Copernicus Marine Environment Monitoring Service (CMEMS) Service Evolution Strategy: R&D priorities

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1. Introduction

The Copernicus Marine Environment Monitoring Service (CMEMS) provides regular and systematic reference information on the physical state, variability and dynamics of the ocean 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 a few days ahead (forecast), and the provision of consistent retrospective data records for recent years (re-analysis). 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, (iv) weather, seasonal forecast and climate. A major objective of the CMEMS is to deliver and maintain a competitive and 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.

A Delegation Agreement¹ has been signed between the European Commission and Mercator Ocean for the CMEMS implementation; it mandates the development and maintenance of a Service Evolution Strategy in order to respond to new needs and also improved methodologies. This strategy is the mechanism by which lessons and knowledge derived during the first phase, as well as new research results, are used to guide change and/or a potential service upgrade in the subsequent phases.

The Service Evolution Strategy will be maintained on the basis of feedback from users together with scientific and technical gap analysis of emerging and existing user requirements as well as the potential to improve the Core Service elements. At the same time, the Service Evolution Strategy can identify potential research needs that can guide external (e.g. H2020) and internal (CMEMS) R&D priorities. Consistent updates of the Service Evolution Strategy and its R&D priorities will be made on an annual basis.

A first R&D roadmap was defined in 2010 in the MyOcean framework, with four key challenges identified that shaped the R&D effort during the period 2010-2015: Challenge #1: seamless modelling from open ocean to regional seas; Challenge #2: coupling with sea-ice, rivers, atmosphere & waves, biology; Challenge #3: intertwining models with observations; and Challenge #4: verification, validation, uncertainty estimates. The MyOcean projects enabled very significant progress and successful achievements that were necessary to establish the scientific basis for the operational service which is in place today.

In order to ensure long-term sustainability of the CMEMS during the next years, a new strategy is required that will benefit from recommendations of the MyOcean community after 10 years of achievements. This strategy will define the key R&D activities required for the evolution of the service.

This document is intended to identify priorities for Science and Technological (S&T) developments that are needed to ensure optimal evolution of CMEMS during the next 3-6 years. Different categories of activities will have to be conducted, with different time horizons, players and objectives:

- long-term objectives (beyond 2 years up to ~10 years) corresponding to the long-term evolution of the CMEMS framework;
- mid-term objectives (1 – 2 year cycle) addressed by dedicated R&D working groups, for implementing and assessing major scientific upgrades of the service during Phase-I (2015-2018) and mostly Phase-II (2018-2021) (see technical annex of the Delegation Agreement);
- short-term activities (several months to 1 year cycle) for addressing issues requiring fast responses for rapid implementation within the existing phases of CMEMS.

The short and mid-term activities will be addressed both through internal CMEMS activities and R&D calls for tenders, while long-term activities will be promoted in the framework of external projects

(e.g. Horizon 2020 or other European 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 mi-term activities for the sustainable evolution of the Service.

2. Scientific and technical backbone of CMEMS

The backbone of the CMEMS relies on an architecture of production centers inherited from the MyOcean projects both for observations (Thematic Assembly Centers – TACs) and modelling/assimilation (Monitoring and Forecasting Centers – MFCs) and a Central Information System (CIS).

- **Four Thematic Assembly Centres (TACs)**, including three “space” TACs organized by ocean variables (sea surface topography, ocean colour, and sea surface temperature plus 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; the detailed operational requirements for space and *in-situ* observation data were initially specified in the Marine Core Service Strategic Implementation Plan (Ryder, 2007).

- **Seven Monitoring and Forecasting Centres (MFCs)**, distributed according to the marine area covered (including Global Ocean, Arctic Ocean, Baltic Sea, North Atlantic West Shelf, North Atlantic 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 Central Information System (CIS)**, encompassing the management and organization of the CMEMS information as well as a unique User Interface.

A very similar architecture for the service production is being implemented in the first phase (up to 2018 at least) of CMEMS operations, except for the Black Sea MFC whose implementation has been slightly delayed because of the political situation in Ukraine. However, it might be appropriate to explore in the future the possibility of some adjustments of the present architecture in order to better respond to user needs.

3. Key drivers of the Service Evolution and related R&D priorities

The guidelines to identify the R&D activities to be organized within Copernicus or in coordination with the service are motivated by several key drivers:

- Requirements from core users in the four main areas of benefit as recalled in the Introduction, accounting for both existing needs and needs likely to emerge in the future;

- Requirements from the CMEMS production centers, considering the limitations in the daily service due to knowledge or technological gaps identified to elaborate the products;

- Outcome of EU projects implemented under the Space theme (R&D to enhance future GMES applications in the Marine and Atmosphere areas), such as MyWave, OSS2015, E-AIMS, OPEC and SANGOMA or under FP7 projects (e.g. JERICO, PERSEUS).

Additional drivers are also taken into account that reflect a more strategic view for the service evolution, such as:

- EU directives implemented to regulate activities in the Marine sector (e.g., Marine Strategy Framework Directive, Maritime Spatial Planning);
• New scientific and technological opportunities in the next 5-10 years, regarding both satellite and in situ observations, modelling and assimilation capabilities, new communication and data processing technologies, etc.

• The need to maintain competitiveness w.r.t. international players in operational oceanography, as keeping a high-level know-how and innovation capacity will be strategic to attract new users;

• Forthcoming activities involving Copernicus developments in the framework of other European (e.g. EMODnet) and global initiatives or programs (e.g. the Global Ocean Observing System in the context of GEOSS, GEO Blue Planet, GODAE OceanView).

The constant dialogue with user communities as outlined above helped in identifying overarching priorities for the Service Evolution. Referring to the Technical Annex of the EU-Mercator Ocean Delegation Agreement, it is anticipated that a response of the Marine Service to identified user needs through the integration of current and future R&D developments should focus on:

i. **better description of biogeochemical ocean parameters** in particular to support reporting on marine environmental status in the regional European seas, as required by the Marine Strategy Framework Directive (MSFD);

ii. service evolution enabling the **incorporation of wave information/products consistent with the ocean state of the CMEMS products**;

iii. **better interface between the CMEMS and coastal monitoring services** operated by Member States or private groups: this will require the provision of suitable connectivity and boundary conditions for an efficient nesting between the Marine Service and the national coastal systems, where adaptations at the level of regional seas benefit from user experience and practices;

iv. **better monitoring and description of the ocean state and its variability**, requiring the preparation and release of annual Ocean State reports describing the state of the global ocean and the European regional seas, in particular for supporting the Member States in their assessment obligation.

Moreover, it is identified that one overarching driver for service evolution remains a **continuous enhancement of modelling, data assimilation and forcing techniques**, in order to optimally exploit the considerable investment in observation infrastructure and to generate products with improved quality and error characterization.

These priorities provide guidelines to the short, medium and longer term developments outlined in section 4 below. The proposed R&D roadmap was identified following an incremental approach based on the outcome of several consultation processes: (i) the MyOcean User workshop organized in Lisbon in June 2014, (ii) the MyOcean Science Days organized in Toulouse in September 2014, (iii) the scientific reports prepared by the production centers at the end of MyOcean-2, including their recommendations for further R&D priorities, (iv) the meeting of the MyOcean-FO Executive Committee held in Helsinki in January 2015, (v) the review of an earlier version of the present document by experts from the MyOcean Scientific Advisory Committee, and (vi) analysis of R&D priorities by the CMEMS Scientific and Technical advisory committee (STAC) that was set up to assist Mercator-Ocean for the organization of the CMEMS service evolution activities. This roadmap has been revised after the CMEMS user uptake and service evolution workshop that took place in Brussels, September 7-8, 2015.
4. R&D areas and required developments

In this section are described the 12 R&D areas required to support the service evolution guided by user needs, the required developments that are categorized in terms of time horizons (short- to mid-term, and long –term) and expected objectives. The developments with short- to mid-term objectives refer to R&D activities that are expected to deliver significant results in less than 2 years, while longer-term activities are thought to need more than 2 years to bear results on the service. Sections 4.1 to 4.4 correspond to cross-cutting developments, while the following sections address R&D priorities of the 4 over-arching themes that emerged from the strategic analysis made by the STAC: ocean circulation, ocean-wave and ocean-ice coupling (sections 4.5 to 4.8), biogeochemistry and ecosystems in the marine environment (section 4.9), coastal (section 4.10) and ocean-atmosphere and climate (section 4.11 and 4.12).

4.1 Observation infrastructure and related developments

Expected evolution

The observation infrastructure which today provides regular and systematic data on the physical state and dynamics of the ocean and marine ecosystems is expected to evolve in several directions during the next years:

- The in situ component is expected to collect data on new chemical and biogeochemical state variables (oxygen, bio-optical properties, nutrient, pH) and benthos variables, in addition to conventional temperature and salinity profiles, and increase the sampling of the deep (below 2000 m) and ice-covered seas (using dedicated versions of Argo profiling floats and gliders);
- New capabilities are emerging to establish the ocean variability at a variety of scales through multi-platform observing systems that include more and more autonomous platforms with multi-disciplinary sensors;
- The space component will rely on a mixture of operational (e.g. the Sentinel suite) and exploratory missions, providing sea-level (both along-track and wide-swath), SST, ocean color, surface salinity, surface wind and currents, waves properties and sea-ice parameters;
- The coastal ocean will be monitored through more coordinated, multi-sensors and multi-parameter networks including HF radar, cabled structures, ferry box, surface drifters, gliders;
- New technologies such as ocean gliders, monitoring at key choke points/transects, monitoring at the right scales, adaptive sampling;
- Coordinated and sustained monitoring, e.g. undertaken under EuroGOOS, EMODnet, the EOOS (European Ocean Observing System) initiative and other projects (AtlantOS);
- Integrated ocean observing systems – integrated, multi-platform systems, observing the ocean at multiple scales and delivering quality controlled data to science and society.

New multi-platform and multi-disciplinary approaches combining both in situ (e.g. gliders, Argo, ships, drifters) and satellite observations at high resolution will be needed to resolve a wide range of temporal and spatial scales (from basin to meso- and submeso- scale) and to fill gaps in our knowledge connecting physical processes to ecosystem response. In addition, there is a huge potential to more efficiently access/use data from different industrial platforms, including off shore power stations.

The data assimilated in CMEMS real-time models or multi-year reanalysis systems include SST and sea-level and T/S profiles (almost systematically), sea-ice concentration (whenever possible), and chlorophyll concentration (occasionally). However, within the next 3-10 years a broader list of parameters should be integrated into monitoring and forecasting systems.

Required developments with short- to mid-term objectives

- Adaptation of existing quality-control methods to new observing system components (including new biogeochemical parameters); advancement and adoption of world calibration and quality-control procedures;
• Developments of new protocols for real-time quality checking and automated flagging procedures that are more consistent with nowcast/forecast information delivered by MFCs;

• More consistent processing and assembly of data from different, heterogeneous observation platforms and sensors (e.g. for deriving surface current or sea-ice products);

• Network studies that will provide guidance to deployments; this includes identifying critical ocean observation points and regions where the benefit to forecasting skill is a maximum.

**Required developments with longer-term objectives**

• Adaptation of assembly centers procedures to take advantage of new sensors, communication technologies and unification of procedures, protocols, access and download systems;

• New observing network simulators that will simulate realistic space-time coverage and observation error estimates, as required to perform design studies, Observing System Simulation Experiments (OSSEs) or Observing System Experiments(OSEs) using methodologies explored in the GODAE OceanView program;

4.2 **From big data streams to high-level data products**

**Expected evolutions**

CMEMS needs to enrich its offer with free, open and quality controlled data, in adherence to scientific community standards. In the future, users will be requesting advanced data products that will rely on more complex processing and assembling of measurements of essential ocean variables (sea surface temperature, sea level anomaly, currents, ocean color, sea-ice, surface winds, sea surface salinity …) at higher resolution, including the provision of composite products and their error estimates. Those data products will be essential elements to feed monitoring and forecasting systems, or validate model outputs. The ESA Climate Change Initiative, for instance, will deliver advanced data products that should benefit CMEMS reanalysis production.

The methodologies in place today for merging, filtering, compressing and interpolating observations (until now mostly based on statistical interpolation methods) will need to be adapted to face the challenges of new observing systems that are being progressively implemented and will be more heterogeneous in terms of space-time sampling and resolution, accuracy and big data streams. An additional issue to address is how to take advantage of the high quality delayed mode data in order to get an improved ‘reanalysis’ of the ocean state for change assessment and ‘climatology’ products.

**Required developments with short- to mid-term objectives**

• Specific processing and mapping of product uncertainties following world class processing and calibration/correction, for direct use and for assimilation;

• Reprocessing of existing data sets with more advanced quality control methods, to facilitate the continuous ocean reanalysis activities;

• Production of additional physical variables from existing instruments;

• Relative importance of steric and non-steric components in sea level anomaly signals;

• Preparation of composite data product and derivation of quantities that can be used to infer transport from tracer information, or vice versa;

• Development of interfaces with the EMODnet system for long term archives of multidisciplinary data;

• Development of advanced data products merging different type of observations through multivariate analysis (e.g. for surface currents, ice drift and ice thickness).
Required developments with longer-term objectives

- Data mining and image processing techniques needed to facilitate the automatic extraction and analysis of patterns from big data sets (produced by observing and/or modelling systems);
- Inverse methods that will incorporate simplified balance relationships (e.g. geostrophic and vorticity balance, omega equation) to ensure physically consistent products;
- New bathymetric data with high resolution and possibly information about changes in ocean bottom.

4.3 Advanced assimilation for large-dimensional systems

Expected evolutions

The operational suites implemented in the CMEMS MFCs essentially rely on traditional assimilation methods inherited from the Kalman filter or the 3DVAR approach including simplifications and adaptations to make them tractable with large-dimensional systems. Only the Arctic MFC has explicitly implemented the EnKF to propagate the spread of an ensemble of likely states between successive updating steps. The current assimilation systems need to be revisited in order to (i) improve the physical consistency of ocean state estimations, ensuring for instance that the small-scale dynamics simulated by ocean models is in balance with the larger scales captured by the observing systems, (ii) further develop the assimilation methods to enable implementation into systems involving different components (coupling with atmosphere, biology, biogeochemistry, cryosphere …), (iii) implement effective production of probabilistic information as needed by users to support decision-making, and (iv) improve coupling between assimilative systems with different target resolutions and different assimilation parameterizations.

In 2012, the FP7 SANGOMA project was funded under the GMES umbrella to explore advanced stochastic assimilation methods and prepare the new generation of operational model applications. In parallel, the NEMO team implemented a new assimilation component in the reference NEMO version that includes several modules (observation operators, linear-tangent and adjoint of the circulation model, incremental updating schemes) to facilitate the coupling with various assimilation systems. Independently of SANGOMA, other efforts on modular software development have also been initiated at other European institutions, such as the OOPs project at ECMWF. A convergence between these parallel efforts is expected in the next years, in order to ensure effective implementation of these developments into the large-scale systems based on NEMO.

Required developments with short- to mid-term objectives

- Common developments on assimilation modules to connect models and assimilation kernels shared between different MFCs;
- Development of a capacity to assimilation new/novel observations (ice thickness, currents, SWOT data products);
- Efficient methods to account for complex observation and modelling error structures in assimilation algorithms, including the treatment of correlated errors and bias in observations;
- Adaptations of conventional analysis schemes to preserve the consistency of non-observed quantities at small scale such as vorticity, diffusion, vertical velocity, passive tracers etc;
- Adaptations of advanced assimilation methods developed to address non Gaussian error statistics to large-dimensional systems and coupled systems;
- Development of community tools and diagnostics in observation space, sharing of assimilation tools with the ocean modelling community and observational experts;
• Verification methods and intercomparison protocols suitable to probabilistic assimilation systems;
• Developments of software infrastructure that can accommodate different assimilation methods and facilitate the sharing of algorithms and optimization of computer codes (models, assimilation schemes) on HPC;

Required developments with longer-term objectives

• Combinations of 4DVAR and ensemble methods in ocean data assimilation such as EnVAR, with focus on reanalysis applications and the treatment of model biases and forcing errors;
• Development of ensemble and super-ensemble techniques for future probabilistic forecasting;
• Development of data assimilation tools for coupled models (ocean-atmosphere including waves, physics-biogeochemistry, ocean-shelf models), including consistent coupled initialization approaches and flux correction schemes to account for model biases;
• Development of standardized validation method/system for quantifying the improvements of assimilation products (particularly related to non-assimilated observations/variables) based on different assimilation methods.

4.4 Observing systems: impact studies and optimal design

Expected evolutions

Regarding future observing systems (from space or in situ), the best possible rationality is required in the design and exploitation of observation networks and satellite constellations. This goal can be ideally achieved using observing system impact (Observing System Experiments - OSEs) and design studies (Observing System Simulation Experiments - OSSEs) type experiments to extract the maximum information from data to improve product quality and optimize the assimilation of new observation types. OSEs and OSSEs are scientifically and technically feasible; they represent a useful investment when expanding an existing observing system, defining a new one, or preparing the assimilation of new data types or data with improved resolution/accuracy from space; they are also required for design studies to re-assess the sampling of the present in situ networks, define the required extensions or optimizations and prepare the assimilation of new in-situ data types taking into account the synergies with satellite observations. Such approaches enable to ensure a consistent assessment of observation data, assimilation techniques and forecast and analysis models upstream and downstream the definition and operation of space missions and complementary in-situ networks.

The existing CMEMS building blocks provide an excellent opportunity to develop a new functionality within the Service and conduct impact studies and observing system design based on rigorous and objective methodologies. This functionality will consolidate the link between CMEMS and the data providers by formalizing recommendations on future observing systems. In return, improving the design of future observing systems will be of great benefit to CMEMS itself given the direct impact on the products quality.

Required developments with short- to mid-term objectives

• Development of automatic observation evaluation tools that can eventually be implemented in operational centers to monitor observation impact;
• Development of more robust methodologies (i.e. to ensure results as independent as possible from model and error assumptions) to conduct impact studies (including the OSSE class);
• Adaptation of assimilation interfaces (e.g., observation operators) to new satellite sensors: wide-swath altimetry, ocean color, SST from Sentinels, surface currents, etc.
• Impact studies of new observation data types or products for ocean analyzing and forecasting (e.g. SSS from space, Sea Ice thickness from Cryosat and SMOS, surface current data sets / globcurrent, bio-Argo, HF Radars, etc.)
• Adaptation of ensemble-based assimilation platforms to new in situ sensors and platforms, including those which can be remotely guided
• Methods for explicit estimation and treatment of bias and correlated observation errors.

Required developments with longer-term objectives

• Design studies to re-assess the sampling of the present-day in situ T/S network (Argo including Bio-Argo, ships, buoys, moorings; guidance and leadership to the in situ observing communities on how to optimize observing strategies to improve the MFC data products (integrated model-remote sensing-in situ products) and the complementarity with Sentinel missions.

4.5 Circulation models for global ocean, regional and shelf seas

Expected evolutions

To support Copernicus marine users and decision-makers there will be an increasing demand for model information on fine spatial scales, higher frequencies and with a more complete representation of dynamical processes of the turbulent ocean. This is relevant to all areas from the open ocean where the dynamics are significantly impacted by mesoscale to sub-mesoscale dynamics, to transition areas connecting coastal and shelf seas and to critical regions (e.g. straits, boundary layers) requiring high topographic resolution. Numerical models with resolutions more compliant with the spatial scales that will be captured from space by future Earth Observation observing platforms (e.g. high-resolution wide-swath altimetry, geostationary sensors, direct estimations of surface currents, high resolution SST, etc) will also result into reduced representativeness errors.

In addition, future operational circulation models implemented in the open ocean (essentially those using the community NEMO code) should enable more flexible coupling with a variety of model codes and regional configurations specifically customized for coastal dynamics, including those interfaced with near-shore, estuary models and hydrological models. Specific developments are expected to ensure more flexible and efficient coupling with downstream systems with limited geographic coverage.

Required developments with short- to mid-term objectives

• Development of advanced numerical schemes and parameterizations required for numerical codes implemented with a target effective resolution in the kilometric range
• Better resolution of surface currents (0-20 m) and high-frequency processes (e.g. tides) including their effects (rectification) and associated uncertainties on the circulation and transport of tracers
• Adaptation of multi-scale and downscaling/nesting capabilities to achieve kilometric to sub-kilometric resolution locally
• Development of advanced physical parameterizations, numerical schemes and alternative grids to improve the performance of the medium-resolution ocean models
• Adaptation of atmospheric forcing methods that preserve the benefit of the fine scales (fronts, filaments) of surface ocean patterns
• New strategies and algorithms to solve the model equations efficiently on next generation computing systems: this should result in code performance improvements on most intensive HPC applications, which is crucial to sustain operational production
- Development of coupling with atmospheric pressure, tidal forcing, river outflow for fully 3-D storm surge forecasting.

**Required developments with longer-term objectives**

- Improved capability in storm surge forecasting for global and regional models;
- Development of coupled current-wave-atmosphere-sea-ice ocean boundary layer models which can be run independently or coupled to the interior ocean and atmosphere;
- Development of more general interfaces between models and assimilation platforms.

**4.6 Sub-mesoscale - mesoscale interactions and processes**

**Expected evolutions**

Our knowledge on the relationship between the physical, chemical and biological processes in the upper ocean will improve over the next years. This is essential for understanding and predicting how the ocean and the marine ecosystems respond to changes in the ocean dynamics and atmospheric forcing. Advection and mixing associated with mesoscale and sub-mesoscale oceanic features such as fronts, meanders, eddies and filaments are of fundamental importance for the exchanges of heat, fresh water and biogeochemical tracers between the surface and the ocean interior, but also exchanges between the open oceans and shelf seas, and between the pelagic ocean and the benthos.

The challenges associated with mesoscale and sub-mesoscale variability (between 1-20 km) imply therefore high-resolution observations (both in situ and satellite) and multi-sensor approaches. Accordingly, multi-platform synoptic experiments have to be designed in areas characterized by intense density gradients and strong mesoscale activity to monitor and establish the vertical exchanges associated with mesoscale and sub-mesoscale structures and their contribution to upper-ocean interior exchanges. *In situ* systems, including ships, gliders and drifters should be coordinated with satellite data to provide a full description of the physical and biogeochemical variability and will be combined with both routine *ad hoc* high resolution numerical simulations.

Focus should be made on a range of scales (15-100 km) traditionally not resolved by conventional altimeters but in which the wide swath alimeter SWOT will make an unprecedented contribution. High-resolution numerical models are able to represent the full evolution of oceanic structures in the three spatial dimensions, thus providing a complementary and very valuable source of information to describe and understand mesoscale and submesoscale processes. At the same time, the realistic generation and evolution of such processes stills remains very challenging due to the chaotic nature of the oceanic flow, making direct model-data comparisons often hazardous at the smallest scales.

**Required developments with short- to mid-term objectives**

- Numerical studies aimed at (i) understanding and (ii) characterizing the predictability limit associated with dynamical structures of the sub-mesoscale regime in open ocean and regional seas;
- Lagrangian techniques and numerical modules to simulate and predict 3D dispersion of particles and pollutants;
- Development of new statistical metrics adapted to the increased resolution in both observations/products and models to be able to quantify the impact of meso and sub-mesoscale structures on the general/regional circulation, its variability, both physical and biogeochemical;
- Proposals to aggregate results from multidisciplinary field experiments and numerical studies with the objective to improve our understanding of fine-scale processes for (i) ocean modelling and prediction, particularly those that would alleviate the levels of systematic error in ocean models, (ii) establish the vertical exchanges associated with mesoscale and sub-mesoscale structures, and (iii) enable verification, validation and assessment of operational products in specific areas.
Required developments with longer-term objectives

- High-resolution operational model forecasts that will be used to support the preparation and execution of the sea trial;
- Alternate observational approaches integrated with numerical simulations supporting both realistic and process oriented studies of the mesoscale – sub-mesoscale regime and their impact on ecosystem dynamics of this regime;
- Quantified and improved understanding of vertical exchanges associated with oceanic mesoscale and sub-mesoscale features (e.g. fronts, meanders, eddies and filaments) through the combined use of, in-situ and satellite data in synergy with numerical models. The ultimate goal is to enhance our understanding of fine scale processes on biochemical and associated ecosystem variables.

4.7 Coupled ocean-marine weather information, surface currents and waves

Expected evolutions

The most important ocean weather parameters delivered by CMEMS are ocean currents, temperature, (in particular in the near-surface layer of the ocean), sea ice, sea level and ocean color. Currently the CMEMS parameter list does not include ocean waves but wave products will be included in the CMEMS catalogue in early 2017. For a number of marine and coastal applications, information on surface parameters (total and non-tidal currents and waves) is of great importance and in great demand. One example is the off-shore industry, where information on wave height and period are fundamental in the decision making e.g. when ocean platforms need to be demaned during violent storms. Everyday activities along the coasts depend heavily on wave information. Information on surface waves is also an essential input to the risk analysis in storm flood events.

Scientifically waves are a bridge between the ocean and the atmosphere, and there should be consistency between the surface fluxes and winds used to drive the wave and ocean models. Waves are also important mixing agent with an active role in erosion and resuspension processes. In 2012 the EU funded project MyWave was established to lay the foundation for a future Service that also includes ocean waves. MyWave has achieved important R&D toward a unified system for providing wave forecasts and wave products. It is expected that these advances will be connected to those achieved in CMEMS in order to eventually support the production of more consistent ocean-marine weather information including on surface waves, as often requested by users.

Besides it is important to consider that the quality of wave prediction and analyses is strongly linked with the quality of the wind forcing. This is the reason why a tight connection with the atmospheric forcing fields should be sought.

Required developments with short- to mid-term objectives

- Improved processing methods to retrieve wave and surface currents (total and non-tidal) information from the relevant satellite data, such as wave height based on altimeters (e.g. Sentinel 3) and wave information from SAR (e.g. Sentinel 1);
- Improved processing methods to retrieve wave information (including integrated parameters such as significant wave height) from in situ platforms (buoys, moorings, HF radars, etc.);
- Investigations of wave model errors on swell parameters (usually source of the largest errors) and improved parameterizations;
- Developments of ocean model forcing that will explicitly include the effect of waves from wave models on the upper ocean dynamics;
• Co-location methods and related metrics to generate model-observation match-up data for wave verification;
• The interaction of waves and currents at small scales both in the middle of oceans and near the shoreline.

**Required developments with longer-term objectives**

• Improved wave modeling near the ice edge or in ice-infested waters;
• Improved modeling of extreme and rough waves based on coupled wave-current-stratification interactions;
• Developments to implement fully coupled ocean-wave models in which both components will exchange information at high frequency, or development of coupling parameterizations (bulk parameterizations for instance);
• Implementation of advanced techniques to assimilate data into coupled ocean-wave-atmosphere model systems, that take into account the wave field as a boundary condition problem (as opposed to an initial value problem);
• Improved predictive skills for coupled ocean-wave models and uncertainty estimation based on probabilistic techniques.

### 4.8 New generation of sea-ice modelling

**Expected evolutions**

There is evidence of a number of shortcomings in modelling the coupled ocean-sea-ice-atmosphere system at high latitudes that continue to limit the quality of operational products (both real-time as well as reanalyses) delivered to users. The 10 km to 100 km wide Marginal Ice Zone where both ocean waves and sea ice processes are coupled is expected to widen in a warmer Arctic, but is still not well represented, neither in data nor in operational models. Additionally, products for fisheries (having a very strong economic value) depend on several qualities of both physical models (mixing, horizontal and vertical advection of larvae) and primary and secondary production models.

Some shortcomings are inherent in the traditional viscous-plastic sea-ice rheology (and elastic-viscous-plastic as well) in the sea-ice models in use today, the deformations of sea ice being not correctly represented and in turn the velocity of sea ice drift being also incorrect. The ability to assimilate sea ice drift is also impaired by such model bias. In addition, the inclusion of more non-linear, chaotic processes are expected to become increasingly challenging for assimilation methods, in a context where more observations will be delivered from space, especially through the Sentinel suite.

**Required developments with short- to mid-term objectives**

• Sea-ice models based on more realistic rheology, for instance rheological models based on solid mechanics rather than fluid mechanics and their inclusion into operational models;
• Improved physical modeling of mixing below sea ice, in particular the cold halocline layer, which is still a serious issue for the Arctic Ocean modeling community and the climate modeling community at large;
• Improved sea ice thermodynamics that will include effects of surface melt ponds;
• Coupling with snow models to account for ageing of snow and blowing snow;
• Development of a new generation of sub-kilometer scale dynamic sea ice models able to resolve ice floes;
• New data assimilation methods designed to handle strongly nonlinear dynamics and semi-
qualitative information from satellites such as the type of sea ice, the thickness of thin and
detailed information available for example from SAR imagery;

Required developments with longer-term objectives

• Representation of biological cycles in sea ice, including optical properties of sea ice and
vertical migration of nutrients in sea ice;

• Specific development for modeling of the Marginal Ice Zone, taking into account the
heterogeneity in sea ice coverage and coupling effects with ocean and atmosphere and waves
at fine scales;

• Developments on sea-ice models and data assimilation targeted to initialize coupled ocean-
atmosphere and sea-ice forecasts for a wide range of time scales. The coupling between
atmosphere and sea-ice models is complex, and it should be taken into account in the
development of models and data assimilation.

4.9 Data assimilative modelling of marine ecosystems and biogeochemistry

Expected evolutions

Our capacity to assess the state of the marine environment regularly and accurately will have to be
consolidated in the future. Users of the future CMEMS will benefit from the gradual improvement of
models and tools to monitor the biogeochemical state of ocean and marine ecosystems in ocean basins
and marginal seas, based on model-data integration and assimilation methodologies inherited from
physics. This will require very significant strengthening the observation system of the “green” ocean
component at a range of scales, including in regional and coastal seas. The potential of future satellite
sensors (e.g. imagers from geostationary satellites) in particular should induce a breakthrough in the
monitoring of coastal areas and land-ocean interface. Monitoring also the concentration and
distribution of pollution and its overlap in time and space with effects on biological species will be
essential for predicting ecosystem responses to pollution. Other challenges on the marine component
of the carbon/GHG cycle will also require significant R&D effort as significant gaps in monitoring
tools also exist in this area.

During the past 3 years, the FP7 OPEC project has developed and evaluated ecosystem monitoring
tools to help assess and manage the risks posed by human activities on the marine environment, thus
improving the ability to predict the “health” of European marine ecosystems. OPEC developed
prototype ecological marine forecast systems for European seas (North-East Atlantic, Baltic,
Mediterranean and Black Seas), which include hydrodynamics, lower and higher trophic levels
(plankton to fish) and biological data assimilation and made demonstration reanalysis simulations,
assessed the effectiveness of current operational ecosystem monitoring systems and demonstrated the
potential to make robust seasonal ecosystem forecasts. Simultaneously, the FP7 OSS2015 project has
developed R&D activities with the objective to derive representations of biogeochemical variables
from the integration of gliders and floats with EO satellite data into cutting-edge numerical
biogeochemical and bio-optical models. There is an expectation that the integrated Atlantic ocean
observing system (AtlantOS) will increase the number and quality of in-situ observations on
chemistry, biology and ecology over the next decade. A co-evolution of the data use in assessment and
predictive models holds great potential for new products and users.

It is required that results from these projects as well as similar advances in the field be transferred to
CMEMS in order to consolidate the core ecosystem component of the service.

Required developments with short- to mid-term objectives

• Improved performance of marine ecosystem models including uncertainty estimation
capabilities;
• Extension of existing monitoring capabilities for primary production to ecosystem variables describing higher trophic levels (plankton to fish) and ecological products;

• Improved ocean colour products in regional seas;

• Tailored provision of operational products in addition to standard (T, S, Chl, – oxygen, pH, nutrients, light, plankton biomass) in support of predictive habitat forecasts, for ecological status and fisheries modelling and risk assessment (e.g. invasive species, HABs);

• Multi-data assimilation capabilities (combining state and parameter estimation), combining ocean colour and sub-surface data from Bio-Argo, gliders and other relevant ecological observations especially in regional seas; simultaneous assimilation of physical and biological properties;

• New modules linking optical properties in the near-surface ocean to biomass; improved representation of key processes such as primary production, nutrient uptake, grazing etc. in models resolving the diurnal variability;

• Demonstration of consistent interfacing (nesting, downscaling) between open ocean biogeochemical models and regional/coastal ecosystem models and downstream applications;

• Develop a standardized validation method/system for ecosystem model products/variables (particularly related to non-assimilated observations/variables).

**Required developments with longer-term objectives**

• Improved description of benthic-pelagic coupling on short-term (seasonal) and long-term (decadal) scale; identification of on good initial conditions;

• Improved methodologies for supplying operational information on sources of nutrients and pollution/chemicals to the oceans;

• Develop a system for routine model estimates of the dose and direct and indirect effects of pollution on communities of algae, zooplankton and fish larvae (based on dose/effect laboratory studies on individuals);

• New capabilities for ecosystem projections at seasonal (to decadal) scales;

4.10 **Seamless interactions between CMEMS and coastal systems**

The coastal monitoring services operated by Member States or private groups will form an important and strategic group of users of the CMEMS. These activities will enhance the socio-economic value of CMEMS by contributing to the MSFD, spatial planning and other downstream applications (offshore operations, coastal engineering, habitat monitoring, aquaculture, HAB monitoring, adaptation and mitigation to climate change). Downscaling also include the integration with coastal observatories and the role of CMEMS regional products is also to fill gaps in the coastal observatories.

However, the “one-way” vision of a core service delivering information to downstream users without feedback to upstream providers has a number of limitations since the coastal strip should also be considered as an “active” boundary layer that also influences the deep ocean region connected to coastal areas. We are now at the stage to include the local scale into the regional scale. It is therefore needed to develop the CMEMS in such a way as to enable more efficient interfacing with a large variety of coastal systems describing the physical, biogeochemical and ecosystem. This will require the provision of suitable connectivity between the Marine Service and the national coastal systems, where adaptations at the level of regional seas benefit from user experience and practices.

Scientifically, interactions between littoral, shelf, regional and abyssal seas are still a major unknown, poorly characterized and modelled, yet vital to ecosystems and the health of a high percentage of
ocean productivity and coastal ocean science based management. In FP6, the ECOOP project was
developed with the objective to consolidate, integrate and further develop existing European coastal
and regional seas operational observing and forecasting systems into an integrated pan-European
system targeted at detecting environmental and climate changes, predicting their evolution, producing
timely and quality assured forecasts, and providing marine information services (including data,
information products, knowledge and scientific advices). The objectives and progress made in the
framework of ECOOP and other similar projects should be reconsidered within the context of
CMEMS now in operation. Such initiative should rely on the coordination role of EuroGOOS with
regard to operational oceanography and its contribution to define and implement a marine monitoring
system in Europe.

Required developments with short- to mid-term objectives

- Comprehensive impact studies of CMEMS boundary conditions on coastal systems (physics,
biology) and their applications (e.g. MSFD);
- Upscaling approaches to enable incorporation of river inputs from observatories or services;
- Development of consistent wave-current-atmosphere coupling in regional seas with
assimilative capabilities;
- Data assimilation and ensemble forecasting improvements to better serve the coastal
applications;
- Development of flexible interfaces between regional and coastal models, including near-shore
and estuarine models and with the capability to connect structured and unstructured grids;
- Identification of key common components of the regional/coastal observing system (space and
in situ) needed for sustained operations;
- Interface with the GODAE COSS Task team to incorporate lessons learned from regional-
coastal coupling and intercomparison exercises at international level.

Required developments with longer-term objectives

- Exploration of the benefit of two-way information exchange between coastal and CMEMS;
- Adoption of robust standards to ensure compatibility between CMEMS and downstream
systems;
- Development of two-way nesting/coupling methods with assimilative capabilities;
- Connection and coupling with land hydrology models.

4.11 Coupled ocean-atmosphere models with assimilative capability

Expected evolutions

The MFC systems in CMEMS are based on a “forcing mode” approach in which the ocean dynamics
is driven by surface momentum, heat and salt fluxes computed using prior atmospheric information at
fairly coarse space-time resolution, independent of the current ocean state at high resolution. This
approach has several limitations with respect to the description of the upper ocean variables and
related products requested by users. Dynamical feedbacks between ocean and atmosphere are
generally considered neither in atmospheric nor in ocean models, a neglect which has quantitative
implications on the predictability of coast and ocean and regional atmospheric model systems. This
could be an issue due to the different scales of variability in the atmosphere and ocean systems.

While coupled ocean-atmosphere models have been developed for a while in the frame of climate
research and weather forecasting, several specific constraints need to be considered for operational
oceanography: (i) the discrepancy in the space-time scales resolved in oceanic and atmospheric models, (ii) the existence of observations at the ocean-atmosphere interface to be assimilated into coupled models, (iii) the different prediction capabilities of the ocean and atmospheric systems, especially for regional/coastal applications of interest to Copernicus users.

In MyOcean2, global and regional modelling systems (North West Shelf, Baltic and Med Sea) have been used for this purpose. This work needs to be consolidated in order to respond to the more generic needs of the CMEMS.

**Required developments with short- to mid-term objectives**

- Representation of diurnal variability and cool skin layer in forced ocean and coupled ocean-atmosphere models;
- Consistent numerical schemes to improve the representation of ocean-atmosphere interactions for regional oceanic applications;
- Adaptation of assimilation methods to observations of the air-sea interface (sea surface temperature, sea surface salinity, surface currents, ocean colour) consistent with the turbulent nature of oceanic and atmospheric boundary layers;
- Use of ocean wave spectra to determine boundary layer fluxes.

**Required developments with longer-term objectives**

- Novel ocean forcing approaches that will include simplified atmospheric boundary layer dynamics and ocean feedbacks at high spatial resolution; development of coupled ocean-atmosphere-sea-ice data assimilation with full general circulation models;
- Analyses of impacts and feedbacks resulting from coupling between ocean and atmosphere on the surface ocean biology, including in the case of extreme events;
- Facilitate collaboration with the atmospheric community for exploitation of the surface observations common to the coupled ocean-sea-ice-atmosphere interface, such as surface winds, surface currents, SST, waves, sea-ice concentration, sea-ice thickness and sea-ice temperature;
- Focused research on the observational control of systems with different time scales, which can be extrapolated to the application of coupled reanalyses of the Earth system.

### 4.12 Ocean climate variability: reanalysis and scenarios for future changes

Data assimilative modelling systems are used to produce ocean reanalyses describing the variability and detect climate changes during the past, observed decades. However many users are interested in the knowledge of future trends, ocean evolutions under different climate conditions, likely modifications of the marine environment variability, and probability of extreme or harmful events (e.g. HAB) that will occur during the next, unobserved period. Earth system simulations provide a relevant framework to predict and project the present oceanic state in the future, which could be used together with ocean reanalysis to infer likely changes in the ocean physics, biogeochemistry and the marine environment.

Methodologies to derive meaningful information about the ocean climate variability and evolution using a combination of ocean reanalysis and Earth System models with assimilative ocean components should be developed. This will also require the production of improved ocean reanalyses, with reduced systematic errors and improved dynamical consistency.

The progress in reanalysis product quality delivered by the CMEMS will have to be monitored on a continuous basis, using proven, verifiable and robust methodologies that can be shared with external
partners from the operational oceanography community. This activity can rely on standard metrics (e.g., as defined in the international GODAE framework) or on new approaches to be developed by CMEMS in coordination with other relevant groups at international level.

These activities will contribute to the consolidation of Ocean State reports delivered by CMEMS, and to the development of the Copernicus Climate Change Service (C3S) line.

*Required developments with short- to mid-term objectives*

- Reduction of systematic errors in the modelling and assimilation components of reanalysis systems, improved methods to account for representativity and sampling observation errors;
- Probabilistic framework and metrics for ocean reanalysis using ensemble techniques;
- Framework for coordination / intercomparisons with international community efforts (EuroGOOS, GODAE OceanView, CLIVAR, CMIP activities...);
- Development of spatial verification methods based on those used by the NWP community;
- Development of a user feedback mechanism that ensures that the new products are addressing the user requirements, are delivering at the highest possible standards and are designed to be flexible and adaptive.

*Required developments with longer-term objectives*

- New methods and diagnostics to evaluate the predictability of the ocean circulation, biogeochemistry and marine ecosystems at global, basin scale or regional scale;
- Methodologies to project information about the present ocean state and variability into future, based on a combination of reanalysis and Earth system models;
- Methods to ensure quality, homogeneity and robust uncertainty measures in long-term time-series reconstructed from data or model reanalyses.
5. Implementation of a service evolution roadmap

The R&D areas listed in section 4 were identified following a bottom-up consultation approach initiated in the framework of the MyOcean projects and pursued in the CMEMS context. The CMEMS user uptake and service evolution workshop that took place in Brussels, September 7-8 2015 was an opportunity to identify missing developments, further develop the roadmap and refine the scale of priorities between short to mid-term and longer term objectives based on the feedback from users, research community and CMEMS teams.

The R&D plan during the next 6 years period should be organized along two lines of activities, depending on the time horizon expected to yield impact on the CMEMS:
- the first line will rely on short- to mid term activities implemented through R&D projects that will gather scientists with relevant expertise in the corresponding topical areas; it is recommended to develop this line through R&D calls for tenders directly managed by the CMEMS, with priorities compliant with the overall CMEMS strategy; the selected task forces will have to develop their activities in tight connection to the CMEMS teams coordinated by Mercator-Ocean;
- the second line will rely on longer-term external R&D activities, to be carried out by collaborative project consortia in the frame of H2020 or other funding opportunities.

In order to ensure consistent developments between the two lines, it is recommended to regularly organize meetings between projects from the first and second line in order to ensure cross-fertilization of ideas across the CMEMS and R&D partners.