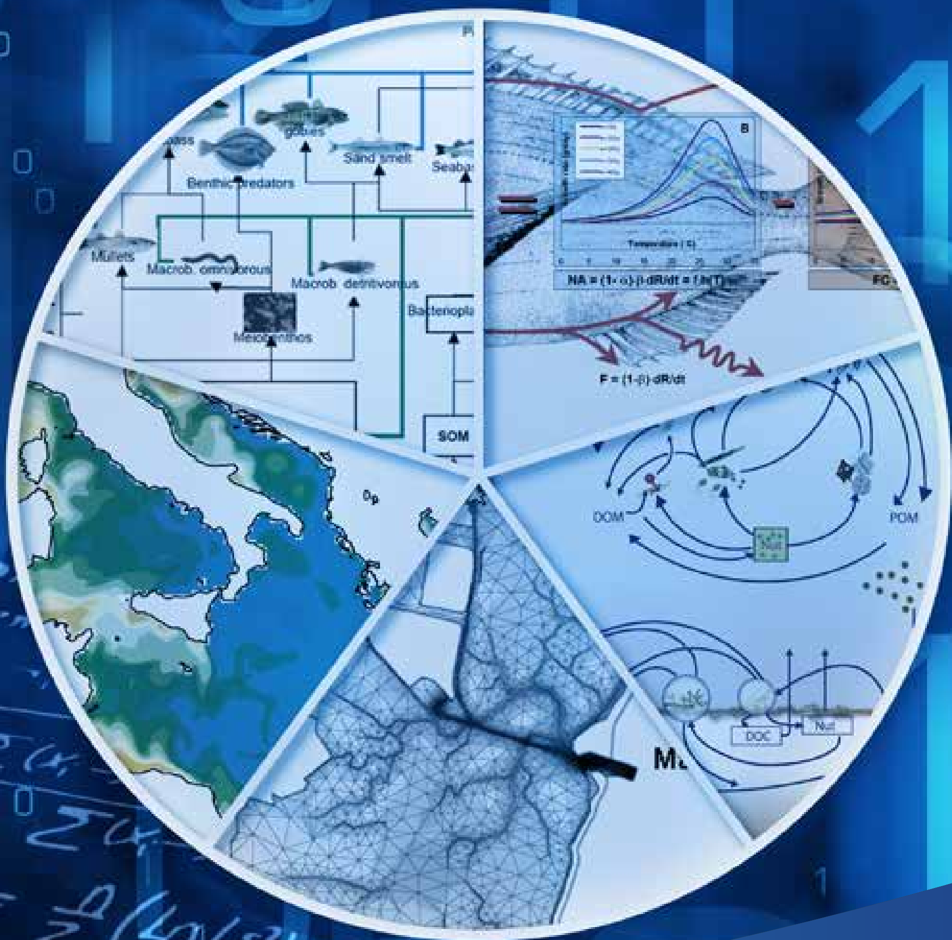
Future Science Brief

Nº 4 October 2018

Enhancing Europe's Capability in Marine Ecosystem Modelling for Societal Benefit



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This future science brief is a result of the work of the European Marine Board Expert Working Group on Marine Ecosystem Modelling (WG MODELLING) and an expert workshop (see Annex I and II for WG members and workshop participants).

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Foreword

Europe has an excellent capability in Marine Ecosystem Modelling and this is being increasingly used as a tool for ecosystem management. However, there remains a mismatch between scientific research and what policy makers need to know. In addition, there is a need to increase the predictive power in marine ecosystem models, including forecasting to predictions and scenarios, which still lag behind capabilities for weather predictions.

In 2017 EMB identified it was timely to conduct a foresight activity to communicate community-driven European research needs and priorities on marine ecosystem modelling to policy makers and wider stakeholders. The triennial Advances in Marine Ecosystem Modelling Research (AMEMR) conference in July 2017 in Plymouth, UK, was an ideal opportunity to kick-off EMB's activities on this topic. For this, EMB organized a back-to-back science-policy event, attracting over 30 international experts in marine ecosystem modelling to assess future research needs and priorities in this field. Recommendations from this workshop, together with wider reviews and stakeholder inputs, were taken forward by a working group on marine ecosystem modelling which was launched in summer 2017.

On behalf of the EMB membership, I would like to thank the members of the EMB working group on marine ecosystem modelling (Annex I), workshop participants (Annex II) and reviewers for their contribution in delivering this Future Science Brief. Special thanks go to the Chairs of this group, Morten Skogen and Sheila Heymans for their efforts in coordinating this activity and to members of the EMB Secretariat who enabled the publication of this document, namely, Kate Larkin, Joke Coopman, Ángel Muñiz Piniella, Paula Kellett, Charlotte Simon, Christine Rundt, Cláudia Viegas and Sheila Heymans.

Throughout the course of the working group, there has been an increasing recognition by the European marine science-policy community of the societal benefits of improving predictive capability of marine ecosystems and the key role that marine ecosystem models can play. During preparation of this publication, EMB have interacted with the Directorate for Environment (DG ENV) and Joint Research Centre (JRC) of the European Commission, which are currently working on a number of related initiatives to assess and make available information on Europe's full capability in marine environmental models. In addition, the European Union's Horizon 2020 Work Programme 2018-2020 includes a Blue Growth flagship initiative on the future of seas and oceans where the need for integrating ocean observing systems, data management systems and appropriate models is recognized as vital to deliver ocean information, products and services to a growing user community.

In parallel, we are seeing an exponential growth in the amount of ocean data collected leading to a new era of big data, particularly in terms of information-rich biological and biodiversity data. This presents many opportunities for marine ecosystem modelling which, together with artificial intelligence, are leading to new emerging methodologies which utilize machine learning. This will require human, infrastructure and computational capacities to be assessed and, potentially, further developed to meet these future needs.

Jan Mees
Chair, European Marine Board
October 2018

Table of Contents

Executive summary

Marine ecosystem models are an important approach to: integrate knowledge, data, and information; improve understanding on ecosystem functioning; and complement monitoring and observation efforts. They also offer the potential to predict the response of marine ecosystems to future scenarios and to support the implementation of ecosystem-based management of our seas and ocean.

There are many marine ecosystem models, but there is no single model that can answer all policy questions, making it difficult to achieve a fully end-to-end (E2E) model. In each case the context, specific knowledge and scale need to be taken into account to design a model with the appropriate level of complexity. It is more practical to assemble several models in order to reach the full E2E spectrum. This requires a transdisciplinary approach and the inclusion of socio-economic drivers.

This Future Science Brief has identified the following research and development needs to improve model development as well as key recommendations to strengthen the marine ecosystem modelling capability:

- Collect and incorporate new data and information into marine ecosystem models;
- Model marine biodiversity and ecosystem services, based on critical understanding of marine ecosystems;
- Model changes in behaviour, based on understanding adaptive responses in marine organisms;
- Evaluate and reduce uncertainty in marine ecosystem forecasting; and
- Use new approaches in machine learning to enhance marine ecosystem models.

Key recommendations to strengthen marine ecosystem modelling capability include:

- Enhance models by identifying crucial unavailable data, linking models to new and existing observations and data, and by strengthening links to data assimilation centers;
- Increase model predictability through coordinated model experiments and the ensemble approach;
- Develop a shared knowledge platform for marine models and support the development of next generation models;
- Make marine ecosystem models more relevant to management and policy by being more transparent about model limitations and the uncertainties in their predictions; including socio-economic drivers; promoting co-design and dialogue between model developers and users; and
- Enhance trans-disciplinary connections and training opportunities.

Credit: Sheila Heymans

Credit: Nicolas Bailly

1 Introduction

Integrated management of the marine environment requires a holistic understanding of marine ecosystems, rather than focusing on single issues, species, or ecosystem services in isolation. Marine ecosystem models provide an important approach to integrate knowledge, data, and information in order to boost understanding of ecosystem functioning, to interpolate and complement monitoring and observation efforts, and to highlight data gaps. Such models also offer the potential to project the response of marine ecosystems to future scenarios, and to support the implementation of ecosystem-based management of our coastal seas and global ocean.

There are a growing number of stakeholders who ask to use ecosystem models products, ranging from the scientific community, environmental managers and policy makers to ocean industries such as fisheries, tourism, offshore energy and aquaculture. However, the successful use of marine ecosystem models in evidence-based policy making relies on designing models that are fit-for-use and that deliver outputs with full information of any model limitations and uncertainties. Models, simplifications of reality, are imperfect representations of natural systems and are continually undergoing development and evaluation cycles. In addition, advances in marine science and observation capabilities coupled with information technology and artificial intelligence, are enabling a new era of marine modelling approaches with the potential to better analyze data and synthesize knowledge across the full array of ecosystem components and interactions, including human activity.

This Future Science Brief looks at the current capability and state-of-the-art in marine ecosystem modelling for ecosystem-based management and assesses the current disconnect between scientific model development and policy requirements. It presents recommendations to enhance the use of marine ecosystem models as effective decision support tools in evidence-based policy making. This publication has a European focus, but is set in a global context. It includes international examples and makes recommendations relevant to model development and implementation worldwide.

INFOBOX 1.1

A **marine ecosystem** is a system comprising all biotic (living organisms) and abiotic components (physical and chemical properties) of a specific space, as well as all the interaction between and among them. Ecosystem functioning is fueled by energy flows and dissipation, and supports biogeochemical cycling of chemical elements.

Marine ecosystem modelling is a quantitative approach to integrate information and assessing the interactions between marine organisms, the environment they live in (both physical and/or chemical), and external pressures such as human interactions.

Ensemble modelling is the process of running a set of different models to get a more robust estimate of model results and uncertainty.

Ecosystem-based management is an environmental management approach that recognizes the full array of interactions within an ecosystem, including humans, rather than considering single issues, species, or ecosystem services in isolation.

Credit: Sheila Heymans

2 State-of-the-art in marine ecosystem modelling

Over the past 70 years, marine ecosystem models have significantly developed and diversified. An example of the range of different marine ecosystem model types that may be used to enable ecosystem-based management in a single system is given in Figure 1 and some more detailed examples of specific models are given in Table 1 and in selected case studies. This diversity highlights that there is no universally appropriate, or intrinsically superior model. It also highlights the need, and challenge, of identifying a useful model tailored to the appropriate policy question to aid decision-making.

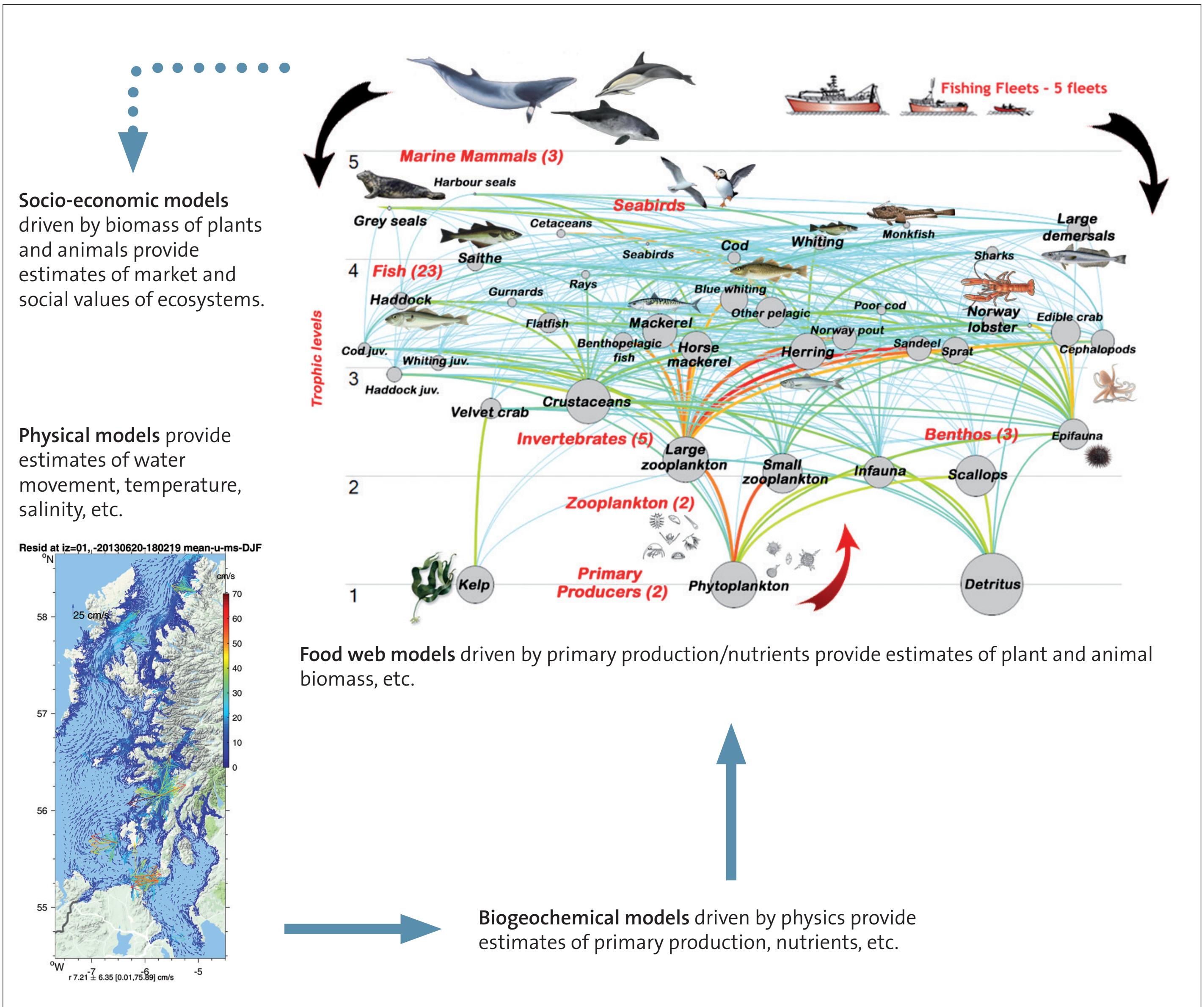


Figure 1 Example of the coupled model framework used for the West Coast of Scotland marine ecosystem (Serpetti *et al.*, 2017). See Table 1 for examples and descriptions.

Table 1: Example of models currently used to describe parts of the marine ecosystem (non-exhaustive list). Examples of where some of these have been used for policy purposes are given in the case studies presented in section 3.

PHYSICAL	**NEMO** (Nucleus for European Modelling of the Ocean)[2] and **ROMS** (Regional Ocean Modelling System)[3] are ocean modelling frameworks that describe the evolution of currents and physical properties in the ocean and have components that describe the evolution of sea-ice and biogeochemistry.
	FVCOM (Finite Volume Community Ocean Model)[4] and **SHYFEM** (Shallow water Hydrodynamic Finite Element Model)[5] are unstructured grid, ocean circulation hydrodynamic models that permit variable resolution across a domain and are therefore optimal for coastal and other applications where high resolution is needed.
BIO-GEO-CHEMICAL	**BFM** (Biogeochemical Flux Model)[6] and **ERSEM** (European Regional Seas Ecosystem Model)[7] are biogeochemical models that describe cycling of carbon and nutrients (N, P, Si, O_2, Fe) as an emergent property of ecosystem interactions in a number of plankton, detritus and benthic compartments.
	MEDUSA (Model of ecosystem dynamics, nutrient utilisation, sequestration and acidification) is an intermediate complexity model of lower-trophic level ecosystems run within a global earth system model to address biogeochemical response to anthropogenic drivers[8].
MASS BASED FOOD WEB	**Ecopath** with Ecosim (EwE) and Ecospace models food-web and fishery interactions in wet mass, carbon or other nutrients in time (Ecosim) and space (Ecospace), with extensions for contaminant tracers and policy optimization[9].
	StrathE2E models the dynamics of nitrogen in solution, plankton, benthos, fish, birds and mammals according to coarse feeding categories, natural and human induced changes[10].
SIZE BASED	**MIZER** is a multispecies size spectrum ecological model that represent size and abundance of all organisms from phytoplankton to large fish predators in a size-structured food web[11].
	FishSUMS is a length-structured partial ecosystem model that represents the changing size distribution and population dynamics of a set of predators and prey species predicting biomass by length class[12].
SYSTEM	**ATLANTIS** is a system model that tracks nutrients through habitats and other biological groups, with a sub model to deal with economic and social interactions such as pollution, coastal development, environmental change and ocean industries such as fisheries[13].
COUPLED MODELS	**NORWECOM.E2E** (NORWegian ECOlogical Model.End-To-End) couples physics, chemistry and biology to model primary production, nutrients and particles dispersion (fish larvae and pollution) with an Individual Based Models (IBMs)[14] for key species in the Norwegian Sea[15].
	ECOSMO.E2E is a mechanistic coupled physical-biogeochemical functional group system, which resolves nutrients, cyanobacteria, phyto- and zooplankton, fish and macrobenthos. It provides Individual Based Models for fish larvae and includes chemical pollution modules[16].

[2] https://www.nemo-ocean.eu/
[3] https://www.myroms.org/
[4] http://fvcom.smast.umassd.edu/fvcom/
[5] https://github.com/SHYFEM-model/shyfem
[6] http://bfm-community.eu/
[7] http://www.pml.ac.uk/Modelling_at_PML/Models/ERSEM
[8] http://imarnet.org/Models/MEDUSA
[9] http://ecopath.org/
[10] https://www.strath.ac.uk/science/mathematicsstatistics/smart/marineresourcemodelling/researchtools/strathe2e/
[11] http://www.mesopp.eu/catalogue/test-mizer/
[12] https://www.strath.ac.uk/science/mathematicsstatistics/smart/marineresourcemodelling/researchtools/fishsums/
[13] http://atlantis.cmar.csiro.au/ ; https://www.niwa.co.nz/ecosystem-modelling-at-niwa/atlantis-ecosystem-model
[14] https://naes.unr.edu/shoemaker/teaching/NRES-470/LECTURE10.html
[15] https://www.imr.no/temasider/modeller/norwecom.e2e/nn-no
[16] https://hzg.de/institutes_platforms/coastal_research/system_analysis/matter_transport/models/index.php.en

The focus of an ecosystem model can be as wide or as narrow as needed, depending on the question being asked. Sometimes an ecosystem model will only encompass the physico-chemical environment and lower trophic levels (e.g. Nutrient, Phytoplankton, Zooplankton or NPZ models). At other times, the model might encompass the physical environment, primary producers, secondary producers, consumers, top predators, and human activities (these are known as End-to-End or E2E models). The extent of the model or level of complexity used (NPZ, E2E, or anything in between) will depend on the relevant policy and management questions. In turn, the lack of appropriate data will often limit the ability of a model to predict all possible species, functional groups or processes.

Observations and experiments remain vital to provide a mechanistic understanding of marine ecosystem dynamics, to design conceptual models, inform model design and parameterization, and assess model reliability. Models provide a useful framework to interpolate and extrapolate experimental findings, generate hypotheses about food web interactions and ecosystem functioning, test hypotheses, provide scenario analysis and support ocean management.

Over the past decade, the number of research papers using models has increased exponentially, and there have been a number of European funded projects and initiatives advancing the capability of marine ecosystem modelling, including: CLIMEFish[17], COCONET[18], COPERNICUS and CMEMS[19], EMECO[20], EuroBASIN[21], Eur-Oceans[22], KnowSEAS[23], MAREFrame[24], MEECE[25], PERSEUS[26], VECTORS[27]; in addition to multi-national projects e.g. SEAMAN[28] and nationally funded initiatives e.g. MERP[29] and RITMARE[30]. These projects have used, or are using some of the model systems listed in the Table 1. The table highlights examples (not a comprehensive list) of European and worldwide capability in marine ecosystem modelling varying in complexity from physical models to full system model frameworks.

Credit: Nicolas Bailly

[17] http://climefish.eu/

[18] https://cordis.europa.eu/project/rcn/101654_en.html

[19] http://marine.copernicus.eu/

[20] https://emeco.azurewebsites.net/

[21] http://eurobasin.dtuaqua.dk/eurobasin/index/about.html

[22] http://www.vliz.be/projects/clamer/index8de4.html?option=com_clamerprojects&ProjectId=49

[23] https://www.msp-platform.eu/projects/knowledge-based-sustainable-management-europes-seas

[24] http://mareframe-fp7.org/

[25] http://www.meeceatlas.eu/Menu/

[26] http://www.perseus-net.eu/

[27] http://www.marine-vectors.eu/

[28] https://org.uib.no/seaman/goals.html

[29] http://marine-ecosystems.org.uk

[30] http://www.ritmare.it/

3 Marine ecosystem models currently used for environmental management and policy

There are a broad range of motivations for the sustainable management of our seas and ocean, including understanding natural and human pressures and impacts. Marine ecosystem models are already a key part of the toolbox used to support marine management decisions, policies and governance. This section summarizes key topics where marine ecosystem models are currently utilized and presents specific case studies from Europe and worldwide.

Credit: Sheila Heymans

The range of topics where marine ecosystem models are used for ecosystem-based management are summarized in Hyder *et al.*, (2015) and include:

Environmental change and climate adaptation:

- Natural variability and monitoring, including current system state, inter-annual variability, long-term trends; and
- Understanding how ecosystems change over time, including the impact of environmental changes e.g. climate.

Management measures, goods and services:

- How to manage resources and wider biodiversity and ecosystem services more sustainably and holistically, e.g. spatial distribution of marine carbon sequestration;
- Marine environmental protection (including Marine Protected Area designation);
- Good Environmental Status and projections of ecosystem health related indicators; and
- Evaluating the management of an ecosystem objectively, such as in Management Strategy Evaluation, and in Environmental Impact Assessments.

Successful application of models for societal needs include specific issues, such as water quality, eutrophication[31], pollution, harmful algal blooms[32], fishing[33], climate warming[34], acidification[35], sea lice forecasting[36], and other management questions[37]. However, impacts of multiple stressors, and in particular terrestrial run-off, warming and acidification on marine biogeochemistry are not yet fully integrated into marine ecosystem models. The explicit incorporation of economic and social dynamics, already made in several terrestrial based integrated ecosystem models, is also not very common in the marine realm, possibly due to the complexity of the feedbacks to be incorporated, and the lack of quantitative information. One example where this is included is the Aquacross[38] project which is using a cumulative effects risk assessment approach to integrate the assessment of all impacts on the socio-ecological system, with the aim to expand this to include fully quantitative methods. However, the dynamics of e.g. fishing fleets, nutrients and pollutants discharge, and marine resource exploitation often require a description of human behaviour, market dynamics, governance frameworks, over large spatial and temporal scales.

3.1 Selected case studies

The case studies below show examples where ecosystem models have been used for specific policy questions. These also give some idea of the possible model uncertainties or data needs for each case.

3.1.1 MERP: reducing uncertainty using multi model ensemble approaches

In spite of the large effort devoted to marine ecosystem modelling, there still is a lot of fragmentation in the field. The need for an integrative and comparative framework has been recognized and partially addressed. A good example of such a framework has been provided by the UK MERP programme[39], which has implemented a multi-model ensemble approach for ecosystem predictions by using various modelling tools to describe the same ecosystem and make coherent forecasts that take into account all that can be learnt from the suite of models (Spence *et al.,* 2018). MERP brings together observations, data and modelling to provide a more complete picture of how different ecosystem components (living organism, abiotic parameters, external pressures) are distributed in space and time, and to develop scenarios reflecting future states of marine food webs and ecosystem services at spatial and temporal scales relevant to management and policy.

MERP showed that even if the important West Coast of Scotland fisheries were well managed, the cod stocks will not be able to sustain fisheries under all climate change scenarios (Figure 2), while whiting would flourish due to their temperature preferences (Serpetti *et al.,* 2017). The MERP model ensemble outcomes are also being linked to bio-economic models to describe the impact that future climate change and management scenarios may have on both ecological and social wellbeing.

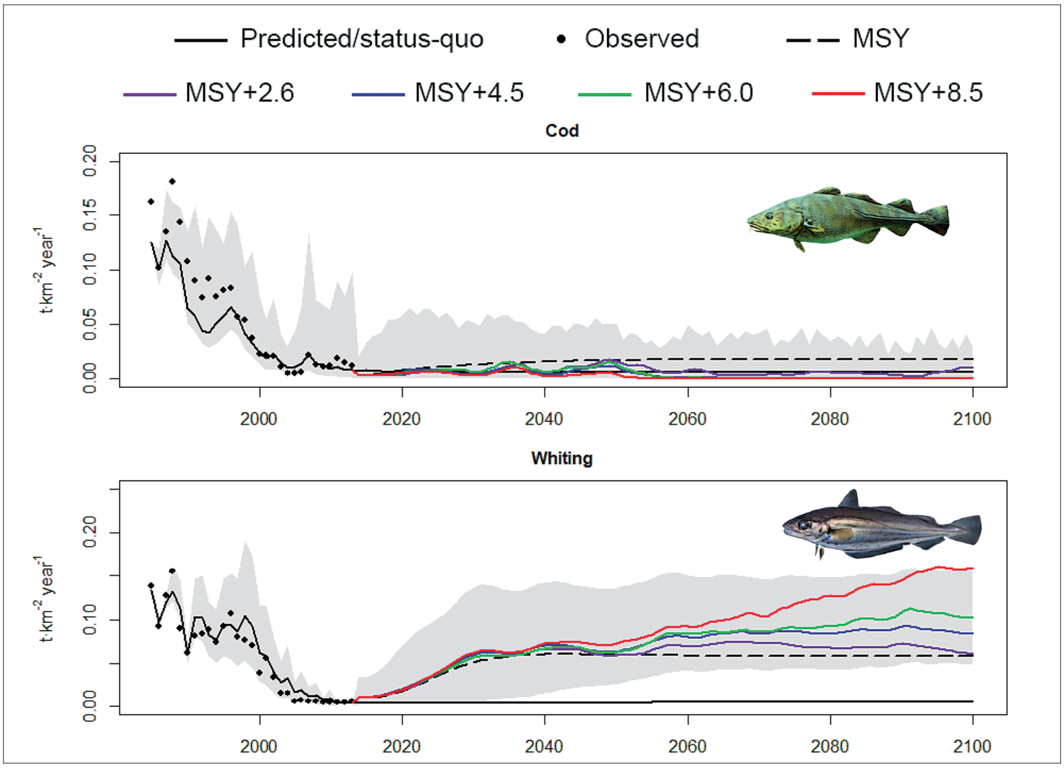


Figure 2 Predictions of biomass of well managed cod (top) and whiting (bottom) fisheries, managed at Maximum Sustainable Yield (MSY) under future climate change scenarios: MSY+2.6 is lowest and MSY+8.5 highest IPCC scenarios. Grey area shows uncertainty in model predictions based on uncertainty in input data. Adapted from Serpetti *et al.,* (2017).

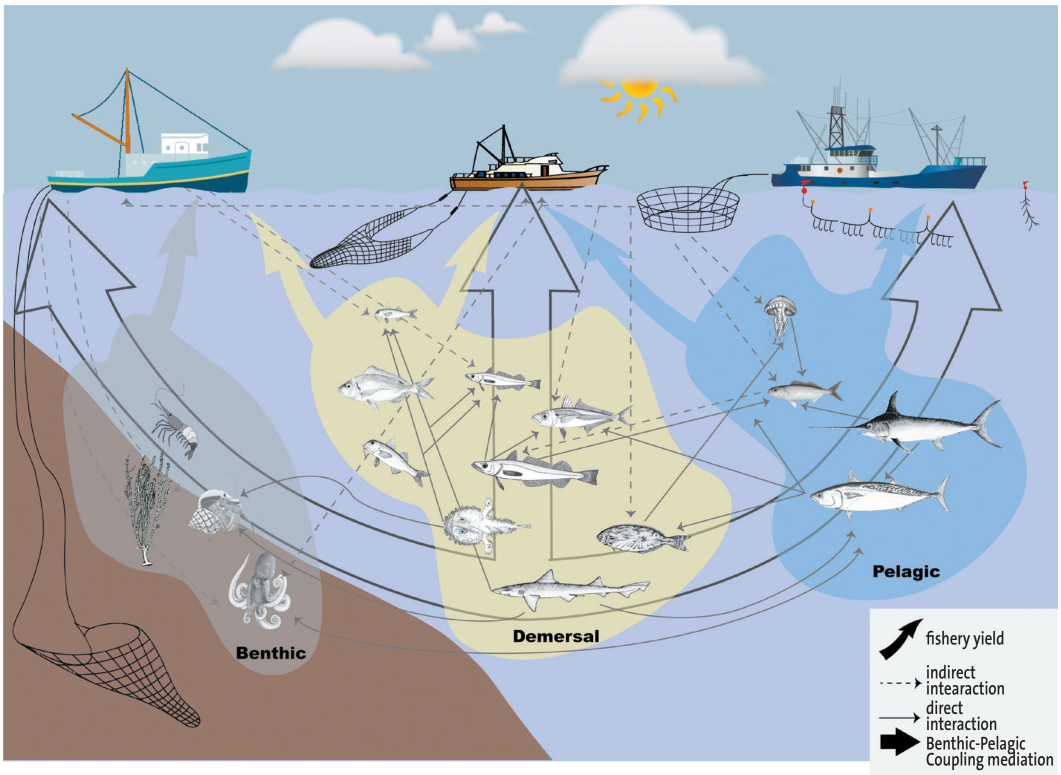
Credit: Natalia Serpetti.

[31] http://www.balticnest.org/nest
[32] www.habreports.org
[33] http://ices.dk/community/groups/Pages/WGSAM.aspx
http://www.ices.dk/community/groups/Pages/WGIPEM.aspx
[34] http://link.springer.com/chapter/10.1007/978-3-319-39745-0_6
[35] http://www.meeceatlas.eu/Menu/
[36] http://www.imr.no/lakseluskart/html/lakseluskart.html#
[37] http://marine.copernicus.eu/services-portfolio/access-to-products/
[38] https://aquacross.eu/
[39] http://www.marine-ecosystems.org.uk

Credit: Sheila Heymans

3.1.2 RITMARE: co-design and spatial based fisheries management

In a similar ensemble modelling approach for the Mediterranean Sea, the Italian RITMARE[40] project implemented a multi-model approach, by integrating physical, biogeochemical, food web, machine learning and socio-economic evaluation to gain a better understanding of ecosystem functioning in fishery relevant regions, and to identify and evaluate ecosystem based fishery management strategies. Stakeholder engagement at an early stage, both to co-design the model and to identify policy questions and scenarios to be tested, insured good connections between policy-makers and scientists. This resulted in suggestions on spatial based management of fisheries in Italian waters, including interactions and trade-offs in mixed fisheries (Figure 3), as well as a quantitative assessment of the impacts of EU policies such as the Common Fisheries Policy's (CFP) landing obligation in the Mediterranean (Celic *et al.*, 2018).



Credit: from Agnetta *et al.*, (submitted).

Figure 3 Figure of the Italian fisheries depicting direct and indirect interactions in the food web and interactions in the mixed fisheries mediated through coupling of the benthic and pelagic parts of the food web.

[40] http://www.ritmare.it/

3.1.3 OSPAR: using ensemble modelling to address eutrophication

An ensemble approach has also been used in the prediction of eutrophication in a future climate change scenario in the North and Baltic Seas. In 2005, OSPAR[41] addressed the modelling community with the questions: "How can the use of marine ecosystem models help to understand what could be achieved in improving the eutrophication status and in what time frame?" A number of model comparisons on nutrient reduction scenarios for the North Sea put into practice the objectives set by OSPAR. Using the OSPAR common procedure to assess eutrophication status (Skogen *et al.,* 2014) no significant changes in the North Sea were predicted under future climate scenarios, while the analysis also revealed that most "potential problem areas" currently defined in the Baltic Sea are likely to become real "problem areas" with changing climate. From this exchange, the modellers gained the capability to define improvements by the use of eutrophication thresholds, while OSPAR benefit from the forecast capability on reduction measures by the models.

3.1.4 Invasive crabs: combining natural and social science modelling approaches

Atlantis was used to model the impact of invasive snow crabs on the Norwegian and Barents Sea. Atlantis (Figure 4) is a modelling framework for holistic end-to-end modelling of the marine environment that includes human pressures. It describes the food web comprising key species and contains a biophysical sub-model that tracks nutrient flows, an exploitation sub-model that focuses on the dynamics of the fishing fleets, pollution, coastal development, economics and social interactions. In the Norwegian and Barents Sea, it has been applied *inter alia* to project the impact of the introduction, in 1996, of snow crabs into the Barents Sea ecosystem. Information such as cod and haddock eating snow crab juveniles and snow crabs eating different seafloor organisms (benthos) was included in the model. Model simulations showed that contrary to expectations, not all impacts were negative: whilst benthos decreased, the introduction of snow crabs benefited haddock and cod and reduced the predation pressure on capelin, benefiting the capelin stocks.

Whilst Atlantis is being increasingly used for marine resource management, it is not a universal model that can be applied for all purposes. Although there is a modelling standards movement that creates audit chains around any information contributing to policy discussions or management decisions, the Atlantis model still has low predictability and large uncertainties are present in model output due to the complexity of the model itself. All ecosystem models require significant observational data and experimental information to parameterize, calibrate and validate, but for Atlantis this is amplified by the complexity of the sub-routines.

3.2 European coordination efforts

The European Commission (EC) has noted the need for greater coordination in European capability in marine ecosystem modelling and making this more directly relevant and applicable to policy requirements. The EC's Joint Research Centre (JRC) is building a marine modelling framework specifically focused on the Marine Strategy Framework Directive (MSFD) including an informal network of experts on the modelling of the European marine environment (MEME)[42]. Related to this, the EU BLUE2 Study part B[43] is developing a framework for the integrated socio-economic assessment of policies affecting the quality of the freshwater and marine environments and aims to link ecosystem models to policy drivers and uses computer

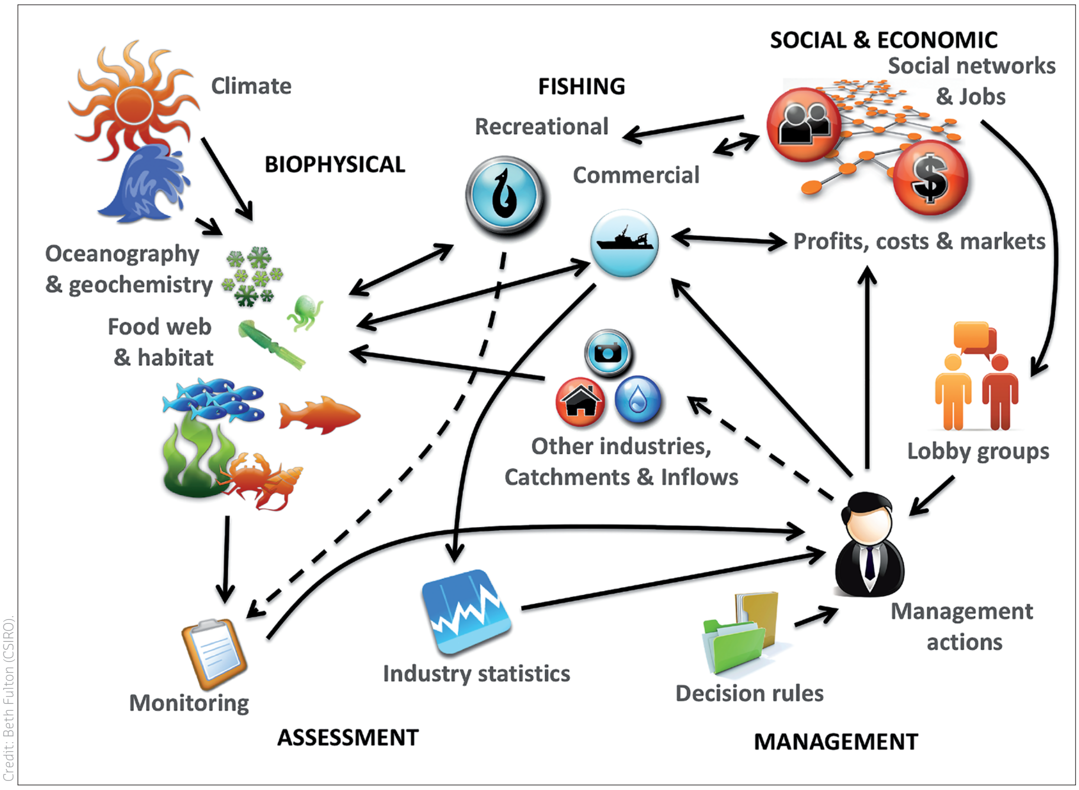


Figure 4 Graphic representation of the Atlantis modelling framework.

[41] OSPAR: Oslo/Paris Convention for the protection of the marine Environment of the North-East Atlantic https://www.ospar.org/
[42] http://mcc.jrc.ec.europa.eu/dev.py?N=simple&O=11
[43] http://ec.europa.eu/environment/blue2_en.htm

models to simulate the physical, chemical and biological aspects of the freshwater and marine environment. To achieve this objective, hydrological, hydrodynamic, biogeochemical and higher trophic level models will be incorporated into a single modelling framework, or toolbox, which will eventually be used to assess the ecosystem impacts of EU Policies. In addition, the BLUE2 project adds the economic aspect to the environmental analysis to help evaluate and advise on the cost and benefits for policy implementation.

INFOBOX 3.1

AMEMR End-to-End modelling workshop outcomes:

On 7 July 2017, the EMB organized a workshop on Marine Ecosystem Modelling in Plymouth, UK in association with the 2017 AMEMR (Advances in Marine Ecosystem Modelling Research) conference. The focus was on "End-to-end Marine Ecosystem Modelling: Current capabilities and research and development needs for Ecosystem-Based Management". It brought together 30 international experts from 12 countries in marine ecosystem modelling for interactive discussions (http://www.marineboard.eu/marine-ecosystem-modelling). Participants identified the following areas where knowledge is limited or lacking and emerging areas likely to impact ecosystem modelling:

Natural science knowledge inputs:

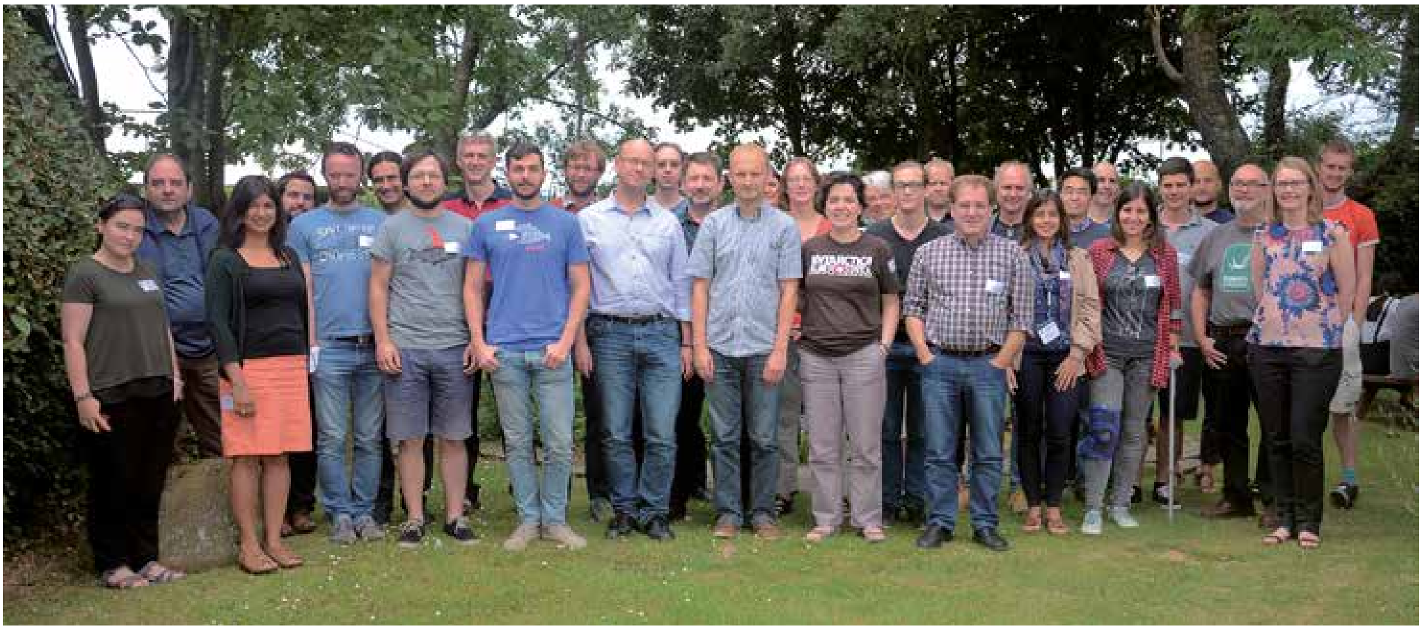
- Processes and fluxes e.g. benthic-pelagic coupling are not well described;
- Some gaps remain in defining benthic systems;
- There is a lack of zooplankton data to validate models and more links should be made across trophic levels;
- Land-sea interface, for example nutrient and alkalinity inflows;
- Heavy metal and wider pollutants presence; and
- Multi-stressor approach to understanding impacts or vulnerabilities of marine environments (e.g. pollutants).

Other areas for further development:

- More coupling between ocean and wider earth system models. Since this creates very computationally expensive systems priority should be on policy-driven requirements;
- Co-design of model development with trans-disciplinary experts from ocean observation experts to policy decision-makers; and
- Adaptation of current codes/languages to new computing architecture

Emerging areas likely to influence future marine ecosystem modelling:

- Capability in genomics and other biological ocean observations is increasingly leading to a high diversity of data-rich biological information which doesn't necessarily fit the traditional data needs of the modelling community;
- Visualizations such as games and apps (and wider information technology developments) will be important in communicating outcomes; and
- Artificial Intelligence e.g. machine learning may offer new opportunities for coupled and end-to-end models.



Credit: PML

Participants at EMB expert workshop on marine ecosystem modelling, PML, Plymouth, U.K., 7 July 2017.

4 Research & development needs

4.1 Linking models to observations

The ocean is heavily under-sampled and observations and experiments are vital to provide a mechanistic understanding of marine ecosystem dynamics, design conceptual models, inform model design and parametrization, and assess model reliability. However, most observations are confined to a small portion of the ocean, may present a seasonal bias, and have their own uncertainties and problems of representativeness. Whilst physical variables are routinely measured, automated biological variables are only just emerging and rates and fluxes are comparatively rarely measured. This lack of data makes model parameterization and validation more difficult and therefore reduces model quality. There are a number of data portals including Copernicus Marine Service[44], EMODnet[45] and ICES[46], but more needs to be done to obtain biological data and to include biological data (e.g. marine taxonomic information on species, etc.) into these portals. In addition, models could inform ocean observation and monitoring system design, to identify which observations should be taken and to define the appropriate location and temporal/spatial resolution to improve the models.

4.2 Incorporating new information into marine ecosystem models

The understanding of ecosystems will always depend on the knowledge of their building blocks, making taxonomy and proven sampling techniques imperative. These techniques are now being augmented by rapidly developing capability for biological observations, offering new modelling challenges and opportunities. Emerging biological data include molecular genetics ('-omic' tools e.g. eDNA), changes in population size, biodiversity and behavior through imaging and optics techniques and hydro-acoustic approaches such as echosounding, sonar and hydrophones (Benedetti-Cecchi *et al.,* 2018). Such observations are generating an unprecedented amounts of information-rich data, which will require new approaches to handling big data in a meaningful way. New experiments will also remain crucial to quantitatively parameterize processes presently not considered in marine ecosystem models, such as evolution, adaptation and plasticity. These challenges cannot be ignored any longer in view of the need for long term simulations required by climate change studies (~100 years).

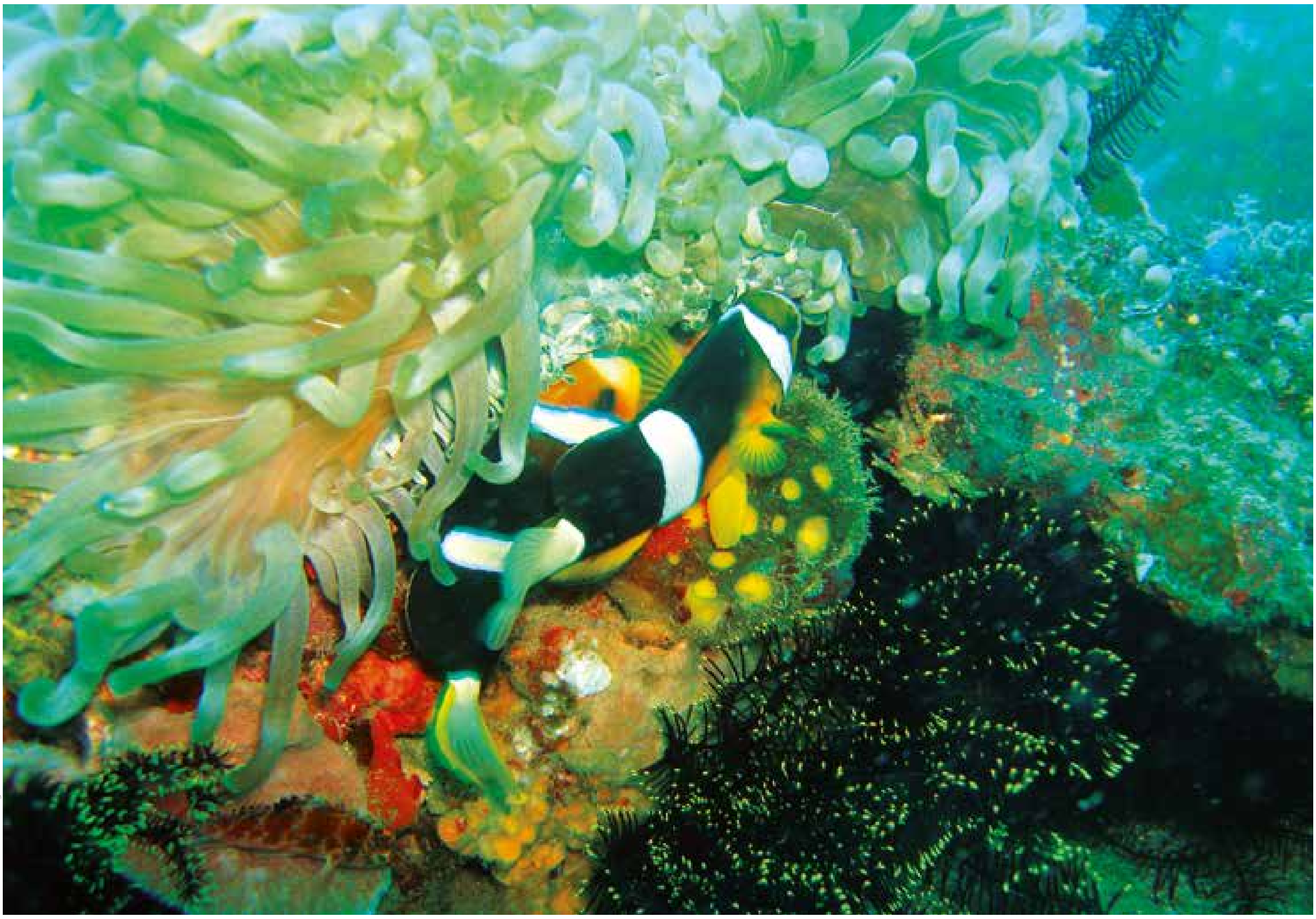
4.3 Modelling marine biodiversity and ecosystem services

Marine biodiversity and other ecosystem services contribute to human welfare. The IPBES (2016)[47] has highlighted the need for modelling marine biodiversity and ecosystem services to meet policy needs (see Infobox 4.1). However, to model biodiversity we need to describe biodiversity, which requires taxonomy. In addition, while several attempts have been made to identify, evaluate and model ecological indicators (Coll & Steenbeek, 2017), and many models provide some information on ecosystem services (Lynam *et al.,* 2016), no model totally describes biodiversity and the link between biodiversity and drivers. In most models, species with similar functions are grouped together and information on true biodiversity is therefore lost. There are examples of models that attempted to overcome this, such as the MIT-Darwin model[48] which takes into account adaptation processes that define which behavioural traits phytoplankton develop in order to thrive. However, whilst the MIT-Darwin model considers a large number of competing planktonic taxa, it does not include all the species at higher trophic levels. We are far from including the full spectrum of diversity at all trophic levels. This field still needs a lot of effort to expand to full biodiversity and fully link it to oceanographic and ecological models. Similarly, to strengthening the links between ecosystems and the services they provide and the two way coupling between ecosystem models and socio-economic models remains an exciting challenge for the near future.

INFOBOX 4.1
The International Platform for Biodiversity and Ecosystem Services (IPBES)

IPBES has called for the use of modelling as a key part of the decision support frameworks needed to protect biodiversity and ecosystem services. They found that models of biodiversity and ecosystem function are critical for predicting and understanding responses to environmental change. These models depend heavily on our understanding of ecosystem structure, function and process and on their adequate representation in these models. They also advocate for the development of consistent protocols to ensure the quality of the models and the outputs used in assessments of Biodiversity and Ecosystem Services.

[44] http://marine.copernicus.eu/
[45] http://www.emodnet.eu/
[46] http://www.ices.dk/marine-data/dataset-collections/Pages/default.aspx
[47] https://www.ipbes.net/
[48] http://darwinproject.mit.edu/



Credit: Nicolas Bailly

4.4 Modelling changes in behaviour

When considering long term dynamics such as the impact of climate change, it might be important to consider that species might adapt to changes, migrate or evolve, generating new food webs or new dynamic within existing food web. This calls for models that can change structure over time, or other approaches that can deal with these issues (Solidoro *et al.,* 2010), such as trait-based models[49], game theory approaches (Mariani *et al.,* 2016), artificial neural networks (Barreiro *et al.,* 2018) and optimization methods (Kiørboe *et al.,* 2018). Incorporating the behaviour of species, specifically higher trophic level species including fish, is another step to make models that reflect complex ecosystem change and interactions between species. For example, such models could be applied to assess how an invasive species introduced into an ecosystem would affect the food web in terms of biodiversity and ecosystem functioning, or for more accurate projection of climate change impacts.

4.5 Reducing uncertainty in marine ecosystem forecasting

There is an increasing demand for marine ecosystem forecasts and projections, which is hampered by their capability and reliability. The impact of uncertainty is an important emerging question. There are at least three different types of uncertainty: scenario uncertainty (reflecting the unknown future socio-economic landscape), model uncertainty (reflecting inaccuracies in the model), and internal variability (reflecting the difficulty in detecting a clear signal) (Hawkins & Sutton, 2009). In this context it is useful to distinguish short term and long term predictions. In short term predictions (or forecasts) model output uncertainty can be reduced by using observations to continually correct/adjust the initial conditions of the model. This data assimilation approach is largely used in operational oceanography and it is the basis of the data-model fusion used in the Copernicus[50] system. However, for mid- to long term prediction (or projections), in which it is not possible to use data assimilation and model runs are 'unconstrained', uncertainty is usually assessed by performing sensitivity analysis and statistical methods such as Monte Carlo simulations (Serpetti *et al.,* 2017, Celic *et al.,* 2018). However, uncertainty testing is often computationally expensive and does not always happen. The quantification and communication of uncertainties in forecast predictions are critical, and still needs significant research.

[49] bio.uib.no/te/papers/Dutkiewicz_2012_Trait-based.pdf

[50] http://marine.copernicus.eu/

INFOBOX 4.2

Prediction/forecasts vs. projections/scenarios:

Model predictions are similar to weather predictions, i.e. it is possible to predict what the weather will do tomorrow, but not on the same date in 50 years' time. By contrast, projections are used for climate change: thus given a certain range of parameters (CO_2 projections for instance) you can project what the climate might be like in 50 years. Examples of predictions are those used for Harmful Algal Blooms each week (www.habreports.org), while an example of projections are shown in the MERP example above (Serpetti *et al.,* 2017) which used long term IPCC projections to drive a food web model to predict changes in the food web and incorporate uncertainties over the next 100 years.

4.6 Applications of machine learning

Machine learning, a form of Artificial Intelligence, is a method whereby computer systems find patterns in observed data to make short term future predictions. Machine learning tools for handling of data, pattern and process analysis and prediction of the emergent properties of complex systems has led to significant breakthroughs in disciplines from quantum physics, earthquake prediction to human health. One example is Artificial Neural Networks (ANN) that have been used to study ecosystems over the past two decades (Quetglas *et al.,* 2011), including creating a model of models to assess uncertainty in marine ecosystem indicators using model ensemble approaches (Spence *et al.,* 2018). ANN have been proposed for understanding the processes impacting on ecosystem state (Barreiro *et al.,* 2018), to predict the distribution of phytoplankton groups over the global ocean (Palacz *et al.,* 2013), and fish recruitment in the marine environment (e.g. Krekoukiotis *et al.,* 2016). Other popular applications of machine learning to marine ecosystem models include statistical analyses such as Bayesian Beliefs Networks (BBN), which have been used for the identification of trade-offs among multiple uses of marine ecosystems and random forest algorithms. There is a need to advance the field in the prediction of future ecosystem states and the dynamics of key species via the integration of model predictions, historic data and ANN to generate adaptive modelling tools that are sensitive to the complex interactions of evolving marine ecosystems.

The use of machine learning to model marine ecosystems has so far been limited by the fact that machine learning needs large amounts of data, while ecosystems are often under-sampled in space and time. However, the exponential increase in availability of data offers unprecedented potential for new exploitation of these powerful data-driven models. Additionally, Artificial Intelligence might offer a new way to analyze and synthesize large amounts of data and information in real time, and support the next generation of observing and decision systems. This will require additional hardware and software capacity, in addition to enhancing skills and training of current and future experts for optimal use (Vincx *et al.,* 2018).

Credit: Miriam Godfrey

5 Challenges for meeting societal needs

5.1 Co-design of policy relevant models

Despite clear capability and progress in marine ecosystem modelling in Europe and worldwide (see sections 2, 3 and 4), scientific research and what policy makers need to know are not fully aligned. Many models are designed to answer scientific, not policy, questions. However, ecosystem models that are designed to address policy questions need to be linked to policy goals and targets, which means that these models often need to be linked to social data and/or socio-economic models. This is done to some extent in the USA, Australia and Canada. There is therefore a need to further develop an integrated approach across the natural and social sciences, such as socio-ecological-system models. If an ecosystem model is to be used for policy purposes, it is important that policy makers and stakeholders are involved in the conceptual design stage of the modelling process and throughout where appropriate, to ensure that the model delivers policy relevant outputs and that policy makers have a better understanding of the limitations and uncertainties of the model.

5.2 The need for more than one model

There is often the expectation that a single model (E2E or otherwise) can be used to answer all questions asked by policy makers. This is unrealistic, as models are parameterized to address specific questions and only consider processes that are defined by the model equations. As an example, climate change, including ocean warming, can result in the migration of marine species into new geographical areas. This knowledge is vital to include in the model set-up, to ensure such a shift in species composition is reproduced in the model. However, without sufficient information on these invasive species, models cannot be parameterized correctly. There is also often a need for models at multiple spatial and temporal scales depending on the policy question and species involved. For example, modelling harmful algal blooms is appropriate at daily-local scales while addressing questions about whales would need models at decadal and basin scales. Thus, a flexible and adaptable approach is needed, which cannot be provided by a single model.

5.3 Communicate model limitations and uncertainties

It is important that the limitations of the model are well explained and the capabilities of the models explicitly stated. Lack of communication can lead to unrealistic expectations of what the models can deliver for decision-making. Model results depend on the processes considered, assumptions, input and forcing data used and model applicability might be limited and may change, requiring regular assessment. Early engagement with model users during the model design, evaluation and interpretation phases will contribute to a real understanding of the strengths and weaknesses of a model.

Credit: Jacob Bentley.

Marine Spatial Planning (MSP) Challenge: Celtic Marine Region Edition

5.4 Coordinated experiments

There is a need for coordinated experiments in which different ecological models are used for the same case study, similar to what is done in climate science, where different climatic models are used under the same scenarios and over a set of geographical domains. This should be done for marine ecosystems, with common data sets for both parameterization and evaluation, due to the high variability in model design and parameterization in ecological models. This has been done to some extent using model ensembles, such as the work of the OSPAR working group (ICG EMO), and is done by FABM[51]

[51] fabm.net/

for biogeochemistry and FishMIP[52] for fishery and ecosystem models but a more extensive, Europe wide implementation of this would increase model predictability. This would require a common funding scheme that runs models in coordinated experiments rather than through competitive calls.

5.5 Visibility and access to ecosystem model output and products

Although many ecosystem models are open source and data are made available to the general public[53], there is a need for a more transparent process that includes information on all models, their outputs and model metadata. There should also be a closer dialogue between observationalists and modellers on what, where, how and when to measure for model validation, and to enable the design of field experiments. Model output can run into tens of terabytes and data storage needs careful planning. Methodologies for data management and analysis together with data visualizations, are also needed to enhance understanding and uptake of these model outputs.

5.6 Integration of socio-economic drivers into ecosystem models

To make ecosystem models useful for policy makers there is a need for the incorporation of more sophisticated socio-economic scenarios to drive future projections. However, these scenarios require an understanding and description of human behaviour, market dynamics and governance over similar spatial and temporal scales as the ecosystem models they would influence, which is not always available. The uncertainties in, and predictive capacity of, socio-economic models are often larger than those of ecosystem models, as key process such as technological development, non-linear societal dynamics and global politics are not included. In order for socio-economic models to be linked to ecosystem models these uncertainties should be explicitly incorporated. This is an important area of future research need.

5.7 Creating interaction space between modellers and policy makers

There is a real need for a venue where models can be iteratively discussed for policy choices, both for strategic and tactical questions. For strategic planning, models can be used to describe what are the best policy decisions given multiple EU legislation (i.e. Marine Strategy Framework Directive, vs. Common Fisheries Policy vs. Water Framework Directive requirements). Tactical decisions that can be addressed in this space include the best place to put an MPA, what water quality levels will exceed which Good Environmental Status limits, etc. These interactions would be enhanced by Management Strategy Evaluations, which allows testing a range of models and model decisions, and allow interactions among stakeholders and policy makers which facilitates good decision space.

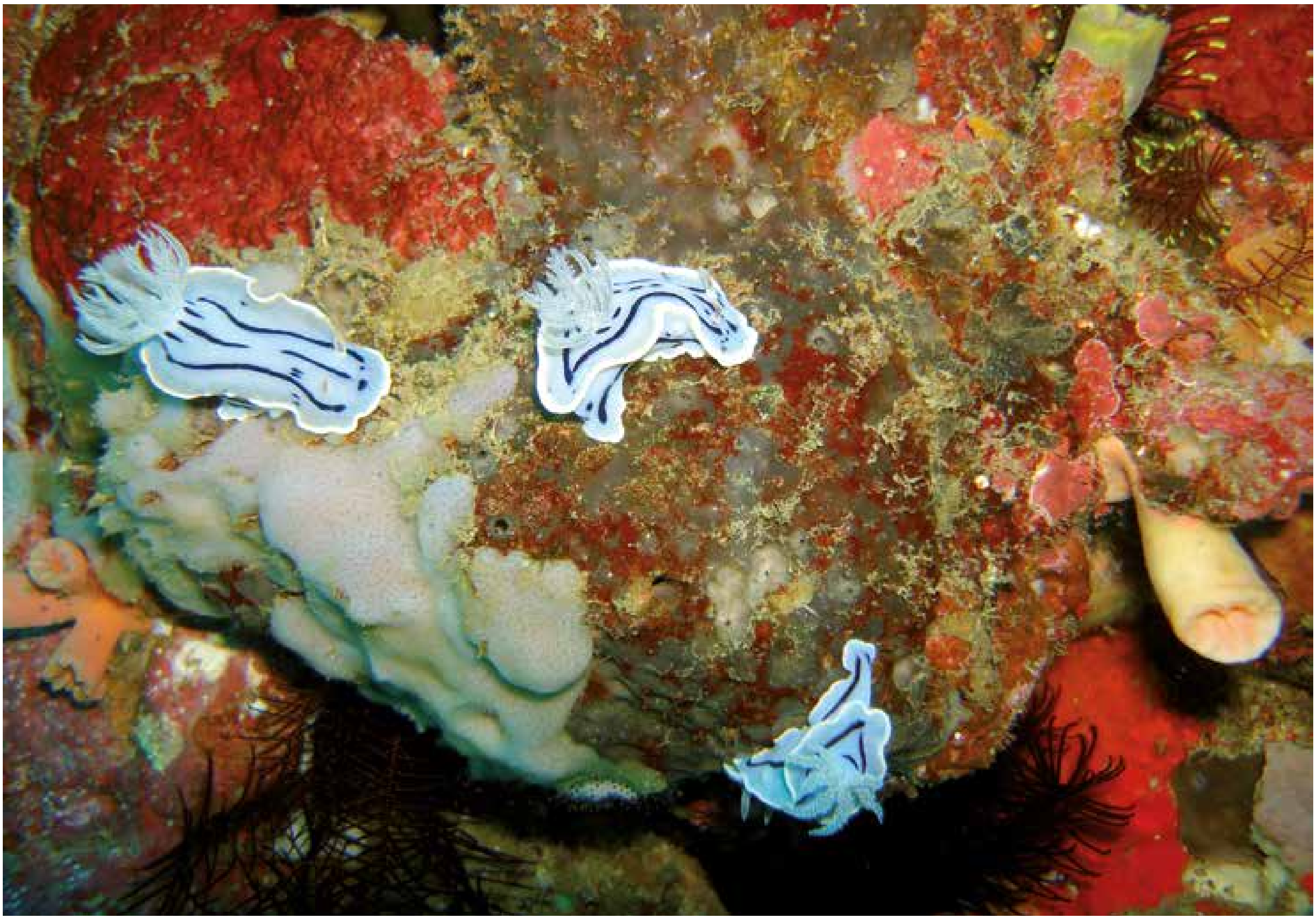
Credit: EU Copernicus Marine

Copernicus Marine Week - European Parliament Session- 26 Sept 2017 - Interactive & Touch screen application based on Copernicus Marine Service products powered by Mercator Ocean International (picture : Global Ocean Model 1/12º - Sea Surface Temperature).

[52] https://www.isimip.org/gettingstarted/marine-ecosystems-fisheries/

[53] For example: https://www.coastdat.de; http://ecobase.ecopath.org

Credit: Ifremer - Olivier Dugornay



Credit: Nicolas Bailly

6 Recommendations

There is no single model that can answer everything, making it difficult to achieve a fully end-to-end (E2E) model. It is more practical to assemble several models to reach the full E2E spectrum, which requires a transdisciplinary approach and the inclusion of socio-economic drivers. Key recommendations to strengthen marine ecosystem modelling capability and use in environmental management and policy are:

Link models to observations and data

- Models are only as good as the data they are built on: thus taxonomy, observations and experiments are crucial to quantitatively parameterize processes presently not considered in marine ecosystem models (e.g. evolution, adaptation and plasticity);
- Models should also be used more actively when designing observation networks, and interactions between models and observations should be strengthened;
- Ensure that data assimilation centres (e.g. the Copernicus Marine Service, EMODnet, etc.) include all data streams needed to increase predictive capabilities of models; and
- Develop models or coupled models that can incorporate the full spectrum of biodiversity from microbes to top predators.

Increase predictability through coordinated experiments and the ensemble approach

- Implement the ensemble approach to model uncertainty, to increase model predictability. This requires a common funding scheme that runs models in coordinated experiments rather than through competitive calls and would be improved by a shared platform for marine models; and
- Integrate model predictions, historic data and machine learning to generate adaptive modelling tools that are sensitive to the complex interactions of evolving marine ecosystems.

Develop a shared knowledge platform for marine models and support the development of next generation models

- Develop an open access modelling platform, linking the different expertise in Europe with the aim to preserve knowledge, reduce fragmentation, and enhance the capability to develop models and use model results;
- Foster the development of next generation models, to better use new observations, describe neglected features, such as changes in ecosystem structure and functioning and behaviour, with better links to ecological indicators and societal needs; and
- This could be linked to the EU Pilot Blue Cloud, as a marine component to the developing European Open Science Cloud, and the Marine Modelling Framework under development by the JRC of the European Commission and the Network of Experts for Redeveloping Models of the European Marine Environment and associated framework.

Make marine ecosystem models more relevant to management and policy

- Increase the credibility of models by making uncertainties explicit, so that the outputs meet the needs of decision makers and stakeholders;
- Further develop coupling between ecosystem models, physico-chemical models, and socio-economic drivers to include the human dimension;
- Promote closer connection between stakeholders (including users) and modellers, through early stakeholder involvement and co-design of marine ecosystem models;
- Be more transparent and educate stakeholders about model possibilities, limitations, and the uncertainties that underlie their predictions; and
- Uncertainty testing of all models used for policy making should be a pre-requisite and communication of these uncertainties should be explicit.

Enhance trans-disciplinary connections and training opportunities

- Promote multi- and trans-disciplinary training in fundamental marine sciences, marine ecosystem research, multiple modelling tools and policy; and
- Develop an online knowledge training platform to connect marine ecosystem modellers, share opportunities for training (including short courses) and promote interdisciplinarity.

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List of Abbreviations and Acronyms

AMEMR	Advances in Marine Ecosystem Modelling Research (Conference series)
ANN	Artificial Neural Networks
ATLANTIS	Marine ecosystem model considering all parts (biophysical, economic and social)
AQUACROSS	Knowledge, Assessment, and Management for AQUAtic Biodiversity and Ecosystem Services aCROSS EU policies
BBN	Bayesian Beliefs Networks
BC3	Basque Centre for Climate Change, Spain
BFM	Biogeochemical Flux Model
BLUE2 study	Assistance for better policy-making on freshwater and marine environment (EC study)
CCMAR	Centre for Marine Sciences, Faro, Portugal
CEFAS	Centre for Environment, Fisheries and Aquaculture Science, U.K.
CefMAT	CEFAS Marine Assessment Tool
CFP	Common Fisheries Policy
CLIMEFish	Climate Change and Fisheries project (European H2020 project)
CMEMS	Copernicus Marine Environment and Monitoring Service
CO_2	Carbon Dioxide
COCONET	Towards COast to COast NETworks of marine protected areas (from the shore to the high and deep sea), coupled with sea-based wind energy potential
COPERNICUS	European Earth Obervation Programme
CSIRO	Commonwealth Scientific and Industrial Research Organisation, Australia
DG ENV	Directorate for Environment (EC)
E2E	End to end
EC	European Commission
ECHO	Ecology and Computational Hydrodynamics in Oceanography (OGS group)
ECOSMO.E2E	Ecosystem Model based on HANSOM, HZG, Germany
eDNA	Environmental Deoxyribonucleic acid
EMB	European Marine Board
EMECO	European Marine Ecosystem Observatory (see also CefMAT)
EMODnet	European Marine Observation and Data Network

ERSEM	European Regional Seas Ecosystem Model
EurOcean	European Centre for Information on Marine Science and Technology
EwE	Ecopath with Ecosim
FABM	Framework for Aquatic Biogeochemical Models
FishMIP	Fisheries and marine ecosystem intercomparison project
FishSUMS	Length-structured partial ecosystem model, University of Strathclyde, U.K.
FP	Framework Programme (European funding)
FVCOM	Finite Volume Community Ocean Model, University of Massachusetts, U.S.A.
H2020	Horizon 2020 (European FP8)
HAMSOM	HAMburg Shelf Ocean Model
HZG	Helmholtz Center for Materials and Coastal Research
IBM	Individual-Based Model
ICES	International Council for the Exploration of the Sea
ICG EMO	Intersessional Correspondence Group for Ecological Modelling (OSPAR)
IFREMER	French Research Institute for the Sustainable Exploitation of the Sea
IMR	Institute of Marine Research, Norway
IPBES	Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
IPCC	Intergovernmental Panel on Climate Change
IPMA	Portuguese Institute of the Sea and the Atmosphere
ISIMIP	Inter-sectoral impact model intercomparison project
JRC	Joint Research Centre (EC)
KnowSEAS	Knowledge-based Sustainable Management for Europe's Seas (European FP7 project)
MAREFrame	Co-creating Ecosystem-based Fisheries Management Solutions (European FP7 project)
MEDUSA	Model of ecosystem dynamics, nutrient utilisation, sequestration and acidification
MEME	Modelling of the European Marine Environment
MERP	Marine Ecosystems Research Programme
MESOPP	Mesopelagic Southern Ocean Prey and Predators
MIT	Massachusetts Institute of Technology

MIT-Darwin	MIT project on modelling marine microbes
MIZER	Multispecies size spectrum ecological model
MSFD	Marine Strategy Framework Directive
MSP	Marine Spatial Planning
MSY	Maximum Sustainable Yield
NIOZ	Royal Netherlands Institute for Sea Research
NOC	National Oceanography Centre, U.K.
NORWECOM.E2E	NORWegian ECOlogical Model.End-To-End
NEMO	Nucleus for European Modelling of the Ocean
NN	Neural Networks
NPZ	Nutrient, Phyoplankton, Zooplankton (model)
OGS	National Institute of Oceanography and Experimental Geophysics, Italy
OSPAR	Oslo and Paris Commission. Regional Sea Convention for the Protection of the Marine Environment of the North-East Atlantic
PERSEUS	Policy-oriented marine environmental research in the southern European seas (European FP7 project)
PML	Plymouth Marine Laboratory, U.K.
RITMARE	Italian marine research network
ROMS	Regional Ocean Modelling System
SAMS	Scottish Association for Marine Science, U.K.
SEAMAN	Spatially resolved Ecosystem models and their Application to Marine MANagement (European FP7 project)
SHYFEM	Shallow water Hydrodynamic Finite Element Model
StrathE2E	Marine food web model, University of Strathcylde, U.K.
SST	Sea Surface Temperature
VECTORS	Vectors of Change in Oceans and Seas Marine Life, Impact on Economic Sectors (European FP7 project)
UiB	University of Bergen, Norway
WFD	Water Framework Directive
WG	Working Group
WG MODELLING	Working Group on Marine Ecosystem Modelling (EMB)

Annexes

Annex I: Members of the European Marine Board Working Group on Marine Ecosystem Modelling (WG Modelling)

NAME	FAMILY NAME	INSTITUTE	COUNTRY
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Corinna	Schrum	Helmholtz Center for Materials and Coastal Research (HZG)	Germany
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Annex II: Participants in the expert workshop, 7 July 2017, PML, Plymouth, UK

NAME	FAMILY NAME	INSTITUTE	COUNTRY
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Paul	Blackwell	University of Sheffield	UK
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Baixin	Chen	Heriot-Watt University	UK
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Kevin	Flynn	Swansea University	UK
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Hermann	Lenhart	University Hamburg	Germany
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Chris	Lindemann	University of Bergen	Norway
Martin	Marzloff	French Research Institute for the Sustainable Exploitation of the Sea (IFREMER)	France
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NAME	FAMILY NAME	INSTITUTE	COUNTRY
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Arnaud	Pourchez	Takuvik Joint International Laboratory	Canada
Paul	Somerfield	Plymouth Marine Laboratory (PML)	UK
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