Executive summary:

Marine ecosystems are increasingly under pressure from the activities of man and are consequently changing. Climate change may lead to large scale changes in climate patterns, ocean circulation and climatic variables such as temperature and light and simultaneously, combinations of direct anthropogenic drivers such as fishing, eutrophication and pollution impact on marine ecosystems. The primary goal of MEECE was to improve the knowledge base on marine ecosystems and input to the development of innovative tools for understanding and assessing Good Environmental Status (GES) in marine waters in European regional seas to inform the implementation of the MSFD. The implementation of the Marine Strategy Framework Directive (MSFD) 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.

MEECE explored multiple driver impacts on complex environments through numerical simulation models which include dynamic feedbacks, unlike statistical approaches. The project followed a logical process starting with targeted data synthesis, experimentation, model parameterisation and development, followed by model exploration through a range of scenarios addressing the full set of drivers. This innovative approach was designed to help scientists and decision makers to respond to the multiple driver impacts with appropriate, knowledge-based, management applications.

MEECE has improved the knowledge base on marine ecosystems and how they are impacted by drivers by undertaking meta-analysis of existing data and targeted experimentation to investigate the response of key species and ecosystem to climate and direct anthropogenic drivers. By developing a library of modelling tools and a generic model coupler (FABM), MEECE has made an important step towards integrated end-to-end modelling tools which include a range of feedbacks between drivers and ecosystems from both physiological and population scale processes.

These modelling tools have been used to investigate the response of European regional seas ecosystems to climate change, direct anthropogenic perturbations and to combinations. The response of marine ecosystems to combinations of climate change and anthropogenic drivers was made using regional coupled hydrodynamic-ecosystem models. The results are complex and variable from region to region. For example the ecosystems of enclosed basins such as the Adriatic, Black and Baltic Sea are highly responsive to wind stress and eutrophication. In contrast the ecosystems of shelf seas with connection to open ocean (e.g. NE Atlantic, Biscay, Benguela) are responsive to changes in the nutrient supply from the open ocean. In contrast the impacts of fishing are generally a function of the local fish stock and which species are targeted.

To contribute to the development of innovative tools and strategies for rebuilding degraded marine ecosystems MEECE has undertaken an integrated assessment of marine resources which linked human activities to the MSFD descriptors. Outputs from the experiments and model simulations were used to devise decision support tools and develop management strategies which address combinations of climate, pollution, eutrophication, invasive species and fishing. Furthermore MEECE developed concepts and strategies for implementing management strategy evaluation procedures capable of integrating fisheries management in the context of interactions between climate, fishing, pollution, NIS and eutrophication. Tools have been developed which can be used to evaluate management strategies including both data demanding quantitative models and a semi-quantitative indicator-based framework. In addition the Working Group, indiSeas has worked jointly to evaluate the status of world marine ecosystems by providing a generic set of synthetic ecological indicators to accurately reflect the effects of fisheries on marine ecosystems, to facilitate effective dissemination of these effects to the general public, stakeholders at large and fisheries managers, and to promote sound fisheries management practices.

Finally MEECE was a genuinely European project. It brought together expertise and intellectual resources from across Europe and the progress made was only possible through Europe wide interdisciplinary cooperation.

Project Context and Objectives:

Marine ecosystems are increasingly under pressure from the activities of man and are consequently changing. For example climate change may lead to large scale changes in climate patterns, ocean circulation and climatic variables such as temperature and light. Enhanced atmospheric CO2 levels will lead to acidification of the oceans with significant impacts on ocean biogeochemistry, planktonic ecosystems and potentially the reproductive success of higher trophic levels (e.g. changing survival rates of larval stages of metazoans and fish). These changes will all impact on the overall trophic structure and function of marine ecosystems. Simultaneously, combinations of direct anthropogenic drivers such as fishing, eutrophication and pollution impact at both an organismal and population level thereby influencing the competitive ability and dominance of key species and thus the structure of marine ecosystems. Finally, the introduction of alien invasive species has the potential to restructure marine ecosystems, a mechanism of change which has the potential to be exacerbated when key species are already under stress due to the combined effects of abiotic and biotic stressors. In many regions these activities are acting on the ecosystem simultaneously, potentially leading to additive, synergistic or antagonistic effects. Ultimately if we do not understand how the ecosystems responds to combinations of these drivers either in the past or in the future we will find it very difficult to manage marine ecosystems in the future.

The Marine Ecosystem Evolution in a Changing Environment (MEECE) FP7 project was launched in September 2008 to investigate the responses of marine ecosystems to both climatic change and the direct effects of human activity. The work in MEECE has focused on the key drivers of change set by the European Union's Marine Strategy (changes in temperature, ocean circulation, stratification and acidification, consequences of pollution, overfishing, invasive species and eutrophication). The project has gained a better understanding of the direct and interactive effects of these factors on marine ecosystems. Meeting the goals of policies such as the European Maritime Policy and its ecological pillar the Marine Strategy Framework Directive (MSFD) and the Common Fisheries Policy aimed at protection of marine resources from degradation and a sustainable exploitation of these resources requires integrative approaches that consider multiple drivers and biological interactions in ecosystems. The only tools we have which can address non-linear combinations of driver impacts in a dynamic environment are numerical simulation models which include dynamic feedbacks, the approach applied in MEECE; the use of dynamic simulation models with feedbacks allows us to assess driver impacts outside of the observed envelope.

MEECE addressed two specific goals:

-To improve the knowledge base on marine ecosystems and their response to climate and anthropogenic driving forces and

-To develop innovative predictive management tools and strategies to resolve the dynamic interactions of the global change drivers (changes in ocean circulation, climate, ocean acidification, pollution, over fishing and alien invasive species) on the structure and functioning of marine ecosystems

The scientific and technical objectives were;

To review the impacts of the drivers on the marine ecosystem and define model parameterisation and scenarios.

The responses at both an organism and ecosystem level to perturbations by drivers will be reviewed. Data on key physical, biogeochemical, ecological and physiological properties in relation to the drivers: acidification, temperature, nutrients, pollution, fishing activity and circulation will be collated. Furthermore, a database on the biological traits of invasive plankton and macrofauna, will identify the main representative types, rates of spreading and environmental tolerance ranges. As well, a bio-pollution index will be developed to classify the impacts of alien invasive plankton species on native species and ecosystem functioning. Experiments will be undertaken to investigate the response of ecosystems to multiple stressors and model parameterisations will be developed. The envelopes of response of the different drivers will be defined for each driver.

To develop a library of ecosystem modules to predict ecosystem response from plankton to fish and couplers.

At present most models in marine ecosystems are developed to address specific trophic levels, species or processes and consist of either a single code or are driven ‘offline’ using the stored results of hydrodynamic models. As such these modelling tools are limited in their ability to address the impacts of multiple drivers and to critically to incorporate two way feedbacks between and within trophic levels and the abiotic environment. Hence the overall goal of MEECE is to create an integrated model structure following a modular approach and employing couplers on key nodes in order to understand and develop the predictive capacities necessary to assess the impact of a number of drivers, including ocean circulation, climate, ocean acidification, pollution, over fishing and invasive species on the dynamics of marine ecosystems.

To scenario test the impacts of climate drivers on the structure and functioning of marine ecosystems.

The response of marine ecosystems to climate change drivers and acidification will be explored using coupled hydrodynamic-ecosystem models. These models with representation of phytoplankton, zooplankton and fish will employ IPCC climate change scenarios on global and regional scales. Combinations of different models and scenarios will be used to define the envelope of response allowing us to assess with estimates of uncertainty the range of responses of marine ecosystems (from plankton to fish) to changes in ocean circulation, climate and acidification.

To scenario test the impacts of direct anthropogenic drivers on the structure and functioning of marine ecosystems.

Coupled physical-biogeochemical-mid to higher trophic level modelling will be performed to resolve, the potential response of the marine ecosystem to direct anthropogenic stress using IPCC climate change scenarios. The following types of anthropogenic impacts will be examined:

-Impacts of pollutant substances on the population dynamics of key trophic players having the capability of altering the marine ecosystem structure and functioning (e.g. eutrophication) or with direct toxic effects on the biota (e.g. heavy metals, herbicides).

-The effects of exploitation of marine living resources (direct and indirect effects of fishing) on populations, ecosystem structure and functioning.

-The potential effect of anthropogenic mediated input of invasive alien species having the potential to change trophic interactions and marine communities on all trophic levels.

To develop decision support tools, which assess key vulnerabilities and risks of global change for the marine ecosystem.

Decision support tools provide a structured link between a management question and the knowledge base necessary to address that question. Hence, they provide effective means for communication between scientists and end-users and have evolved considerably during the past two decades. Besides investigating how our management capabilities are affected by trends in major ecosystem drivers, MEECE will contribute to the development and implementation of tools and management strategies being robust against trends in uncontrolled drivers or allowing a better management of drivers under human control (i.e. fisheries and introduction of alien species). Specifically this includes:

-Development of a methodology to integrate the dynamic response of marine ecosystems to the combined effects of various anthropogenic and natural drivers into multi-criteria tools supporting the decision-making process

-Development of management strategies that support the EC Marine Strategy, EC Maritime Policy and the EC Common Fisheries Policy and their long-term ecological and resource management objectives

-Further development and implementation of Management Strategy Evaluation (MSE) tools that allow the evaluation of strategies for the rebuilding of degraded marine ecosystems, the protection and the sustainable use of the sea and its resources, in the perspective of the ecosystem approach.

-Evaluation of the tools supporting the decision-making process and management strategies using the MSE tools.

To develop indicators of ecosystem status.

Employing a comparative approach across ecosystems MEECE will develop common methods to select and estimate ecological indicators of environmental status specifically for anthropogenic impacts and a common protocol for elaborating ecosystem state. Due to the difficulty in establishing baseline levels and reference points for most ecosystem indicators, the comparative approach across ecosystems will provide a range of reference values against which each ecosystem could be assessed. The comparative approach will also help in identifying robust ecological indicators that would be meaningful and measurable over a set of diverse and contrasted situations, and in specifying their conditions of use.

To transfer knowledge to society.

MEECE will disseminate research-based knowledge, expertise and skills from the project to 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). As a policy driven project MEECE's target groups are the User community, the project will also engage where appropriate with outside organizations, groups, specific audiences or to the general public. Our approach to both Knowledge Transfer and Public Outreach will be based on a two-way information flow, focusing on engagement with end users rather than solely upon dissemination or education.

Project Results:

MEECE followed a logical process starting with targeted data synthesis, experimentation, model parameterisation and development. This was followed by model exploration through a range of scenarios addressing the full set of drivers. This innovative approach was aimed at helping scientists and decision makers to respond to the multiple driver impacts with appropriate, knowledge-based, management applications. Outputs from the experiments and model simulations were used to devise decision support tools and develop management strategies.

The report has been split into three sections to reflect this:

-Tools, methods and data: This section summarises the data collection and experiments undertaken along with technical achievements in terms of model coupler development, new parameterisations and methodologies for running climate scenarios and model validation.

-Ecosystem Response: This section summarises the responses of marine ecosystems to the full range of MEECE drivers, firstly considering each individual driver then in terms of combinations of drivers. Each subsection combines information from the laboratory and numerical experiments and data synthesis as appropriate to the driver in question.

-Implications for resource management: The final section is a synthesis of the resource management tools that have been developed and applied (e.g. integrated assessments, decision support tools, indicators and management strategy evaluation tools).

The MSFD identifies 11 high level descriptors, 7 of which are considered by MEECE (D1 Biodiversity, D2 Non Indigenous species, D3 Commercial Fish, D4 Foodwebs, D5 Eutrophication, D6 Hydrography and D8 Pollutants). 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.

Tools, methods and data:

Datasets and meta-analysis: Recognising the need for structured, coherent databases on observational and experimental results of ecosystem- driver interaction and response, MEECE has collated existing data on key process and drivers into new meta-databases for the ecosystem drivers and model validation datasets. MEECE has also collated a large dataset on discharge of European and non-European rivers integrating information from other European and global projects like globalNEWS and Waterbase. The database contains field data and model outputs on rivers flow and chemistry (for example nutrients), useful for analysing the impact of past policies on riverine nutrient loads and to force biogeochemical models such as those used in MEECE. The meta- database for ecosystem drivers contains information on climate and ocean acidification, pollution, fishing, invasive species and plankton metabolic rates. Meta-analysis of these databases has generated new parameterisations and scenarios on critical processes pertinent to ecosystem models. Of particular note is the meta analysis of plankton metabolic rates, which demonstrated that, in spite of their primitive life-style, jellyfish exhibit similar instantaneous prey clearance and respiration rates as their fish competitors and similar potential for growth and reproduction; this work was published in Science (Acuña et al, 2011, Science, Vol. 333 no. 6049 pp. 1627-1629). A range of meta- analysis have been completed on invasive alien species (IAS) impacts, ecological traits and the functional traits and environmental tolerance limits for phytoplankton in order to parameterise a climate envelope modelling approach and a bio pollution expert system for the Baltic. Meta-analysis of ocean acidification (OA) experiments on calcifying organisms suggests the current evidence is highly ambiguous even in terms of the sign of the impact of OA on calcification, thus preventing the extrapolation of this work to a consensus model parameterisation.

Experiments: MEECE has completed a range of experiments to investigate the impacts of key stressors (temperature, pH, copper and organic pollutants and herbicides) on a range organisms at different trophic levels. The goal of this exercise was to develop multi stressor vital rate parameterizations for key lower trophic level species. To this end, targeted experiments were performed in three clusters to resolve the physiological and biogeochemical responses of key species to the combined effects of acidification, pollution and temperature. The key species examined represented different trophic levels from pelagic autotrophs (diatom, Skeletonema marinoi, dinoflagellate, (Gonyaulax spinifera), heterotrophic plankton (protozoa, Euplotes crassus, copepod, Acartia tonsa) and fish (herring, Clupea harengus membras) egg and pre feeding larval stages as well as the potentially invasive benthic species (Mytilus galloprovincialis). Within a single species (Mytilus galloprovincialis) we applied biological/ ecological methods, developed to clarify the biological effects of pollutants at molecular level exploiting genomic and proteomic approaches. The information generated has when appropriate been synthesised into parameterisations of the impacts of pollution and temperature on the growth of key organisms and hence into model code.

Advancing marine ecosystem modelling: Marine ecosystem models are highly diverse in terms of the scientific and computational approaches used. The modeling tools are designed, programmed and optimised for a particular question, and often only focus on a particular component of the ecosystem. This diversity poses a challenge for the application and comparison of models and the assessment of simulations across models and ecosystems. Ultimately it limits the ability of both researchers and stakeholders to interpret and use multiple models outputs. MEECE identified key-species from an ecosystem modelling perspective, for each of the project targeted geographical systems and in the context of climatic and anthropogenic drivers and relevant feedbacks. The key species as listed by model developers reflect the significant overlap of approach at lower trophic levels (LTL - nutrients, phytoplankton, zooplankton), with the trophic difference across systems evident at higher trophic levels (HTL). The most recurrent priority for data gathering and future experimental data generation across all trophic levels, is focused on better quantification of all physiological rates (ingestion, assimilation, excretion, growth, mortality) with respect to the multiple environmental drivers (temperature, acidification, pollution). Predator-prey interactions were also identified as a key area of further experimentation and data generation, in terms of grazer control, prey preferences and prey quality for lower trophic levels and visual predation, gut contents and diet definition of key species for higher trophic level predators.

MEECE Model Library: The MEECE model library is a set of models and sub models describing the carbonate system, acidification processes higher trophic levels, pollution impacts and invasive species which can be coupled to a lower trophic level (plankton) model. Each sub module provides stand-alone code along with the necessary documentation for use. The information is summarised in a web interface (see http://www.meece.eu/Library.aspx online). The model library has been mapped onto the MSFD descriptors and a search tool developed which allows users to find the available modelling tools in a geographic region of interest.

The following submodules were developed during the MEECE project:

-Carbon Phytoplankton: a parameterisation of the enhancement of primary production and carbon assimilation in marine phytoplankton in response to increasing inorganic carbon concentrations.

-Carbonate System and Calcification: code to simulate carbonate system variables (total alkalinity, dissolved inorganic carbon, pH, pCO2) and an algorithm for calculating the acidification-sensitive pelagic calcification rate.

-Calcifiers: computational method and code for calculating the ecological success of the abundant coccolithophore Emiliania huxleyi.

-Zooplankton: code for a size structured copepod population model

-Individual Based Models (IBM): describes a generic IBM model, followed by specific examples for Sand eels, Anchovy, Calanus Finmarchicus and the 2 way coupled NORWECOM.E2E system (Herring, Blue Whiting, Mackerel).

-Stochastic Multi Species Model (SMS): model description and code for the stochastic multispecies model describing stock dynamics of interacting stocks linked by predation.

-Ecopath with Ecosim (EwE): summary of Couplerlib; a software interface which exchanges information between the LTL (e.g. ERSEM) and EwE models allowing a 2 way coupling.

-OSMOSE: The Object-oriented Simulator of Marine ecOSystems Exploitation model is a spatial multispecies and Individual-based model (IBM) which focuses on fish species and communities, and their exploitation. It is 2 way coupled to ROMS-NPZD.

-APECOSM: Apex Predators ECOSystem Model is a spatially explicit size-based model of marine ecosystems, 2 way coupled to the PISCES biogeochemistry model.

-Ecotoxicology: parameterisations and code describing the impacts of pollutants on different components of the ecosystem. These sub-models describe the impacts of herbicides on the growth rates of phytoplankton, the impact of nonylphenol on zooplankton mortality, the impact of copper on the egg survival and growth rates of larval fish and benthic filter feeders. Our approach is to derive a pollutant concentration dependent penalty function based on the MEECE experiments.

-Invasive Alien Species (IAS): in MEECE we adopted two different approaches,

--The biogeographic approach which uses biogeochemical models to evaluate the change in abundance and distribution of the specific non indigenous species (NIS) studied.

--The Darwinian approach, the modification of a standard biogeochemical model to simulate a large number of phytoplankton types (hereinafter called species) allowing the simulation of the invasion of an IAS, evaluation of its ability to settle in the new environment and to assess the impact on the ecosystem.

Model Coupler Framework for Aquatic Biogeochemical Models (FABM): Recognizing the shortcomings of coupling software that is presently available, the development of a generic model coupler was a key target for MEECE. The result is the Framework for Aquatic Biogeochemical Models (FABM), which delivers an easy to use, highly efficient coupling between a hydrodynamic model and one or more ecosystem components. Its primary role is to specify explicitly and in detail how physical and biogeochemical models communicate. Accordingly, it consists of a thin layer of code (approximately 2500 lines) for communication and data exchange, enveloped by an extensive set of explicit programming interfaces through which a physical host (hydrodynamic model) and any number biogeochemical models pass information. These models run side-by-side and can communicate without being aware of each other's specifics. As a result, both physical and biogeochemical models only need to be developed or modified once to interface with the general framework; after that, arbitrary combinations of physical and biogeochemical models can be made without requiring any source code change. Furthermore, the framework supports (i.e., it can be compiled with) any number of biogeochemical models, which can selectively be enabled and linked at run time. Thus, the selection of biogeochemical models, and the links between them, can be made by the end user - it does not require any programming expertise.

The framework is designed to be sufficiently general to accommodate the variety of circulation models (e.g. 1D water column, 3D world ocean, figure right) and ecosystem models in use by MEECE partners. Such generality cannot be achieved without some computational cost. However, the framework's communication layer between models is thin and has been designed to be as efficient as possible. It is, therefore, written in Fortran 90, as are the models that are coupled. Evaluation of model performance indicates that the loss of performance is small: in the 1D General Ocean Turbulence Model (GOTM), 3D General Estuarine Transport Model (GETM), and the 3D Modular Ocean Model version 4 (MOM4), the use of the generic framework instead of a direct, custom coupling between physics and biogeochemistry has a negligible effect on performance. The use of the framework has been demonstrated using the GOTM- and a standard Nutrient-Phytoplankton-Zooplankton-Detritus (NPZD) model and coupling the MEECE carbonate chemistry system model (one-way coupling) and a model of Mnemiopsis, an invasive comb jelly species now common in the Black Sea. This configuration requires bidirectional communication (two-way coupling), as Mnemiopsis growth is dependent on the presence of zooplankton, and zooplankton removal is dictated by Mnemiopsis. Both setups allow for complete configuration of the model, in terms of parameter values and coupling, at run time. Primarily, the framework is of benefit to scientific experiments that use different combinations of physical and biogeochemical models. Its key achievement is that it brings this functionality to the end user, who is no longer required to possess expert knowledge on both the physical and biogeochemical models. Given that physical and biogeochemical models continuously increase in complexity and code size, while the dynamic combination of different physical and biogeochemical models becomes a more standard element of scientific research, the usefulness of this generic framework is expected to extend beyond MEECE.

Regional models and Scenarios:

Global and regional model systems: The following seven regions (six European seas and the Benguela upwelling) and the global ocean have had model systems implemented in them.

-Global

-Barents and Nordic Seas

-NE Atlantic (Atlantic Margin, Greater North Sea, Celtic Seas, Bay of Biscay)

-Baltic Sea

-Black Sea

-Adriatic Sea

-N. Aegean Sea

-Benguela Upwelling

End-to-end models of marine ecosystems have been implemented for each region which try to represent the entire ecosystem by including all relevant processes in the system, from physics to biology, and plankton to fish. Each comprises a hydrodynamic model which is forced by both reanalysis data (for validation purposes) and a coupled ocean-atmosphere general circulation model (OAGCM) to explore the behaviour of the system under possible future climate change conditions. Coupled to the hydrodynamic model, a lower trophic level model (bacteria, phytoplankton and zooplankton) including biogeochemical cycling in turn coupled to a higher trophic level model (mainly with an emphasis on fish species) are also implemented.

Definition of common scenarios: All regional simulations have made the following common simulations.

-Hindcast forced by ERA40 or NCEP re-analysis atmospheric forcing to explore present day variability and validate oceanographic models. Time slices are defined here specifically by the region and can be variable since it depends on the historical data availability.

-Three IPSL-CM4 forced simulations (CNTRL, BU and A1B) to explore the behaviour of the system under possible future climate change conditions IPSL-CM4 run is an example of an OAGCM, as used in the IPCC assessment reports. The CNTRL simulation is a simulation forced by either the IPSL-CM4 20C model or reanalysis for the present day period 1980-1999. The business as usual (BU) is a future climate scenario representative of possible conditions in 2030-2040. This time-slice was chosen to be closer to the policy relevant period. A1B is a future climate scenario representative of possible conditions in 2080-2100 under a business as usual emissions scenario: SRES (Special Report on Emission Scenarios) A1B. In terms of greenhouse gas (GHG) emissions throughout the 21st century, A1B is a scenario at an intermediate level (850 ppm of CO2-eq concentrations in 2100). Specifically, we have used the difference between A1B (within 2080-2100) and CNTRL (1980-2000) to assess climate change impacts at the end of the century.

-Multiple driver scenarios combine both climate and anthropogenic drivers (eutrophication, pollution, fishing and invasive species). To ensure policy relevance the climate scenario considers the BU (2030-2040) as a common climate scenario, with additional perturbations by anthropogenic drivers i.e., IPSL-CM4 A1B + SC1 world market (A1), IPSL-CM4 A1B + SC2 global community (B1)1 and IPSL-CM4 A1B + SC4 local responsibility (B2)2 where 1 is N Sea, NE Atlantic, Baltic, Biscay, Benguela, Barents and 2 is Adriatic, N Aegean, Black Sea.

Downscaling Climate Forcing to regional models: A major technical challenge MEECE addressed is downscaling the outputs from the OAGCM to scales which can be used to drive a regional hydrodynamic-ecosystem model. MEECE has produced a synthesis of the common methodologies; for a given choice of forcing data there are 5 basic approaches downscaling:

-Direct forcing

-Delta change approach

-Bias correction (linear) or statistical downscaling (nonlinear)

-Dynamic downscaling of atmosphere only

-Dynamic downscaling using a coupled atmosphere-ocean model

The preferred MEECE downscaling strategy is the Delta change approach, using a multiplicative factor applied to atmospheric boundary conditions, marine boundary conditions and marine initial conditions. This approach is chosen because it removes the influence of biases from the climate model forcing and preserves the mean climate change signal. This is seen as the most robust part of the signal from the climate models. However IPSL-CM4 model forcing has a pronounced bias in many regions, for instance simulating unrealistically extensive sea ice cover in the present day reference and projecting extreme changes in nutrients sea ice bias in the Barents Sea region. A downscaling strategy has been adopted in some regions to minimise the bias; e.g. statistical downscaling of winds in the Benguela region to improve the representation of upwelling and the use of regional downscaled atmospheric forcing in the Adriatic and Black Seas. In the North Sea comparative simulations with different OAGCM atmospheric forcing identified the impact of the atmospheric parameters on projected changes in primary production. The projected changes in primary (and secondary) production differ in pattern and sign for different forcing OAGCMs and the uncertainty in the amplitude of the projected climate change is large and locally as large as the projected changes.

Central to any scientific analysis of environmental systems is the processing of the resulting information into a form that aids the interpretation of the analysis in the context of our empirical and theoretical understanding, and also aids the comparison between similar and contrasting sources of information. Central to this is model validation and MEECE defined a set of quantitative metrics and procedures for comparing model output with observational data. Each region has been modelled independently and validated with present-day climate.

Ecosystem response to Drivers:

Marine Ecosystem Responses to Drivers

In order to summarise the responses of marine ecosystems to the full range of MEECE drivers the MEECE scientists provided their expert opinions on how sensitive a regional system is in general to each driver on a scale from 0 (no response) to 3 (highly responsive). The summary table (see attached pdf) combines these expert opinions, with a value judgement as to how confident they are in their views (red = low, yellow = medium, green = high), thus providing a systematic overview of the sensitivity of the marine ecosystem to key drivers in each region. It should be noted that the quantitative and specific nature of the response on an individual scenario basis is generally less certain.

1.2.2.1 Climate change

Ocean ecosystems are increasingly stressed by human-induced changes of their physical, chemical and biological environment. Among these changes, warming, and changes in circulation and stratification leading to de-oxygenation and changes in primary productivity by marine phytoplankton can be considered as the major stressors of marine ecosystems.

Metabolic Scaling: It is well know that marine ecosystems are sensitive to warming. In MEECE we have further developed metabolic theory to explain the effects of body size, temperature and resources on the metabolism of the oceans going from organism to population and communities to whole ecosystems. The objective was to develop a theory that enables us to explain and model the effects of changing light levels, temperature, stoichiometry and size structure on planktonic metabolism. An analysis of temperature-abundance-size relationships in marine plankton showed that, picophytoplankton abundance increased with temperature in a similar manner to that previously reported for total phytoplankton, secondly that temperature and picophytoplankton cell size were inversely related and finally that the proportion of biomass in the picoplankton size-class significantly increased with warmer temperatures. A unified model of life history optimization and metabolic scaling theories for developmental time was developed which integrates metabolic theory and life-history evolution to provide a synthetic theory of population energetics. Our model is a step in this direction and shows that both theories play a major role in controlling developmental time.

A key result of metabolic theory is the differential temperature dependence of the metabolic and growth rates of autotrophs and heterotrophs, the implication to marine plankton community dynamics and biogeochemical cycles being potentially far reaching. A numerical model sensitivity analysis of the ecosystem response to climate was performed in the Northern Adriatic Sea using ERSEM, which shows the zooplankton to phytoplankton production ratio increasing as temperature increases as expected from metabolic theory.

Lower trophic level response: Globally and in temperate and southern European seas, primary production is expected to decrease on average under future climate change scenarios, whilst in the most northern European seas (Baltic and Barents) is expected to increase. The general latitudinal pattern of increasing primary production pole-wards is reproduced by both the global and the European regional models.

Global primary production will decrease 9% and zooplankton biomass 11%. This triggers a change in the trophic ratio (zooplankton biomass divided by phytoplankton biomass) from 1.74 to 1.66, which indicates a re-structuring of the food web pyramid. The general primary production decrease is explained by the reduced input of nutrients into the euphotic zone related to enhanced stratification, reduced mixed layer depth, and slowed circulation. However, spatial variation is very high.

In arctic regions such as the Barents Sea, in semi-enclosed and shallow seas such as the Baltic, in shelf regions such as Southern North Sea, Celtic Sea, Irish Sea, English Channel and Armorican Shelf, primary production is expected to increase with climate change, and consequently, zooplankton biomass. The spatial variation is exemplified in the Black Sea projection map. Whilst overall primary production is expected to vary weakly (-3%) and zooplankton biomass are expected to not change significantly, Black Sea has two highly contrasting areas (increase of net primary production and plankton biomass in the eastern area and decrease near the Bosphorus).

Higher trophic level response: In response to climate change an 18% decrease in fish biomass is expected globally by the end of the century. This is due to the mean decrease in primary and secondary production. However, once again the spatial distribution is highly variable. This projection is in agreement with recent studies indicating reduced fish size and production at global scales. On a regional basis, cod population have been studied throughout several regions; cod can be favoured by higher primary production in the Barents Sea (+8%), while lower plankton biomass would reduce potential larval survival in the North Sea. Also, decreasing salinities in the Baltic Sea will dramatically reduce suitable spawning habitats for this species' population. In regions (N Aegean Sea, Bay of Biscay) where multiple species have been modelled with its interactions, overall fish biomass generally responds to overall zooplankton trend, although this relation is highly dependent on spatial variation and seasonal shift of these two trophic levels. For instance, the slight increase in total fish biomass on the whole Bay of Biscay (5%), compared with the high increase in overall zooplankton (44%), is explained because of the spatial variability in zooplankton change. Thus, in the French shelf, zooplankton is expected to decrease and peak earlier in the year and also it is the main area of spawning for fish species, such as European anchovy, at present day climate. Moreover, the spawning season of European anchovy has its maximum peak between May and June; whereas the maximal value of zooplankton would occur earlier (i.e. April) in the future scenario than at present day climate (i.e. June). This could produce a mismatch between anchovy larvae growth and zooplankton bloom, which is critical for the population growth and has been reported, for instance, for Atlantic cod in the North Sea during last few decades. A study of climate change effects on the growth potential of larval Atlantic cod in the Nordic Seas revealed that it had a negative effect on larval survival caused by reduced prey conditions combined with increased ocean temperatures that forced the larval fish to take higher risks to sustain feeding rates. To obtain greater amounts of food, larvae positioned themselves higher in the surface layer, making them more vulnerable to visual predation and higher mortality rates. The potential future loss of larval cod may have strong negative effects on the recruitment potential for Atlantic cod.

Uncertainty of models and projections: Each region has been modelled independently and validated with present-day climate. Thus, the reliability of each region is different. In general the simulation skill for a variable decreases as the trophic level increases because of error propagation. Projecting top-predator dynamics is hence subjected to more uncertainty than lower trophic levels such as plankton, which in turn, is less accurate than ocean climatology. Another issue is that comparable projections consider only one greenhouse gases emission scenario of the Intergovernmental Panel on Climate Change, termed A1B which assumes increasing emissions during the first half of the present century that turn to decreasing in mid-century due to the utilisation of more efficient technologies. For climate change modelling, it is well known that averaging of results from an ensemble of models reduces uncertainty. To explore these uncertainties MEECE scientists analysed recent simulations performed in the framework of the Coupled Model Intercomparison Project 5 to assess how these stressors may evolve over the course of the 21st century. The 10 Earth System Models used here project similar trends in ocean warming, acidification, deoxygenation and reduced primary productivity for each of the IPCC's representative concentration pathways (RCP1) over the 21st century. For the 'business-as-usual' scenario RCP8.5, the model-mean changes in 2090s (compared to 1990s) for sea surface temperature, sea surface pH, global O2 content and integrated primary productivity amount to +2.73 °C, -0.33 pH unit, -3.45% and -8.6%, respectively. For the high mitigation scenario RCP2.6, corresponding changes are +0.71 °C, -0.07 pH unit, -1.81% and -2.0% respectively, illustrating the effectiveness of extreme mitigation strategies. Although these stressors operate globally, they display distinct regional patterns. Large decreases in O2 and in pH are simulated in global ocean intermediate and mode waters, whereas large reductions in primary production are simulated in the tropics and in the North Atlantic. Although temperature and pH projections are robust across models, the same does not hold for projections of sub-surface O2 concentrations in the tropics and global and regional changes in net primary productivity.

In studies performed within the same area with different models, we have found certain agreements and some discrepancies that provide an additional source of uncertainty assessment. For instance, the Bay of Biscay has been modelled with POLCOMS-ERSEM and with ROMS-NPZD models. For the Bay of Biscay, results obtained with ROMS-NPZD model in terms of sea warming are in agreement with those obtained with POLCOMS-ERSEM and previous works using model ensembles (1.5 to 2.1 ºC), although they present slight discrepancies for zooplankton biomass. Different resolution of the models could explain partially the different results; nevertheless, additional analyses and use of other models is need for assessing future productivity in this area. For the North Sea, ECOSMO and POLCOMS-ERSEM models provide similar projections of decrease in primary production and zooplankton biomass.

Thresholds and abrupt changes: Several studies showed that marine ecosystems are not equally sensitive to climate change and reveal a critical thermal boundary where a small increase in temperature triggers abrupt ecosystem shifts seen across multiple trophic levels. Analysis of CRP data and a hindcast simulation using SMS of the North Sea indicated major structural changes in the North Sea ecosystem, which coincide with changes in trophic control, especially between piscivores and planktivores as well as zooplankton. The results further indicate the importance of the Atlantic Multi-decadal Oscillation in determining the control state, as well the importance of fisheries effects.

Implications for management: Changes in meteorological patterns may result in changes in temperature along with changes in stratification and ocean circulation. This will lead to changes in pelagic habitats and may result in changes in biological communities and hence the goods and services they provide. The hydrodynamic models provide useful information on MSFD descriptor D7 Hydrography (temperature, circulation and stratification) at a regional scale. This provides useful information on pelagic habitats (D1 Biodiversity in) terms of, for example, temperature, salinity, nutrients, and stratification at regional scales. The consequence of changes in these habitats for GES remains an open question. Changes in light and nutrients transport impact on the phytoplankton and hence on the foodweb (D4). In the context of the marine system such changes are currently unmanageable and rather represent a factor that management strategies being formulated for other drivers may need to take account and adjust to. Climate change projections for the higher trophic level coupled to lower levels and physical processes are still uncertain although this constitutes the first attempt, as far as we know, of evaluating quantitatively future climate change impacts from phytoplankton to fish stocks on a global and regional basis at high spatial resolution. Future research is needed to combine the effects of climate tolerance limits and food resources in fish biomass within a trophic approach, to assess future climate change impacts.

1.2.2.2 Acidification

Ocean Acidification refers to increasing CO_2 dissolved in seawater leading to the lowering of pH in the marine environment and impacts at all spatial scales. This is occurring mostly as a consequence of anthropogenic carbon emissions into the atmosphere. Increasing CO_2 may lead to enhanced phytoplankton growth, at the same time the lowering of pH it induces may have negative impacts on the health and reproduction of a wider range of marine organisms for example plankton and fish larvae. Currently the experimental evidence on impacts is often contradictory making it hard to predict what the future may bring. Many organisms, particularly those in extreme coastal environments are adapted to large pH ranges and are likely only to be affected once the pH range moves away from their natural tolerance. The ocean acidification response of other species may depend on the food supply and the ability to transfer energy costs over to repair and survival. The ability of marine biota to rapidly adapt to pH changes remains largely unknown and should be seen also in the context of other changing stressors (e.g. warming, de-oxygenation, nutrient supply). Similarly to climate, acidification is currently unmanageable in a marine context, but represents an issue that management strategies for other drivers may need to take into account.

The response of an Arctic pelagic ecosystem to ocean acidification was studied, for the first time. The experiment employed a range of CO_2 scenarios corresponding to eight pCO_2 levels ranging from 160 to 1600 µatm (and pH between 8.4 and 7.4). We specifically investigated changes in biological carbon uptake and the stoichiometry of nutrient consumption. Different states of nutrient and CO_2 availability allowed different species to dominate at different experimental phases.

This suggests that there was a species-specific response to CO_2 perturbation during the different stages of the experiment.

Both global and region scales are expected to experience oceanic acidification under A1B CO_2 emission scenario (mean pH change of -0.24) by the end of the century. Future acidification will occur on a global scale but with high spatial and temporal variability. Regions showing the largest changes in surface pH are the Arctic Ocean (down to -0.4 regionally, and even greater changes at the local scale) and the North Atlantic. The Equatorial Pacific, the North Pacific, the Southern Ocean show more moderate changes between -0.15 and -0.20.

On a European level, pH change ranges from -0.3 (in the Atlantic margin) to -0.2 (in the N Aegean Sea). MEECE simulations highlight how the impacts of Ocean Acidification in the shelf ecosystem vary in space and time and how they are interconnected with those of climate change. While changes in atmospheric CO2 drive OA, it is not the only factor regulating the carbonate system in regional seas. For example the OA simulations in the NE Atlantic indicate that biological processes are particularly important in controlling the seasonality of the impact: in the areas where an increase in net PP is projected the minimum of acidification is observed (e.g. in spring in the Northern Atlantic or in the southern North Sea in summer). Similarly the under saturation of aragonite projected in bottom waters in the central North Sea is caused by the accumulation of DIC during spring and summer due to community respiration (both pelagic and benthic) and the concurring stratification that prevents ventilation. Increasing inorganic carbon concentrations have been shown to promote primary production and carbon assimilation in marine phytoplankton. A model study which included both climate change and carbon enhancement due to high CO2, showed the change in net PP due to the OA alone is of the same order of magnitude of the one due to climate change: sometimes they have opposite sign and tend to cancel out, sometimes they have the same sign and OA magnifies the climate change impact. This impact is transferred up into trophic network at zooplankton level and potentially to higher trophic levels.

Implications for management: increasing CO2 dissolved in seawater will lead to the lowering of pH in all MEECE regions and impacts at all spatial scales. On one hand increasing CO2 may lead to enhanced phytoplankton growth. On the other hand lowering of pH may have negative impacts on the health and reproduction of a wider range of marine organisms for example plankton and fish larvae. Currently the experimental evidence on impacts is often contradictory making it hard to predict what the future may bring. MEECE models are able to provide useful information on the inorganic carbon cycle (e.g. pH, pCO2, aragonite saturation) at regional scales; this is hampered in coastal regions by the lack of knowledge of alkalinity sources, nutrients and organic matter supply and freshwater supplies from river. The knowledge of the ecological implications of change is currently limited, but improving.

1.2.2.3 Eutrophication

Eutrophication results from the anthropogenic nutrient enrichment of the marine environment leading to a variety of outcomes including enhanced algal blooms, harmful algal blooms, de-oxygenation and mortality of benthic fauna. The standard approach for modelling eutrophication processes and the consequences of changes in anthropogenic nutrient inputs on the eutrophication status of a region is to apply coupled hydrodynamic ecosystem models. This is the approach we have taken in MEECE.

Simulations of the whole northwest European continental shelf show (POLCOMS-ERSEM) that reducing river inputs of nitrogen and phosphate reduces nutrient levels and net primary production over the whole northwest European continental shelf, with the strongest impact (an average 16% reduction) in the southern North Sea; the effect on concentrations of chlorophyll-a is similar while increasing the amount of nitrogen input from rivers has a negligible impact on net primary production and chlorophyll-a. Similarly simulations of the North Sea (with ECOSMO) show that coastal and front related regions are most sensitive to changes in nutrient loads. Because the North Sea is semi-enclosed and exchanges water and nutrients with the Atlantic Ocean, the characteristic residence time-scales for nutrients are short (1-2 yrs) and the North Sea response to anthropogenic drivers is small especially when compared to enclosed ecosystems. Application of the same model in the enclosed Baltic Sea indicates that eutrophication is a dominant factor and changing the river loads has a strong impact on the level of primary production. This is due to the unique hydrography of the region characterised by long time scales for flushing, resulting in the system showing long-term responses to changes in nutrient supply. The enclosed Black Sea behaves in a similar manner, model simulations of the Black Sea ecosystem; indicate it is highly sensitive to a reduction in nutrient loadings, suggesting management of river water quality is vital for the improvement of the ecosystem state of the region.

In the North Aegean Sea decreasing phosphate river loads (approximately -20%) over the 1980-2000 period resulted in a significant overall decrease in plankton biomass and productivity (approximately -25%), followed by a similar decrease in total fish biomass. Varying river nutrient loads also affected the phytoplankton composition in coastal river influenced areas, with dinoflagellates being favoured under increased phosphorus or/and nitrogen availability when compared to silica. Model simulations of the Adriatic Sea also show showed the potential for considerable sensitivity of the marine ecosystem to such reductions, highlighted by a general temporal decrease of the phytoplankton biomass, in both the coastal and the offshore domain when forced by estimates of river runoff and nutrient inputs which account for the progressive reduction of the phosphate load into the Sea as a result of changes in land management.

Implications for Management: Eutrophication can act at both local and regional scales depending on the scale of the nutrient sources. The impact of eutrophication is generally a function of the hydrodynamic and light climates of the region in question; for example strongly stratified regions are more often prone to low oxygen environments while, highly turbid environments may mitigate the effects because there is not enough light for the plankton to grow. In the future the impacts of eutrophication may be enhanced or mitigated by the effects of climate change, the effects varying from place to place and will need to be considered when developing future management strategies. At regional scales this often requires international cooperation to reduce terrestrial nutrient inputs. The consequences of managing nutrients inputs may take many years before the effects are fully felt.

1.2.2.4 Invasive species

Non-indigenous species (NIS) introduced by humans, both intentionally and un-intentionally, can have both significant ecological and economic impacts and their increasing spread is a major concern for many European seas. NIS can represent very large numbers (e.g. approx 1000 species in the Mediterranean) of very different taxa ranging from parasites to fish. A subset of NIS is the Invasive Alien Species (IAS) which have spread, can spread or have demonstrated the ability to do so and have the potential to impact biodiversity, communities, habitats and ecosystem functioning. Although the term biopollution has been used in connection to IAS, they do not respond in the same way as classic chemical pollution, which can be tackled at source with appropriate local measures. Arrival, distribution and spread of an IAS can involve a suit of vectors and pathways, although main pathways linked to arrival are shipping (through ballast water & fouling), canals and the mariculture and aquaria trade. Established NIS may expand their distribution and increase their abundance beyond a local starting point through processes, which may not be controllable. Further, vectors and pathways are not static i.e. they can change over time, impacting the spatial extent of the NIS (and further facilitating secondary spread) which depends on both species life history traits and the state of the receiving ecosystem upon arrival. Equally complex and varied is the timescale component of an invasion event, as this will depend on the species life cycles and can vary from days to decades, and have a permanent or seasonal nature. In addition, climate warming has been reported as an additional stressor modifying marine ecosystems and enabling and enhancing biological invasions. While mitigating the spread or eradicating existing IAS is currently very challenging, the risk of new biological invasions can be reduced by controlling vectors and implementing pathway-relevant precautionary measures e.g. aquariology prohibitions or the Ship's Ballast Water Convention. Consequently, the best management strategy regarding invasive alien species is to avoid new invasions as targets for biopollution levels are not possible to set. Therefore, the work on invasive alien species in MEECE has focused on understanding ecosystem responses to this driver and related parameterizations to include alien species in ecosystem models, estimating biopollution levels and their impacts on ecosystems and incorporating these to expert systems.

A method to assess biopollution assessment level (BPL) has been developed to categorize and rank the degree of disturbance caused by invasive alien species. BPL can identify areas where the impacts from alien algae are the greatest on native species, marine communities, habitats and the wider ecosystem. This knowledge can in turn help steer policy decisions to avoid environmental damages and economic losses. In the case of the Baltic Sea, BPL has been used to assess a microscopic invasive alga called Prorocentrum minimum which has become established over the past two decades. As shown in the map, its impacts range from moderate to massive across the sea, impacting all regions. The only area currently free of these potentially toxic planktonic algae is the Gulf of Bothnia, the northernmost, coldest and nearly freshwater part of the Baltic.

Biogeochemical models can be used to assess if a specific NIS could find the right habitat, and eventually how frequently this will occur and in which areas of the domain. Habitats can be described by providing ranges of values for several variables in which the NIS tend to flourish. These variables can describe the physical environment (e.g. temperature, salinity, light and currents), its chemistry (e.g. nutrients) and/or the biology (e.g. abundance of competitors). A set of rules describing the potential habitat for Prorocentrum minimum have been defined, and they have been used to estimate the number of months in which the North Sea and the Baltic Sea shows favourable condition for the establishment of this species under Present Day scenario (1980-1990) and future climate scenario (2090-2100 under the IPCC AR4 A1B scenario).

The results show how climate change may potentially lead to an expansion of the area of invasion for this species in the Central and Northern North Sea, and also an increase in occurrence of the suitable habitat in the Baltic Sea. This is particularly important because this species has already been recorded as highly impacting in this area with a Bio-Pollution Level index up to 3 (strong) and occasionally 4 (massive). Presently this species has reached the adjustment phase in the Baltic Sea, but climate change could push the species in a new expansion phase. Although this species is not directly toxic, it is still classified as harmful because it tends to produce high biomass/abundance blooms with potential disruptive effects on the food web.

A comparative modelling study of the impact of climate change on the susceptibility to invasion of marine ecosystems was undertaken for the Adriatic Sea, Baltic Sea, Barents Sea, Black Sea and the North Sea. Its focus was to assess how climate change may alter the likelihood that a Non-Indigenous Species (NIS) of phytoplankton invading one of these European Seas and the potential impact on the community structure. Two scenarios were considered: a present day scenario (1980-2000) and the SRES-A1B scenario at the end of the century (2080-2100) except for the Barents Sea where the future scenario focuses on the middle of the 21st century (2046-2066). The major findings are firstly that climate change can affect diversity of indigenous community, decreasing the species richness in the ecosystems with higher diversity. The likelihood of having a successful colonization of the ecosystem from a NIS does not significantly change with climate change. Nevertheless the model forecasts a potential change in the groups that are more likely to colonize the environment with consequences on community composition. These changes are site-specific. Nutrient concentrations play an important role in determining which functional group is more likely to successfully invade the ecosystem, hence any policy directed to manage nutrient concentration should include this driver in a complete cost-benefit analysis. The impact of the NIS invasions on the community structure may increase under future climate as a consequence of the decrease in diversity of the indigenous community.

Implications for Management: Non-indigenous species (NIS) introduced by humans, both intentionally and un-intentionally, can have both significant ecological and economic impacts. Currently there are no modelling tools which can usefully predict invasion and colonisation by invasive species. This is partly due to lack of knowledge of the ecology of invasive species and is confounded by the fact that new species periodically appear so there are always unknowns. Bioclimatic envelope modelling (as described above) can provide useful information on changes in the distribution of species whose habitat is well characterised.

1.2.2.5 Pollution

Contaminants enter marine environments from both diffuse (e.g. atmospheric fall-out) and punctual sources (e.g. estuaries, urban areas, industrial plants, aquaculture, oil spills, etc.) affecting marine ecosystem quality. Marine contamination control is crucial in light of the more recent European Directives on water quality assessment. In particular, MSFD GES descriptors clearly require a shift in monitoring activities from classical techniques based on determining chemical concentrations to risk-based methodologies integrating chemical data with biological results thus discriminating contamination and pollution. From a management perspective, persistent contaminants (pollution) may require decades to be removed. Further, chemical data 'per se' can only furnish partial information of the system. Understanding the effects (i.e. ecotoxicological test and ecological surveys) of exposure (i.e. chemical concentrations) is needed to determine risks due to chemicals, supporting the MSFD goals. Further, only a minimal part of toxic compounds in the world (more than 295.000 compounds) is quantified in monitoring programs; while interactions among chemicals in a mixture can give unpredictable effects (i.e. additive, antagonistic, synergistic). Also, different processes can alter pollutants bioavailability in the system. Consequently, the work in MEECE relating to the pollution driver has focused on improving the knowledge base and modelling capabilities regarding these issues and developing expert systems for decision support.

Data from the MEECE experiments shows that marine organisms such as mussels and protozoa are more sensitive to metal pollutants such as Copper and Nickel at higher temperatures. For examples the survival rate of the protozoa (Euplotes crassus) exposed to copper decreases as the temperature increases suggesting an additive effect of the two stressors .

Herbicides are known to have a toxic effect on microorganisms impacting on biochemical processes from photosynthesis to biosynthesis inhibition). Phytoplankton cultures were carried out, exposing phytoplankton to varying concentration of the herbicide terbuthylazine, which is known to inhibit photosynthesis. Our experiments identified a negative effect of the herbicide on the growth of the two algal species under examination. Specifically, algal abundance progressively declined with increasing herbicide concentration. Interestingly, as with the metal pollutants the effect of the herbicide on growth seemed to be enhanced at higher temperatures; exposure to the same concentration appeared to cause a reduced growth at higher temperature indicating an additive effect of the two stressors. To parameterise these effects in models our approach was to derive a penalty function which is dependent on the concentration of the pollutant in question. Model scenarios describing the ecosystem response to both climate change and terbuthylazine in the Adriatic Sea show a minimal effect of herbicides on phytoplankton in the coastal zone. However herbicides might be significant in limited areas where the impact of organic pollutants might be acute which are not resolved in the models.

Other experiments examined the vital rates of the marine copepod Acartia tonsa, a common species in the coastal waters of the Baltic Sea and the Mediterranean when exposed to nonylphenol over a temperature gradient. Nonylphenol is discharged into the marine environment from many different sources such as produced water from oil platforms. Nonylphenol had no significant effect on egg production at the concentrations examined but did impact upon the developmental stages after hatching as expected; typically developing stages of an organism are considered to be the most sensitive. Similar results were found for herring larvae (Clupea harengus). The experimental results were used to parameterise and run scenarios to explore the potential impacts of nonylphenol on zooplankton in the North Sea . The scenario indicates that nonylphenol causes small changes in phytoplankton and zooplankton production on local scales. The response of zooplankton is, as expected, stronger than in phytoplankton showing not only a decrease in zooplankton production, but also that phytoplankton production increases locally, most likely due to the release of grazing pressure.

Implications for management: Pollution covers a wide range of compounds (greater than 100,000) many of which are poorly characterised, particularly in terms of their ecological impacts. New compounds are constantly being developed so there are always unknowns. Similarly, the ecological implications of mixtures of compounds remain a topic of on-going research. If the source of a contaminant is well defined then models have the ability to trace its distribution at local and regional scales. The work in MEECE regarding pollution has focused on improving the knowledge base and modelling capabilities, these models are currently in the proof of principle phase. In general the results indicate localised responses to high pollutant loads. The experiments all point to concentration dependence as being indicative of the first order response in terms of either chronic effects on reproduction and growth or acute affects in terms of enhanced mortality. At all trophic levels we see a tendency for the pollution impacts to increase with temperature, which suggest that climate change may cause the effects of pollutants to increase at lower concentrations implying pollution impacts may become more significant in the future.

1.2.2.6 Fishing

Broadly speaking the impact of fishing is to selectively remove certain species which have a commercial value, and to perturb habitats. The consequences of selectively removing species can restructure foodwebs, while demersal trawling in particular can cause extensive damage to benthic habitats. There are a wide range of models of higher trophic levels which include fish and commercial fisheries of varying skills which provide information on fish stocks as well as the wider fish community and their response to changes in fishing pressure at regional scales. A variety of such models are employed in MEECE. All of these models can be driven by the outputs of coupled hydrodynamic plankton models through either 1 way or 2 way coupling. In terms of exploring top-down fisheries impact in an integrative way, end to end models are required. Such end-to-end models combine hydrodynamics, nutrient-phytoplankton-zooplankton (NPZ), and higher trophic level (HTL) organisms, into a single modelling framework. Such models are currently in the proof of principle phase to show that they can be developed and implemented to further explore the top-down effects of fishing down to the lowest trophic level organisms.

Consequences of fishing on the species biomass and trophic structure: A number of regional studies were undertaken to explore the impacts of fishing pressure on regional ecosystems. In the Benguela we explored in more details the consequences of fishing using both OSMOSE and EWE models in comparison. One of the scenario consisted in overfishing small pelagic fish, i.e. anchovy, sardine and redeye, which all display a decrease as a result, particularly marked in the case of sardine. An increase in competitors of small pelagic fish (mesopelagic fish and juvenile horse mackerel) is observed in both models. At the top predator level, the responses of individual species (snoek, silver kob and hake) are more divergent between the two models, but were consistent when the HTL species were considered altogether. In the North Aegean Sea, the effect of changing the anchovy fishing mortality was found to be strongly bottom-up controlled: a change in anchovy biomass affected systematically the biomass of their predators in the same direction. For example, an increased anchovy biomass resulted in an increase in the biomass of Merluccius and Scomberwhile all other species decreased, with an overall increase in the mean Trophic Level of fish. The Biscay region was found to be much less responsive; the total fish biomass is not sensitive to the FMSY and Fpa scenarios. Nevertheless, the results of fishing scenarios show differences in impacts on different species, especially the anchovy stock which shows a significant decrease for the Fpa scenario. In the North Sea simulations with EwE, fishing at MSY has a significant long term positive effect on Cod, Saithe, Hake, Mackerel, Sand Eel as well as Catfish and, indirectly, Large Shark and Seals.. Some species are negatively affected through predation / competition: Whiting, Blue whiting, Norway Pout, Herring and Sprat. In the Baltic Sea, higher trophic levels were found to be more sensitive to environmental change, the projected future environmental conditions clearly hamper successful cod recruitment. However the contrary is found for sprat for which the spawning stock biomass is predicted to increase markedly and almost independently of the fishing regime. In the Black Sea, the relative fraction of large fish is highly dependent on the level of fishing pressure. Under reduced fishing pressure scenarios large fish make up a much higher percentage of the total stock during all years. In summary the regional response of higher trophic levels to fishing pressure is highly variable, being dependent on both the region of choice and the structure of the HTL model used.

Reconciling MSY and conservation objectives: MEECE scientists were co-authors on a paper published in Science (Smith et al. 2011) reporting results of simulations of depletion of anchovy, sardine and other low trophic level (LTL) species undertaken using three ecosystem modelling approaches, EwE , OSMOSE and Atlantis, in a comparative fashion. In five well studied ecosystems, including the southern Benguela ecosystem and North Sea, fishing LTL species at conventional maximum sustainable yield (MSY) levels was found to have large impacts on other parts of the ecosystem particularly when the LTL species constitute a high proportion of the biomass in the ecosystem or are highly connected in the food web. Moving from MSY by halving exploitation rates would result in much lower impacts on marine ecosystems, while still achieving 80% of MSY. The study suggests that inferences from well-designed and parameterised models are robust enough to the assumptions behind each model approach and that qualitative, strategic inferences can be drawn for ecosystem impacts of fishing low trophic level species.

Implications for Management: Fishing is one of the drivers with most widespread and substantial impacts on marine ecosystems, particularly on the higher trophic levels. It should be noted that in most ecosystems, 1-way coupled LTL and HTL models have been implemented, reducing the potential ecosystem impacts of fishing down the foodweb, i.e. down to the plankton level. In the southern Benguela where a 2-ways coupled end-to-end model has been developed, the impacts of fishing propagate down to the zooplankton level, but no effects on phytoplankton has been reported in the simulations. It should also be noted that the sensitivity to fishing is very much a function of the particular species targeted in a region. Direct economic interests and needs have motivated the development of management models and related research for decades. There are a wide range of models of commercial fisheries of varying skills which provide information on fish stocks as well as the wider fish community and their response to changes in fishing pressure at regional scales. Among the drivers considered in MEECE, fisheries can be managed at local or sub-regional spatial scale with generally relatively short (annual/multi-annual) response time in populations to management measures. Thus, compared to other drivers, management of fisheries is relatively specific and can be implemented by direct restrictions on the driver in the area and regarding the ecosystem component concerned. At the same time, fishing is clearly one of the drivers with most widespread and substantial impacts on marine ecosystems where direct economic interests and needs have motivated the development of management models and related research for decades. Accordingly, the scientific basis for developing management strategies and their evaluation tools is most advanced with respect to fisheries, where sophisticated modelling frameworks are being developed and continuously improved (including contributions from MEECE presented) to facilitate moving towards a holistic ecosystem based approach to fisheries management.

1.2.3 Multiple drivers: Impacts on Foodwebs

Amplification from lower to higher trophic levels: To compare, in a synthetic way, the ecosystem response to combinations of drivers we applied a framework to assess the processes of amplification and attenuation in the ecosystem response from lower to higher trophic levels. In this approach, the response (i.e. fractional change) of a given trophic level to climate change is compared with the response of the immediately lower trophic level to the same driver. Thus, the response can be split into four classes of trophic propagation: amplification, attenuation, proportional response and top down control; all classes having both a corresponding positive or negative case.

At global scale, the overall change in fish biomass (18%) is more pronounced than changes in zooplankton biomass (11%), which in turn, is more pronounced than phytoplankton biomass change (6%) suggesting a potential amplification of climate change-driven modifications of trophic level biomass through a bottom-up control. This is interpreted as the ecosystem in these regions (predominantly in the tropical oceans) being more vulnerable to collapse.

On the other hand, when phytoplankton biomass changes positively, zooplankton biomass is prone to respond proportionally. At regional basis, negative amplification is found in two cases in the N Aegean Sea, where zooplankton biomass change (mean decrease of 5%) is amplified at increasing trophic levels (fish biomass decrease of 11%); and in the North Sea, from phytoplankton to zooplankton biomass. In the North Sea, the biomass of small zooplankton decreases while large zooplankton amounts increase indicating an additional food web restructuring, which is in accordance with previous studies in this sea showing the propagation of the temperature through the food web favouring jellyfish using 50 years records. Most of regional cases analysed here show proportional responses. An exception is found in Barents Sea: high positive zooplankton biomass change is expected related to negative phytoplankton biomass change. This is explained because net primary production changes positively and high spatial variation is found in this region.

Synergy and Antagonism: Combined effects of multiple drivers: When considering multiple drivers it is informative to consider whether the interactions in the ecosystem may be additive, synergistic or antagonistic. The effects of combining the effects of changing the fishing pressure and climate on the North Sea ecosystem were examined using a 2 way coupled ERSEM-EwE model. The impacts are found to be either additive or weakly antagonistic; the simulated effect of combining fishing at MSY and warming are very close to the addition of the two effects simulated in isolation. A second study this time made with a two way coupled ROMS-NPZD-OSMOSE model illustrates the biomass changes for adjacent trophic levels under several intensities of environmental (varying wind stress) and fishing pressures. In the scenarios, the lower part of the food chain from phytoplankton to forage or LTL fish (anchovy, sardine, round herring) is predominantly driven by bottom-up control of upwelling-favourable winds. Top-down control dominates the relationship between top-predators and forage fish, the latter becoming the 'meeting point' of bottom-up and top-down controls. Forage species are considered a key functional group in upwelling systems that are usually driven by wasp-waist control. In addition, the set of scenarios shows that fishing pressure and upwelling-favourable wind stress have a synergistic negative effect at the level of forage species, indicating that this group is very sensitive to simultaneous pressures. Both studies show the potential sensitivities of ecosystems to combinations of top down and bottom up controls. How the effects of fishing and climate propagate through a food web will depend to a large extent on which trophic level the climate and fishing forcing is specifically acting.

Summary of Regional Responses to Multiple Drivers

NE Atlantic: Climate, Eutrophication and demersal trawling

For the northeast Atlantic, the sensitivity of the ecosystem to changes in multiple anthropogenic drivers (river nutrient and benthic trawling) in the near future was also studied, as is the impact of the anthropogenic changes combined with the climate change signal. In the northeast Atlantic, away from the European continental shelf, river nutrient loads and benthic trawling effort have little impact on the pelagic ecosystem. Climate change effects dominate in this area. In the scenarios considered here, these reduce net primary production and the biomass of zooplankton and small phytoplankton in the future. On the continental shelf, the impact of climate change on net primary production and phytoplankton biomass may be mitigated to some extent by environmental policies that reduce river nutrient loads, particularly in near coastal regions. However, such environmental policies amplify the effects of climate change on the biomass of small zooplankton. Policies that allow river nitrogen loads to increase in the absence of any increase in river phosphate loads have little impact on net primary production and phytoplankton and zooplankton biomass. Reducing trawling effort in the North Sea leads to an increase in benthic biomass. However, climate change in the long term is expected to decrease the benthic biomass on the shelf and therefore counteracts the reduction in fishing effort.

North Sea: Climate, Eutrophication and Fishing

The water temperature is projected to increase along with the potential for ocean acidification (decreasing pH). Additionally changes in river nutrient supply might exacerbate the climate effect. Here, we compared two scenarios for varying nutrient loads projected for 2030-2040 and found that for this period climate impacts were projected to dominate over direct anthropogenic impacts in the North Sea. The wider effect of changes to the North Sea food web is necessarily a complex emergent property of the interactions of the many groups. In general though there are some broad conclusions about some of the trends that might be experienced as a result of changes in production: the highest trophic level species respond positively to less fishing and more nutrients, whereas the effects on demersal and flatfish are smaller. Moving to a Maximum Sustainable Yield (MSY) based fishing approach clearly benefits the fish that are fished less whilst their competitors may be adversely affected. In other words, the fishing quotas of some groups that are being fished sustainably now may have to be revisited as a result of changes in population of competitors and predators. Smaller pelagic fish are the 'closest' trophically speaking to the plankton whose levels may change and are likely to see the most dramatic effects of any deliberate or inadvertent change in plankton composition.

Baltic Sea: Climate, Eutrophication and Fishing

The dynamics of the Baltic Sea ecosystem are rather complex and impacted by the very limited exchange with the North Sea, the imbalance in the freshwater budget and the upwelling response to the atmospheric forcing. This makes them quite sensitive to climate and hence, climate variability/change can affect the ecosystem in many different ways and on several time scales. Scenarios that account for short-term ecosystem response combined forcing from the interaction of policy related changes in the river nutrient supply and climate indicate that both factors affect the Baltic Sea lower trophic level ecosystem dynamics with the same order of magnitude. Direct anthropogenic impacts accumulate in the Baltic Sea due to a long characteristic time scale and limited exchange with the North Sea and the North Atlantic. The Baltic Sea is therefore especially vulnerable to anthropogenic impacts and the importance of ecosystem relevant policies for the Baltic Sea is emphasized. In terms of higher trophic levels, the projected future environmental conditions clearly hamper successful cod recruitment. However the contrary is found for sprat. The fishing regime has no major effect on sprat biomass, instead, sprat spawning stock biomass is predicted to increase markedly and almost independently of the fishing regime.

Bay of Biscay: Climate and Fishing

In the Bay of Biscay, one of the main anthropogenic drivers for the pelagic ecosystem is fishing. The main conclusion from the simulations performed here is that fish total stock responds differently to the FMSY and Fpa scenarios following the simulated period (near past 1980-2000 or future 2010-2099), and thus following the plankton input prey fields.

Black Sea: Climate, Eutrophication and Fishing

This study projects potential responses of the current Black Sea ecosystem to eutrophication in combination with climate change and therefore provides useful information for those concerned with mitigating and managing eutrophication in the Black Sea. Simulated chlorophyll concentrations are found to be a poor indicator of eutrophication, with zooplankton biomass found to be more responsive to changing nutrient loads. One interesting result of these simulations is that in two of the scenarios considered the opportunistic and non-native heterotrophic dinoflaggelate Noctilua scintillans disappears from the simulations as nitrate concentrations become too low to sustain its food sources (flagellates, diatoms and microzooplankton). The models described in this work may be applied to predict changes in relative phytoplankton biomass, relative fish biomass, nutrient enrichment and frequency distribution of events such as phytoplankton blooms etc. corresponding to thresholds defined by the MSFD.

N Aegean Sea: Climate, Eutrophication, Fishing and Pollution

Under a warming scenario, small phytoplankton cells will become even more dominant in the autotrophic group while the heterotrophs to autotrophs ratio will increase. All scenarios describe decreasing river phosphate loads, resulting in a similar decrease of plankton productivity in coastal areas; which affects phytoplankton composition, showing a relative decrease of dinoflagellates. The reduction in plankton biomass led to a decrease of total fish biomass in the baseline scenario. This decrease was counterbalanced by decreasing fishing mortality in 'global community' and 'local responsibility' scenarios that also affected the overall structure of the food web, showing an increase in the Mean Trophic Level and the small pelagic/large fish ratio. A similar, although weaker, counterbalance in the effect of decreasing plankton with decreasing fishing mortality and copper concentration was also simulated in scenarios with the Anchovy IBM, being more sensitive to changes in phytoplankton productivity than the pollutant.

Adriatic Sea: Climate, Eutrophication and Pollution

Large differences in the trophic state of the Adriatic Sea were driven by the reduction of the land based phosphate load occurred in the last two decades of the 20th century. The annually averaged chlorophyll profiles suggest how the reduction of phosphate load from rivers determines an overall decrease of the phytoplankton biomass at all depths (not only at the surface). The lower trophic level dynamics of the basin are very sensitive to variation in the land-based nutrient load, decreasing nutrients resulting in a shift towards more oligotrophic conditions. Progressive warming of the Adriatic basin is effectively boosting primary production but at the same time all the respiration losses are concurrently enhanced, therefore providing a compensating effect. Organic pollutants such as the herbicide terbuthylazine seem to have minimal effect when considering the region as a whole but may have an important role in limited areas where the impact may be acute.

Benguela upwelling: Climate and Fishing

The impacts of a combination of climate and fishing pressure on the Benguela ecosystem have been explored for the period 2030-2040. The "Business as Usual" scenario seems to favour an overall increase of fish biomass while all the other fishing scenarios cause fish biomass to decrease.

Implications for Management: The objective of the MSFD with respect to foodwebs is to ensure the long term abundance and maintain the reproductive capability of key species. The interactions between species within foodwebs are complex and constantly changing making them difficult to assess. A key challenge is understanding the responses of ecosystems to multiple and combined drivers is to better determine the potential sensitivities of ecosystems to combinations of top down and bottom up controls. In MEECE end to end models are used to evaluate the marine foodweb response to future climate change, ocean acidification, and human pressures such as fishing, eutrophication and pollution. For example how the effects of fishing and climate propagate through a food web, whether the effects are synergistic vs antagonistic, whether they are dampened across TLs vs amplified, will depend to a large extent on which trophic level the climate and fishing forcing is specifically acting. End-to-end models can be used to explore these combined responses.

1.3 Implications for resource management

The goal of this aspect of MEECE was to contribute to the development of tools and management strategies to which take account of trends in uncontrolled (e.g. climate) or difficult to control drivers (eutrophication, pollution) and allowing a better management of drivers under human control (i.e. fisheries and introduction of alien species), as an important contribution to the ecosystem approach to management. Decision Support Tools (DST) are interactive computer-based systems that help decision makers utilise data and models to solve unstructured problems. We distinguish four major categories of DST that are applied in different stages of the process intended to provide relevant scientific advice to policy:

-Problem structuring: integrated assessments involving stakeholders in order to identify the problem, explore options to resolve the problem and agree a set of criteria against which these options can be evaluated.

-Information synthesis: tools which essentially synthesize monitoring data into meaningful metrics summarizing ecosystem state.

-Expert systems: tools that mimic the way decisions are reached by experts.

-Scenario planning: tools involving numerical models which can simulate and predict changes in the state of marine ecosystems in response to different management and climate driven scenarios (Management Strategy Evaluation).

1.3.1 Integrated Ecosystem Assessments (IEA)

The purpose of this IEA was to determine the main human activities, pressure/ impacts and ecosystem components from a management/policy perspective. As the integrated management of the human activities should be driven by the European Integrated Maritime Policy of which the Marine Strategy Framework Directive (MSFD) provides the ecological pillar this assessment was aimed at determining the risk that the main MSFD objective (i.e. Good Environmental Status, GES, in 2020) is not achieved. As only the pressures caused by human activities can be managed this IEA was based on establishing all relevant links between these activities and the 11 descriptors that determine GES. A risk assessment framework was developed and applied in order to determine for each of these activities their importance in terms of their contribution that GES is compromised. This was done through a qualitative/semi- quantitative assessment based on expert judgement in three regional teams covering some of the main MSFD (sub-) regions; the North Sea, Bay of Biscay, Mediterranean and Baltic Sea. The outcome of this IEA was then used as the basis for an evaluation of the relevance of the outputs of the MEECE simulation models in a policy/management context. When considering this relevance we distinguish between the pressure- and state-type of descriptors as the pressure descriptors are often directly linked to a specific pressure/activity while the descriptors of state essentially integrate the impacts of these different pressures. The IEA shows that fisheries were considered the most important human activity. Others are transportation, dumping, coastal protection, land reclamation and dredging but here their relative importance may differ depending on the region but also the uncertainty in this exercise. For the descriptors, state results show that overall biodiversity is the descriptor most likely to be compromised which follows from the fact that it encompasses most ecosystem components including those that contribute most to the risk of not achieving GES (i.e. several habitats and top predators like cetaceans, seals and seabirds). Most of the main ecosystem components are covered by the MEECE models except for the different habitats.

The MEECE drivers as they occur in the proposal map directly onto the GES pressure descriptors (except for energy and noise) so this IEA provides a first formal attempt not just to rank these drivers in terms of their importance but also show how these drivers and other pressures could potentially affect the state of the ecosystem (as expressed by the State descriptors) which essentially integrates the effects of all pressure/impacts. The main aim of this exercise was to identify the gaps in coverage of policy related topics that are not adequately covered by models with an emphasis on those most likely to compromise policy objectives. This would then deliver an evaluation of the suitability and relevance of the MEECE models from a policy perspective. In spite of this limited coverage of the various ecosystem components the MEECE models cover three of the four state descriptors reasonably well in several of the MSFD (sub) regions. Even though this may only include a limited part of the attributes and/or indicators, at least part of the descriptor is covered.

Decision support tools (DST): MEECE has contributed to the development of a number of DST which go beyond application in the management of fisheries and now involve other human pressures such as pollution and non-indigenous species or an environmental driver, i.e. climate. Information synthesis DSTs have been applied in the North Sea and Baltic Sea and involve the representation of the status of commercial fish stocks in simple graphs, as well as the combination of environmental, ecosystem and fisheries data from a variety of monitoring programs into a synthesis at the level of the whole ecosystem.

MEECE has developed a number of expert systems. One is a web-based application that assists in identifying which policy-relevant indicators describing Good Environmental Status (GES) for the Marine Strategy Framework Directive (MSFD) which can be covered by MEECE models in the different MSFD regions. Others involve the incorporation of an environmental (i.e. climate) driver in fisheries management through the development and application of so-called environmental Harvest Control Rules (eHCRs) or the potential application in the management of human pressures such as pollution and non-indigenous species. For example a framework was developed that should allow the combination of scientific information based on MEECE modelling output with stakeholder preferences to select the preferred management scenarios to achieve the ecological objectives taking into account the social and economic impacts of the proposed management measures. This approach has demonstrated that decision-support tools could be used to deliver a preferred management scenario to achieve policy objectives in a formal and transparent process that takes the stakeholders opinion into account and combines this with scientific evidence, provided that the management scenarios utilised are meaningful and that there is sufficient appropriate and reliable information to parameterise the underlying modelling approaches.

Biopollution may pose a serious threat to the environment and human uses of the sea, interacting with other stressors, such as eutrophication, chemical pollution, habitat destruction or overexploitation. In order to address the need to measure, report and verify the impacts of an Invasive Alien Species (IAS), a standardized method to assess the magnitude of the bioinvasion impacts, i.e. the 'Biopollution Level' (BPL), was devised. The BPL method is based on a classification of the abundance and distribution range of alien species and numerically expresses the magnitude of their impacts on communities, habitats and ecosystem functioning aggregated in a BPL index which ranges from ‘no impact’ (BPL=0) to 'massive impact’ (BPL=4) . In the course of the MEECE project a novel expert system the Bioinvasion impact (biopollution) assessment system (BINPAS htt://www.corpi.ku.lt/databases/binpas) BINPAS is a computerized system (a practical application) based on the BPL method. The purposes of this system are to: a) provide a user-friendly system to calculate BPL; b) accumulate and store information on abundance and distribution range of various AS in different geographical domains as well as their impacts on communities, habitats and ecosystem functioning; c) enable comparisons between different species, ecosystems and time periods. BINPAS translates the existing data on miscellaneous invasive alien species impacts into uniform biopollution measurement units.

The environmental risk index for pollution by contaminants DST is able to objectively integrate chemical and eco-toxicological data into numerical indices useful to support decision makers in managing contaminated marine coastal sediments, with a view to planning remediation or rehabilitation activities. It utilizes chemical and ecotoxicological data to calculate a binary sediment risk index (ranging between 0 and 1). However, in cases where a general evaluation of the environmental risk in a particular area is requested, it is possible to complete a multitude of biological investigations with ecological data, calculating an environmental risk index (EnvRI), following a classical 'Triad' approach. The system is able to correctly rank sediment samples in terms of contamination and bioavailability. The indices produced are highly dependent on the quality of the available data and there is a requirement for the definition of common Environmental Quality Standards for the most diffuse pollutants throughout Europe.

Finally there is an expert system that provides a formal way of including stakeholder preferences into the selection of the preferred management measures towards the sustainable exploitation of the marine resources including all three pillars of sustainability (i.e. ecological, social and economic). All scenario planning DST are essentially about Management Strategy Evaluation (MSE).

1.3.2 Management Strategy Evaluation (MSE)

MSE tools provide a methodology for assessing the consequences of a range of management strategies or options and presenting the results in a way which helps the decision maker to make a rational decision, in the context of their own objectives, preferences, and attitudes to risk. The approaches developed in MEECE include analyses of empirical data and development and application of advanced quantitative models and methods, with examples of their use in management context of different drivers. The degree to which a given ecosystem is manageable partly depends on which are the most dominant pressures influencing the system. For example, eutrophication is one of the key pressures in the Baltic Sea, which can in principal be regulated by nutrient inputs, although the time scales of ecosystem response may be long. However, compared to, for example, the open waters of the North East Atlantic largely driven by ocean currents, the coastal ecosystems, which are relatively more directly and heavily influenced by human activities, are more susceptible to effective management. Nevertheless, climate impacts also interact with other human pressures in these relatively closed ecosystems and developing a general risk-based framework to support decision making and environmental management in marine ecosystems should allow the incorporation of climate change in order to be effective. For example, the information generated in MEECE suggests introducing temperature-induced effects (as well as effects due to other environmental stressors, such as pH) in the determination of reference values (EQSs) for marine and freshwater ecosystems, thus allowing the incorporation of climate change in the implementation of classical environmental management tools. Climate-driven alterations of environmental parameters (e.g. temperature, salinity, pH, oxidative potential) can, for example, act on contaminant bioavailability as well as on organism sensitivity to chemicals, thereby directly altering environmental risk on marine biota.

One general message emerging from MEECE is that changes in productivity in marine ecosystems due to natural or not- directly manageable human drivers is an important consideration when developing management strategies for pressures that can directly be controlled by management actions, such as fisheries. Productivity is a major factor influencing population dynamics in marine ecosystem components and can in some cases be the cause of stock collapse or a pre-requisite for recovery of depleted stocks. The aspect of biological variation is relevant also for example in setting MSY reference values which may change depending on several biological processes (recruitment, growth, condition, maturity and natural mortality) that are known to vary over time and may depend on the environmental (e.g. climate) circumstances. Therefore, the management frameworks should allow sufficient flexibility to adapt to changes in productivity when these occur. Forecasting productivity in a changing environment can be facilitated by process oriented ecosystem models covering processes from biochemistry to fish, as demonstrated below.

The spatial component is relevant and often considered in marine management. However the appropriate spatial scale at which the management of a particular driver needs to operate, however, is often not straightforward as the scale of the actual pressure may differ markedly from that of the impact. The pressure of pollution may be very local, given the point source nature of toxin addition to the marine environment (e.g. toxin spills, release from oil platforms, river outlet etc.) while it may have a large-scale impact. In contrast, some other drivers, such as climate, act on a wider regional or global scale. Potential habitats for native or alien species within an ecosystem are to a large extent dependent on local conditions. Concerning resource management, different ecosystems or even sub-systems may allow different optimal fishing pressure, and tolerance limits at which level of pressure stock collapses occur may be area-specific. Consequently, spatial heterogeneity in environmental conditions and human pressures can cause locally distinct production patterns, with implication for local ecosystem structure and functioning, important to take into account in ecosystem based approach to resource management. As concluded in the integrated assessments, the ecosystem components that mostly contribute to the risk that GES is compromised all have distinct spatial patterns as do many of the most important human activities. Thus, the applicability of the models in a management context is improved when these include a spatial component.

The spatially explicit nature of some coupled modelling tools covering processes from physics to fish, developed in MEECE, can provide e.g. warning signs for levels of pressure which places the ecosystem at risk. For example from spatial signatures of how habitats are depleted, as well as risk of stochastic extinction of local fish stocks. More generally, the various modelling approaches provide advanced tools for producing high resolution information on spatial heterogeneity of distribution of organisms, environmental condition and human pressures, and can aid in development of spatial management strategies and measures, such as Marine Protected Areas, including assisting in development of Marine Spatial Planning.

Advancements in MSE tools applicable to the ecosystem approach: Among the drivers considered in MEECE, the most direct relationship between management of the human activity and the response of the ecosystem is observed for fisheries. This probably explains the relatively longer tradition of developing complex frameworks for evaluating management strategies and related risks compared to other drivers, such as pollution and eutrophication. Consequently, the quantitative management frameworks for fisheries are well advanced, while the management aspects of other drivers are mainly handled in semi-qualitative decision support tools, which also reflect the temporal and spatial scales involved in driver impacts and consequent possibilities to control these by management actions.

The major advancements in Management Strategy Evaluation frameworks developed through MEECE include direct incorporation of environmental drivers, and moving away from single species MSE to more holistic ecosystem based evaluations. This is triggered by the needs of the MSFD and ecosystem approach, as developing management strategies robust to changes in environmental drivers is a step towards implementing such approaches, and to achieve or maintain Good Environmental Status of the ecosystems. Further, the coupling of single stock based MSE frameworks to multi-species models allows the demonstration of trade-offs between species and thereby serves as a tool for testing management targets and strategies which take into account biological interactions, and to develop test indicators for fish stocks and food webs (MSFD Descriptors 3 and 4). The next step is developing community models and applying these in a MSE context, which allows wider ecosystem questions to be addressed, such as those related to ecosystem functioning and biodiversity (MSFD Descriptor 1), and additionally take into account uncertainties associated with ecosystem models.

A key message emerging from applications of MSE tools which consider ecological communities and food-webs is the need for defining clear management objectives, as the yield of predator species depends on the harvest rate of prey species and vice versa. Importantly, development of new tools and methods for MSE and estimating management reference points should put a specific focus on related uncertainties, which can reduce the risks and contribute to optimizing the management.

1.3.3 IndiSeas (Indicators for the Seas)

IndiSeas uses ecosystem indicators to evaluate the status of the world's exploited marine ecosystems in support of an ecosystem approach to fisheries, and global policy drivers such as the 2020 targets of the Convention on Biological Diversity(. Key issues covered relate to the selection and integration of multi-disciplinary indicators, including climate, biodiversity and human dimension indicators, and to the development of data- and model-based methods to test the performance of ecosystem indicators in providing support for fisheries management. A major gap identified in IndiSeas and MEECE was that fishing may not always be the only or even the main driver of some ecosystem indicators of fishing. To determine whether, when, where and how ecosystem indicators can be used to measure effects of fishing in a fluctuating environment, specific aims of IndiSeas are to: (i) assess the relative importance of fishing and environment for different ecological indicators; (ii) identify years where the environment was more important than fishing; and (iii) compare relative effects of fishing and climate across ecosystems. To enhance the robustness of our cross-system comparison, unprecedented effort was put in to gathering regional experts from MEECE partners but also from other non-European developed and developing countries, working together on multi-institutional survey datasets, and using the most up-to-date ecosystem models.

Potential Impact:

Potential Impacts

Coastal seas provide many beneficial goods and services to humankind, such as fisheries, recreation, climate regulation and coastal defence; however, marine environments are being disrupted by climate change and human activities. MEECE has explored a wide range of climatic and direct human influenced drivers which may affect the marine system. Policies related to marine resources and environments today require the development of management strategies that are robust to changes in the drivers affecting ecosystem productivity, such as climate change. The successful implementation of an ecosystem based approach to management requires evaluation of management strategies which take into account biological processes such as species interactions and their variability over space and time. 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.

The target audience for MEECE research is primarily, decision makers in both the policy and management arenas but also includes SMEs interested in the application of knowledge, the wider marine science research community and the interested public. A particular focus of MEECE 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 outputs from MEECE will also benefit the Common Fisheries Policy (CFP) aimed at protection of the marine resources from degradation and a sustainable exploitation of these resources needs integrative approaches that consider multiple drivers and biological interactions in ecosystems.

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, 7 of which are considered by MEECE (D1 Biodiversity, D2 Non Indigenous species, D3 Commercial Fish, D4 Foodwebs, D5 Eutrophication, D6 Hydrography and D8 Pollutants). 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, this requires a regional approach as used in MEECE.

It is important to recognize that only a few of the MEECE drivers (the ones directly related to human pressures) can actually be influenced by direct management actions. The simplest example is fisheries where management decisions have direct impacts on the ecosystem at a relatively small spatial and temporal scale. In contrast, the drivers of eutrophication, pollution and acidification in the marine environment mostly require land based management solutions, with possibly long time lags in environmental response. Whereas climate, as a natural driver, acts at a more global scale over extreme timescales, and is arguably beyond management possibilities but may be a factor to consider when developing management of the direct impacts.

The simulation models developed and applied in MEECE provide tools for addressing complex driver impacts and ecosystem responses. Such numerical models which can simulate and predict changes in the state of marine ecosystem in response to different drivers and management scenarios can support the decision-making process. A schematic view (figure 14) of the ability of the current models to provide policy-relevant information gives a subjective representation of the general skill of the models for each driver in relation to the knowledge base to usefully exploit the model information.

More specifically:

-Warming, Circulation and Stratification: Hydrodynamic models are able to provide useful information on temperature, circulation and stratification at a regional scale. This provides useful information on habitats and the transport of nutrients from which impacts on phytoplankton can be inferred. As we move up the foodweb, the implications of change become less clear.

-Acidification: Currently models are able to provide useful information on the inorganic carbon cycle (e.g. pH, PCO2) at regional scales; this is hampered in coastal regions by the lack of knowledge of alkalinity sources. The knowledge of the ecological implications of change is currently limited, but improving.

-Habitats: Models can provide useful information to define pelagic habitats (e.g. temperature, salinity, nutrients, stratification) at regional scales. The consequence of changes in habitat on the ability to achieve GES remains an open question.

-Eutrophication: Coupled hydrodynamic ecosystem models can provide useful information of nutrient loads, and chlorophyll concentrations and in some cases summer oxygen levels, but require the land derived sources to be well characterised. The consequences of change are well understood.

-Commercial Fishing: There are a wide range of models of commercial fisheries of varying skills which provide information on fish stocks as well as the wider fish community and their response to changes in fishing pressure at regional scales. The capacity for simulating the impact of fishing on the whole ecosystem has been increased through the development of coupled end to end models. However these models are still in the proof of concept phase and should be applied with care.

-Pollution: This includes a wide range of compounds (greater than100,000) whose ecological impacts are often poorly characterised. Additionally there are always unknowns as new compounds are constantly being developed. Finally, the ecological implications of mixtures of compounds remain a topic of on-going research. If the source of a contaminant is well defined then existing models have the ability to trace its distribution at local and regional scales.

-Invasive Species: Currently there are no modelling tools which can usefully predict invasion and colonisation by invasive species. This is partly due to lack of knowledge of the ecology of invasive species and is confounded by the fact that new species periodically appear so there are always unknowns. Bioclimatic envelope modelling can provide useful information on changes in the distribution of species whose habitat is well characterised.

MEECE and the Marine Strategy Framework Directive:

To meet the goals of EU Marine Strategy Framework Directive to achieve Good Environmental Status for marine ecosystems a holistic view considering all ecosystems is required. To illustrate and provide examples of the kind of information and outputs models can provide the MEECE Descriptor fact sheets were developed. Each one focuses on a Descriptor and demonstrates via detailed case studies how models and related tools developed during the project can be applied to help answer some of the difficult questions that need to be addressed in order to meet the objectives of the MSFD. A fact sheet has been written to address each Descriptor that was relevant to MEECE's activities; the full suite of fact sheets have been compiled into a distribution pack for broad dissemination and are available to download from http://www.MEECE.eu/kt/fs.html . A brief summary of what MEECE can contribute to each Descriptor follows.

D1 Biodiversity: Marine biodiversity is the range of life forms in the seas and oceans. This biodiversity may be measured 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. The state of an ecosystem and therefore biodiversity is highly dynamic; changes in the state or pressures in one part of the ecosystem can lead to unexpected changes in another part, easily affecting overall biodiversity. This descriptor therefore has a strong inter-relationship with other MSFD descriptors. 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. MEECE has developed a number of models that can be used to predict indicators of biodiversity. For example, the impact of a range of drivers on functional biodiversity can be examined by looking at changes in phytoplankton and zooplankton populations. Plankton can be classified by size, function (carnivorous versus omnivorous) or taxonomically, providing information on the health and changing state of a defined region.

The OSMOSE model predicts spatial extent and temporal community population trends of fish species in regions including the Bay of Biscay and the Adriatic. Individual based modelling can be used to predict the fate of fish larvae leaving the spawning grounds. The size range of communities have been modelled by linking the APECOSM model (a model of top predator dynamics) to models at the bottom of the food web, and categorizing results in terms of habitat. Using the EwE model changes in abundances of many species can be examined providing an indicator of population dynamics in marine communities. Regions studied include the North Sea, Black Sea and the Benguela uprising off South Africa. This approach allows biodiversity to be evaluated through looking at; the replacement of native species by invasives, the relative number of the least common and higher trophic level groups such as sharks, mammals and seabirds, and the status of commercially important stocks.

D2 Invasive Species: Non-indigenous species (NIS) are those that are introduced from their native range through the ballast water of ships, through marine and inland canals, via culture and stocking procedures, or by other unintentional or deliberate human vectors. Some NIS may become invasive, increasing their abundance and spreading over large regions, with adverse impacts on native biodiversity, habitats and ecosystem functioning, and even economy and human health. Such an adverse alteration of ecosystems is called biological pollution (biopollution). GES is achieved if non-indigenous species introduced by human activities are at levels that do not adversely alter the ecosystems. The EC decision on criteria and methodological standards on GES of marine waters (EC 2010/477/EU) calls for scientific and technical development of indicators of impacts of invasive NIS. To classify the level of invasive species impacts an integrative method, the 'Biopollution level index' (BPL), was developed. The index is based on the classification of the abundance and distribution range of NIS and the assessment of the magnitude of their impacts on native communities, habitats and ecosystem functioning. BPL ranges from 0 ('no measurable impact') to 4 ('massive impact'). Such a scale for biopollution impacts helps to reduce subjectivism in measurement and reporting impacts, but also makes possible initial and trend assessments to determine the status quo according to MSFD requirements.

The MEECE project supported development of the online Biological Invasion Impact / Biopollution Assessment System (BINPAS) based on BPL methodology. BINPAS was created using open source web technologies and relational database management systems. It provides a user-friendly interface to calculate BPL and allows for the sharing of ecological data, providing inter-regional comparisons and meta-analysis of biological invasion effects at different spatial and temporal scales http://www.corpi.ku.lt/databases/index.php/binpas

BPL may be estimated only for the areas with known history of biological invasions. Data on abundance and distribution of NIS present in the system is a prerequisite for the assessment, and at least, basic knowledge on local native biodiversity and environmental impacts of invasive species is required. Extensive literature searches are required to make the assessment and despite robust rule-sets, still a certain level of subjectivity may be present in the assessments, because the assessor needs to deal with incomplete scientific information. However, all background data is stored in BINPAS may be easily extracted and checked for validity.

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.

Fishing is the only driver explicitly considered as part of this descriptor and the only activity subject to tactical management at the appropriate scales of space and time. Other drivers such as climate, however, could become relevant and should be considered for the longer-term strategic management of fishing activities. At the scale of several decades, considerable and regionally-different changes in productivity can be expected due to climate or eutrophication which should be considered when setting management targets for this descriptor.

A suite of modelling tools has been identified, 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 single- or multi-species stock assessment models. Several of these models can be coupled to models of the bottom of the food web, allowing the exploration of the impact of fishing pressures and other drivers. One important exercise within MEECE has been the application of such models to explore the reference levels required for operationalizing the objectives/criteria for GES of this descriptor.

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.

The MEECE project provides climate and ecosystem (from plankton to fish) response scenarios, to support decision making for marine policy and management. In MEECE, coupled physical to ecosystem models are used to evaluate the marine food web responses to climate scenarios in the medium (2030- 2040) and long-term (2080-2100). In these scenarios, oceanographic circulation models are forced by climate drivers, which in turn, are coupled with lower trophic models (phytoplankton and zooplankton) to evaluate changes in oceanic primary production.

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. The eutrophication descriptor focuses on both anthropogenic and natural causes (i.e. human induced increased river nutrient loads, and coastal nutrient increases due to climate effects), and their direct (increased phytoplankton blooms or decrease in transparency) and indirect (decrease of benthic plants) effects. Eutrophication has broad reaching impacts and can have negative impacts on other descriptors such as biodiversity, non-indigenous species, food webs and commercial fish.

MEECE has produced a number of tools that can be used in decision making and management around eutrophication in European regional seas. The MEECE suite of regional biogeochemical models provide state of the art tools to understand the impacts of eutrophication, and how climate change and policy management could affect this descriptor. Current models are able to provide estimates for recent trends and future forecasts for several of the indicators for eutrophication. Although each model has different structures and characteristics, indicators relevant to this descriptor that can be addressed by MEECE biogeochemical models include: 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. It should be born in mind that uncertainties related to the coarse resolution of models and process formulations of growth, respiration, mortality and regenerative production in state of the art biogeochemical models are responsible for large model spread in eutrophication risk assessments. Such uncertainties currently limit the applicability of single model approaches to eutrophication management problems, looking at the outputs from a number of biogeochemical models could provide a more robust assessment.

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.

At the scale of the continental shelf these properties are however largely determined by natural phenomena and so less responsive to management action on human activities. However they are subject to large-scale changes driven both by climate change (including warming and ocean acidification) and natural variability. These can have important and long lasting consequences for marine ecosystems, both beneficial and adverse. 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.

MEECE has made a substantial contribution to the international capability to simulate these effects and explore possibilities resulting from particular climate scenarios, which can include both natural and human induced changes. A particularly relevant aspect of hydrographical change that these models can explore is global warming, including changes in sea temperature and density stratification, as the surface layers of the open ocean warm much faster than the water at depth. Stratification reduces the vertical mixing of nutrients needed to support the growth of the microscopic plants (phytoplankton) that form the base of the marine food chain. Other effects include changes in nutrient transportation from the open ocean to the shelf seas, the timing of spring blooms and the speed at which organic material is 'recycled' back to the inorganic nutrients that support the growth.

While we are not yet in a position to make accurate forecasts for these properties, simulations provide important evidence that can be used alongside expert judgement to inform adaptation policies on issues such as the definition of Marine Protected Areas, the level of exploitation of marine living resources and marine renewable energy resources. There is still a high degree of uncertainty in projecting future change in marine ecosystems resulting from changes in hydrographical conditions. However, many of the principles are well established and by relating the output of models such as these to well-founded scientific concepts, such as the increase in growth rates with temperature or reduction of mixing with density stratification, these simulations can build a body of increasingly reliable evidence.

D8 Pollution: Good Environmental Status for Contaminants under the MSFD states that 'concentrations of contaminants are at levels not giving rise to pollution effects'. Pollution effects are defined as 'direct and/or indirect adverse impacts of contaminants on the marine environment, such as harm to living resources and marine ecosystems, the hindering of marine activities, impairment of the quality for use of sea water and reduction of amenities or, in general, impairment of the sustainable use of marine goods and services'. Consequently, chemical pollution is closely linked to other GES descriptors, such as biodiversity, integrity of food webs and sea-floor ecosystems.

Impacts of contamination have been considered in several tasks of the MEECE project. In particular, project activities were focused on target contaminants such as heavy metals, alkylphenols, antibiotics and herbicides. Available scientific information about the fate of key-pollutants and the biological effects on marine organisms were collected and collated into structured databases. A set of multi-driver experiments was then carried out in order to parameterise biological responses induced by key-pollutants and other climate change relevant drivers.

MEECE has developed an expert Decision Support System (DSS), focused on managing contamination in marine coastal areas which calculates the pollution-related environmental risk on a scale from 0 (no risk) to 1 (maximum risk) integrating a complex set of chemical (concentration of target contaminants) and biological data (ecotoxicological effects on model organisms), thus supporting environmental managers in the estimation of environmental quality. The framework of the expert DSS is mainly based on the integration of heterogeneous (chemical and biological) data, through a weight of evidence approach, into risk indexes useful in improving the decision-making process. With this objective, the quality and quantity of input data are key factors in determining the reliability of results obtained.

1.4.2 Managing marine ecosystems in a changing environment

Management strategy Evaluation (MSE) in a broad sense involves addressing the consequences of a range of management strategies or options and presents trade-offs in performance across a range of management objectives. An MSE framework generally includes a model of a virtual ecosystem where parts are affected by human activates. Feedback loops ensure the system is dynamic and responsive to changes in human and ecosystem response. MEECE has developed a number of bespoke MSE frameworks and models to address management questions, including:

-Forecasting changes in productivity

-Assessing potential spatial expansion of the habitat of Non-Indigenous species

-Assessing the extent of spawning habitat of key fish species and distribution of fish in relation to climate change

-Quantifying spatio-temporal overlap between ecosystem components and pressures

-Evaluate management strategies for fisheries (Bay of Biscay, Baltic and North Seas), taking into account species

Web-based Dissemination Tools:

MEECE has developed a number of online tools to help disseminate its outputs. The Model Atlas provides interested users and site visitor's access to model derived outputs and simulations produced as a result of the efforts of the MEECE scientific community. The Model Library gives users an overview of the available modelling tools and indiSeas provides online indicators of the status of 34 marine ecosystems worldwide, both are described in more detail below. The online decision support tool for NIS, BINPAS is described in section D2 Non Indigenous Species.

The MEECE Model Atlas (see http://www.meeceatlas.eu online) covers the main European regional seas and provides simulations and projections for how ecosystems will respond to different scenarios for environmental change, in a form that's readily accessible to policy-makers, fisheries officials and other users of marine science. Using ecosystem end-to-end models, the Atlas provides a holistic view of the continent's marine resources. Marine ecosystems are represented at all levels, from the physics and chemistry that underlie it to plankton, fish and human activities. During the MEECE project predictive regional models and have been developed and refined to explore the combined impacts of ecosystem drivers of change. The results of these efforts are presented through a publically available web Atlas. Aimed at environmental managers and marine policymakers to help make scientifically informed decisions about resource management and usage strategies, the Atlas incorporates a range of potential future scenarios based on climate trends and socio-economic development over the coming decades. These scenarios include the Intergovernmental Panel on Climate Change (IPCC) climate projections for near future (up to 2040) and the far future (up to 2100) alongside the human development scenarios of 'Local Responsibility', a community-based approach with slow economic growth but increases in small scale production; 'World Markets', rapid growth and favouring consumerism over environmental objectives; and 'Global Community', growth that balances economic, environmental and social needs.

Web-based model library tool with mapping to GES indicators: MEECE consortium created the MEECE Model Library, available from (see http://www.meece.eu/Library.aspx online). To increase its functionality and policy relevance, the capabilities of the modelling tools in the Model Library have been mapped onto the EU's Marine Strategy Framework Directive's descriptors for Good Environmental Status. Users are able to search for a modelling tool addressing specific descriptors in a geographic region of interest, or browse the technical content of the library. The Library currently proposes modelling tools that can be applied in European Seas to address questions on 7 of the 11 GES Descriptors for the regional sea of interest.

IndiSeas (see http://www.indiseas.org online) was initially launched in September 2009, was developed to disseminate results of analyses of the original eight ecological indicators for assessing the status of exploited marine ecosystems, to marine resource managers, fisheries scientists, policy-makers, interested and affected stakeholders and the general public, i.e. beyond a scientific audience. This complemented the suite of scientific papers published in the ICES Journal of Marine Science.

The website presents information at increasing levels of detail. An overview is provided for each ecosystem in a synthetic and understandable form, plots of time-series (1980–2000) for each ecological indicator are provided, and more detailed information e.g. on key species for each ecosystem are also made available. The website offers the capability for the user to select a sub-set of ecosystems for comparison of the states and trends of ecosystems and various graphical representations are offered for comparative purposes. For ease of interpretation, indicators are represented so that larger values or increasing trends signal a less degraded or improving ecosystem, respectively. For this reason, some indicators are represented as inverses (e.g. the coefficient of variation of the biomass, labelled 'biomass stability'). Trends in indicators are represented by means of bar graphs of the short-term slopes of fitted linear trends (1996-2005; currently being updated to 2010); increasing trends represent improvement, and vice versa. Details on the graphic representations, justifications, choices of time frames, and standardization procedures are provided. To complement the visual diagnosis suggested by state and trends graphs, a textual summary of the status of each ecosystem is provided by the ecosystem experts, serving to aid interpretation of an ecosystem's diagnosis, report potential limits of the comparative approach for some specific ecosystems or potential biases in the calculation of some indicators for certain ecosystems, providing information on other drivers that could interact with fishing.

Working sessions were held in 2012 to explore the most appropriate and effective ways of presenting the expanded set of biodiversity indicators, as well as the sets of environmental and human driver indicators that are needed to contextualize the states and trends suggested by the ecological indicators per ecosystem. The expanded version of the website will be made public by mid-2013.

Exploitation of MEECE Outputs: towards operational applications:

MEECE has achieved its two major goals. Firstly through the development and application of regional ecosystem modelling tools combined with meta-analysis and experimental work the knowledge base on response to climate and anthropogenic driving forces of marine ecosystems has been expanded. In particular models provide information of the state of the system (historic, present and future), the pressure state interactions, and how the probability of a negative indicator event may change. Secondly by developing innovative decision support and management strategy evaluation tools and strategies to resolve the dynamic interactions of the drivers, in support of marine management and policy. This is augmented by the MEECE Atlas and indiSeas websites. The challenge for the future is to ensure this work is taken forward and used both in a research and a policy / management context.

The schematic diagram shows the relationships between research and operational applications, illustrating how starting with experiments and observational data, models are developed and applied and then used in an operational context.

MEECE has been proactive in engaging with the development of the MSFD; MEECE scientists led the working groups which developed the D2 (Non Indigenous Species) and D3 (Commercial fish) descriptors. Other scientists have been involved in working MSFD, Arctic acidification and ICES working groups. This type of activity is on-going and will ensure that the MEECE knowledge base is disseminated widely amongst users. These activities are backed up by the MEECE Atlas and the accompanying factsheets.

The MEECE regional modelling tools along with the associated methodologies for downscaling and simulation assessment will be exploited both in new national and European research programs and through the GMES Marine Core service through the development of Operational Ecology. Operational Ecology refers to the provision of operational services for biogeochemical and ecological parameters through a forecast system to project the future status of marine ecosystems by delivering a suite of error quantified indicators which describe changes in ecosystem function. The system should include an observational network along with models of the hydrodynamics, lower and higher trophic levels (plankton to fish) and biological data assimilation. Such systems are required to help assess and manage the risks posed by human activities on the marine environment. For example a number of MEECE models and regional model systems (NE Atlantic, N Aegean, Black Sea, SMS-Baltic) are being further evaluated as to their suitability for making operational rapid environment assessment of the state of the ecosystem in the recent past terms of key indicators. In addition the indiSeas and BINPAS activities provide valuable information on the state of regional ecosystems. BINPAS is being used to make assessments for D2. Both activities will carry on after MEECE.

The Decision Support and Management Strategy Evaluation tools sit on the boundary between the research and operational domain. MEECE has developed a number of frameworks and models which address management questions in the context of the interactions between climate, fishing, pollution, NIS and eutrophication. The next step is the practical application of such systems to develop management strategies which are robust to changes in environmental drivers. Many of these tools were developed by MEECE and will be further exploited by organisations directly involved in the implementation of the MSFD at a national level.

Finally MEECE was a genuinely European project. It brought together expertise and intellectual resources from across Europe. The progress made by MEECE in understanding the response of marine ecosystem to external perturbations and developing tools and strategies to manage them was only possible through Europe wide interdisciplinary cooperation.

List of Websites:

http://www.MEECE.uk

http://www.MEECEatlas.eu