2018

Learning about Copernicus Marine Environment Monitoring Service "CMEMS": A Practical Introduction to the Use of the European Operational Oceanography Service

Marie Drevillon, Pierre Bahurel, David Bazin, Mounir Benkiran, Jonathan Beuvier, Laurence Crosnier, Yann Drillet, Edmee Durand, Michele Fabardines, Isabel Garcia Hermosa, Cedric Giordan, Elodie Gutknecht, Fabrice Hernandez, Stephane Law Chune, Pierre-Yves Le Traon, Jean-Michel Lellouche, Bruno Levier, Angelique Melet, Dominique Obaton, Julien Paul, Mathieu Peltier, Diane Peyrot, Elizabeth Remy, Karina von Schuckmann and Cecile Thomas-Couroux

CHAPTER 25

Learning about Copernicus Marine Environment Monitoring Service "CMEMS": A Practical Introduction to the Use of the European Operational Oceanography Service

Marie Drévillon, Pierre Bahurel, David Bazin, Mounir Benkiran, Jonathan Beuvier, Laurence Crosnier, Yann Drillet, Edmée Durand, Michèle Fabardines, Isabel Garcia Hermosa, Cédric Giordan, Elodie Gutknecht, Fabrice Hernandez, Stéphane Law Chune, Pierre-Yves Le Traon, Jean-Michel Lellouche, Bruno Levier, Angelique Melet, Dominique Obaton, Julien Paul, Mathieu Peltier, Diane Peyrot, Elizabeth Rémy, Karina von Schuckmann, and Cécile Thomas-Courcoux

MetOcean Mercator Océan, Ramonville St Agne, France

The Copernicus Marine Environment Monitoring Service (CMEMS; http://marine.copernicus.eu) is one of the six services of the European Copernicus Programme for Earth Observation (http://www.copernicus.eu). CMEMS was implemented by Mercator Ocean beginning in 2014, under a delegation agreement from the European Commission. The operational services of CMEMS were set up gradually as part of a series of European projects, starting 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 the Copernicus Marine Environment Monitoring Service (CMEMS) has required collaboration and innovation across research and technology in observations, modelling, data assimilation, and product and service delivery (Le Traon et al., 2017). There is a growing need for accurate and timely oceanographic information for defense, weather and seasonal forecasts, maritime transports security and routing; and coastal management. Since 2008, the European Union's (EU's) Marine Strategy Framework Directive aims to achieve good environmental status of the EU's marine waters by 2020 and to protect the resource base upon which marine-related economic and social activities depend. This directive ensures that member states put in place the assessment of the marine environment of the European Seas. Cooperation has extended across Europe and into the international community to achieve this aim, and also in support of the sustainable development of downstream economic activity based on the exploitation of marine resources (energy, food, oil and minerals, health, and tourism), often called "Blue Growth" or the "Blue Economy."

Drévillon, M., et al., 2018: Learning about Copernicus Marine Environment Monitoring Service "CMEMS": A practical introduction to the use of the European operational oceanography service. In "*New Frontiers in Operational Oceanography*", E. Chassignet, A. Pascual, J. Tintoré, and J. Verron, Eds., GODAE OceanView, 695-712, doi:10.17125/gov2018.ch25.

In order to stimulate Blue Economy innovation and progress, CMEMS provides open, free, regular, and systematic reference information on the physical state, variability, and dynamics of the ocean, sea ice, and marine ecosystems for the global ocean and the European regional seas. This capacity encompasses the description of the current ocean state (analysis), the variability at different spatial and temporal scales, the prediction of the ocean state 10 days ahead (forecast), and the provision of consistent retrospective data records for recent years (reprocessing and reanalysis).

After a short description of CMEMS services, we will illustrate the benefit of CMEMS operational oceanography products through a selection of use cases. Scientific collaboration is an important asset of CMEMS, in particular through validation and Ocean State Reporting activities, which we will explain in the third section of this chapter. In the fourth section, we will briefly address how the calls for tenders entitled service evolution and user uptake guarantee the connection of CMEMS with the research community and with the future needs in operational oceanography. We will reference training materials currently available from CMEMS in the fifth section and we will describe the "hands-on CMEMS" tutorial given during the GODAE international school "New Frontier in Operational Oceanography," with a focus on the main take-home-messages to be derived from this tutorial.

Open, Free, and Easy Access to a European Operational Oceanography Service

A vast portfolio of physical and biogeochemical ocean variables is available for download from marine.copernicus.eu, as summarized in Table 25.1. Fourteen different parameters are estimated by both observations and, except for winds, ocean models (most of them assimilating these observations). They are produced, quality controlled, updated, and delivered daily on several platforms (ftp, subsetter, and direct getfile).

As shown in Fig. 25.1, CMEMS relies on a central product management system (the Central Information System) as well as on production centres for observations (Thematic Assembly Centres – TACs) and modelling/assimilation (Monitoring and Forecasting Centres – MFCs). The TACs gather observational data and generate elaborate products (e.g., multi-sensor and gridded observational products) derived from these observations. The TACs are fed data by the operators of the space and in situ observational infrastructure. The global MFC and six regional MFCs generate model-based analyses, reanalyses, and forecasts of the ocean physical state and biogeochemical characteristics. The six regional MFCs take advantage of regional modelling advances for the European seas (i.e., the better description of the physical and biogeochemical local processes, higher resolution). The Central Information System is in charge of the management and organization of CMEMS information and products, as well as a unique user interface. Under Mercator Ocean's coordination, the TACs and MFCs meet at least once a year during CMEMS operation reviews, and their scientific experts collaborate on a regular basis around the definition of quality control procedures and around the development of ocean monitoring activities. Additionally, TACs and MFCs share knowledge to support the development of models and data assimilation techniques (in particular for biogeochemistry) and for the assimilation of new types of observations.

PARAMETER	MODEL			SATELLITE		IN SITU	
	20 years in the past	Today	10-day forecast	20 years in the past	Today	20 years in the past	Today
Sea Surface Height	X	X	X	X	X	X	X
Temperature	X	X	X	X	X	X	X
Salinity	X	X	X			X	X
Waves	X	X	X				
Currents/velocity	X	X	X	X	X	X	X
Mixed Layer Depth	X	X	X			X	X
Sea ice	X	X	X	X	X		
Turbidity/Transparency				X	X		
Reflectance				X	X		
Nutrients	X	X	X			X	
Primary Production	X	X	X			X	
Oxygen	X	X	X			X	
Plankton	X	X	X			X	
Wind				X	X		

Table 25.1. Summary of (global or regional) ocean parameters available from the CMEMS portfolio. The online catalogue available at marine.copernicus.eu provides information on the contents and scientific qualification of each product.

CMEMS evolves continuously using a rigorous change management process in order to maintain state-of-the-art services and to answer requirements from its users. Short-term (< 1 year) R&D and part of the mid-term R&D (1 to 3 years) are carried out by CMEMS production centres. Longer-term R&D is fostered by service evolution calls for tenders, and user uptake calls for tenders build dedicated collaborations with users and efficient feedback on future needs (see section below).

CMEMS is distributed across Europe. Each TAC and MFC is led by a different institute, and most of them rely on consortiums of pan-European companies, including oceanographic research laboratories, marine environment monitoring institutes, meteorological agencies, or IT companies.

Some of them provide R&D while others produce observational products, analyses or forecasts, and others provide IT services. All companies involved in CMEMS are listed in the Appendix.

CMEMS' operational oceanography community continually faces scientific and technical challenges in order to improve the products for users, starting with the increase of spatial and temporal resolution of the products. Other challenging evolutions of the catalogue in the coming years are the dissemination of reliable ocean monitoring indicators close to real time such as regionally averaged heat content time series or pH time series, new observational products for surface currents (satellite, high frequency radars), and in situ biogeochemical measurements. Big data technologies and new visualization tools are also being utilized for the future versions of viewing and downloading capabilities.

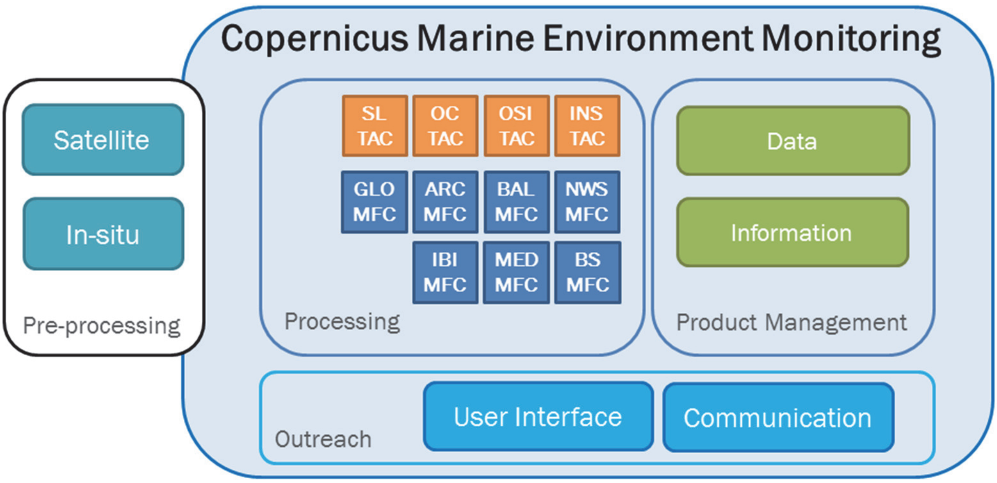

Figure 25.1. Schematic of the CMEMS organization in 2017. The products use satellite and in situ upstream data, they are produced and disseminated by four TACs (satellite sea level –SL TAC-, In situ observations –INS TAC-, satellite Ocean Colour –OC TAC-, and satellite SST, Sea Ice, and Winds -OSI TAC-) and seven MFCs (Global Ocean –GLO MFC-, Arctic Ocean –ARC MFC-, Baltic Sea –BAL MFC-, North Western Shelves –NWS MFC-, Iberian Biscay Ireland –IBI MFC-, Mediterranean Sea –MED MFC-, Black Sea –BS MFC-). The CMEMS is managed (administration, product management) and coordinated (technical and scientific coordination, outreach) by Mercator Ocean.

Use Cases

Copernicus services are designed to stimulate and facilitate the development of innovative downstream applications that produce effective economical value and societal benefit. Use cases are available online and are a good communication tool to demonstrate how CMEMS open data is used within the CMEMS community of users. CMEMS data serve many marine applications that can be broken up into four categories: Coastal & Marine Environment; Marine Resources; Maritime Safety; and Weather, Climate & Seasonal Forecasting.

Use cases highlight the use of CMEMS data by a large panel of users including scientific institutions, governments, European agencies and business. The CMEMS use cases web page[1]

[1] http://marine.copernicus.eu/markets

advertises many applications developed in various countries. Use cases are developed into factsheets that advertise how users transform CMEMS data to create the Blue Economy. Use case factsheets highlight the work of users and their organization.

All users can visit the CMEMS use case website, see examples, and learn more about the domains where CMEMS open data can be applied. Users can also submit their own use cases and fill out a short form with details of how they have used CMEMS data. A PDF will automatically be generated (after a validation process) that can then be downloaded by the user to share. CMEMS also employs these use cases for promotion during its various events and among its stakeholders, including the European Commission.

Moreover, CMEMS invites its users to many events where they can testify about how CMEMS data are useful for their applications and where they can express their requirements and provide feedback to drive CMEMS service evolution. Many users' feedback focuses on the added value of an open and free service for observations and model estimates available from a single website. The accuracy of CMEMS ocean model products in general, and the reliability and timeliness of their delivery, is also very important for many users of near real-time products.


COPERNICUS MARINE SERVICE | USE CASES
Version 1.0

MET-OCEAN STUDIES AND KEY ENVIRONMENTAL PARAMETERS FOR FLOATING OFFSHORE WIND TECHNOLOGY

NOVELTIS

USE CASE OVERVIEW

Floating wind turbines are an up-and-coming technology that can be installed in deeper and very windy water far from the shore. French Mediterranean coast is particularly well suited to the development of this renewable offshore energy source. In 2016, the French government has selected a pilot floating wind farm project called EFGL (Eoliennes Flottantes du Golfe du Lion), conducted by joint venture comprised of ENGIE, EDP Renewables, Caisse des Dépôts, Eiffage, Principle Power and GE. Located 16 km off the coast of Leucate and Le Barcarès, EFGL project includes 4 GE Haliade TM 150-6MW turbines with semisubmersible floaters designed by Principle Power (Aix-en-Provence) and built by Eiffage Métal (Fos-sur-Mer). NOVELTIS, a private service company in oceanography contracted by ENGIE will perform the metocean study and define environmental parameters at the wind farm location for offshore site characterization. These inputs are required for both engineering and environmental studies. NOVELTIS uses CMEMS ocean model temperature and salinity from 1955 up to 2015 to build a statistical analysis of the oceanic circulation patterns of the area.

BENEFITS FOR USER

- Free and sustained information provision.
- Ready to use, global coverage, expertised ocean products.

- NOVELTIS - MARINE RENEWABLE ENERGY - FLOATING OFFSHORE WIND TECHNOLOGY - GREEN ELECTRICITY - METOCEAN STUDY - ENVIRONMENTAL PARAMETERS

COASTAL & MARINE ENVIRONMENT

Implemented by

COPERNICUS MARINE SERVICE | USE CASES
Version 1.0

FACTS AND KEY NUMBERS

Marine renewable energy is rapidly being developed to help meet Europe energy needs and reduce its fossil fuel footprint. Several technologies have emerged to harness the energy of the seas. The Copernicus Marine Service ocean models provide key input for such technologies, as they can be used to estimate the ocean energy resources available, to help minimize the risks for operations at sea and to provide key environmental parameters typically associated with metocean studies.

CMEMS PRODUCT IN USE

CMEMS Mediterranean Sea reanalysis model provides 3D ocean temperature and salinity in the past starting in 1955 up to now. These environmental parameters are typically associated with metocean studies required by floating offshore wind projects.

Product in use 1

CMEMS USER

Noveltis is an innovative private company serving the space, environment and sustainable development. It offer services of scientific engineering, studies, and implementation of tailor-made operational solutions. it develops high-tech solutions that combine strong physical and environmental expertise in the fields of atmosphere, ocean and land.

Les éoliennes flottantes du golfe du Lion

More information here

Contact
Jeliazovski Florian
Florian.jeliazovski@noveltis.fr

www.noveltis.com/

COASTAL & MARINE ENVIRONMENT

COPERNICUS MARINE SERVICE
Any question, please contact
communication@mercator-ocean.fr
http://marine.copernicus.eu/

Figure 25.2. Example of a use case summary that can be downloaded as a PDF from CMEMS webpage, here for offshore wind farms in the Mediterranean Sea.

Among the many use cases displayed on the CMEMS webpage, we briefly highlight three examples:

- OCEAN ENERGY: Several technologies have emerged to harness the energy of the seas (see Fig. 25.2 the example of the floating wind farm). The CMEMS ocean models provide key input to estimate the ocean energy resources, minimize the risks and help with the mandatory environmental monitoring of offshore sites[2].

- SHIP ROUTING: Ship routing allows maritime shipping companies to reduce fleet navigation risks, save fuel and reduce CO2 emissions. The CMEMS products provide input conditions for ship routing software for safer navigation routes including ice covered areas[3].
- SUSTAINABLE FISHERY MANAGEMENT: A new sustainable strategy for fisheries is becoming possible thanks to numerical modelling of the marine ecosystem and its food chain from small organisms to top predators. The CMEMS products are used in modelling of fish habitats[4].

A Community of Scientists

Products quality monitoring

One of the major objectives of CMEMS is to deliver useful scientific quality information, such as reliability of the forecasts, accuracy of the analyses, quality control of the observations, etc. Moreover, this quality information has to be scientifically sound and as consistent as possible across the variety of products that CMEMS delivers. Validation is usually two-fold: 1) new products have to be validated prior to their entry into service (operational delivery to users) and their quality communicated effectively to users; and 2) the operational products' quality has to be checked routinely in order to ensure that the quality standards are met. In CMEMS, the TACs and MFCs validate all their products following a well-defined protocol. The validation is mostly based on the verification of the distribution, mean, and mean square of the differences between CMEMS products and reference datasets. Deviations between climatologies and observations are used for the control of observations, while differences between observations (or observational products) and their model counterparts are used for the control of model outputs. The scales and processes represented by either models or observational products must be taken into account when producing this verification, and observation operators (as in data assimilation) usually have to be applied to model outputs, for instance daily averages of the models sea surface temperature are performed before comparing to OSTIA (Operational Sea Surface Temperature and Sea Ice Analysis) daily sea surface temperature products. Estimated accuracy numbers are derived from these verifications. Currently, for model products these numbers are based on root-mean-square (RMS) departures between models and observations—and will probably evolve towards scatter index RMS/mean in the future—while for observations, those accuracy numbers rely on comparisons with climatologies or on upstream observations availability. The estimated accuracy numbers provide indicators of the

[2] http://marine.copernicus.eu/wp-content/uploads/use-cases/environmental-monitoring-offshore-wind-farm-offshore-leucate-mediterranean-sea.pdf
[3] http://marine.copernicus.eu/wp-content/uploads/use-cases/ship-routing-save-fuel-reduce-co2-emissions.pdf
[4] http://marine.copernicus.eu/wp-content/uploads/use-cases/supporting-jrc-eu-common-fisheries-policy-cfp-1.0.pdf

average quality level expected over basin scale areas. These statistics and their history are published on a central webpage, which is updated quarterly. Reference values computed on a long period are available in the Product Quality Information Documents (QuIDs) associated with each product, together with a summary of the quality of the product.

The evolution of the CMEMS validation protocol is coordinated by Mercator Ocean and relies on a product quality working group involving experts from all production centres (TACs and MFCs). This group aims at developing validation metrics and associated validation capabilities, and is also making the link with state-of-the-art validation practices and international standards and metrics, such as those defined by MERSEA (Crosnier and Le Provost, 1997) and GODAE OceanView (Hernandez et al., 2015, 2018 this book). In particular, the CLASS4 approach for the computation of the analysis error and of the forecast error in the observation space (at the time and spatial location of the observation), which allows deriving skill scores, was adopted as a standard by the MERSEA project. The product quality working group gathers scientists with various backgrounds (observations or models, in situ or satellite, global or regional) and each participant has the opportunity to share his/her own expertise by proposing dedicated metrics for specific variable and/or region of interest.

Following results obtained by this group of experts, categorical and site-specific metrics, as well as specific biogeochemistry metrics (Maksymczuk, 2016) will be implemented in the future. User feedback also provides indirect quality measurements—external qualification—through the evaluation of the CMEMS products for specific applications. The latter approach will be encouraged and developed in the future.

Ocean state monitoring and reporting

One of the main requirements from CMEMS users is to have long time series of data that can be used to produce a statistical and quality reference framework for their applications. CMEMS ensures 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, organizing their interoperability, their inter-dependencies, and joint operations closer to real time (a few months only) with a systematic yearly update. CMEMS reprocessing aims at an optimal use of high-resolution input data and at a seamless connection with CMEMS real-time observations. CMEMS reanalyses aim at a seamless connection with CMEMS real-time analyses and forecast, thus CMEMS produces regional reanalyses that benefit from both high-resolution and specific regional tunings. Specific efforts are made on the processing of sea ice and biogeochemistry components for all CMEMS reanalyses, global and regional. To reach those ambitious objectives, the coordination of the production of multi-year products was set up at the beginning of CMEMS and a working group of reanalysis and reprocessing experts from each production centre has been created. The other responsibility of this group is to coordinate the ocean state reporting activities. In the context of the Marine Strategy Framework Directive, environmental agencies require ocean state and marine environment monitoring. This is achieved through the annual release of the CMEMS Ocean State Report to monitor and describe ocean variability and change from the past to present, and through the development of operational ocean monitoring indicators (OMIs), and related error bars. The OMIs are an ensemble of average or integrated quantities describing the state and evolution of the oceanic environment, such as heat content, sea level rise, sea ice extent, and pH. These developments must rely on continuous and high-quality time series from reanalyses and reprocessed observations, which go up to real time and which ensure high-resolution coverage of the European regional seas (e.g., those implemented by CMEMS). The OMIs can be downloaded from the CMEMS website, together with a short scientific context description and a dedicated QuID.

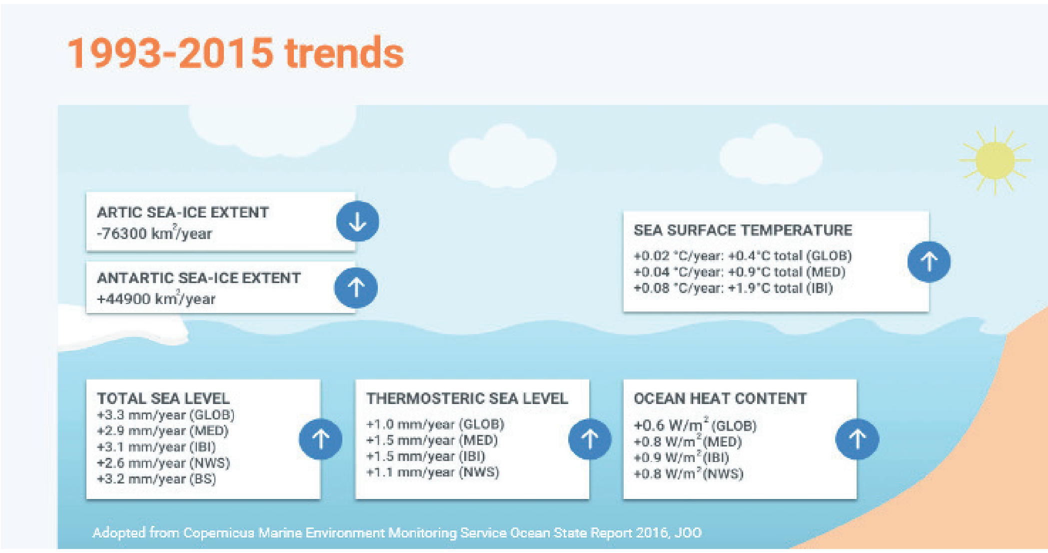

Figure 25.3. Summary of major ocean trends reported in the Ocean State Report #1 von Schuckmann et al. (2016). See also http://marine.copernicus.eu/wp-content/uploads/2017/03/Ocean-State-Report-Summary.pdf

The CMEMS Ocean State Report provides a comprehensive and advanced 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 (EEA) and international organizations (e.g., the Intergovernmental Panel on Climate Change, 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 analyses and provides a four-dimensional view (reanalysis systems) from above (through remote sensing data) and directly from the interior (through in situ measurements) of the blue (e.g., hydrography, currents), white (e.g., sea ice) and green (e.g., chlorophyll) global ocean and European regional seas. The first issue was prepared in collaboration with ~80 scientists involved in CMEMS. It provides information on the physical ocean state and change over the period 1993–2015 and has been published in the *Journal of Operational Oceanography*. The first issue reports on a number of trends (Fig. 25.3), including decreasing Arctic and increasing Antarctic sea ice extent, global and regional sea level rise, sea surface temperature rise, and the warming of the global and European regional seas[5].

[5] http://marine.copernicus.eu/science-learning/ocean-state-report/ocean-state-report-2016-1st-issue/

The second issue was accepted for publication in April 2018 and highlights changes in the marine environment for the period 1993–2016 as well as specific remarkable events during the year 2016. Most diagnostics from this second issue will be implemented as OMIs on CMEMS website, and subsequent issues of the Ocean State Report will serve as a peer-reviewed platform for the definition and acceptance of new OMIs. Future issues will include additional essential variables, not yet published in previous issues, describing changes in ocean climate at global and regional scale. Strong efforts are put on monitoring biogeochemical changes, improving progressively the accuracy and uncertainty assessment for biogeochemical OMIs, with a specific focus on European regional seas.

New Frontiers in CMEMS

Mid-term and long-term R&D activities are mainly addressed through calls for tenders for CMEMS service evolution and through external programmes (e.g., Horizon 2020 and national R&D programmes). Long-term R&D activities, although implemented in those external programmes, are as crucial for the sustainable evolution of the service as short- and mid-term activities led at the CMEMS production centre level. High level strategy documents for CMEMS service evolution[6], as well as for product quality and multi-year products coordination, were prepared by Mercator Ocean and the Scientific and Technical Advisory Committee of CMEMS. The service evolution strategy document describes four key areas of innovation and research: ocean circulation, ocean-wave and ocean-ice coupling; biogeochemistry and ecosystems in the marine environment; coastal environment; and ocean, atmosphere and climate. Regarding the last key area “ocean, atmosphere and climate,” high-level interactions are established with the Copernicus Climate Change Service (C3S), which is in charge of providing global climate change scenarios and developing earth system models including all components of the climate system. The CMEMS focuses on complementary high-resolution ocean models and observations, including scenarios of the regional/coastal impacts of climate change on the marine environment. At the mid- to long-term planning scales, making innovations in the four key areas will require overcoming the following challenges: very high-resolution (kilometric) modelling for ocean and sea ice, including tides, coupling of wave and ocean circulation, with data assimilation; improvement of biogeochemical products and their assessment, including the data assimilation of ocean colour observations and bio-Argo profiles, and in the longer term modelling of higher trophic levels; ocean, waves and atmosphere coupling for improved ocean analyses and forecasts; improved satellite products [higher resolution, new sensors such as SMOS (Soil Moisture Ocean Salinity) or Sentinel missions], and new in situ data for coastal areas, river inputs, stronger links with downstream coastal systems; longer reanalyses time series, seasonal/decadal/climate projections and on the longer-term downscaled scenarios including impacts on the ecosystems and coastal environment. There will also be challenges to improving the CMEMS system such as improving the access to Sentinel data and all Copernicus Services through technological advances such as DIAS (Data and Information Access Services) platforms. A more

[6] http://marine.copernicus.eu/science-learning/service-evolution/service-evolution-strategy/

detailed description of each of these research topics and how they will be addressed with mid-term or long-term objectives can be found in the "CMEMS Service Evolution strategy: R&D priorities" document, available online.[7]

CMEMS will have to keep up with technological advances and to implement the service upgrades or changes expected by users, while also keeping them explicitly involved, to evolve together with the downstream sector to provide the level of service expected by EU member states and other national users, for instance. The user uptake calls for tenders intend to build privileged relationships with a series of users in order to help them evolve towards the use of CMEMS core products, but also to answer to the growing need for cooperation with downstream users in the mid- to long-term.

A Series of Practical Tools to Introduce CMEMS

As part of CMEMS, expert information on products and their quality, as well as outreach documentation, is continuously improved upon thanks to dedicated communication activities, exchanges in between TACs and MFCs production centers, and user feedback. Focused tutorials[8] are available on the CMEMS website, which provide scientific or technical assistance to both beginner and advanced users on the CMEMS portfolio and access to service.

In-person training sessions and user workshops are also regularly organized by CMEMS. Practical trainings were developed using Jupyter notebooks, which allows interactive navigation into Python scripts developed for downloading and handling data files[9].

For instance, the "Global Ocean Week," which took place in October 2016, included a training session co-sponsored by Mercator Ocean as leader of CMEMS Global Monitoring and Forecasting Centre and the COST Action "Evaluation of Ocean Syntheses"[10]. Keynote lectures on ocean reanalyses evaluation were filmed[11]. In this context, several practical exercises were also prepared, introducing the core scientific activities of global ocean forecasters, from the design of the analysis system to its validation. Specific attention was paid to ocean variability monitoring capacities thanks to ocean reanalyses. Based on this material, a tutorial called "Hands on CMEMS" was proposed during the 2017 GODAE-OceanView international school, "New frontiers in operational oceanography." This tutorial from the Global MFC uses Jupyter notebooks and will be available for download on the marine.copernicus.eu website together with Jupyter notebooks developed by other TACs and MFCs. It allows interactive evaluation of several CMEMS reanalyses, with Python and Ferret routines, as used by ocean reanalysis producers to explore their experiments. It provides practical illustrations of the main strengths and weaknesses of ocean reanalyses. In the following section, we will explore the three different themes developed in the hands-on CMEMS tutorial: the

[7] http://marine.copernicus.eu/wp-content/uploads/2017/06/CMEMS-Service_evolution_strategy_RD_priorities_V3-final.pdf
[8] http://marine.copernicus.eu/training/online-tutorials/
[9] See for instance the In-situ TAC training (http://marineinsitu.eu/material)
[10] http://eos-cost.eu
[11] available on YouTube (search COST-EOS training or CMEMS training)

balance between statistical and physical processes analysis when evaluating reanalyses; the importance of the atmospheric boundary, forced or coupled, and its resolution; and the impact of changes in the observations network onto the quality of the reanalysis.

A view on the ocean: the statistical view or the physical view?

CMEMS reanalyses are global as well as regional. Their aim is providing reference data over the last decades using optimal resolution and observations coverage, and using an analysis system consistent with the one producing real-time analyses and forecasts. Regional reanalyses usually benefit either from better physics, from a model configuration specifically tuned for the region of interest, and/or from higher resolution. The IBIRYS reanalysis at 1/12° for the Iberian Biscay Ireland area is developed at Mercator Ocean, as well as the GLORYS global reanalysis at ¼°. Both reanalyses are based on the NEMO model and the SAM2 data assimilation system (Lellouche et al., 2013) and are forced with ERA-Interim atmospheric reanalysis, but their physics and resolution are different. For instance, IBIRYS explicitly resolves tides and benefits from variable volume-free surface and a state-of-the-art mixing scheme consistent with the near real-time Iberian-Biscay-Ireland (IBI) monitoring and forecasting system (Maraldi et al., 2013).

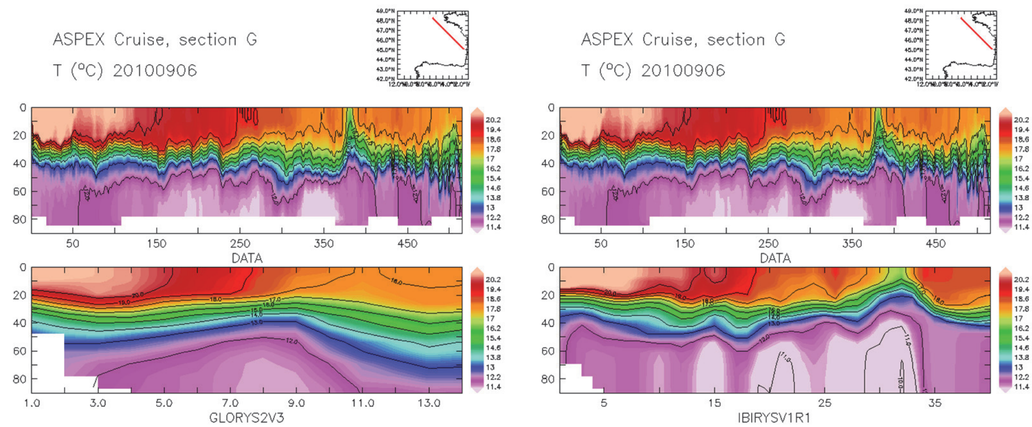

Figure 25.4. Illustration from Tutorial Hands on CMEMS #1 “A view on the ocean: the statistical view or the physical view?” The regional high-resolution model (IBIRYS) produces a better stratification compared to the global model with a low resolution (GLORYS) and using data of the Aspex campaign as a reference (courtesy of L. Marie; Ifremer, from ASPEX3 cruise).

In the first part of the tutorial, we compare GLORYS and IBIRYS with a series of standard GODAE metrics, at the time and location of available in situ observations. Statistical comparisons (CLASS4 type) and analysis of the physical processes (CLASS1 eyeball validation, for instance Fig. 25.4.) are complementary techniques used to explore the differences between the two experiments and highlight the added value of IBIRYS with respect to GLORYS. It is particularly important to consider scales and representativity of both observations and models when evaluating high-resolution model products in respect to coarser ones. The high-resolution models produce small-scale features that may be shifted in space or time with respect to observations, inducing higher RMS errors. These small scales are not present in coarser models, which will give smoother statistics but will not be as realistic in terms of dynamics. For this reason, standard deviations from observations may not be significantly improved in higher-resolution models with respect to coarser ones. A complementary look at physical processes and scales shows the interest of dynamical solution of the high-resolution model. The benefit of high-resolution biogeochemistry models is shown in the second part of the tutorial, comparing model outputs with CMEMS Ocean Colour and sea surface temperature observations.

Finally, this tutorial stresses the need for higher-resolution observations in order to constrain small scales in high-resolution models, as well as the improvement expected on the short term from operational assimilation of biogeochemistry observations. Another mid-term challenge, for the IBI analysis system in particular, is to constrain tidal signal with data assimilation.

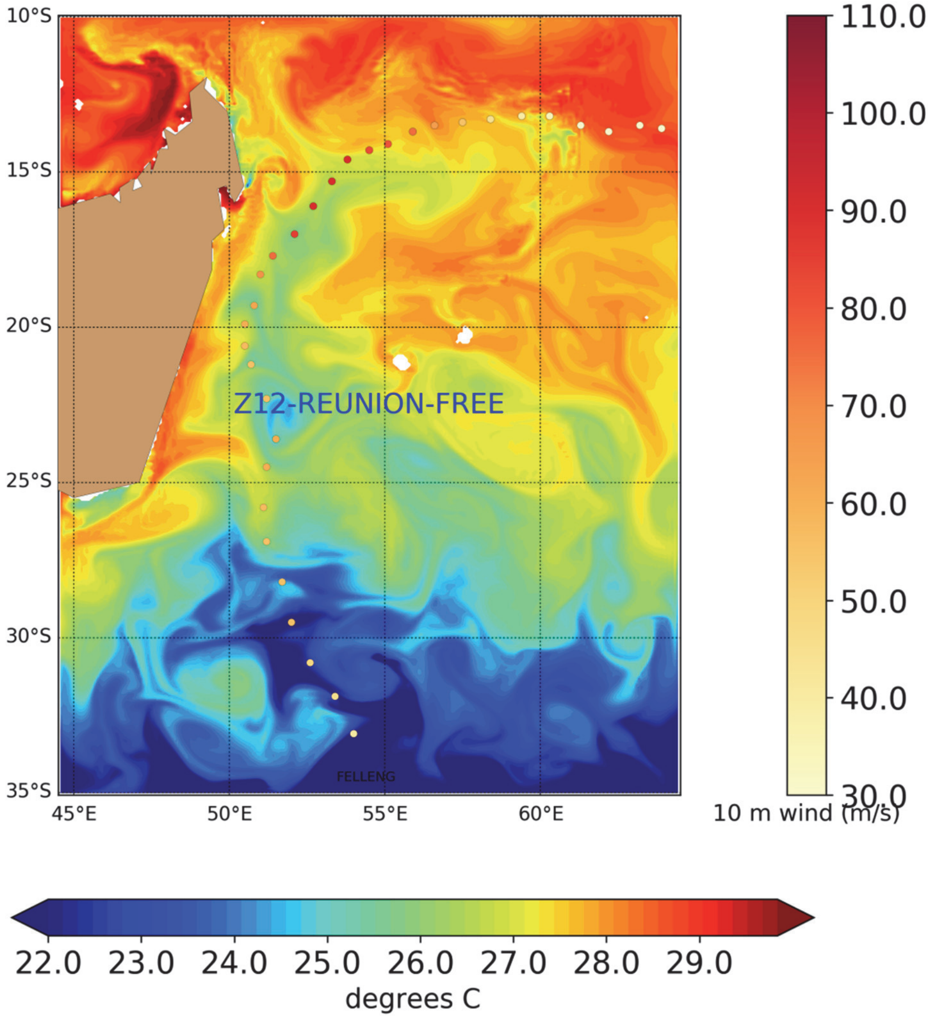

Figure 25.5. Illustration from Tutorial Hands on CMEMS #2 « Sail the global ocean: at the interface with the atmosphere”, showing the signature of the Felleng cyclone (2013/02/04) on the sea surface temperature (°C) of a model zoom at 1/12° embedded in the GLORYS reanalysis. The observed wind velocity (m/s) of the cyclone is reported inside color dots showing the track of the cyclone from north to south.

Sail the global ocean: at the interface with the atmosphere

At the surface of the ocean, the accuracy of currents, temperature, and salinity strongly depends on the accuracy of the atmospheric forcing. Ocean reanalyses are often forced with atmospheric reanalyses. Most CMEMS reanalyses use ECMWF ERAInterim forcing (Dee et al., 2011). One known limitation of this forcing is the underestimation of cyclonic winds. In this tutorial, we look at the oceanic impact of the Felleng cyclone, which ran along the coasts of La Reunion Island in January-February 2013 (Fig. 25.5). We compare the global reanalysis GLORYS at ¼° (forced with ERA Interim) with the near real-time CMEMS global ocean analyses at 1/12°, which are forced with near real-time atmospheric forcings from ECMWF (with realistic cyclonic winds amplitude). We also look at the outputs of a nested NEMO configuration at higher resolution (1/12°), with updated physics but no data assimilation, embedded into GLORYS and forced with near real-time atmospheric forcings from ECMWF. This tutorial shows how downscaling is not only about improving the resolution, but also allows users to add the missing physical parameterizations in order to correctly capture oceanic phenomena. This tutorial also demonstrates that ocean atmosphere coupling at the global scale or using a downscaling approach is a major research topic for cyclone forecasting activities.

In the second part of this tutorial, we run the ARIANE software (Blanke and Raynaud, 1997, see also Beuvier et al., 2012 for a use case example) to compute water particles trajectories using CMEMS surface currents in the Indonesian Throughflow area. The spread of Lagrangian trajectories after a few days illustrates the importance of improving the quality of small-scale representation. Currently, the forecast skill is low after one or two days. Improvement is expected in the coming years thanks to data assimilation of current observations and high-resolution observations.

Dive into a 3D virtual ocean: in between observations and model solution

Three-dimensional (3D) ocean analyses produced in near real-time, thanks to models and data assimilation of ocean observations, provide gridded and dynamically consistent 3D estimates of the ocean variables. Ocean *re*-analyses use comparable model plus data assimilation systems (although often with coarser horizontal resolution), but they use re-analysed atmospheric forcings, better quality-controlled input ocean observations, and aim at providing four-dimensional views of the state of the ocean over the last decades, as homogeneous as possible in space and time. These tools are powerful and very useful for a variety of applications, especially because they provide estimates when and where no observations are available. By construction, the quality of ocean analyses and re-analyses should be lower when and where there is a lack of observations; but also, because of this lack of observations, there are often no means to quantify properly the uncertainty.

Interannual variability in the Leeuwin Current along the western coast of Australia is strongly linked with the El Nino Southern Oscillation (Feng et al., 2013), and the Leeuwin Current experiences a strong seasonal cycle that is well captured by altimetry (Ridgway and Godfrey, 2015). In the first part of this tutorial, we quantify with a few simple metrics how data assimilation modifies the 3D solution, first looking at the variability in the ocean (interannual and seasonal variability) and then comparing that to independent results from the literature.

In the second part of the tutorial, we inter-compare a series of sensitivity experiments where only the altimetry assimilation changes. These Observing System Experiments (OSEs; Oke et al., 2015a, 2015b, Lea et al., 2014, Turpin et al., 2016) were performed with an eddy-permitting-resolution analysis system for the Atlantic Ocean and Mediterranean Sea (20°S-70°N) assimilating sea surface temperature, in-situ temperature and salinity profiles, and sea level anomalies. The number of altimeters considered for data assimilation varies from zero to three, and the user observes how the increase in assimilated data improves the overall solution (Fig. 25.6). This is confirmed by Observing System Simulation Experiments (OSSE; Verrier et al., 2017), which allow testing observing network configurations using synthetic observations from a model as assimilated observations. We explore some of the limitations of data assimilation and stress the need for a sustainable observation network filling the gaps of unexplored oceanic areas or phenomena (higher-resolution observations such as SWOT, observations of the deep ocean such as Deep Argo, biogeochemical observations such as Bio Argo).

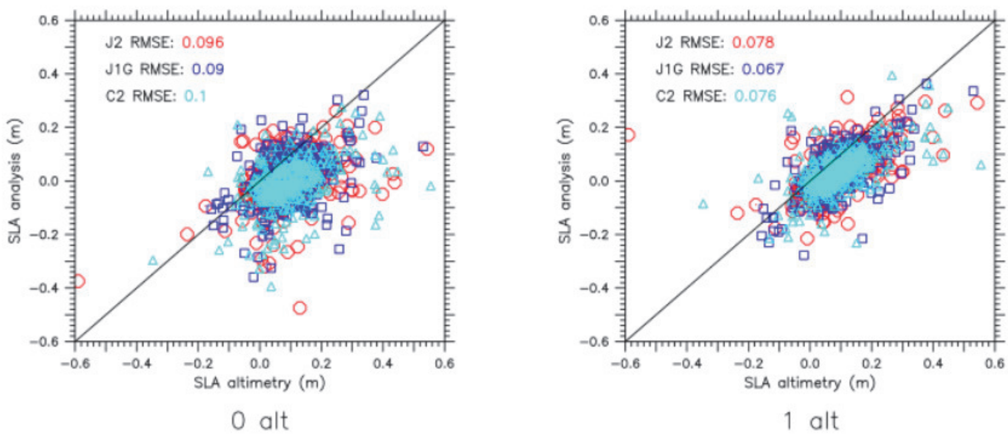

Figure 25.6. Illustration from Tutorial Hands on CMEMS #3 "Dive into a three-dimensional virtual ocean: in between observations and model solution" showing how the assimilation of observations from one altimeter improve the statistics with respect to all altimeters.

Conclusion

The Copernicus Marine Service reaches the end of its first phase in 2017, and it is an achievement of European Operational Oceanography. It currently provides observations, analyses, and forecasts of the ocean, reanalyses, and reprocessing of observations, as well as regular reports on the state of the ocean. Last, but not least, it is a *service* and it is organized around its users. CMEMS is about helping the users of operational oceanography and training them, but also about knowing the users and noting their needs and collecting feedback. The Copernicus Marine Service is also an investment of the European Commission to stimulate the Blue Economy and foster innovative downstream activities. The main challenges for the future will be to improve the uptake of the products and the interaction with coastal users, and to utilize big data capabilities to improve the service. The scientific challenges will be to increase the resolution of the products (observations and models), while also improving the representation of the interactions between the ocean, the sea ice, the waves, and the atmosphere in the models. Documentation and tutorials about CMEMS are referenced that can provide a practical view on the scientific content of operational oceanography products, their strengths, and current limitations. Useful and practical tutorials to ease the download and handling of CMEMS data are also referenced. The hands-on CMEMS tutorial helps users understand the strengths and weaknesses of ocean analyses and reanalyses, and what will be the major sources of improvement in the future (higher-resolution observations, sustainable ocean observing network, higher-resolution models with better physics, improvements of the biogeochemical models, …). Now you can become an actor of the Copernicus Marine service!

Acknowledgments

We thank the authors of Jupyter notebook tutorials from the CMEMS scientific community who kindly agreed to share their notebooks in addition to the ones described in this article: Paz Rotllan (SOCIB, for INS TAC), Pierre Prandi (CLS, for SL TAC), Ben Loveday (PML, for OC TAC), Patrick Raanes (NERSC, for ARC MFC). We also thank the GODAE international school organizers for this very nice opportunity to improve our tutorials. Finally, we warmly thank the students, Jessica Anderson, Barbara Barcelo-Llull, and Theo Baracchini, who reviewed this article, and the anonymous reviewer for their careful reading and very pertinent comments.

References

Beuvier, J., K. Beranger, C. Lebeaupin Brossier, S. Somot, F. Sevault, Y. Drillet, R. Bourdallé-Badie, N. Ferry, and F. Lyard (2012): Spreading of the Western Mediterranean Deep Water after winter 2005: Time scales and deep cyclone transport. *J. Geophys. Res*., **117**, C07022, doi:10.1029/2011JC007679.

Blanke, B., and S. Raynaud (1997), Kinematics of the Pacific Equatorial Undercurrent: An Eulerian and Lagrangian approach from GCM results*, J. Phys. Oceanogr.*, **27(6)**, 1038–1053.

Crosnier, L., & Le Provost, C. (2007): Inter-comparing five forecast operational systems in the North Atlantic and Mediterranean basins: The MERSEA-strand1 Methodology. *Journal of Marine Systems*, **65(1)**, 354-375.

Dee, D. P., Uppala, S. M., Simmons, A. J., Berrisford, P., Poli, P., Kobayashi, S., Andrae, U., Balmaseda, M. A., Balsamo, G., Bauer, P., Bechtold, P., Beljaars, A. C. M., van de Berg, L., Bidlot, J., Bormann, N., Delsol, C., Dragani, R., Fuentes, M., Geer, A. J., Haimberger, L., Healy, S. B., Hersbach, H., Hólm, E. V., Isaksen, L., Kållberg, P., Köhler, M., Matricardi, M., McNally, A. P., Monge-Sanz, B. M., Morcrette, J.-J., Park, B.-K., Peubey, C., de Rosnay, P., Tavolato, C., Thépaut, J.-N., and Vitart, F. (2011): The ERA-Interim reanalysis: configuration and performance of the data assimilation system. *Q.J.R. Meteorol. Soc.*, **137**, 553–597, doi:10.1002/qj.828

Feng, M., McPhaden, M.J., Xie, S. & Hafner, J. (2013) La Nina forces unprecedented Leeuwin Current warming in 2011. *Sci. Rep. 3*, 1277, doi:10.1038/srep01277.

Hernandez F., E. Blockley, G. B. Brassington, F. Davidson, P. Divakaran, M. Drévillon, S. Ishizaki, M. Garcia-Sotillo, P. J. Hogan, P. Lagemaa, B. Levier, M. Martin, A. Mehra, C. Mooers, N. Ferry, A. Ryan, C. Regnier, A. Sellar, G. C. Smith, S. Sofianos, T. Spindler, G. Volpe, J. Wilkin, E. D. Zaron & A. Zhang (2015). Recent progress in performance evaluations and near real-time assessment of operational ocean products. *Journal of Operational Oceanography*, **8(sup2),** s221-s238.

Lea, D. J., Martin, M. J. and Oke, P. R. (2014): Demonstrating the complementarity of observations in an operational ocean forecasting system*. Q.J.R. Meteorol. Soc.,* **140**: 2037–2049. doi:10.1002/qj.2281

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

Le Traon P.Y., A. Ali, E. Alvarez Fanjul, L. Aouf, L. Axell, M. Ballarotta, M. Benkiran, A. Bentamy, L. Bertino, L.A. Breivik, S. Cailleau, N. Mc Connell, G. Coppini, E. O'Dea, M. L. Grégoire, S. Guinehut, C.

Harris, V. Huess, S. Kay, J. de Kloe, G. Korres, F. Dinessen, M. Drevillon, Y. Drillet, Y. Faugère, I. Garcia Hermosa, G. Garric, I. Golbeck, J. Gourrion, J. Johannessen, F. Hernandez, R. King, P. Lagemaa, J.F. Legeais, M. Martin, A. Melet, J. Murawski, E. Özsoy, A. Palazov, E. Peneva, D. Peterson, L. Petit de la Villeon, N. Pinardi, S. Pouliquen, M.I. Pujol, P. Rampal , A. Ryan, A. Samuelsen, A. Saulter, J. She, M. Sotillo, A. Storto, T. Szekely, G. Taburet, M. Tonani, L. Tuomi, D. van Zanten, K. von Schuckmann, E. Stanev, P. Sykes, A. Stoffelen , T. Williams, H. Zuo , J. Xie (2017). The Copernicus Marine Environmental Monitoring Service: Main Scientific Achievements and Future Prospects. *Mercator Ocean Journal,* **56**, https://www.mercator-ocean.fr/en/science-publications/mercator-ocean-journal/mercator-ocean-journal-56-special-issue-cmems/

Maksymczuk J., F. Hernandez, A. Sellar, K. Baetens, M. Drevillon, R. Mahdon, B. Levier, C. Regnier, A. Ryan, (2016), Product Quality Achievements Within MyOcean, *Mercator Ocean Journal* **#54**

Maraldi C., J. Chanut, Bruno Levier, Nadia Ayoub, Pierre De Mey, G. Reffray, Florent Lyard, Sylvain Cailleau, Marie Drévillon, E. Fanjul, M. G. Sotillo, Patrick Marsaleix, and the Mercator Team (2013): NEMO on the shelf: assessment of the Iberia-Biscay-Ireland configuration. *Ocean Science, European Geosciences Union*, 2013, **9**, 745-771

Marie L. (2016) ASPEX8 cruise, RV Thalia, http://dx.doi.org/10.17600/16006500

Oke, P.R., G. Larnicol, Y. Fujii, G.C. Smith, D.J. Lea, S. Guinehut, E. Remy, M. Alonso Balmaseda, T. Rykova, D. Surcel-Colan, M.J. Martin, A.A. Sellar, S. Mulet, V. Turpin. (2015): Assessing the impact of observations on ocean forecasts and reanalyses: Part 1, Global studies. *Journal of Operational Oceanography,* **8**:sup1, s49-s62.

Oke, P.R., G. Larnicol, E.M. Jones, V. Kourafalou, A.K. Sperrevik, F. Carse, C.A.S. Tanajura, B. Mourre, M. Tonani, G.B. Brassington, M. Le Henaff, G.R. Halliwell Jr., R. Atlas, A.M. Moore, C.A. Edwards, M.J. Martin, A.A. Sellar, A. Alvarez, P. De Mey, M. Iskandarani. (2015): Assessing the impact of observations on ocean forecasts and reanalyses: Part 2, Regional applications. *Journal of Operational Oceanography* **8**:sup1, s63-s79.

Verrier, S., Le Traon, P.-Y., and Remy, E. (2017): Assessing the impact of multiple altimeter missions and Argo in a global eddy permitting data assimilation system, *Ocean Sci. Discuss*., doi:10.5194/os-2016-104, in review.

von Schuckmann K., Le Traon P.Y., Alvarez-Fanjul E., Axell L, Balmaseda M., Breivik L.-A., Brewin R.J.W., Bricaud C., Drevillon M., Drillet Y., Dubois C., Embury O., Etienne H., García Sotillo M., Garric G., Gasparin F., Gutknecht E., Guinehut S., Hernandez F., Juza M., Karlson B., Korres G., Legeais J.-F., Levier B., Lien V. S., Morrow R., Notarstefano G., Parent L., Pascual A., Pérez-Gómez B., Perruche C., Pinardi N., Pisano A., Poulain P.-M., Pujol I. M., Raj R.P., Raudsepp U., Roquet H., Samuelsen A., Sathyendranath S., She J., Simoncelli S., Solidoro C., Tinker J., Tintoré J., Viktorsson L., Ablain M., Almroth-Rosell E., Bonaduce A., Clementi E., Cossarini G., Dagneaux Q., Desportes C., Dye S., Fratianni C., Good S., Greiner E., Gourrion J., Hamon M., Holt J., Hyder P., Kennedy J., Manzano-Muñoz F., Melet A., Meyssignac B., Mulet S., Buongiorno Nardelli B., O'Dea E., Olason E., Paulmier A., Pérez-González I., Reid R., Racault M.-F., Raitsos D.E., Ramos A., Sykes P., Szekely T. & Verbrugge N. (2016): The Copernicus Marine Environment Monitoring Service Ocean State Report, *Journal of Operational Oceanography*, **9** , sup2

Ridgway, K. R., and J. S. Godfrey (2015): The source of the Leeuwin Current seasonality, *J. Geophys. Res. Oceans*, **120**, 6843–6864, doi:10.1002/2015JC011049.

Turpin, V., Remy, E., and Le Traon, P. Y. (2016): How essential are Argo observations to constrain a global ocean data assimilation system?, *Ocean Sci.,* **12**, 257-274, doi:10.5194/os-12-257-2016.

Appendix

The Copernicus Marine Thematic Assembly Centres - TACs -

The Copernicus Marine Monitoring and Forecasting Centres - MFCs -