OPerational ECology: Ecosystem forecast products to enhance marine GMES applications

Reporting

Project Information

OPEC

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Final Report Summary - OPEC (OPerational ECology: Ecosystem forecast products to enhance marine GMES applications)

Executive Summary:
Executive Summary
Coastal seas provide many beneficial goods and services to humankind, such as fisheries, recreation, climate regulation and coastal defences. It is important that the marine environment is observed and monitored to provide high quality environmental information / data, understand its role in our Earth system, track changes and predict the potential response of the ocean to stressors. Operational Ecology is the systematic provision of long term information on the status of marine ecosystems to stakeholders, exploiting both observations and models.
The aim of OPEC (the OPerational ECology project) was to develop and evaluate ecosystem forecast tools. OPEC has developed prototype ecological marine forecast systems for European seas, which

include hydrodynamics, lower and higher trophic levels (plankton to fish) and biological data assimilation.
The research undertaken in OPEC has delivered the following data products and research outcomes:
• Marine Data portal: The OPEC data portal (http://portal.marineopec.eu) allows users to query and export simulated ecosystem data for European Regional Seas, visualise it, download and process it, all free of charge including;
a. Simulations of the last 20 years: 20 year hindcast simulations of the NE Atlantic, Baltic, Black and Mediterranean Seas describing the past states and trends in the ecosystem in terms of physics, nutrients, plankton and fish.
b. Rapid Environmental Assessment: The Rapid Environmental Assessments blend model and observation data to provide the best available estimates of the current state (the past 3 months) of the ecosystem.
• Monitoring System Assessment: OPEC has assessed the effectiveness of current operational ecosystem monitoring systems and made recommendations for future monitoring.
• Seasonal forecast: OPEC has demonstrated that its systems have the potential to make robust seasonal ecosystem forecasts. The next step is to trial a pre-operational model.
• Downstream services: Through consultation with end-user groups OPEC has developed new services and products by combining modelled and satellite. These are delivered through the WAQSS system (http://portal.waqss.de/).
Operational Ecology products are useful to a wide range of stakeholders including marine management authorities, government departments, coastal managers, NGOs and marine industries. Model simulated data from the project is already freely available to download and manipulate from the project's unique data portal.
OPEC feeds into several key policy areas, such as the European Marine Strategy Framework Directive and Common Fisheries Policy. By providing information on the state of the past and current environment for key indicators related to MSFD Descriptors, regional and national stakeholders will be better able to plan, monitoring and report on their waters. Products and services generated by OPEC provide information for environmental managers, policy makers and other related industries, laying the foundations for the next generation of operational ecological products and identification of knowledge gaps.
Our future aspiration is to transition these systems into the operational suites of the Copernicus Marine Core Service.

Project Context and Objectives:
1.1 Summary description of project context and objectives
Coastal and shelf seas form a vital part of our environment, currently providing many beneficial goods and services to mankind but also posing a risk to coastal populations. At the same time, the fragile balance of marine environments is increasingly being disrupted by the impacts of climate change and human activities.
Strongly affected by the global environment (ocean, atmosphere and land), marine ecosystems are a major source of biodiversity and a focal point for biogeochemical cycling. They provide direct tangible benefits including protein sources and economic activity associated with fisheries and aquaculture, and the economic benefits associated with tourism renewable energy and relational activities. However, human utilization of the seas natural benefits can have negative impacts, with fisheries, industries, and agriculture/aquaculture along the world's coastlines contributing to significant physical, chemical and ecological impacts on the surrounding seas. The great scientific challenge is to understand, and predict the consequences of environmental changes (e.g. climate change and ocean acidification) and exploitation

the consequences of environmental changes (e.g. climate change and ocean acidification) and exploitation of natural resources upon our coastal ecosystems and upon society.

A key commitment in the United Nations Framework Convention on Climate Change (UNFCCC) is systematic observation and the development of data archives that are essential for understanding, mitigating and adapting to climate change. The Global Climate Observing System (GCOS) established a list of Essential Climate Variables (ECVs) that are feasible to measure and closely matched to UNFCCC requirements. This set of variables is being developed in line with progress in scientific understanding and the development of instrumentation. For marine ecosystems the key variables are, chlorophyll, carbon dioxide partial pressure, nutrients, carbon, and phytoplankton, chosen because of their significance in biogeochemical cycles at a global scale and because they enable the projection of global climate change information down to regional and local scales.

To address such challenges the European Union implemented the Marine Strategy Framework Directive (2008/56/EC) (MSFD) which requires member states to develop strategies to achieve a healthy marine environment and make ecosystems more resilient to climate change in all European marine waters by 2020 at the latest. The strategies must contain a detailed assessment of the state of the environment, a definition of "Good Environmental Status" (GES) at regional level and the establishment of clear environmental targets and monitoring programmes. Through a scientific and technical assessment prepared by the Task Groups set up by the Joint Research Centre and the International Council on the Exploration of the Seas, the Commission has consulted all interested parties on the development of criteria and methodological standards to measure GES. One major conclusion of this study is the substantial need to develop additional scientific understanding for assessing GES in a coherent and holistic manner to support the ecosystem-based approach to management.

To deliver the goals of the MSFD and GCOS, high quality environmental information is of crucial importance. The European Earth observation program GMES (Global Monitoring for Environment and Security) makes a major contribution to the provision of such information through the development of a marine monitoring service. The GMES marine monitoring service provides regular and systematic reference information on the state of the oceans and regional seas. The FP7 funded MyOcean project is the implementation project of the GMES Marine Service, aiming at deploying the first concerted and integrated pan-European capacity for Ocean Monitoring and Forecasting providing the best available information on the Ocean at global and regional scales (European seas), based on the combination of space and in situ observations, and their assimilation into 3D simulation models. The GMES Marine Service addresses four key domains, Marine safety (e.g. marine operations, oil spill combat, ship routing, defence, search & rescue); Marine resources (e.g. fish stock management), Marine and coastal environment (e.g. water quality, pollution, coastal activities); Climate and seasonal forecasting (e.g. climate monitoring, ice survey, seasonal forecasting). While being vitally important for the implementation of policy and the management of coastal seas the ecologically relevant components are relatively undeveloped within both the existing and proposed extension to the GMES Marine Service; with the emphasis placed on near real time forecast of biogeochemical properties. OPEC aims to rectify this by undertaking the research and development to develop Operational Ecology for the GMES Marine Service which will contribute directly to the Marine Strategy Framework Directive, the monitoring of climate change and to the assessment of mitigation and adaptation policies. The primary goal of OPEC was to improve the quality of operational services for biogeochemical and ecological parameters and hence our ability to project the future status of European marine ecosystems by delivering a suite of error quantified indicators which describe changes in ecosystem function suitable for implementation in operational centres.

In order to advance our understanding and predictive capacities for the response of marine ecosystems to

In order to advance our understanding and predictive capacities for the response of marine ecosystems to global change, OPEC employed a combination of numerical simulations, data assimilation of satellite and in situ data, observational strategy evaluation and cross-disciplinary synthesis. The MSFD takes a regional approached to the development of strategies for environmental status, identifying four main regions, NE Atlantic, Baltic, Mediterranean and Black Seas. The MSFD also identifies a number of high level descriptors of environmental status (e.g. biodiversity, commercial fish, eutrophication, food webs, and invasive species) each of which has a defined set of indicators. Using the regional approach as framework OPEC implemented and test suite of indicators in each region. These descriptors along with the ECVs provide a framework for the definition of new environmental applications (e.g. habitat for biodiversity, oxygen depletion/eutrophication, fisheries and marine climate change research). A common set of descriptors with associated GES indicators and ECVs.

1.2 Scientific Objectives

The overall goal of OPEC was to undertake R&D to improve the quality of operational services for biogeochemical and ecological parameters and hence project future marine ecosystem states by delivering a suite of error quantified indicators of Good Environmental Status (GES) which describe changes in ecosystem state. OPEC will establish and improve the hindcast skill of key indicators through

implementing indicators for three core descriptors in every region (biodiversity, eutrophication, and foodwebs) as well as individual descriptors for specific regions (e.g. commercial fish, invasive species). Without this research, the GMES marine resource, climate change and marine and coastal environment products will not be able to fulfil the requirements of the MSFD, CFP, WFD, European and regional environmental management.

1.3 Scientific objectives by Work Package

WP2 Next Generation model setup and benchmarking

The objective of this work package is to set-up the ecological model system for the next generation GMES marine ecological service in European Seas. Each region will have a model system comprising a core coupled hydrodynamic-plankton model, a HTL component, a representation of the carbon chemistry and a data assimilation system. These will be used to perform 20yr hindcast of each region and to benchmark model performance.

WP3 Rapid Environmental Assessment

The overall objective of this work package is provided error quantified estimates of the state of the ecosystem in the recent past to provide up to date information for environmental management.

WP4 Assessing the predictability of seasonal forecast

Seasonal forecast is essential for marine management yet potentially complicated. It is limited in part by the quality of current meteorological seasonal forecasts, which limits our ability to reach a good seasonal forecast during the project period. For this reason in OPEC we choose to explore the potential predictability of the seasonal forecast, with a view to defining operational services in the future. The impacts of changes in external drivers such as land derived nutrients and fishing mortality on predictability will be assessed. The overall objective of this work package is to assess the predictability of target variables at seasonal timescales.

WP5 Assessment of ecological monitoring system and data needs for GMES ecological service

Drawing on existing data from FP7, MY ocean thematic assembly centres and various ESA initiatives, we will evaluate the effectiveness of the current data availability for the delivery of operational ecology. By undertaking ecosystem monitoring system evaluation experiments for the planktonic ecosystem, OPEC will make recommendations for the future satellite and in situ monitoring of the system. These recommendations will be feed to relevant bodies including ESA, the GMES Marine Service, the EC

recommendations will be feed to relevant bodies including ESA, the GMES Marine Service, the EC, OSPAR, HELCOM etc.
Consequently this WP aims:
To quantitatively assess existing European coastal and regional sea observational networks for ecological parameters and establish the future data requirements.
WP6 Data Delivery and Downstream Services
The success of the OPEC concept is dependent in being able to deliver information to its stakeholder in a timely and relevant manner. The stakeholder should be able to query and export data, visualise it, download and process it. The economic exploitation of OPEC products by SME's requires the further development of information products relevant to marine water quality, which are both relevant to the end user and suitable for operational production.
The aim of this work package is to establish the technological infrastructure to disseminate OPEC products and to develop a suite of end user relevant downstream data products.
WP7 Knowledge Transfer
Knowledge Transfer is the facilitation of the dissemination of research-based knowledge, expertise and skills between the project and the users of its results (e.g. Policy makers, advisory bodies, research

managers, conservation and user groups, management bodies, all at European, regional and national level).

Project Results:
1.4 Main Scientific and technical results
Operational Ecology is the systematic provision of long term information on the status of marine ecosystems to stakeholders, exploiting both observations and models. Operational Ecology reconstructs past history and aims to predict the future status of the marine environment and ecosystem in support of environmental assessment and ecosystem-based management. It is application focussed, delivering regular quality ensured information products in support of management and decision making via information that is relevant and in a format which can be easily accessed.
The research and development efforts undertaken in OPEC were based on developing pre-operational regional modelling systems, data assimilation, seasonal forecast and the assessment of monitoring systems. The section of the report has been split into three sections to reflect this:
• Regional modelling systems: this section summarises the operational ecology forecast system set- up in each region, with illustrative examples of the results taken from the hindcast and rapid environmental assessments (REA) reported by region.
• Seasonal forecast: this section reports on the assessment of the potential predictability of seasonal ecosystem forecast, with a view to defining future operational services.
• Assessment of monitoring systems: this section reports on the effectiveness of the current data availability for the delivery of operational ecology.
1.4.1 Regional modelling systems
The primary technical goal of OPEC, to establish core ecosystem forecast model systems in the NE Atlantic, Baltic, Mediterranean and Black Seas has been achieved. In each region a model system has been set-up which comprises a core coupled hydrodynamic planktonic ecosystem model, a higher trophic level (HTL) component and a representation of the carbonate system. Appropriate model meteorological forcing, boundary conditions, validation data and metrics have been identified and implemented. Finally a data assimilation system has been implemented and evaluated in each region. A range of indicators are available to support MSFD objectives and in line with the marine knowledge action of the Blue Growth

available to support MSFD objectives and in line with the marine knowledge action of the Blue Growth strategy. Indicators have been selected for which the scale of monitoring and assessment is consistent with the time frame used in making predictions from models. OPEC has identified modelling products that deliver direct access to indicators of ecosystem status through the OPEC data-portal, including amongst others, chlorophyll, nutrient concentrations and oxygen which are indicators of MSFD Descriptor Eutrophication. The pre-operational simulations performed by OPEC are as follows:

- Hindcast simulation of the period 1990-2009 has been completed without data assimilation.
- Reanalysis simulation of the period 2000-2009 has been completed, i.e. a hindcast with data assimilation of satellite data and or in-situ data.
- Rapid environmental Assessments (REA): Rolling reanalsysis for the lower trophic components of the ecosystem in each region for the last 12 months. Simulations cover the period Jan 2010 to June 2013.

All simulations have been have been validated against in-situ data and their skill assessed by expert judgement for key OPEC indicators. The resulting data products are publically available and free to download from http://portal.marineopec.eu .

1.4.1.1. Operational Ecology capability in the North East Atlantic

The OPEC North East Atlantic region spans the area from 40˚ to 65˚ North in latitudinal direction (approximately Lisbon to Iceland) and from 20˚ West to 13˚ East in longitudinal direction (Iceland to the Belt). This vast area spans the entire North West European shelf and ranges from estuarine and coastal waters over typical shelf seas (like the North Sea or the Celtic Sea) to parts of the deep North Atlantic Ocean basin.

The region can largely be categorised as a seasonally stratified, downwelling shelf sea system with a net inflow of surface waters and a net outflow on the sea floor across the shelf break into the deep Atlantic with a generally anti-clockwise circulation of the North-Sea. The drivers of ecosystem pressures for this region are balanced between weather related effects like temperature changes, increase in storm events and water column stratification, and direct human-induced drivers like eutrophication or fisheries. The effects may be synergetic or antagonistic, leading to a complex interplay of pressures that must be combined in this system in order to predict the resulting future of the NE-Atlantic ecosystem.

The model system (Figure 1.4.1) deployed for the hydrodynamic and lower trophic level component of this area (including data assimilation of satellite ocean colour using an Ensemble Kalman Filter) is the coupled POLCOMS-ERSEM system, a well-established system subject to numerous peer-reviewed scientific publications. This system was preferred over the next generation operational model due to its robustness and efficiency. Two elements that are crucial for the data assimilation component within this project involving the computationally heavy Ensemble Kalman Filter.

Two higher trophic level models have been implemented through an offline coupler. Firstly a size based model encompasses two linked size-spectra: a pelagic spectrum and a benthic detritivore spectrum. The pelagic spectrum comprises primary producers (plankton) and pelagic predators (i.e. fish). The size based model is therefore able to link the dynamics of the lower trophic levels (plankton and benthic detritivores) and higher trophic levels (pelagic predators). The biological processes underlying growth and mortality in the model have led to patterns consistent with data from the North Sea. Secondly EwE (Ecopath with Ecosim) model has been chosen because of its ability to handle large food webs (66 species / functional groups for the Cefas North Sea Model) and its ability to find a balance point between the flows of energy into and out of a group without giving rise to an unstable attractor round the equilibrium point. The spatial model Ecospace was used to encapsulate the various gradients contained within the North Sea.

Developments in the assimilation of satellite chlorophyll data have led to improved model estimates of key ecosystem indicators compared to pre OPEC simulations. The greatest improvements have been seen for ecosystem indicators compared to pre OPEC simulations. The greatest improvements have been seen for predictions of chlorophyll and phosphate. The benefits of assimilation are lower in the winter, when cloud cover reduces the amount of satellite data available for assimilation.

Temperature and salinity provide useful information about changes in hydrological conditions, whilst chlorophyll, dissolved oxygen and nutrient concentrations are useful in monitoring and forecasting eutrophication and potential anoxic threats to aquaculture. Figure 1.4.2 shows how a rapid environmental assessment has identified oxygen concentrations below critical thresholds, signalling potential threats to the benthic living community in summer 2013. However the concentrations remained above the commonly applied hypoxia threshold of 2 mg-1, which is considered a potential trigger of fishery collapse. Primary production along with biomass estimates of phytoplankton and zooplankton, relate to the Biodiversity and Foodweb Descriptors providing valuable information about the state of the ecosystem at lower trophic levels. The system also provides simulated data in support of these descriptors on growing season, juvenile and adult populations of certain fish species such as cod and sandeels, abundance and distribution of commercially (i.e. cod and herring) and environmentally important species (seabirds, marine mammals). Marine Laboratory, UK

The Large Fish Indicator (LFI, weight fraction of fish larger than 40 cm over all fish) is used throughout policy as an indicator for biodiversity and food web complexity. In the UK, DEFRA have adopted the LFI as a means of monitoring change in the trophic structure of demersal fish communities, while on a European scale OSPAR has chosen the LFI as its fish community Ecological Quality Objective (EcoQO) metric. Long-period hindcast results showed higher LFI values in the North Sea's southern bight, due to the local importance of the benthic community as a direct food source for larger fish in the shallow areas as opposed to smaller fish (fig 1.4.3). High LFI variability was found in the Oyster Grounds region of the North Sea: this region is a hot spot for macrobenthos diversity and is currently being considered for protective measures by the governing authority (the Netherlands).

1.4.1.2 Operational Ecology capability in the Baltic Sea

The Baltic Sea region has been experiencing problems of hypoxia, harmful algal blooms, eutrophication and regime shift of fishery species in the past decades. This is due to a less-dynamic water cycle, warming climate and increased anthropogenic impacts. From a systems perspective, identifying which components of the ecosystem are manageable and which components must simply be adapted to, is a key part of sustainable fisheries management and may be achieved by including anticipated climate change in determining biological reference points. In unstable environments the adaptation of management to changing conditions is a crucial aspect of sustainable exploitation of marine resources.

The Baltic Sea operational ecology model system is described in Figure 1.4.4. The circulation model is HBM (HIROMB-BOOS ocean circulation model) and the biogeochemical model is ERGOM. They were selected as the operational models by the members of the Baltic Framework of the MyOcean project. HBM has a well-documented development history and features a two-way nesting technique. In the Baltic Sea, modelling is regarded as part of monitoring. Models represent the relationship between the forcing and biogeochemical processes and internal ecosystem dynamics. The latter may not be perfect, but major processes in the trophic levels are included. Through data assimilation, the model-based dynamics and correlation patterns can be used for spreading the observations in space and time. This has proved far more efficient and robust than purely statistical interpolation. The model quality is the central issue of this methodology. The main higher trophic level model used was the SMS model is a stochastic multispecies model describing stock dynamics of interacting stocks linked together by predation. It operates on annual or seasonal time steps.

The Baltic Sea models are capable of simulating variability of lower trophic level and biogeochemical

The Baltic Sea, models are capable of simulating variability of lower trophic level and biogeochemical variables at the surface. For the subsurface and bottom variables, through data assimilation, models can generate reasonable and useful products but it is clear there is room for improvement. Higher trophic level models improve their predictive skill by including environmental forcing, where appropriate.

Regional hindcast simulations for the period 1990-2009 have been made both the biogeochemical and HTL model components. The results indicate that all the model systems demonstrate a range of skill, depending on the variables chosen. Physical variables (e.g. T, S) are generally have the most skill) followed by chemical variables (e.g. O_2, Nutrients) then plankton variables (e.g. chlorophyll) for the coupled hydrodynamic LTL models. The HTL models have more skill for small pelagic fish (e.g. Sprat in the Baltic) than the plankton model that drives them.

Reanalysis simulations were performed for the period 2000-2009 using a 3DVAR scheme, which was implemented to assimilate satellite SST and temperature/salinity in situ profiles, since the satellite chlorophyll-a data products have large uncertainty/error in this optically complex region. In the Baltic the reanalysis improves the seasonal evolution of the phytoplankton blooms and nutrient concentrations in the surface and can also reproduces the overall features of the vertical profiles. Although the data assimilation scheme is rather simple, it improves model results for chlorophyll, nitrate, phosphate and pH in some areas but there are also negative impacts (Figure 1.4.5). In sense of nitrogen cycling, the Baltic Sea is rather open a system, because of denitrification in anoxic bottom layers and nitrogen fixation in surface by cyanobacteria. Carbon cycling is determined by circulation, air-sea carbon flux and biogeochemistry. Model performance for DIN and pH are poorer than for chlorophyll and phosphate. The reliability of the model performance itself impacts the efficiency of data assimilation. As we can see, data assimilation doesn't improve nitrate and pH as so much as for chlorophyll and phosphate.

1.4.1.3 Operational Ecology capability in the Mediterranean Sea

The Mediterranean Sea (MS) is a semi-enclosed sea, characterised by an inverse estuarine circulation with the Atlantic Ocean. Morphologically, it can be divided in two sub-regions (the Strait of Sicily separates the western and eastern Mediterranean), and it is characterized by the presence of a narrow continental shelf and two marginal sub-regions (the Adriatic Sea and the Aegean Sea). The major inflow into the Mediterranean is nutrient-poor, oxygenated Atlantic surface water through the Strait of Gibraltar. The western sub-basin is seasonally stratified and large parts of the open ocean eastern sub-basin are permanently stratified.

Physical processes create a dynamic and complex system in which mesoscale, thermohaline and wind driven circulations interact at different scales, resulting in a dominant west to east surface transport partially compensated by east to west transport at intermediate depths. The Mediterranean Sea is considered an oligotrophic region and it exhibits low productivity (generally <150 gC m-2 yr-1), with the highest levels occurring in the open ocean convection areas (mainly in north-western sub-region), along the coasts, near major cities and at river estuaries. The lowest productivity levels occur in the south-eastern Mediterranean Sea. These spatial trophic patterns are reflected in the deep chlorophyll maximum (DCM), a quasi-permanent structure (absent during the winter mixing period) in the MS, which is characterised by a zonal gradient: shallower in the west and deeper in the east. Despite its oligotrophic features, the MS maintains high levels of biodiversity and some hot spots for fisheries. Clupeoids (sardines and anchovies) represent the most important target group comprising 35% of catch on average.

The Mediterranean Sea has two operational ecology model systems:

- The OGS model system (OPATM-BFM) is part of the MyOcean Mediterranean Forecast System (MFS). The hydrodynamic model of MFS, based on NEMO, is run by INGV (Italy) which provides the physical fields for the transport-biogeochemical OPATM-BFM model. Within MyOcean and OPEC the system has fields for the transport-biogeochemical OPATM-BFM model. Within MyOcean and OPEC the system has been upgraded by adding a 3D variational assimilation (3DVar) scheme. The assimilation scheme use satellite MODIS surface chlorophyll to update the phytoplankton groups. The Ecopath with EcoSim modelling approach has been widely used to represent HTL group's dynamics as it allows for a representation of the food web in terms of functional groups and permits representation of exploitation activities.

• The HCMR model system (figure 1.4.6) comprises a coupled hydrodynamic/biogeochemical (POM-ERSEM) model implemented in the Mediterranean with 1/10 x 1/10 (~10Km) resolution. A higher resolution (1/15o x 1/15o) model is downscaled in the Aegean Sea, using open boundary conditions from the basin-scale model. A high-trophic-level (HTL) model (anchovy-IBM) is implemented in the Aegean. The data assimilation for satellite ocean colour data, is based on the SEEK (Singular evolutive Extended Kalman) filter approach.

Regional hindcast and reanalysis simulations for the period 1990-2009 have been made for both the biogeochemical and HTL model components with both model systems. In addition REA simulations have been made for the period 2010 to June 2014. These have be analysed to assess how seasonal variability impacts on assimilation effectiveness. Data assimilation is most effective in correcting the chlorophyll in winter and spring in the north western part of the Mediterranean Sea, where it corrects both the timing and the spatial patterns of the blooms. A significant effectiveness is also depicted in autumn both in the western and eastern sub-regions reflecting the correction on the vertical profiles during the end of the summer stratification. The effectiveness of carbon, phosphorus and nitrogen has, in general, comparable spatio-temporal patterns to that of chlorophyll (the assimilated variable). In particular, phosphorus is very similar to chlorophyll, while carbon and nitrogen show some differences with respect to chlorophyll in spring and autumn, a fact that reflects a partial uncoupling of carbon and nitrogen with chlorophyll and phosphorus. Phosphorus is the limiting nutrient in the Mediterranean Sea and therefore its covariance with chlorophyll is always very high. Nitrogen quota is already at the optimal growth status and therefore it remains unchanged during assimilation in spring and autumn.

The domains of two OPEC model systems (MED-HCMR and MED-OGS) are nearly identical. The two model results have been used to produce blended data products. An assessment was then performed to see whether the blended products improved the model skill for certain key indicators. Merging multiple models is feasible for the Mediterranean region. This requires as a first step the standardization of different model outputs with a common format and the sharing of a common analysis procedure. Three blending schemes have been developed: a simple average, a weighted average based on the overall model skills and a weighted average based on model variability maps (Figure 1.4.7). However, it was not clear which scheme presented the best performance, as different blending schemes showed the best skill, depending on the variable and the skill index considered.

The poor availability and spatial coverage of data in the Mediterranean is a significant problem when trying to assess the skill of different models and any increase of performance obtained from multi-model blended products. Based on the present availability of data (mean annual assessment), the skills of the blended products are, in general, in between of the skills of the two individual models, although some skill indexes of the blended products were found to be better than those of the two individual models: correlation of chlorophyll, correlation and RMSE of phosphate. As the skill of different models may show a significant spatial variability (e.g. one model is better in one area and the other model is better in another area), a next step would be to examine the performance of the blended products based on the model skills in different areas. In that way, the blended product would probably be more skilful than both individual models, as the blended product would incorporate the most skilful results of both models. However, this would require blended product would incorporate the most skilful results of both models. However, this would require better data coverage of in situ data.

OPEC has also simulated the anchovy biomass mean distribution for 2003-2006 in the Aegean Sea. When compared with biomass estimates from acoustic surveys, the model distribution is in good agreement with the observations (figure 1.4.8) showing an increase in coastal more productive areas, particularly Thermaikos gulf, Strymonikos gulf and Thracian Sea. The model underestimates the anchovy biomass in the Limnos Island area that is influenced by the BSW discharge.

1.4.1.4 Operational Ecology capability in the Black Sea

The Black Sea, a major semi-enclosed sea, has experienced striking ecological changes under the concurrent impacts of climate change, intense eutrophication, and population explosion of some invasive species, unsustainable fishery, and their density-dependent feedback processes. Land derived nitrate loading increased nearly four-fold during the 1970s due to increased use of agricultural fertilizers. Rapidly intensifying eutrophication has caused comparable increases both in the subsurface nitrate concentrations and phytoplankton biomass, degradation of the classical mesozooplankton-dominated food web by flourishing of the opportunistic species Noctiluca scintillans and Aurelia aurita in the 1980s. The intense eutrophication phase was ended by a sequence of events; the collapse of total small pelagic stock and the simultaneous outburst of ctenophore Mnemiopsis leidyi population at 1989-1991 and the subsequent marked decline of anthropogenic nutrient loads from the River Danube and other northwestern rivers following the disintegration phase of the former Soviet Union during the early 1990s. The subsequent years are referred to as the post-eutrophication phase in which the nutrient reduction led to approximately a two-fold decrease in the phytoplankton and small pelagic standing stocks and Noctiluca and Mnemiopsis populations (BSC, 2008), and 30-40% decline in the subsurface nitrate and phosphate peak concentrations. Invasion of the opportunistic gelatinous species Beroe ovata and their predation on the Mnemiopsis population has introduced further changes in the food web structure by the end of 1990s.

Black Sea model is an end-to-end coupled model (figure 1.4.9) that includes a physical model (POM), a lower-trophic-level model (BIMS_ECO), a higher-trophic-level box-type model (EwE) and an individual based model larvae model (Anchovy IBM). The model is able to reproduce all of the major features of the observed vertical profiles for of nitrate, phosphate, oxygen and hydrogen sulphide concentrations, partial pressure of carbon dioxide in water as well as net primary production in the Black Sea however there are still some issues that need to be resolved. Figure 1.4.10 shows the surface distribution of zooplankton biomass from the REA for November 2013, and shows high biomass on the biologically productive NW Shelf. This illustrates the ability of the model to produce snapshot of the current state of the Black Sea ecosystem.

In-situ nitrate observations were assimilated into the biogeochemical model using a relaxation scheme. A one-dimensional nitrate profile was obtained by computing the open-basin (>500m) average of observed nitrate profiles for the period 2005-2009, which were present in the IMS-METU in-situ measurements database. Such a scheme was found to be necessary in order to maintain the peak nitrate values within the sub-oxic layer. In the simulations performed without the assimilation of nitrate, peak nitrate values deviated from observed values due either to processes unknown or uncertainties in the river nutrient loads and discharge rates.

1.4.2 Impact of data assimilation on non-assimilated variables

OPEC has assessed the performance of the reanalysis model systems with an emphasis on evaluating the performance of non-assimilated variables. A synthesis of the reanalysis results and lessons learnt for the future implementation of data assimilation leads to the following conclusions and recommendations:

1. In all regions the reanalysis simulations demonstrated improved skill for the assimilated variable(s) at

1. In all regions the reanalysis simulations demonstrated improved skill for the assimilated variable(s) at the scale of the whole domain.
2. For non-assimilated variables the assimilation improved the skill of some variables and degraded others.
3. There were no common patterns between different regions using similar models (ERSEM/BMF, NE Atlantic, and Mediterranean) but different assimilation schemes. There is a requirement for a data assimilation system inter-comparison experiment (I.e. testing different schemes with the same, hydrodynamic ecosystem model and data sets).
4. The impact of the assimilation schemes was variable across model domains and in part a function of the variability in both models and assimilated variable uncertainty. Further improvement in the quantification of uncertainty in satellite data products is required. Perturbed parameter model ensembles are required to help quantify model uncertainty.
5. The ability to assess data assimilation skill is limited by the available independent data. In some cases the data rich areas are in regions where the assimilation has little impact because of large uncertainties. Improved monitoring of key variables is required.

1.4.3 Assessing the predictability of seasonal forecast

The marine ecosystem is subject to changes due to climate (global warming, acidification) and human activities (fishing, pollution etc.). To maintain good environmental status and to help mitigate risk, the management of marine resources needs information on a seasonal time scale. Marine ecosystem models could provide information, for example on the occurrence of Harmful Algal Blooms (HABs) that is be valuable for assessing risk on deleterious impacts on the tourism and aquaculture industries etc. Perhaps the most familiar forecasts are weather conditions but due to the chaotic nature of weather, its prediction is limited to a few days and a longer forecast often requires an ensemble of model integration covering the possible evolutions. Marine ecosystems are driven by seasonally varying physical processes and follow a relatively stable seasonal pattern so an ability to predict seasonal changes in the ocean will help in continued management of marine resources.

OPEC is a proof of concept project; this section highlights the work achieved towards developing an approach to making seasonal forecasts of the health of marine ecosystem using an ensemble of ecosystem models. A series of experiments were performed in different model systems to explore their potential for making predictions over a seasonal time scale, considering their sensitivity to initial conditions and meteorological forcing. In the Baltic Sea, a downscaled seasonal model forecast was performed using the European Centre for Medium-Range Weather Forecasts (ECMWF) SEAS atmospheric ensemble forecast with perturbations on wind and sea surface temperature. In the Mediterranean an atmospheric ensemble was developed for the seasonal forecast of the ecosystem (Figures 1.4.11).

A key aspect of this project was data assimilation which aims to bring model results closer to observations and corrects its initial conditions for the next forecast. In each regional sea of study, the skill of a three-month model simulation (that mimics seasonal forecast) initialized each month of the year from a data assimilative run was assessed against climatology (Figure 1.4.12). In this way, the benefit from using the “correct” initial conditions, assimilating all the presently available information, was compared with the best-available seasonal climatology obtained from re-analysis. The sensitivity of a seasonal forecast on the uncertainty in the initial (winter) nutrients was also examined to calculate the response of primary production and zooplankton.

The re-analysis climatology provides a skilled approximation for a seasonal forecast, since it has been produced by assimilating data from previous years. However, at present it represents a mean state of the ecosystem, rather than capturing the inter-annual variability. Given that the seasonal forecast has the

ecosystem, rather than capturing the inter-annual variability. Given that the seasonal forecast has the 'correct' initial conditions using data assimilation, it is expected that forecasts will show a better skill than the climatology at least for a period of time.
The results are assessed by comparing them with a simulation that has used data assimilation, assuming this is our best estimate of the marine ecosystem state. In the Baltic Sea for example, the seasonal model forecast, using the ECMWF SEAS atmospheric ensemble, shows a better skill for chlorophyll after three months (March) compared to the climatology, particularly in the North Eastern coastal areas (figure 1.4.12). However, its predictability decays after two months (May), showing a high chl-a relative error in the eastern coastal region of the central Baltic Sea.
Ensemble seasonal forecast also provide information on the predictability or uncertainty in different regions. By looking at the spread of the different ensemble members represented by their standard deviation the range of the model prediction is further illustrated (Figure 1.4.13). Here the standard deviation is higher in areas that are less predictable, showing a stronger variability, as is the case in the Gulf of Lions and Adriatic Sea, where intense vertical mixing occurs in the winter-spring period. The use of ensemble methods in the simulation of small pelagic fish not only offers prediction of the future fish stock, but also estimates of their biomass range.

These experiments are the first step towards a protocol for seasonal forecasts using model ensembles. The ability to predict changes and understand variability within marine systems at a seasonal scale will support the monitoring and management of marine systems at a regional level. Development in this area, sustained by improvements in data assimilation and numerical modelling will further increase the value of ensemble prediction. Continued work is needed in this area and as meteorological predictions continue to grow in skill the application of seasonal forecasting will improve. It is clear from the work undertaken by OPEC that the predictability of ecosystem variables varies between years, across the Mediterranean, Atlantic, Baltic and Black Sea with strong evidence that these variations are also related to atmospheric and hydrodynamic variability. Most metrics of seasonal forecast quality are mainly technically presented in a nature not easily communicated to audiences outside the seasonal forecasting community. Several broad qualitative and quantitative outcomes have been produced from the experiments reported leading to the following recommendations:
• Seasonal predictions are more skilful in some regions the others, skill generally being higher in areas when the oceanographic response to meteorology is relatively small. Furthermore, climatology, or persisting recent seasonal anomalies in many cases can provide useful information.
• The quality of seasonal predictions varies on an inter-annual basis, partly connected to inter-annual variability of the specific marine ecosystem dynamics; average quality also differs between specific seasons.
• Of the major seasonal variables of interest, predictions of hydrodynamic variables (temperature, salinity, etc.) generally are of a better quality than biogeochemical variables, such us chlorophyll, nutrients, primary production etc.
• As rule of thumb, but with some exceptions, initial conditions provided from data assimilation, improve the model projections. However information on spatial patterns is lost quite quickly. Forecast initialization is an area that requires active research.
• Ocean data assimilation has improved forecast quality. Coupled data assimilation should be a field of active research requiring enhanced support and maybe international coordination. There is certainly significant evidence that coupled atmosphere-ocean-biochemical data assimilation should improve forecast quality.
• OPEC has demonstrated that in some regions and during some seasons, seasonal predictions have

• OPEC has demonstrated that in some regions and during some seasons, seasonal predictions have quality, but their translation into useful information for end-users is far from optimal. It is essential that a concerted effort is made to engage customers and seek their quantitative definition of value, so that the forecasts will be able to be used in decision-making issues. Since the direct connection between seasonal forecast quality and value has not been established, appropriate processes need to be engaged to measure value in specific decision making instances independently from the assessment of quality. It should be noted that experience in climate variability (e.g. the chances of varied scenarios, despite forecasts) could aid applications/planning/management. The application of forecasts requires trust in the overall quality of the forecasts and knowledge of the forecast uncertainty.
• Multi-model methodologies are a useful and practical approach for quantifying forecast uncertainty as a consequence of the model formulation. Still, there are open questions associated with the multi-model approach. For example the approach is ad-hoc meaning that the choice of models isn't optimized. Nor has the community converged to any best strategy for combining the models. Multi-model calibration activities tend to yield positive results, but considerable work has to be done. These problems as well as others require additional research. It is also important to realize that the multi-model approach should not be utilized to obviate the need to improve models.

• Validation needs to be routinely undertaken on seasonal dynamical application models. These models ought to be complex enough to capture non-linear interactions, and at the same time being sufficiently simple to avoid over tuning through non-constrained parameters.
• The relationship of forecast quality, in applications of fish models is often highly non-linear with respect to meteorological and biophysical models. Consequently, quality inside the prediction of seasonal chlorophyll might not be translated into quality within the prediction of mean fish stock, for example. Such application models like fish models should have additional metrics of forecast quality. Furthermore, these metrics should be suitable for a selected user group.

1.4.4 Assessment of ecological monitoring system and data needs for GMES ecological service

A major goal of OPEC was to assess the effectiveness of current operational marine biogeochemical monitoring network in European Seas for the purpose of operational ecology, such as activities of rapid environment assessment, hindcast, reanalysis and forecasting in a various range of scales. The purpose of this assessment is to test the feasibility of the assessment method and find out the data adequacy for operational forecasting and rapid environment assessment.

In this task, methodology of quantitative assessment of physical monitoring networks, which was developed in EU projects ODON and ECOOP, is effectively applied to assess the biogeochemical monitoring networks in Baltic, NE Atlantic, Mediterranean and Black Sea. The assessment is focused on the method development and application, thus only limited number of parameters such as chlorophyll-a, nitrate, phosphate and Dissolved Oxygen (DO) were investigated. The effective coverage and explained variance of current monitoring networks are estimated by using the same code developed in DMI and the covariance metrics estimated from model hindcast and/or reanalysis.

This work used mathematical formulae to quantitatively assess the efficiency of existing biogeochemical monitoring networks in European regional seas. Two indicators were used in this assessment, effective coverage and explained variance.

• Effective Coverage: For a given location and parameter, the effective coverage (rate) provides the ratio where the location is effectively covered by the monitoring network. This is determined by both the amount and distance of observations near the location and the spatial-temporal characteristic scales of the parameter at the location (figure 1.4.14). This method can therefore identify the gaps and the effectively covered areas by a given monitoring network, but it does not assess the quality of the information product

covered areas by a given monitoring network, but it does not assess the quality of the information product.
• Explained Variance: The explained variance by a given monitoring network aims to assess the relative importance of the existing observations by their ability to infer the time series at locations in the absence of observations (figure 1.4.15).
The focus of variables and assessment indicators are complementary in different basins. The effective coverage and explained variance of current monitoring networks are estimated by using the same code developed in DMI and the covariance metrics estimated from model hindcast and/or reanalysis. The purpose of this assessment is to test the feasibility of the assessment method and find out the data adequacy for operational forecasting and rapid environment assessment. The monitoring network put in the assessment includes those available from MyOcean In-Situ TAC (Thematic Assembly Centre), regional commissions e.g. HELCOM database and some national monitoring networks e.g. UK.
It was found that the surface chlorophyll-a and DO are reasonably well monitored in the Baltic Sea (figure 1.4.14) and North Sea, attributed to a combination of FerryBox, research vessels and mooring buoys. The vertical profiles are less well covered. The monitoring network based on regional Commission such as HELCOM is a major contributor. However, such data are normally delivered in a delayed mode, therefore not suitable for short-term and seasonal forecasting, and even Rapid Environment Assessment.

In most of the Baltic Sea, phosphate is observed with an effective coverage ratio of more than 40%. For the Black Sea, the regular national monitoring programmes can only explain about 7-20% of the total variance of chl-a, nitrate and phosphate. For Mediterranean and NW Shelf Sea, only very limited number of moored buoys was assessed, which well covers local areas of 100km radius for given buoy stations.
It was also found that the sampling frequency has a big impact on the explained variance of FerryBox lines. For one FerryBox line in Adriatic Sea, the daily sampling has an explained variance of more than 90% for surface chl-a while weekly sampling can only explain about 35% of the total variance (figure 1.4.15).
Potential Impact:
1.5 Potential Impacts
OPEC was targeted at three major target audiences. The first is the European operational oceanography community; OPEC was primarily funded to undertake R&D in support of the marine core service. The second audience group is primarily decision makers in both the policy and management arenas, but also including the wider marine science community and the interested public. The final group are the SME's interested in knowledge with a view to the development of downstream services.
1.5.1 Copernicus Marine Service – implementation of the Operational Ecology
Operational ecology aims at the systematic and operational provision of quality assured data and information on the status of marine ecosystems (environment, low trophic and high trophic levels) to stakeholders through integrating research, operation and service. The data products are generated from remote sensing and in-situ measurements and marine ecosystem models with data assimilation for the past (reprocessed long-term observation time series and reanalysis), current and recent (analysis and updated rolling reanalysis) and future (short-term/seasonal/decadal forecast and scenario projections). The information products are value-added ones, such as ecological indicators and descriptors (as defined in MSFD implementation plan) and seasonal/annual marine ecosystem status reports, derived from the data products.
The relationship between Research, Operation and Service is shown in a flowchart in Fig. 1.5.1. The objective of the Research module is to develop state-of-the-art monitoring, modelling and assessment. With inputs on the service and service data requirements from the OE Service module, the OE Research will firstly identify the corresponding scientific and technical requirements for the next generation

will firstly identify the corresponding scientific and technical requirements for the next generation monitoring and modeming platforms as well as a roadmap for implementing the research and development. Operational Ecology research covers, but not limited to, the optimisation of monitoring platforms/networks and marine ecosystem models, efficient combination of the two through data assimilation, technology to assess and reduce the product uncertainty, and methodology and tool development for the integrated ecosystem assessment and service.

The objective of the Operation module is to generate quality-assured data and information products on an operational basis by using the platforms developed in through Research. It includes implementation of the platforms, calibration and operational verification of the platforms and products and operational maintenance of the dataflow (quality control of raw data, pre-processing, historical states reconstruction, analysis, forecast and projection, value-added post-processing).

The objective of the Service module is to ensure a user-driven approach. It includes timely and effectively broadcast and dissemination of the data and information products generated in the Operation to the stakeholders, facilitation of user uptake, down-stream services, user requirements/feedbacks/verifications, specification of service evolution strategy (service and service data requirement, technical requirement) and implementation plan together with the OE Research and Operation modules.

In the past decade, Europe has implemented a program of Global Monitoring for Environment and Security (GMES, currently renamed as Copernicus), aiming at a provision of operational services based on the earth monitoring. The Copernicus Marine Service is one of the three fast track services which aiming at providing quality-assured operational data and information products for both the physical ocean and the marine ecosystem. A pre-operational service was developed through EU FP6/FP7/Horizon 2020 project series of MERSEA, BOSS4GMES, MyOcean I, II and Follow On. Currently the Copernicus Marine Service provides data and information services with a strong emphasis on physical and a limited subset of biogeochemical parameters (chlorophyll, nitrate) for the global and European regional seas (Arctic, Baltic, NW Shelf Sea, NE Shelf Sea, Mediterranean Sea and Black Sea).

The next phase of Copernicus Marine Service will be full operation mode from April 2015 – March 2021. Mercator Ocean is the entrusted entity of the European Commission (DG Enterprise) to implement the Service. At the time of writing they are undertaking a tendering exercise to appoint the delivery partner for the regional production centres (Arctic, Baltic, NW Shelf, Mediterranean and Black Seas), MERCATOR Ocean will be responsible for the provision of global and SW Shelf Sea (IBI region). There will also be a separate procurement focusing on the coupled global atmosphere-ocean model system and multi-model ensemble global ocean reanalysis.

Research for next generation platforms: OPEC was funded to develop and evaluate ecosystem forecast tools. To this end OPEC has developed prototype ecological marine forecast systems for European seas, which include hydrodynamics, lower and higher trophic levels (plankton to fish) and biological data assimilation. The vision for the OPEC project was to provide a range of data products describing the past (historical reanalysis simulations), present (Rapid Environmental Assessment (REA) of the current state of the system) and future (seasonal forecast) states of European marine Ecosystems. The emphasis is on providing information which describes the environmental status of marine ecosystems (e.g. Indicators, habitat descriptions), intermediate services (e.g. nutrient budgets, primary production) and final services (e.g. fish stocks). OPEC has developed four new services with the potential to be implemented in the Marine Core Service. A prototype of each of these products has been implemented in the NE Atlantic, Baltic Sea, Mediterranean Sea and Black Sea regions as follows;

Reanalsysis hindcast for the period (1990-2020): These simulations provide a baseline estimate of the state of European marine ecosystems, allowing the determination of climatological seasonal cycles, inter state of European marine ecosystems, allowing the determination of climatological seasonal cycles, inter-annual variability and trends for a range of key ecosystem variables.

• NE Atlantic: Coupled hydrodynamic (POLCOMS) ecosystem model (ERSEM), with data assimilation of satellite ocean colour (EnKF) and offline simulation of off line HTL / fisheries using Ecopath with Ecosim and a size spectra model (PML, Cefas).

• Baltic Sea: Coupled hydrodynamic (HBM) ecosystem model (ERGOM), with data assimilation of in-situ optics and nutrient profiles (nudging method) and offline simulation of off line key fish commercial species (Cod, Sprat, Herring) using SMS. (DMI, DTU).

• Mediterranean Sea:

a. Coupled hydrodynamic (POM) ecosystem model (ERSEM), with data assimilation of ocean colour (SEIK) and a two-way coupled simulation of anchovy in the N. Aegean Sea using an IBM. (HCMR)

b. Offline hydrodynamic (NEMO, My ocean operational model), ecosystem model (BFM), with data assimilation of satellite ocean colour (4D var)) and offline simulation of off line HTL / fisheries in the Adriatic Sea using Ecopath (OGS).

• Black Sea: Coupled hydrodynamic (POM) ecosystem model (BIMS_ECO) and offline simulation and offline simulation of off line HTL / fisheries in the Adriatic Sea using Ecopath (METU).

Rapid Environmental Assessment (rolling hindcast or reanalysis of recent past): The OPEC REA experiments have demonstrated that coupled oceanographic/marine ecology models can be operationalized combining model with observations to interpolate and/extrapolate experimental observations to areas and time periods not covered by existing observational networks. In addition REA's provide an indication of ecosystem properties which cannot be measured in near real time (e.g. phytoplankton species) or are difficult to observe (e.g. foodweb structure). Such estimates can be updated in quasi real time, by exploiting the causal relationships which constrain the dynamic of those properties to those of measured properties (e.g. a model which produce skilled assessment of nutrients and chlorophyll is likely to produce reasonable estimates of primary production and, possibly, of secondary production). The REA can be undertaken with all the regional model systems.

Monitoring system assessment: OPEC has developed tools to assess the effectiveness of current operational marine biogeochemical monitoring networks in European Seas for the purpose of operational ecology.

Potential for seasonal forecast: The predictability of a model is influenced by various factors, including initial conditions, external forcing functions (e.g. meteorological forcing, open boundary conditions, freshwater and nutrient inputs) and model process descriptions and parameterisations. Predictability experiments showed that initial conditions provided from the assimilation experiments and used for the initialization of the seasonal forecasts, produce an improvement in model projection but information on spatial patterns is lost quite quickly, evidencing the need of assimilating surface chlorophyll data at a time frequency higher than monthly. To represent model uncertainties, ECMWF downscaled forecast ensembles were used in the Baltic Sea, while for the Mediterranean, an ensemble of atmospheric perturbations was generated using data assimilation techniques.

The downscaled ocean and ecosystem forecast ensemble showed a better prediction skill than the climatology on a seasonal scale, although this decayed with time. A multi-model ensemble approach is foreseen as a final solution for forecasting pan-European regional sea ecosystems in seasonal or longer time scales.

In addition OPEC has developed the following tools which should be of benefit to the COPERNICUS MARINE SERVICE:

• An open source webGIS Data portal, which allows users to visualize, plot and download large spatial

• An open source webGIS Data portal, which allows users to visualize, plot and download large spatial-temporal data sets (http://portal.marineopec.eu/) and section 1.5.4.
• A model benchmarking tool, for the automated validation of numerical simulations available as open source python scripts.
Roadmap for transition to the Marine Core Service
The OPEC project has provided a robust evaluation of the regional ecosystem forecast models. Our aspiration is to maintain and transition these systems into the operational suites of the Copernicus Marine Core Service. Consequently OPEC had defined a roadmap for the transitioning its research into the Marine Core Service.
There are three key objectives of the roadmap:
• To identify and work with stakeholders to determine the user requirements for the system.
• To transition to an operational status in the Marine Core Service, OPEC model systems and data products, in terms of both quality assurance (monitoring administrative and procedural activities) and quality control (verification of data products)
• To determine the future R&D requirements to deliver the full range operational ecology products.
Stakeholder requirements: A primary requirement for the marine operational ecosystem service is to have a clear idea of its stakeholders and their requirements. At the heart of this is the provision of an evidence base which demonstrates to the management teams of the operational centres that the prosed product(s) are a genuine user requirement. A major challenge is communication to resolve the tension between research driven products and user defined products.
Implementing systems and evaluation of OPEC products: Once the user requirements have been established and potential new products have been accepted by the operational centres, then OPEC regional systems and products can be transitioned to operational status. The key challenges include:
• Feasibility of integrating the new products into the existing forecast system.
• Establishing the data feeds from the COPERNICUS MARINE SERVICE (met data, EO for data assimilation, open ocean boundary conditions).
• Establishing the QA procedure for OPEC services.
• Developing the QC procedure for OPEC services.
• Data delivery systems.

Future R&D: Operational ecology is a new and developing field. For the moment, no countries have provided a quality assured ecology service including seasonal forecasting, annual assessment, decadal reanalysis and scenario projections of marine ecosystems on an operational basis. Significant knowledge gaps exist in:
• Understanding and modelling biogeochemical cycle in the regional seas.
• Understanding and modelling interaction between low trophic level and high trophic level.
• Data assimilation techniques for biogeochemical parameters and with focus on improving long-term forecasts and statistics.
• Forecasting technology in seasonal and longer time scales.
• More accurate modelling and estimation of river nutrient load their fate in the sea.
• High trophic level modelling and forecasting technology.
• End 2 End ecosystem modelling for operational scenario projections.
1.5.2 Operational Ecology to inform policy
1.5.2.1 Marine Strategy Framework Directive
The OPEC modelling tools and data sets have the potential to help to assess and manage the risks posed

The OPEC modelling tools and data sets have the potential to help to 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. The target audiences for OPEC research are primarily, decision makers in both the policy and management arenas but also include SMEs interested in the application of knowledge, the wider marine science research community and the interested public. A particular focus is the Marine Strategy Framework Directive (MSFD) which provides a transparent, legislative framework to apply an ecosystem based approach to the management of human activities in the marine environment. The MSFD aims to achieve ‘Good Environmental Status’ (GES) across Europe’s regional Seas by 2020. The strategies to achieve this must contain a detailed assessment of the state of the environment, a definition of "good environmental status" at regional level and the establishment of clear environmental targets and monitoring programmes. The MSFD also identifies 11 high level descriptors, 5 of which are considered by OPEC (D1 Biodiversity, D3 Commercial Fish, D4 Foodwebs, D5 Eutrophication, and D6 Hydrography). Each descriptor is characterised by a set of indicators which characterise marine ecosystems and requires and understanding of the possible pressures and impacts on them. The diversity in environmental conditions and the issues of scale have implications for the implementation of the descriptors in the assessment of Good Environmental Status (GES). There is no single set of criteria and indicators which can meaningfully be applied to all marine regions/sub-regions, and often not even for a single descriptor within a marine region/sub-region, and this requires a regional approach as used in OPEC. The impacts OPEC products can potnetial provide at descriptor level are as follows:

D1 Biodiversity: Marine biodiversity may be measured in many ways e.g. by number of species, genetic resources and functional diversity. This makes assessing biodiversity a difficult process, given the variety of species and their functions in an area or region, as well as the genetic variation between individuals of a species, the structure of plant and animal communities, and their physical environment. GES for biological diversity is deemed to be maintained when the quality and occurrence of habitats and the distribution and abundance of species are in line with prevailing physiographic, geographic and climatic conditions. OPEC has developed a number of products that can be used as indicators of biodiversity, particularly in terms of pelagic habitat (e.g. chlorophyll, oxygen, pH, primary production).

D3 Commercial Fish: The Descriptor 3 definition for GES is: “Populations of all commercially exploited fish and shellfish are within safe biological limits, exhibiting a population age and size distribution that is indicative of a healthy stock.” Key criteria for measuring GES include the level of fishing pressure, the reproductive capacity of the stock and the age and size distribution of the assessed population. A suite of modelling tools has been implemented by OPEC, each targeting the major exploited fish resources in each of the MSFD regions. A diversity of approaches has been used ranging from foodweb and size structured models to Individual Based (IBM) and multi-species stock assessment models.

D4 Foodwebs: Climate change will exacerbate the impacts of human activity on the structure and function of marine ecosystems, and the services they provide. The combined effects of climate, fishing, nutrient loading and pollution impacts at both organismal and population levels, influencing the competitive ability and dominance of key marine species, which in turn reorganises the structure of marine food webs. The MSFD states that GES is achieved if the integrity of food webs ensures the long-term abundance and reproduction of its species. Coupled physical to ecosystem models (OPEC models e.g. Ecopath with Ecosim, Ecospace)allow us to calculate marine foodweb properties.

D5 Eutrophication: Eutrophication refers to the processes related to discharge of macronutrients in the marine environment that stimulate the rapid growth of microalgae and lead to disruptive effects on the marine environment. Eutrophication has broad reaching impacts and can have negative impacts on other descriptors such as biodiversity, non-indigenous species, food webs and commercial fish. OPEC models descriptors such as biodiversity, non-indigenous species, food webs and commercial fish. OPEC models are able to provide estimates for recent trends and future forecasts for several of the indicators for eutrophication: nutrient concentration in the water column, chlorophyll concentration, phytoplankton biomass, dissolved oxygen. Additionally some models can provide more detailed information on nutrient ratio and phytoplankton community composition.

D7 Hydrography: Hydrographical conditions are the physical properties of seawater (temperature, salinity, depth, currents, waves, turbulence, turbidity). They play a crucial role in the dynamics of marine ecosystems. In the near shore regions many of these are directly influenced by human activity so can be targeted by policy and management actions. GES assessment and targets are based on quantifying the extent, distribution and severity of permanent alterations in hydrographical properties as a result of human activities. OPEC models can be used to provide informaiton on temperature, salinity, mixed layer depth and currents thus providing information on the physical state of the marine environment.

1.5.2.2 Implementing ecosystem-based management

Ecosystem models are central to delivering current and future policy requirements including: predicting the effects of competing management options, assessing potential impacts across the whole ecosystem, testing the sensitivity of socio-ecological indicators, optimising monitoring programmes, understanding the application of theoretical concepts like Maximum Sustainable Yield (MSY), developing ecosystem service flows, and providing an assessment of the risk associated with management measures.

The potential for quick wins in the policy and regulatory environment were explored as part of the MSCC/MASTS ecosystem modelling workshop (Table 1). However, there were still concerns expressed by both stakeholders and modellers about the translation of policy needs to tractable modelling questions. More work is required on each of these quick win topic areas to identify where work is already being done that will deliver these aims and, if not, exactly how this might be taken forward. This should focus on attributing drivers of change, integration of models and monitoring to maximise the efficiency and utility of those programmes, assessing MSFD indicators and interactions between descriptors, and cost-benefit of legislation (Table 1).

Table 1: Potential for use of ecosystem models in addressing policy needs in terms of quick wins, multi-model ensembles (in italics), and gaps that cannot currently be addressed.

Theme Quick Wins Gaps

Environmental change and climate adaptation • Regional scale climate impacts and their value
• Attributing change in ecosystems to environmental drivers and the systems response
• Impacts of shelf-seas biogeochemistry on ecosystem state • Introductions and impacts of non-native species
• Animal and human disease
• Local effects of pressures
• Impacts of ocean acidification
• Impacts on the land-sea transition zone
• Impacts of geo-engineering
• Impacts of offshore structures

Natural variability and monitoring • Distinguishing between different indicators.
• Quantifying uncertainty
• Integration of models with monitoring to increase efficiency
• Identifying current system state • None identified

Management measures, goods and services • Efficient programme of measure for achieving GES
• Impacts of landing obligations on MSY through food webs interactions

• Impacts of landing obligations on MSY through food webs interactions
• Management strategies for achieving MSY in a mixed fishery
• Effects of fishery management on food webs
• Cost-benefit of implementation of legislation (e.g. MSFD, CFP, WFD)
• Marginal costs / values of changes in ecosystem services
• Links between ecosystem function and services • Assessing networks of MPAs in terms of connectivity, achieving management objectives and socio-economics.
• Cumulative effects
• Risk of decline of endangered species from CFP reform
• Coupling between ecosystem services and benefits in socio-ecological systems
Good Environmental Status, state and pressure • Sensitivity of indicators to management measures and identification of better indicators
• Effects of pollution on the marine environment
• Interdependencies between MSFD descriptors • Impacts of population dispersants
• Interdependencies between different descriptors within MSFD
• Model interoperability – modular approaches

1.5.2.3 Towards sustainable fisheries management in the Baltic Sea
Over 80% of the commercial catches in the Baltic Sea consist of cod, herring and sprat. Cod are cannibalistic and forage on herring and sprat. More than 50% of the stomach content in Eastern Baltic cod greater than 40 cm is herring and sprat, and these two species contribute more than 80 % of the total fish fraction in the diet of cod. Oxygen and temperature condition in the Baltic vary considerably, due to the intermittent exchange of water with the North Sea. All three species are affected by this variability. Two key questions arise:
• How does variability affect these species?
• How can this knowledge be used in support of ecosystem based fisheries management?
The relationship between spawner abundance and biomass, and the size of the recruiting year-class is crucial for understanding fish population dynamics and supporting fisheries management.
Especially the term 'density-dependence' has to be understood mechanistically, in order to understand recent changes in cod condition (Fig.1.5.2) – Are they due to high recruitment, lack of prey fish, lack of bottom dwelling prey, or other causes?
In the Baltic Sea, the relationship between spawner abundance and the size of the recruiting year-class is to a large extent influenced by environmental conditions which vary from year to year. While knowledge of the impact on herring year class strength is still limited, it is accepted that sprat depends on temperature, and cod on the availability of oxygen for eggs and larvae. The cod eggs need at least 2m l-1 oxygen concentration to develop, but even at this minimum threshold, only about 20% of the eggs survive to the larval stage. In OPEC, quantitative empirical models have been further developed to help account for these dependences. The models were, for the first time, included in the hindcast runs of the multispecies model that is applied in the Baltic. It is also now possible to include climate change in model predictions; these developments have increased our understanding of the historical stock development of cod and sprat.
There are three important issues which so far have not been addressed comprehensively, but might form the major challenge of ecosystem based fisheries management in the future:
1. Include anticipated climate change in the determination of biological reference points. In unstable environments such as the Baltic Sea (Fig. 1.5.3) the adaptation of management to changing conditions is a key point for sustainable exploitation of marine resources.

key point for sustainable exploitation of marine resources.
2. Understand changes in vital rates for exploited key species. OPEC information has already been used in understanding recruitment variability in Baltic cod. But also changes in body growth rates, food consumption and maturation can be more easily anticipated now.
3. Identifying which components of the ecosystem are manageable and which components must just be adapted to is a key part of sustainable fisheries management. Some elements of the ecosystem, for example the benthos and plankton production are almost impossible to manage. Instead we have to be ready to anticipate expected changes and incorporate them into management decisions, for example as a limitation of food for exploited species, or modifications in the control mechanisms inherent in the marine food web, ultimately modifying the stability properties of the ecosystem.
Use in Management: Extending the standard model used for eastern Baltic cod with the knowledge gained in OPEC, we could make probable links that oxygen depletion actually resulted in much lower recruitment than anticipated (Fig 1.5.3). We did this by accounting not only for the total size of the reproductive water volume, but also including the oxygen conditions inside this volume for the first time, the oxygen related egg survival. Standard models do not include oxygen at all, but only spawner biomass. Accounting for oxygen related egg survival; OPEC could show that recruitment was lower as anticipated, because although there were enough spawners, the environmental conditions did not support recruitment. This model will be used in innovating predictions for cod population dynamics and vital rates in ecosystem assessments and management.

1.5.3 Monitoring strategy assessment

Operational Ecology applications require a robust scientific and technological base of modelling, optimised use of observations in the models (e.g. data assimilation, Observing System (Simulation) Experiments etc.) and multi-sensor data processing. Recommendations for future monitoring and data infrastructure have been made based on our assessment of current European observing systems. Two types of activity are recommended: improvement of data availability and accessibility through shortening data delivery times and improvement of data adequacy through optimising sampling schemes and deployment of new platforms where required. In order to support the decision making, research efforts are need to demonstrate the impacts of implementing the two types of activities on the OE applications. The following research priorities are suggested:
1. Further development of quantitative assessment and optimal design methods to fit the purpose of Operational Ecology: this includes statistical methods based on the spatial and temporal correlation patterns, OSEs and OSSEs. It is important to investigate the consistence of spatial-temporal correlation patterns from different models and from observations.
2. Cost-benefit analysis of different schemes of shortening the data delivery time: the cost should cover upgrade of technology and operational system and operations. The benefit should cover quantitative improvement of effective coverage, explained variance and the performance of OE applications
3. Optimisation of temporal sampling schemes of the existing monitoring networks: the purpose is to derive where possible more cost-effective sampling schemes for existing networks. In OPEC we have found that sampling frequency makes big difference in explained variance.
4. Optimisation of European Sea buoy arrays: it is recommended to deploy at least one mooring buoy for measuring biogeochemical variables in each Member State. The optimal locations of the buoys should be defined through quantitative optimal design methods and their impacts can be assessed through the OSSEs.
5. Optimal design of ferrybox lines: the ferrybox has been proved as a cost-effective platform for surface biogeochemical monitoring. The technology may include nutrient measurements in the future. Now

biogeochemical monitoring. The technology may include nutrient measurements in the future. New ferrybox lines may be added in the Med. Sea and Black Sea. A thorough assessment of the existing and proposed rationalized ferrybox lines (locations, sampling frequency and parameters) using OSEs and OSSEs is necessary.

It should be noted that cost-effective monitoring technology is also an important issue for optimising future monitoring networks. The current analysis has recommended sharing the best practice of ferrybox and Smart Buoys but has not made a full coverage analysis of all the new technologies.

1.5.4 OPEC Data Portal

The Marine OPEC Data Portal provides access to the model simulations/outputs (referred to as indicators) generated by advanced marine ecosystem model systems developed throughout this project. The new data produced by them is made available, quickly and simply, through the data portal for the following regional seas: the NE Atlantic, and the Baltic, Black and Mediterranean Seas. The suite of ecosystem indicators paints a picture of the state of the marine environment from 1990 to 2014 in these four European regional seas. Ecosystem models are fundamentally numerical simulations of real world systems which can be used to make predictions about the dynamics of the system. They are developed by combining our understanding of ecological relationships with field data.

The Marine OPEC Data Portal provides free access to data on a range of ecosystem indicators. Models output a wide range of information including maps and plots. Improved understanding of ecosystem state indicators can help build management plans, set targets and monitor the marine environment.

Data products: Key indicators in the portal include: temperature, salinity, phosphate, nitrate, silicate, chlorophyll, phytoplankton, zooplankton and fish biomass. These indicators are available for all regions extracted from the following simulations;

• Simulations of the last 20 years: 20 year hindcast simulations of regional seas describing past states and trends in the ecosystem in terms of physics, nutrients, plankton and fish are available.

• Rapid Environmental Assessment: The Rapid Environmental Assessments (REA) blends model and observations to provide the best available estimates of the current state (represented as the preceding 3 months) of the ecosystem.

These two data streams have been joined within the portal to provide one seamless data product. Full metadata is available for each indicator providing detailed information for example on: the data provider, models used and their skill assessment, the simulation period and the data provider's level of confidence in the data. Multiple indicators may be loaded and displayed on the same base map for comparison and a graphical "time bar" allows for the selection of a particular date and shows the availability of data for each indicator. Finally time series graphs can be generated for multiple indicators to highlight how they interact with each other or change over time showing seasonal variation and long-term trends.

An open source, open standards approach has been taken throughout. This has allowed us to create an identity for the portal code independent from the OPEC project itself. The code has already been reused in other projects such as EartH2Observe (EC FP7), AQUA-USERS (EC FP7), ESA Ocean Colour Climate Change Initiative (ESA) and EarthServer (EC FP7), and some improvements have already been fed back in to the OPEC version; the OPEC portal will continue to be maintained and improved for the foreseeable future.

1.5.5 Development of a downstream services

Downstream services deliver information to stakeholders in a timely and relevant manner. They allow the stakeholder to query and export data, and to visualize and process data as per their individual needs thus creating bespoke data products that are fit for purpose. A key aim of the OPEC project was to develop improved products and novel services for marine water quality, to develop new markets. The downstream improved products and novel services for marine water quality, to develop new markets. The downstream service is dedicated towards tailoring the core OPEC products to the user requirements so that the products can be easily picked up by the users and integrated into their running systems.

The Water Quality Service System (WAQSS) is a bespoke downstream service product developed in 2006 by Brockmann Consult (BC) in order to provide value-added and tailored satellite data to users. A key challenge within the OPEC project has been to extend the system to include model data allowing access to the two combined important data sources.

A major challenge was to move the WAQSS processing chain from single nodes to the BC Calvalus cluster. This greatly enhances the throughput of value-added satellite data due to its highly parallel nature, and allows for fast and systematic distribution via a dedicated WMS/WCS server, and via FTP servers.

One of the key requirements for the modelled data is its validity. In order to ensure validity, a dedicated benchmarking tool was developed, and successfully employed during model development across all regional model systems. OPEC has developed ecosystem models in the north east Atlantic, Baltic, Black and Mediterranean Seas.

Combining modelled and satellite data within the same work environment in a transparent and easy to manipulate manner will provide much needed added value. User surveys have been carried out throughout the development of the data delivery service to ensure the final product actually meets the needs of its intended customers.

Bespoke subsets of satellite data, in terms of time, space, and ecological variables, projected onto user-specified grids are provided systematically in near-real-time or on request to the users via FTP access.

Delivering bespoke data products: In order to allow users to work with the model data created within the OPEC project, an open source GIS data portal was created (portal.marineopec.eu). This data portal was adopted and customized to include the satellite products available through the WAQSS system. Features have been customized according to user requests including:

• Provision of a shapefile support feature which allows users to upload their own shapefiles and choose the specific geometries as regions of interest within the portal (figure 1).

• A dedicated user management system to allow user-customizable access to data and visualisations. Users also required a personal login, so that previous WAQSS users could be assigned to their specific user groups.

Accessing the WAQSS Portal: The WAQSS portal is running at the URL http://portal.waqss.de/ and a guest user account (guest / guest) has been created.

2.1 Dissemination activities

OPEC has been involved in a range of dissemination activities over the life time of the project as listed in the table 2. OPEC scientists have actively engaged with members of the user community including ICES working groups and the MyOcean project, as well as the broader scientific community. A key lesson learnt from engagement with User communities was the significant impact of face to face contact. Project partners took every opportunity to discuss potential operational ecology products and tools with potential stakeholders directly throughout the life of the OPEC project. We found this to be highly effective in not only gather immediate feedback but also to raise awareness of this area of science and promote its future application.

Web Portal: The Marine OPEC Data portal is one of the project’s key dissemination tools, providing free access to model simulated data on a regional scale. WP6 and WP7 have worked closely on developing the Portal to ensure that its content was not only user relevant but also the user interface was produced to a high standard. As a result of the portal software being adopted by other EU funded projects new tools and new features will continue to be developed and added to the OPEC data portal over the coming years

and new features will continue to be developed and added to the OPEC data portal over the coming years.
Press releases have been used strategically to announce the start of the project along with a final press release to announce the launch of the OPEC Marine Data Portal. Press releases were sent to a range of national and international platforms including: New Scientist, The Guardian, BBC Worldwide, BBC World Service, Nature, European Environmental Programme, Euro News, Thomason Reuters, Marine Management Organisation, Basque Research, Alphagalileo, Eurekalert! gCordis Wire, SINC, Science Daily, Euskadi Innova.
Project website: The project website was regularly updated throughout the project. The website acted as both an internal and external dissemination tool. A wiki page was used to provide extra support to communication between work packages. Interested stakeholders are able to join the OPEC mailing list through the website. Since the launch of the website there have been 6,854 visits and 12,871 pages views from 50 different countries. To facilitate the dissemination of OPEC results dedicated Knowledge Exchange pages were developed as a discrete section of the project website where user relevant information was provided. The aim of these pages was to support the exchange of ideas and advancements arising from the project with the non- scientific community.
For the conclusion of OPEC the entire website (http://marine-opec.eu/) was redeveloped and now acts as a project archive to ensure the project's legacy continues and to pool all project outputs into one place where they are available to the wider community.
OPEC Fact Sheet series: The key aim of the fact sheet series was to provide user relevant information in a digestible format. They translate complex scientific ideas and results into a message that is clear and understandable, highlighting how the work can be applied in a broader context and applied to Operational Ecology. This tool thus brings OPEC's scientific achievements into the public realm and helps to ensure the developments made in advancing the state of the art in OE are captured and disseminated for wider use. A set of nine general project fact sheets were produced to highlight the scientific achievements of the project. They focus on the key areas of the project with one produced for each WP.

- Fact Sheet 1: The OPEC Project
- Fact Sheet 2: Monitoring Networks
- Fact Sheet 3: Rapid Environmental Assessments
- Fact Sheet 4: Operational Ecology in the Northeast Atlantic
- Fact Sheet 5: Operational Ecology in the Baltic Sea
- Fact Sheet 6: Developing an approach for Seasonal Forecasting
- Fact Sheet 7: Marine OPEC Data Portal
- Fact Sheet 8: Downstream Services
- Fact Sheet 9: From modelling to resource management: the Baltic example

The full suite of fact sheets has been compiled into a distribution pack for broad dissemination and is available to download from http://marine-opec.eu/factsheet.html.
Project Brochure: a brochure providing a simple summary of the entire project was produced to highlight the advancements in OE, tools created and how they can best be applied for societal gain. This has been sent in hardcopy to over 80 members of the user community and is available electronically, http://marine-opec.eu/downloads/OpEc-WebBrochure.pdf

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Related documents

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