracy of the products; 3) Quality/Performance of the prediction; and 4) Fitness-for-purpose of the products.

Two approaches are identified and promoted:

- an internal assessment, where the Product Quality assessment aims at verifying that the estimating/predicting systems are matching the scientific requirements. This is the approach adopted by most of the ocean science teams, whether operational or more academic. Whereby a series of metrics and diagnostics are calculated to verify if the solutions provided by the system are representing the ocean processes that the system should be able to represent.
- an external assessment, which aims at providing the users with an evaluation of the product accuracy, or forecasting skill; with respect to the actual observed ocean signals and taking into account the way the product is used for a given application.

PRODUCT QUALITY ORGANISATION

A detailed description of this activity is given by the Product Quality Strategic Plan (Mercator Ocean, 2016b). In practice, this activity is split between production centres, and cross-cutting tasks. The bulk of the validation/verification and quality control of the production, as well as the monitoring of the operational system are performed and managed at the production centre level. They include: 1) the routine online near real-time or delayed mode validation; 2) the dedicated assessment of Multi-Year products; 3) the pre-operational qualification of future systems; 4) the implementation of new metrics; and 5) the reporting, in particular in order to inform users on the quality of products. The dedicated description of products and operational systems, later in this article, rely on such validation activities carried out by the production centres.

New validation metrics are defined by the Product Quality Working Group composed by experts working in each production centre together with experts from Mercator Ocean. These new metrics when agreed are implemented in the production centres.

All metrics, diagnostics and methods are documented in operational Validation Plans (ScVP), and Pre-Operational Qualification Plans (ScQP). This allows sharing scientifically and technically the product quality framework among all CMEMS interested parties. The overall Product Quality activity is coordinated by Mercator Ocean which role is to: 1) define the strategy; 2) verify that the product quality activity in production centres is matching the requirements; 3) take into account and collect user's requests and feedback; and 4) organize the communication of product quality information towards users.

This communication towards users relies first on comprehensive documents the "QuIDs" –stands for Quality Information Documents– available for each product in the CMEMS online catalogue, and written by validation/verification experts in production centres. QuIDs provide a scientific description of the operated system, the validation methods, the performance of the system, and the quality of the products, in particular, with estimated accuracy figures. QuIDs are revised at each upgrade of the systems and for changes in the production.

Then QuIDs are complemented by a Product Quality Online Monitoring in the CMEMS website (http://marine.copernicus.eu/services-portfolio/scientific-quality/). This monitoring is based on a series of dedicated metrics "product against observations", quarterly updated, showing main performances for each European basin and each type of products.

FIRST ACHIEVEMENTS

The CMEMS Product Quality activities started with the MyOcean project framework. Whose main identified weaknesses (Mercator Ocean, 2016b) were a lack of homogeneity among the production centre's validation activities and QuIDs; a lack of multi-estimate, multi-model ensemble approaches; the need for more efficient use of existing observations; to enhance biogeochemical and wave products' quality assessment.

Through annual meetings and coordinated tasks, the cross-cutting Product Quality Working Group is improving the standardization of metrics and the common adoption of best practices. For instance, the common use of moorings along the European coast, and the definition of common metrics allowed by comparison: 1) to provide evidence between overlapping MFCs of the differences and potential biases; 2) to measure the added value of regional versus global products; 3) to quantify improvements of Multi-Year products compared to real time operational production; and 4) to exhibit strengths and weaknesses between TAC and MFC products.

The effort to provide the requested quality information for all the CMEMS products pushed all production centres to quantify errors. As described later in this article, all TACs are now providing error levels for L4 gridded products. Similarly, with the introduction of wave products there has been a dedicated effort to provide error levels by all MFCs on significant wave height and main wavelength of the wave spectrum.

A common effort has also been made to share best practices concerning new reference data sets. The IBI MFC was pioneering the validation against HF Radar and then supported similar efforts and testing carried out by the North-West European Shelf (NWS) MFC. Similarly, new instruments like the Biogeochemical (BGC) Argo profilers, still under validation by the In-Situ (INS) TAC, are subject to common work with the OC TAC. This work should allow the development of common practices for biogeochemical product validation that will be shared with the MFCs.

MULTI YEAR PRODUCTS (REPROCESSING, REANALYSIS, OCEAN STATE REPORT)

OVERVIEW

One of the main requirements from CMEMS users is to have long time series of data as a reference statistical and quality framework. Among those users, environmental agencies also require ocean state and marine environment monitoring. This is achieved through the annual release of the CMEMS Ocean State Report (OSR), which aims to monitor and describe ocean variability and change from the past to the present; and through the development of operational Ocean Monitoring Indicators (OMIs), and related error bars. These developments must rely on continuous and high-quality reanalyses and reprocessing time series, which go up to real time, and which ensure high resolution coverage of the European regional seas, as described in the Multi-Year products strategy document (Mercator Ocean, 2016c). CMEMS assures the collection of "best quality" input data and maximal use of multiple observation systems, and on the long term, aims at a fully consistent approach across global and regional reanalyses. CMEMS organises their interoperability, their inter-dependencies, and joint operations closer to real time (a few months only) with a systematic yearly update.

REPROCESSING

CMEMS reprocessing products are strongly dependent on upstream data as processed by space agencies and other programs (ESA, EUMETSAT, OSI SAF, etc.). These include reprocessed Level 1 and Level 2 data. Interfaces between CMEMS and space agencies have been developed, as well as with the C3S. The latter delivers dedicated reprocessing of climate information focussed on the quality, consistency and homogeneity of the observing system for a list of Essential Climate Variables. The CMEMS reprocessing products is different and complementary to the C3S (Copernicus Climate Change Service) reprocessing. CMEMS reprocessing aims at an optimal use of high resolution input data, and at a seamless connection with CMEMS real time observations.

REANALYSIS

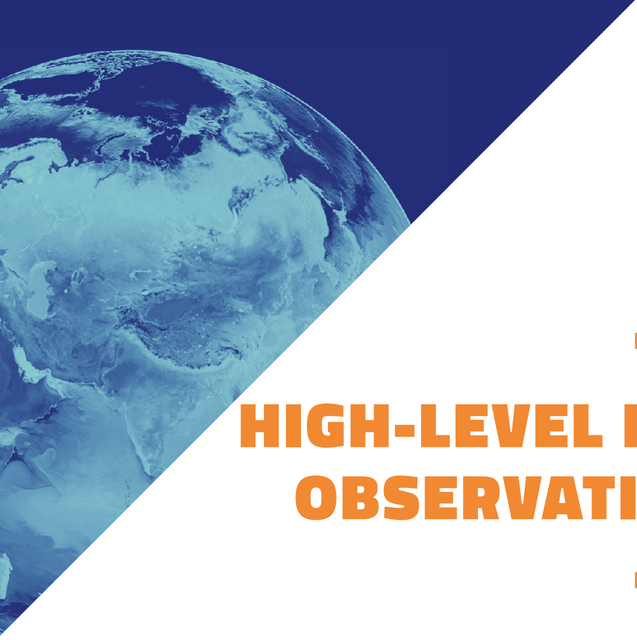
CMEMS reanalyses aim at a seamless connection with CMEMS real time analyses and forecasts. CMEMS produces global and regional reanalyses both for physics and biogeochemistry. Regional reanalyses benefit from both higher resolution and specific regional tunings. Particular attention is paid to sea ice and biogeochemistry components for all CMEMS reanalyses. CMEMS reanalyses are different and complementary to the C3S reanalyses that are global and which first objective is to achieve an accurate description of multi-decadal climate variability to initialize global coupled ocean/atmosphere forecasts.

OCEAN STATE REPORT

The Copernicus Marine Environment Monitoring Service (CMEMS) Ocean State Report (OSR) provides a comprehensive and state-of-the art assessment of the state of the global ocean and European regional seas for the ocean scientific community as well as for policy and decision makers. It will contribute to the reporting tasks and activities of European environmental agencies (e.g. EEA) and international organizations (e.g. IPCC and United Nations Sustainable Development Goal 14). In addition, the report aims at increasing general public awareness about the status of, and changes in, the marine environment. The Ocean State Report draws on expert analysis and provides a 4-D view (reanalysis systems), from above (through remote sensing data) and directly from the interior (*in-situ* measurements) of the blue (e.g. temperature, salinity, currents), white (e.g. sea ice) and green (e.g. chlorophyll) global ocean and European regional seas. The first issue of the year 2016 provides information on the physical ocean state and changes over the period 1993–2015 and has been published in the Journal of Operational Oceanography (von Schuckmann *et al.*, 2017).

Principal findings of the first Ocean State Report focused on the fundamental role of the oceans in the Earth's climate system; as an energetic and biogeochemical buffer affecting the ocean's physics and chemistry; and as a regulator through its ability to absorb and transport large quantities of heat, moisture, and biogeochemical gases around the planet. Anomalous changes were reported for the year 2015 relative to the reference period 1993-2014, using parameters such as ocean temperature and salinity, sea level, ocean heat, sea ice extent, chlorophyll and oxygen. The first issue reported on a number of trends, including decreasing Arctic and increasing Antarctic sea ice extent, global and regional sea level rise, sea surface temperature increase and the warming of the global and European regional seas.

The second issue in the year 2017 is under evaluation and highlights changes in the marine environment for the period 1993-2016, and brings into focus remarkable events during the year 2016. Future issues will include innovative and new uncertainty assessments based on a unique multi-product approach and will be extended to additional Essential Variables. More efforts will be put into monitoring biogeochemical changes and improving progressively the accuracy and uncertainty assessment for biogeochemical OMIs with a specific focus on European regional seas.



HIGH-LEVEL DATA PROCESSING AND OBSERVATION PRODUCTS (TACs)

OVERVIEW

The role of the CMEMS Thematic Assembly Centres (TACs) is to collect, process and quality control upstream satellite and *in-situ* data required both to constrain and validate modelling and data assimilation systems and to directly serve downstream applications and services. The satellite TACs main functions are to work on homogenization and intercalibration of data from multiple missions (so called L2P processing) and the development of higher level data products (L3 and L4). The In-Situ TAC deals with the collection of data from a wide range of networks and the development of homogenized quality control and validation procedures as well as high-level data products. Both satellite and In-Situ TACs include global and regional (European seas) products as well as near real-time and reprocessed data.

SEA LEVEL

Overview

The main objective of the Sea Level (SL) TAC is to provide, in an operational context, sea level products from satellite altimetry missions for the MFCs and external users. This is a major input for operational oceanography systems that rely on multiple altimeter data sets to reliably locate and position mesoscale eddies and fronts. The SL TAC production is based on DUACS (Data Unification and Altimeter Combination System). All the altimetry data are homogenized and cross-calibrated to obtain a consistent set of products easy to use for assimilation in ocean models. This production includes along-track data and gridded products, generated both in real time (3h) and reprocessed offline (6 months). The SL TAC catalogue of products is composed of Global Sea level products including: sea level anomalies (SLA), absolute dynamic topographies (ADT) and geostrophic currents. Regional products in the Mediterranean Sea, Black Sea, Arctic, and European regions complement this portfolio. The SL TAC products, formerly available on the CNES/AVISO website are now available on the CMEMS portal. This transfer was completed in 2017. This is a major achievement of the first half of CMEMS, allowing the SL products to be the second most downloaded products of the catalogue.

The production and delivery of the SL TAC products (external and internal) have been performed during the last three years on a nominal basis. Using 3 to 5 altimetric missions, with the integration of 2 new satellites in 2016 (Jason-3 and Sentinel-3A). This configuration ensures a consistent and high quality spatial coverage of the ocean and will allow us to maintain a high level of product quality for the coming years. Notably, the use of the synthetic-aperture radar (SAR) mode altimetry on board Sentinel-3A allows better retrievals of the small scale ocean signals. A complete reprocessing of the 25 years (80 years adding up/taking into account all the missions) of the altimetry time series is in progress. This processing will use the most recent reprocessed geophysical data record (GDR) that ensures a maximum consistency between missions. This product will benefit from significant improvements both for mesoscale and for climate scales.

In the coming years the SL TAC intends to use the full potential of the Sentinel-3A/B SAR modes and maximize the use of all the altimetry missions flying at the same time (up to 6) by improved mapping techniques (Ubelmann *et al.*, 2016) with the goal of reaching a 100 km/7 day resolution for gridded fields. In the longer-term perspective the integration of the Surface Water Ocean Topography (SWOT) mission will improve the resolution further to better fit user needs.

The most significant R&D advances over the past 3 years are summarized below.

Integration of Jason-3 and Sentinel-3A

For the last three years, the SL TAC system has used all the altimetry missions available to provide products with an optimal quality. The management of the constellation has been a priority during these three years, with the integration of new missions, but also the management of anomalies on flying satellites. A good illustration of the constellation variation is given by the relative contribution of each altimeter in the gridded multi-mission product shown in Figure 2. The contribution is derived from the degrees of freedom of signal analysis (Dibarboure *et al.*, 2011). At the end of Myocean-2, the altimetry constellation was composed of 4 satellites: Jason-2 (the reference mission), Altika; and 2 opportunity missions Cryosat-2; and the Chinese satellite HY-2A integrated in June 2014. Jason-3 was replaced by Jason-2 as reference mission in October 2016. A seamless transition was ensured in real time and offline products thanks to the optimal coordination between all the actors (space and operational agencies, Calibration/Validation teams). The integration of Sentinel-3A SRAL (synthetic aperture radar altimeter) data were performed early 2017.

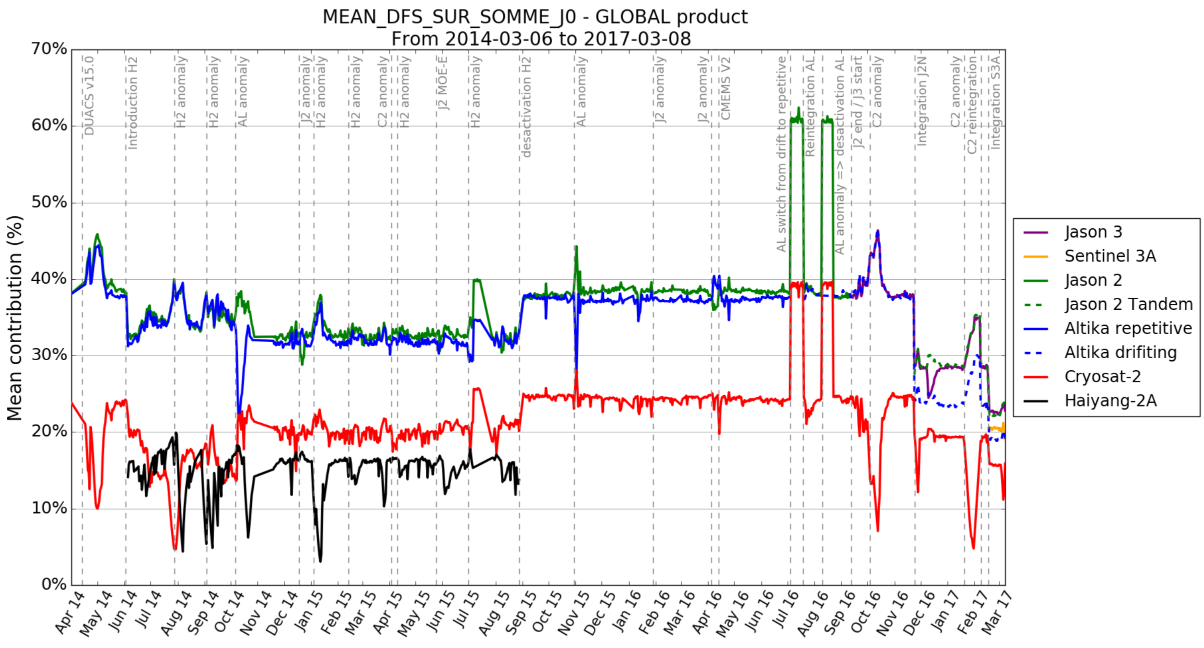


FIGURE 2

Relative contribution of each altimeter in the multi-mission CMEMS maps for 2015-2017 and link with altimeter events. The contribution is derived from the degrees of freedom of signal analysis described by Dibarboure *et al* (2011). Unit: %.

The orbit of Sentinel-3A complements the reference mission Jason-3. Figure 3a illustrates the coverage of the current constellation over the Gulf Stream area for a 4-day period. The CMEMS assessment exercise allowed us to confirm the great performance of Sentinel-3A. Figure 3b shows that, thanks to Sentinel-3A, more eddies are retrieved in areas of large oceanic variability and at high latitudes, where Sentinel-3A data interestingly complements the Cryosat coverage.

These new satellites will ensure the continuity of the sea level time series with consistent and high quality coverage of the ocean allowing us to maintain a high level of product quality in the coming years even after the decommissioning of the longest operated satellite missions. The launch of Sentinel-3B in early 2018 will continue to improve the sea level coverage from space.

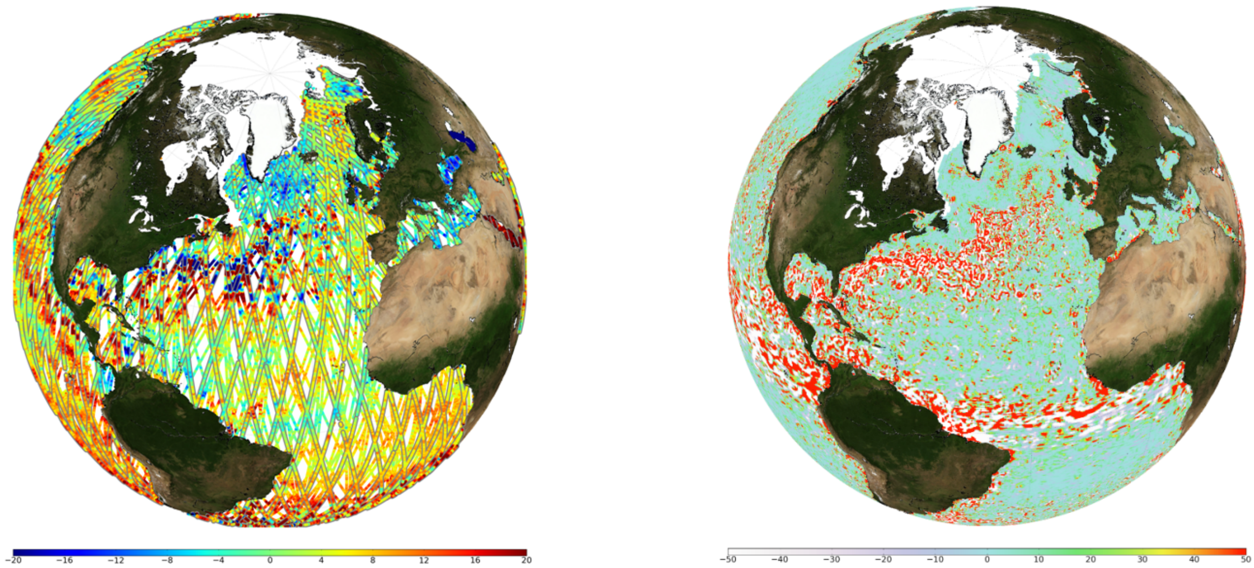


FIGURE 3

(a) Coverage of Sentinel-3A (gray edges), Jason-3, Jason-2, Altika and Cryosat for the 1st-4th March 2017 period. (b) Mean eddy kinetic energy difference with/without using Sentinel-3A for the January-February period (unit in cm^2/s^2) where positive values show the energy retrieved by Sentinel-3A.

Sentinel3A SRAL: a new instrument to improve the product resolution.

The SAR altimeter on-board Sentinel-3A is a brand-new instrument with high-resolution capabilities (SAR mode, SARM) covering the full extent of the Earth. Similar technical capabilities were available, though only for certain ocean regions, in the Cryosat-2 mission. The low noise level of the SAR instrument (Sentinel-3A) compared to the low resolution mode (LRM) (on Jason-3) is illustrated in Figure 4. Figure 4 shows the comparison of the variance of the filtered energy of the SLA (with a wavelength smaller than 65 km) for Jason-3 and Sentinel-3A. On average the energy is decreased by 30%, highlighting the reduced errors in the product from Sentinel-3A. The DUACS R&D activities should, in the near future, allow users to benefit from the full potential of SARM. The low noise level of the SAR data was highlighted in Heslop *et al.* (2017), where the across-track geostrophic velocity from Sentinel-3A was compared to ADCP and glider data in the South Mallorca region. With a 30 km cut-off filter, lower than the one used previously in similar experiment with LRM mission, a high correlation coefficient was obtained between the ADCP the Glider and Sentinel-3A. The root-mean-square (RMS) velocity difference was smaller than 10 cm/s which demonstrated the improved capacity of SAR instruments to retrieve the small scale features of the Algerian current.

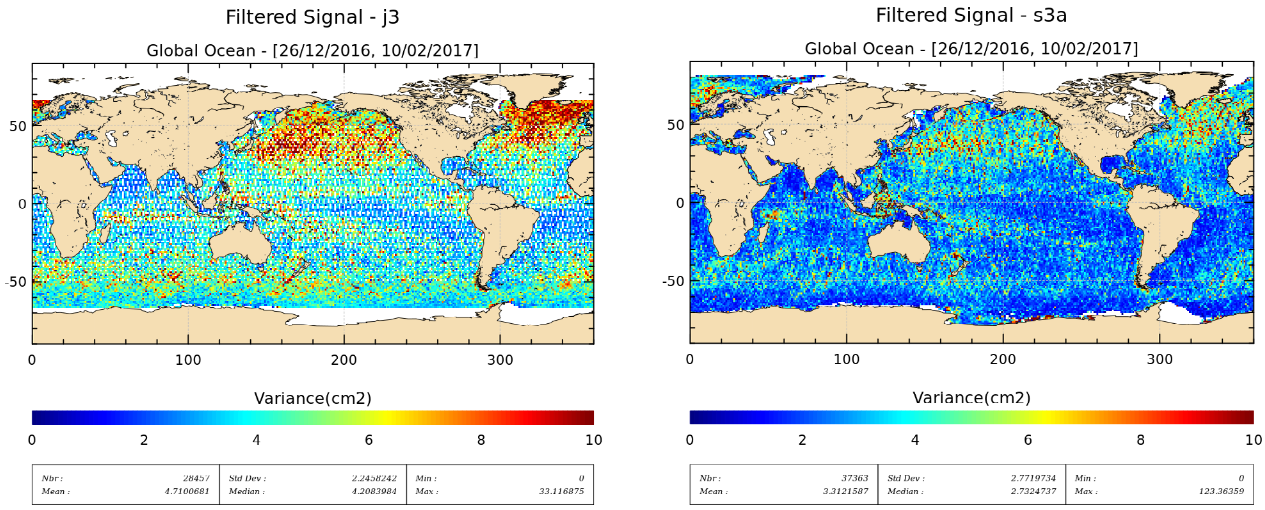


FIGURE 4

Variance of the filtered energy (wavelength lower than 65 km) for a 2 month period Jason-3 (left) and Sentinel-3A (right). Units are cm^2.

State-of-the-art processing for optimal quality to fulfilL MFC needs

The processing implemented in CMEMS has strongly evolved during the last 3 years. The data set were entirely reprocessed and delivered in 2014. An extensive assessment exercise was carried out and comparison with independent measurements underlined the improved quality of these reprocessed products (Marcos *et al.*, 2015; Juza *et al.*, 2016; Pujol *et al.*, 2016). Two important standards, the tide model and the mean sea surface (MSS) model were upgraded in V2 for all the missions in real time, and contributed to strongly improve the sea level products notably in shallow waters and coastal areas (Lyard *et al.*, 2017). No mean profile is available on the Cryosat-2 mission which flies on a geodetic orbit. A gridded mean sea surface is used instead. Using such proxy along an unknown satellite track adds new error sources to the reference errors already present in the mean profiles. For example, the mesoscale signal may not be properly removed from the MSS away from repetitive tracks.

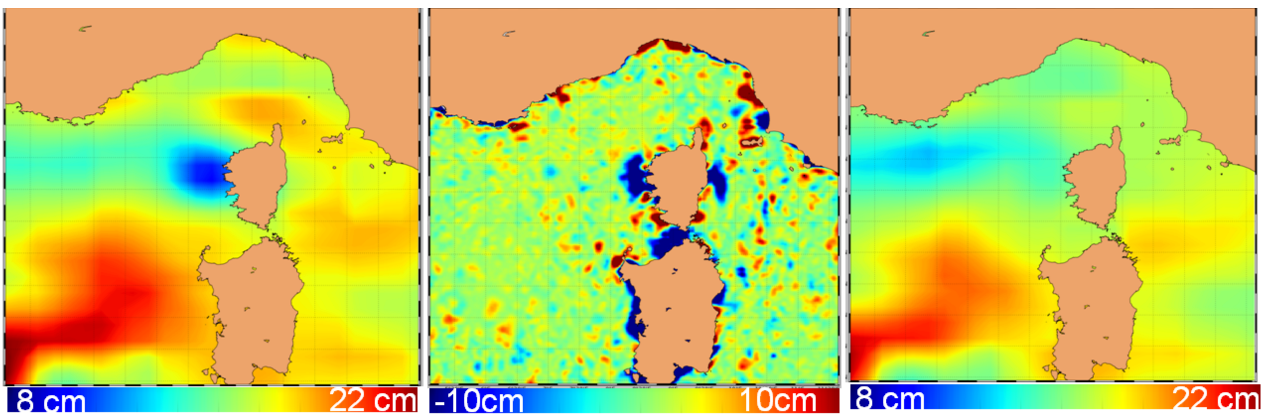


FIGURE 5

Example of a Mean Sea Surface induced error in October 2016 on the SL gridded products in the Mediterranean Sea in two configurations: MSS CNESCLS11 used for Altika and Cryosat (left) MSS CNESCLS15 used for Altika and Cryosat (right). Differences between the two MSS are shown in the middle figure.

There are also omission errors due to the inhomogeneity of altimetry data coverage. The same additional errors affected Altika when it was moved onto a new ground track in June 2016. An example of signature of the MSS on Altika and Cryosat-2 on the sea level anomaly (SLA) gridded product is given in Figure 5. Finally, note that for Sentinel-3A, no repeat track analysis will be available at the beginning of the mission. The CMEMS SL TAC decided then to upgrade the MSS standard to limit the degradation due to the large number of missions that have to use a MSS to estimate SLAs. A short term prospect is the ongoing complete reprocessing of the SL time series. In April 2018, a new version of the products will be released with several significant upgrades. The whole range of products, in near real-time and delayed-time, along-track and gridded, will be upgraded in terms of scientific content and format. In parallel, a complete reprocessing of the whole altimeter time series record (25 year time series) will be distributed. At the end of the reprocessing exercise, 80 years of data (Topex/Poseidon, Jason 1/2/3, ERS-1/2, ENVISAT, GFO, Cryosat-2; Altika, Sentinel-3A) will be processed using the most recently reprocessed GDR to ensure a maximum of consistency between the missions used for the whole period.

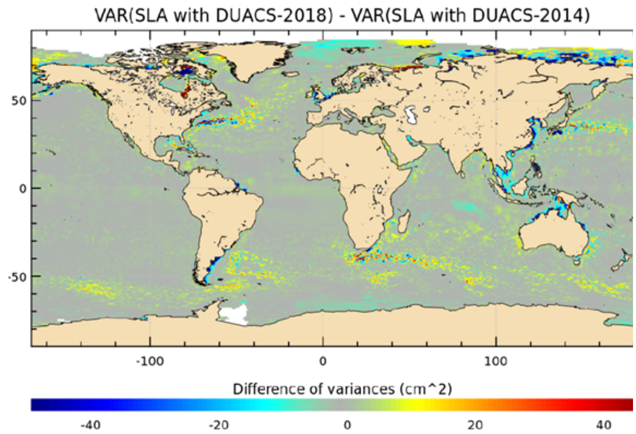


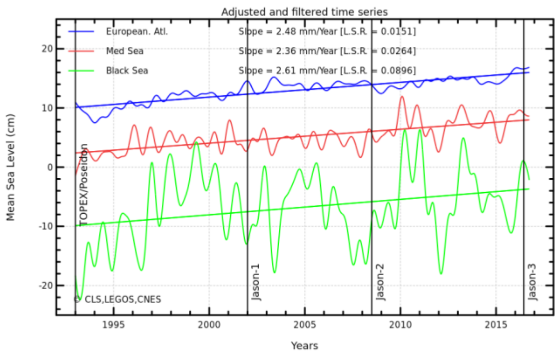
FIGURE 6

Impact of the V4 processing on 1 year (2003) in terms of variance (units in cm^2).

An illustration of the impact of the upgrades in V4 processing over 1 year in terms of SLA variance is given on Figure 6. It highlights the gain (in red) of energy in the area of strong mesoscale activity (e.g. Gulf Stream and Circumpolar currents) as well as the reduction (in blue) of the errors in shallow water areas, where the use of the new geophysical correction strongly improves the SLA. The TAPAS initiative (Tailored Altimetry Products for Assimilation) started during MyOcean-1. The loop from R&D to operation was closed at the end of MyOcean-2 with the creation of new Mediterranean Sea SL products tailored for assimilation. Several TAPAS meetings were organised, focusing on the consistency of the physical content between altimeter products and the physics of the models considered. In this way various subjects were analysed: the dynamic atmospheric corrections (DAC) and long wavelength errors (LWE); the along-track filtering and editing; as well as the impact and use of a new mean dynamic topography (MDT). TAPAS meetings also focused on the altimeter along-track product error description and the continuity in space and time between global and regional products. This collaborative work was very rewarding and led to the creation of a new product in the Mediterranean Sea in 2014 and overall European seas in 2016, allowing improved performances of the SLA assimilation into the models.

Sea Level product error budget refinement

A lot of progress finally has been made in the understanding of the error of the products. Maps of altimeter error levels have been computed for each altimeter mission (Dufau *et al.*, 2016) and this information is now given to the modellers in order to tune the error budget in their assimilation schemes. In the same studies the along-track mesoscale resolution was found to be approximately 40 km for SARAL/AltiKa, 45 km for Cryosat-2, and 50 km for Jason-2 in favourable signal to noise regions. Extensive assessment of the 2014 reprocessed products (DT2014) led to the refinement of the gridded SL product (Pujol *et al.*, 2016). The errors at mesoscale ranged from 1.4 cm^2 in low variability areas, to more than 30 cm^2 in high mesoscale activity areas. The DT2014 products, compared to the previous DT2010 version, present additional signals for wavelengths lower than ~250 km, inducing SLA variance and mean eddy kinetic energy (EKE) increases of +5.1% and +15% respectively. The error reduction at the mesoscale is nearly 10% of the error observed with the DT2010 version.



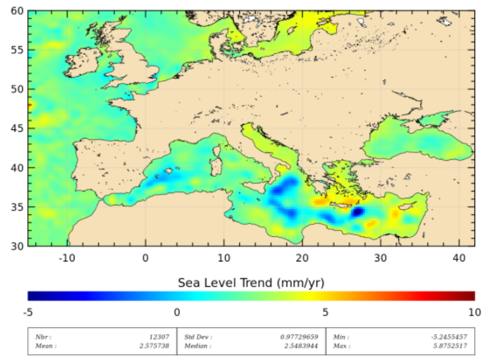


FIGURE 7

(a) Temporal evolution of the mean sea level in the European area for the CMEMS V3 product without annual and semi-annual signals, and 3-month filtered. The trend and the associated Least Squared Residual are mentioned (GIA not included) (b) Map of the SL TAC CMEMS V3 sea level trend in the European area during Jan. 1993 – Sept. 2016.

Impact on applications and users

The gridded Sea Level products, previously distributed on the Aviso website were transferred progressively to the CMEMS web portal between 2015 and 2017. Since the CMEMS V3 in April 2017, the whole catalogue including L3 and L4 SLA, ADT and corresponding geostrophic currents has been available on the CMEMS web portal. Thanks to the last improvement in terms of content, format and accessibility, the SL products are now the second most downloaded products. The Sea Level products are directly used to monitor the global and European sea level change in the context of global warming. Figure 7 illustrates the crucial role of the Jason-3 reference mission to ensure the continuous monitoring of the sea level rise. The SL products are also indirectly used for a wide range of applications (e.g. offshore industry, fisheries, etc.) through their assimilation in MFCs.

SEA SURFACE TEMPERATURE, SEA ICE AND WINDS

Overview

The OSI TAC is in charge of the near real-time (NRT) and delayed mode (REP) processing of SST, Sea Ice and Wind observations required for CMEMS modelling and data assimilation and for applications. CMEMS OSI TAC has strong links with the Eumetsat OSI SAF and its activities have been developed to complement Eumetsat OSI SAF products to answer CMEMS needs. The most significant R&D advances of CMEMS OSI TAC are described below.

A SST reprocessed L4 dataset over the Mediterranean and Black Sea

CNR has produced daily (night time) 4 km resolution reprocessed L4 (REP L4) long-term SST datasets for the Mediterranean and Black Sea covering the period from November 1981 to December 2012 (Pisano *et al.*, 2015). These products are based on the latest Pathfinder v5.2 Advanced Very High Resolution Radiometer (AVHRR) dataset (Casey *et al.*, 2010). They provide the longest SST time series at 4 km resolution with respect to other similar existing products. However, Pathfinder has not released yet an update of its product, so the REP data end in 2012. To fill in the gap from 2013 to 2015, the possibility to extend the time series was investigated by using the Mediterranean (MED) and Black Sea (BS) near real-time, multi-sensor L4 SST data at Ultra-High spatial Resolution (UHR) (i.e. 1 km resolution) produced by the CNR (Buongiorno Nardelli *et al.*, 2013) and also disseminated through the CMEMS.

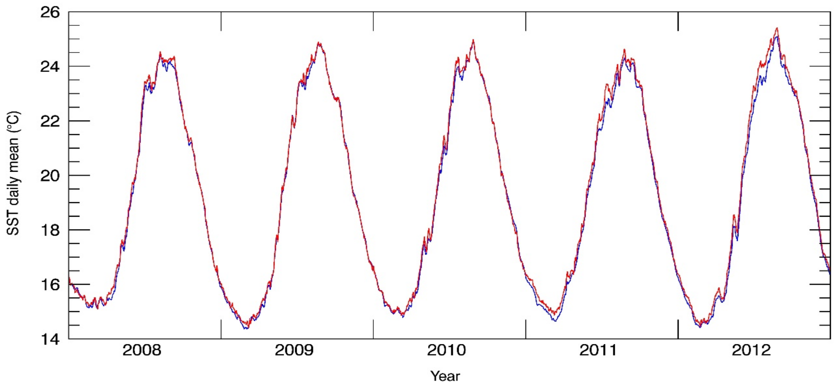


FIGURE 8

Time series of SST daily mean of the Mediterranean Sea for the REP L4 dataset (blue line) and the NRT L4 dataset (red line) over the overlap period 2008-2012. Trend: 0.21 °C/year and 0.25 °C/year for REP and NRT respectively (99% confidence level).

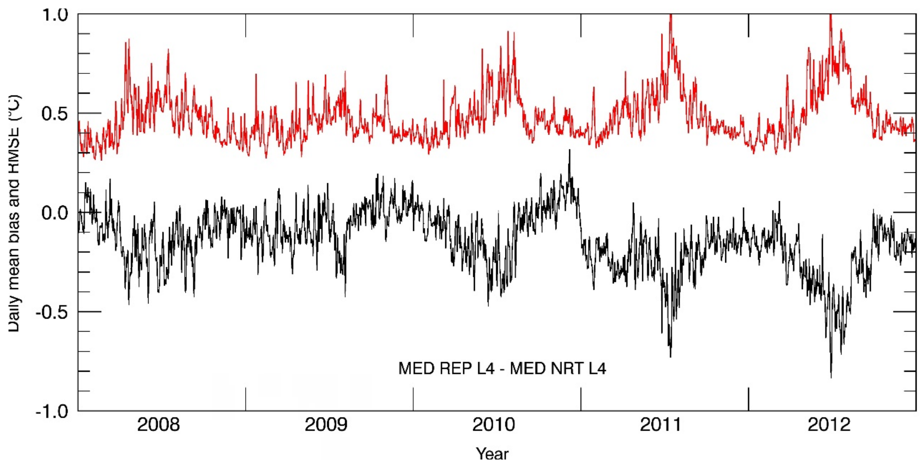


FIGURE 9

Mean bias (black line) and RMSE (red line) of the differences MED REP L4 – MED NRT L4 data over the overlap period 2008-2012. Trend: -0.03 °C/year (mean bias) and 0.01 (RMSE).

Since this operational product is available from 2008 to present, the REP and NRT UHR L4 products could be compared over the 2008-2012 overlap period, and hence assess its consistency. To do this, the following strategy was used:

- Downsize the MED/BS NRT UHR L4 (1 km) product to the MED/BS REP L4 grid resolution (4 km);
- Estimate the differences in terms of bias and root-mean-square error (RMSE) between the two products for the overlap period (2008-2012);
- Perform a bias correction of the NRT products from 2008 to 2015;
- Extend the REP L4 time series to 2015.

Figure 8 shows the time series of SST daily mean built from the MED REP and downsized MED UHR product for the 2008-2012 overlap period. From this first comparison, the REP SST appears to be slightly colder than the NRT SST. For the Mediterranean Sea an overall mean bias for the REP - NRT UHR differences was estimated to be -0.15 °C with an RMSE of the differences attaining around 0.47 °C. The spatial distribution of the bias, not shown here, is quite homogeneous except along the coastal regions subject to strong upwelling phenomena. In addition, by using the Mann Kendall test and the Sens's method to estimate the trend and its confidence level (Mann, 1945; Kendall, 1975; Sen, 1968), a daily mean bias trend of -0.03 °C/year (Figure 9) has been estimated. Similar results have been obtained for the Black Sea. Indeed, a mean bias of -0.11°C and a RMSE of 0.66 °C were estimated for the differences between the BS REP and BS NRT products, with a bias slope of -0.04 °C/year for the overlap period. While these numbers might seem to indicate that it is not possible to extend the REP series even correcting NRT biases, it must be highlighted that during the overlap period the observed Mediterranean Sea (Black Sea) SST trends attain values of 0.21 (0.34) °C/year and 0.25 (0.38) °C/year (Figure 8), when estimated from REP and NRT data, respectively. Hence, the trend in the REP/NRT bias does not exceed 15% of the signal. Until a new release of the updated Pathfinder data becomes available, it therefore seems reasonable to apply a bias correction by subtracting the bias map, namely at pixel level, from the NRT UHR downsized product, for both the Mediterranean and the Black Sea NRT data.

The bias-corrected product is called the "REP interim" product. By using the REP L4 dataset (1993 - 2012) and the REP interim dataset (2013 - 2015), monthly mean maps were computed, in order to investigate long-term changes in the Mediterranean and the Black Sea SST. To estimate the magnitude (°C/year) and significance of eventual trends, the Mann Kendall test and the Sens's method were applied, as above. The long-term variability in the SST was assessed by computing the seasonal temperature anomalies, i.e. removing the seasonal signal from the time series. In detail, the monthly mean climatology was subtracted from the original monthly mean time series, thus obtaining SST monthly mean anomalies. Figure 10 shows the 1993-2015 time series of SST monthly mean anomaly for the Mediterranean Sea (solid line) and the Black Sea (dashed line)

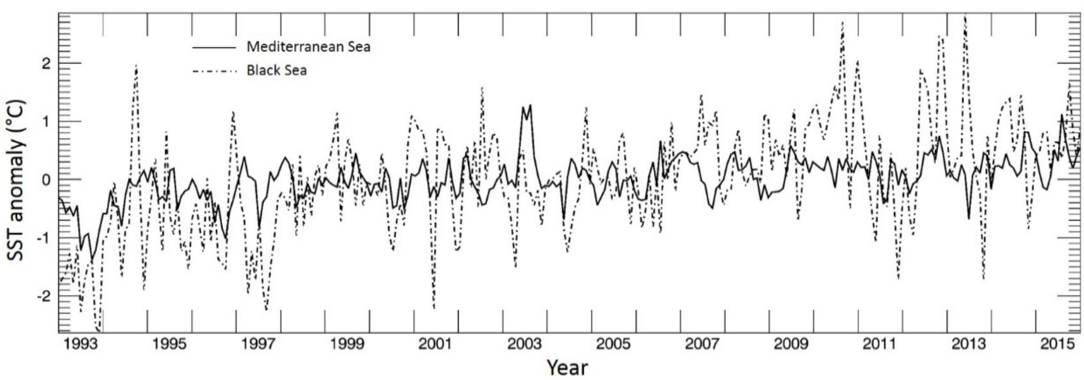


FIGURE 10

The 1993-2015 time series of SST monthly mean anomaly for the Mediterranean Sea (solid line, slope of 0.028 °C/year at 99% confidence level) and the Black Sea (dashed line, slope of 0.08 °C/year at 99% confidence level).

From Figure 10, the warming of the sea surface during 1993 - 2015 is already evident, in addition to some clear interannual signals. An average trend was estimated of 0.028 °C/year (Mediterranean Sea) and 0.08 °C/year (Black Sea) at 99% confidence level, corresponding respectively to an average total increase of about 0.6 °C and 1.8 °C, over the entire period. For the Mediterranean Sea, the SST minima were registered during 1993 and 1996, while maximum SST values occurred during the summer of 2003 (see also Feudale *et al.*, 2007; Jung et al., 2006) and 2015. Regarding the Black Sea, the estimated trend is in agreement with the 0.075 °C/year trend found in Buongiorno Nardelli *et al.* (2010), for the period 1985 - 2005. Moreover, the SST anomaly in the Black Sea has a higher temporal variation than in the Mediterranean Sea. This is probably due to the alternate meteorological influence of the cold Siberian anticyclone and the milder Mediterranean weather system on the Black Sea

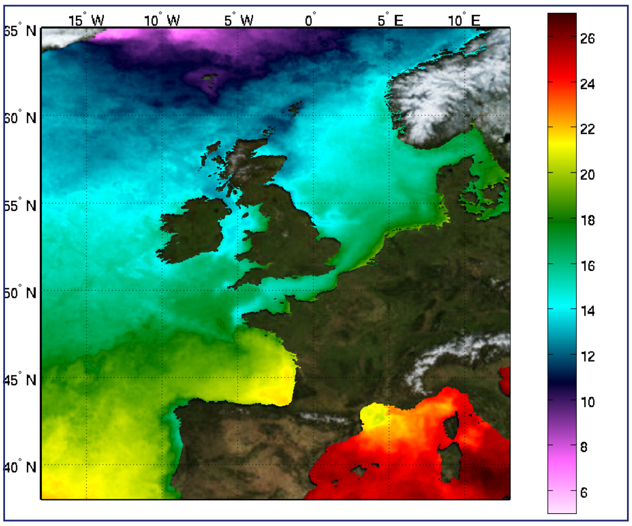


FIGURE 11

1982-2012 reanalysis in the European North West Shelves region from the AVHRR Pathfinder dataset.

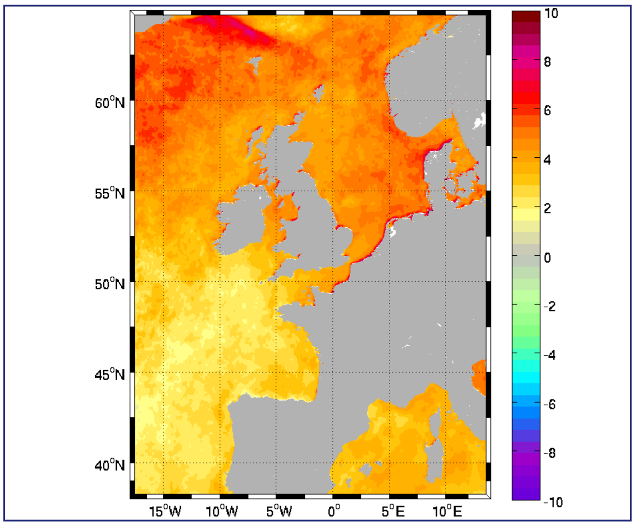


FIGURE 12

Slope x 100 (°C/year) from 1982-2012 time series.

A new SST reprocessed L4 dataset over the European North West shelves

A new processing chain (ODYSSEA 3.0) has been developed for the Sea Surface Temperature reprocessing over the European Northwest Shelves (38°N-65°N 18°W-13°E). The method used to reconstruct gap-free SST fields differs from the "classic" ODYSSEA chain using optimal interpolation (OI) for the reconstruction and using the previous analysis as a first guess. The satellite derived SST data used to reconstruct the daily gap-free SST fields are extracted from the global AVHRR Pathfinder dataset. Only observations with quality levels greater than 4 have been included in the analyses. The reconstruction of the daily gap-free SST time series relies on the interpolation at each point of the time series with a Kalman smoother, as described in Tandéo *et al.*, 2011. This interpolation has been done on the time series of SST anomalies obtained by removing a first-guess SST. The model used to generate the first-guess was based on the formulation of a mean seasonal cycle and a linear long-term trend (Saulquin et al., 2009; Gohin *et al.*, 2010) at each point. Figure 11 shows one of the daily gap-free SST fields of the new time series and Figure 12 shows the warming slopes estimated for the period 1982-2012)...

A new variational analysis scheme for global SST products

The OSTIA SST mapping technique is being transitioned from using an OI type assimilation scheme to NEMOVAR, a 3D-Var assimilation scheme. Results are very promising, with the new system showing global and regional improvements in the mean difference and standard deviation of differences to independent Argo observations and notable improvements in feature resolution.

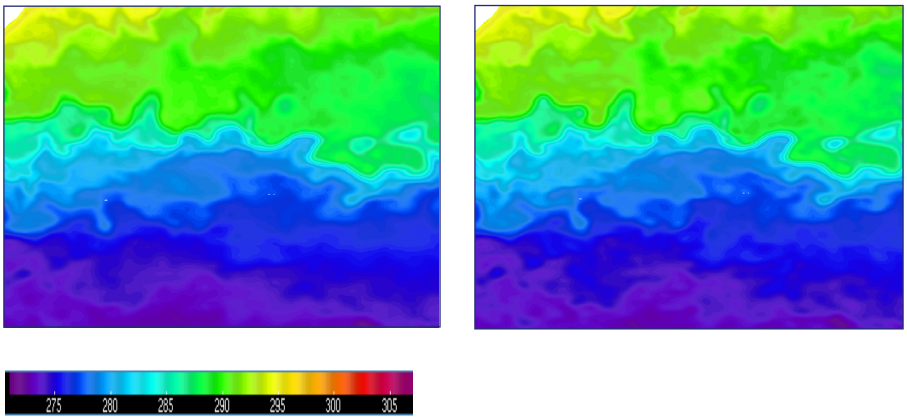


FIGURE 13

SST (K) for 20160731 for OI OSTIA (left) and NEMOVAR OSTIA (right) for the Agulhas Current region.

Tests using the NEMOVAR OSTIA system as a boundary condition for numerical weather prediction (NWP) demonstrate considerable improvements compared to the OI OSTIA system, particularly for longer range forecasts. Figure 13 illustrates the improvement in the resolution of SST features:

Sea Ice: new products based on Sentinel 1 SAR observations

SAR data is very important input data for sea-ice charting. Sea-ice charting is a key service for anyone operating in sea-ice infested oceans, or anyone making weather and ocean forecasts in polar regions. Several meteorological institutes are providing sea ice charting as a part of their core services. In CMEMS this has been coordinated into a Copernicus service and with the launch of the Sentinel-1A and 1B satellites the amount of available data has dramatically increased. This wealth of data makes it necessary to focus on automatic derived sea-ice parameters. A focus has therefore been on utilising the high resolution Sentinel-1 data in an automatic sea-ice concentration analysis.

The OSI TAC is working on developing multi-satellite sensor sea-ice concentration products where satellite data from *passive microwave, optical/Infra-Red (IR)* and *Sentinel-1 SAR (S1)* are combined in an optimal interpolation method. Passive microwave data is the backbone of ice monitoring, but gives generally too coarse resolution for navigational use or use in high-resolution models. Optical/IR is affected by clouds and limited light (polar winter). However, in combination with S1 SAR, the system is well equipped for a try on a new-multi sensor classification. The basic principle of the algorithm consists of minimizing a cost function with contributions from the satellite data and from a background. The background can be a previous analysis or a sea-ice model forecast. The S1 data used are the *Extra Wide swath dual polarisation (HH/HV) mode.* The radar signals are transmitted in horizontal polarisation (H) and the backscatter is received in both horizontal (H) and vertical (V) polarisation. Dual polarisation S1 products has shown to improve the ability to separate ice from water even under wind roughened conditions. The algorithm has been trained on a large training dataset where S1 data has been co-located with ice charts from the manual Ice Service at MET Norway for selection of training area. Statistics from one sea-ice class and two water classes (calm and wind affected water) have been calculated. The Bayesian algorithm classifies each pixel into one of these classes with a given probability. The sea-ice concentration is then derived from the number of ice-pixels within an area of 1 x 1 km.

Even if the HV polarization has improved the ability to separate ice and water in windy condition, strong wind over open water may still result in ambiguities. Therefore we are reducing the trust of the S1 classification in areas where weather models indicate strong wind. We are also reducing the trust in the S1 product in areas where sea ice concentrations from S1 are too low compared to concentrations derived from passive microwave data.

The method is running at MET Norway in a pre-operational mode. Before introducing it as a product in the CMEMS service, it needs to be fully validated and documented. However, the results obtained in the daily analysis so far look very promising. An example is illustrated in Figure 14, where the upper panel shows the S1 coverage on 3 April 2017 over the Svalbard area: the left-panel shows the manual analysis from MET Norway ice analysis (CMES operational product); and the right panel shows the results from the automatic analysis.

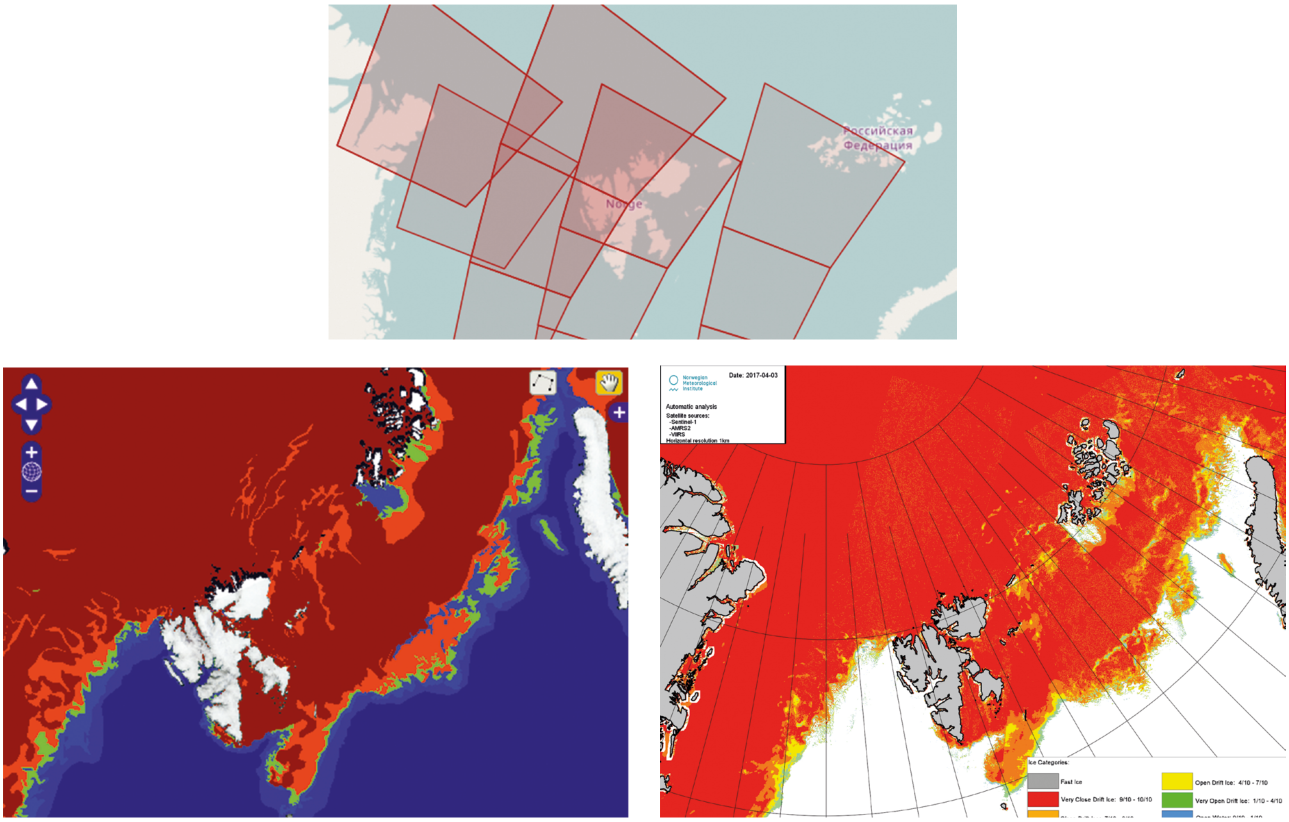


FIGURE 14

The upper panel shows the S1 coverage April 3 2017 over the Svalbard area. The lef panel shows the manual analysis from MET Norway ice analysis (CMEMS operational product). The right panel shows the results from the automatic analysis.

The main contribution from S1 versus AMSR-2 is on the details in the ice edge and detection of polynyas within the ice shelf.

Wind and wind stress

Wind stress forces ocean dynamics, triggers mixing of water and evaporates water. While, on the other hand, the water surface may trigger moist convection in the atmosphere and redistribute its momentum, humidity and heat. Winds change very fast and users need to assess its complete variability in order to arrive at an adequate ocean forcing, while scatterometers and radiometer provide incomplete sampling only. MFCs are working towards coupling the atmosphere and the ocean, but there still exist large systematic biases when comparing to the scatterometer wind products as illustrated in Figure 15. A new strategy is being devised in the OSI TAC to help marine users extract the relevant information from the incomplete scatterometer and radiometer observation records, as outlined below.

The OSI TAC develops wind and wind stress vector products, but also their derivative curl and divergence fields at both L3 and L4 from scatterometers and radiometers. The scatterometer winds are of excellent quality and are obtained from the EUMETSAT OSI Satellite Application Facility (SAF). Due to innovations in processing and inter-calibration by the EUMETSAT OSI SAF, wind component random measurement errors are of the order of 0.7 m/s, while instrument stability easily reaches 0.1 m/s per decade (Belmonte Rivas *et al*, 2017; Stoffelen *et al.*, 2017a; Stoffelen *et al.*, 2017b; Wang *et al.*, 2017; Verhoef *et al.*, 2017; Wentz *et al.*, 2017). All OSI SAF NRT products are collocated in time and location with the operational ECMWF (European Centre for Medium-Range Weather Forecasts) stress-equivalent winds. Stress-equivalent winds compare closely to scatterometer winds, as scatterometers do not sense the atmosphere, but rather the ocean roughness. Therefore, ECMWF model winds and buoy winds (used for comparison) are converted to take out the effects of atmospheric stability and air mass density, resulting in so-called stress-equivalent winds *(u10s)*.

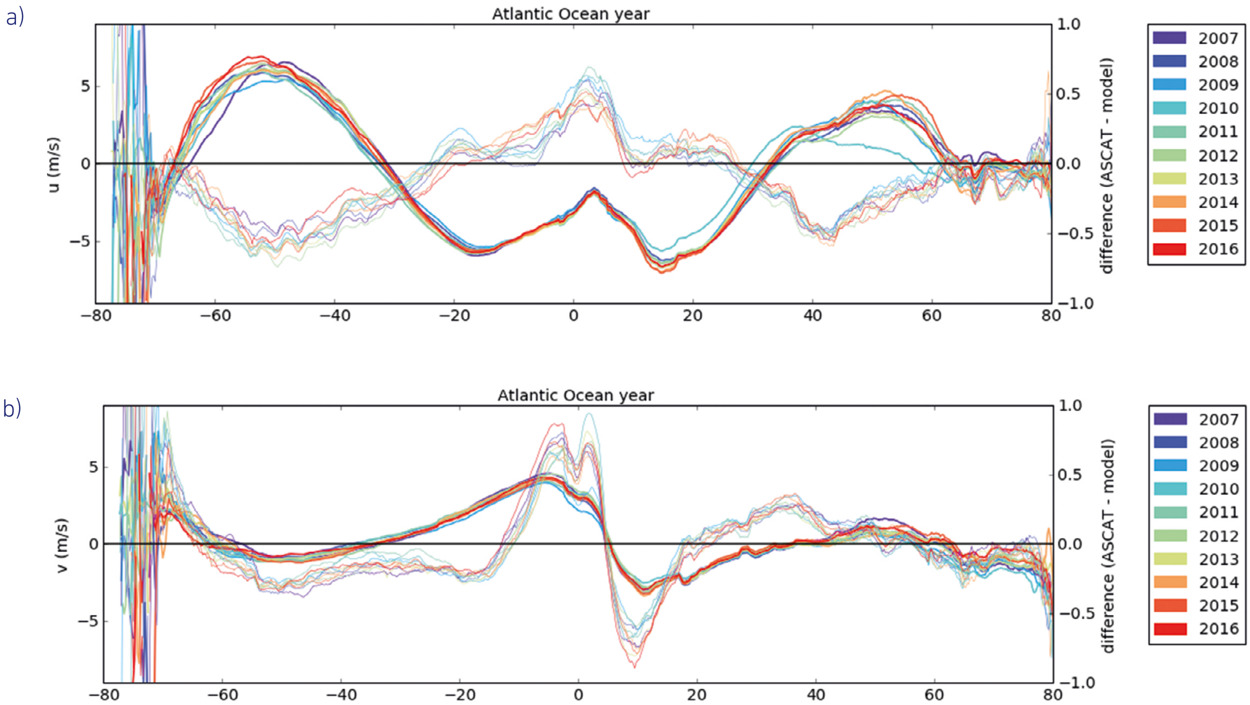


FIGURE 15

a) Zonally-averaged 10 m zonal wind speed distribution over the main basins for ASCAT-A on left axis (thick) and the difference with ERA-interim on the right axis (thin). Note that ERA westerlies and ITCZ easterlies are 0.5 m/s too high.

b) As a), but for the meridional winds. Note that the ERA-interim winds show far too little convergence towards the ITCZ and somewhat reduced polarward flow, probably due to known errors in the PBL boundary layer closure (Sandu et al., 2013).

Moreover, *u10s* can be easily converted to surface stress, using one's favorite surface layer scheme (de Kloe *et al.*, 2017).

The ECMWF collocations at L2 are processed in exactly the same way as the scatterometer *u10s* in the OSI TAC and also provide stress, curl and divergence products at L2 and L3. These may be aggregated in e.g. monthly mean products, and subsequently compared to monthly mean ECMWF products (that are nevertheless obtained from uniform spatial and temporal sampling). The comparison of these differently processed and sampled ECMWF products provides an estimate of the error due to scatterometer sampling. These errors depend, *inter alia*, on the diurnal cycle and on transient winds. The lack of wind variability and air-sea interaction in the ECMWF model, due to e.g. lack of moist convection downbursts is, on the other hand, not accounted for in this estimated sampling error. Since ECMWF fields are available in the L3 products, to evaluate such variability errors, both systematic mean errors and variability deficit of the ECMWF fields can be computed from the differences with the scatterometer observations.

In a future step, time-continuous fields may be created that correct these systematic biases and deficits in the synthetic ECMWF model forcing fields, since both mean and variability statistical errors are on a slow manifold.

Since scatterometer winds are processed on regular swath grids, the derivatives are best processed on a staggered L2 grid at full resolution. All OSI TAC products are subsequently interpolated to L3 onto an earth grid on a daily basis for ascending and descending swaths separately, thus resulting in two daily fields per scatterometer and retrieved variable. The L3 products are integrated in the OSI TAC L4 wind product.

With ASCAT-A (2007-2017) and QuikSCAT (1999-2009) almost two decades of wind and wind stress products are now available. After the recent intercalibration and reprocessing of the ERS scatterometer winds at OSI SAF L2, OSI TAC ERS L3 products are being produced for the next marginal CMEMS release, providing almost another decade of global reprocessed wind and stress products (1992-2000).

KNMI also processed HY-2A products and collaborates with China on the preparation of the CFOSAT fan-beam scatterometer, the HY2 series of scatterometers and WindRad on FY3, all with planned launches in 2018. Moreover, KNMI started to process ScatSat data from ISRO in NRT and looks forward to the launch of OceanSat-3 in 2019. Finally, EUMETSAT plans to operate three ASCAT scatterometers in the morning orbit (9:30 LTAN) from 2018 to 2022. As such, the NRT coverage of scatterometers will much increase in the years to come.

The intercalibrated and homogenized NRT and REP OSI TAC L3 wind, wind stress and derivative products are used to produce L4 products at IFREMER. Wind stress curl can now be compared for an ASCAT sample from 2007 to 2014 inclusive between ASCAT and ERA-interim, thanks to the collocation procedure. Figure 16 shows that also on a decadal time scale ASCAT-A shows more resolution, particularly in coastal and current regions.

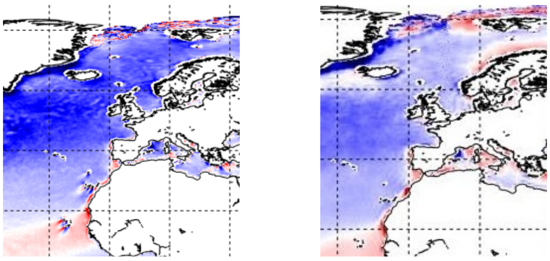


FIGURE 16

ASCAT-A (left) and collocated ERA-interim (right) wind stress curl averaged over 2007-2014. Both relevant open ocean and coastal differences occur, e.g. over the Mediterranean and Arctic.

OCEAN COLOUR

Overview

The ocean colour (OC) TAC operates the European Ocean Colour component within the CMEMS, providing worldwide global, pan-European and regional (Atlantic, Arctic, Baltic, Mediterranean and Black Sea) high-quality core ocean colour products based on Earth Observation Ocean Colour missions. The OC TAC relies on current and legacy OC sensors: MERIS, from ESA, SeaWiFS and MODIS from NASA, and VIIRS from NOAA. The Copernicus Sentinel 3 OLCI sensor is expected to have a significant impact on product provision, quality, and volume.

Global and regional products are high level L3 and L4 observational combined products, thus providing an added value to standard L2 products delivered by the space agencies. Regional products provide higher accuracy than standard OC data available from space ground segments thanks to the regionalization of processing chains that takes into account the bio-optical characteristics of each regional sea for production and data validation. The OC TAC bridges the gap between space agencies, providing ocean colour data to all users that need the added-value information not available from space agencies. The users include: the operational modelling communities (e.g. CMEMS MFCs) which use OC data to assimilate into their ecosystem models or to validate their products; the environmental agencies; the research community; and private companies that provide further added-value services that require ocean colour-derived information.

Ocean Colour Observation high level processing

The OC TAC is a distributed system with three production units (PU) and one single dissemination unit at CNR. Each PU is responsible for its own chain and all necessary information about product quality. Despite the PU activities being devolved, all activities, including Cal/Val, are harmonised and coordinated through the OC TAC acting as a centralised sub-system presenting CMEMS users with a single ocean colour service. A graphical description of the OC TAC system is provided in Figure 17 which highlights the main data flow from upstream data providers to end users.

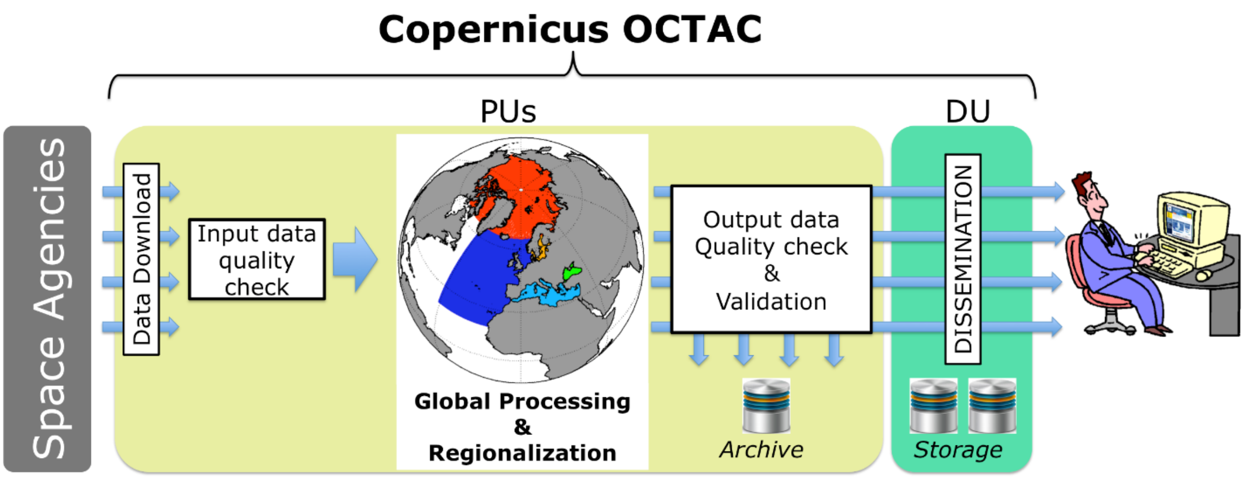


FIGURE 17

Overview of the OC TAC system.

Data Ingestion and quality control

Upstream data (L1 and/or L2 Ocean Colour and auxiliary data) are acquired from the Space Agency ground segments. Input (Level 1, 2 and ancillary) data are stored in an internal PU database and used for product generation. To check input and final satellite data quality, a database of *in-situ* data is maintained and an established climatology is also used for quality control and checks to be performed when generating the final products. Input data from the upstream providers are checked for availability, auxiliary data files, completeness of the files, and quality flag analysis. Depending on the upstream data source and data level used, pre-processing may be required to harmonise inputs before the data are passed to the product generation module.

Products Generation

The OC TAC service generates either Level-3 (L3) or Level-4 (L4) products in near real-time, delayed time (DT) and as reprocessed (REP) data. To provide multi-sensors products, single passes and/or multi-sensor merged products are spatially binned and temporally binned to compute L3 daily and multi-day products. For the global and the regional seas, OC TAC selected the state-of-the-art product algorithm on the basis of optical characteristics of the basin and round robin procedure. Table 1 provides a synthesis of the algorithm used to produce NRT and reprocessed dataset available from CMEMS. Daily ATL, MED, BS and BAL chlorophyll fields are produced by applying two different algorithms for open ocean (Case I) and coastal waters (Case II). The data are then merged into a single chlorophyll daily field providing a unique regional product with an improved accuracy of estimates on coastal waters. L4 are those products for which a temporal averaging method and an interpolation procedure are applied to fill in missing data values on daily images. The interpolation procedures currently used by OC PUs span from Optimal Interpolation to DINEOF procedure (see Table 1). Temporal averaging is performed on 8-day and monthly bases.

The NRT OC products are produced every day, operationally, and provide the best estimate of the ocean colour variables at the time of processing. These products are generated by using available satellite passes and climatological ancillary data (meteorological and ozone data for atmospheric correction, and predicted attitude and ephemerides for data geolocation). Improved DT products are also produced operationally and are obtained by reprocessing OC upstream data using updated, hindcast, ancillary information (precision orbital data and meteorological fields used for atmospheric correction). The DT products not only have improved quality but also the delayed processing allows any observational gaps to be filled which arose from incomplete upstream data provision. Thanks to improved atmospheric correction, errors associated to the DT files are in general lower than the NRT one. The difference between NRT and DT chlorophyll is shown in Figure 18. The DT files supersede the previous NRT data typically within 15 days from sensing, and the timing largely depends on the provision of ancillary data from space agencies and forecast centres.

TABLE 1

Input data and algorithm used by OC PUs to generate the CMEMS OC products.

Products	data	L3 processor	Chlorophyll Algorithm	L4 method
NRT Global	L2 MODIS L2 VIIRS	GlobColour (GlobColour, 2007)	GSM (Maritorena,*et al* 2012)	Advanced OI (Saulquin *et al*, 2010)
REP Global (two REPs are generated)	SeaWiFS, MODIS, MERIS, VIIRS L1 by OC-CCI L2 by Globcolour	REP1: OC-CCI (OC-CCI, 2014) REP 2: GlobColour (GlobColour 2007)	OC3, OC4, OC5 and CI, depending on pixel water type (OC-CCI 2014) GSM (Maritorena,*et al* 2012)	Weekly & Monthly average Advanced OI (Saulquin *et al*, 2010)
NRT Arctic NRT Atlantic	L1 MODIS L2 VIIRS	PML	OC5CI developed by PML: Case 1: CI (Hu *et al.* 2012) Case 2: OC5 (Maritorena *et al.* 2002)	Weekly & Monthly means Advanced OI (Saulquin *et al*, 2010)
REP Arctic REP Atlantic	L1 SeaWiFS, MODIS, MERIS, VIIRS	OC-CCI upgraded to L1 full resolution	OC5CI developed by PML	Weekly & Monthly means
NRT Mediterranean	L2 MODIS L2 VIIRS	CNR MED Processor (Volpe *et al* 2012)	Case1: MedOC (Volpe *et al.* 2007); Case 2: Ad4 (Berthon &. Zibordi, 2004).	DINEOF Beckers and Rixen (2003)
NRT Black Sea	L2 MODIS L2 VIIRS	CNR BS Processor (Volpe *et al* 2012)	BSAlg (Kopelevich *et al.*, 2013)	DINEOF Beckers and Rixen (2003)
REP Mediterranean	L3 merged (SeaWiFS, MODIS, MERIS, VIIRS) (OC-CCI Processor)	CNR MED Processor (Volpe *et al* 2012)	Case1: MedOC (Volpe *et al.* 2007); Case2: Ad4 (D'Alimonte & Zibordi, 2003).	Weekly & Monthly means
REP Black Sea	SeaWiFS, MODIS, MERIS, VIIRS L3 merged Rrs (OC-CCI Processor)	CNR BS Procesor	BSAlg (Kopelevich *et al.*, 2013)	Weekly & Monthly means
NRT Baltic	L1 MODIS	HZG processor Doerffer, R (2015)	Neural Network (Hieronymi,et al 2015)	Weekly & Monthly means
REP Baltic	SeaWiFS, MODIS, MERIS, VIIRS L3 merged Rrs (OC-CCI Processor)	CNR Baltic (Pitarch *et al.*, 2016)	OC4v6 Baltic recalibrated (Pitarch *et al.*, 2016)	Weekly & Monthly means

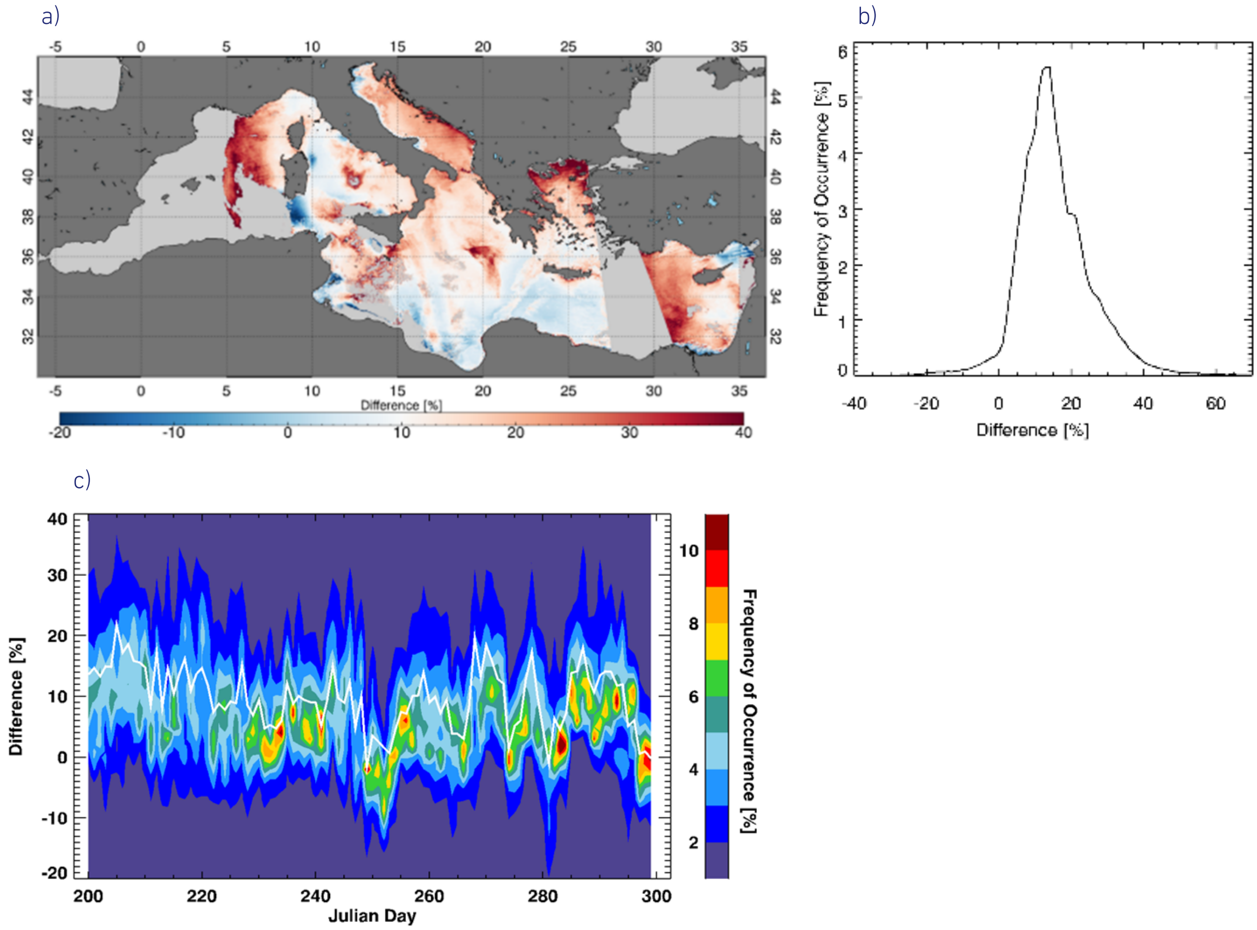


FIGURE 18

Effect of including relevant ancillary data in the delayed time processing on OCTAC operational processing chain: relative difference in Mediterranean CHL concentration between delayed time and near real-time processing for MODIS/AQUA. A) spatial distribution of the relative difference in CHL concentration for 31 August 2015; B) histogram of the relative difference in CHL concentration for 31 August 2015; C) time series of histogram of the relative difference in CHL concentration for 20 July- 20 October 2015.

The OC REP products, on the other hand, are multi-year time series produced using a consolidated and consistent input dataset, with a unique processing software configuration which results in a solid dataset suitable for long-term and climate studies. To this aim, OC REP data are generated taking the advantage of the ESA OC-CCI initiative results. The last version of OC-CCI time series is ingested by OC TAC and converted into CMEMS OC format to generate the global OC REP at 4 km resolution. OC-CCI targets climate quality consistency with minimal inter-sensor bias and can therefore be considered as the most consistent long term multi-sensors (SeaWIFS, MODIS, MERIS and VIIRS) global ocean colour time series. The regional REP products are produced to improve the chlorophyll retrieval accuracy and to provide a finer resolution (1 km) to address regional user needs. To this aim, OC-CCI processor is used to generate consistent reflectance time series of the European regional Seas at 1 km. These time series are ingested into the OC regional processing chains and the same regional bio-optical algorithms used in NRT production are applied to generate chlorophyll products (see Table 1).

Products conversion storage and dissemination

For each ocean region, the OC TAC delivers two types of products: CHL and OPTICS. CHL is the phytoplankton chlorophyll concentration whereas OPTICS refers to other variables retrieved from ocean colour sensors, and includes: Inherent Optical Properties (IOPs), such as absorption and scattering; the diffuse attenuation coefficient of light at 490 nm (Kd490); Secchi depth (transparency of water); spectral Remote Sensing Reflectance (Rrs); photosynthetically available radiation (PAR); Coloured Dissolved Organic Matter (CDOM); and the Suspended Particulate Matter (SPM).

All products are converted to a harmonized data and metadata format and distributed in NetCDF 4 using CF convection through the DU interfaced with the CMEMS web portal. Products, metadata and documentation (e.g. manual and quality information) are delivered by DU to users in compliance with the INSPIRE directives.

Product Quality control

Each PU performs routine product validation using predefined protocols, for both NRT and DT products. Validation metrics and statistics are automatically generated during operational processing. Routine validation includes the analysis of: number of input data and their quality; processed data quality; geophysical signal consistency; product visualisation (graphical images); and production of scientific performance indicators. If anomalies are detected, a warning is sent to the support operator and appropriate actions are taken depending on the anomaly.

Product quality assessment

The assessment of ocean colour product uncertainties faces several particularities. First of all, a broad set of quantities of various natures can be derived from OC, some of them have a spectral dependency (e.g. remote sensing reflectance, inherent optical properties of backscattering and absorption, etc.). Second, the *in-situ* observations are fairly restricted in size (with the exception of chlorophyll-a). Third, *in-situ* observations required for validation are not generally available in real time. Moreover, the uncertainties associated with *in-situ* data depend on the methodology and protocols used to acquire them. Only high quality *in-situ* observations acquired during research field experiments are recognized by the space agencies and ocean colour scientific community to be good enough to be used for OC product assessment (Zibordi & Voss, 2014).

Two core products have been identified by OC TAC: remote sensing reflectance (Rrs or its normalised version nRrs) and chlorophyll-a concentration (Chl-a), for which assessment is particularly mandatory. The assessment of other products depends on available (and scarcer) data sets and is conducted on a best-effort (BE) basis. Due to the considerations given above, the assessment of the OC TAC products is essentially carried out in an off-line context (assessment of full time series; i.e. Class 4 before entering into production), and not in a real-time. The off-line assessment is based on matchup analysis between satellite estimation and *in-situ* observation by common metrics: dataset mean, the determination coefficient, the root mean square error, and the bias. This off-line analysis reveals that the OC products distributed by CMEMS in generally meet the accuracy required by scientific community, implying that regional products have accuracy higher than standard OC data available from space ground segments. For example, in the Mediterranean Sea, a basin characterized by complex bio-optical characteristics, the chlorophyll generated by OC TAC and distributed by CMEMS have a bias of -0.029 $mg.m^{-3}$ with respect to *in-situ* observation while MODIS and VIIRS data distributed by NASA have a bias of 0.316 and 0.282 $mg.m^{-3}$ respectively.

In absence of NRT *in-situ* observation, OC on-line validation is based on comparison of the near real-time data with climatology to highlight significant events. In particular, OC TAC uses a pixel-based approach where each NRT retrieval is compared with its climatological value, determined by the daily climatological mean and standard deviation of pixels within six days of the given Julian day (J-6, J+6). Where both a valid retrieval and climatology exist the pixel-wise difference with the climatology is computed and recorded. This difference parameter is also expressed in terms of the number of retrievals in climatological standard deviation bin intervals or Quality Index (QI). A QI map is thus generated. These daily indicators are produced in NRT and made available through the OC website (see http://marine.copernicus.eu/services-portfolio/validation-statistics/#tacs|oceancolour).

Applications: European Policies

The achievement of a Good Environmental Status in European waters by 2020 is the principal goal of the Marine Strategy Framework Directive (MSFD) that establishes 11 Descriptors. The Environmental European Agency (EEA) has defined the eutrophication indicator that computes the Chl trend using *in-situ* data averaged over the summer season (defined as the May-September period). However, such an *in-situ* dataset is characterized by low resolution in time and space and cover only coastal waters up to 12 miles from the shore. In CMEMS, an evolution of the EEA eutrophication indicator was developed to provide information of the state of European marine waters at high sampling frequency and spatial resolution (Ferreira *et al.*, 2010; 2011, Coppini *et al.*, 2013, Colella *et al.*, 2016). To this aim, daily pan-European chlorophyll reprocessed dataset were used to derive the Chl climatology and trends. Pan-European Chl data derived from OC regional reprocessed data by merging regional ATL, BAL, MED, BS Chl generated by applying corresponding regional bio-optical algorithms into a single pan-European product. These daily fields were used to compute the summer climatology of Chl concentration and its standard deviation, available as EUR_OC_INDEX_001 and to estimate the summer Chl trend, available as EUR_OC_INDEX_002. According to the EEA's definition, the summer is defined from 1st of May to 30th of September and the climatology and trend are computed using the observation covering the years between 1997 and 2015 at 1 km resolution. In this context, the use of a more accurate evaluation of satellite Chl fields allows a more robust and realistic trend estimations.

The summer Chl climatology (Figure 19) shows a latitudinal pattern with the southern regions less productive than those in the North. Absolute minima concentrations are found in the eastern area of the Mediterranean Sea (less than 0.06 $mg \cdot m^{-3}$), well known for its ultra-oligotrophic features. Low Chl values (< 0.1 $mg \cdot m^{-3}$) characterize also the southwestern corner of the Atlantic Sea, where the concentrations are comparable to those of the offshore waters in the western Mediterranean basin. On the contrary, high Chl values are registered in all the European coastal regions with the highest concentrations (> 2 $mg \cdot m^{-3}$) occur in the Baltic Sea areas. Maxima concentrations are shown along the western African coastal areas, in the Gulf of Arguin, Gabès and Nile Delta, and in the North Adriatic in relation to the Po river outflow.

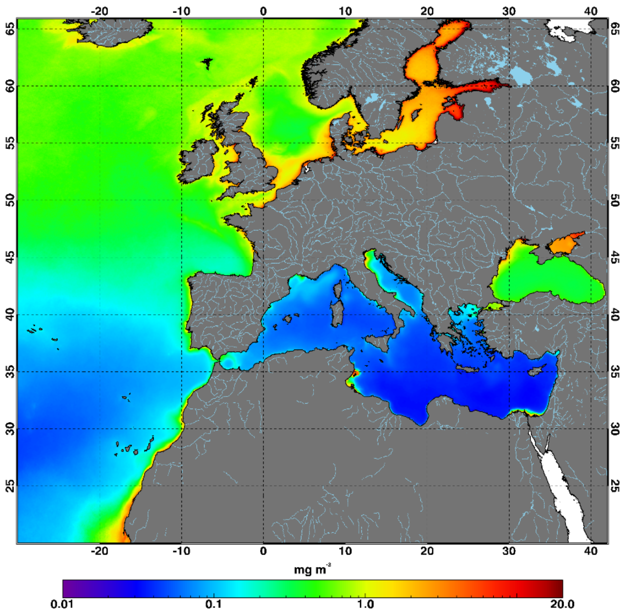


FIGURE 19

Summer (May-September) Chl climatology relative to 1998-2015 time series.

Figure 20 shows the EUR_OC_INDEX_002 for the European seas, the trend was computed with a statistical significance of the 70%. The areas with the most significant positive trend (>0.1 $mg \cdot m^{-3} \cdot yr^{-1}$) are the coastal zones of the Baltic Sea, especially in the Gulf of Bothnia, Finland and Riga, while a less significant positive trend (<0.05 $mg \cdot m^{-3} \cdot yr^{-1}$) characterizes all the offshore waters of the North Atlantic at the southern side of Greenland. In contrast, a complex pattern characterizes the region west of 10°. Here, a significant negative trend characterizes a narrow area of the southern North Sea, along the coast of Germany, Netherlands, Belgium and France, and the open waters at the western side of Ireland and Scotland. In the North Sea, a positive trend is shown in the offshore areas of the eastern coast of England. In the Mediterranean Sea, this indicator displays essentially no trend in the Case 1 waters, while a significant trend is observed only off the Po river delta and the Gulf of Gabès. The Black Sea is generally characterized by a negative trend, which is stronger in the Danube off-shore regions (about -0.05 $mg \cdot m^{-3} \cdot yr^{-1}$) and along the western coast of the basin with respect to the eastern region. On the contrary, the Sea of Azov is characterized by a positive trend, which reaches its maximum (about 0.15 $mg \cdot m^{-3} \cdot yr^{-1}$) in the Taganrog gulf.

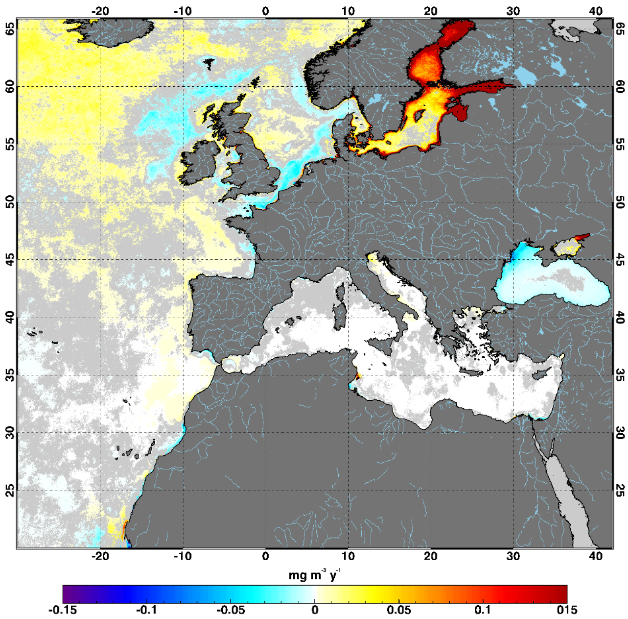


FIGURE 20

Chlorophyll trend indicator relative to 1998-2015 time series. Light grey pixels indicate non-significant value.

No trend is observed in southern part of the Atlantic Sea (south of 42°N) with the exception of the coastal waters from the Gibraltar Straits to Lisbon, which are characterized by a negative trend. In the Bay of Biscay, the trend is characterized by negative values in the coastal region and positive values off-shore up to the Celtic Sea, itself characterized by a positive trend. In the offshore Atlantic waters off Morocco, the trend shows significant positive values that extend along the coastal areas of Portugal.

IN-SITU

Overview

In order to satisfy the needs of internal and external users, the In-Situ (INS) TAC integrates and quality controls (in a homogeneous manner) all available *In situ* data provided on a voluntary basis to the CMEMS service. It provides access to integrated datasets of the defined core parameters for initialization, forcing, assimilation and validation of ocean numerical models and for analysis of the state of the ocean. The numerical models are used for forecasting, analysis and re-analysis of ocean physical and biogeochemical conditions. The INS TAC comprises a global and six regional In-Situ centres (one for each EuroGOOS ROOSs). The focus of the CMEMS INS TAC is on parameters that are presently necessary for Copernicus Monitoring and Forecasting Centres namely temperature, salinity, sea level, currents, waves, chlorophyll-a fluorescence, oxygen as well as nutrients (full list of parameters is available on http://dx.doi.org/10.13155/40846). The initial focus has been on observations from autonomous observatories at sea (e.g. floats, buoys, gliders, ferryboxes, drifters, and ships of opportunity) and on delivering near real-time products. The second objective was to integrate products over the past 25 to 50 years for re-analysis purposes (reprocessed products). In addition, integrating data into a unique data base requires definition and use of standard formats and agreed quality control procedures. The complexity of handling *in-situ* observations depends not only on the wide range of sensors that have been used to acquire them but also on the different methodologies used (e.g. vessels with on board human supervision, autonomous instruments, etc.). Presently about 7000 multi-parameter platforms from more than 120 institutions are integrated every month. About 80% of those provide temperature, 10% sea level, about 30% current, salinity or waves, while 30% are providing measurements of atmospheric parameters. The main R&D activities and achievements are described below.

A new method to detect anomalies in salinity data

For years, manual QC (quality control) has been applied to detect random, systematic and gross errors. However, the increasing amount of data available for quality control has gradually implied that manual control has become excessively time-consuming. Hence, the necessity of automatic, computerized QC procedures has become more and more obvious. Basic QC procedures usually applied in automatic real time mode, consist of checking for obvious inconsistencies. Smaller inconsistencies are often addressed through comparison to local statistics from a historical reference dataset; a common practice consists of defining the validity interval from climatological means and standard deviations. When defining an efficient validity interval for a given parameter, choosing the extrema ever seen in an historical dataset is an appealing idea. Minimum and maximum values are, however, extremely sensitive to measurement errors, so that an adequate strategy must be set up. The chosen procedure is manual, iterative and based on the spatial consistency of Min/Max maps. While the method is also being developed at regional scale (Arctic, Mediterranean Sea), we now provide numbers concerning only the work done at global scale. At global scale, Min/Max reference fields are estimated on a 110 km resolution grid in every 20 dbar depths from the surface down to 2000 dbar; the reference fields are the maximum and minimum measured values within a set of 1.2 million Argo profiles, 30000 CTD profiles and over 300000 sea mammals measured profiles. In order to quantify the relative efficiency of the classical climatological test and the Min/Max approaches at the global scale, both QC methods are applied to the same dataset; «good» and «bad» detections are estimated using the CORA 5.0 flags as truth, assumed to be perfect. Given the absence of an independent global dataset for validation purpose, the Argo dataset is used but perturbed by a local white noise which amplitude is defined by the scale of the local variability reduced by a factor P. All detections are qualified as "good" or "bad" depending on the agreement with CORA 5.0 flags, assumed to be perfect. Figure 21 summarizes conclusions of the methodological validation procedure. Grey/black symbols refer to the classical approach for which validity intervals are estimated from climatological mean and standard deviation scaled by a factor N. Colour symbols refer to the Min/Max approach for different P values. For each approach and parameters N or P, the information on statistics of "good" and "bad" detections is synthesized in terms of anomaly relative to a perfect approach with coordinates (1,1) in that frame.

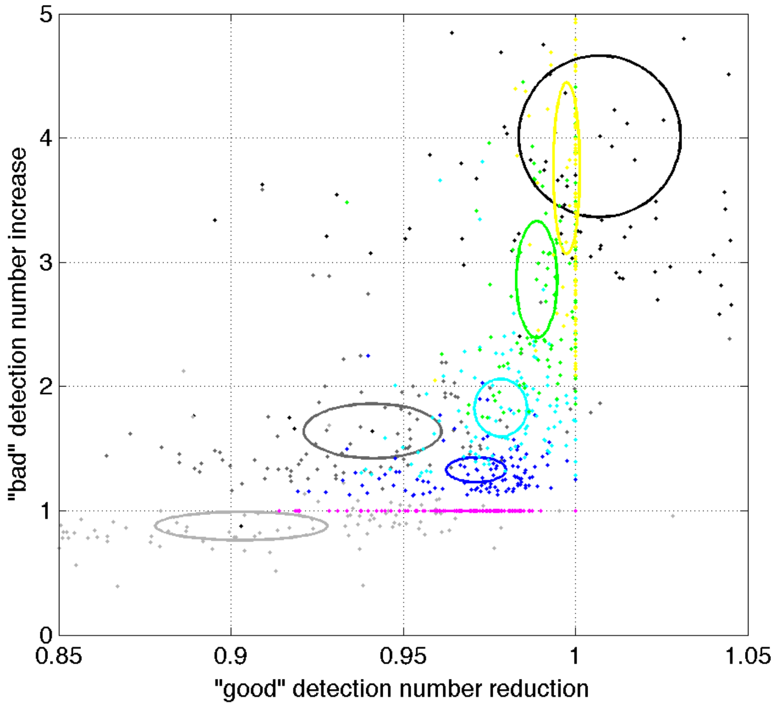


FIGURE 21

Comparative synthesis in terms of "good" detection number reduction and "bad" detection number increase relative to optimal conditions. Black/grey lines refer to the classical mean/std approach for N=4 (light grey), N=5 (grey) and N=6 (black); colour curves refer to the Min/Max approach for a range of P parameter values: 0 (red), 0.015 (blue), 0.025 (cyan), 0.04 (green), 0.05 (yellow).

For similar bad detection statistics the Min/Max approach systematically misses three times less good than the classical approach does. As a summary, the Min/Max approach offers the best trade-off between maximal number of good detections and minimal number of bad ones. Following the successful implementation of the method for the production of CORA 5.0, we are now testing it for the NRT T&S CMEMS product. First results are really promising and will contribute to the enhancement of the NRT product

CORA 5.0 a new product for reanalysis

A large effort was undertaken in Europe to develop *in-situ* temperature and salinity products for the use in ocean reanalysis. Within the INS TAC both Coriolis (Ifremer/CNRS) and UK-MetOffice (UKMO) are continuing to develop those products and combining their effort in order to make use of the best of both methods and increase space and time coverage as well as their quality. First, the cooperation with the UKMO allowed us to compare the ENSEMBLE 4 (EN4) and CORA (Coriolis Reanalysis) database contents. The objective was to detect the duplicated profiles along with the unique profiles (the profiles finally distributed by a single database). We consequently extracted and formatted about 3 million unique profiles from the UKMO *in-situ* REP product (EN.4) to update the CORA database. The location of the EN.4 profiles to the CORA dataset is shown on Figure 22. Most of the new profiles are MBTs (mechanical bathy thermographs) and Bottles data acquired before 1990, CTD data from 1990 to the early 2000s and sea mammals mounted profiles from the late 2000s. All these profiles have been validated in delayed time mode by the Coriolis R&D team. The evolution of the global ocean coverage by the CORA dataset is given on Figure 23. It shows the improvement of the CORA coverage, especially before 1985.

This work should bring the Copernicus dataset CORA to the top rank *in-situ* datasets by providing a larger data coverage using a semi-automatic validation process for the period 1950-2015..

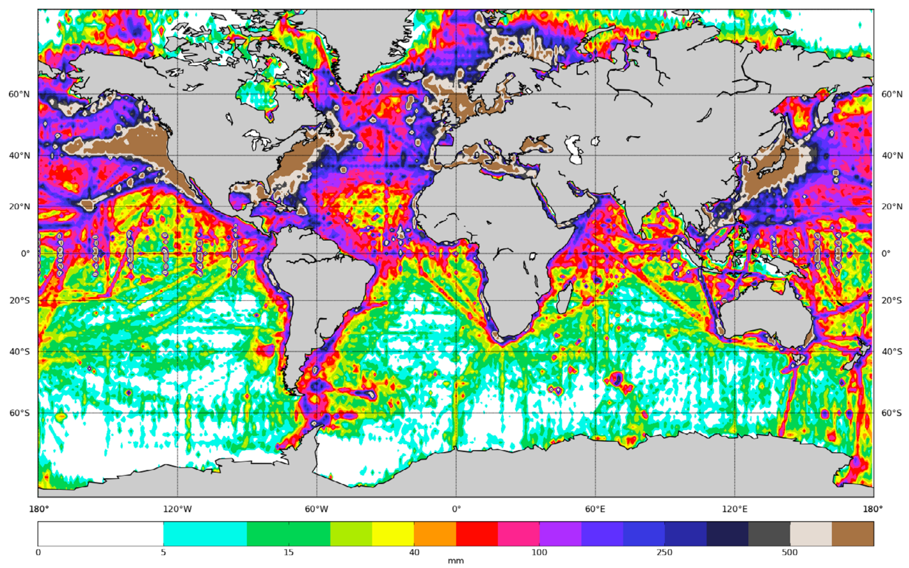


FIGURE 22

Number of EN4 imported profiles inside 1° per 1° cells, from 1950 to 2015.

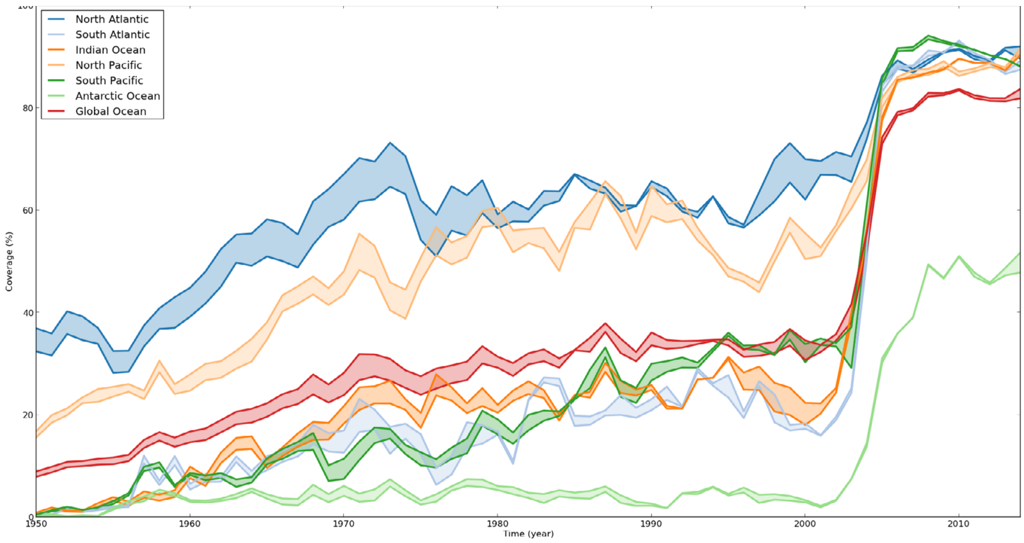


FIGURE 23

Yearly percentage of 3° per 5° ocean cells filled by at least one measurement, as a percentage of a basin surface. The shaded surface gives the EN4 intake.

A new service for Wave

The wave parameter was introduced in CMEMS in V3 (April 2017). This required an important work from the CMEMS partners to set up a service coherent between the different CMEMS components. These data are mainly acquired by monitoring institutes and are mainly distributed via the WMO GTS and the institutes' servers. An important activity has been to unify the naming convention not only within the INS TAC but also within the MFCs in collaboration with standardization bodies such as IODE (SeaDataNet vocabs) and different conventions (CF convention). Focus has first been placed on wave height and direction, while the decision was to delay standardization of spectral information for V4 (April 2018). A Real time QC procedure has also been defined and harmonized within INS TAC (http://doi.org/10.13155/46607) to detect gross anomalies. In partnership with EuroGOOS and EMODNet-Physics, the INS TAC has integrated the main part of the wave platforms from European countries for V3 and presently nearly 400 stations are integrated in the wave product (see Figure 24). At global scale two main data sources for the INS TAC are Meteo France (that provides the link to the Global Telecommunication System) and NDBC/USA (that provide access to US wave data). The coverage is still sparse in the Pacific and Southern Oceans. The next steps are to prepare a historical product covering 1990-present and extend the spatial coverage.

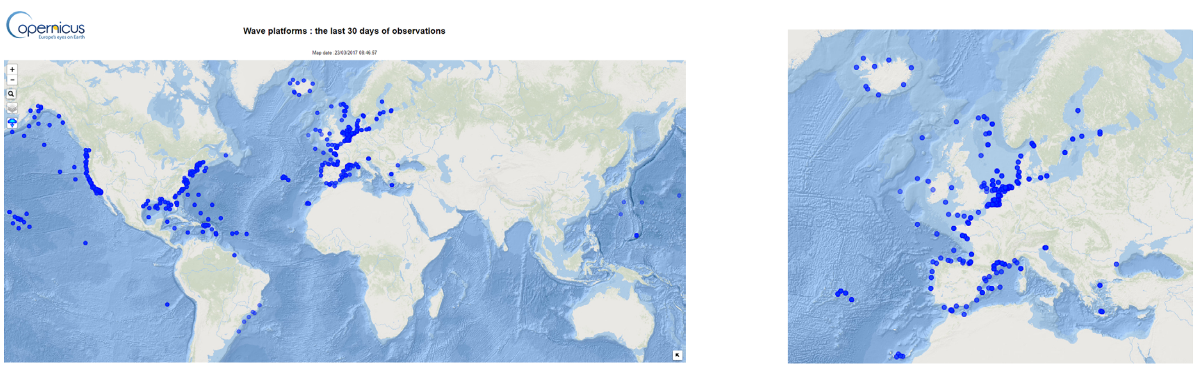


FIGURE 24

Location of CMEMS In-Situ TAC wave observations.

MONITORING AND FORECASTING CENTRES (MFCS)

GLOBAL MFC

Status and main characteristics of the global systems

The Global Monitoring and Forecasting centre (GLO MFC) provides global ocean forecasts, analyses and reanalyses for physics and the biogeochemistry with several systems which are: a global high resolution system with a physical component at resolution of 1/12°, a biogeochemical component at 1/4° resolution, a global ocean atmosphere coupled system providing forecast at 1/4° resolution, and a wave forecast system at 1/5° resolution. The reanalyses are produced with systems close to the forecasting systems with a resolution at 1/4° for the physics and the biogeochemistry. A reanalysis ensemble multi-system product, based on several reanalyses developed by different centres in Europe, is similarly produced at 1/4° resolution but distributed at lower resolution (1°) and lower frequency (1 month). The forecast and reanalysis systems assimilate the available *in-situ* and satellite observations which are temperature and salinity profiles, sea level anomaly, sea surface temperature and sea ice concentration. The ocean colour observations are not yet assimilated in the biogeochemistry system but research and development activities are in progress in the framework of CMEMS. Multi-observation products are also disseminated by the GLO MFC in near real-time and in reprocessing mode; these products are derived using statistical interpolation methods and do not use any model. More details about each system are provided below, and some comparisons between analyses, forecasts and observations are illustrated in the following sections.

The Global high resolution physical forecasting system

The Global high resolution forecasting system (Lellouche *et al.*, 2013; Lellouche *et al.*, 2016) has been developed and is operated by Mercator Ocean and has been providing forecasts since the beginning of CMEMS and even during the demonstration project MyOcean. The system is based on a global configuration of the NEMO (Madec *et al.*, 2016) model coupled to LIM2 sea ice model at a 1/12° resolution. It assimilates *in-situ* and satellite observations with the SAM2 assimilation scheme (Lellouche *et al.*, 2013) based on a SEEK filter and a 3D-var large scale bias correction. The system is forced by the operational ECMWF atmospheric analysis and forecast. A new version of this system has been recently developed and is operational since October 2016. The ocean/sea ice model and the assimilation scheme benefited among others from the following improvements: large-scale and objective correction of atmospheric quantities with satellite data; new freshwater runoff from ice sheets melting; global steric effect added to the model sea level; new mean dynamic topography taking into account the last version of GOCE geoid; new adaptive tuning of some observational errors, new quality control on the assimilated temperature and salinity vertical profiles based on dynamic height criteria; assimilation of satellite sea-ice concentration; and weak constraint imposed on temperature and salinity in the deep ocean (below 2000 m) to prevent drift. A simulation to calibrate this system was started in October 2006 from a 3D temperature and salinity initial condition based on the EN4 climatology and the time series from 2007 is distributed on the CMEMS server. This physical system is now used to force the biogeochemical forecasting system in an offline approach with a coarsening of the physical fields. The biogeochemical model used is PISCES which is a model of intermediate complexity designed for global ocean applications (Aumont and Bopp, 2006) and is part of the NEMO modelling platform.

The global ocean atmosphere coupled system

The Met Office GloSea5 coupled forecast system and the FOAM system (Blockley *et al.*, 2013) used to initialise the ocean in GloSea5 share an almost identical ocean and sea ice science configuration using the NEMO model coupled to the multi-thickness-category sea ice model CICE. The FOAM global ocean configuration is forced by Met Office global atmospheric NWP fields using CORE bulk formulae to specify the surface boundary condition. The scientific configuration of Met Office Unified Model used as the atmosphere component of the GloSea5 system is near identical to the NWP system providing the FOAM forcing fields, although the latter is higher resolution (~17 km rather than ~50 km). The data assimilation uses NEMOVAR, a variational (3D-var) scheme recently developed specifically to be used with NEMO and further tuned for the 1/4° resolution global model. Key features of NEMOVAR are the multivariate relationships which are specified through a linearized balance operator and the use of an implicit diffusion operator to model background error correlations. Operationally there are two 24 hour data assimilation cycles performed each day where observations are assimilated using a 24 hour window and increments are applied to the model with an incremental analysis update (IAU) step. Observations assimilated include satellite SST data (AVHRR data supplied by the GHRSST project), *in-situ* SSTs from moored buoys, drifting buoys and ships (these are considered unbiased and used as a reference for satellite SST bias correction), sea level anomaly observations from Jason-2, Cryosat-2, Saral and Jason-3, sub-surface temperature and salinity profiles (from Argo, underwater gliders, moored buoys, marine mammals, and manual profiling methods) and sea ice concentration (SSMIS data provided by OSI SAF as a daily gridded product). The NEMO global ocean configuration uses the ORCA025 grid (with a 1/4° or 28 km horizontal grid spacing at the equator reducing to 7 km at high southern latitudes, and ~10 km in the Arctic Ocean).

The Global wave forecast system

The global wave system of Météo France is based on the wave model MFWAM which is a third generation wave model. MFWAM uses the computing code ECWAM-IFS-38R2 with a dissipation term developed by Ardhuin *et al.* (2010). The model MFWAM was upgraded in November 2014 thanks to improvements obtained from the European research project MyWave (Janssen *et al.*, 2014). The model mean bathymetry is generated by using 2-minute gridded global topography data ETOPO2/NOAA. The native model grid is irregular with decreasing distance in the latitudinal direction close to the poles. At the equator the distance in the latitudinal direction is more or less fixed with grid size of 1/5°. The operational model MFWAM is driven by 6-hourly analysis and 3-hourly forecasted winds from the IFS-ECMWF atmospheric system. The wave spectrum is discretized in 24 directional bins and 30 frequency bins from 0.035 Hz to 0.58 Hz. The model MFWAM uses the assimilation of altimeters with a time step of 6 hours. Currently the altimeters Jason-2 & 3, Saral and Cryosat-2 are used in operations. The global wave system provides analysis 4 times a day, and a forecast of 5 days at 0:00 UTC. The wave model MFWAM uses the partitioning to split the swell spectrum in primary and secondary swells. The global CMEMS provides 3-hourly wave products and the validation is mainly implemented for the significant wave height and the peak period

The Global multi observation near real-time and reprocessing system

GLO-OBS is the multi-observations component of the GLO MFC. In this context, it provides:

- L4 global 3D ocean fields of temperature, salinity, sea level and geostrophic currents computed by combining satellite (Sea Level Anomalies, Geostrophic Surface Currents, Sea Surface Temperature) and in-situ (Temperature and Salinity profiles) observations through statistical methods (Guinehut *et al.*, 2012; Mulet *et al.*, 2012).
- L4 global ocean fields of sea surface salinity (SSS) and sea surface density (SSD) computed by combining satellite (sea surface temperature) and *in-situ* (surface salinity and density) observations through an optimal interpolation method (Droghei *et al.*, 2016).

All fields are defined on a 1/4° regular grid at a weekly period (Wednesday only). The 3D ocean fields are defined down to the bottom on 33 depth levels. The 3D ocean fields are available in NRT with a delay of 7 days.

For the 3D ocean fields, the processing is performed in three steps:

- The SLA (L4 from CMEMS SL TAC) and SST (OI-daily from NOAA) satellite observations are projected onto the vertical via a multiple linear regression method and using covariances deduced from historical observations. This leads to synthetic fields.
- The synthetic fields and all available *in-situ* T/S profiles (CMEMS INS TAC) are combined through an optimal interpolation method. This leads to the combined fields.
- The thermal wind equation with a reference level at the surface is used to combine geostrophic current fields from satellite altimetry (L4 from CMEMS SL TAC) with the combined T/S fields and thus to generate the global 3D geostrophic current and geopotential height fields.

For SSS/SSD, the processing provides a correction to the ISAS-CORA SSS field, combining QC SSS measurements obtained from ISAS-CORA (both distributed through the CMEMS INS TAC) and high-pass filtered SST L4 satellite observations (OI-daily from NOAA).

Long time series of the 3D and surface ocean fields described above with the multi observations system are available since 1993.

The Global reanalysis

The global Mercator Ocean reanalysis GLORYS2V4 is available from 1993 to 2015 at a 1/4° horizontal resolution. The system is based on the NEMO platform with 75 vertical z-levels, driven by ERA-Interim atmospheric reanalysis. Observations are assimilated by SAM2 (*Système d'Assimilation* Mercator version 2) which includes a reduced-order Kalman filter and a large scale 3D-VAR bias correction of temperature and salinity. The following data are assimilated into the system: along track L3 sea level anomalies together with the recent of the CNES-CLS013 mean dynamical topography, *in-situ* temperature and salinity profiles coming from the latest CORA4.1 database, AVHRR sea surface temperature from NOAA and Ifremer/CERSAT sea ice concentration. In this new version, specific attention has been devoted to the surface mass flux forcing, global steric signal and initial conditions of water masses better balanced with altimetry signal. The main differences between this new version and the previous one are described in more detailed in Garric *et al.* (2016).

The global biogeochemical multi-year product covering 1998-2015 is a non-assimilative biogeochemical hindcast forced by a non-assimilative physical hindcast in an offline mode with a daily frequency and with the same horizontal resolution at ¼°. The biogeochemical system is really close to the system used in real time and described below.

The Global ensemble physical reanalysis

Global ocean reanalyses disseminated by CMEMS are eddy permitting homogeneous 3D gridded descriptions of the physical state of the ocean spanning several decades, produced with a numerical ocean model constrained with data assimilation of satellite and *in-situ* observations. The diversity of ocean reanalyses currently developed with that same NEMO model grid ORCA025 at ¼°, see Masina *et al.* (2015), is used by the GLO MFC to produce a multi-model ensemble product, which spread allows uncertainties or error bars to be estimated. In a number of regions, the ensemble mean is found to provide a more reliable estimate than any individual reanalysis product.

Four reanalyses have been selected to contribute to the project; including GLORYS2V4 from Mercator Ocean (Garric *et al.*, 2017), ORAS5 from ECMWF (Zuo *et al.*, 2015), GloSea5 from the UK Met Office (McLachlan *et al.*, 2014; Blockley *et al.*, 2013), and C-GLORSv5 from CMCC (Storto *et al.*, 2016). The four different time series of global ocean 3D monthly estimates have been post-processed to create the new product called GREP-V1 (Global Reanalysis Ensemble Product), covering the recent period during which altimetry observations are available: 1993-2015. Starting from April 20th 2017, the ensemble mean and standard deviation of the ensemble, as well as the four individual members for the period 1993-2016, are thus made available on a 1° x 1° grid and monthly frequency. The time series will be extended by one year each year..

Main R&D achievements for the forecasting systems

The main details on the performance of the GLO MFC systems and information of the products quality are available in the QUID which are associated to each product. Some statistics between analysis, forecast and observations are systematically performed and an intercomparison of systems is also produced to identify the improvements of new developments as for example a resolution increase, an improvement in the atmospheric forcing, a new data assimilation scheme, etc. The RMS misfit computed at global scale between the analysis, the forecast and the sea level anomaly along the altimetry tracks illustrates this kind of improvement. The RMS error for the new version of the global system computed in December 2016 is 5.2 cm in analysis and 6 cm in forecast (for forecast range from 1 to 7 days). The forecast error for the current version of the high resolution system is the same as the analysis error of the previous version of the system. This is mainly due to the new algorithm used to compute the observation error in the data assimilation scheme (Desrozier *et al.*, 2005) which tends to reduce the altimetry error observation at global scale and especially close to the coast. The improvement of the sea surface salinity between the old and new global high resolution system at 1/12° is illustrated on Figure 25. The improvement is quantified via the comparison with the sea surface salinity produced with the GLO-OBS system. The main improvement occurs in the tropical regions and can be mainly attributed to the atmospheric correction and especially to the precipitation correction which was largely biased in the tropic. It also results from improvements of the global circulation due to model modifications (e.g. changes to the diffusion and/or wind forcing) and data assimilation of the sea level anomaly (e.g. modification of the MDT). Focusing on some areas, it is possible to compare the global high resolution assimilation system to other observations as Figure 26 illustrates. The sea surface salinity in the Gulf Stream is compared to the GLO-OBS SSS and in Figure 27 the predicted surface currents in the Agulhas area are compared to the Globcurrent ESA product (http://www.globcurrent.org/).

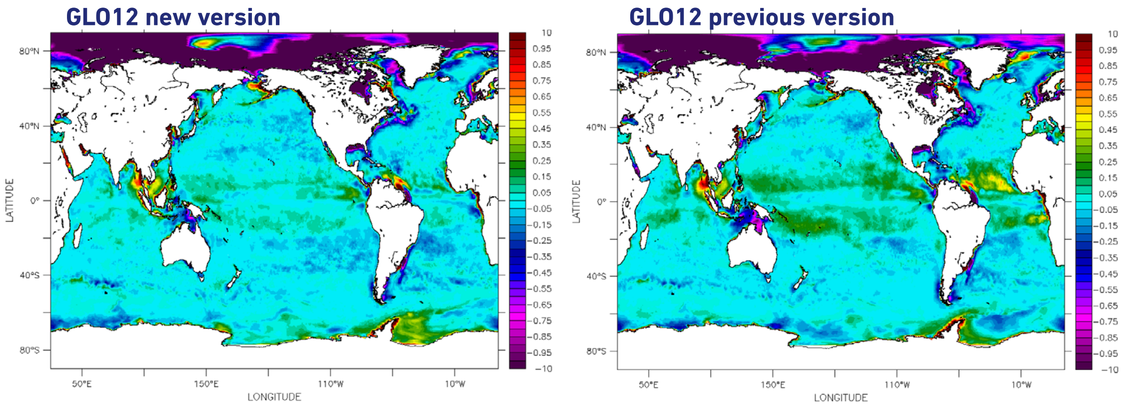


FIGURE 25

Sea surface salinity bias between GLO-HR and GLO-OBS for a 4-year period (2013-2016). On the left using the new version of GLO-HR, on the right the previous version.

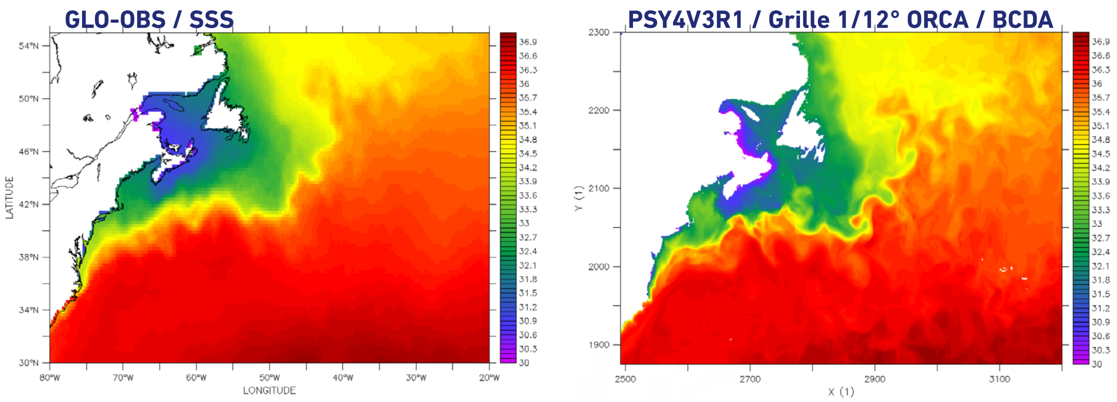


FIGURE 26

Sea surface salinity in January 2014 (monthly mean) from GLO-OBS (left panel) and GLO HR (right panel).

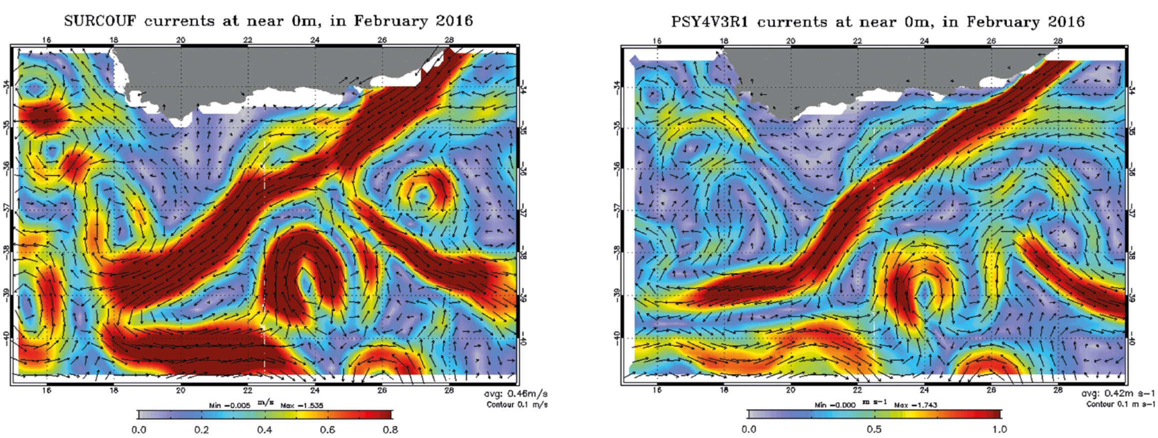


FIGURE 27

Surface currents in February 2016 in the Agulhas area (South of Africa) on the left panel with the globcurrent ESA product and in the right panel with the global high resolution system.

In comparison with the SSS it can be seen that the global high resolution product contains much more small structures like some salty eddies in the northern part of the Gulf Stream front but the large pattern are really comparable in term of position of the main fronts or of the extension of the North Atlantic current. The surface current products are more comparable in terms of horizontal resolution and the zoom on the Agulhas area illustrates the retroflexion current and the associated mesoscale.

Another example concerning the sea surface temperature illustrates the impact of a coupled ocean atmosphere forecasting system. Testing of an upgraded coupled ocean-atmosphere system for V3.1 using a weakly coupled data assimilation initialisation has shown a reduction in global scale RMS (and bias) 1-day forecast SST errors when comparing to *in-situ* surface drifter observations. During the first part of 2017, the RMS error has reduced from larger than 0.3 °C in the previous system (initialised from a forced ocean analysis system), to around 0.25 °C in the new system.

Altimetric observations (Jason-2 and Saral in this case) are used in the validation of significant wave height of the global wave model in the 12-hour forecast. The evaluation of the statistics indicates the good performance of the model with a global average scatter index of 10.2% and a very small bias of 3 cm. The statistical analysis is carried out in three main regions: high latitudes (|lat|>50°), intermediate latitudes (20°<|lat|<50°) and the tropics (|lat|<20°). The scatter index values are good, with the best performance for the intermediate latitudes and the tropics with values of less than 10% and 9%, respectively. Figure 28 shows the maps of the average scatter index for the validation period from April 2014 to March 2016. It can also be noticed that the scatter index of significant wave height increased near the coastal areas (between 13% and 18%).

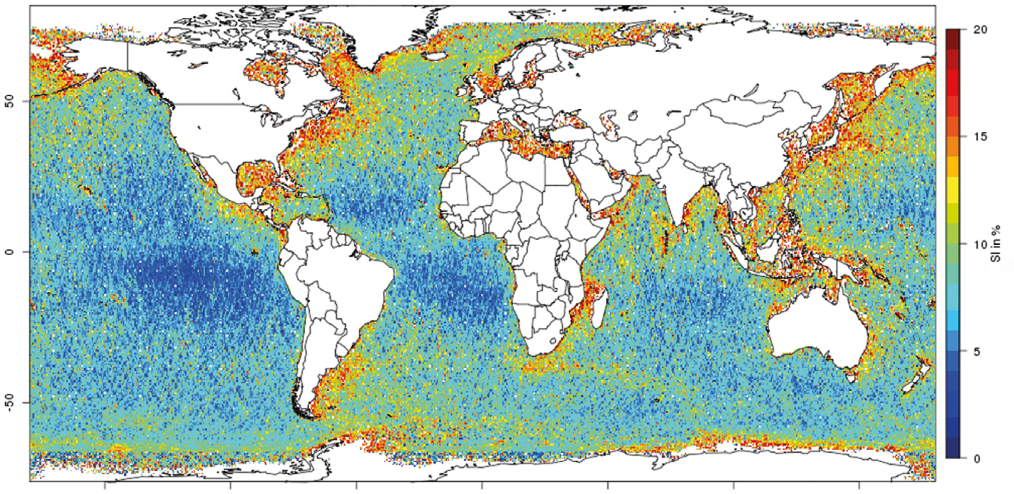


FIGURE 28

Map of scatter index (%) of 12-hour forecasted significant wave height in comparison with altimeters for the period from March 2014 until March 2016.

Main R&D achievements for global reanalysis and reprocessing

Temperature and salinity RMS differences computed in the profiles' observation space help quantifying the average accuracy performance of the reanalyses, and its stability in time. As they capture interannual fluctuations, ocean reanalyses are expected to give RMS time series of lower amplitude than climatology would give. The departures between the two RMS difference time series, that of the reanalysis, and that of the climatology, gives an estimate of the capacity of the reanalysis to represent interannual variability in the ocean. Figure 29 shows that the ensemble of reanalyses GREP-V1 displays skill in that sense, and that this skill improves dramatically after 2002, with the setting of the Argo network. The spread of the reanalyses RMS differences is reduced during the Argo period (2002-now) with respect to the previous period, while the departure from the "climatological performance" is increased with the development of the Argo network. During the decade 1992-2002, the added value of reanalyses is clear for temperature, whereas the spread of the salinity results is large, and on average the reanalyses and the climatology have similar levels of accuracy.

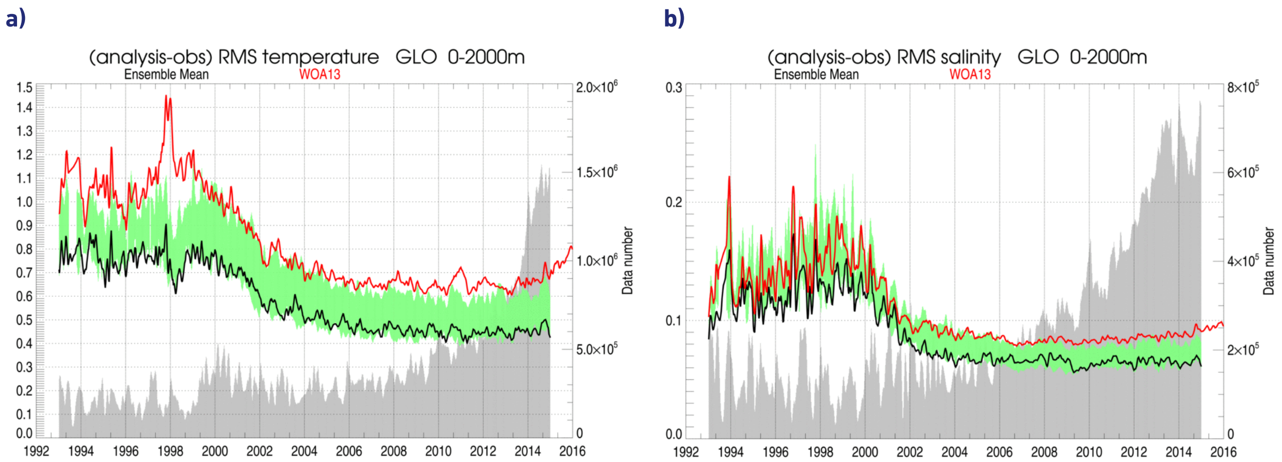


FIGURE 29

Global average 0-2000 m RMS difference computed in the observations' space, between monthly ocean reanalyses estimates and daily observations for temperature in °C (a) and salinity in psu (b). Statistics are computed daily and smoothed at the monthly scale for visualisation. The black line is the RMS of the ensemble mean product GREP-V1, the Green shading indicates the spread of the RMS of the four members of GREP-V1, eventually the red line shows the RMS obtained using the WOA 13 monthly climatology for the 2005-2012 decade. The grey shading shows the number of individual observations used to compute the statistics.

Thanks to Argo, the ocean reanalyses improved dramatically the skills for both temperature and salinity, which is crucial for the representation of ocean circulation, and the balance with the other assimilated observations (SLA and SST).

The Copernicus Marine Service also provides 3D gridded global ocean estimates based on observations only. One product (disseminated by the INS TAC) is based on an optimal interpolation of all available *in-situ* T/S profiles data (Gaillard *et al.*, 2016). The other product is based on a multi-observations approach and uses satellite SST and SLA observations and *in-situ* T/S profiles data and statistical methods (Guinehut *et al.*, 2012), and for this reason it is disseminated via the GLO MFC.

Hydrographic variability patterns have been analysed in the seven estimates (2 observational products, 4 members and the ensemble mean of GREPV1) in terms of spatial patterns and time evolution of these patterns (for the period between 1993-2016). As illustrated in Figure 30, robust features appear in the different products, and the GREP-V1 product is closer to the observational product in the 0-800 m layer. Below 1000 m, where observations are sparser, especially before the setting of the Argo network, the spread between global estimates is large in many areas, which explains the differences observed between the GREP-V1 ensemble mean, GLORYS2V4 and the GLO-OBS estimates. Work is in progress to estimate error bars or uncertainty levels from this work.

The plan is to compute signal-to-noise ratios, as a specific contribution to the Ocean State Report #2.

Impact for users and applications

The number of regular users of the GLO MFC products and the volume of downloaded GLO MFC products has grown regularly during the first 3 years of CMEMS. The number of regular users, which are users who download products at least every week, has been multiplied by 2 (from 70 to 140) and the volume of the downloaded data has been multiplied by 4 (from 5 to 20 Tb/month with a value larger than 30 Tb/month during November and December 2016). Diversity of applications is large and covers the four areas of benefits defined in CMEMS. Examples are: operational applications on search and rescue, marine resources management and monitoring; downscaling applications from the global to regional and coastal forecasting systems; and initialization of ocean atmosphere coupled forecasting system for short-term meteorological forecast or seasonal forecast.

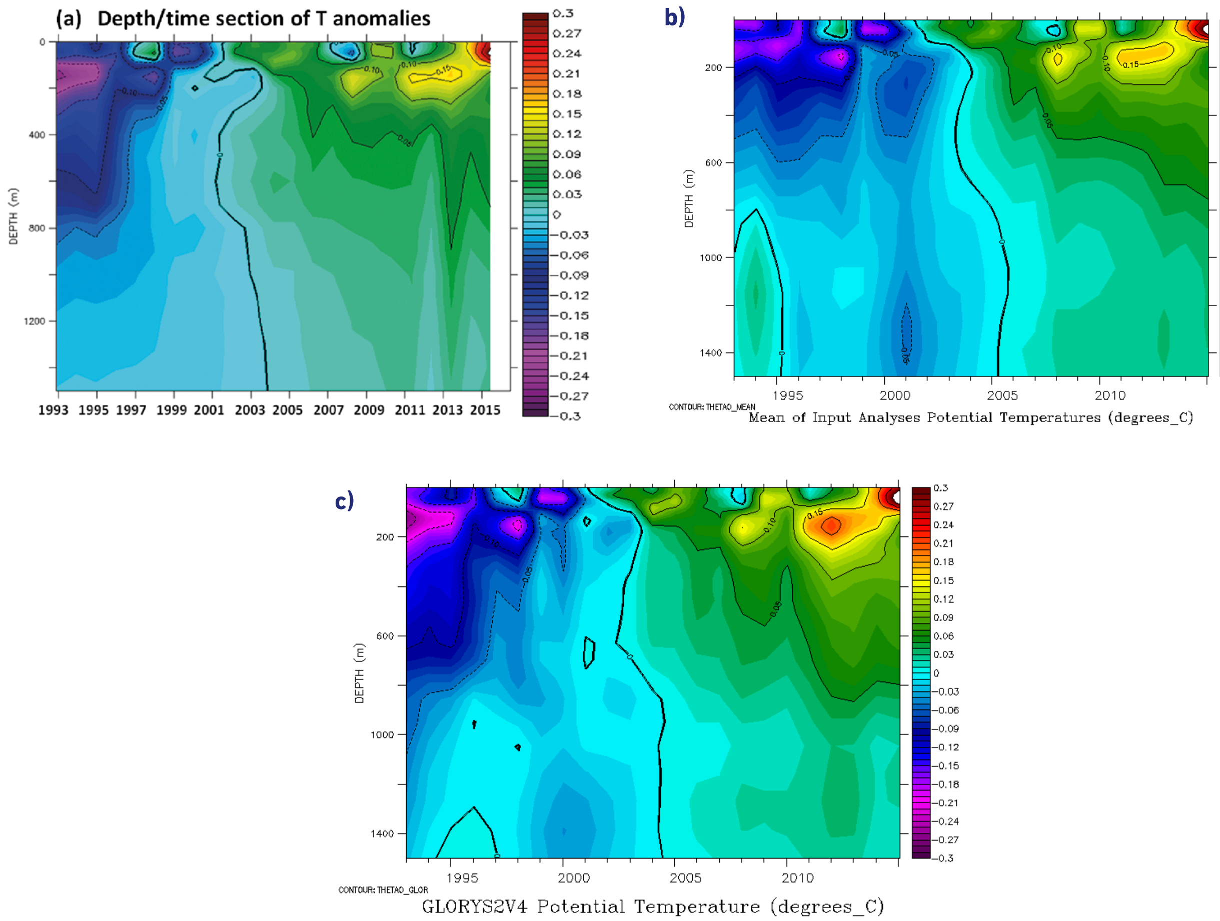


FIGURE 30

Intercomparison of 3D average temperature anomalies as a function of depth and time, and with respect to a 1993-2014 climatology. Anomalies are computed in (a) from GLO-OBS 3D estimates and GLO-OBS climatology, in (b) from GREP-V1 ensemble mean monthly estimates and GREP-V1 climatology, and in (c) from GLORYS2V4 monthly averages and GLORYS2V4 climatology.

ARCTIC MFC

Overview

The Arctic (ARC) MFC is covering the Nordic Seas and Arctic Ocean north of 63°N with forecast of the ocean and sea ice physics, waves and ocean biogeochemistry. Ocean physical and biological reanalyses (25 years and 4 years respectively) are also provided. The ARC MFC ocean modelling and data assimilation system was previously known as the TOPAZ system since 2003. It uses the Ensemble Kalman Filter (EnKF) to assimilate different types of satellite and *in-situ* observations (Sakov *et al.*, 2012, Xie *et al.*, 2017). The ocean model is a regional configuration of the Hybrid Coordinate Ocean Model (HYCOM) (Bleck, 2002) and coupled with a dynamic-thermodynamical sea ice model and two ecosystem models (NORWECOM and ECOSMO). The use of a dynamical EnKF was motivated by the problem of coupled ice-ocean assimilation (Lisæter *et al.*, 2003) and the ability to estimate biological model parameters when assimilating biological observations (Simon *et al.*, 2012, Gharamti *et al.*, 2017). The waves are forecasted by an Arctic configuration of the WAM model developed in the MyWave project.

Physics

A steady increase of the resolution of forecasting systems is necessary to keep up with the state of the art. Since the ARC MFC data assimilation integrates 100 dynamical members, the available computing facilities have so far restricted the choice of the model resolution to about 12 km horizontally and 28 hybrid vertical layers. In the course of the first phase of CMEMS, the ARC MFC is doubling both its horizontal and vertical resolution, and the domain can be restricted to the Northern latitudes, taking benefit from lateral boundary conditions from the GLO MFC. This increase in resolution is expected to resolve better the narrow topographically-steered currents in the Nordic Seas and Arctic Ocean. The new domain will also include the Bering Sea in the Pacific Ocean.

Biology

The ARC MFC has implemented a chlorophyll component in the ECOSMO model following the formulation from Bagniewski *et al.* (2011). This replaces a fixed diagnosis of chlorophyll from the phytoplankton biomass and is intended to improve the assimilation of satellite retrievals of chlorophyll from the OC TAC.

Waves

The inclusion of waves in CMEMS provides a historical opportunity to include wave terms into the ocean surface circulation as well as the wave processes that shape the Marginal Ice Zone (MIZ).

As part of the Retrospect project funded by the Research Council of Norway, the following wave-to-ocean terms have

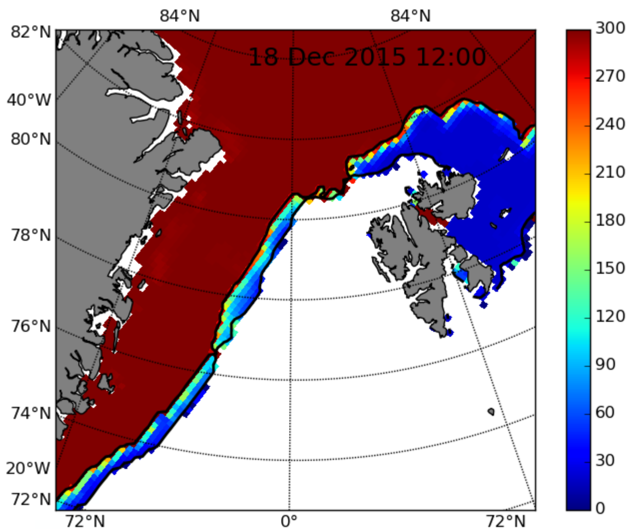


FIGURE 31

Maximum floe size predicted by the model on 18th Dec 2015 following the passage of a storm. The ice pack is represented in dark red, the MIZ defined by the action of waves has a variable floe size up to 300 m.

been implemented in HYCOM, following the SHOM implementation (R. Baraille, pers. comm.): the Coriolis-Stokes drift, the surface stress due to wave generation and decay, and the wave induced mixing by Langmuir cells. The Coriolis-Stokes drift uses a deep-water approximation of the Stokes profile based on the Phillips Spectrum (Breivik *et al.*, 2016), which conserves the wave momentum to be fed to the ocean mean flow. Four different parameterizations of the Langmuir cells are being evaluated. These wave-to-ocean terms are expected to improve the prediction of drift of surface objects, including the drift of biological material.

When waves reach the sea ice, the mechanical flexure efforts break the ice into smaller floes, which in turn attenuate the waves by both scattering and dissipation processes. The waves-in-ice model proposed by Williams *et al.* (2013) includes the above effects and has been implemented and tested in HYCOM within the EU FP7 SWARP project (see Figure 31 for an example extracted from a NRT experiment using the WAVEWATCH III model from Ifremer as input). The resulting predictions of waves in ice and floe size are relevant to the offshore industry, which is more likely to work in the MIZ than in heavier ice pack conditions.

Product quality assessment

Measuring the skills of a sea ice forecast requires some user-defined metrics: since most navigators would like to remain safely outside of the ice edge, the distance to the ice edge has been used as an intuitive way to quantify and compare sea ice forecast skills in the ARC MFC and GLO MFC (Figure 32).

The ARC MFC physical ocean reanalysis provides one of the most extensive demonstrations of ensemble data assimilation to date, and an opportunity to challenge the convergence of the EnKF. Xie *et al.* (2017) have used diagnostics of the Reduced-Centered Random Variable and show that the EnKF remained reliable throughout the 1200 assimilation cycles of the reanalysis and that the solution was balancing well the different observations assimilated (none of the six different remote sensing and *in-situ* data types was assimilated at the expense of the others).

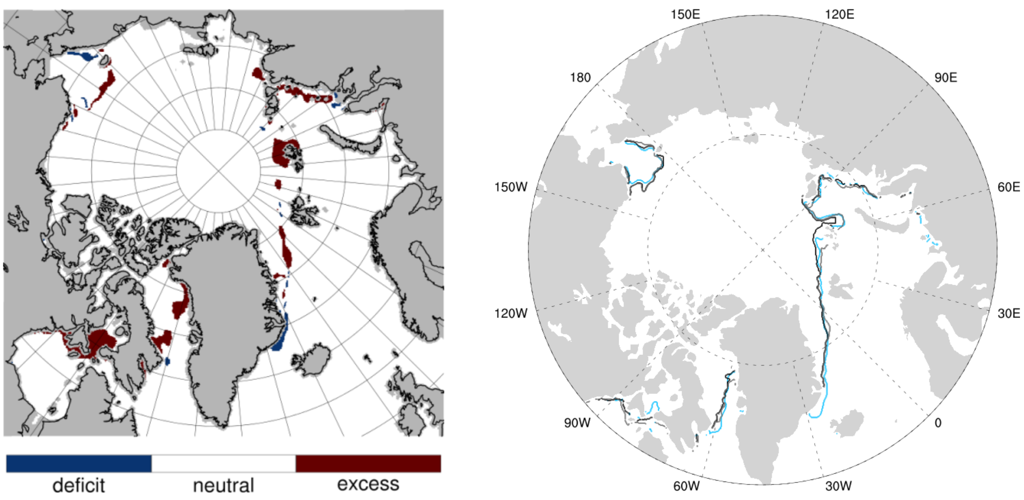


FIGURE 32

Maps displaying regions with deficit and excess of sea ice (left) and ice edge delineation from observations, forecast and model best estimate (right).

Towards the assimilation of sea ice thickness

The value of assimilating sea-ice thickness (SIT) measurements for short term forecasting has been evaluated by Xie *et al.* (2016). Even though only measurements of ice thinner than 40 cm were retained, the SMOS data proved beneficial to forecast thicker ice, as well as a slight improvement of sea ice concentrations (Figure 33). The assimilation updated jointly ocean and sea-ice variables and was not detrimental to ocean properties.

Impact of R&D advances for users and applications

Weather,seasonal and climate. Although CMEMS targets shorter time scales than the climate modelling community, the developments of the ARC MFC system shares common conceptual and software components with the Norwegian Climate Prediction Model (NorCPM): both use isopycnal vertical coordinates (both in MICOM and HYCOM): apply the EnKF for data assimilation; and coupling to the CICE sea ice model and the OSA EnKF for the biogeochemical component (Counillon et al., 2016, Gharamti et al., 2017b). These methodological exchanges could be exploited in future seamless predictions from days to decades, which have a strong appeal to those using both NRT and climate forecasts.

Marine resources (fishery and aquaculture). The monitoring of fish stocks is relying on properly simulating the drift of biological material at the ocean surface, be it for the availability of nutrients and plankton at the basis of the food web or the nearly passive drift of fish larvae. Ocean temperature is also an important condition to the early stages of fish development in high latitudes (Stige *et al.*, 2015).

Offshore industry and Marine Renewable Energies. The Arctic Response Technology Joint Industry Project has emphasized the importance of knowing the diffusive properties of the sea ice dynamics in view of forecasting the fate of hypothetical oil spills trapped in the ice. Rampal *et al.* (2016) have compared such properties in the classical sea ice model used in the ARC MFC to the neXtSIM model using a more advanced Maxwell Elastic-Brittle rheology and showed that neXtSIM had the most realistic diffusive properties.

Marine Safety and maritime transport. The shipping industry relies on e-Navigation services (optimal routing) that must be continuous from harbour to harbour (B. Å. Hjøllo, NAVTOR AS). This continuity requires a dynamical downscaling approach from the GLO MFC to all regional MFCs, which is being practiced more and more broadly across the CMEMS MFCs.

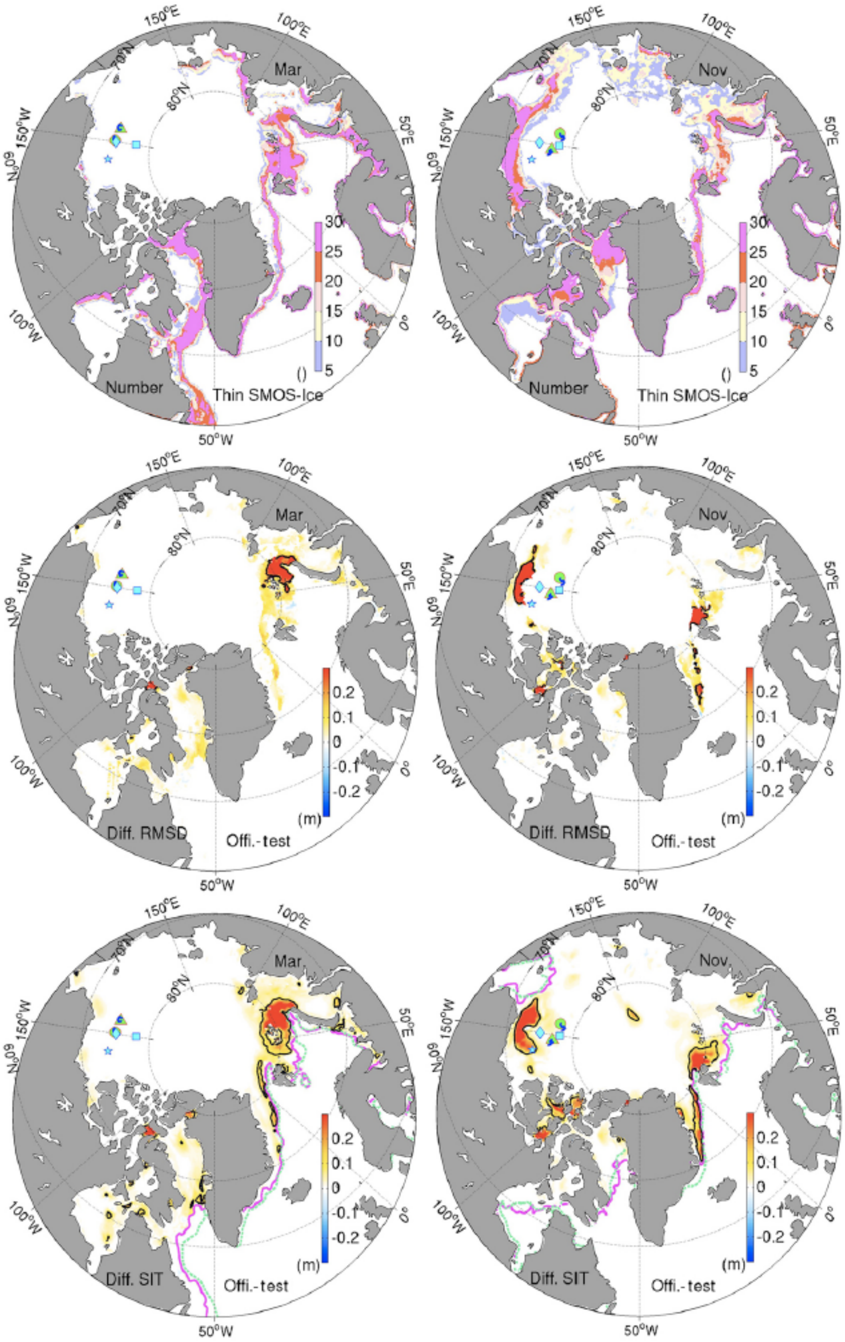


FIGURE 33

Top row: number of SMOS data points assimilated in March (left) and in November (right) 2014. Middle row: difference of RMSDs for the thin SIT between standard run and test run. The black line denotes the 0.2 m isoline. Bottom row: difference of SIT between official run and test run. The black line denotes the 0.2 m isoline, and the green (magenta) line is the 15% concentration isoline from the OSI TAC (official run).

NORTH-WEST SHELF MFC

Overview

The North-West European Shelf (NWS) MFC is delivering physical and biogeochemical real time and reanalysis products for the European continental shelf area. Starting from April 2017 a wave component has been added to deliver forecast products.

Physical and Biogeochemical component

The Forecasting Ocean Assimilation Model 7 km Atlantic Margin model (FOAM AMM7) is a coupled hydrodynamic-ecosystem model, nested in a series of one-way nests to the Met Office global ocean model. The hydrodynamics are supplied by the Nucleus for European Modelling of the Ocean (NEMO), Madec 2016, with the NEMOVAR 3D-Var First Guess Appropriate Time (FGAT) system used for the data assimilation (Waters *et al.*, 2015). This is coupled to the European Regional Seas Ecosystem Model (ERSEM), developed at Plymouth Marine Laboratory (PML), which is run on the same model grid as the physical model.

The model is located on the European North-West continental Shelf (NWS), from 40°N, 20°W to 65°N, 13°E, on a regular lat-lon grid with 1/15° latitudinal resolution and 1/9° longitudinal resolution (approximately 7 km square). The domain extends beyond the shelf to include some of the adjacent North-East Atlantic, but the focus of this system is on the shelf itself and the deep water is primarily included to ensure there is appropriate cross-shelf exchange. The domain is shown in Figure 34. The CMEMS products delivered from this system cover the full model domain (i.e. on and off shelf).

A hybrid s-sigma terrain following coordinate system (following Siddorn and Furner, 2013) with 51 levels is employed in order to retain vertical resolution on the shelf. To reduce horizontal pressure gradient errors over extreme topography the scheme includes a z-S hybrid as described in Madec *et al.* (1996). The loss of vertical resolution at these points is more than compensated for by reduced errors in the horizontal pressure gradient term. A key feature of the bathymetry dividing the shelf from the deep ocean is the shelf slope, running south to north from Portugal to Norway. Associated with the shelf slope is the important "joint effect of baroclinity and bottom relief" (JEBAR) (Huthnance, 1984) which drives a poleward shelf slope current. The shelf slope itself varies in width and steepness. It is particularly steep along the Iberian slope to the west of Portugal and the Cantabrian slope to the north of Spain. The combination of very step bathymetry and sigma coordinates requires special treatment for modelling horizontal pressure gradients, which is done using a Pressure Jacobian formulation. Bathymetry was supplied by North-West Shelf Operational Oceanographic System (NOOS) partners, who have processed GEBCO 1 arc-minute data together with a variety of other local data sources. The bathymetry was further interpolated in-house to fit with the model grid.

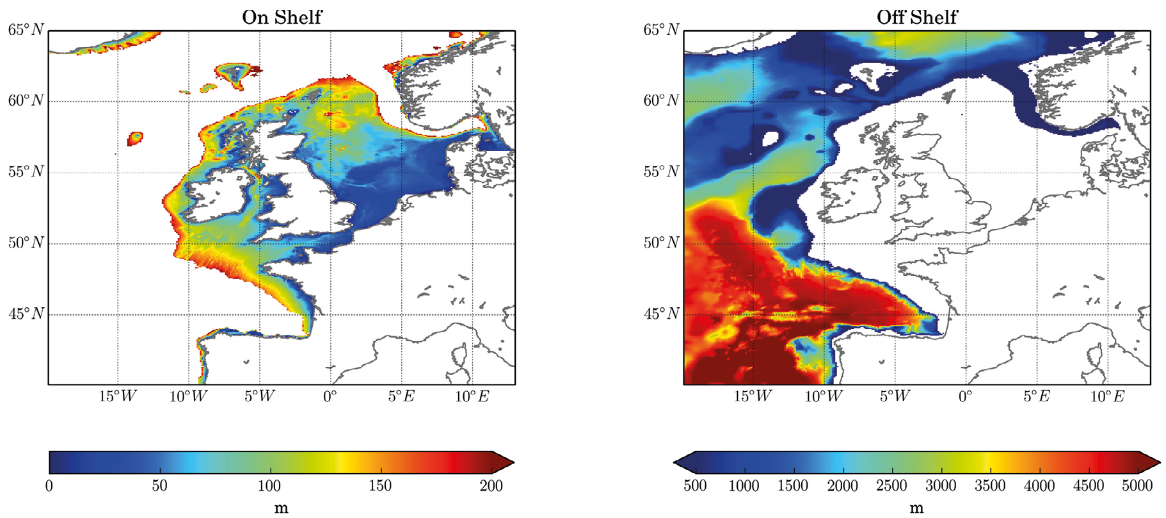


FIGURE 34

FOAM AMM7 bathymetry (m) showing (left) the domain on the European North-West Shelf (defined here as total depth less than 200 m) and (right) the domain off the shelf.

Tidal forcing is included both on the open boundary conditions via a Flather radiation boundary condition (Flather, 1976) and through the inclusion of the equilibrium tide. The external elevation and depth mean velocity was determined from 15 tidal constituents taken from a tidal model of the northeast Atlantic (Flather, 1981). The model is also one-way nested with the Met Office operational FOAM 1/12° deep ocean model (Storkey *et al.*, 2010) and the CMEMS Baltic MFC system that provides temperature, salinity, sea surface height and depth integrated current information at the open boundaries. Freshwater river fluxes are from a climatology of daily discharge data for 279 rivers from the Global River Discharge Data Base (Vörösmarty *et al.*, 2000) and from data prepared by the Centre for Ecology and Hydrology as used by Young and Holt (2007). Surface forcing is provided from the Met Office's Numerical Weather Prediction model using three-hourly heat and moisture fluxes, and hourly instantaneous fields of wind and surface pressure.

The ecosystem component of the model is supplied by the European Regional Seas Ecosystem Model (ERSEM, Baretta *et al.*, 1995, Blackford *et al.*, 2004). Initially developed collaboratively within the EU, ERSEM has since been further developed at Plymouth Marine Laboratory. It was conceived as a generic model and when coupled to a qualitatively correct physical model it is designed to be capable of correctly simulating the spatial pattern of ecological fluxes throughout the seasonal cycle and across eutrophic to oligotrophic gradients. There are perhaps three reasons that allow ERSEM this flexibility. Firstly, it includes detailed representations of the benthic system, which are vital for the correct treatment of shelf seas. Secondly, it decouples carbon and nutrient dynamics which gives a far better approximation to how nutrient limitation acts on cells than simpler models with fixed carbon:nutrient ratios. Thirdly, it can simulate both the "classical" large cell production / grazing dynamics and the small cell microbial loop, thereby representing the continuum of trophic pathways evident in marine systems.

Wave model

The WWIII-AMM7 model is a nested regional wave model configuration, defined on an identical grid to other North-West Shelf MFC modelling systems for hydrodynamics and ecosystems. The domain extends beyond the continental shelf in order to place the model's boundary region in the deep waters of the adjacent North-East Atlantic, but the focus region for the model comprises open waters of the shelf seas, i.e. using UK terminology, the North Sea, Irish Sea, English Channel, Celtic Sea and Bay of Biscay. The present 7 km resolution of the model restricts its utility in the coastal zone, where topographic sheltering (e.g. reductions in wave height in the lee of headlands) and strong sub-grid scale variability in shallow water bathymetry will affect the wave field.

Wave models describe ocean surface conditions only, so do not require a vertical coordinate system. Furthermore, the majority of effects on wave propagation and dissipation occur in waters of intermediate or shallow depth as defined relative to the wave frequency (inverse of wave period):

$$d \leq \frac{g}{4\pi f^2}$$

Where: *d* is water depth, *g* acceleration due to gravity and *f* is wave frequency.

Thus bathymetry is only a controlling mechanism on the wave field for depths below approximately 490 m, based on a minimum frequency in the model of approximately 0.04 Hz (period 25 seconds). The WWIII-AMM7 configuration uses the same bathymetry as the equivalent NWS hydrodynamic model, which has been derived from data supplied by the NOOS partners, using a synthesis of GEBCO 1-arc minute data together with local data sources. In order to match the grid set-up in the hydrodynamic model, but improve the estimate of wave energy transmission in the vicinity of sub grid scale topographic features such as small islands and coastal headlands, a number of sub grid blocking cells are defined for the wave model following the method described by Chawla and Tolman (2008).

Reanalysis products

The coupled system NEMO-ERSEM described above has been used for the production of the reanalysis time series, 1985-2014. Daily and monthly mean products are available for the following variables: temperature, salinity, horizontal velocities, mixed layer depth, bottom temperature, chlorophyll, nutrients, oxygen and phytoplankton concentration, primary productivity. A new time series, 1992-2016 will be released in one year's time, using the latest version of the model and with the addition of chlorophyll data assimilation. A new product, based on different reanalysis products available for the NWS area, will be released to provide information on uncertainty in the ocean state estimates. A Multi Model Ensemble product (Golbeck, 2015) will provide a monthly mean, based on Multi Model Products, for salinity and temperature.

Evolution of the forecasting system

The system and its components are continuously evolving in order to increase the number of products offered and their quality. One of the major improvements during the last couple of years has impacted mostly the physical component

TIDES	SST	TEM	SAL	Bottom TEM	MLD	SSH
=	↑	↑	↑	=	=	↑

FIGURE 35

New system and its impact on the quality of the CMEMS products.

of the system. The model code, NEMO has been updated to the latest available version (3.6) and the data assimilation scheme has been improved to include SST as well as vertical profiles of temperature and salinity, and satellite sea level anomaly data. Due to a bias in salinity the fresh water river discharge dataset has been changed as well. These three modifications have impacted the quality of the products with an increased quality of the temperature and salinity at the surface as well as at intermediate depths and in the model sea surface height. The accuracy of other physical variables like tides has not been affected by these modifications (Figure 35).

The major differences between the system running since the beginning of CMEMS and the new system, available to the users starting from 19 April 2017, are summarized in Table 2 below:

New versus Old system: product quality improved and impact on the forecast

The impact of the latest modifications have been tested in a trial experiment for years 2014-2015 running the two systems (old and new) with the only differences listed in Table 2. The initial conditions, lateral boundaries, atmospheric forcing and model parameterization are the same for the two experiments. The major improvements in the new system are in the temperature and salinity variables (Figure 36) with a mean reduction of the temperature RMS error of 0.7 ° C between 500 and 1300 m depth. The salinity is improved not only due to the data assimilation, of vertical profiles and SLA but also due to the different river discharge dataset used, with a reduction of the RMS error of 0.04 PSU at surface, increasing to 0.12 PSU at 1000-1300 m. The new version model code and the SLA data assimilation have improved the sea level statistics, the products no longer have larger errors in winter when there are strong storms in the western part of the model domain. Even if the number of vertical profiles in the shelf area is quite limited and the SLA is assimilated only in the model domain deeper than 700 m, there is a positive impact even on the shelf area.

	OLD (V1)	**NEW (V3)**
Freshwater river fluxes	e-hype historical and forecasted river discharge	Climatological daily discharge data for 279 rivers from the Global Discharge Data Base (Vörösmarty *et al.*, 2000) and from data prepared by the Centre for Ecology and Hydrology as used by Young and Holt (2007)
NEMO code version	3.4	3.6
Data assimilation	2D SST	3D SST, vertical profiles of T and S and SLA

TABLE 2

Differences between the old and the new North-West European Shelf MFC system.

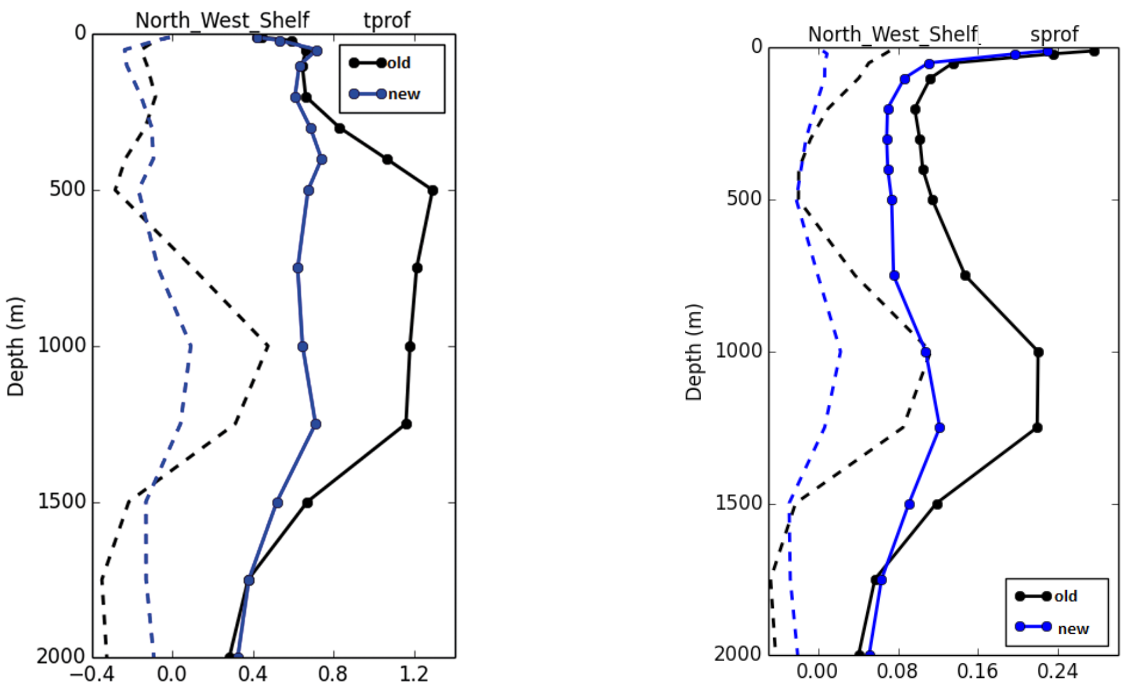


FIGURE 36

Observations minus model temperature (left) and salinity (right) for the old (black) and the new (blue) North West Shelf MFC system. The RMS error is shown by the solid lines and the mean error is shown by the dashed lines (positive value indicates a cold model bias). The statistics are computed over the two years run.

Impact on the users

Improved quality for the analysis should reflect in a better predictability capability of the system. Preliminary assessment of the forecast accuracy has been done against SST observations provided by USGODAE, from ships, drifting buoys and fixed buoys. An assessment was performed for four months over the assessment period, one from each season, these being January 2014 (winter) and April 2014 (spring), July 2014 (summer) and October 2014 (autumn). Data is sparse for this assessment, particularly so on the shelf. Drifting buoys are generally in the deeper waters to the west and north of the domain, with only occasional buoys drifting onto the shelf. Fixed buoys are clustered around the southern North Sea coast, English Channel and western shelf break. Ships tend to be concentrated in the southern North Sea and English Channel and the observations tend to be more unreliable.

Looking at each forecast lead time (Figure 37) the analysis from the new system has RMS error of approximately 0.35 °C with errors growing to around 0.5 °C throughout the forecast. In contrast, mean error starts at around 0.02 °C (a cold bias) and grows only slightly through the forecast. These results compare reasonably well with the old system; the RMS error for the new one is lower than the old in the analysis and similar through the forecast (Figure 37). The mean errors have opposite signs in the two systems and while the magnitude of the mean error is similar for the analysis, the mean error of the old system increases to a much larger extent through the forecast.

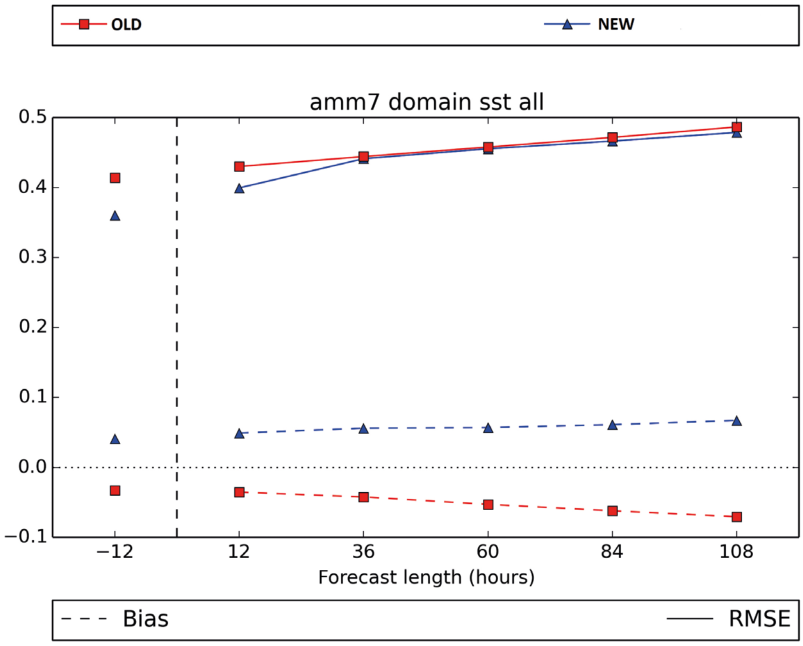


FIGURE 37

Observation minus model SST (°C) statistics against forecast lead time for the old (blue) and new (red) North West Shelf system. A positive mean error indicates a cold model bias.

IBERIA-BISCAY AND IRELAND MFC

Overview

The CMEMS IBI (Iberia-Biscay-Ireland) MFC provides information and forecasts on the state of the ocean for the European Atlantic facade, including information on physical, biogeochemical and wave parameters.

The IBI MFC has been providing continuous daily ocean model estimates and 5-day forecasts for the IBI regional seas since 2011. The operational IBI Ocean Forecast Service, based on an eddy-resolving 1/36° NEMO model can realistically reproduce high frequency processes required to characterize regional marine scales. Since 2014, the IBI MFC has provided a multi-year product comprising both physical and biogeochemical parameters. This product currently covers the altimetric decade period (2002-2014) and it is generated by means of a 1/12° resolution NEMO/PISCES coupled run, assimilating through the SAM data assimilation tool, SST and SLA fields together with *in-situ* profiles. Sotillo *et al.* (2015) provides further information on the products and services delivered by the IBI MFC from the MyOcean times till present.

These existing IBI MFC systems have steadily evolved in the last years, already in the context of the CMEMS service framework. Furthermore, two new near real-time (NRT) IBI forecast services for biogeochemical and wave parameters have been recently put in place (CMEMS V3 release; April 2017). This continuous IBI MFC system and service evolution has been possible thanks to, and based on, the scientific works developed within the IBI MFC context, mostly organized along the R&D axes described below

Physics (the road towards data assimilation in IBI)

The Iberia-Biscay-Ireland MFC ocean forecast system performs satisfactorily in the IBI area, including coastal and shelves regions. However, some limitations remain and, among others, the lack of a direct data assimilation scheme.

For an ocean forecasting system, it is mandatory to incorporate actual sea state information into the system via data assimilation. In global and basin scale ocean modelling, data assimilation has proved to be an invaluable component for operational forecasting (Bell *et al.*, 2000; Drevillon *et al.*, 2008). On the contrary, for shelf seas, the necessary inclusion of shorter temporal and spatial scale processes, particularly in relation to the interaction of tides and the shelf, have discouraged the widespread use of data assimilation in operational systems (Annan and Hargreaves, 1999). However, progress has been made in recent years, and some MyOcean/CMEMS operational regional modelling systems progressively incorporated data assimilation schemes (O'Dea *et al.*, 2012).

Data assimilation in a high-resolution ocean model system, working on a complex and very active tidal region (such as the IBI one) represents, certainly today, a scientific challenge. Consequently, the IBI MFC is dedicating a significant part of its R&D resources to generate a weekly regional analysis for IBI waters. The IBI MFC scientific team is tackling this challenge, doing data assimilation in the IBI tidal environment on shelf seas, using (and evolving) the SAM2 (*Système d'Assimilation* Mercator version 2) data assimilation method. SAM2 relies on a reduced order Kalman filter, based on SEEK formulation (Pham et al., 1998), and has been used by Mercator Ocean in different approaches (i.e. the CMEMS Global MFC – see previous section).

The need for a forecast system to keep track of real measurements has been considered since the first version of the IBI MFC model. A step-by-step approach has been followed, and the IBI NRT forecast service has evolved towards full data assimilation, to be implemented at the CMEMS V4 release (April 2018). A substitution of the periodic re-initialization method (originally applied in the IBI system) by a new spectral nudging technique was tested and finally applied in operations (in April 2016, see Sotillo *et al.*, 2017).

The chosen spectral nudging method permits to "nudge" the low frequency IBI solution towards the large scale CMEMS GLOBAL one in those areas where the latter is supposed to be better (mainly off the shelf and in deep waters) due to the assimilation of low frequency signals. Furthermore, this new spectral nudged IBI solution overcame two drawbacks of the previous existing IBI versions: a) to avoid the temporal discontinuity inherent to the periodic re-initialization; b) to minimize dependency from the GLOBAL parent solution on the shelf, where water properties are largely biased by the physics missing in the GLOBAL solution (tides and other high frequency physical processes). Note that the SAM2 DA tool has been recently updated to be able to run this continuous IBI nudged solution. The high frequency IBI best estimates are now operationally produced through this new SAM2 spectral nudging capability. It will operate in this way until April 2018, when data assimilation through the upgraded SAM2 will be fully implemented in IBI operations.

SAM2 tool data assimilation and its present use in multi-year product. The IBI MFC reanalysis system has been a key element in the IBI MFC research on data assimilation in the IBI area.

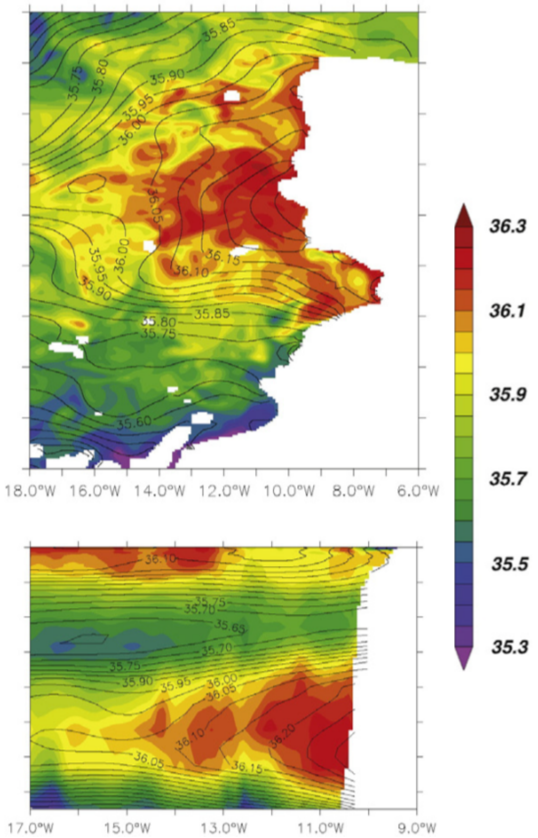


FIGURE 38

Spatial fields at 1000 m (top) and vertical section at 39°N of monthly mean salinity (psu) for IBI reanalysis (date: April 2011). Contour lines correspond to WOA13 climatology. (Figure from the paper Aznar *et al.*, 2016).

The SAM2 DA system, with novelties required to make it an adequate tool for its later application as part of the 1/36° resolution IBI MFC forecast service, has been tested and applied firstly in the 1/12° IBI reanalysis to constrain the NEMO model solution in a multivariate way with satellite SST, sea level anomalies, and *in-situ* observations from the CORA product. This IBI reanalysis can reproduce a large range of physical processes from tidal to seasonal scales. Some of the IBI reanalysis strengths are: realistic reproduction of inter-annual variability in temperature and sea level together with a realistic reproduction of the Mediterranean Intermediate water (Figure 38), and some other regional features (e.g. Bay of Biscay summer jet). On the other hand, some weaknesses mainly related to local biases (i.e. summer upwelling conditions in the western Iberian coast) or unrealistic simulation of dynamics (i.e. Gibraltar Strait transports, or Alboran gyres) can be noticed. Nowadays, the IBI MFC is performing a re-run of the IBI reanalysis to extend its physical and biogeochemical multi-year product back to the year 1992. Product quality improvements are expected since this new re-run is using the updated model and DA scheme (NEMO3.6 + SAM2V1) together with improved ocean boundary conditions (from recently upgraded CMEMS Global reanalysis) and the assimilation of the latest released observational products (i.e. new filtering and subsampling of altimetric data and new *in-situ* CORA (V4.1))

Comparison of assimilated vs. non assimilated and advances in multi-platform validation. The quality of the IBI forecast products is assessed by means of the NARVAL (North Atlantic Regional VALidation) tool (Lorente *et al.*, 2016). The validation of IBI against independent *in-situ* and remote-sensing measurements is routinely conducted to evaluate model veracity and prognostic capabilities. Noticeable efforts are in progress to define meaningful skill scores and statistical metrics to quantitatively assess the quality and reliability of the IBI model solution. Likewise, the IBI MFC compares the IBI forecast products with other diverse model solutions by setting up specific inter-comparison exercises on the overlapping areas at diverse timescales. This highlights the coastal quantitative quality assessment of local operational ocean forecasting systems, dynamically embedded in the regional CMEMS IBI solution, as well as the comparison between these downstream costal model solutions and the CMEMS core regional and global ones. Together with this routine on-line comparison of local and regional solutions, different off-line scientific validation exercises have been carried out taking advantage of specific observational campaigns (Capó *et al.,* 2016; Sotillo *et al.,* 2016).

The IBI MFC is also assessing its IBI multi-year reanalysis product in comparison with the NRT forecast solution. Some interesting results from this exercise are shown in Aznar *et al.* (2016). Both the IBI forecast and the reanalysis products, compared with several observational data sources, present realistic patterns at regional scales. The results also highlights a better performance of the 1/36° forecast in coastal areas whereas the 1/12° reanalysis shows a better performance

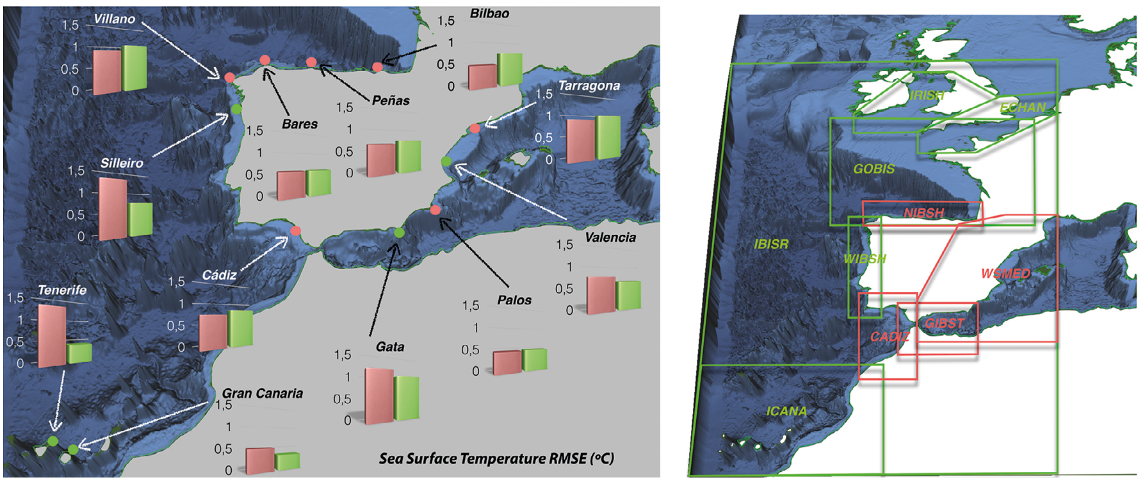


FIGURE 39

Left Panel: RMSE histograms of IBI forecast (red) and reanalysis (green) vs. observational SST (in °C) at Puertos del Estado buoy locations. Locations are coloured according to the product with best RMSE performance. Period: April–December 2011. Right Panel: Studied regions in IBI domain. Regions are coloured according to the best statistical performance (best bias, RMSE and time correlation) vs. OSTIA temperature: IBIop (red), IBIre (green). Figure from Aznar *et al.* 2016.

in offshore deep waters. The comparison emphasizes the possible benefits of the data assimilation scheme in areas away from the coastline, but also its limitations in complex coastal regions. Spatial resolution seems to play a key role in such areas, especially around the Iberian Peninsula, where the higher resolution of the forecast model brings in generally better results than the coarser resolution reanalysis (Figure 39). This suggests that observational data assimilation represents a crucial step towards improving the performance of regional modelled solutions, as long as a fine enough spatial resolution is kept to prevent higher uncertainties in coastal and shelf areas.

Waves

Design, Implementation and scientific Qualification of the operational wave system. The IBI MFC has been delivering a new wave forecast service for the whole IBI region from the last CMEMS operational release (V3; April 2017). The service has been jointly developed through collaboration between Meteo France, AEMET and PdE (Puertos del Estado) together with the computer support of CESGA. The new IBI wave system uses the MFWAM model and provides a 5-day regional wave forecast product updated twice a day. This model is based on the IFS-ECWAM (38R2) code with changes regarding to dissipation by wave breaking and swell damping source terms as developed by Ardhuin *et al.* (2010), and with the last 2014 update (including improvements from MyWave Project; Janssen *et al.*, 2014). The model performs a partitioning technique on wave spectra that allows the separation between wind sea and swell wave systems and a classification of primary and secondary swell system. The IBI wave system is run with a 10 km spatial resolution and with a spectral resolution of 24 directional bins and 30 frequency bins. The IBI WAV runs are driven by 3-hourly ECMWF winds and use boundary conditions (wave spectra) from the global CMEMS wave system, which has wave data assimilation. The quality of the IBI WAV operational system and its associated CMEMS product has been extensively assessed by comparison with observations both from *in-situ* mooring and remote sensed satellite altimeters. The wave model validation in the IBI region with *in-situ* data has been performed through two parameters: significant wave height and mean wave period. Figure 40 illustrates the very good performance of the new IBI wave product (further details in Aouf *et al.*, 2017)

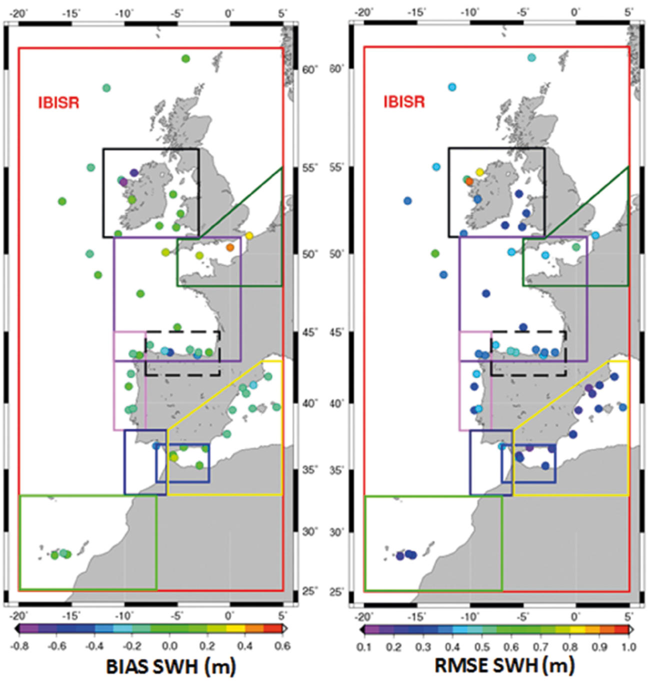


FIGURE 40

Maps of skill metrics derived from the comparison of the significant wave height provided by the IBI WAV product and the observations from the mooring buoys: bias (left) and root mean squared difference (right) obtained for an entire two-year period (2014-2015). Figure from the IBI wave Quality Information Document (Aouf *et al.*, 2017).

Ocean-Wave Coupling. The IBI Wave Team is developing the R&D actions required to incorporate wave coupling parameters to be operationally used as forcing in the daily IBI NEMO ocean forecast. The main wave-circulation interaction processes studied for inclusion in the IBI operations are: sea state dependent momentum flux, Stokes-Coriolis forcing and sea state dependent energy flux. Sensitivity test runs are being performed to evaluate the impact of these wave-circulation coupling mechanisms. The results are being extensively validated with external independent observations: the IBI wave model run is being validated and the effect of the different coupling mechanisms are being checked, verifying the impacts not only on the surface currents but also on other physical ocean variables (i.e. temperature, salinity, mix layer depth). To do this, a comparison with independent observations from different sensors (i.e. *in-situ* moorings, *in-situ* Argo profiles, satellites, HF Radars, etc.) at different levels is being performed. All this research on wave-circulation coupling is being performed by the IBI MFC in close collaboration with other CMEMS MFCs as well as with other related CMEMS R&D Service Evolution Projects.

Analysis of the impact of ocean currents from the IBI MFC physics system on the IBI wave system is currently being carried out. The ocean circulation/wave coupling will be incorporated in future versions of the IBI wave system.

Biogeochemistry

The first operational release of an IBI BIO forecast service was done this April 2017 (CMEMS V3 release). This new operational system delivers on a weekly basis a +7 day high resolution (1/36º) biogeochemical forecast. Together with the forecast products, hindcast data are delivered as historic IBI BIO best estimates. The system is based on an application of the biogeochemical model PISCES, running coupled to the IBI ocean forecast solution. The PISCES model can simulate the first levels of the marine food web, from nutrients up to mesozooplankton. The main biogeochemical variables, such as chlorophyll, oxygen, iron, nitrate, ammonium, phosphate, silicate, net primary production and the euphotic zone depth, are distributed as part of this IBI biogeochemical forecast product. Further details on the IBI BIO forecast service can be found in the CMEMS technical reports associated to the IBI MFC NRT biogeochemical forecast product.

Impact on users and applications

Climate monitoring. The IBI MFC is making computation of different climatic metrics and implementing the required procedures to perform a routinely monitoring of different essential climatic variables for further analysis of trends and uncertainty estimation. To this aim, the IBI MFC is using the existing multi-year IBI products as well as other CMEMS observational products. The IBI MFC scientific experts involved in this climatic research, contribute to the elaboration of the CMEMS Ocean State Report (von Schuckmann *et al.*, 2017), highlighting some regional features of interest from the IBI area. The IBI MFC contribution to the OSR#1 showed an analysis of the summer upwelling conditions in the western margins based on the CMEMS IBI multi-year products (Figure 41). For the next OSR issue, the IBI regional focus will be on the spreading of the Mediteranean outflow water (MOW) and its variability along the IBI region.

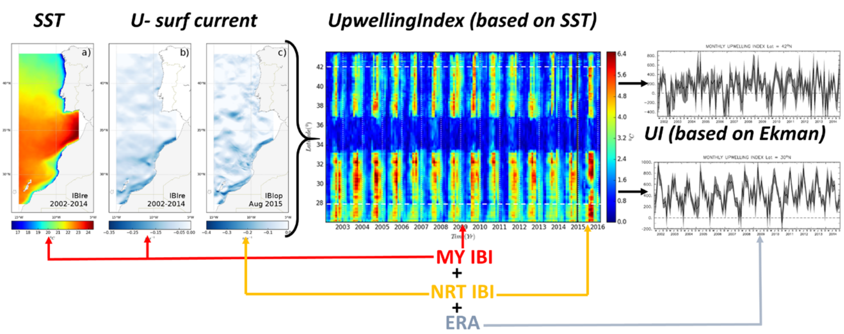


FIGURE 41

Example of OMIs (Ocean Monitoring Index) compute to monitor the summer upwelling conditions in western IBI coastal margins. Upwelling indexes computed based both on the wind (the classical Ekman one) and on IBI SST products (both from the reanalysis multi-year and NRT forecast data) are shown. The figure is a composite of figures from the OSR#1 (von Schuckmann *et al.*, 2017).

Downscaling IBI MFC solution: SAMOA project. Puertos del Estado provides operationally customized information for port and harbour authorities' decision making: in harbour safety, environmental management and infrastructure operations. PdE delivers in near real-time very high resolution met-ocean forecast data products to feed operational decision support systems in ports and harbours. In recent years, PdE has boosted local operational oceanography developments, and particularly ocean dynamical downscaling in harbour environments, through the SAMPA and SAMOA initiatives. Both SAMPA and SAMOA forecast systems are set up as CMEMS downstream services using the regional IBI forecast solution as imposed boundary condition.

Based on the IBI MFC operational validation tool NARVAL, PdE is developing a very ambitious validation tool to routinely evaluate the downscaled SAMPA and SAMOA local solutions: a multi-parameter ocean model skill assessment is being carried out by using all the available observational sources (encompassing *in-situ* and remote sensing instruments, including HF Radar) and primarily focusing on Class 1 (gridded model output) and Class 2 (time series at specified locations) metrics (Figure 42). Apart from validating the local solution, the objective is to evaluate the effectiveness of the dynamical downscaling performed, providing an objective measure of potential added value with respect to the regional Copernicus IBI solution, in which the local models are nested. Note that these comparisons of large-scale global, regional and downscaled coastal systems with the same set of metrics are quite useful for model developers. They are useful not only during the model implementation phase (i.e. testing of the most adequate initialization and boundary schemes, choice of right parameterizations, identifying issues in the set up or detecting bugs), but also during the operations (evaluating the consistency and/or detecting potential issues in the operational suite). The approach, focused on evaluating the potential added value of downscaled solution with respect to their father solution, has been proved to provide a wealth of diagnostics, objective quality indicators and uncertainty estimates, which can be ultimately delivered to inform end users about the quality and reliability of the marine forecast products, fostering downstream services and their user uptake.

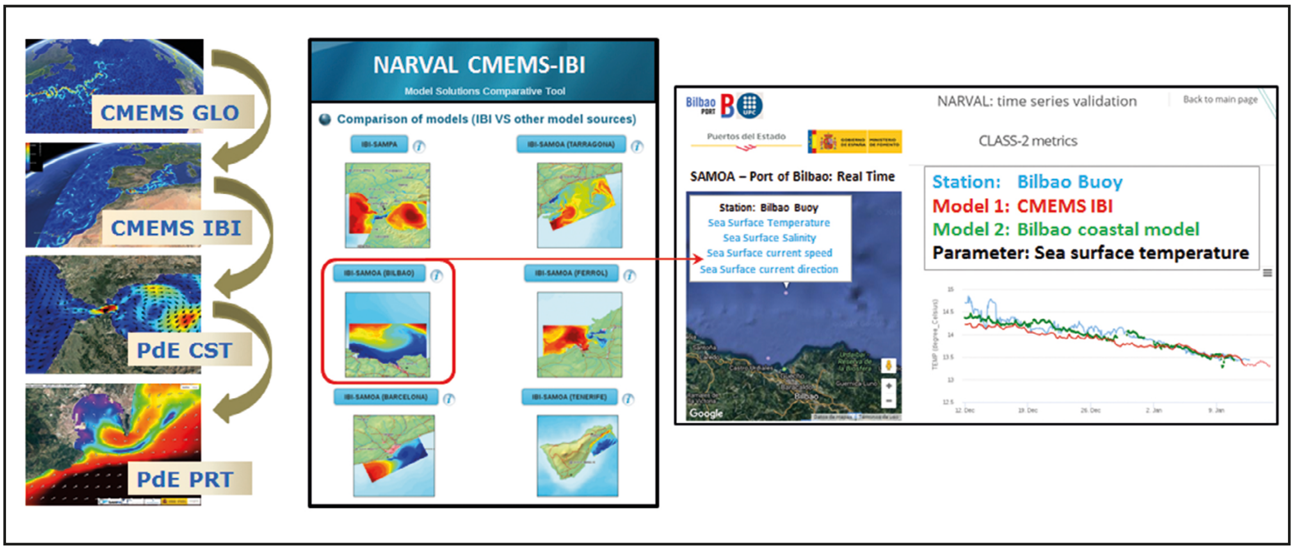


FIGURE 42

Snapshot of the Multi-parametric Ocean Model Skill Assessment tool, implemented by PdE to evaluate downscaled local solutions and to compare them with the regional CMEMS IBI solution.

CMEMS and the real time response to marine oil spills: the Oleg Naydenov case. After the sinking of the Oleg Naydenov (14 April 2015), in 2700 m of water south of Gran Canaria (Spain), several oil slicks were spotted on the sea surface. Emergency actions were taken by the Spanish local and national authorities to mitigate the environmental damage. One of the main steps in this direction was the monitoring of the evolution of the spill. The CMEMS IBI MFC forecast product played a significant role in achieving this goal. Indeed, the monitoring of the Oleg Naydenov case during the crisis and the research developed afterwards provides with strong evidence about the high quality of the CMEMS IBI MFC forecast products. The accuracy of the oil spill predictions, using the IBI currents as forcing, and the verification of the oil spill beaching confirms the usefulness of the IBI surface currents forecast for studying pollution dispersion (García-Garrido *et al.*, 2016).

MEDITERRANEAN SEA MFC

Overview

The Mediterranean Sea (MED) MFC is led by CMCC and gathers three European research institutes (INGV, OGS and HCMR). The implemented service adopts the state-of-the-art knowledge in the scientific modelling development for the currents, biogeochemistry and waves. The consortium ensures the cutting edge state of the system upon the yearly update of the service catalogue. The user-driven nature of this service organization fosters the vision of ensuring the benefit for major users (e.g. scientific community, national authorities, EEA, EMSA, REMPEC and other EU decision makers). The service is focussed on key target applications such as oil spill emergency management, industrial and private sector applications, MSFD implementation and climate change monitoring. The planning of the catalogue evolution is based on requirements from the main users and applications, and, in particular, from new value-added innovative downstream applications with industry. The system considers as products a number of fields on the physical state and dynamics (currents and waves) and marine ecosystem. Main R&D advances are described in the following sections.

MED MFC Physical Analysis and Forecast System

The analysis and forecast physical component of the CMEMS MED MFC is provided by means of a coupled hydrodynamic-wave (NEMO-WW3) modelling system with data assimilation components (3D variational scheme with a daily assimilation cycle of satellite Sea Level Anomaly and vertical profiles of Temperature and Salinity). This modelling system is nested in the coarser Global Ocean operational system (CMEMS GLO MFC) in the Atlantic Sea (Oddo *et al.*, 2009). The system is actually implemented in the Mediterranean Sea at 1/16° horizontal resolution and 72 vertical forced by ECMWF atmospheric fields at 1/8o horizontal resolution (Oddo *et al.*, 2014; Clementi *et al.*, 2013 and 2017). Within the next period a higher resolution implementation of the modelling system is foreseen (with 1/24° horizontal grid and 141 vertical levels).

The modelling system has been upgraded over the past years in order to better represent the Mediterranean Sea dynamics and its forecasting skill. The main improvements are related to the use of daily ECMWF precipitation fields (instead of climatological values) and a series of modifications to the data assimilation scheme: (1) improved evaluation of the vertical background error covariance matrix (30 grid-point EOFs); (2) improved observational error covariance matrix (z-dependent with monthly variability); (3) correct representation of DAC (dynamic atmospheric correction) in the SLA dataset assimilated; (4) assimilation of temperature and salinity vertical profiles up to 2000 m; (5) use of a 20 year referenced mean dynamic topography (Rio *et al.*, 2014). These improvements have led to an overall increased accuracy in predicting the Mediterranean Sea dynamics and main physical variables, with a relevant benefit in the sea level representation. The model skill enhancement is evident when considering the SLA RMS misfits (observation minus model value transformed at the observation location and time) achieving an error decrease of around 1 cm: from 4.5 cm in system CMEMS-V1 (January 2012-May 2016, blue line in Figure 43) to 3.5 cm in system CMEMS-V2 (January 2013-ongoing, red line in Figure 43).

MED MFC Waves Analysis and Forecast System

Within the framework of CMEMS MED MFC, a high resolution operational wave forecasting system (Med-waves) has been developed in order to provide daily accurate products –simulation and forecast– of the wave environment of the Mediterranean Sea to the general public. This system is based on WAM model Cycle 4.5.4 which is a modernised and improved version of the well-known and extensively used WAM Cycle 4 wave model (WAMDI Group, 1988; Komen et al., 1994). WAM computes the 2D wave variance spectrum through the integration of the transport equation. The source function is represented as a superposition of the wind input, white capping dissipation, nonlinear transfer, bottom friction and wave breaking.

The Med-waves set-up includes a coarse grid domain with a resolution of 1/6° covering the North Atlantic Ocean from

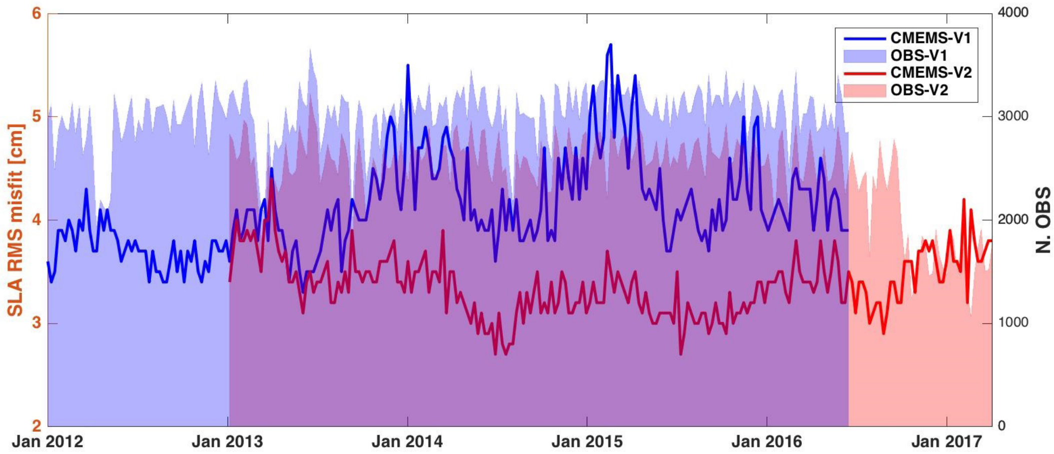


FIGURE 43

Blue line: SLA RMS misfit in Med MFC system CMEMS–V1 from January 2012-May 2016; Blue shaded area: number of SLA observations assimilated by CMEMS–V1; Red line: SLA RMS misfit CMEMS–V2 from January 2013-ongoing; Red shaded area: number of SLA observations assimilated by CMEMS–V2.

75°W to 10°E and from 10°N to 70°N and a nested fine grid domain with a resolution of 1/24° covering the Mediterranean Sea from 18.125°W to 36.2917°E and from 30.1875°N to 45.9792°N. In this way, the Mediterranean Sea model receives from the North Atlantic model a full wave spectrum at hourly intervals at its Atlantic Ocean open boundary. The latter model is considered to have all of its four boundaries closed with no wave energy propagation from the adjacent seas. Because of the wide geographical coverage of the North Atlantic model, the consideration of closed boundaries does not affect the swell propagation towards the open boundary of the Mediterranean model, which is the main interest of this nesting approach. In both models calculations are executed on a regular (in space) latitude-longitude grid, a regular directional grid and a logarithmic frequency grid. The frequency grid is specified by 32 terms of a geometric sequence with a scale factor 1.1 and the first frequency 0.04177 Hz while the propagation directions are discretized with a 15° step (24 directional bins). The Mediterranean model runs in shallow water mode considering wave refraction due to depth and currents in addition to depth induced wave breaking. The North Atlantic model runs in deep water mode with wave refraction due to currents only. The North Atlantic model additionally considers wave energy damping due to the presence of sea ice.

The system is forced by 10 m wind fields obtained from the ECMWF Integrated Forecasting System (IFS) at 1/8° resolution. The temporal resolution of the wind forcing is 6 h for the simulation mode, 3 h for the first 3 days of the forecast and 6 h for the rest of the forecast cycle. Sea ice coverage fields are also obtained from ECMWF at the same horizontal resolution (1/8°) and are updated daily. With respect to current forcing, the Mediterranean Sea model is currently forced by daily averaged surface currents obtained from CMEMS Med MFC at 1/16° resolution and the North Atlantic model is forced by daily averaged surface currents obtained from the CMEMS Global MFC at 1/12° resolution.

A series of sensitivity tests have been performed in order to assess the importance of surface currents in wave refraction; the effect of Atlantic swells propagating to the Alboran Sea through the Gibraltar Strait; and to tune the white-capping dissipation coefficients of the WAM model in order to increase the overall forecasting skill of the system. For these tests the Med-waves system has been integrated for one year period (2014) and forced with ECMWF 6-hourly 10 m analyses winds at 1/8° resolution and with Global (1/12°) and Mediterranean re-analysis surface currents.

Med-waves which has been pre-operational since 1 August 2016, is run every day at 12 UTC and generates a 1-day simulated and 5-days forecast wave fields at hourly intervals over the Mediterranean Sea at 1/24° horizontal resolution. These wave fields include wave parameters computed by integration of the total wave spectrum, and wave parameters computed using wave spectrum partitioning into: wind sea, primary, and secondary swell.

MED MFC Biogeochemistry Analysis and Forecast System

The Med-biogeochemistry system consists of the 3DVAR-OGSTM-BFM model (Lazzari et al., 2010 and 2012; Teruzzi *et al.*, 2013; Cossarini *et al.*, 2015, and references thereby). OGSTM-BFM is designed with a transport model based on the OPA system and a biogeochemical reactor featuring the Biogeochemical Flux Model (BFM), while 3DVAR is the variational assimilation scheme for the correction of phytoplankton functional type variables. During the first Copernicus stage, the Med-biogeochemistry system -already able to reproduce nutrient and chlorophyll space and time dynamics (Lazzari *et al.*, 2010, 2016)- has been upgraded to include a carbonate system module (Cossarini *et al.*, 2015; Melaku Canu *et al.*, 2015). The simulated dynamics of seawater inorganic carbon accounts for the consumption (i.e. photosynthesis) and production terms (i.e. respiration of both phytoplankton and heterotrophic plankton groups), the air-sea CO_2 exchanges, the $CaCO_3$ precipitation/dissolution and the concentration (dilution) effect at the surface due to evaporation minus precipitation. Alkalinity, a measure of the capability of seawater to buffer acidification, is driven by $CaCO_3$ dynamics, concentration (dilution) effect at surface and uptake (release) of ions (NO_3, PO_4, NH_4) by the plankton functional type groups. As a result, the Mediterranean Sea behaves as a net weak sink of the atmospheric carbon (overall average of 0.8 mmolC/m^2/d). Further, air-sea CO_2 exchanges and carbonate system variables show very high spatial and seasonal variability. Seasonal variability of dissolved inorganic carbon (DIC) and alkalinity, which accounts for up to 20-25 mmol/kg in the surface layer (range of colour lines in Figures 44c and d), is driven by the seasonality of the E-P (evaporation minus precipitation) cycle and of phytoplankton production.

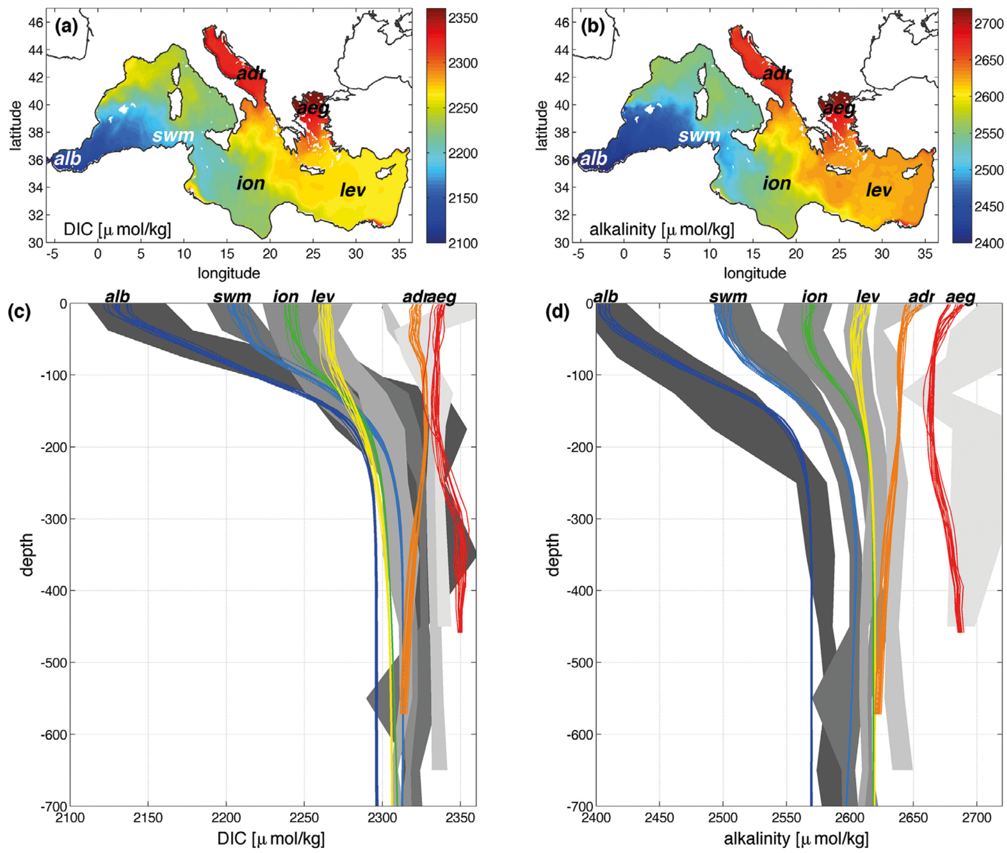


FIGURE 44

Annual mean surface maps of DIC (a) and alkalinity (b) and monthly mean vertical profiles (coloured lines in c and d) simulated by the CMEMS MED MFC for selected Mediterranean areas. The range of variability of observations in the selected areas is also shown (grey shading). The areas are: Alboran Sea (alb, blue and darkest grey shading); south-western Mediterranean (swm, light blue), southern Ionian Sea (ion, green), southern Levantine basin (lev, yellow), central and southern Adriatic Sea (adr, orange), and Aegean Sea (aeg, red and lightest grey shading).

At the surface, the inflow of low DIC and low alkalinity Atlantic waters, the terrestrial inputs in marginal seas (mostly Adriatic and Aegean Seas) and the positive E-P budget in the Levantine basin trigger the simulated strong zonal and meridional gradients of alkalinity and DIC (Figures 44a and b). Temporal and spatial variability of alkalinity/DIC decreases with depth where timescales of processes are much longer. Below 300-400 m the alkalinity zonal gradient is preserved, whereas a more efficient carbon pump (both soft and hard tissue) is responsible for a higher DIC accumulation in the deeper layers of the western areas with respect to the eastern ones. Furthermore, the marginal seas continental shelf pump (Cossarini *et al.*, 2017) contributes to increase the bottom accumulation of DIC.

The foreseen directions of the future evolution of the BFM model and of the Med biogeochemistry system include: the revision of the plankton functional type parameterization; the improvement of the optical properties description; the online/operational implementation of biogeochemical boundary conditions at the Gibraltar Straits, at the Black Sea and at the rivers; and the development of a multi-platform and multi-variate data assimilation scheme to integrate BGC Argo floats and satellite observations.

MED MFC Physical multi-year products

The MED MFC has produced two multi-year ocean physics reanalyses which describe the physical state of the Mediterranean Sea. The first product covers the period 1987-2015 and includes 2D daily/monthly fields of sea surface height and 3D daily/monthly fields of temperature, salinity, meridional and zonal currents at 1/16° horizontal resolution and 72 vertical levels. The quality has been assessed for the entire 1987 to 2014 time period by comparing results with observations, climatology and literature. The results are gathered by ocean state variable and detailed as in Table 3 below.

The second product consists of the 60 year reanalysis that has been produced by combining, every day, the output of the ocean model, forced by atmospheric surface fluxes and relaxed to SST, and quality controlled ocean observations. This second reanalysis product includes 2D monthly fields of sea surface height and 3D monthly fields of temperature, salinity, meridional and zonal currents at 1/16° horizontal resolution and 72 vertical levels. The quality has also been assessed for the entire 1955 to 2014 period by comparing results with available observations, consolidated climatological products and current knowledge of the ocean circulation. The results for each variable assessed are presented in Table 4.

Parameter	BIAS	RMS
SST [°C]	0.18 ± 0.25	0.56 ± 0.13
T [°C]	-0.02 ± 0.005	0.34 ± 0.02
S [psu]	-0.01 ± 0.003	0.1 ± 0.01
SLA [cm]	0.09 ± 0.13	3.5 ± 0.55

TABLE 3

Mediterranean Sea MFC reanalysis (1987-2014) performance for different parameters and over the entire time period.

Parameter	BIAS	RMS
SST [°C]	0.22 ± 0.3	0.59 ± 0.16
T [°C]	-0.02 ± 0.004	0.4 ± 0.02
S [psu]	0.01 ± 0.004	0.12 ± 0.01
SLA [cm]	-0.1 ± 0.07	3.75 ± 0.29

TABLE 4

Mediterranean Sea MFC reanalysis (1955-2014) performance for different parameters and over the entire time period.

MED MFC Biogeochemistry multi-year products

The list of biogeochemical Multi Year products has been extended, by adding to nutrients and chlorophyll the time series of the CO_2 partial pressure in the ocean (pCO_2) and the additional derived variable of the CO_2 air-sea fluxes (CO_2 fluxes), which is directly linked to the CMEMS product pCO_2. Such variables are of high societal interest, since the CO_2 adsorption from the ocean has buffered the impacts of anthropogenic CO_2 emissions in the atmosphere, but is also a main driver of ocean acidification. The CO_2 flux is proportional to the difference between partial pressures of surface oceanic and atmospheric CO_2 and the proportionality exchange coefficient varies in time, and depends non-linearly on wind and water physical properties (Sarmiento and Gruber, 2006; Takahashi *et al.*, 2002; Wanninkhof, 1992). Therefore, CO_2 fluxes should be rather computed from daily values, and not from the annual averages.

Results of the biogeochemical reanalysis indicate that in the last decade, the Mediterranean Sea as a whole acted as a weak sink of atmospheric carbon (around 4 $gC.m^{-2}.yr^{-1}$ on average over the 1999-2014 period). The pCO_2, and the related CO_2 atmospheric fluxes, have a marked seasonal variation, linked to changes in temperature and trophic dynamics, but they also display some inter-annual variability. Inter-annual changes might be linked to inter-annual variability in physical or biogeochemical parameters, but also to changes in the input and exchanges with the system boundaries, which in the Mediterranean Sea involve the properties of the Atlantic waters inflow from Gibraltar Strait (Melaku Canu *et al.*, 2016). Figure 45 highlights both the seasonal (a) and inter-annual (a, b) variability, and shows that over the last 15 years no significant trend emerges from the basin-averages of CO_2 fluxes.

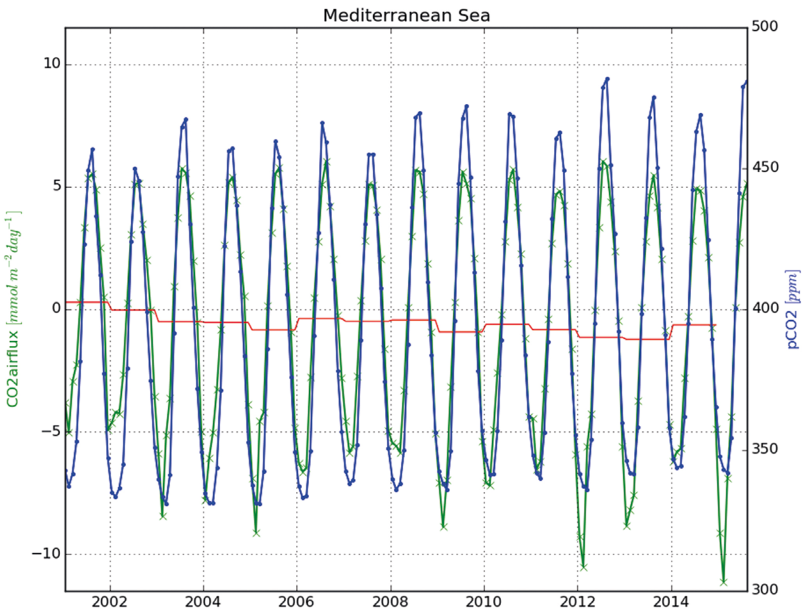


FIGURE 45

Time series of partial pressure of CO_2 in the ocean, pCO_2 (ppm, blue line, right Y-axis), and the closely related CO_2 fluxes at the ocean-atmosphere ($mmol.m^{-2}.d^{-1}$, green line, left Y-axis) for the years 2000 – 2015 and annual mean (red line). Values refer to spatial averages over the whole in the Mediterranean Sea, as simulated by the Mediterranean Biogeochemistry Reanalysis (MEDSEA_REANALYSIS_BIO_006_008). Negative values indicate a flux towards the ocean (sink).

Validation of MED MFC

The accuracy of each MED MFC product is monitored during the operations through near real-time and delayed mode comparison with *in-situ* and remote sensing observations and with climatologies, as well as during the pre-qualification phase (when the quality improvements of a new release of the system is assessed with respect the previous one).

The quality assessment framework is consistent among the different Mediterranean Sea components and provides coherent information on 16 Mediterranean physical-biological sub-regions to the users. To this end, regular quarterly information on product quality pre-defined metrics (i.e. RMS and bias of temperature, salinity, SLA, SST, chlorophyll, significant wave height, mean and peak wave periods) are displayed through the central CMEMS validation webpage (http://marine.copernicus.eu/services-portfolio/scientific-quality/#mfcs|medsea). Moreover, the users can explore more in detail the quality of the MED MFC products, through three dedicated regional validation websites that provide additional and more specific metrics:

- time variability of RMS misfits (quasi-independent validation with respect to SLA/INS/OSI TACs) of SLA, salinity and temperature at different depths are evaluated to check the ability of the system to reproduce both horizontal and vertical processes (http://medforecast.bo.ingv.it/mfs-copernicus/). In addition, main physical analysis and forecast field patterns are shown by 2D horizontal maps and along vertical specified transects, and volume transports through the Mediterranean straits are displayed by means of time series;
- time evolution of predicted physical parameters at specific mooring locations are compared to observations showing RMS and bias along selected time periods (independent validation, http://calval.bo.ingv.it);
- quick visualization of the variability of all biogeochemical MED MFC products, the time series of the bias and RMS of the chlorophyll MED MFC forecast versus CMEMS OC TAC data, and the accuracy of fundamental vertical processes (such as the deep chlorophyll maximum, the nutricline and oxycline displacements) by comparing CMEMS products with Biogeochemical Argo float data.

The Med-waves system has been validated over a period of 1 year (2014) against *in-situ* and satellite observations. Specifically, hindcast model output of significant wave height (H_s) and mean wave period (T_m) have been compared with measurements from 32 wave buoys, obtained from the CMEMS INS TAC, and separately with satellite observations from 2 satellite missions (Jason-2 and SARAL). It has been found that, overall, H_s is accurately simulated by the model. Considering the Mediterranean Sea as a whole (Figure 46), the typical difference with observations (RMSE) is 0.21 m with a bias ranging from -0.03 m (3.7%), when the comparison is against the *in-situ* observations (Figure 46), to -0.06 m (5.5%), when the comparison is with satellites.

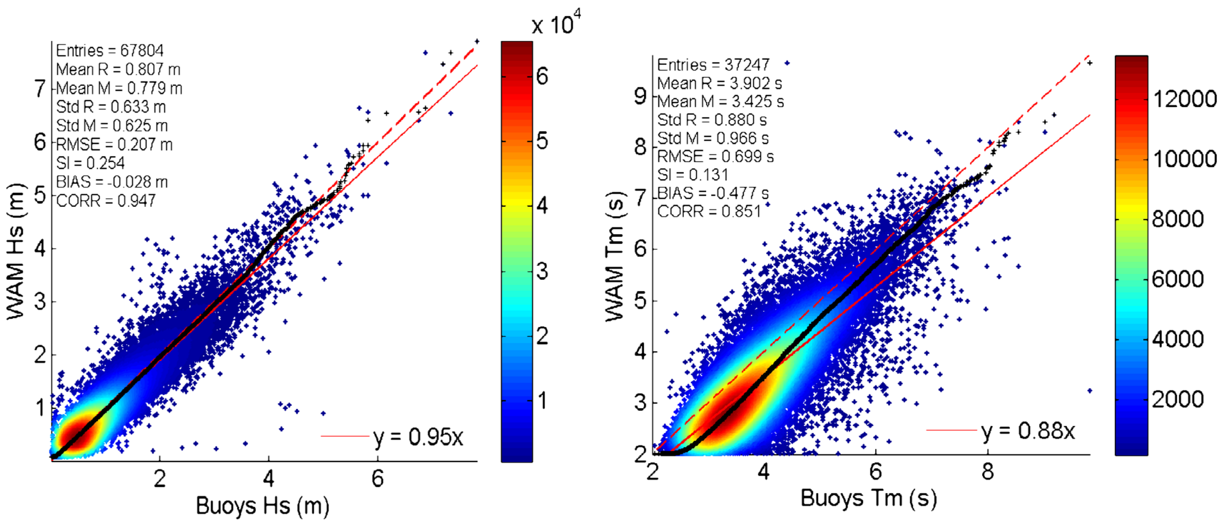


FIGURE 46

QQ-Scatter plots of Med-waves hindcast H_s (left) and T_m (right) versus wave buoy H_s and T_m respectively, for the full Mediterranean Sea, for 1 year (2014) period. : QQ-plot (black crosses), 45° reference line (dashed red line), least-squares best fit line (red line).

In general, the model somewhat underestimates the observations for wave heights below 4 m, whilst it mostly converges to the observations for higher waves. The prediction of H_s is better in winter when the wave conditions are well-defined. Spatially, the model performs optimally at offshore wave buoy locations and well-exposed Mediterranean sub-regions. Within enclosed basins and near the coast, unresolved topography by the wind and wave models and fetch limitations cause the wave model performance to deteriorate. Regarding T_m, it is reasonably well simulated by the model. The typical difference with observations (RMSE) is 0.7 s and is mainly caused by model bias which has a value of -0.48 s (12%). In general, the model underestimates the observed mean wave period and exhibits greater variability than the observations. A relatively larger model underestimate is found for T_m below 4.5 s. As with wave heights, model performance for T_m is a little better in winter when wave conditions are well-defined. Spatially, the model somewhat overestimates the high mean wave period values in the western Mediterranean Sea, west and south of France. Otherwise, the model typically underestimate the values of T_m. Similarly to the wave height, the model performance is best at well-exposed offshore locations and deteriorates near the shore mainly due to fetch limitations.

Impact of R&D advances for users and applications

Many operations at sea may take advantage of the use of CMEMS data and products. These activities include fishery and aquaculture, navigation, search and rescue, oil spill and pollution management, off shore activities, tourism. In the Mediterranean Sea many downstream applications have been developed using CMEMS products in order to support activities at sea by a variety of users (e.g. public authorities, mariners, fishermen, coast guards, sportsmen). In several cases, these applications provide smart and interactive user-friendly services that display Mediterranean Sea conditions in specific areas and support user needs in the different sectors. An example of downstream application is reported in Figure 47.

Another example is the CADEAU CMEMS User Uptake project whose aims is to exploit the MED MFC products to drive a high-resolution model system integrated with water quality coastal data. This project aims to provide products that will inform the public authorities on the level of impacts associated to urban waste water treatment plants; the water quality in the Adriatic Sea for the Water framework directive (WFD)/Bathing waters directive (BWD)/MSFD requirements; and the nutrient availability and primary production nearby aquaculture plants and its relation to annual fishing landings.

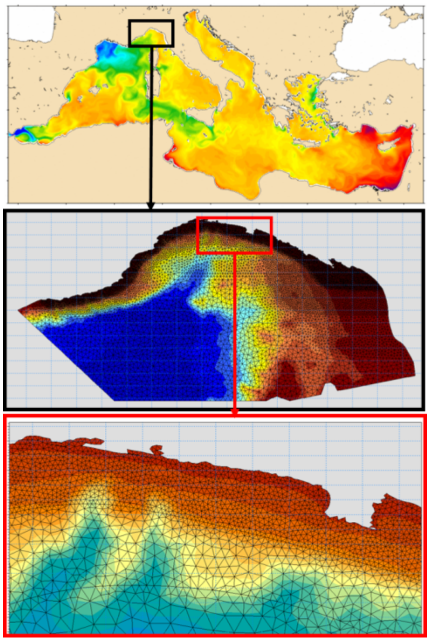


FIGURE 47

Mediterranean downstream application developed by DHI Italia as a set of marine water quality applications for the Environmental Protection Agency of the Liguria Region (Agenzia Regionale per la Protezione dell'Ambiente Ligure – ARPAL, Italy). Starting from the CMEMS physical products at Mediterranean basin scale, very high resolution close to the coast is reached (50 meters approximately) through subsequent model nesting, allowing to solve typical coastal dynamics and scales. The detailed circulation model thus obtained is the basis for several operational applications supporting ARPAL, such as litter modelling, bathing water quality forecast, algal bloom forecast, monitoring of aquaculture pollution.

BLACK SEA MFC

Overview

The Black Sea Monitoring and Forecasting Centre (BS MFC) provides physical, biogeochemical and wave ocean forecasting and reanalysis for the Black Sea area. R&D achievements for the different subsystems are presented below.

BS MFC Physics Analysis and Forecast

BS MFC Physics analysis and forecast system (BS-Currents) is based on state-of-the-art NEMO model (Madec *et al.*, 2012, 2016). The primitive equations are discretized on a horizontal grid at 1/36°x1/27° resolution and 31 vertical levels with partial steps. ECMWF 1/8° spatial resolution is used for computing the momentum, heat and water fluxes at the air-sea interface based on the Black Sea bulk formulae (Grayek *et al.*, 2010). Atmospheric fields used are zonal and meridional components of 10 m wind (ms^{-1}), total cloud cover (%), 2 m air temperature (K), 2 m dew point temperature (K) and mean sea level pressure (Pa). Precipitation fields over the basin are from GPCP rainfall monthly data (Adler *et al.*, 2003; Huffman *et al.*, 2009). Concerning the land forcing, in particular the freshwater input, the system uses an estimate of the inflow based on monthly mean dataset provided by the SESAME project (Ludwig *et al.*, 2009). The impact of the Bosporus Strait on the Black Sea dynamics is accounted for in terms of a surface boundary condition, taking into account the barotropic transport, which has been computed to balance the freshwater fluxes on monthly basis (Stanev and Beckers, 1999; Peneva *et al.*, 2001). The data assimilation system of BS-Currents is based on a three-dimensional variational (3DVAR) assimilation scheme called OceanVar, originally developed for the Mediterranean Sea (Dobricic and Pinardi, 2008) and later extended for the global ocean (Storto *et al.*, 2011; Storto *et al.*, 2015) and to the Black Sea. The variational cost function is solved with the incremental formulation (Courtier *et al.*, 1994). The pre-conditioning of the cost function minimization is achieved through a change-of-variable transformation. In the OceanVar implementation for the Black Sea the control vector in physical space is formed by the three-dimensional fields of temperature and salinity. The assimilation frequency is daily, with a 1-day assimilation time-window. Background-error covariances are decomposed into vertical covariances and horizontal correlations. The former are modelled through 15-mode multi-variate Empirical Orthogonal Functions (EOFs). EOFs were calculated from a dataset of anomalies with respect to a long-term mean of a model simulation without data assimilation, using the full model resolution. Horizontal correlations are modelled through a third-order recursive filter (Farina *et al.*, 2015), with spatially inhomogeneous correlation length-scales (Storto *et al.*, 2014) specified as a function of the distance from coast, ranging approximately from 9 to 27 km. The assimilation of sea level anomaly (SLA) is performed by imposing local hydrostatic adjustments as multi-variate balance between the sea level innovation and vertical profiles of temperature and salinity (Storto *et al.*, 2011). Observations assimilated in the BS-Currents include: i) *in-situ* hydrographic profiles (mostly Argo floats) from the CMEMS In-Situ TAC. If profiles are disseminated at high vertical resolution, a vertical thinning is applied to the profile before ingestion in OceanVar; ii) along-track sea level anomalies pre-processed and distributed by the CMEMS Sea Level TAC. The mean dynamic topography for the assimilation of SLA is computed from a 4-year (2011-2014) model mean sea surface height, rescaled through gridded sea level products from the CMEMS Sea level TAC to match the reference period for altimetry (1993-2012); iii) gridded sea surface temperature (SST) observations provided by the CMEMS OSI TAC. The assimilation of SST assumes that satellite observations are co-located with the first model level. In BS-Currents, the observation pre-processing includes a background quality-check, which rejects observations whose square departure from the background exceeds the sum of background and observation error variances by a certain threshold (3.3). For satellite observations (SLA, SST), a horizontal thinning is also applied, approximately to retain one observation only every 6 km. The observational error specification is vertically varying for the *in-situ* and horizontally varying for the satellite observations, and is based on a prior analysis of the assimilation output statistics. The operational system produces BS-Currents analysis and forecast using two different cycles: one cycle is daily, in which the system produces 3-day analysis, 1-day hindcast and 10-day forecast every day. The second cycle is weekly, in which on Tuesday the system produces 14-day analysis, 1-day hindcast and 10-days of forecast in order to incorporate a large number of *in-situ* and satellite observations into the data assimilation. Irrespective of the cycle, the starting fields for the initialization of each forecast are taken as the instantaneous field at 12:00:00 UTC of day J resulting from the chain of daily analyses done for the previous 3 (or 14) days and 1-day hindcast (http://marine.copernicus.eu and Figure 48).

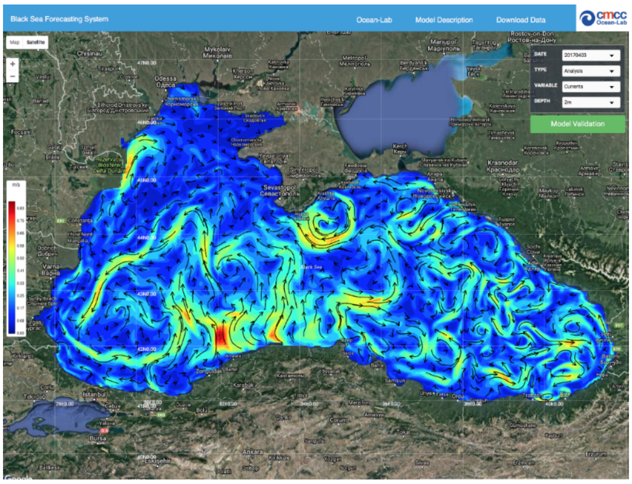


FIGURE 48

Example of CMEMS Black Sea ocean currents forecasting product.

One of the BS MFC activities of Phase II (starting 2018) will focus on setting up a physical connector "Mediterranean Sea – Black Sea" using operational high resolution unstructured modelling approach. In the present phase of the BS MFC, we have started to develop a complex dynamical system "Dardannelles Strait – Marmara Sea – Bosporus Strait" based on a multi model approach. The effort with the FESOM model (Gurses, 2016; Aydoğdu et al., 2017a,b) is presented here.

The first attempts of this model predictions supported by observations have confirmed expected nonlinear, multi-scale response characteristics which could only be revealed by high resolution coupled modelling, elaborating specialized roles of the stratified turbulent exchange subject to nonlinear hydraulic constraints and localized mixing and dissipation mechanisms at the elongated, narrow straits.

The FESOM model is based on a high-resolution grid of fine local details (Figure 49). It is now developed further to produce a 3-day forecasts using ECMWF atmospheric surface conditions (based on relaxation to the adjacent basin's seasonal conditions) and initialization based on seasonal climatology of the Marmara Sea, constructed from historical observations (Özsoy and Altıok, 2016a, b).

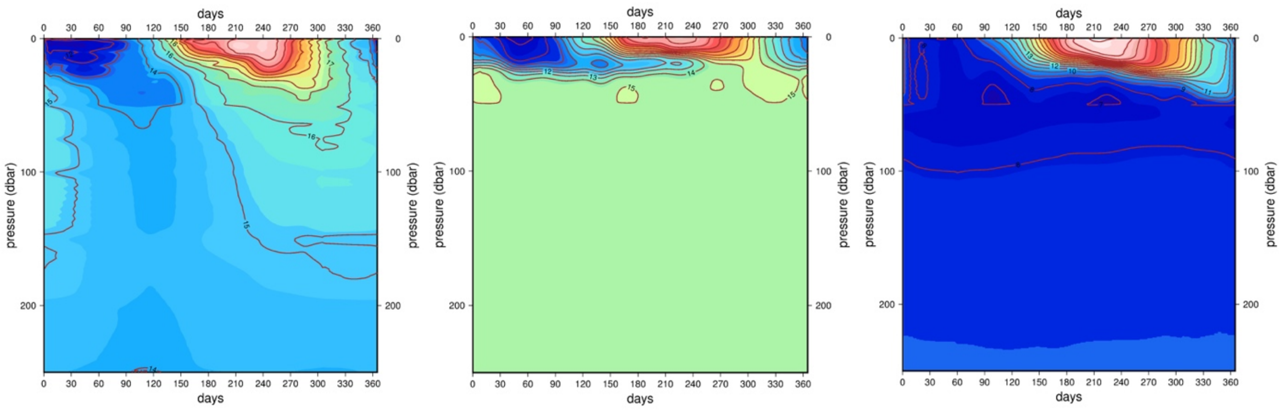


FIGURE 49

Seasonal evolution of temperature in the Aegean, Marmara and Black Sea sub-regions of the BS MFC FESOM model domain.

BS MFC Biogeochemistry Analysis and Forecast

BS MFC biogeochemical model (BS-Biogeochemistry) is based on the Biogeochemical Model for Hypoxic and Benthic Influenced areas (BAMHBI, Grégoire *et al.*, 2008; Grégoire and Soetaert, 2010; Capet *et al.*, 2016). This model is a plankton functional-type model that describes the foodweb from bacteria to zooplankton and simulates oxygen, nitrogen, silicate and carbon cycling. The model explicitly represents biogeochemical processes in anaerobic conditions using an approach similar to that used in the modelling of diagenetic processes in the sediments to correctly represent the peculiar biogeochemical conditions of the Black Sea. In particular, to represent the transition from well oxygenated to suboxic (O_2< 5 µmol/l) and anoxic (no oxygen, huge amounts of sulphide) waters . On the wide, shallow shelf where the pelagic and benthic systems strongly interact, the model includes a representation of diagenetic processes (Capet *et al.*, 2016) using an efficient and economic representation. The incorporation of a benthic module allows to represent the impact of sediment processes on important biogeochemical processes such as sediment oxygen consumption, benthic denitrification, and the shelf primary production. In addition to a representation of diagenesis, the biogeochemical model represents the transport of sediments by waves. This is an important feature that is necessary in order to sustain the primary production of the deep basin. Due to the explicit coupling of aerobic-suboxic-anoxic processes and pelagic-benthic systems, the model can be run for several decades of integration to simulate the long-term changes of the Black Sea biogeochemistry. In particular, the model has been used in order to simulate the multi-decadal evolution of the bottom oxygen open the Black Sea shelf and to investigate the occurrence of hypoxia (O_2< 63 µmol/l). So far, the model is run in free mode (without data assimilation). During this first year of project running, the resolution of the model has been improved and moved from a 15 km to a 5 km horizontal resolution.

BS MFC Waves Analysis and Forecast

The BS MFC wave analysis and forecast systems are based on the third-generation spectral wave model WAM. BS-Waves runs in shallow water mode on a model grid situated between 40°51'36" N to 46°48'16" N and 27°22'12" E to 41°57'45" E, with a spatial resolution of about 3 km. The required bathymetry for the model grid is the same as for the BS-Currents. WAM calculates the two-dimensional energy density spectrum at each of the 44699 active model grid points in the frequency and directional space. The solution of the energy balance equation is provided for: 36 directional bins at 10° each, starting at 5° and measured clockwise with respect to true north; and 30 frequency bins logarithmically spaced from 0.042 Hz to 0.66 Hz at intervals of Δf/f = 0.1. The driving force for the wave model are the six-hourly analysed U_{10} wind fields provided by the atmospheric model of the ECMWF. The Black Sea is a data sparse semi-enclosed sea with regard to the availability of traditional *in-situ* wave measurements recorded by usual wave rider buoys. The only possibility for systematic validation of wave model results in such a regional area is the use of satellite data. The operational system is demonstrated based on systematic comparisons with satellite data. The aim of this investigation was to answer two questions. Is the wave model able to provide a reliable description of the wave conditions in the Black Sea? and are the satellite measurements suitable for validation purposes on such a regional scale?

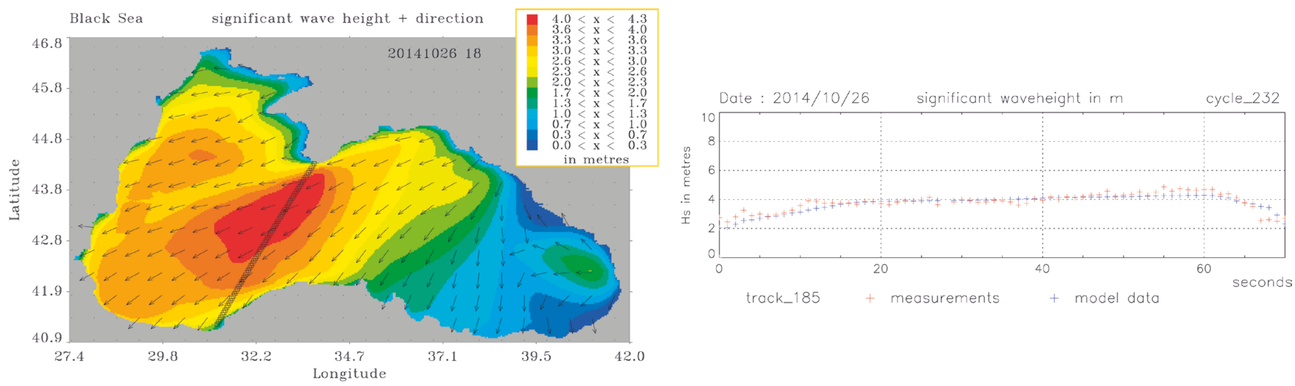


FIGURE 50

Distribution of significant wave height and total wave direction on 26 October 2014, 18 UTC (left) and time series of measured and computed significant wave heights along the ascending satellite path 185 of the Jason-2 cycle 232 (right).

Detailed comparisons between measured data and computed model results for the Black Sea including yearly statistics have been done for about 300 satellite overflights per year. The agreement between measured and modelled data supports the expectation that the wave model provides reliable results and that the satellite data is of good quality and offer an appropriate validation alternative to buoy measurements. This is the required step towards further use of those satellite data for assimilation into the wave fields to improve the wave predictions. Figure 50 shows the comparison between measurement and computed data along the ascending satellite track 185 of the Jason-2 cycle 232. The track crosses a storm area south of the Crimean peninsula on the 26 October 2014 at about 6 pm UTC. The comparison is good, and this is valid especially for the wave heights in the storm area with values around 4 m

Figure 51 includes the QQ-scatter plots for the significant wave heights for 2014 to 2016 respectively. The BIAS between 12 and 15 cm and the regression lines of 0.86-0.87 in the H_s QQ-scatter plots indicate a systematic underestimation of the measured values by the wave model results. The values of the scatter index are between 23 and 25 cm and together with the correlation coefficient of over 0.9 supports the good agreement between the model results and the measured data.

With regard to a coupling of the wave model with a hydrodynamic model new parameters have been calculated, amongst others the wave-induced velocity or Stokes drift that may contribute significantly to the total mean surface currents in the ocean.

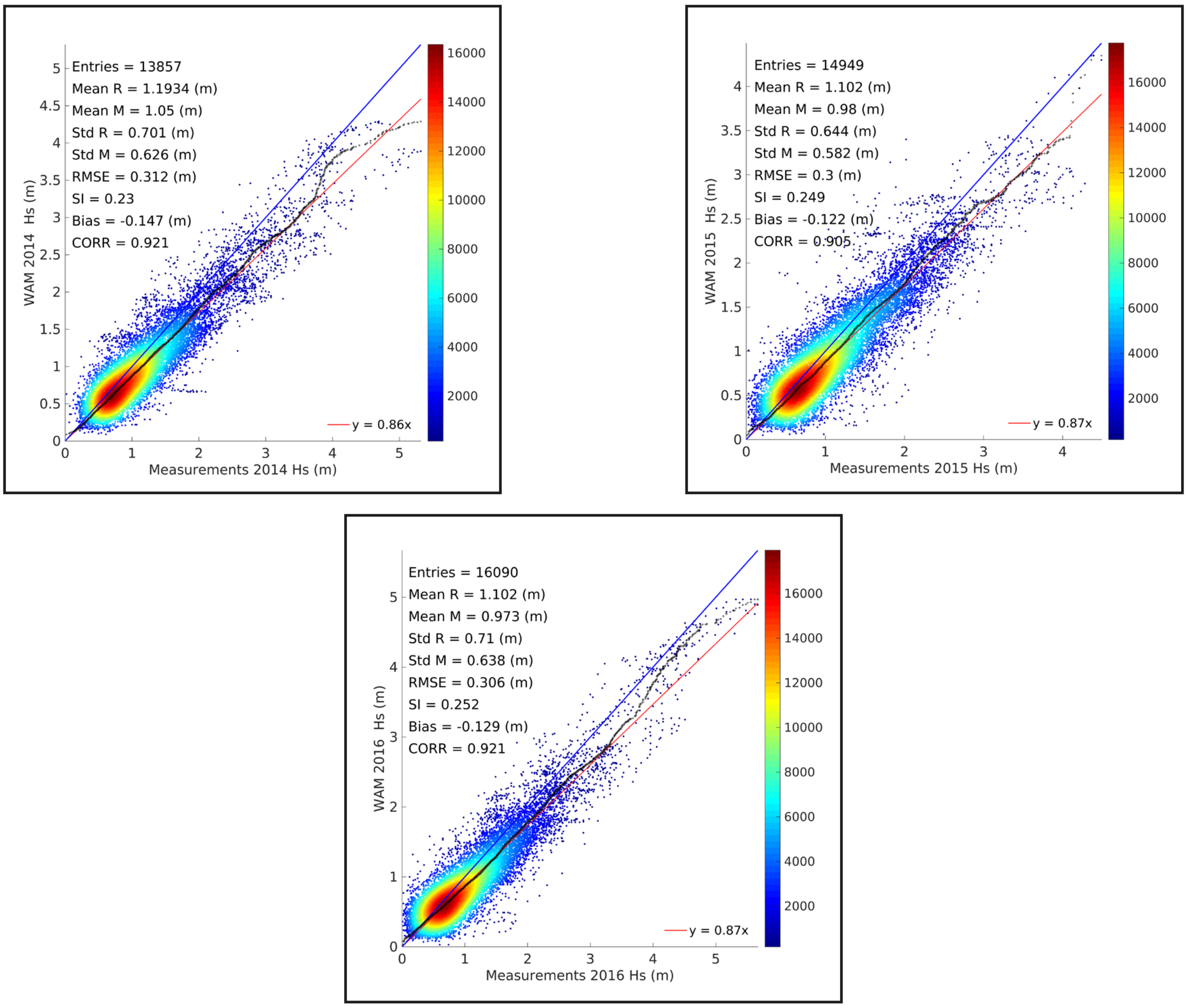


FIGURE 51

QQ-Scatter plots for measured and computed significant wave heights in 2014 (above, left), 2015 (above, right) and 2016 (below, left): QQ-plot (black crosses), 45° reference line (blue line), least-squares best fit line (red line).

Reanalysis

The lack of sub-surface *in-situ* observations in the Black Sea before the deployment of the Argo floats makes the reproduction of multi-decadal heat and freshwater content trends from reanalyses particularly challenging (e.g. Grayek *et al.*, 2015), thus requiring dedicated strategies to avoid shocks and drifts before and after the change in the observation sampling. During the second half of 2016 and the beginning of 2017, CMCC has produced and released two versions of the physical ocean reanalysis, hereafter referred to as: V2 (period 2005-2015) and V3 (period 1993-2015). Version V3 does not only extend back to cover the entire altimetry era, but also provides some improvements with respect to its predecessor. In particular, a large-scale bias-correction scheme (Storto *et al.*, 2016) has been implemented in V3 (April 2017) to avoid possible drifts when altimetry data are assimilated without being constrained by sub-surface observations. Unlike the operational system, both reanalyses implement overlapping assimilation time-windows (Fisher *et al.*, 2011) with a 3-day assimilation frequency and a 6-day centred assimilation time-window, in order to provide a smoother ocean state and maximize the observation coverage in the Black Sea region. Figure 52 shows the monthly means of the basin-averaged temperature for the two versions, along with the number of *in-situ* observations, indicating that the new bias-correction scheme prevents spurious variability linked to changes in the observing network. Improvements foreseen for V4 (April 2014) will be a combination of vertical physics improvements already included in the operational analysis and forecast system with a retuning of the background-error covariances used in the data assimilation system to account for changes in the observing network with time.

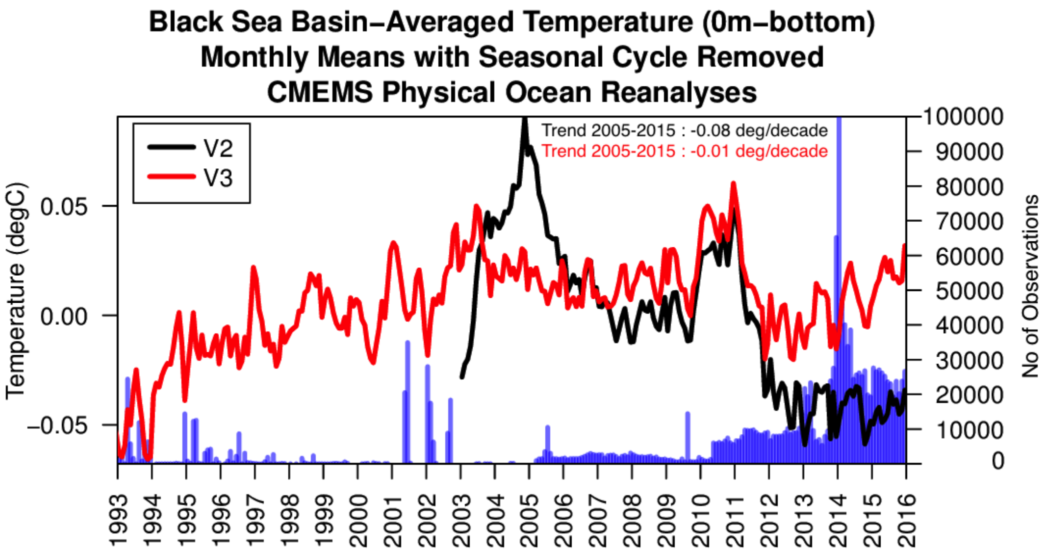


FIGURE 52

Monthly means of Black Sea basin-averaged temperature (0 m-bottom) for areas deeper than 800 m of depth. The seasonal cycle is removed. The number of single-level *in-situ* observations is overlapped with blue histograms (right-side axis). Linear trends for the period 2005-2015 are also reported in the plot.

Product quality assessment

The assessment of the quality of the BS MFC products follows the general recommendation of the CMEMS Product Quality Working Group. The lack of continuous real-time *in-situ* data in the Black Sea (to be used both for verification of the MFC simulations and satellite observations) is a significant obstacle to do an independent and systematic validation from the data assimilated. The data used in the validation procedure of the analysis and forecast system and the reanalysis, are as follows:

- The results of the physical module BS-Physics is validated against satellite observations for sea surface temperature and height, as well as Argo profiles of temperature and salinity, made available by the CMEMS OSI, SL and INS TACs. These data are semi-independent from the model, as they are assimilated during the integration.

- The simulations of the biogeochemical module, BS-Biogeochemistry, use the Biogeochemical Argo data and vessel measurements of dissolved oxygen, nitrate, phosphate and chlorophyll concentration, as well as the satellite chlorophyll, distributed by CMEMS OC and INS TACs. These are independent data for the model as it still does not assimilate data.
- The module BS-Waves entered in operations for the first time in V3 (April 2017) and the results are validated against Jason-2 satellite data for the significant wave height.

The metrics to measure the modelling system error are typically the BIAS and RMS deviation of the model from measurements averaged for the whole basin. For the biogeochemical variables is also useful to calculate the Nash-Sutcliffe coefficient. Statistics are calculated every three months and overall the numbers improve in V3 comparing to V2.2. Table 5 summarizes the results for the different V3 BS MFC products and validated variables.

Validated Variable	**BIAS**	**RMS**	**Nash Sutcliffe [no units]**
BS-Physics Analysis and Forecast (2014-2016)			
Sea surface temperature [˚C]	-0.01	0.27	
Sea level anomaly [cm]		3.4	
BS-Physics Reanalysis System (1995-2015)			
Sea surface temperature [°C]	-0.08	0.57	
Temperature [°C] layer 0-100 m	-0.06	0.87	
Temperature [°C] layer 100-300 m	-0.04	0.17	
Temperature [°C] layer 300-800 m	-0.02	0.10	
Salinity [psu] layer 0-100 m	0.01	0.36	
Salinity [psu] layer 100-300 m	0.0	0.20	
Salinity [psu] layer 300-800 m	0.004	0.06	
Sea level anomaly [cm]	NA	3.68	
BS-Biogeochemistry Analysis and Forecast (2014-2016)			
Sea surface chlorophyll			0.39
Depth of maximum chlorophyll [m]	13	22	
Oxygen [mmol m^{-3}]	46	97	0.16
BS-Biogeochemistry Reanalysis (1992-2015)			
Nitrate [mmol m^{-3}]	1.04	4.53	12.38
Phosphate [mmol m^{-3}]	0.4	1.33	0.54
Oxygen [mmol m^{-3}]	15.74	63.40	0.76
BS-Waves Analysis and Forecast (2014-2016)			
Significant wave height [cm]	-13	30	

TABLE 5

Overview of the validation of BS MFC v3 products.

Overall, the estimated quality is very good and gives confidence to use the BS MFC products for scientific and applied research. More information about the BS MFC performance can be found in the relevant QUID. Concerning the BS MFC Biogeochemistry near real-time products, validation has been performed using satellite chlorophyll time series as well as Biogeochemical Argo oxygen and chlorophyll data collected during the period 2014-2016. A pre-operational validation framework is now being implemented. For multi-year biogeochemical products, the quality assessment of the performed simulation (at 15 km resolution: 1980-2015, at 5 km resolution: 1992-2015) has been done using all the observations available for the Black Sea in existing databases and those provided by INS TAC, using various error metrics and checking nitrate, oxygen and phosphate data. We contribute to the OSR by providing an assessment of the long-term evolution of the deoxygenation process in the Black Sea (Figure 53).

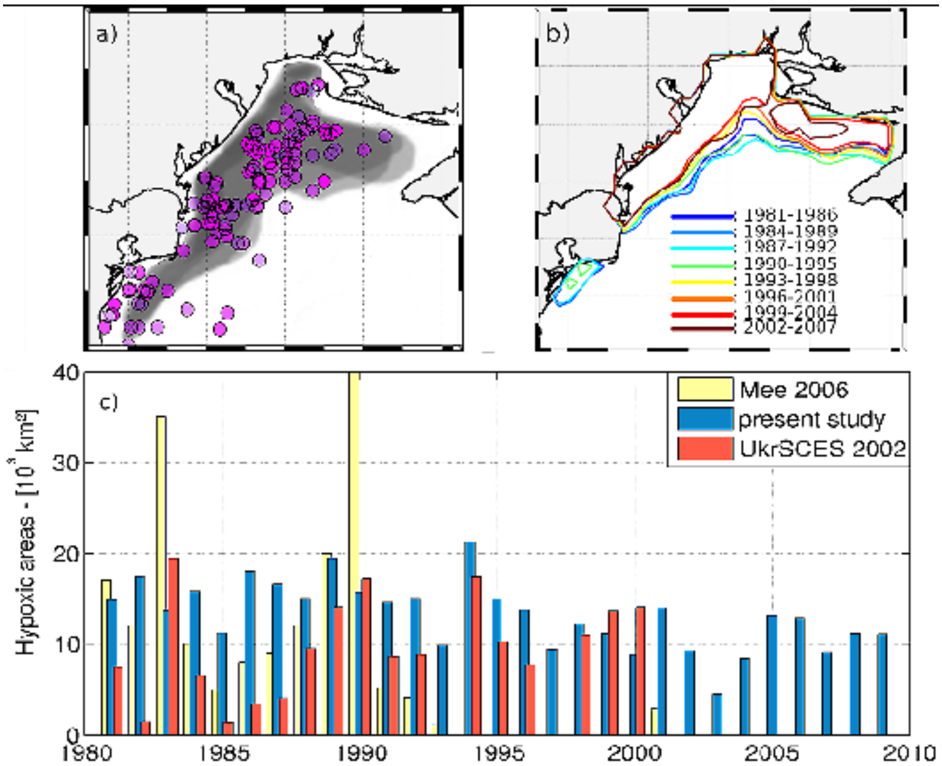


FIGURE 53

a) Area affected by hypoxia, redrawn from Zaitsev (1997), and locations of hypoxic records from the WOD database. (b) Spatial extension of the area over which the model predicts hypoxia lasting more than one month. Variability due to meteorological effects is filtered out by averaging the results over 6 yr periods. (c) Extension of the surface affected by bottom hypoxia, as reported in the literature (Mee, 2006; UkrSCES, 2002) and simulated by the BS-Biogeochemical model used for BS MFC (in blue).

Impact on users and applications: marine safety and maritime transport

Oil spill pollution is recognized as one of the severe threats to the marine environment of the Black Sea (Lavrova and Mityagina, 2013). It is therefore crucial to provide the decision makers and stakeholders, with trustworthy modelling tool that is able to produce a forecast of oil spills in the basin. To this end, CMCC has coupled the Lagrangian model MEDSLIK-II (de Dominicis *et al.*, 2013) to the BS MFC Physics. MEDSLIK-II (http://medslikii.bo.ingv.it) calculates the advection-diffusion processes using a Lagrangian approach. The oil slick is discretized into constituent particles. Each particle moves due to currents provided by Copernicus Marine Service for the Black Sea Monitoring and Forecasting Centre (at ~3 km horizontal resolution) and ECMWF wind (at ~12.5 km horizontal resolution). The JONSWAP wave spectrum as a function of wind speed and fetch is applied (Hasselmann *et al.*, 1973) to calculate the Stokes drift., The oil transformation processes at the surface are calculated by means of bulk formulas that describe the changes in the surface oil volume due to three main processes (evaporation, dispersion and spreading) known collectively as weathering. The formation of water-in-oil emulsion is also taken into consideration. If an oil particle arrives on the coast, the model is able to simulate the adsorption of particles into the coastal environment taking into account a probability that oil may be washed back into the water. In the Black Sea, MEDSLIK-II has been intensively tested along the main shipping lanes and in the areas of main basin-scale sea circulation features, including the Rim Current and anticyclonic eddies on the coastal side of the Rim Current: Sevastopol, Batumi, Suchumi, Sakarya, Bosphorus, etc. Figure 54 shows a 24-hour forecast of a virtual oil spill located at the Sevastopol-Varna shipping lane. It can be concluded that, on 28 November 2016, the spill could drift under the direct influence of the Sevastopol anticyclonic eddy. The oil spill forecasting service described here and based on CMEMS currents, ECMWF winds and MEDSLIK-II oil spill models is provided by the EMODnet Black-Sea check point in the framework of the Oil Platform Leaks challenge (http://emodnet-blacksea.eu/portfolio/oil-platform-leaks).

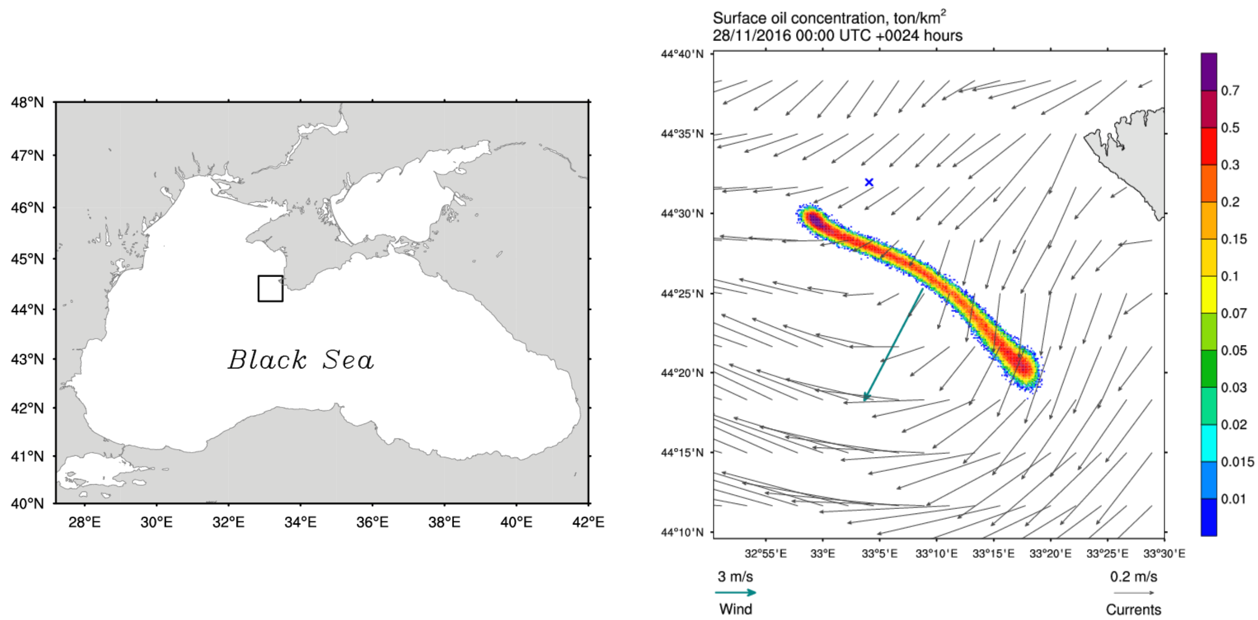


FIGURE 54

An example of the oil spill forecast produced by MEDSLIK-II forced with the BS MFC Physics analysis and forecast of currents (black arrows) and the ECMWF wind (green arrow in the oil slick center).

BALTIC MFC

Overview

The CMEMS BAL MFC (Baltic Monitoring and Forecasting Centre) provides forecasts and reanalysis of the Baltic Sea physical and biogeochemical state. The BAL MFC consortium consist of five institutes, namely DMI, BSH, FMI, MSI and SMHI. The physical and biogeochemical forecasts have been available since the beginning of the CMEMS service in 2015 and have been provided for users already during the MyOcean-1/2 and follow on projects (since 2009). The Baltic Sea wave forecasts product entered the CMEMS service in April 2017 along the V3 version upgrade. The physical, biogeochemical and wave analyses and forecasts are provided with 1 nautical mile (nmi) horizontal resolution for the Baltic Sea. The physical and biogeochemical analysis and forecast are produced using the HBM-ERGOM and the wave forecast with the WAM model. At present there is physical reanalyses available with 3 nmi resolution produced with HIROMB (High Resolution Oceanographic Model for the Baltic). The reanalysis will soon be updated to include also the biogeochemical products. A detailed description of the BAL MFC R&D achievements can be found below.

NRT physical-biogeochemical prediction system

The Baltic Sea is a semi-enclosed sea strongly affected by water and mass transport from the North Sea, river discharge and atmospheric forcing, which lead to: dynamic inter-basin and inter-sub-basin exchange; ocean-ice-atmosphere interaction; and semi-permanent halocline and stratification features. A qualified operational system should be able to resolve these features and to predict significant phenomena in multiple spatiotemporal scales, e.g. storm surge and low water level events; Baltic-North Sea water transport and inter-sub-basin transport; upwelling; bottom oxygen depletion; algae bloom; seasonal variation of nutrients and biomass, etc. The current Baltic Sea operational physical-biogeochemical model HBM (HIROMB-BOOS Model[1]) – ERGOM (Ecological Regional Ocean Model), has been developed in the past decade to solve the above challenges (She *et al.*, 2007; Berg and Weismann Poulsen, 2012; Wan *et al.*, 2013; Weismann Poulsen *et al.*, 2014).

[1] HIROMB is an abbreviation for High Resolution Oceanographic Model for the Baltic. BOOS stands for the Baltic Operational Oceanographic System.

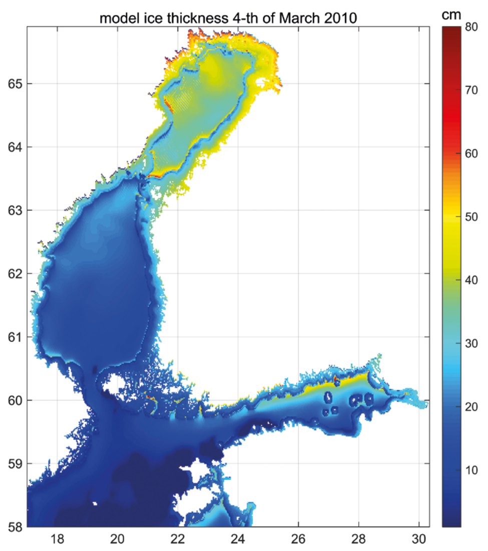
HBM is a three-dimensional, hydrostatic, free-surface, baroclinic ocean circulation and sea ice model. The model has been through a high level of rigorous testing and standardisation, and an efficient hybrid OpenMP-MPI memory parallelization. Portability and model correctness in term of reproducible output are key pillars of HBM model development (Weismann Poulsen *et al.*, 2014). The model allows for flooding and drying and fully dynamic two-way nesting of grids with different vertical and horizontal resolution, as well as time resolution (Berg and Weismann Poulsen, 2012). This makes the model very flexible for high resolution coastal applications. For example, the model maintains its quality and stability with multiple nesting layers and up to 10 nesting regions in a single executable and minimum grid size of 185 meters.

HBM has demonstrated high quality in forecasting sea level and its extremes as well as Major Baltic Inflow events in the past few years (Golbeck *et al.*, 2017). A fast ice module, describing the formation, consolidation and disintegration of fast ice; and the advance and retreat of its front, has been developed, calibrated and became operational. An illustration of the new fast ice module showing the ice thickness in the Baltic Sea is shown in Figure 55. The implementation of the fast ice feature was motivated to strengthen the near coastal ice and to prevent overly breaking and drift ice formation in situations with off shore winds.

The biochemical model ERGOM (Neumann, 2000) is online coupled with HBM. The current operational version ERGOM contains 12 biogeochemical state variables. The model parameters, calibrated originally with observations from the 1980's, were recalibrated for the particular CMEMS setup with observations from the period 2000-2014 (Wan *et al.*, 2012; Golbeck, 2017). The impact of suspended particulate matter on light attenuation is parameterized based on turbidity and bathymetry depth (Wan *et al.*, 2013).

For CMEMS, HBM is set up with four two-way nested regions covering the Baltic-North Sea in a horizontal resolution of 0.5 – 3 nmi and up to 122 levels in the vertical. Freshwater runoff from more than 800 rivers in the region is obtained from hydrological forecasts. A k-ω turbulence closure scheme, with stability functions from Canuto et al. (2010), has been extensively tuned for the Baltic-North Sea so that the stratification can be simulated reasonably. The system has been undergoing comprehensive version upgrades on an annual basis. The model numerics, parameterisation of physical and biochemical processes, resolution and forecast quality have been constantly improved in response to user needs.

A data assimilation system is now in the development based on the PDAF (Parallel Data Assimilation Framework) (Nerger and Hiller, 2013; Nerger *et al.*, 2016). Experiments show that assimilating level 3 SST (sea surface temperature) will improve not only SST but also subsurface temperature and salinity in the Baltic-North Sea. The SST assimilation scheme will be operational in the release of the CMEMS V4 system in 2018



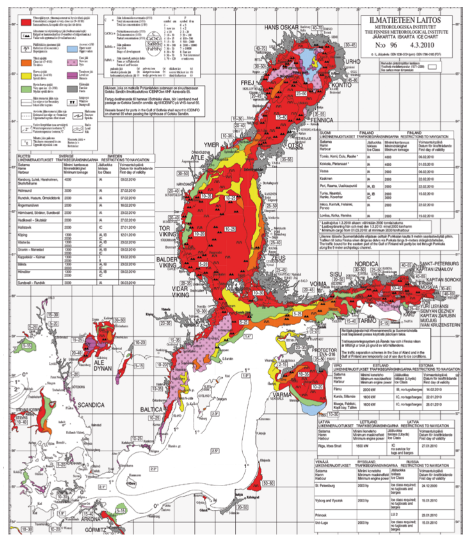


FIGURE 55

Ice model performance of HBM in the northern Baltic Sea illustrated by a snapshot during the winter 2010. The ice thickness calculated by HBM (on the left) and the ice chart produced by FMI Ice Service (on the right) shows an overall good agreement of the ice field. The modelled fast ice is visible in the near coastal zone of higher ice thickness which corresponds well to the observed fast ice (grey area in the FMI ice chart).

Wave forecast system

The BAL MFC wave analysis and forecast product is based on WAM cycle 4.5.4. The system has been set up on a 1 nmi grid for the whole Baltic Sea. The system uses boundary spectra from ECMWF's deterministic wave forecast at the western boundary at Skagerrak. Wind is taken from FMI's high-resolution numerical weather prediction system HARMONIE. This is the first time HARMONIE NWP system is being used for operational wave forecasting in the Baltic Sea. The seasonal ice conditions are taken into account by excluding grid points that have ice concentration of over 30% from calculations. The ice concentration data are obtained from FMI's ice charts available in the CMEMS catalogue. The accuracy of the wave prediction system was shown to be good in the pre-operational qualification, with slight tendency to overestimate the significant wave height in comparison against the *in-situ* measurements (Tuomi *et al.*, 2017).

The accuracy of the BAL MFC wave forecast system in the coastal archipelagos was enhanced by using a method to handle unresolved islands with a given resolution. The WAM code was modified based on method proposed by Tolman (2003), according to which the energy in the wave spectra propagating from one grid cell to the next is reduced according to the obstruction caused by unresolved islands. Obstruction grids for the northern Baltic Sea archipelagos were compiled based on information available in coastal nautical charts. Each archipelago area was handled with a method presented in Tuomi *et al.* (2014), in which the balance between the land points and grid obstructions is carefully evaluated to build an optimal bathymetry and obstruction grid for the wave model. The use of this method has been shown to improve the quality and usability of the coarser resolution forecasts in the coastal areas and archipelagos of the Baltic Sea (Tuomi and Björkqvist, 2014).

Although, the Baltic Sea is relatively small, the waves in the severest storms can be high enough to be of importance for shipping and safety at sea. The highest measured significant wave height (H_s) is 8.2 m, which was recorded by the northern Baltic Proper (NBP) wave buoy in December 2004. An H_s of over 7 m has been measured five times at this location since the observations started in 1996. The most recent occurrence was in January 2017 during storm 'Toini' when the wave buoy measured an H_s of 8.0 m (Björkqvist *et al.*, 2017). To evaluate the capability of the BAL MFC wave forecast system it was set to simulate the wave conditions during storm 'Toini'. The highest hindcast value of H_s at the NBP buoy location during the storm was 7.8 m, which is a good match to the measured maximum value. The wave model was able to simulate the development of the storm with good accuracy (Figure 56). However, it slightly overestimated the length of the storm and the H_s did not decay as fast as in the measurements.

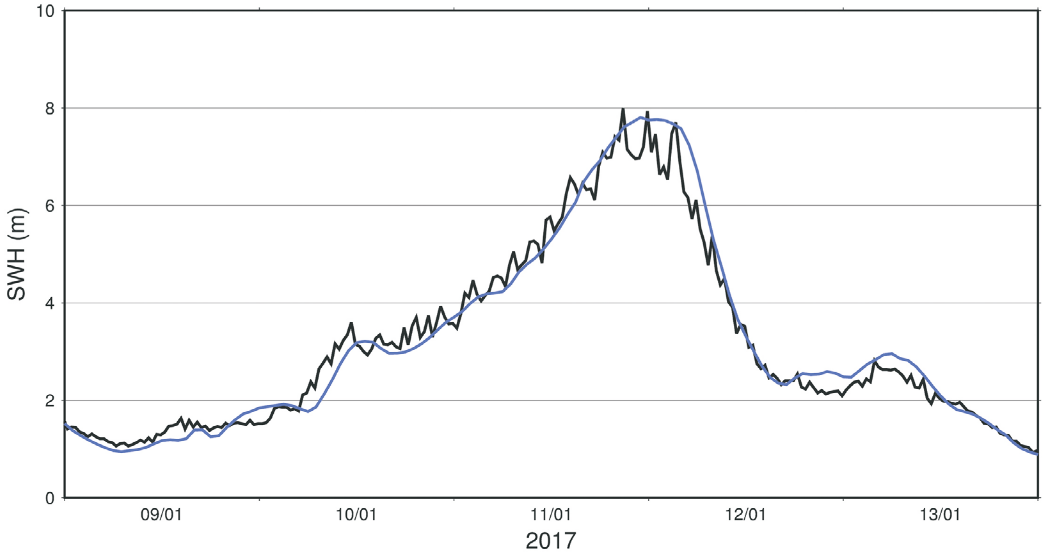


FIGURE 56

Modelled (blue) and measured (black) significant wave height at the Northern Baltic Proper wave buoy (DWR, 59°15' N, 21° 00' E, depth 100 m). The modelled values are the best-estimate time series of the BAL MFC wave production system.

Reanalysis system evolution

The BAL MFC reanalysis in CMEMS product catalogue V3 consists only of a physical part, but a coupled physical-biogeochemical system is planned for CMEMS V4. Today's physical reanalysis system consists of the ice-ocean circulation HIROMB (not to be confused with the HIROMB-BOOS Model, HBM, used in the BAL MFC NRT forecasts) in combination with 3D ensemble variational (3D EnVar) data assimilation (DA). Lateral boundary conditions in terms of sea levels are supplied by a storm surge model with 44 km grid resolution covering the northeastern North Atlantic (NOAMOD) and climatology for salinity and temperature profiles and ice variables. The horizontal resolution is 3 nmi (about 5.5 km) and there are up to 50 vertical grid cells with 4 m resolution down to 80 m depth. The meteorological forcing is from the atmospheric reanalysis project Euro4M and the rivers' runoff is from the hydrological model E-HYPE. The reanalysis system was run for the period 1989-2015 for the CMEMS product catalogue V3 release.

The ice-ocean model was the operational model at SMHI between 1995 and 2016 and was developed continuously during that period (Wilhelmsson, 2002; Funkquist and Kleine 2007; Axell, 2013). It has two ice categories (level and ridged ice) and a fast ice parameterization. The turbulence model is a state-of-the-art k- ω model with parameterizations of internal wave energy and Langmuir circulation.

The DA system is of ensemble type (3D EnVar; Axell and Liu, 2016), which implies that an ensemble of model states is used to calculate the error statistics used to spread the effect of the observations. One result is that the length scales of the assimilation increments tend to be larger along coasts than across; see Figure 57.

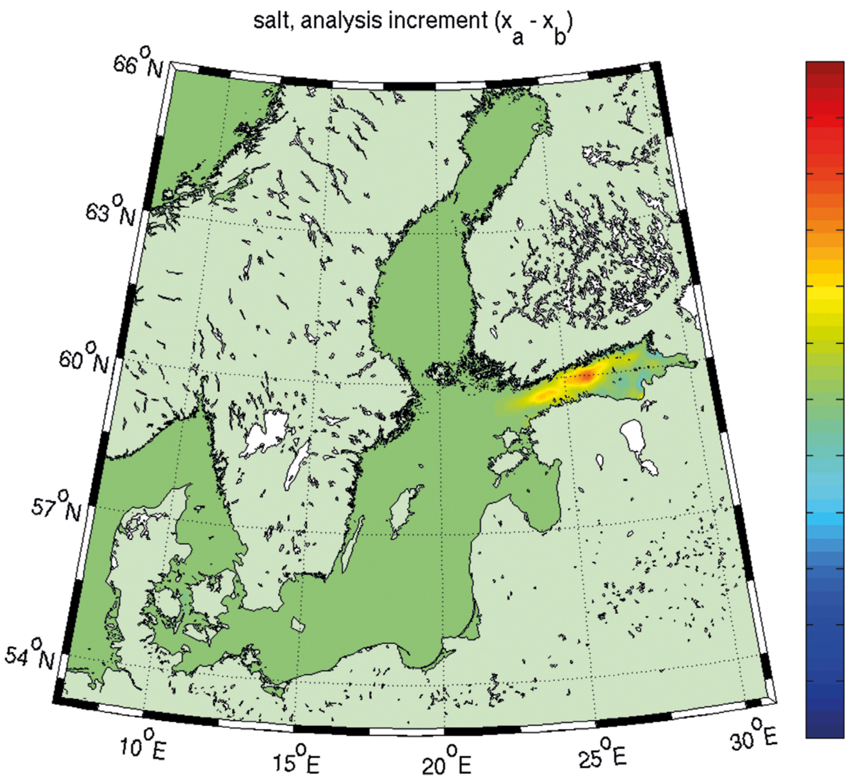


FIGURE 57

Example of a salinity analysis increment, showing the non-isotropic nature of Background Error Covariances.

The Baltic Sea ice is important from a climate perspective as a winter climate indicator, as the annual maximum ice extent varies between about 10% and 90% of the total area of the Baltic Sea depending on the severity of the winter season. Figure 58 shows a time series of observed and simulated (a free run and the V3 reanalysis) sea ice extent for the whole reanalysis period 1989-2015. It also shows the benefit of assimilating observations as the free run overestimates the ice extent compared to observations.

Because of the narrow and shallow sills in the Danish Straits, inflows of high-saline, dense bottom water into the Baltic Sea occur only intermittently. As Baltic inflows are still a challenge to model correctly, DA can be used to correct model biases. Figure 59 shows salinity profiles with time in the Bornholm Basin in the SW Baltic proper. It is clear that the free run has a severe negative bias in the deep water and an increasing negative bias in the surface waters. These are corrected by the DA in the CMEMS catalogue V3 reanalysis product.

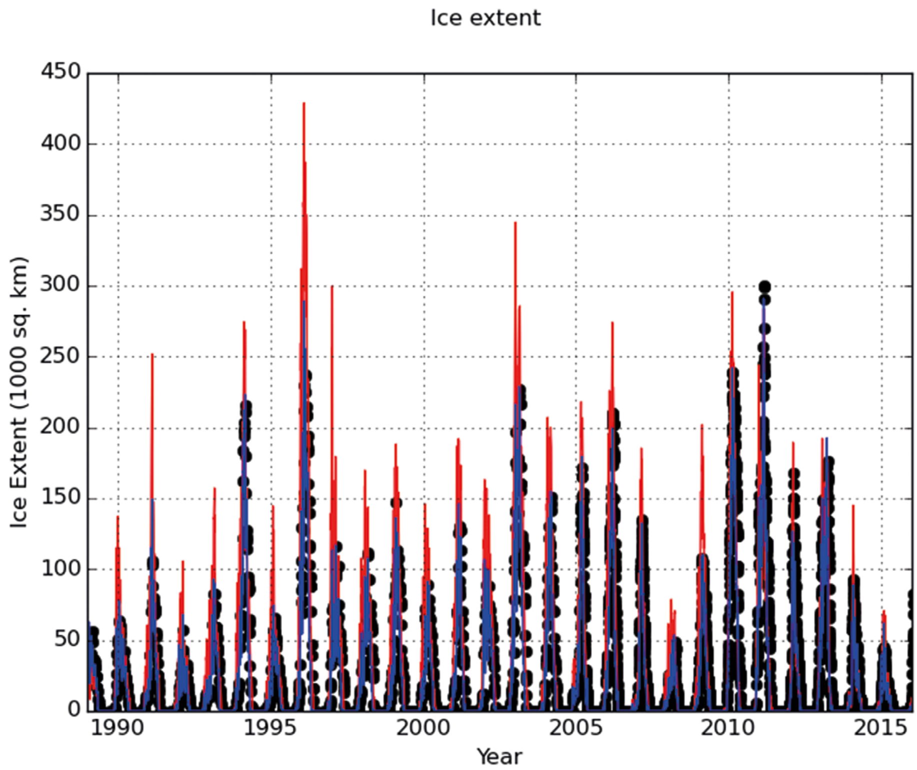


FIGURE 58

Annual maximum sea ice extent, according to observations (black dots), a free model run (red) and the V3 reanalysis (blue).

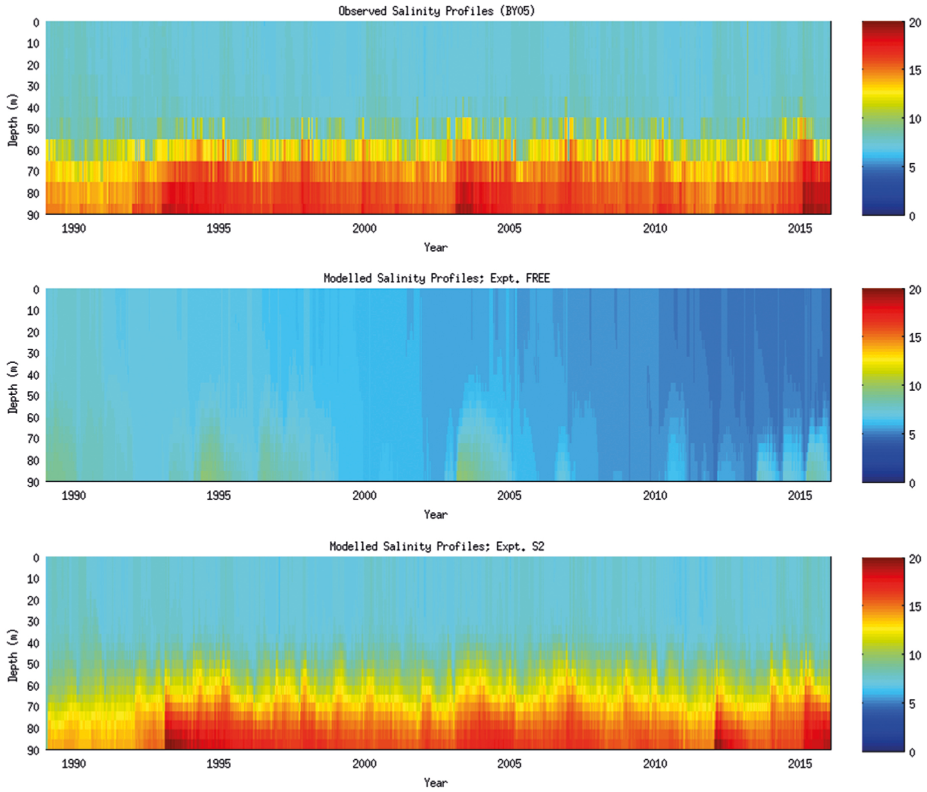


FIGURE 59

Salinity profiles in the Bornholm Basin vs. time, according to (top) observations, (middle) a free model run, and (bottom) the V3 reanalysis.

Product quality

BAL MFC product quality is routinely monitored using the validation framework for the Baltic Sea (Lagemaa *et al.*, 2013) that has been developed by the MyOcean BAL MFC (Leth *et al.*, 2014) quality control group during the MyOcean project, implemented and further developed during the CMEMS Phase 1 contract. The validation framework has validation routines for the time series data (mooring stations), profile data (profiling stations), along track data (ferrybox) and 2D field data (SST, Chl-a, etc).

Product quality monitoring is implemented in two steps: preoperational qualification and operational validation. The preoperational qualification assures that the product to be released to the operational production qualifies for state-of-the-art quality standards. The preoperational validation covers the entire BAL MFC product portfolio: (i) sea surface height, temperature, salinity and sea ice for forecast and multiyear products; (ii) mixed layer depth for forecast; and (iii) Chl-a, nitrogen, phosphorus and oxygen for bio forecast product (Golbeck *et al.*, 2017). The operational validation is performed during the production and shows the quality of operational products via quarterly validation and multi model ensemble.

The Baltic Sea is unique in terms of ferry traffic equipped with ferrybox observation devices allowing validation of surface salinity and temperature in high resolution and near real-time. The BAL MFC quality control includes data from six ferryboxes covering the Baltic Sea relatively well (Golbeck *et al.*, 2017). Ferrybox observations are especially valuable for validating sea surface salinity for which other observations are rather sparse. The validation methodology includes comparison of modelled and observed temperature and salinity patterns along ferrybox lines, as well as the deviation maps from model to observations. High resolution validation allows calculating reliable statistics that are used in quarterly near real-time validation, and visualized in Taylor diagrams (Taylor, 2001) for preoperational qualification purposes. The validation results indicate that for most of the Baltic Sea basins, the temperature and salinity RMSE along ferrybox tracks are below 1 K and 1 g/kg, respectively. However, for some regions (e.g. Gulf of Finland and Straits) the accuracy of BAL MFC salinity product can be much lower.

One of the major improvements in the product quality monitoring is the development of the sea ice validation methodology. The new method validates the ice thickness and concentration for each ice class, which allows more detailed analysis of BAL MFC ice product. This gives valuable information for the users as well as ice model developers. According to the methodology the ice is divided into ten equally distributed classes along the parameter under validation. For ice concentration the class 1 includes the ice areas which have ice concentration from 0%-10%, class 2 from 10%-20%, etc. (Golbeck *et al.*, 2017). The new analysis method showed that the number of ice covered grid cells is overestimated for all ice concentration ranges except class 1 which is underestimated by the model. Also the new validation methods followed to a recommendation that the thin ice forecast (0–6.5 cm) should be used with caution at the moment.

A multi model ensemble (Golbeck *et al.*, 2015) (MME) method is used at BAL MFC to estimate the model accuracy and monitor the quality in near real-time. The MME encompasses different forecasting models that are independent systems differing in model code, atmospheric forcing, boundary conditions, model resolution and data assimilation schemes, run in different forecasting centres. Parameters included in the MME are sea surface currents, sea surface salinity, sea surface temperature (SST), sea bottom salinity and sea bottom temperature, water level, as well as estimates of water transport on a daily basis. Ensembles and corresponding ensemble statistics are calculated for each variable separately including information about the spread of the forecast together with the ensemble mean and median. The advance of MME compared to a single deterministic forecast is the ability to evaluate uncertainties in forecast parameters. Furthermore, Golbeck *et al.* (2015) showed that the MME mean was able to produce better results than most of the individual forecast e.g. for SST. Also, no single forecast system was shown to be superior in forecasting accuracy for all parameters in all areas. The recently implemented multi model weighted mean sea level forecast has high added value to the forecasters allowing near real-time accuracy estimation of sea level forecast and more reliable warnings for the extreme weather situations. The MME method also provides an opportunity to estimate model accuracy for the regions and parameters for which observations are not available. The MME are produced for the Baltic Sea and the North Sea and are available in the BOOS (Baltic Sea Operational Oceanography System) and NOOS web pages, respectively.

BAL MFC requirements on observations

In the Baltic Sea BOOS is providing observations as an integrated service, including 10 ferrybox lines, a comprehensive tidal gauge array and around 10 moorings. New instruments, e.g. shallow water Argo floats have been used in the Baltic Sea since 2012 and are used for operational monitoring in the Bothnian Sea and Gotland Deep by FMI (e.g. Purokoski *et al.*, 2014; Westerlund and Tuomi, 2016). Gliders are used in field experiments during which data are acquired also in near real-time. Regular environmental monitoring cruises are carried out with full basin and three-dimensional coverage by the member states and coordinated by HELCOM (Helsinki Commission, the Baltic Marine Environment Protection Commissions). Most of these observations are delivered offline (available after 1 year or longer time) except for CTD observations from SMHI. Data assimilation experiments show that the impact time window of temperature/salinity profile data is 3 weeks (Zhuang *et al.*, 2011). Temperature/salinity assimilation has also been shown to improve the biogeochemical product quality (Fu, 2016). Hence shortened delivery time of HELCOM observations will greatly benefit the operational ocean and biogeochemical forecasting. A strong diurnal signal is linked to low winds, highly stable surface condition and often cyanobacteria blooms in the summer. It is recommended to have hourly skin temperature for the Baltic Sea which can be very useful in forecasting the skin temperature diurnal variation and cyanobacteria bloom. Satellite Chl-a is a major data source for near real-time assimilation for biogeochemical modelling in the Baltic Sea. Its quality, however, is still an open issue in the Baltic Sea.

Impact of R&D advanced for users and applications

The BAL MFC products can be widely used for different applications ranging from navigation and search and rescue to monitoring the environmental state of the Baltic Sea. The BAL MFC products are presently used in many national forecasting centres to bring added value to the national forecasts. For example, the good quality of the BAL MFC sea level forecasts has enhanced its use in evaluating the length of extremely low sea level cases in Estonia, thus helped to reduce the damage costs in several fields, industries and public. Also, in Latvia the CMEMS physical analysis and forecasts products are utilised in a FIMAR software, which integrates marine data from different sources and then distributes the products to several Latvian authorities.

Continuous improvements in BAL MFC models and assimilation enhance the quality of the products which have a wide range of applications. The BAL MFC products have been used: in forcing the local scale models; storm surge forecast; Baltic Major Inflow (MBI) and its impact study; assessment of bottom oxygen depletion and eutrophication status; e-navigation; offshore wind-farm service; search and rescue and prediction of low sea level events; etc.

For example, local government in Denmark used HBM forecasts in 2014/15 MBI event to identify the massive death of pike – a brackish water fish species. Estonia, Latvia and Poland use HBM forecast to force their local operational models; ERGOM bottom oxygen shows a similar trend of improved conditions as compared to observations, which are used in eutrophication assessment. The high quality of HBM surface current prediction in areas of heavy traffic and high currents have been good applications for e-navigation research projects, e.g. MONALISA2, EfficienSea2 and EONAV etc.

CONCLUSIONS AND FUTURE PROSPECTS

CMEMS service evolution R&D activities are essential to better answer to user's needs, maintain state-of-the-art systems and to benefit from improved observing systems and scientific advances in processing, validation methodologies, modelling and data assimilation. As described in this paper, important R&D advances have been achieved during CMEMS Phase 1 (April 2015 – April 2018) and significantly improved service is or will be soon proposed to the users: wave observations and models, improved resolution, wave/circulation coupling, better use of existing satellite and *in-situ* observations, uptake of Sentinel-1 data (sea ice, wave) and Sentinel-3 (altimetry, sea surface temperature, ocean colour) data, longer time series of reprocessed *in-situ* and satellite data and ocean reanalyses, improved and more homogenized product quality assessments, ocean monitoring indicators and ocean state report.

CMEMS service evolution R&D activities are essential to better answer to user's needs, maintain state-of-the-art systems and to benefit from improved observing systems and scientific advances in processing, validation methodologies, modelling and data assimilation.

In April 2018, CMEMS will enter its Phase II (April 2018-April 2021). Over this time period, the following improvements or evolutions are planned:

- Improving product quality and product quality assessment.
- Improving product consistency (interfaces and boundary conditions between MFCs, reprocessed time series and reanalyses).
- Improved horizontal and vertical model resolution, explicit representation of tides, wave/circulation coupling to better represent upper ocean dynamics (e.g. currents).
- Improved data assimilation methods (e.g. ensemble methods) and assimilation of new types of data (e.g. sea ice thickness).
- Improved CMEMS biogeochemical products and assessment (for the Marine Strategy Framework Directive, ocean state/health assessment, carbon/CO_2/pH) (observations, modelling). Assimilation of ocean colour in all biogeochemical models. Assimilation of biogeochemical Argo data.
- New observation products (e.g. surface currents, sea ice thickness from Cryosat-2, SMOS and Sentinel-3, HF Radars).
- Better addressing requirements of coastal users. Improved satellite products (e.g. ocean colour) will be proposed and stronger links with downstream coastal systems will be set up.

- In parallel the development of the Copernicus data information access services (DIAS) platforms is expected to provide new services through an integrated access to data and products from all Sentinels and Copernicus Services.

These evolutions will require and build on R&D activities carried out by TACs and MFCs but also by CMEMS Service Evolution R&D projects[2] or H2020 projects. Developing innovative, state-of-the-art and well-focused R&D will remain essential for Phase II and post 2021 CMEMS service evolution.

Maintaining and improving the service also depends on the sustainability and improvements of the *in-situ* and satellite observing systems. CMEMS has a high dependency on upstream *in-situ* and satellite observations. CMEMS systems are, in particular, highly dependent on the status of altimeter constellation and the assimilation of Argo profiling float data. There is a clear degradation of analysis and forecast quality when reducing the number of assimilated altimeters (e.g. Le Traon *et al.*, 2017). Temperature and salinity forecast errors are typically reduced by 20% to 60% when Argo float are assimilated (Turpin *et al.*, 2016).

CMEMS has defined its main requirements for the evolution of the Copernicus satellite component (CMEMS, 2017). Based on user requirements and the evolution of the CMEMS for the next decade, the main CMEMS recommendations/priorities for the evolution of the Copernicus satellite component (evolution and new generation of Sentinels) are as follows:

- Ensure a continuity of the present capability of the Sentinel missions (S1, S3, S6) and S2 for downstream coastal applications.
- Develop new capabilities for wide swath altimetry. This is essential to constrain future CMEMS high resolution ocean models and downstream coastal models.
- Fly a geostationary ocean colour mission over Europe to strongly improve the time resolution of ocean colour observations over European seas.
- Fly a European microwave mission for high spatial resolution ocean surface temperature and sea ice concentration.
- Ensure continuity (with improvements) of the Cryosat-2 mission for sea ice thickness monitoring and sea level monitoring in polar regions.
- R&D actions should be developed, in parallel, to advance our capabilities to observe sea surface salinities and ocean currents from space.

Waves are observed today through altimeter (S3, S6) and SAR (S1) missions. New concepts will be flying soon (CFOSAT) allowing a better retrieval of directional wave spectra. This could lead to an improved design of future Sentinel missions. Ocean Surface Vector Wind (OSVW) measurements through scatterometers are also important to improve NWP forcing fields. Europe through the Eumetsat MetOP series provides a unique contribution to the international virtual OSVW constellation. This should be pursued and international coordination should be reinforced to optimize the existing and future scatterometer constellation.

The consolidation and sustainability of the global and regional *in-situ* observing systems remain a strong concern. There are critical sustainability gaps and major gaps for biogeochemical observations (e.g. carbon, oxygen, nutrients, Chl-a). New mechanisms need to be set up between the EU and member states to address them. Mercator Ocean as the EU delegated body for the Copernicus Marine Service is working with European Environment Agency, Euro-Argo ERIC and EuroGOOS in the framework of a future European Ocean Observing System (EOOS) to consolidate and improve global and regional *in-situ* observing systems. Sustaining the Argo global array, consolidating its regional components and implementing its major extension (Biogeochemical Argo and Deep Argo) are strong priorities to CMEMS. Improving ROOSes (Regional Ocean Observing Systems) and key observing systems such as FerryBoxes, gliders, tide gauges and HF Radars are also strong priorities for regional CMEMS products.

[2] see https://www.mercator-ocean.fr/en/mercator-ocean/copernicus/service-evolution/

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ANNEX 1: MAIN EVOLUTIONS OF CMEMS TACS AND MFCS FROM V1 TO V4

NRT: NEAR-REAL TIME, REA: REANALYSIS, REP: REPROCESSED.

CMEMS V1 - MFCs, MAY 2015 - PHYSICS

GLOBAL:

- NRT global high resolution: Uses the physical ocean model NEMO, with 1/12° resolution and 50 vertical levels. The model is forced by ECMWF operational analysis and forecast at 3 h frequency and coupled with LIM2 sea-ice model. Uses SAM2 (SEEK filter) data assimilation scheme assimilating SST, SLA and *in-situ* Temperature and salinity profiles. Running 1-week assimilation window, 1-week assimilation cycle and daily 7-day forecast. The products delivered are 3D daily fields and 2D hourly fields on a 1/12° regular grid.
- NRT global coupled: Uses the physical ocean model NEMO, at 1/4° resolution and 75 vertical levels, coupled with CICE sea-ice model and forced by UKMO operational analysis (resolution of 17 km and 3-hourly fluxes) and coupled with the atmospheric model for the forecast (resolution of 50 km and 3-hourly coupling). NEMOVAR (3DVAR) data assimilation scheme assimilating SST, SLA, *in-situ* temperature and salinity profiles and sea-ice concentration. 2-day assimilation window, daily assimilation cycle and daily 7-day forecast. Products delivered are 3D daily fields and 2D hourly fields on 1/4° regular grid.
- NRT: Multi observations ARMOR3D ocean state estimate obtained by combining satellite (sea level anomalies, geostrophic surface currents, sea surface temperature) and *in-situ* (temperature and salinity profiles) observations and a MDT through statistical methods. Global 3D L4 weekly fields (temperature, salinity, geopotential height and geostrophic currents) are delivered on a regular ¼° grid.
- REA: 4 global physical reanalysis based on NEMO ocean model and assimilating SST, SLA, *in-situ* temperature and salinity profiles. Products delivered are 3D monthly mean on the native ORCA grid. Reanalysis are produced by Mercator Ocean (GLORYS2V3); CMCC (CGLORS); ECMWF (ORAP5); and Reading University (UR025.4). Time series covers at least 1993-2012 with some products starting in 1980 and some products updated to 2013. Also disseminated is a non-assimilative hindcast based on the same model configuration and produced by CNRS.
- REP: ARMOR3D reprocessing from 1993 based on the same method that the NRT system.

ARCTIC:

- NRT: HYCOM v2.2.37 and CICE-NERSC, ~12 km resolution and 28layers. It uses ECMWF T71279 and includes no waves.
- The REA covers 1991-2011 and uses HYCOM v2.2.18. Lateral boundary conditions from climatology.
- DEnKF with 100 members, assimilates SLA, SST, sea-ice concentrations, ice drift, *in-situ* T and S profiles both in NRT and reanalysis.

BALTIC:

- NRT: Uses the physical ocean model HBM with 1-2 km horizontal resolution and 122 vertical layers. It is forced by DMI HIRLAM forecast (3 km resolution), twice-daily 60 h forecast without data assimilation. The turbulence model uses structure functions from Canuto scheme. Sea-ice is based on a Hibler-type thermodynamic model at 1 nmi resolution.
- REA physical ocean model includes both HBM and HIROMB. For HBM reanalysis, T and S profiles were assimilated with a 3D-VAR method and a horizontal resolution of ~10 km for the period of 1990-2009. For HIROMB reanalysis, satellite SST, sea-ice concentration and T and S profiles were assimilated with a 3D-EnVar method and a resolution of ~5 km for the period of 1989-2014.

NORTH WEST SHELF:

- NRT: Uses the physical model NEMO-CO5, resolution of ~7 km and 51 levels (native grid)/24 (standard grid for dissemination). Forcing from UK Met Office global NWP (hourly 10 m wind speed), SSP (1 h), short and long wave radiation (3 h), moisture, E-P (3 h). NEMOVARv3 2D SST data assimilation (satellite and *in-situ* observations).
- REA: Period of 1985-June 2014. Same characteristics of real time but NWP from ERA-Interim.

IBERIA-BISCAY-IRELAND:

- NRT: Uses the NEMO model v3.4. Resolution of 1/36° and 50 vertical layers. Atmospheric forcing from ECMWF IFS. Rivers from a combination of observations, climatology and hydrological models. No coupling with waves. No data assimilation, but periodic 3D weekly re-start from global MFC to include assimilated structures.
- REA: NEMO model v2.3. Resolution of 1/12° and 75 vertical layers. Atmospheric forcing from ECMWF ERA-interim. Data assimilation with SAM2. Period of reanalysis: 2002-2014.

MEDITERRANEAN:

- NRT: Uses the NEMO model. Resolution of 1/16˚ (6-7 km) and 72 unevenly spaced vertical levels. Coupled with the WaveWatch-III (WWIII) wave model. The model solutions are corrected by the variational assimilation (based on a 3DVAR scheme) of temperature and salinity vertical profiles and along track satellite Sea Level Anomaly observations. Mapped Sea Surface Temperature fields are used for the correction of surface heat fluxes. The analysis is done weekly, on Tuesday, for the previous 15 days. The assimilation cycle is daily (24 h) and is done in filter mode. A 10-day forecast is produced every day. The forecast is initialized by a hindcast every day except Tuesday, when the analysis is used instead of the hindcast.
- REA: Uses the NEMO model. Resolution of 1/16˚ (6-7 km) and 72 unevenly spaced vertical levels. Variational data assimilation scheme (OceanVAR) for temperature and salinity vertical profiles and satellite Sea Level Anomaly along track data. The reanalysis is initialized with a gridded temperature and salinity climatology computed from *in-situ* data sampled before 1987 from SeaDataNet FP6 project. The available data starts in 1987.

BLACK SEA: not available in v1

CMEMS V1 - MFCs, MAY 2015 - BIOGEOCHEMISTRY

GLOBAL:

- NRT: Uses the PISCES model at 1/4° resolution forced in an off-line mode by the 1/4° physical operational analysis and forecasting system. Output: 1-week mean on a regular 1/2°grid are disseminated for the current week and for a 1-week forecast.
- REA: Two non-assimilative biogeochemical hindcasts based on PISCES and BFM models and forced by the physical 1/4° non-assimilative hindcast are disseminated. Products delivered are monthly means on the native 1/4° grid from 1998 to 2012.

ARCTIC:

- NRT: Uses model NORWECOM, coupled online to HYCOM (same resolution), assimilation of physical data only and ECMWF forcing.
- REA: Uses NORWECOM, coupled online at lower resolution (50 km, 28 layers). Assimilation of 8-days composite OC reprocessing (REP) data in 2008-2010 with the DEnKF (100 members), jointly with physical remote sensing data. Online estimation of model parameters.

BALTIC:

- NRT: BIO model ERGOM with horizontal resolution of ~1-2 km and 122 vertical layers. Instantly coupled with the NRT ocean model HBM, twice-daily 460 h forecast without data assimilation.
- REA: BIO model SCOBI, ~3-4 km horizontal resolution and 83 vertical layers. Instantly coupled with climate ocean model RCO. T and S profiles and nutrient profiles were assimilated with an EnOI (optimal interpolation) method and a resolution of ~4 km for the period of 1990-1999.

NORTH WEST SHELF:

- NRT: Model NEMO-CO5-ERSEM, resolution ~7 km and 51 levels (native grid) and 24 (standard grid for dissemination). Forcing from UK Met Office global NWP (hourly 10 m wind speed (1 h), SSP (1 h), short and long wave radiation (3 h), moisture E-P (3 h). NEMOVARv3 2D SST data assimilation (satellite and *in-situ* observations).
- REA: Period of 1985-June 2014. Same characteristics of real time but NWP from era-interim.

IBERIA-BISCAY-IRELAND: Not available in v1

MEDITERRANEAN:

- NRT: The biogeochemical analysis and forecasts are produced by means of the 3DVAR-OGSTM-BFM model system, using as physical forcing the outputs of the Med-currents products. Producing twice-weekly 7 days of analysis/hindcast and 10 days of forecast with assimilation of satellite chlorophyll concentration.

- REA: Uses the OGSTM-BFM biogeochemical model at 1/16° resolution and data assimilation of surface chlorophyll concentration. Time period of 16 years (1999-2014). OGSTM-BFM was driven by physical forcing fields produced as output by the Med-Currents model. This reanalysis provides monthly means of 3D fields of chlorophyll, nutrients (phosphate and nitrate) and dissolved oxygen concentrations, net primary production, phytoplankton biomass, ocean pH, and ocean pCO_2. The reanalysis has been initialised with a gridded climatology for nutrients, dissolved inorganic carbon and alkalinity computed from MEDAR MEDATLAS database.

BLACK SEA: not available in v1

CMEMS V1 - MFCs, MAY 2015 - WAVES

Global: Not available in v1

Arctic: Not available in v1

Baltic Sea: Not available in v1

North West Shelf: Not available in v1

Iberia-Biscay-Ireland: Not available in v1

Mediterranean Sea: Not available in v1

Black Sea: Not available in v1

CMEMS V4 - MFCs, MAY 2018 – MAIN DEVELOPMENTS COMPARED TO V1 – PHYSICS

GLOBAL:

- NRT: Global high resolution: The new version of the physical analysis and forecasting system is based on the same model and data assimilation scheme. In addition the system assimilates the sea-ice concentration and an adaptive method has been developed to compute the error observation. The system has been operational since October 2016, a 10-year time series is available from 2007. A 10-day forecast is provided every day and 3D daily products and 2D hourly products are disseminated on a 1/12° regular grid.
- NRT: Global coupled: Physical ocean model NEMO, with 1/4° resolution and 75 vertical levels. Model coupled with CICE sea-ice model and coupled with the UKMO atmospheric model for the analysis and the forecast (resolution of 40 km and hourly coupling). NEMOVAR (3Dvar) data assimilation scheme assimilating SST, SLA, *in-situ* temperature and salinity profiles and sea-ice concentration. The service provides a 2-day assimilation window, 6-hourly assimilation cycle and a daily 10-day forecast. Products delivered are 3D daily fields and 2D hourly fields on a 1/4° regular grid.
- NRT: Global observed: The new version of the ARMOR3D was updated in April 2016; it includes a new first guess climatology and improved parameters for the statistical method.
- REA: A high-resolution physical reanalysis will be disseminated in V4 at 1/12° resolution to replace the ¼° products. The system is close to the real time system. The main differences concern the atmospheric forcing from ERA-interim reanalysis and the observations assimilated in the system which comes from reprocessing the dataset. Daily 3D products and hourly 2D products on a regular 1/12° grid will be available for the period from 1993 to 2016 and the time series will be updated every year.
- REA: Ensemble. An ensemble multi-system reanalysis is performed based on four global 1/4° physical reanalysis using NEMO. The ensemble, the standard deviation and each individual member are disseminated. The time series is updated every year. Initially the temperature and salinity were provided on a regular 1° grid at a monthly frequency but other variables (e.g. velocities, sea ice, etc.) will be disseminated in V4 at a higher frequency (daily) and at higher resolution (1/4°).
- REP: ARMOR3D reprocessing from 1993 based on the same method than the NRT system. New global sea surface salinity (SSS), and sea surface density (SSD) weekly L4 reprocessing from 1993 - obtained by interpolating *in-situ* SSS/SSD through a multi-dimensional covariance model that accounts for space-time and thermal decorrelation (estimated by including information from high-pass filtered daily SST L4 data). This reprocessing is also delivered on a regular 1/4° grid. All time series will be extended each year.

ARCTIC:

- NRT: Models HYCOM v2.2.72 and CICE v5.1 coupled by ESMF, ~6 km resolution and 45 vertical layers. Using the ECMWF T1279 wave forcing in ocean (including Coriolis-Stokes drift, momentum and Langmuir mixing). The lateral boundary condition comes from GLO MFC.
- REA: for the period between 1991-2016, prolongation of the V1 reanalysis. DEnKF 100 members, assimilates SLA, SST, sea-ice concentrations, ice drift, ice thickness, *in-situ* temperature and salinity profiles both in NRT and reanalysis.

BALTIC:

- NRT: Ocean-ice models HBM and data assimilation. A more numerically stable and efficient turbulence model was implemented based on a new set of structure functions (Canuto part III). Turbulence mixing parameters were tuned using sensitivity experiments. Improved river inputs from previous 72 rivers to 846 rivers in the Baltic-North Sea domain. A simplified ice dynamic module and a fast-ice module have been added, to better describe the wind and current driven motion of sea-ice and its deformation. Assimilation: A PDAF-HBM system for assimilating SST has been developed and will be implemented for operation in BAL MFC V4. Level 3 SST is assimilated.
- REA: NEMO-Nordic with data assimilation. The new model system NEMO-Nordic with ~4 km and 56 vertical levels will substitute the old system based on HIROMB with ~6 km and 50 vertical levels. For assimilation the same PDAF LSEIK system will be used as in the BALTIC NRT system. SST, temperature and salinity profiles observations will be assimilated into NEMO-Nordic. Period: 1993-2016.

NORTH WEST SHELF:

- NRT: NEMO-CO7, ~1.5 km resolution and 51 levels (native grid)/24 (standard grid for dissemination). With ECMWF NWP, NEMOVARv4 3D data assimilation of SST, vertical profiles of temperature, salinity, and SLA.
- REA: NEMO-CO6. ~7 km resolution and 51 levels (native grid)/ 24 (standard grid for dissemination). Uses ERA-interim NWP. NEMOVAR v3, 3D data assimilation of SST, vertical profiles of temperature and salinity. Covering the period 1992-2015 (2016).

IBERIA-BISCAY-IRELAND:

- NRT: NEMO model version 3.6. Resolution 1/36° and 50 vertical layers. Atmospheric forcing from ECMWF IFS. Coupling with waves if added value demonstrated between V3 and V4. Data assimilation with SAM2.
- REA: NEMO model version 3.6. Resolution 1/12° and 75 vertical layers. Atmospheric forcing from ECMWF ERA-interim. Data assimilation with SAM2. Period of reanalysis: 1992-2016.

MEDITERRANEAN:

- Implementation of realistic daily precipitation from ECMWF as atmospheric forcing;
- Upgrade on data assimilation by using improved grid-points EOFs (empirical orthogonal functions) for the background vertical error covariance matrix;
- Addition of new parameters in the catalogue such as: mixed layer depth and bottom sea temperature;
- Increase of the temporal extent of the reanalysis products, adding a new reanalysis product, covering a 60-year period;
- Change of numerical model from NEMO 3.4 to NEMO 3.6 with non-linear free surface formulation;
- Increase of spatial resolution from 1/16° latitude and longitude and 72 levels to 1/24° and 141 levels;
- Improvement of the land forcing by adding 32 rivers to the 7 rivers implemented in operational system;
- Implementation of new open boundary tool (BDY);
- Introduction of Strait of Dardanelles as lateral open boundary;
- Implementation of data assimilation scheme on the same spatial resolution of the numerical model;
- Increase of the temporal extent of the reanalysis products, adding a new reanalysis product, covering a 60-year period; and
- Increase of the temporal extent of the reanalysis products, adding one more year (2014, 2015, 2016).

BLACK SEA:

- NRT :products using NEMO ocean model (v3.4 at V2.2 and v3.6 at V3) available at 1/27° x 1/36° horizontal resolution and 31 z-level with partial steps at V3. ECMWF operational data with 1/8° spatial resolution and 3/6 h temporal frequency as atmospheric forcing. Near-real-time SLA, SST and *in-situ* data from CMEMS TACs assimilated into the system using OCEANVAR scheme (based on 3DVAR). Time series available since 1992. Time series available since Jan 2014 and daily updated, providing daily/hourly means of 15/3-days analysis, 1-day hindcast and 10-days forecast.
- REA: NEMO v3.4 at 1/27° x 1/36° horizontal resolution and 31 z-level with partial steps. Using ECWMF ERA-Interim atmospheric forcing. SST, SLA, SST and *in-situ* data from CMEMS TACs and UKMO EN4.1.1 assimilated into the system using OCEANVAR scheme (based on 3DVAR). Time series available since 1992.
- Major improvements planned from V2.2 to V4: 1) the upgrade of the state-of-the-art numerical ocean model with a different turbulent closure model for better resolving the vertical mixing in V3; 2) the upgrade of the numerical ocean to a higher vertical resolution (V4); 3) the Bosporus Strait, now treated as a river in the ocean model, will be implemented as lateral open boundary from specific model simulations (V4); 4) development of an optimal interface between MED MFC and BS MFC through improvements of straits open boundary conditions (V4); 5) improvements in the data assimilation scheme with increased vertical resolution EOF for the background vertical error covariance matrix (V4); 6) refinement and recalibration of background error covariances used in the physical ocean data assimilation system (V3, V4); 7) the addition of new bottom temperature product in the catalogue (V3); and 8) increase of the temporal extent of the reanalysis products from 1992 (V3, V4).

CMEMS V4 - MFCs, MAY 2018 – MAIN DEVELOPMENTS COMPARED TO V1 – BIOGEOCHEMISTRY

GLOBAL:

- NRT: PISCES model at ¼° resolution forced in an offline mode by the 1/12° physical operational analysis and forecasting system assimilating the surface ocean colour observations. Daily means on a regular 1/4° grid will be disseminated for the current week and for a 10-day forecast.
- REA: A non-assimilative biogeochemical hindcast based on PISCES models and forced by the physical ¼° reanalysis will be disseminated. Products delivered will be: monthly mean on a regular ¼° grid from 1993 to 2016, and the time series will be updated every year.

ARCTIC:

- NRT: ECOSMO, coupled online to HYCOM (same resolution), assimilation of physical data only. Using ECMWF forcing. Wave influence on ecosystem.
- REA: ECOSMO, coupled online at lower resolution (50 km, 28 layers), assimilation of 8-days composite OC REP data and INS TAC nutrient profiles in 2007-2015 with the OSA-EnKF smoother (100 members). Online estimation of model parameters.

BALTIC:

- NRT: BIO model ERGOM. Atmospheric deposition: The effect of improving the representation of atmospheric deposition with spatiotemporal variations in the model has been tested. The results show small improvements in the Baltic Sea nitrogen concentrations (V3). Nitrogen/Phosphate (N/P) ratio: The effect of including a spatial varying N/P ratio for the Baltic Sea has been tested further. Results show that spatial varying N/P ratios can complement the simplification of the nutrient cycle in the model and improves the product quality (V3). The light routine has been revised following Neumann et al. (2015) (V4). Furthermore the Secchi depth and ammonium will be included in the products (V4).
- REA: BIO model SCOBI and data assimilation. Model code: SCOBI coupled NEMO-Nordic with 3-4 km resolution and 56 vertical levels instead of RCO-SCOBI with 1-2 km and 83 vertical levels. Compared the RCO-SCOBI covering the Baltic Sea and Kattegat, NEMO-SCOBI covers both the North Sea and Baltic Sea. Assimilation: LSEIK Data assimilation system, compared to EnOI used in V1, has been configured for NEMO-SCOBI. The profiles of NO_3, NH4, PO_4 and O_2 observations are planned to be used in the reanalysis of NEMO-SCOBI. The BIO REA period: 1993-2016.

NORTH WEST SHELF:

- NRT: NEMO-CO5-ERSEM, ~7 km resolution and 51 levels (native grid)/ 24 (standard grid for dissemination, UKMO global NWP(hourly 10 m wind speed (1 h), ssp (1 h), short and long wave radiation (3 h), moisture E-P (3 h).
- REA: 1998-2015 (2016) NEMO-CO6-FABM/ERSEM. ~7 km resolution and 51 levels (native grid)/ 24 (standard grid for dissemination) ERA-interim NWP. NEMOVAR v3, 3D data assimilation of SST, vertical profiles of temperature and salinity, and satellite Chl. Period of reanalysis: 1998-2015 (2016).

IBERIA-BISCAY-IRELAND:

- NRT: PISCES model version 3.6. Resolution 1/36° and 50 vertical layers. Producing 24 prognostic variables. Coupled with 1/36° NEMO model version 3.6.
- REA: PISCES model version 3.6. Resolution 1/12° and 75 vertical layers. Coupled with 1/12° NEMO model version 3.6 with 75 vertical layers. Period of reanalysis 1992-2016.

MEDITERRANEAN:

- Upgrade BFM biogeochemical model including the carbonate system formulation ;
- Addition of new products in the catalogue: ocean acidity and ocean pCO_2;
- Upgrade on data assimilation scheme by adding the assimilation of satellite data for the coastal areas ;
- Increase of the temporal extent of the reanalysis products, adding one more year (2014, 2015, 2016);
- Upgrade of numerical transport model from OGSTM to OGSTMvvl (V3);
- Increase of spatial resolution from 1/16° latitude and longitude and 72 levels to 1/24° and 141 levels; and
- Update of land forcing in the operational system: 39 major rivers and Dardanelles aligned with MED-current.

BLACK SEA:

- NRT: products using GHER-BAMHBI model available at 1/22° horizontal resolution and 31 z-level with partial steps at V3. Using ECMWF operational data at 1/8° spatial resolution and 3/6-h temporal frequency as atmospheric forcing. Time series available since Jan 2014 and daily updated, providing 3D daily mean fields of: chlorophyll, phosphate, nitrate, dissolved oxygen, phytoplankton biomass and 2D fields of bottom dissolved oxygen, and vertically integrated primary production daily updated. No data assimilation at V3.
- REA: Using GHER-BAMHBI model available at 1/22° horizontal resolution and 31 z-level with partial steps at V3. Using ECWMF ERA-Interim as atmospheric forcing. No data assimilation at V3. Hindcast time series available since 1992.

Major improvements planned from V2.2 to V4: 1) the upgrade of the numerical biogeochemical models to a higher resolution (V3, V4); 2) for V4, the biogeochemical model will be fully aligned to the ocean model, allowing to: a) an enhanced representation of the mesoscale dynamics, a better quantification of the export of materials from the north western shelf to the deep sea and its impact on major biogeochemical variables and processes (e.g. intrusion of sulfidic waters from the deep sea to the shelf, export of nutrients and organic materials from the shelf to the deep sea); b) a better representation of the oxygenation and ventilation process; c) a better representation of coastal processes that is needed in order to address the description of indicators associated to the assessment of the Good Environmental Status (water transparency, hypoxic events, water quality) (V4); 3) assimilation of satellite data (e.g. chlorophyll, optical coefficients and/or Argo data) in the biogeochemical model (V4); and 4) increase of the temporal extent of the reanalysis products from 1992 (V3, V4).

CMEMS V4 - MFCs, MAY 2018 - MAIN DEVELOPMENTS COMPARED TO V1 – WAVES

GLOBAL:

- NRT: The wave forecast system which delivered products since April 2017, is based on MFWAM wave model at 1/5° resolution. It is forced by ECMWF wind and assimilates significant wave height from altimeter observation. An updated version is under development and will be available in V4 based on a higher resolution system (at 1/10°) including a forcing by the surface current and assimilating significant wave height and wave spectra from Sentinel-1. Wave products are delivered on a 1/5° regular grid at 3-hour frequency. A 2-year time series is available in the past (hindcast) and a daily 5-day forecast is delivered.

ARCTIC:

- WAM cycle 4.5.4, 8 km resolution. Using ECMWF T1279 winds, sea-ice mask from OSI TAC, lateral boundary conditions from ECMWF WAM. No data assimilation. No reanalysis.

BALTIC:

- NRT: Wave model WAM cycle 4.5.4, 1 nmi horizontal resolution, forced by FMI's NWP system HARMONIE (c. 2.5 km resolution), twice a day with 54 h forecast length, no data assimilation used, seasonal ice cover accounted based on FMI's ice chart.

NORTH WEST SHELF:

- WW-III, 1.5 km resolution. Using ECMWF forcing and currents from PHYS products (off line coupled). No reanalysis.

IBERIA-BISCAY-IRELAND:

- MFWAN at 10 km resolution using ECMWF 2 runs per day.

MEDITERRANEAN:

- A new high resolution wave forecasting system consisting of a Mediterranean wave model nested within an Atlantic Ocean wave model;
- A new and complete (in terms of user needs) set of wave products for a forecast period of 5-days;
- A high resolution wave hindcast dataset for the period 2006 – 2016;
- A periodic (quarterly) wave product quality assessment using all available satellite and *in-situ* wave measurements; and
- Implementation of the data assimilation system.

BLACK SEA:

- NRT: Products using WAM 4.6 model available at 1/27° x 1/36° horizontal resolution since V3. Using ECMWF operational data at 1/8° spatial resolution and 3/6-h temporal frequency as atmospheric forcing. Time series available since Jan 2014 and daily updated, providing 1-day of simulation (forced by analysis wind) and 5-days of forecast as hourly instantaneous fields for the all relevant wave variables. Time series available since Jan 2014 and daily updated. No data assimilation at V3. Major improvements planned from V2.2 to V4: 1) the addition of the new waves products in the catalogue (V3); 2) the beginning of the wave production activities accompanied with a Cal/Val module; and 3) the Black Sea WAM implementation will use the shallow water mode with shoaling and refraction due to bathymetry and surface currents provided in off-line mode by the Black Sea currents system. The Black Sea waves data assimilation system will be implemented based on optimal interpolation of significant wave height satellite observations and subsequent rescaling of the wave spectrum (after being separated into a wind and swell part assuming a first guess relation between wind sea and swell) according to the analysed significant wave height.

CMEMS V1 – TACs, MAY 2015

Sea Level (SL)

- Input data: Jason-2, Altika (repetitive), Cryosat-2, HY-2A (repetitive),
- Global Along Track SLA, Regional Along Track SLA for Med, Black Sea, Europe, Arctic, specific SL for assimilation in Med Sea.

Ocean Colour (OC)

- Input data: NASA L2 MODIS, NASA L2 VIIRS (NASA R2014.0 version); NRT MODIS & VIIRS full resolution L1 passes covering European Sea (ARC. ATL, BAL, MED, BS); OC-CCI multi-sensors (SeaWiFS, MODIS MERIS) L3 reprocessed dataset version 1.
- Thirty-six OC Products: multi-sensor (MODIS-VIIRS) L3 for the global ocean; MODIS and VIIRS single sensors regional products for the ARC, ATL, BAL, MED & BS, L4 chlorophyll products for GLO, ATL, MED & BS, 1 L3 European chlorophyll products, 2 target products, specific OC products for assimilation in Med Sea. Redistribution of OC-CCI products, Regional REP produced using OC-CCI V1 reflectances at 4 km resolution (1997-2012).

Sea Ice, SST and Winds (OSI)

- Twelve Sea ice products; 1 L3 (Arctic ice drift), 10 L4. 1 Antarctic, 5 Arctic, 2 Baltic, 1 Global, 1 Arctic sea ice edge extent. Input data: Sentinel-1a SAR, Radarsat1/SAR, Radarsat2/SAR, CosmoSkyMed/SAR, Terrasar-X/SAR, Tandem-x/SAR.
- Eigteen SST products; 1 L3C, 4 L3S, 13 L4. Input data: PODAAC GHRSST, Global *in-situ* observations, ENVISAT AATSR, ERS-1,2 ATSR, AVHRR Pathfinder V5.2 data.
- Three global wind products: 1 L3 NRT, 1 L4 NRT, 1 L4 REP.

In-situ (INS)

- Input data: JCOMM Global Networks (Argo, OceanSITES, GOSUD and WMO Global Telecommunication System), EuroGOOS ROOS and and SeaDataNET(for historical T&S data).
- Seven NRT products for temperature, salinity, current, sea level, oxygen and chlorophyll.
- Seven REP products for temperature and salinity covering 1990-2013, assessed by Scientist from INS TAC ensuring consistency of the integrated products.

CMEMS V4 – TACs, MAY 2018 – MAIN DEVELOPMENTS COMPARED TO V1

Sea Level and Waves

- New inputs data from altimeter missions Jason-3, Sentinel 3B, Jason-2 interleaved, AltiKa Geodetic Phase, HY-2A Geodetic Phase.

New inputs data from SAR: Sentinel1A

- Along Track SLA with a new reference mission Jason-3, new Sentinel-3 products, New Geophysical corrections (MSS, Tide model), New ADT, specific SL for assimilation in North West Shelf, Experimental High Resolution TAPAS product.
- New gridded SLA, ADT and geostrophic current products.
- Complete reprocessing of the 25 years of altimetry.
- New L3 and L4 wave product from Sentinel3, Jason-3, Cryosat-2, Altika and Sentinel1A&B.

Ocean Colour

- Inputs data: NASA L2 MODIS (R2014.0.1 version), NASA L2 VIIRS (R2014.0.2 version); NRT MODIS full resolution L1 passes covering the Baltic; EUMETSAT L2 OLCI passes, OC-CCI multi-sensors (SeaWiFS, MODIS MERIS, VIIRS) L3 reprocessed dataset data version 3.
- Fifty-four Products: regional L3 multi-sensors for all CMEMS region except Baltic. Multi-sensors L4 products for all regions. Regional multi-sensor & multi water type chlorophyll products (ATL; ARC; MED; BS).
- Regional REP products produced at 1 km resolution using L1 to L2 OC-CCI V3 processor and CMEMS-OC L3 to L4 regional processors (1997-2016). ATL, ARC, BS & MED regional REP produced using chlorophyll algorithm consistent with NRT products. Redistribution of OC-CCI V3 products (1997-2016). Global REP consistent with NRT REP (1997-2017). OLCI L3 single sensor global (4 km) and regional products (1 km). OLCI regional chlorophyll products (ATL, ARC, BS & MED) produced using regional algorithms. BAL OLCI optic and chlorophyll products produced ingesting L1 OLCI data into the OC specialized L1 to L3 Baltic processor.

Sea Ice, SST and Winds

- Both Sentinel-1a and b SAR data are used (in addition to all sensors at V1) and different L4 mosaic products have been developed.
- Two new SST products at V4; the redistributed ESA CCI SST (METO), and the NWS L4 REP odyssea (Ifremer). 1 product has been removed: the Arctic L4 SST (MET Norway), since it was quite similar to an Arctic ice and sea surface temperature (DMI). At V4 the Sentinel-3a SLSTR will be incorporated.
- For wind, the main evolution at V4 is the addition of a Global L3 REP product and the addition of several new scatterometer missions.

In-situ

- Input data: JCOMM Global Networks (Argo, OceanSITES, GOSUD and WMO Global Telecommunication System), EuroGOOS ROOS , SeaDataNET (for historical T&S data). Annual synchronization with ICES and US-NODC operated by NCEI/NOAA have been set up.
- Seven NRT products for temperature,salinity, current, sea level, oxygen, chlorophyll and wave. Wave (amplitude and period) have been included in 2017, spectra in 2018. Standardization of parameters/units for wave and BGC parameters with the other TAC/MFCs from CMEMS.
- Seven REP products for temperature and salinity covering 1950-2016, assessed by scientist from INS TAC ensuring consistency of the integrated products. The T&S REP product for the Global Ocean (INSITU_GLO_TS_REP_OBSERVATIONS_013_001_b) is a merged product between the V1 CMEMS product and ENACT4 product managed by UKMO. The coverage in time and space has been enhanced as well as the assessment method that took the best of each process to provide a product that both serve the research and the operational user needs.
- One surface current REP product designed for reanalysis purposes that integrates the best available version of *in-situ* data for ocean surface currents for the period 1990-2016. The data are collected from the Surface Drifter Data Assembly Centre (SD-DAC at NOAA AOML) completed by European data provided by EUROGOOS regional systems and national systems by the regional INS TAC components. All surface drifter data have been processed to check for drogue loss.
- Seven WAVE REP products that aggregate long time series assessed in delayed mode from WAVE mooring operators covering the period 1990-2016. Whenever possible the consistency between the different platforms is assessed by a scientist.
- One BGC REP product for oxygen and chlorophyll parameters that aggregate long time series assessed in delayed mode assessed by platform operators for the period 1990-2016. Whenever possible the consistency between the different platforms is assessed by a scientist.