

WORKING GROUP ON INTEGRATIVE, PHYSICAL-BIOLOGICAL AND ECOSYSTEM MODELLING (WGIPEM)

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WORKING GROUP ON INTEGRATIVE, PHYSICAL-BIOLOGICAL AND ECOSYSTEM MODELLING (WGIPEM)

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i Executive summary

WGIPEM supports ecosystem modelling development and use for management purposes by exchanging knowledge, identifying knowledge gaps and recommending activities to improve model performance and uptake within management. Our terms of reference are therefore aligned along the different parts of marine ecosystem modelling: a) improving model coupling, b) improving lower trophic level models, c) improving higher trophic level models and d) improving model skill assessments. Focus under these terms may vary per reporting period, and were aligned for this period with single and cumulative anthropogenic stressors, parametrization of function diversity, benthic-pelagic coupling, connectivity and movement and metric comparison, among others. Work presented during WGIPEM meetings showed that survey design can seriously affect survey results, based on model sampling, and that this type of modelling can therefore be used to optimize survey design. This is important as observations as well as models are needed: they should be seen as complementary and both are necessary for understanding, and responsible management of, the marine ecosystem (Skogen et al., 2021). In a similar way, a modelling framework was developed to support the MSFD while population distribution was simulated in a novel way, indicating 3 separate populations in an area where management is based on a single population. Microplastics were shown to affect the spatial distribution of secondary production in the North Sea while simulations of aquaculture practises showed that multispecies aquaculture can reduce the nutrient input compared to monoculture. WGIPEM initiated a special issue of Marine Ecosystem Progress Series (estimated for fall 2021 publication) which will focus exclusively on dynamic modelling and includes multiple studies included in this report. WGIPEM also attended the WKCONSERVE workshop and heard presentations from or had joint sessions with BEWG, WGSAM, WGBIOP, WGINOSE, WGSPF and WGMPCZM. One joint publication was published (Skogen et al., 2021) with another submitted (Van de Wolfshaar et al., 2021). Initiatives for more collaborative papers were started. WGIPEM will continue to promote ecosystem modelling in their new Terms of Reference including a focus on incorporating human dimensions and ensemble modelling for support of management.

ii Expert group information

Expert group name	Working Group on Integrative, Physical-biological and Ecosystem Modelling (WGIPEM)
Expert group cycle	Multi-annual fixed term
Year cycle started	2019
Reporting year in cycle	3/3
Chair(s)	Solfrid Sætre Hjøllø, Norway
	Sonja van Leeuwen, Netherlands
	Marie Maar, Denmark
Meeting venue(s) and dates	25-29 March 2019, Bergen, Norway (30 participants)
	2020, postponed due to Covid-19 situation
	22-25 March 2021, Virtual meeting (47 participants)

1 Background and scoping of WGIPEM work

Members of WGIPEM identified five key topic areas at its first meeting in 2012: understanding the dynamics of primary and secondary production and the two-way coupling of lower and upper trophic level models, representing the movements of fish and other living resources, projecting the impacts of climate change and variability on the productivity and distribution of key species and the composition of food webs, quantifying and conveying uncertainty within various modelling approaches, and coupling novel aspects of socio-economic and ecological science within models. These issues are still at the core of WGIPEM.

The aim of the Working Group on Integrative, Physical-biological and Ecosystem Modelling (WGIPEM) is to advance the state-of-the-art in coupled physical-biological and ecosystem modelling. An important part of the work is the continued development of end-to-end ecosystem models that incorporate hydrodynamics, lower and higher trophic levels and the link to ecosystem services and human impacts (Figure 1 and Annex 3). WGIPEM carries out its modelling work by sharing and discussing simulation results, identifying gaps in knowledge in these modelling activities, and recommending and performing activities to improve model performance. The group forms an important link between the biophysical modelling community that produces estimates of ecosystem components and the managers charged with giving advice on the status of those systems and their resources. Several of the applied models are already operational and used to give advice to stakeholders and managers, whereas others are mainly used for research purposes. The applied models are considered as useful tools that can support the goals of the UN decade of Ocean Science by providing scientific knowledge and data and address the societal outcomes, e.g. ‘a predicted ocean’.

The applied models in WGIPEM can be used to integrate scarce observational data points in space and time and provide a more full picture of the current state of the oceans. This applies both to the state of single fish stocks, ecosystem indicators (e.g. nutrient-, Chl a- and oxygen levels) and ecosystem services (e.g. nutrient remediation, food provisioning). Further, the models can increase our understanding of the oceans through quantification of processes that are difficult/impossible to measure, reveal ecosystem functions and complex food web interactions (e.g. trophic cascading effects) and evaluate responses of ecosystem components to bottom-up and top-down pressures from human activities and natural drivers. For predictions of the future ocean, ongoing modelling studies are investigating ecosystem responses to a range of pressures (e.g. climate change, invasive species, fishery, eutrophication, aquaculture, microplastics, etc.) and how these combine (e.g. additively or synergistically) in different future scenarios. WGIPEM is convening a session on ‘Impacts of human pressures on ecosystem components assessed by dynamic modelling’ at the next ICES Annual Science Conference in Copenhagen 2020. The session aims to present a broad range of ecosystem models and their applications to a wide diversity of research and ecosystem management questions, to demonstrate the use they could have in Integrated Ecosystem Assessments (IEA). EIAs integrate all components of an ecosystem, including humans, into the decision-making process so that marine managers can balance trade-offs. The need for holistic tools in EIAs is now clearly recognized, and dynamic modelling has the potential to contribute significantly to this process.

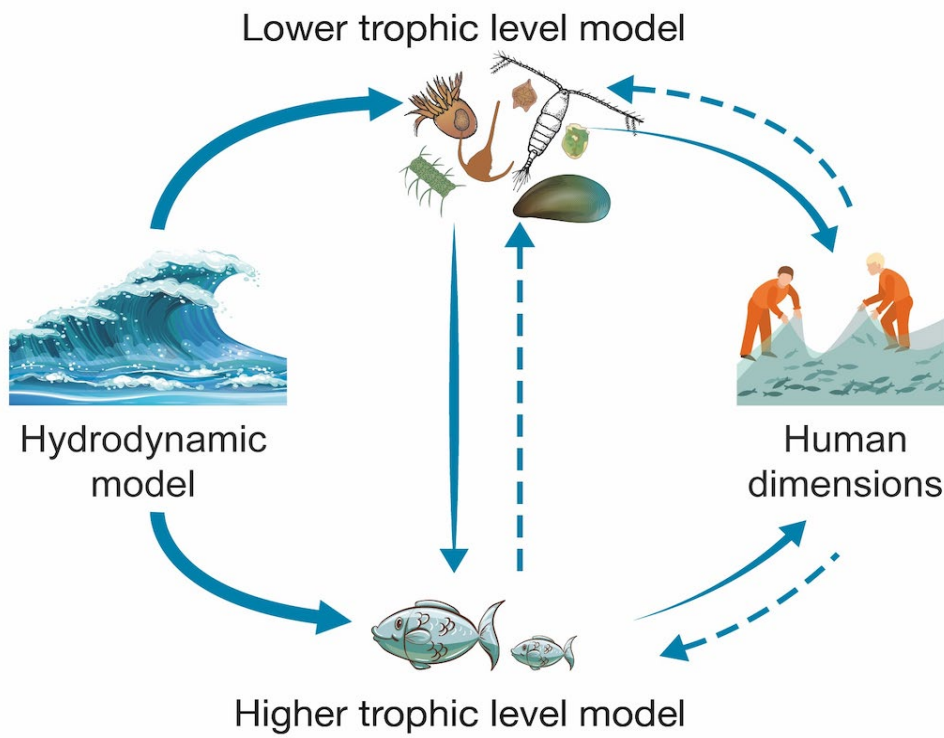


Figure 1: WGIPEM's field of work. The solid arrows are widely used feedbacks, the dashed arrows are connections between models and drivers that are still being developed. WGIPEM's objective is to strengthen all these connections.

2 Improving model interactions between trophic levels (ToR a)

2.1 Assessing human activities effects on ecosystems, including cumulative impacts

The work presented by WGIPEM members under ToR a covers a wide range of human pressures including aquaculture, riverine nutrient inputs, fishing and climatic changes. Acidification was not used as a separate stressor here though it has been included in individual work by members. Johanna Myrseth Aarflot (IMR) presented an overview of stressors on plankton noted that acidification has a much smaller effect on plankton communities than temperature, as studies show that phytoplankton have an inbuilt resilience to pH fluctuations. Thus, nutrient inputs, changing meteorological conditions and fishing pressure remain the stressors of choice within the modelling community for end-to-end studies. One study showed the ability of mussel transplantation at reducing marine nutrient concentrations (by limiting their decay locally and therefore decay-induced hypoxia), but concluded a decrease of anthropogenic nutrient input was still necessary to combat local eutrophication issues. In Irish waters, a study comparing no aquaculture versus mono and multispecies aquaculture found a definite increase in nutrients in the water column with aquaculture, but a lesser increase with multispecies than with mono-species aquaculture, indicating the effect of human farming at sea can be reduced by improving practice. The first end-to-end model of the Bay of Biscay is currently being built, to gauge anthropogenic impact and the effect of cumulative stressors for this area and support ecosystem overviews, while the Marine Modelling Framework (MMF, from JRC, EU), an end-to-end modelling tool box, has already been applied to the Mediterranean. The clear links to the MSFD (Figure 1) will ensure uptake of modelling results within European policy, while they could also inform stock assessment models and ecosystem overviews. Results showed no real change in the total primary productivity for the Mediterranean basin, but a shift in productivity from the (currently) more productive western basin (future decrease) to the (currently) oligotrophic eastern basin (future increase). The MMF allows combinations of climate change scenarios and fisheries management options showing significant impacts on commercial/non-commercial species biomass in the Mediterranean, and as such is an important development in the effort to include modelling in policy setting. A combined stressor study (climate, nutrients) for the Baltic using the Atlantis end-to-end model concluded that excess nutrients were the main driver for ecosystem response but that for cod climate change is the dominant driver on multidecadal time-scales. This study did not include nutrient release from the bed, which is known to negate nutrient reduction impacts in the Baltic. The WGIPEM organized theme session O at the ASC 2021 has several other contributions of multi-stressor studies as well, some of which are included in the MEPS theme section on dynamic modelling (DYNMOD). As such, progress on this part of ToR a has been partly delayed due to COVID restrictions.

It was noted by members that observational data on riverine nutrient loads can be hard to find, particularly as ecosystem models require long time-series of continuous daily data. For the North East Atlantic area sources are known (OSPAR ICG-EMO: contact sonja.van.leeuwen@nioz.nl, E-HYPE results), but for other areas, in particular the Arctic, this represents a serious problem. Global, simulated, daily flow data can be found at Copernicus: <https://cds.climate.copernicus.eu/cdsapp#!/dataset/cems-glofas-historical?tab=overview> but this does not include nutrient loads. Without adequate riverine data sources modellers tend to use climatologies, but these undermine the confidence people can have in future marine

ecosystem studies looking at human impacts. Riverine nutrient loads usually drive the local coastal ecosystem and can have a large marine footprint in shallow shelf seas like the North Sea (Painting et al., 2013), while the fresh water input can drive local and regional circulation patterns (e.g. Nunez-Riboni and Akimova, 2017). As such, good quality riverine discharges and nutrient loads are of prime importance to the modelling community.

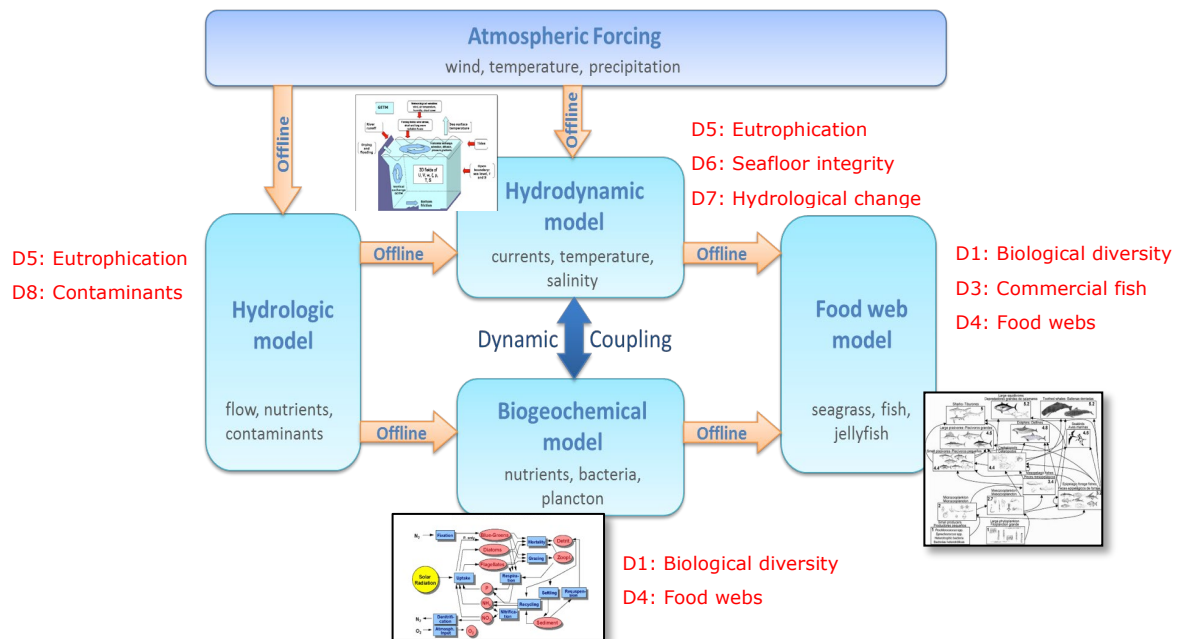


Figure 2: Schematic overview of the Marine Modelling Framework and relevant descriptors of the Marine Strategy Framework Directive. From the presentation by A. Stips et al., 2019 annual meeting. The policy potential of end-to-end ecosystem modelling is clear, and both MSFD and OSPAR have started work within the modelling community to incorporate model results in their advice processes.

2.2 Coupling of lower and higher trophic levels

Concerning the coupling of lower and higher trophic levels several end-to-end model studies were presented. The shift from a lower trophic level model (which mainly simulates organisms as particles moved by their abiotic surroundings) to a higher trophic level model (where organisms can display behaviour and swim against the currents) occurs at zooplankton level. Members have instigated work to include more detail in trophic coupling, by adding species diversity and gelatinous zooplankton. As zooplankton is a closure term for both the LTL and HTL models, it represents a bottle neck for energy transfer in a coupled model. This was investigated by a study using planktonic biomass fields from different LTL models to drive one spatially-explicit HTL model (OSMOSE) in the southern North Sea. This study, a WGIPEM initiative, found clear bottom-up control of the fish biomass in the HTL model. Planktonic biomass fields differed in absolute numbers, spatial and temporal distribution, but the relative biomass contributions gave consistent spatial patterns for selected fish species. This indicates that although the offered phytoplankton biomass varied (and thus the supply of energy to the higher trophic levels) the response was similar. As only one HTL model was used the energy transfer efficiency was the same in all cases, though the energy input varied according to the different LTL models. Therefore, it is recommended to redo this exercise with different HTL models, as well as inclusion of the macro-invertebrate component in the LTL models. This was kept constant for the reported exercise.

There has also been progress on two-way coupling, where fish biomass impacts directly on plankton dynamics in the LTL model (top-down control). Most coupled studies (lower and higher trophic levels) presented at WGIPEM (covering the Mediterranean, Baltic, Norwegian Sea, Gulf of Biscay and the European Shelf) were coupled one-way upwards, i.e. with plankton dynamics driving higher trophic levels (bottom-up pressures, includes abiotic changes like nutrient input and climate). But the Atlantis model (applied to the Baltic) and NORWECOM.E2E (North Sea, Norwegian Sea and Barents Sea) already include two-way coupling, and are thus able to include both bottom-up and top-down stressors throughout the marine ecosystem. WGIPEM will continue to promote 2-way coupling with end-to-end modelling to properly address top-down controls of the ecosystem dynamics, including fisheries and top-predators. Including more diversity and dynamics at zooplankton level is one of the most important ways forward in this respect. The reported progress on inclusion of jellyfish in models is therefore an important step: the jellyfish consume zooplankton and thereby compete with copepods for resources while also preying on them, adding an important new dynamic to the food web at the crucial coupling level. As temperatures increase phytoplankton composition generally shifts towards smaller species and smaller individuals (in nutrient-limited systems smaller species are better at scarce nutrient take up while in general cell size decreases with increasing temperature), and this will impact on plankton composition and the transfer of energy towards higher trophic levels. The reported work on which cues regulate phenology in key zooplankton species like *Calanus glacialis* is therefore equally important, as is the work on herring larvae survival indicating starvation is not the main source of herring larval mortality.

2.3 Investigating the importance of spatio-temporal scales for trophic match-mismatch

No progress, apart from the reported study forcing the OSMOSE model forced by different biomass fields representing different LTL models and the planned work on *Calanus glacialis* focusing on future predation and food supply match-mismatches for this species. As OSMOSE is spatially resolved it can be used to identify match-mismatch occurrence, but further analysis is needed here.

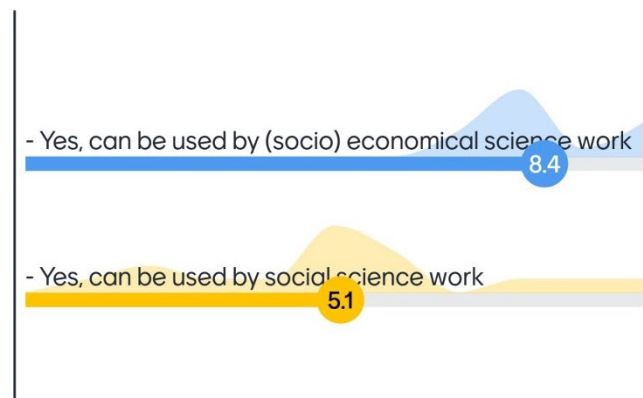
2.4 Human dimensions and ecosystem modelling

End-to-end modelling is often assumed to involve the coupling of a lower and a higher trophic level model. However, these systems are rarely untouched by mankind. A standard procedure is to include anthropogenic influences as external drivers to the system, e.g. by imposing fishing pressure, climate scenarios, acidification impacts, effects of dredging and marine wind farms or pollution (excess nutrients, plastics, toxic substances). Within WGIPEM, we strive for a better inclusion of the human dimension in marine ecosystem modelling. To this end, Sonja van Leeuwen (chair) attended the 2019 WKCONSERVE workshop and we invited a social scientist to both the 2019 (Cecile Hansen, IMR) and 2021 (Andrea Morf, Havsmiljöinstitutet, Sweden and WGMP-CZM chair) annual meeting. At the 2021 meeting we held a survey to gauge member's existing participation with social sciences. Results indicate that 50% of the members present have had interaction with social scientists, usually through funded projects. Most of those had worked with the economical side, e.g. valuing commercial stock yields. Members associated social science most with the words "difficult", "value", "culture", "income" and "interviews", indicating improvements in the relationship between natural and social scientists can be made. Those who had worked with social science reported one-way interaction (only supplying or receiving data) as much as two-way interaction including joint publications. Supplied simulated variables included mainly physical parameters (e.g. temperature) and biomass field from both lower and

higher trophic levels, but nutrients, oxygen and primary production were also used. Thus, variables from across the range in ecosystem modelling had been used, indicating a movement beyond using fish biomass to estimate commercial value. Overall, the interaction with social scientists was deemed "good", with some "super good" experiences and one "difficult". In general, interaction between natural and social scientists was greatly facilitated by employment within the same institute. Obstructions in working together were mainly a lack of funding and time, followed by not knowing any social scientists. A few members also reported that social science did not operate on their spatial and temporal scales.

WGIPEM will more explicitly include social science into the new Terms of Reference for the next period.

7. Do you think your modelling can feed into social or economic science work? Please rank it: 10 is highly likely.



8. Would you personally like to use (more) social and/or socio-economic science in your work? Please rank it, 10 is highest.

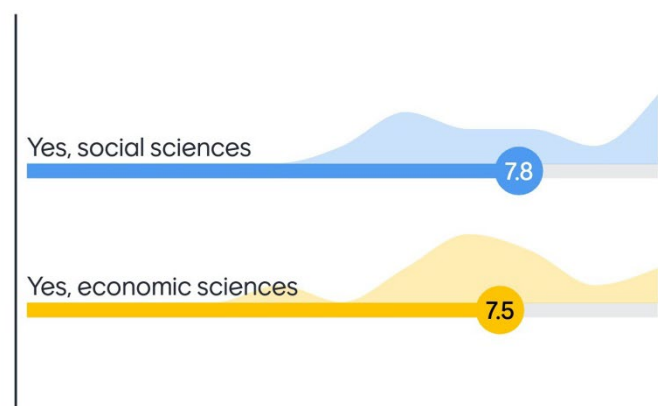


Figure 3: WGIPEM members indicate the suitability and their interest in working with social sciences.

2.5 Knowledge gaps

Regarding ToR the most important knowledge gaps identified were:

- Lack of riverine data (flow, nutrients), particularly for the Arctic but also for other areas and recent times. Quality control processes can take up to 3 years in some countries before nutrient concentrations are made available, this seriously hinders projects which include observations and modelling within a limited time frame.
- Lack of knowledge on (gelatinous) zooplankton diversity and dynamics. As this level is in between LTL and HTL models it can both be transported by the currents and display (complex) behaviour. Knowledge on the latter is necessary for inclusion in modelling.
- Lack of understanding in dredging effects on resuspension of nutrients and oxygenation of the seabed. This will require detailed field and lab studies.
- Lack of knowledge on non-commercial species. This hinders multispecies and food web modelling as characteristics of commercial species are mostly well known but the same information for non-commercial species is lacking, as is information on interactions between commercial and non-commercial species. This was already discussed once at the 2019 annual meeting in a joint session with WGBIOP chairs.
- Temperature impacts on physiology, also for extreme temperatures, for both higher and lower trophic level species.
- Lack of in-situ data (e.g. nutrients, oxygen, chlorophyll-a, zooplankton)
- The general lack of two-way coupling. WGIPEM will include this more explicitly in their next Terms of References.

2.6 Publications

Bossier, S., Nielsen, J. R., Almroth-rosell, E., Höglund, A., Bastardie, F., Neuenfeldt, S., Wählström, I., & Christensen, A. (2021). Integrated ecosystem impacts of climate change and eutrophication on main Baltic fishery resources. *Ecological Modelling*, 453(109609).

Maar, M., Larsen, J., Saurel, C. *et al.* (2021) Mussel transplantation as a tool to mitigate hypoxia in eutrophic areas. *Hydrobiologia* 848, 1553–1573. <https://doi.org/10.1007/s10750-021-04545-6>

Van de Wolfshaar K, Maar M, Daewel U, Troost T & Hjøllø S, Differences in lower trophic level models fade out at higher trophic levels, **resubmitted** to *MEPS* special issue DYNMOD

2.7 Science highlights

Highlights under ToR include:

- Development of the "jellyness" concept to describe gelatinous zooplankton characteristics and dynamics. The jellyfish included have different life stages and histories compared to traditional zooplankton species and are advected differently when grown compared to copepods. This is new development at a critical level for end-to-end models, which has the potential to significantly alter existing transfer of energy and spatial dynamics to higher trophic levels.
- Sensitivity work coupling different lower trophic levels to one higher trophic level model demonstrated both the difference between LTL models (highlighting the need for ensemble modelling) and little sensitivity in 1 HTL model to the different LTL forcing fields (consistent response between models in the relative biomass contribution and spatial patterns of selected fish groups).
- Presentations of several end-to-end models that include two-way coupling. Improvements may be possible but getting started is the first hurdle. These models showcase the possibilities to other modelling groups for including bottom-up and top-down pressures truly within one coupled model.

- JRC coordinated an ensemble modelling study with the specific aim of supporting the MSFD, which showcases the possibilities for ecosystem modelling to support management.
- Multispecies aquaculture can have less of a detrimental impact on the surrounding ecosystem than single-species aquaculture. This opens doors for new management initiatives that limit aquaculture impacts.

2.8 Abstracts

2.8.1 Can mussel transplantation be used as a tool to mitigate hypoxia in the eutrophic Limfjorden?

Presented by Marie Maar

Mass mortality of blue mussels occurs every summer in the hypoxic, stratified parts of Danish estuaries and the oxygen consumption of decaying mussels is suspected to accelerate the hypoxia. In the present study, the solution of transplanting mussels from donor areas with frequent hypoxia to more suitable growth areas was tested as a tool to mitigate hypoxia in the Limfjorden. The environmental effects in the donor area were estimated by a 3D ecological model of the Skive Fjord-Lovns Bredning using the Flexsem model system. Mussel transplantation was set to take place over four weeks in May-June 2011 before the hypoxic period applying two realistic fishing intensities; 3600 t-mussels and 6000 t-mussels. Oxygen consumption of degrading dead mussel tissue was measured in laboratory experiments and used to parameterize the model. Model results showed that bottom oxygen mainly was improved at 2-5 m water depths close to the fished mussel beds and with highest increases (up to 0.56 mg l⁻¹) from July to August. Mussel biomass soon recovered from the fishing pressure and showed a higher survival during summer due to the better oxygen conditions in the transplantation scenarios. These effects led to lower nutrient concentrations, reduced Chl *a* concentrations (up to 0.9 mg m⁻³) and increased Secchi depths (up to 0.09 m) during summer. However, during the intense mussel transplantation period, measured oxygen concentrations and modelled Secchi depths were shown to be negatively affected by dredging. The nutrient removal by mussel transplantation corresponded to 87 t-N and 3.8 t-P. In conclusion, mussel transplantation may limit the extent of the hypoxic events and the associated negative environmental effects during summer in 'problem' areas, but this is not sufficient to reach the goal of a good environmental status and further nutrient reductions from agriculture is still necessary.

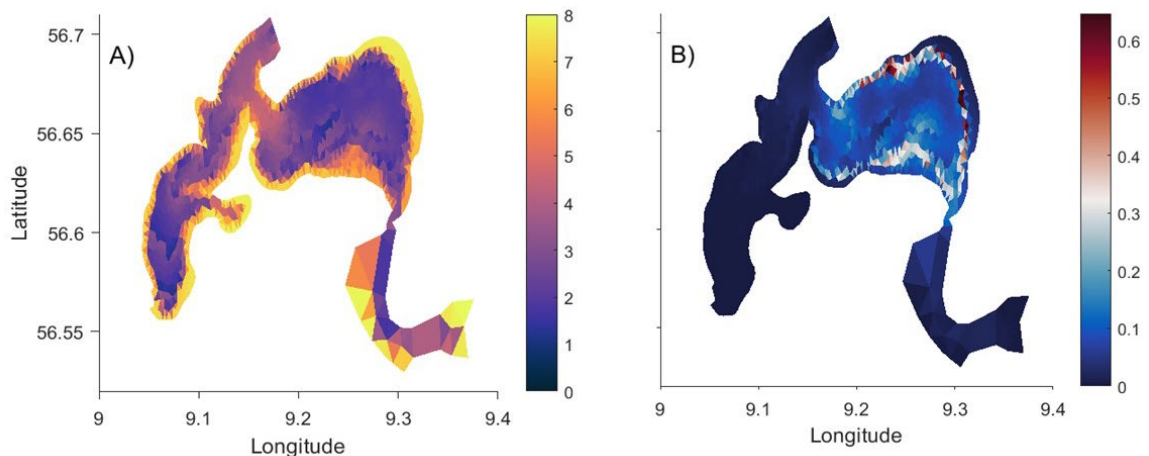


Figure 4: A) Average bottom oxygen concentrations (mg l^{-1}) and B) average change of bottom oxygen in scenario SCE2 in July-August with maximum change of 0.56 mg l^{-1}

2.8.2 Towards an integrated assessment of the Bay of Biscay marine ecosystem (Atlantis model)

Presented by Ane Lopez de Gamiz Zearra

The study focuses on the Bay of Biscay (BoB) ecosystem, a gulf of the Atlantic Ocean situated off the western coast of France and the northern coast of Spain. The area comprises a narrow continental shelf and a submarine canyon, Cap Breton, and corresponds to a subtropical/boreal transition zone with a high diversity reflected in the ecological richness of the area, containing a wide distribution of fish species, some of them with commercial relevance for the surrounding countries. The physical and hydrological features of the bay are of great complexity, e.g. coastal upwelling, coastal run-off and river plumes, seasonal currents, eddies, internal waves and tidal fronts. As in other coastal systems, the Bay of Biscay is subjected to high pressure level caused by different human activities such as fishing, maritime transport, coastal construction, land-based industry, etc. The five most important pressures related to these activities in the BoB ecoregion are, among other things, the selective extraction of species, abrasion, smothering, substrate loss, and nutrient and organic enrichment (ICES 2018). This work aims at: 1) analysing the spatial dynamics of the different human activities occurring in the Bay of Biscay ecosystem and how they interact, 2) exploring how different human activities affect the state of the components of the ecosystem, 3) analysing the cumulative effects of the activities in certain areas, accounting also for the effects caused by natural stressors and climate change. So, to start with, we need to characterize the system, specify the food web ecology, analyse how the environmental variability affect the dynamics of lower trophic levels, couple hydrography with food web, etc. An Atlantis model (Fulton et al. 2011) will be used to achieve the goals described in the previous paragraph, since we want an end-to-end modelling tool that help us move towards an integrated and qualitative assessment of the ecosystem for the first time in the Bay of Biscay.

2.8.3 Modelling secondary production and taking it into account when doing HTL modelling

Presented by Sevrine Sailley

Gelatinous organisms are generally not included in higher trophic level models. Here we present an approach to include jellyfish within the biogeochemical model PML-ERSEM, in order to

display broad ecosystem characteristic like dominance of the system mainly by copepods and takeover by jellyfish with a spatial and temporal separation between the two groups. Most HTL models do not consider zooplankton and the consequence a shift in the dominant zooplankton can have on ecosystem structure. Zooplankton diversity is poor in HTL models beyond broad size groups, and they rarely use zooplankton as one of their drivers when it is one of the main prey item. Inclusion of zooplankton as a forcing for HTL model should take into account the diversity of the group as it can impact the quality of prey items. Most lower and higher trophic level models include zooplankton as a closure term: more functionality at this important trophic level has the potential to greatly enhance lower to higher trophic level coupling of models. To this end the zooplankton groups in LTL models should be more diverse, and they should be included as forcing fields in HTL models. Many higher trophic level models do not include zooplankton at all, with even multispecies models generally limited to commercial species and their direct prey. Exceptions are Atlantis and Ecopath with Ecosim, among others. The jellyfish included in this study have different life stages and histories compared to traditional zooplankton species and are advected differently when grown (compared to copepods). An additional difficulty still to be tackled are colonial jellyfish species. There are spatial and temporal difference between copepods and jellyfish, and generally no co-occurrence.

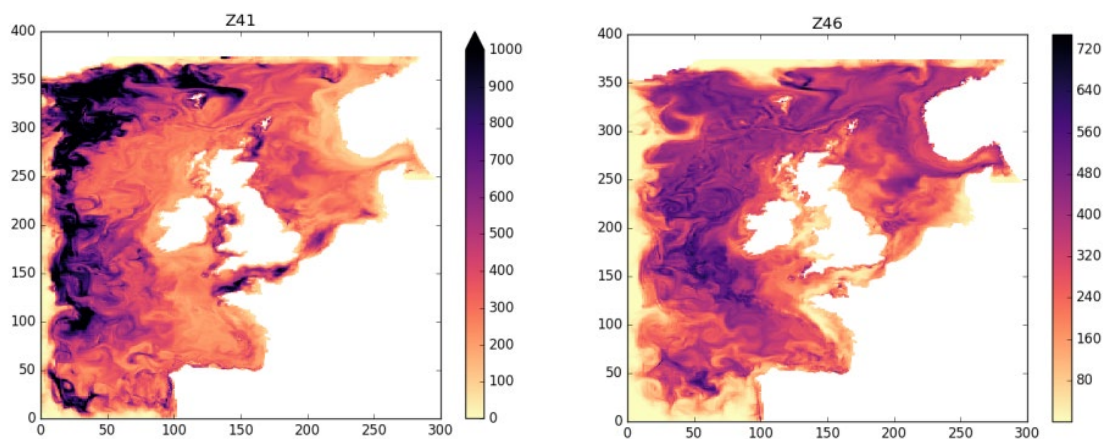


Figure 5: Copepods (left) versus jellyfish (right): spatial pattern max of monthly means for 2001. Note the inverse patterns: where copepods occur in large numbers jellyfish do not, and vice versa.

2.8.4 Zooplankton-phytoplankton relationships in a changing climate

Presented by Johanna Myrseth Aarflot

Phytoplankton represent 1% of photosynthetic biomass on Earth, 50 % of global net primary production and 90 % of marine primary production. Zooplankton are the main grazers of phytoplankton and the principal pathway for energy from primary production to consumers at higher trophic levels (fish, marine mammals etc.). Understanding how the trophic link between phytoplankton and zooplankton will be affected in a changing climate is therefore vital for predicting effects of warming on marine ecosystems. Here, I discuss this aspect using examples from the scientific literature and taking three different angles: warming effects on primary production, phytoplankton size structure, and potential mis-match in the timing of seasonal events.

Current predictions of climate effects on primary production show conflicting results regarding whether we expect the production to increase or decrease in a future warmer ocean. More broadly, expected effects from warming on phytoplankton production can be related to the nutrient regime. Warming leads to increased stratification, which may further limit primary

producers in already nutrient-limited systems (trophic- and mid-latitudes), while light-limited systems at higher latitudes might benefit from earlier stratification and a prolonged growth season. Whether a change in primary production will lead to a similar change in secondary production depends on the trophic control exerted on zooplankton populations, and this will likely differ between oceanic regions.

Phytoplankton cell size varies by several orders of magnitude and is important for the overall structure of the ecosystem. Nutrient-limited systems are typically dominated by small celled phytoplankton, which creates a longer and less efficient energy pathway to organisms at higher trophic levels. In nutrient-rich systems, larger phytoplankton like diatoms and dinoflagellates tend to dominate as primary producers supporting larger zooplankton like copepods as grazers and a shorter, more efficient energy transfer to higher levels. Studies suggest that the contribution of small phytoplankton increases with increasing temperature and stratification, as they are competitive superior at low nutrient levels. This is also supported by fossil records which suggest that increased stratification has corresponded to a reduction in mean community cell size in the past.

Over the course of evolution, life cycles and migration patterns of grazers have been tuned to the timing and location of phytoplankton blooms. If the timing of seasonal events will change in a future, warmer climate this could lead to a decoupling of trophic interactions with a large effect on the food webs. Most studies on match-mismatch between phytoplankton and zooplankton production originate from limnology. Studies suggest that zooplankton behaviour (e.g. vertical migrations) will determine how – or if – a grazer will be affected by a change in phytoplankton phenology. A study from Rippfjord (Svalbard) has suggested that the life cycle of *Calanus glacialis* is tightly linked to phenology of ice-algae and pelagic primary production. However, the current understanding of cues regulating seasonal events in zooplankton populations is incomplete, including how adaptable these traits are.

2.8.5 Integrated Multitrophic Aquaculture (Salmon, Lumpfish, Lobster) in the Fennel BGC model in ROMS

Presented by Joe McGovern

An integrated multi-trophic aquaculture (IMTA) configuration, comprising salmon, lumpfish, lobster and seaweed was integrated into a pre-existing NPZD model which was coupled to ROMS as part of the Horizon2020 TAPAS project (Tools for Assessment and Planning of Aquaculture Sustainability). The main objective of development of the coupled biogeochemical-IMTA model was to provide a model platform to determine the optimum IMTA configuration which capitalizes upon the potential of bio-remediators such as lobster and seaweed. The resultant model described the interaction between finfish excretions and the nitrogen cycle, filter feeding by lobster and inorganic nitrogen uptake by seaweed, within the wider biogeochemical cycle described by the Fennel biogeochemical model.

The resultant ROMS-NPZD-IMTA model was applied to Bertraghboy Bay in the West of Ireland as an initial test of model performance. The model was applied to a scenario comprising 7,000 salmon, 200 lumpfish, 25 lobster and 5g of *Ulva*. Hydrodynamic initial and boundary conditions were taken from the Marine Institute Connemara ROMS model, while biogeochemical boundary and initial conditions were taken from the Copernicus IBI-BGC analysis product. The IMTA simulation was compared to a benchmark ROMS-NPZD model run without any aquaculture instalment. Both simulations spanned from April to July 2018. A spring phytoplankton bloom was hindcast by both models. Comparison between the IMTA and NPZD models for the same period reflected that there was a net decrease in NH_4 of ~10% and a net increase in NO_3 and Chlorophyll a of ~50% and ~30% respectively. An additional scenario was simulated with salmon

monoculture (7000 salmon) to determine the outcome if monoculture was used instead of IMTA. The net impact of adopting salmon monoculture over IMTA was an increase of ~10% in NH₄, ~15% in NO₃ and ~20% in Chlorophyll a. Further detailed model validation, and detailed analysis and forecasting is anticipated in the coming years.

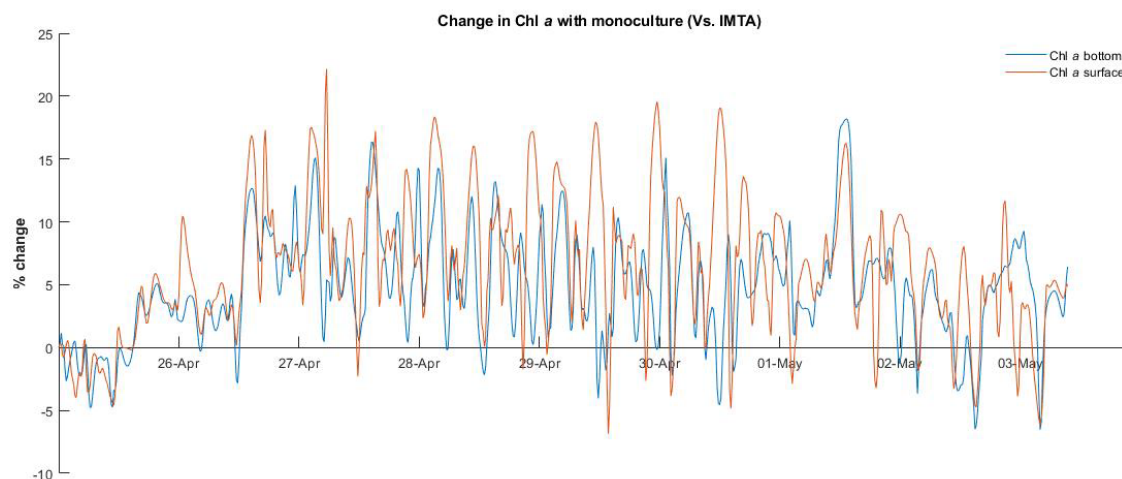


Figure 5: Change in Chlorophyll-a at the surface and at the bottom between the salmon monoculture and the multispecies aquaculture (salmon, lumpfish, lobster, ulva). Positive change means higher levels for the monoculture.

2.8.6 A modelling framework for the marine environment in support of EU policies: combining ecosystem and food web modelling

Presented by Adolf Stips

We presented an integrated water and marine ecosystem modelling framework comprising a suite of selected types of modelling codes, relevant to MFS and other water policies, implemented and validated on different spatial (regional and subregional) and temporal (past and future) scales, complemented by essential data (topography, bathymetry, initial, boundary forcing, in and outflows) that are inherently coupled to each other.

The Marine Modelling Framework (MMF) proposes end-to-end modelling, which tries to represent the entire system by including all relevant processes in the system, from hydrology and physics to chemistry, and plankton to fish. The optimum architecture for the toolbox is developed, by clearly specifying the individual contributing components and the associated EU policies. To achieve the overall objective, four basic types of models are considered: hydrological models providing information on diffusive and river discharge in terms of flow and nutrients, hydrodynamic models (simulating marine water transport), lower trophic level biogeochemical models (including phytoplankton and zooplankton) and higher trophic level food-web models (from phytoplankton to marine mammals/seabirds) into a single modelling framework/toolbox.

Several applications of the MMF for performing past and future simulations of lower and higher trophic levels in the Mediterranean Sea were presented. These examples comprised:

- First, identifying the importance of past river nutrient input to the productivity of the ecosystem from primary productivity up to fish;
- Second, the change in historic food web composition caused by these productivity changes;
- Third, near future changes in deep convection intensity and the related consequences on primary production;

- Fourth, the impact from changing river water quantity on the hydrodynamics and primary production;
- Fifth, the impact from climate change (warming) on primary production and consequently on the food web (fish abundance).

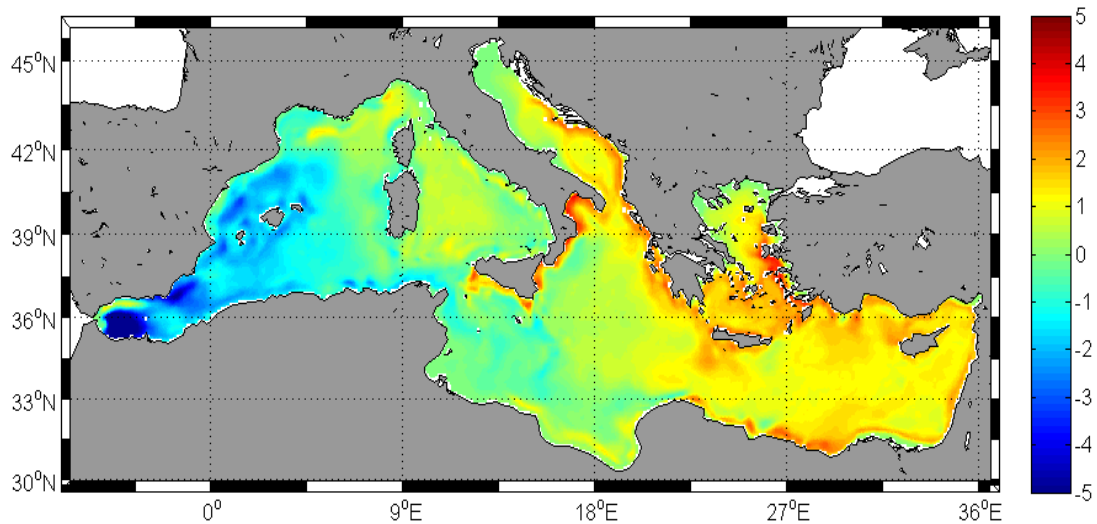


Figure 6: Future Mediterranean Sea PPR anomalies (mmol N m^{-2}) (2094-2099) – (2014-2019) under the RCP8.5 scenario. For similar results see Macias et al. (2015).

2.8.7 Sensitivity of the fish community to different prey fields and importance of spatial-seasonal patterns

Presented by Karen E. van de Wolfshaar

We hypothesize that differences in LTL patterns and magnitude translate into differences in HTL biomass and spatial and temporal patterns. To test this we use prey fields received from five different LTL models (Delft3D-WAQ, ECOHAM, ECOSMO, HBM-ERGOM, and NORWECOM) to force the spatially explicit HTL model OSMOSE in a setup for the North Sea. OSMOSE contains 12 fish species: herring, sprat, sandeel, Norway pout, plaice, sole, dab, cod, saithe, whiting, grey gurnard and haddock. The estimated fish biomass levels were clearly and positively linked to the provided zooplankton biomass, indicating a clear bottom-up control. Sensitivity studies with varying zooplankton biomass revealed that spatial and temporal variation in zooplankton drives differences in absolute fish biomass and that the provided size range of prey was important for the outcome. We found a consistent response between models in the relative biomass contribution and spatial patterns of selected fish groups indicating a low sensitivity of the simulated fish community to the zooplankton input. Relative, not absolute, changes may therefore be used to study effects of management scenarios on the fish community.

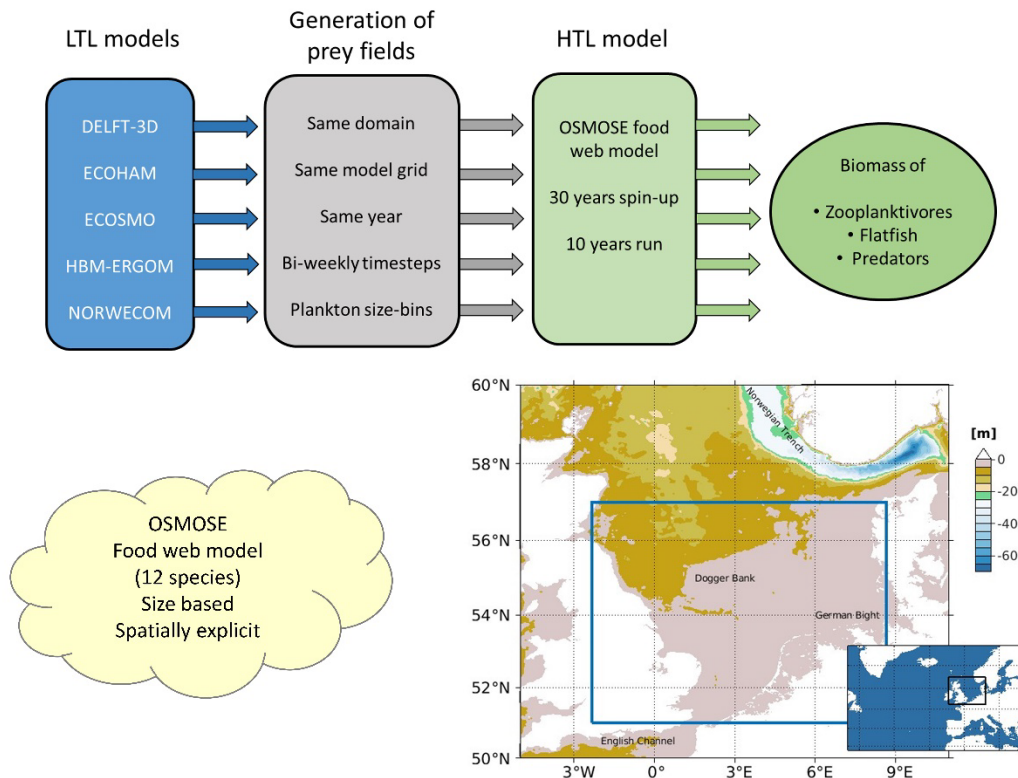


Figure 7: Schematic of the different lower trophic level models feeding into the higher trophic level model OSMOSE and the shared model domain of the 5 participating LTL models.

2.8.8 Foraging, growth and survival of herring larvae in the North Sea

Presented by Anna Akimova

The presented study combined highly resolved datasets on abundance of herring larvae, size-structured zooplankton and environmental conditions measured during the field campaigns in winter and fall 2012-2019. The main goal of the study was to estimate total larval mortality and to quantify the role of starvation in the recruitment variability of the North Sea autumn spawners. A physiological individual-based model was used to simulate larval foraging, growth and mortality. We found that starvation mortality was high only for the very small post-yolk-sac herring larvae (< 9 mm). Mortality rapidly decreased with larval size and herring larvae bigger than 12-13 mm were well-fed and able to grow with their maximal growth capacity at the observed temperatures. The model-based estimates of starvation mortality were highly sensitive to the choice of the initial length distribution of the post-yolk-sac larvae, which appears to be poorly known for the North Sea herring stock. Despite this uncertainty, the model-based estimates of the starvation rates were 3 to 10 times lower than the total mortality rates assessed from the observed larval abundance. These results suggest that starvation mortality is not the main source of herring mortality and the recently observed elevated mortality could be caused by other processes, i.e. predation or dispersion.

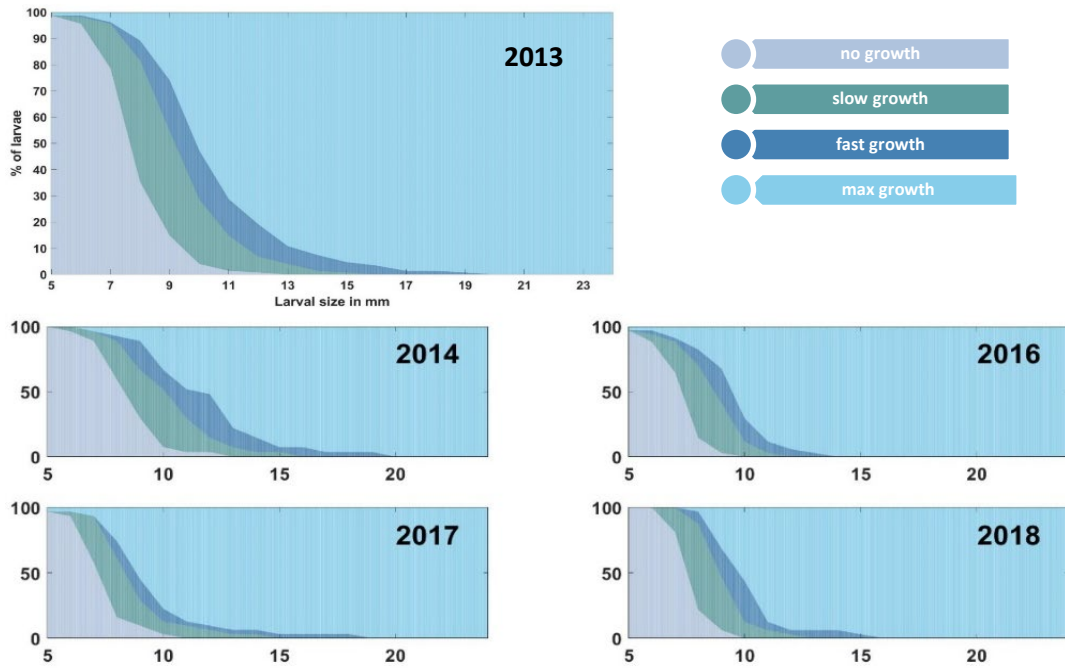


Figure 8: Percentage of herring larvae in each growth category, for different size classes and years.

2.8.9 The effects of climate change and nutrient input on the Baltic Sea ecosystem

Presented by Sieme Bossier

Here we present results of future scenario studies for the Baltic, using the Baltic Atlantis end-to-end model. We consider 3 climate scenarios (present, RCP4.5, RCP8.5) and 3 nutrient scenarios (low, reference, worst case) and combinations of these over the period 2005-2097. For the key species of herring, sprat and cod results show that in general individual weight and total biomass increases while abundance decreases, with herring coping better under possible future conditions than sprat. Future climate and eutrophication pressures show that excess nutrient loads are the main driver of the changes in the ecosystem and that for cod, in the longer run, climate change will have a stronger impact than eutrophication due to its hydrographic spawning limits (Bossier et al. 2021). This study could be improved by considering a species-specific temperature function in the higher trophic levels and more realistic herring spawning by including egg-laying on vegetation. Oxygen should also be included in the abiotic environment of the model as well as nutrient storage in and release from the seabed (not considered here).

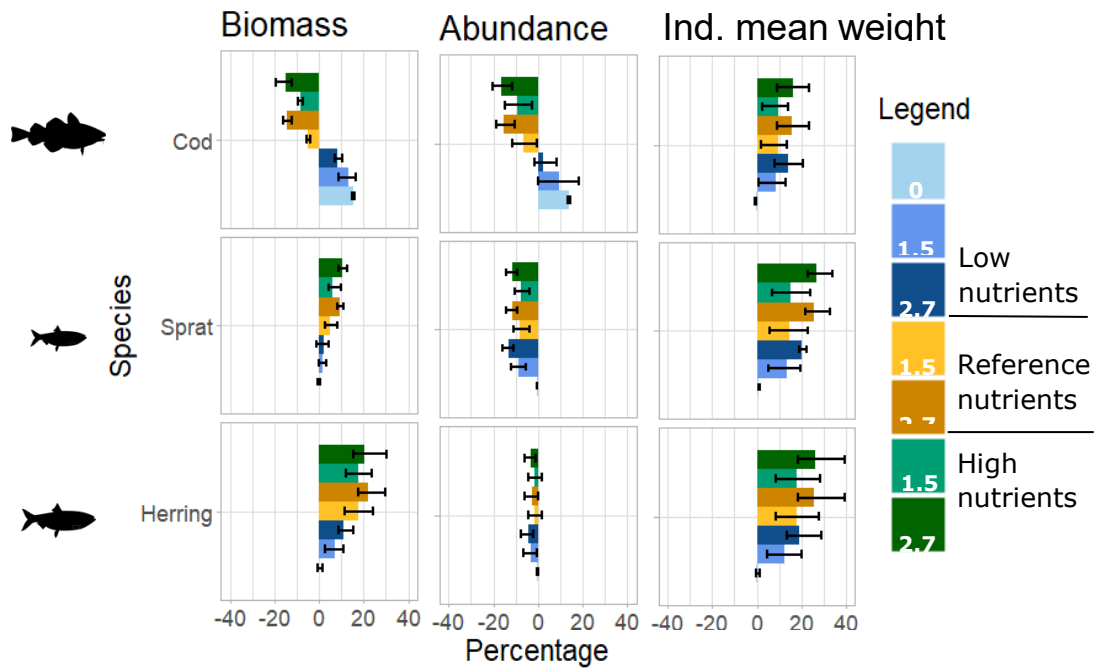


Figure 9: Results for the 3 focus species for all scenarios. Here 1.5 refers to RCP4.5 and 2.7 to RCP8.5, which are the respective temperature increases by 2100. From Bossier et al (2021).

3 Improving lower trophic level models (ToR b)

3.1 Explore patterns and drivers of plankton phenology and productivity across models and ecosystems

Phenology, the study of annually recurring biological phenomena in relation to climate conditions, is particularly useful in examining the system responses to environmental disturbances. Such studies have been conducted extensively in terrestrial and freshwater systems and have received increasing attention for coastal and open ocean systems. Marine plankton phenology differs between temperate and polar systems and have implications for the productivity. Rubao Ji provided different examples in his keynote talk on the drivers responsible for phytoplankton phenological shift, and on the implications for the population dynamics and biogeography of calanoid zooplankton species. Both empirical analyses and quantitative modelling approaches have been used in those studies. The results highlight that correctly identifying specific drivers in a dynamic system is important for establishing links with 'near-field' and 'far-field' climate forcing; and that biogeography is sensitive to phenological variability, especially in high-latitude systems where organisms often need to meet their critical developmental threshold within a short growing season. Challenges remain due to the advective nature of ocean systems and the lack of datasets with high spatio-temporal resolutions.

The group encompasses a large number of lower trophic level models from the North Sea, the Baltic Sea, the Gulf of Main, the Mediterranean Sea, and the Arctic (Barents Sea, Nordic Seas, off Greenland). In Arctic areas, the similarity of coastal areas with terminating glaciers (Disko, Svalbard) with respect to light conditions, ice cover, ice algae and freshwater discharge for productivity (timing and magnitude) was discussed based on new model results. In Disko Bay, sea ice cover determined annual productivity on basin scale, whereas annual changes in discharge showed strong local impacts close to the freshwater sources. In Svalbard, sea-ice algae production was important as it led to a 'seeding' of pelagic diatoms and an enhancement of the zooplankton production. The copepod *Calanus finmarchicus* is an important food source for many fish species, both in the Arctic and the North Atlantic, and has a complex life history with overwintering and several life stages. New modelling results show that the timing of *C. finmarchicus* biomass peak in spring can vary by one month in the North Sea, which is important for fish stocks recruitment. Further, the interannual variability and sustainability of the *C. finmarchicus* biomass was found to depend on the inflow from the Faroe-Shetland Channel and the southern Norwegian Sea. In the North Sea, another model study investigated the potential impacts of microplastics on primary and secondary production based on new experimental evidence. They found that although the model predicted that microplastics do not affect the total primary or secondary production of the North Sea as a whole, the spatial patterns of secondary production were altered, showing local changes with potential implications for the link to HTLs. The representation of phytoplankton community structure in mechanistic ecosystem models are often very simple with only one or a few functional groups. Phytoplankton diversity was tested using a statistical size-case approach. The method showed great promise in including impacts of plankton size structure/diversity on the entire ecosystem while retaining a simple, computationally efficient, lower trophic level representation. In the last study, the implementation of a stoichiometric flexibility of phytoplankton in a low-complexity biogeochemical model was shown to enhance the reproducibility of eco-system dynamics without increasing the computational demand. More details of the mentioned studies are provided in the following subsections.

Phytoplankton phenology: drivers

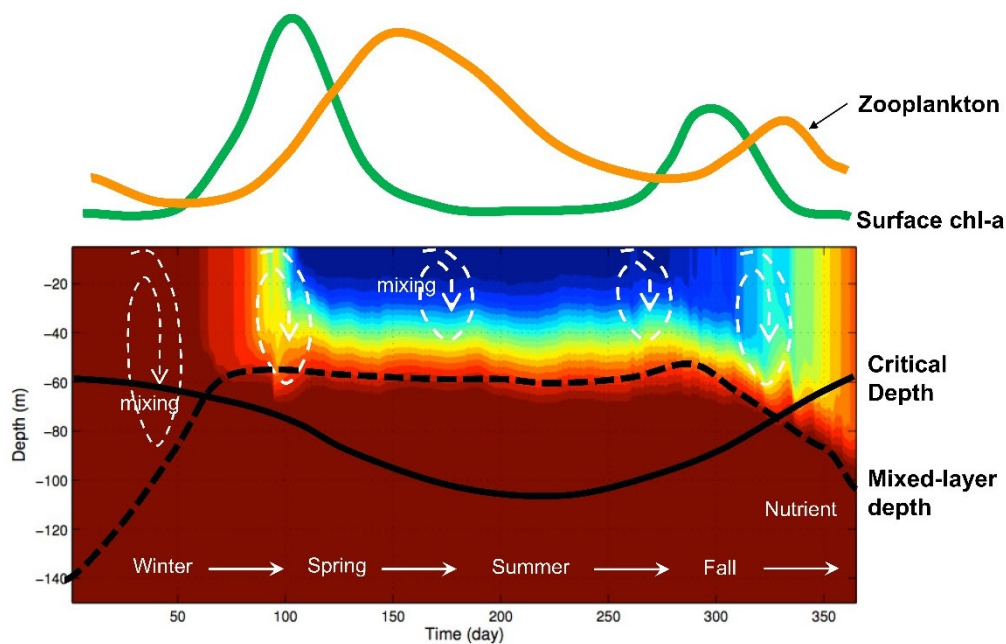


Figure 10: Phytoplankton phenology drivers over the year, from the presentation by Rubao Ji.

3.2 Advancement of benthic-pelagic coupling in models

The benthic-pelagic coupling is important for the biogeochemical cycles of carbon, nutrients, oxygen and trace elements. A large fraction of organic matter produced in the water column is sedimenting out to the sea floor and sustains the benthic community. The benthos can, on the other hand, be a source of material for the water column (e.g. releasing nutrients from mineralization of organic matter) as well as a temporary or permanent sink through ingestion, respiration and burial. Despite this, benthic systems are generally underrepresented in marine ecosystem models, in both regional and global applications, and are mostly present as a simple closure term for mass conservation (Lessin et al. 2018).

During this term, the model description of the benthic-pelagic coupling under ToR b was advanced in several studies. Firstly, the carbon export through sedimentation was improved to include the effects of the plankton community structure on the formation and properties of settling particles in the North Atlantic and the Arctic Ocean. Comparisons show that high latitudes, which sustain larger plankton, receive higher export efficiencies compared to both low latitudes and experiments using constant global rates, while the model effectively simulates slower export at lower latitudes. Secondly, bioturbation and bio-irrigation were improved by including more complex deposit feeder dynamics in a water column model in the North Sea. This modification resulted in a much higher variability of remineralization rates, leading to increased benthic-pelagic exchange, higher benthic biomasses and lower pelagic DIN values. Thirdly, microphytobenthos was included in the sediment model of a 3D coupled model system and their presence increased the sediment content, especially at shallower areas. Lastly, the benthic-pelagic coupling was improved in a study of sea scallops, where their energy balance mostly could be met with an approximation of the vertical food gradient in the benthic boundary layer. The deliverable on a joint paper on productivity and drivers across models and ecosystems was initiated, and a

subgroup will work on how climate change affects the balance between pelagic and benthic production. The work will continue into the next term before completion.

3.3 Knowledge gaps

Regarding ToR b the most important knowledge gaps identified were:

- The lack of observational datasets with high spatio-temporal resolution
- Missing parameter values in relation to predation mortality of *C. finmarchicus* in the North Sea and insufficient observational data to compare, especially in deeper water depths
- Better description of light attenuation in melt water from marine-terminating glaciers
- scarce field data on microplastics and their impacts on ecosystem components
- Large uncertainty in particle sinking speeds resulting in large uncertainty in carbon export
- There are generally too few data on sediment process rates and nutrient content
- Little knowledge on the functions of funnelling deposit feeders processes like search volume, growth and uptake, and bioturbation impact

3.4 Publications

The MEPS special issue includes several manuscripts that fall under this ToR. These are currently under review.

Benkort, D., U. Daewel, M. Heath, and C. Schrum. 2020. On the Role of Biogeochemical Coupling Between Sympagic and Pelagic Ecosystem Compartments for Primary and Secondary Production in the Barents Sea. *Frontiers in Environmental Science* 8:548013. doi:10.3389/fenvs.2020.548013

Gao, S., Hjøllø, S. S., Falkenhaus, T., Strand, E., Edwards, M., & Skogen, M. D. (2021). Overwintering distribution, inflow patterns and sustainability of *Calanus finmarchicus* in the North Sea. *Progress in Oceanography*, 194, 102567, doi: [10.1016/j.pocean.2021.102567](https://doi.org/10.1016/j.pocean.2021.102567)

Macias, D, Huertas, IE, Garcia-Gorriiz, E, and Stips, A. (2019) Non-Redfieldian dynamics driven by phytoplankton phosphate frugality explain nutrient and chlorophyll patterns in model simulations for the Mediterranean Sea. *Progress in Oceanography* 173 (2019) 37–50.

Troost TA, Desclaux T, Leslie HA, van der Meulen MD, Vethaak AD (2018) Do microplastics affect marine ecosystem productivity? *Mar Pollut Bull* 135:17-29

Yumruktepe, C., Salihoğlu, B., Neuer, S. 2020. Controls on carbon export in the subtropical North Atlantic. *Progress in Oceanography*, 187, 102380.

3.5 Science highlights

Highlights under ToR b include:

- Benthic-pelagic nutrient exchange (and subsequent benthos biomass) can be greatly enhanced by including bioturbation species (such as lugworms) in more detail. To do this one has to take into account life stages and absolute numbers of individuals, something rarely done in lower trophic level models.
- Microplastics within the North Sea do not affect the total primary and secondary production but alter the spatial pattern of secondary production.
- Biogeography is sensitive to phenological variability, especially in high-latitude systems

- *Calanus finmarchicus* spring biomass peak timing can vary with a month in the North Sea. Their interannual variability depends on the inflow from the Faroe-Shetland channel and the southern Norwegian Sea.

3.6 Abstracts

3.6.1 The relative importance of sea ice and discharge for primary productivity in Disko Bay

Presented by Marie Maar

Disko Bay is located at the west coast of Greenland at the southern border of the Arctic sea ice and is influenced by both Subarctic waters from southwestern Greenland and Arctic waters from Baffin Bay. The area is one of the most important areas for biodiversity and fisheries around Greenland. The large marine terminating glacier Jakobshavn isbræ is found in the bottom of the bay near Ilulissat. Since the 1980'ies the freshwater discharge has almost doubled. During the same period, Disko Bay has experienced a large decrease in sea ice cover, and also the year-to-year variations have increased in the last decade. In this study, we investigate the effect of changes in sea ice cover and Greenland ice sheet freshwater discharge on the primary productivity in Disko Bay. We use the 3D coupled hydrodynamic-biogeochemical model FlexSem-ER-GOM (Larsen et al 2020) validated against in situ measurement of nutrients, phytoplankton and zooplankton biomass from 2004 to 2018. The model results showed that annual primary productivity on bay scale was correlated to sea ice cover during spring, because an earlier break-up of the ice (less ice cover) resulted in a longer productive period and higher production (Figure 3.2b). Locally, close to the freshwater sources, there was a significant negative correlation between salinity and primary production indicating that higher freshwater inflow (less salinity) leads to higher primary production (Figure 3.2a). In future, less sea ice and more discharge are expected to increase primary productivity with implications for fish stocks and fisheries and, hence, the local population in Disko Bay (Møller et al. in prep). Next steps are to investigate the secondary production patterns, *Calanus* spp. migration and the connection with Baffin Bay.

Correlation between primary production and discharge or sea ice cover

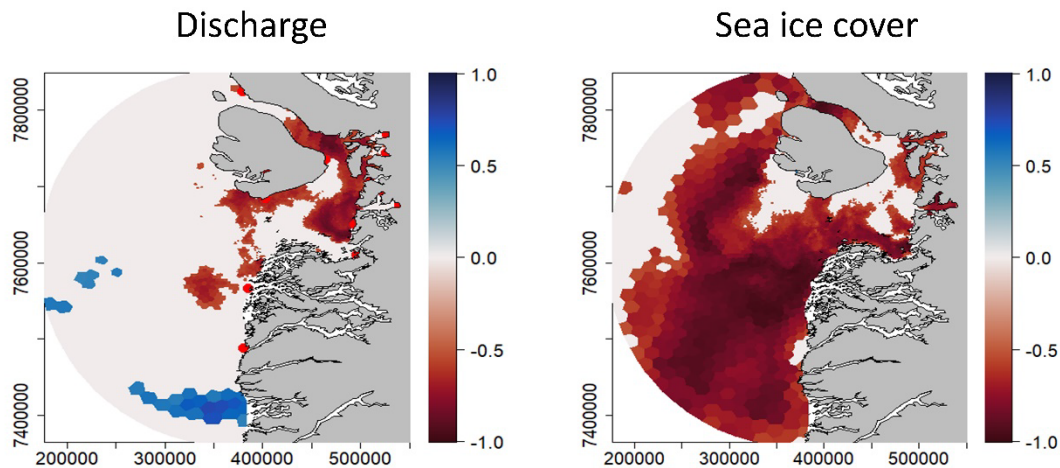


Figure 11: Correlation coefficients between annual primary production and a) salinity, and b) sea ice cover. Freshwater sources are indicated as red points. Non-significant correlations are shown as white background.

3.6.2 Arctic primary production and sea ice

Presented by Deborah Benkort

The Arctic system is subjected to a rapidly changing environment since the last decades. The Barents Sea is characterized by high productivity and represents the Arctic area featuring the most severe decrease in winter sea-ice extent. However, sea-ice algae play an important role in the total arctic primary production, and therefore represent a crucial element in the entire Arctic food web dynamic. Hence, a proper model representation of the sea-ice algae phenology and the linkage with the pelagic and benthic ecosystems, considering the sea-ice structural changes, appears essential to understand the Arctic ecosystem dynamics and its future changes. A biogeochemical sympagic (sea ice) system was implemented into the ECOSMO-E2E food web model. Results demonstrated that the model simulated a realistic seasonal pattern of the sympagic. We highlight the importance of implementing the sympagic system for the timing and the amplitude of the pelagic primary and secondary productions underneath (Figure 3.3). We also showed that sea-ice algae production leads to a 'seeding' of pelagic diatoms and an enhancement of the zooplankton production (Benkort et al. 2020).

Next steps are to i) run a fully couple simulation of the sea-ice algae model in the SCHISM-ECOSMO-E2E framework, ii) further calibrate and validate the 3D coupled model with available data from CAO projects and iii) perform long-term hindcast simulations and projections with IPCC scenarios.

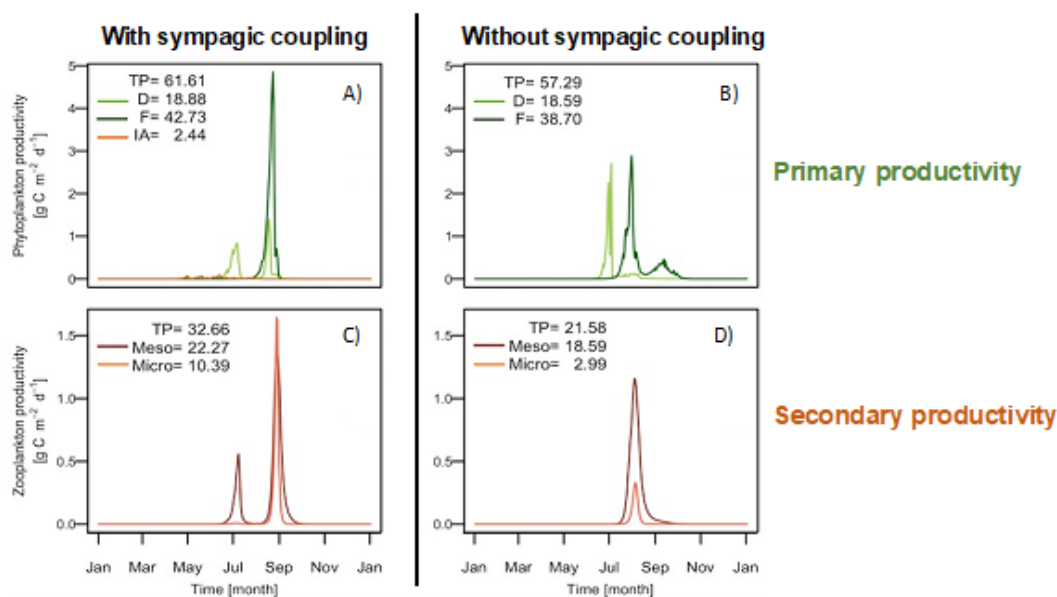


Figure 12: S imulated sympagic and pelagic primary and secondary productivity, for (A,C) experiment with sympagic system coupling, and for (B,D) experiment without sympagic system coupling. (A,B) primary production rates of ice-algae (IA: orange), diatoms (D: light green) and flagellates (F: dark green), (C,D) secondary production rates of mesozooplankton (Meso: dark red) and microzooplankton (Micro: orange). Modified from Benkort et al. 2020.

3.6.3 Effects of microplastics on pelagic productivity

Presented by Tineke Troost

Microplastics were shown to have negative impacts on individual algae or zooplankton organisms in experimental studies. Consequently, primary and secondary productivity may also be negatively affected. Here, we attempted to estimate the impacts on productivity at ecosystem level based on reported laboratory findings with a modelling approach, using our 3D biogeochemical model for the North Sea (Delft3D-GEM). Although the model predicted that microplastics do not affect the total primary or secondary production of the North Sea as a whole, the spatial patterns of secondary production were altered, showing local changes of $\pm 10\%$ (Figure 3.4). However, relevant field data on microplastics are scarce, and strong assumptions were required to include the plastic concentrations and their impacts under field conditions into the model. These assumptions reveal the main knowledge gaps that have to be resolved to improve the first estimate above (Troost et al. 2018). Next steps are to improve and/or validate modelled plastic distribution and zooplankton biomass and productivities, to calibrate the relation between plastic concentrations and impacts, to quantify impacts through toxicity (bioaccumulation) and to study population/community effects.

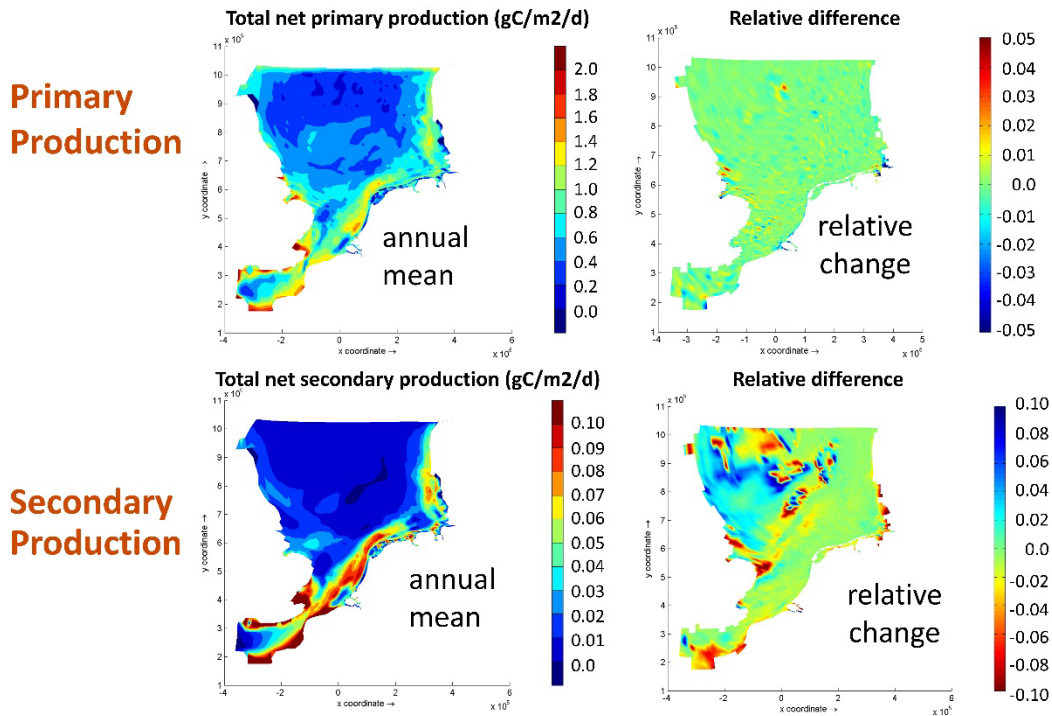


Figure 13: Impacts of microplastics on primary and secondary productivity in the North Sea. Modified from Troost et al. 2018.

3.6.4 Population dynamics of *Calanus finmarchicus* in the North Sea - a modelling study

Presented by Shuang Gao

Calanus finmarchicus is one of the key copepod species in the North Sea as they are the main food source for many fish stocks, such as herring, mackerel and cod. In this study, we use NORWECOM.e2e model with an IBM for *C. finmarchicus* to investigate the population dynamics in the North Sea (Gao et al. 2021). We have validated our model results against CPR data in one section across the northern North Sea. Both temporal and spatial patterns compare well between the model and observations. Our results show that the timing of reaching a certain biomass of *C. finmarchicus* in spring can vary by one month, which is important for some fish stocks recruitment. The interannual variability of the *C. finmarchicus* biomass is up to 30% of the total value. Inflow of *C. finmarchicus* entering the North Sea spans the whole northern opening (3°W-5°E) with varying depths depending on seasons and topography. The *C. finmarchicus* population in the North Sea is not self-sustained and relies on inflow from Faroe-Shetland Channel and the southern Norwegian Sea (Figure 3.5). Predation mortality in the North Sea in our model is parameterized the same as in the Norwegian Sea. This is likely an underestimate especially in winter, since the North Sea is on-average much shallower than the Norwegian Sea. Main knowledge gaps are missing parameter values in relation to predation mortality of *C. finmarchicus* in the North Sea and insufficient observational data to compare, especially in deeper water depths.

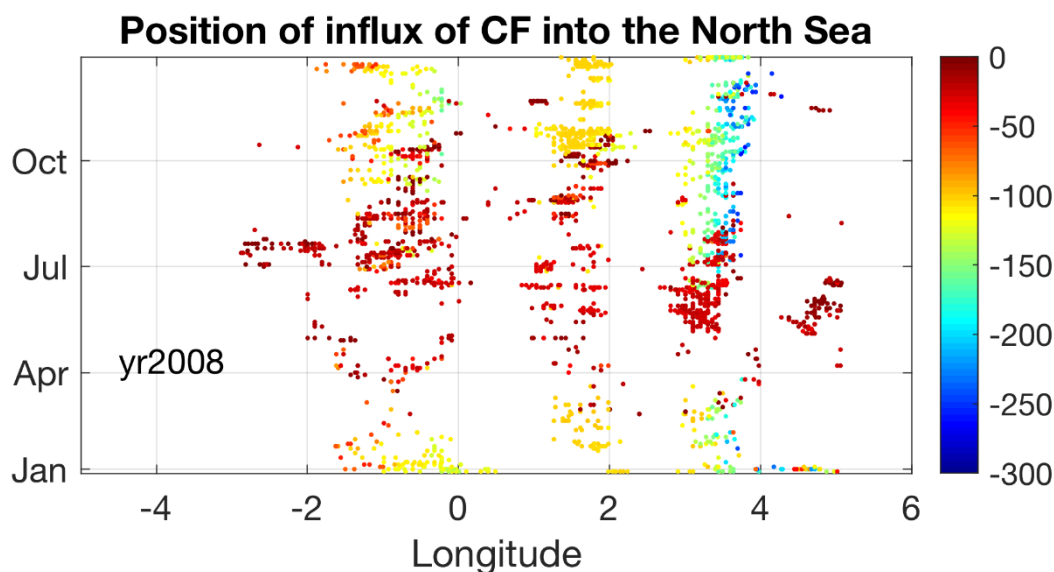


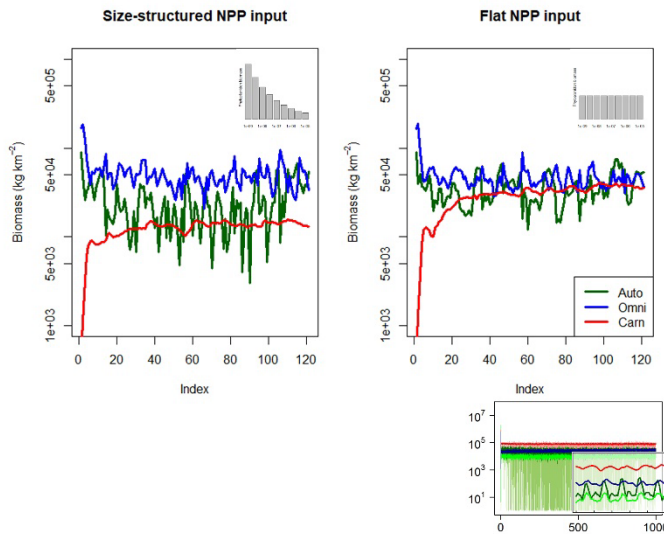
Figure 14: Influx patterns of *Calanus finmarchicus* into the North Sea for different months (y-axis), longitudes (x-axis) and depths (colour). Modified from Gao et al. 2021.

3.6.5 Adding a statistical phytoplankton community size structure to a mechanistic general ecosystem model to improve impact of LTL diversity

Presented by Erik Mousing

Pelagic phytoplankton size covers several orders of magnitude and the size distribution of biomass will affect at which trophic level the energy produced enters the food web (Andersen et al., 2015). Thus, systems dominated by large cells are thought to result in shorter food chains, that are able to sustain a larger biomass of higher trophic levels compared to systems dominated by small cells (Armengol et al., 2019). Despite of this, the representation of phytoplankton community structure in mechanistic ecosystem models are often very simple with only one or a few functional groups. In this study, we use the Madingley general ecosystem model (Harfoot et al., 2014) to explore the possibility of using empirically derived patterns of phytoplankton size structure to inform on phytoplankton size structure without explicitly modelling it. An empirical relationship between size structure vs temperature and nitrate was used to model the internal phytoplankton size structure of the NPP forcing field (REF). Using this relationship, we investigated the potential impact of changes in phytoplankton size structure on herbivory/predation rates, total biomass, and ecosystem size structure. The model showed that shifting the size structure towards larger phytoplankton classes resulted in a higher biomass of larger organisms. The size structure of non-planktonic taxa shifted towards smaller sizes, whereas the planktonic taxa did not appear to be impacted by phytoplankton size structure. The method shows great promise in including impacts of plankton size structure/diversity on the entire ecosystem while retaining a simple, computationally efficient, lower trophic level representation. For example, in models forced by offline fields (e.g. satellite derived NPP estimates). The parameters used to model phytoplankton size structure were estimated from large-scale patterns. To use this method at local/regional scale, parameter estimates from the investigated region is highly recommended.

Biomass



Effect of size structure:

Carnivore biomass decreases about 50 % (assimilation inefficiency -> less biomass reaching HTL)

Omnivore biomass increases about 10 % (decreased top-down control by carnivores)

Autotroph biomass decreases about 30 % (increased top-down control by herbi-/omnivores)

Compared to original with no size structure, new implementation has significantly less carnivore biomass in oligotrophic environment

Figure 15: Example of changes in biomass of autotrophs, omnivores and carnivores with a size structure included (left) and no size structure (right) of net primary production (NPP).

3.6.6 Flexible N:P-ratio in low complexity models

Presented by Diego Macias

The implementation a stoichiometric flexibility of phytoplankton in a low-complexity biogeochemical model was shown to enhance the reproducibility of eco-system dynamics without increasing the computational demand (Macias et al. 2019). The relative abundance of nitrate (N) over phosphate (P) measured as a molar ratio (N:P) is typically considered to determine the macronutrient limiting marine primary production. In low-complexity biogeochemical models, a simple threshold value is usually applied based on the canonical Redfield ratio (N:P=16). However, the N:P ratio is not constant in many oceanic areas, especially marginal, semi-enclosed seas, such as the Mediterranean basin. In this work, a flexible definition of the N:P ratio based on the capacity of phytoplankton to modulate phosphate uptake according to its availability in seawater, the so-called Line of Frugality, is incorporated into the biogeochemical model MedER-GOM. This modification allows the acquisition of a more realistic representation of the stoichiometry of nutrients in the Mediterranean basin and allows to better reproduce the observed phytoplankton biomass in productive areas such as the Gulf of Gabes and the Adriatic Sea. This approach is, thus, especially suitable for coastal areas in which basin-scale biogeochemical models fail to reproduce patterns observed by remote sensing or in situ measurements.

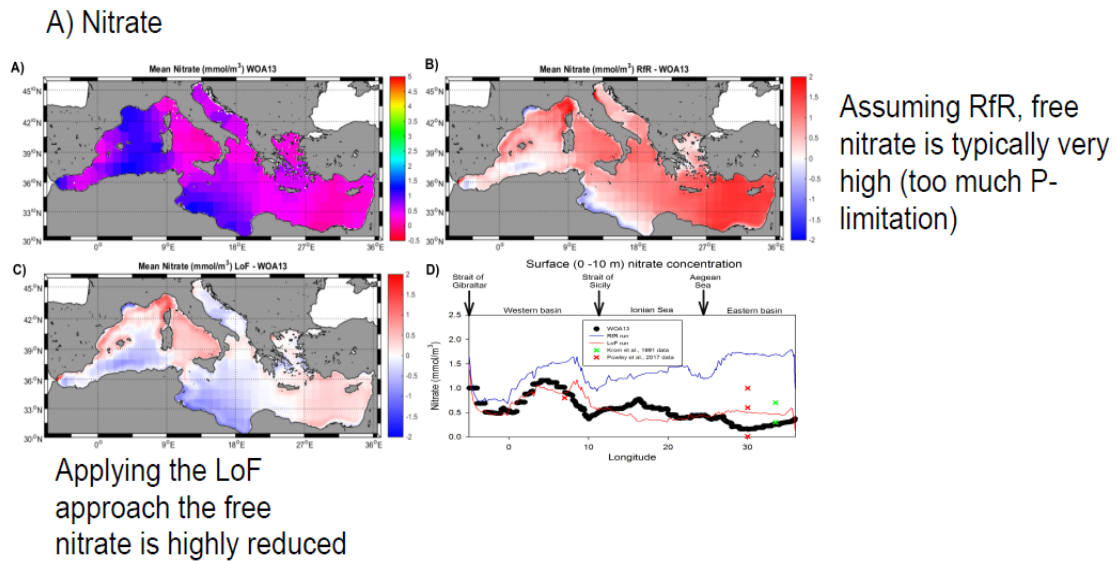


Figure 16: An example of the application of the Line of Frugality (LoF) concept in the Mediterranean Sea showing the obtained changes in nitrate concentrations. Modified from Macias et al. 2019.

3.6.7 Plankton functional type dependent carbon export algorithms in marine ecosystem models: A case study for the North Atlantic and the Arctic Ocean

Presented by Caglar Yumruktepe

We investigate efficient and generic algorithms to improve modelled carbon export variability in marine ecosystem models by emphasizing the influence of plankton community structure on the formation and properties of settling particles. We acknowledge that large-scale coupled models are complex and expensive to operate. Thus, in our approach we aim at minimizing the added complexity while better representing the observed carbon export variability in both temporal and spatial scales, ultimately, our implementations can be efficiently used in high resolution large-scale forecasting systems. We conducted tests on a 3D lower trophic level coupled physical model set in the North Atlantic and the Arctic Ocean, and each plankton community was allowed to modify the settling and remineralization rates of detritus based on their traits (i. e. diatoms produce fast sinking particles with higher remineralization rates, while particles from prokaryotes are slower with lower remineralization rates). Results indicate that a community-based scheme is superior in representing temporal and spatial changes in export and transfer efficiencies without any region-specific parameterization. As communities adapt to different hydrography, so does the regional export efficiency. Comparisons show that high latitudes, which sustain larger plankton, receive higher export efficiencies compared to both low latitudes and experiments using constant global rates, while the model effectively simulates slower export at lower latitudes. The model is also able to simulate seasonal patterns in export efficiency in agreement with the production of the dominant plankton functional types. We further evaluate the effects of changes in detritus distribution on the higher trophic levels, such as zooplankton and benthic organisms, that feed on detritus. Such an export mechanism has important implications in regional and global models, since hydrography is thus tightly coupled to particle export through community structure, which may improve predictive skills for future ocean communities and carbon export. Large uncertainty in particle sinking speeds resulting in large uncertainty in carbon export (Yumruktepe et al. 2020).

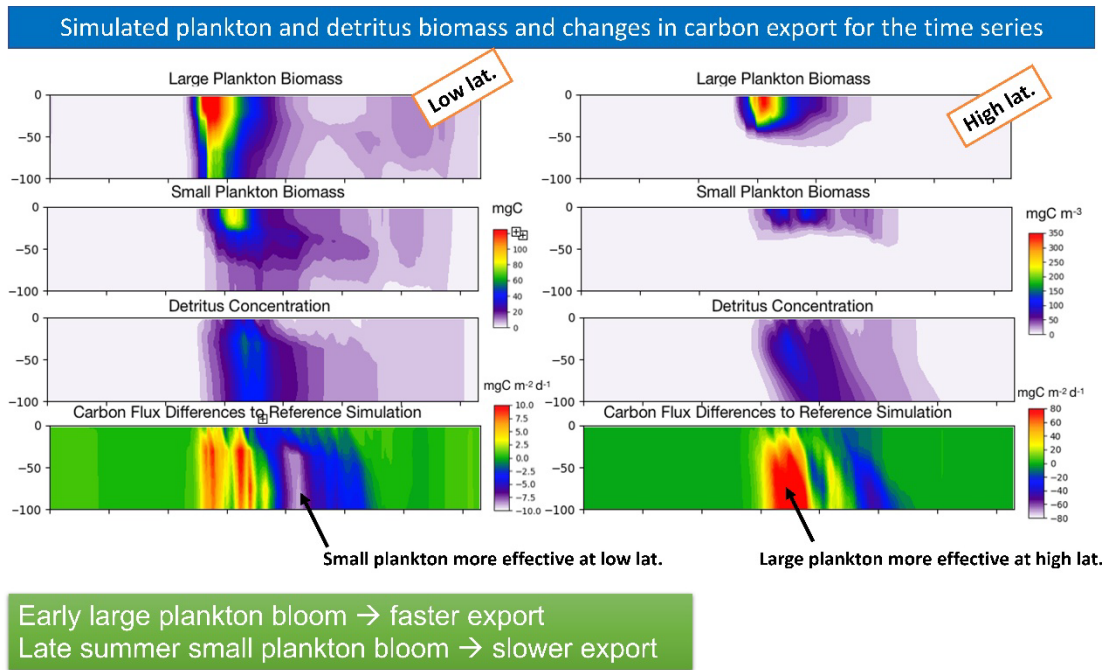


Figure 17: Simulated plankton and detritus biomass and changes in carbon export for the time-series at low latitude (left column) and high latitude (right column).

3.6.8 New deposit feeders dynamics in ERSEM-BFM: impact on bioturbation and benthic-pelagic exchange

Previous results of the ERSEM-BFM model (NIOZ-CEFAS) showed high concentrations of DIN in coastal zones and too low benthos biomass numbers in general. To improve model performance in shallow areas bioturbation and bio-irrigation were improved by including more complex deposit feeder dynamics. Previously an exponential profile of detritus within the bed was assumed, while bioturbation and bio-irrigation were linked via parameters to burrowing benthic functional group biomasses. As the most burrowing animal in shallow systems tends to be a funneling deposit feeder (e.g. Arenicola), these were included in more detail in the model. The new implementation keeps track of the number and length of young and adult funneling deposit feeders, while the larvae are simulated as a part of the near-surface deposit feeders still present in the model. With this information, the detritus profile within the sediment is calculated as the result of a set of 4 partial differential equations representing the different sediment layers (oxygen penetration depth, sulphide horizon depth and bioturbation depth divide these layers). Parameters in each layer are linked to bio-irrigation (linked to the number of funnels) and bioturbation (linked to averaged length of funnellers) in that layer. Bacterial dynamics were also improved to account more specifically for sulphide bacteria and their competition with denitrifying bacteria. First results with a water column set-up show a much higher variability of remineralization rates, leading to increased benthic-pelagic exchange, higher benthic biomasses and lower pelagic DIN values. A 3D implementation is in progress before a proper validation is carried out. It is expected that this extension of model complexity will improve model performance in shallow areas like the coastal North Sea and the Wadden Sea. We implemented specific dynamics of one benthic functional group of animals with the aim to improve benthic-pelagic nutrient exchange. General information was available for a few species representing this functional group (funneling deposit feeders), which was used in the implementation. Calibration data for benthic biomass of this functional group is present, but parameters like search volume, growth and uptake, and bioturbation impact are less well known, and is likely to be site-specific.

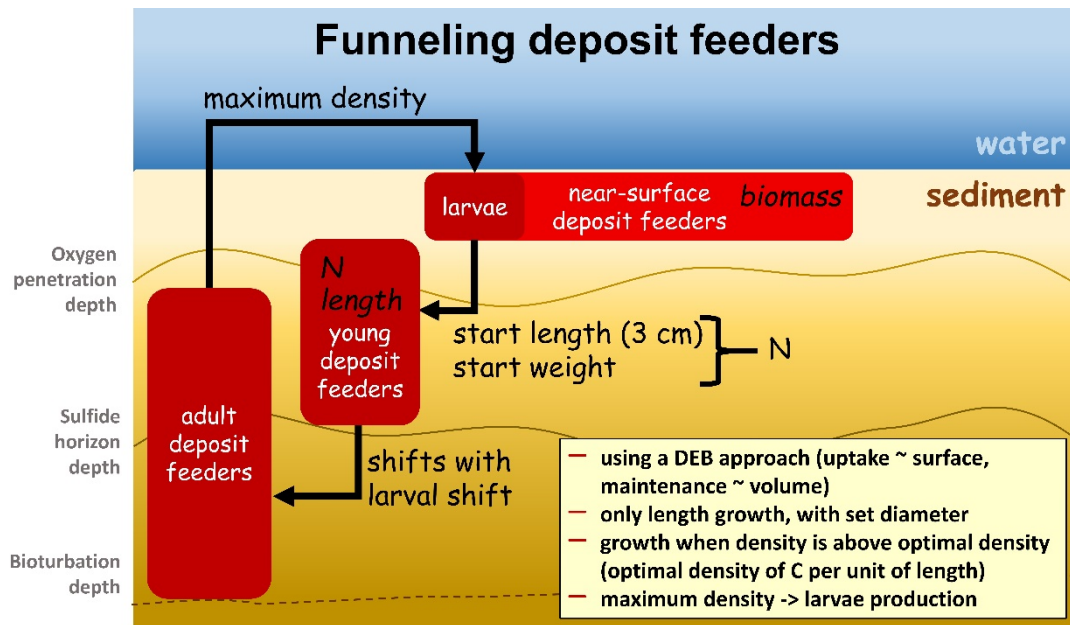


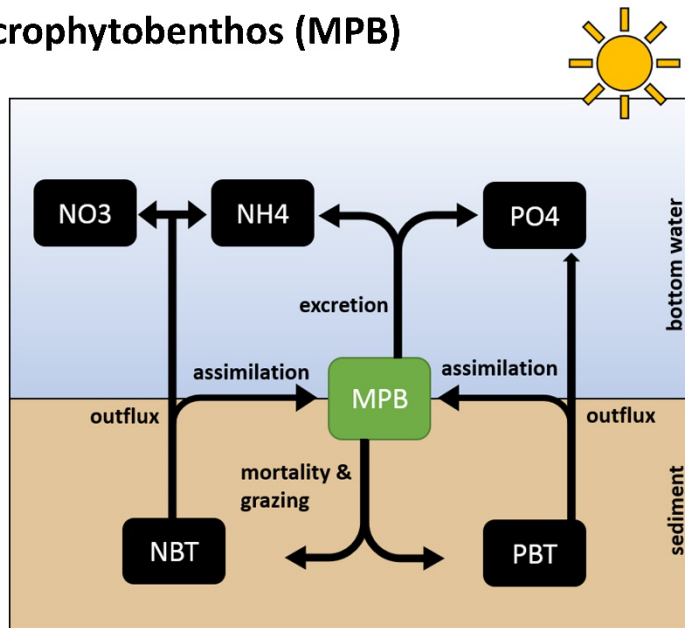
Figure 18: Schematic of new deposit feeder dynamics in ERSEM-BFM. Here N stands for the number of individuals in a given size class per life stage.

3.6.9 Implementing microphytobenthos into a biogeochemical model

Presented by Elin Almroth-Rosell

Microphytobenthos, bioirrigation and bioturbation were implemented in the biogeochemical model Swedish Ocean and Biogeochemical model, which is a part of the Swedish Coastal zone Model (SCM). Microphytobenthos was implemented as a new variable and animals living in and on the sediment was parameterized as bioirrigating and bioturbating functions. The basic growth pattern of microphytobenthos was captured by the model and their presence increased the sediment content, especially at shallower areas. Also, all sediment processes in the model increased, such as burial, denitrification, decomposition etc. Bioturbating and bioirrigating animals affect both biogeochemical processes and concentrations of nutrients in the sediment/water. The effect on the N and P dynamic were initially large, but on a longer time-scale the processes were not affected. There are generally too little benthic data on process rates and nutrient content. The gaps in both calibration data and validation data makes it hard to know if the model only gets only more complex or if it also gets better (Almroth-Rosell et al. 2016, Hoefsloot 2017).

Microphytobenthos (MPB)



$$\frac{\partial MPB}{dt} = Growth - Mortality - Grazing \quad (\text{Hoefsloot 2017, MSc thesis})$$

Figure 19: Concept of the microphytobenthos (MPB) model implemented into the SCOBi model. From Hoefsloot (2017).

3.6.10 Linking pelagic production and sea scallop energy requirement on the Northeast U.S. Shelf: A model-based assessment

Presented by Rubao Ji

Shelf seas often have tight pelagic-benthic coupling through the sinking export of water column production to the benthic zone over a small depth range. The amount of energy supply to benthic organisms is controlled by key processes such as the pelagic productivity and sedimentation/resuspension of organic matters. The latter involves bottom boundary layer dynamics and is critical for the coupling, but its importance is difficult to quantify. We use a 3-D coupled biological-physical model to assess the spatio-temporal variability of production exported from the water column to the bottom of the Northeast U.S. Shelf (NES), with a specific attention to the effect of bathymetry, mixing/stratification regime and phytoplankton size composition. We also evaluated the distribution and energy requirement of Atlantic sea scallop (*Placopecten magellanicus*), an important fishery species on the NES. The model shows that the available phytoplankton near the bottom is not sufficient to meet scallops energy requirement, especially on the outer shelf where the scallops often reach high abundance. Including detrital organic matter as an additional food source for scallops can only partly alleviate the energy deficiency if the model does not consider the vertical gradient of organic particles within the bottom layer. However, the energy balance can be mostly reached with an approximation of the vertical gradient based on the concept of Rouse profile: a concentration profile resulted from the balance of sedimentation and resuspension of particles (Ji et al. 2020).

SFG values when feeding on phytoplankton and detritus

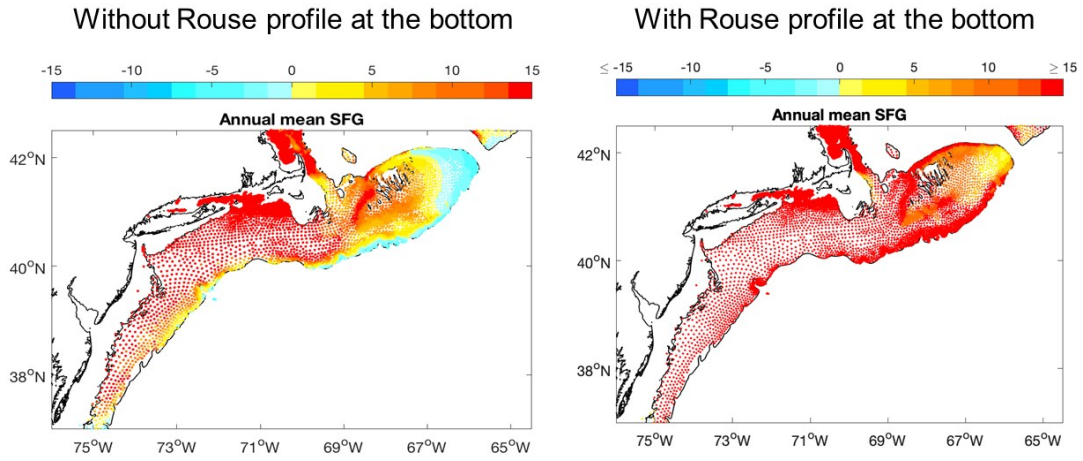


Figure 20: Scope-for-growth (SFG) without (left) and with Rouse profile (right) in the benthic boundary layer. A positive SFG value indicates positive net growth in that region, a negative value that bottom food is not sufficient to meet scallops energy requirement.

4 Improving higher trophic level models (ToR c)

4.1 Effect of connectivity, climate and habitat on emerging species distribution, to support management and fisheries

Several higher trophic level models include different aspects of connectivity, climate and key process formulations. For predictions of the future ocean, ongoing modelling studies are investigating ecosystem responses to a range of pressures (e.g. climate change, invasive species, fishery, eutrophication, aquaculture, microplastics, etc.) and how these combine (e.g. additively or synergistically) in different future scenarios. Connectivity is defined as the exchange of individuals among geographically distributed populations, connecting marine populations. Identifying whether a system can be considered a well-connected system, or features dispersal barriers limiting the transport of marine organisms, could have important implications for the regional and local community dynamics (e.g. recruitment processes). Climate effects on especially early life stages are important, and examples from sole in the North Sea (van de Wolfshaar et al., 2021), show how under warming climate conditions the early arrival of fish larvae in their nurseries results in larger young of the year fish at the end of summer, but with greater mortality for early arrivals due to the initially slow growth. Connectivity modelling can support management as demonstrated by Pastor et al (2021), where mussel larval distribution and connectivity within different subareas in the Limfjorden were studied by the Flexsem model. The study found the subareas to be well connected and thus provided a tool to support site-selection processes in aquaculture.

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4.2 Key process formulation (e.g. mortality, physiological rates)

To collect and incorporate new data and information into ecosystem models is vital to move ecosystem modelling forward, and a list of crucial unavailable data are identified and conveyed to WGBIOP for discussion and potential further progress. Exploration of some of the present

ecosystem models in use by WGIPEM members has identified key processes for spatial and temporal variability. For the Northern Humboldt Current System, it was concluded that input forcing from two different biogeochemical models produced a similar OSMOSE output. The time varying parameters larval mortality and fishing rate are the main drivers of interannual variability in this OSMOSE setup. Another study provides an example of how two functional groups for fish can represent changes in HTL productivity and thus provide mortality rates for LTL models. Choosing the predator to prey ratio to account for food availability and competition, it was shown how this temporal variable closure term can strongly impact the outcome of simulated LTL ecosystem dynamics. Key process formulations identified as important to better constrain the spatial and temporal variability are feeding parameters and preferences, larval mortality (recruitment), swimming speed, and underlying environmental gradients.

4.3 Movement algorithms

Despite the vital roles played by higher trophic levels fish predators, important traits such as migration are often not well represented in ecosystem models. Some progress has been made for herring and mackerel in the Norwegian Sea (Holmin et al., 2020). A food searching and temperature driven migration model (with seasonal cues for herring migration included) was developed and used to test the effectiveness of the current monitoring program and possible options to decrease the costs without loss of effectiveness. Results indicate that the program is efficient. This study demonstrates how improved HTL's can aid in process understanding and then ultimately support management. Recently, also a general mechanistic migration routine for mackerel has been implemented (Mousing et al., in prep). The algorithm is based on local gradient search in a suitability matrix calculated from temperature, prey availability, total mackerel biomass and size structure. In the study case, the increase in mackerel stock size is the primary factor leading to the recent observed spatial expansion (density-dependence). Despite the progress made, ecosystem modelling of HTL can be strengthened by better modelling of adaptive responses in marine organisms (Humston et al 2004), and comparisons of different movement algorithms in a variety of HTL models, how they affect model results, interact in multispecies models or can efficiently be upscaled into functional group type models is still lacking.

4.4 Knowledge gaps

Regarding ToR c the most important knowledge gaps identified were:

- Fish migration depends on two main processes: reactive and predictive processes. Reactive processes are when fish react to cues in their environment such as food availability. However, very little is known of the predictive capabilities of fish (i.e. the ability to predict where to migrate without environmental cues). These processes could be dependent on genetics, memory, schooling behaviour etc., and a better understanding of both processes and parameters is needed
- Methods to constrain the mortality in HTL models
- Impact of predator avoidance behaviour. For example, is predator avoidance only a local response (e.g. schooling or flight) or does fish avoid water masses with a high density of predators based on sensory input such as smell?
- Effect of intra- and interspecific competition on movement behaviour. For example, how and when does fish avoid areas with a high density of competing individuals (same species or competing species)?

4.5 Publications

The MEPS special issue includes several manuscripts that fall under this ToR. These are currently under review.

Pastor, A., J. Larsen, A. Simon, N. Bierne & M. Maar. 2021. Agent-based modelling and genetics reveal the Limfjorden as a well-connected system for mussel larvae. *Marine Ecology Progress Series* in press

4.6 Science highlights

Highlights under ToR c include:

- Climate warming effects on sole early nursery arrivals include larger young-of-the-year size but greater mortality.
- Top-down effects in an end-to-end model alter the LTL results even down to nutrient dynamics. For better constraint of these effects HTL parameters such as feeding preferences, recruitment and swimming speed need to be refined, requiring knowledge of such characteristics of non-commercial species.
- An advanced migration model was used to show that a current monitoring programme for the two species involved (spring-spawning herring and Atlantic mackerel) was efficient, illustrating the importance of using models for management. It also highlighted that survey timing and direction can influence survey results, and that fisheries data should be used with caution as a basis for survey design.

4.7 Abstracts

4.7.1 The fate of juvenile fish growth and survival under climate conditions; preliminary results

Presented by Karen van de Wolfshaar

Many species have an obligatory early life stage in coastal, shallow nurseries, often starting their coastal stay from post-larval stages (BROWN). Especially flat fish rely on the shallow coastal nurseries early in life, and they will be influenced by changes in temperature. Despite the strong dependence on coastal areas as nurseries there are not many studies yet considering climatic effects at nursery level (but see Teal et al). In van de Wolfshaar et al (2021) we studied the fate of YOY sole after settlement, for three scenarios (base, climate and climate with advanced spawning), 6 North Sea nurseries and 9 years. Under climate conditions and advanced spawning the early arrival of fish larvae in their nurseries results in larger young of the year at the end of summer, but the initially slow growth, despite warmer winter and spring temperatures, causes greater mortality for early arrivals. The combination of arrival densities at arrival day determines which nursery has the highest absolute numbers surviving. Despite the differences in sizes and survival the overall effect on biomass produced at the end of summer varies between nurseries, years and scenarios.

4.7.2 Modelling mussel larval distribution for optimal site selections of mussel farming

Presented by Ane Pastor

Fishery of blue mussels constitutes a very important economic activity in Denmark, whereas mussel farming on longlines or nets is a new, growing sector. Spawning from natural mussel beds takes place during early summer, and larvae are spread by the water currents before settling on the bottom or on spat collectors in the farms. In the present study, we coupled a 3D physical model system (FlexSem) with an agent-based model in order to examine the connectivity of this marine system in terms of mussel larval dispersal and settling potential. To address this question we (1) estimated the dispersal and connectivity between 17 areas in the Limfjorden, (2) identified the main donor and receiver areas of mussel larvae, and (3) identified possible dispersal barriers. The results show that the central narrow strait in the Limfjorden is the main donor area in all the studied years, and that the eastern areas adjacent to these are the main receiver areas. As we move towards the inner basins of the Limfjorden, the isolation increases and limited connectivity is observed. The results from the cluster analysis groups the Limfjorden into 3 to 5 clusters, but there is still some exchange of simulated larvae observed among these clusters. Analysis of molecular markers reveals no genetic differentiation between areas and supports the model results, indicating that despite distinguishable hydrographic boundaries, the mussel populations in the Limfjorden are well connected. This study demonstrates how connectivity modelling can be used to support site selection processes in aquaculture (Pastor et al. 2021).

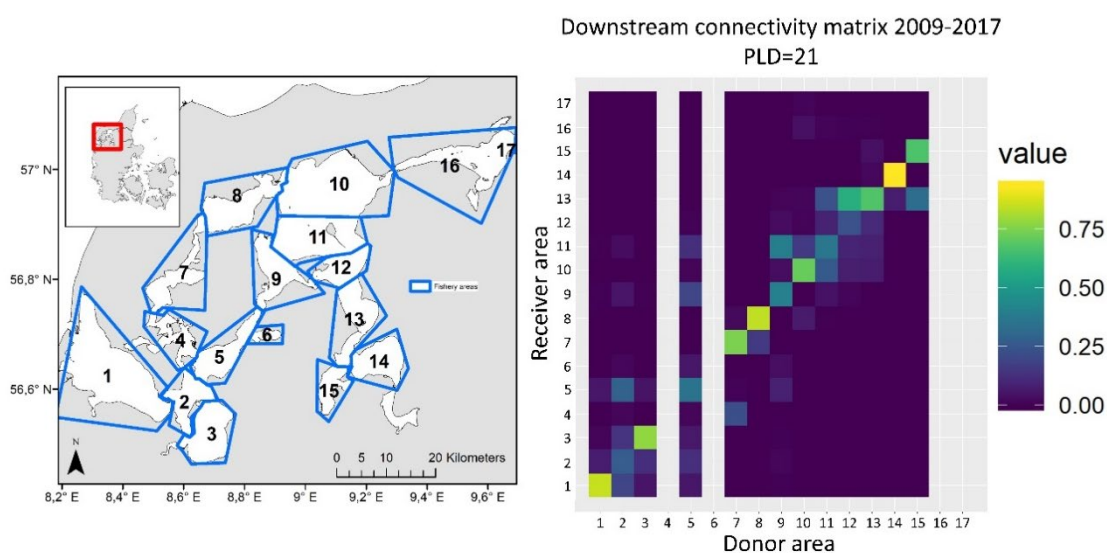


Figure 21; Connectivity matrix of mussel larvae in the Limfjorden divided into 17 subareas, where subarea 5 was the main donor area and subarea 13 was the main receiver area of mussel larvae. See final results in Pastor et al. 2021.

4.7.3 Calibration of the OSMOSE configuration for the Northern Humboldt Current System

Presented by Mariana Hill-Cruz

The OSMOSE model was coupled with the physical-biogeochemical model CROCO-BioEBUS and applied to the Northern Humboldt Current System (NHCS). Our starting point was the NHCS configuration of OSMOSE that was one-way coupled with the physical-biogeochemical model ROMS-PISCES and interannually calibrated by Oliveros-Ramos et al (2017), using time-varying larval mortality, plankton accessibility coefficient and fishing rate. OSMOSE has 9 species/groups: anchovy, sardine, hake, Jack mackerel, chub mackerel, mesopelagic fish, squat lobster, Humboldt squid and euphausiids. In our model configuration, as fish feed, we used large and small phyto- and zooplankton from CROCO-BioEBUS. A series of calibration experiments

revealed that an adjustment of constant plankton accessibility coefficient, maximum growth factor and adult natural mortality improved the fit of the model to observations. On the other hand, adjusting a constant larval mortality and fishing rate, which were varying in time in the original configuration, generally muted the interannual variability and generated the collapse of some species. Calibrating a time varying larval mortality produced a model with a very good fit of fish biomass; however, such model had a different pattern of larval mortality than the original configuration. The main conclusion is that the time varying parameters in the OSMOSE NHCS are the main drivers of the temporal variability in the model. On the other hand, the averaged fish biomasses are mainly controlled by the plankton food input and by the constant parameters of the model. The results of this study suggest that this OSMOSE version is unable to mechanistically simulate the ecosystem shift after El-Niño event of 1998 without adjusting time-varying parameters. Further work is required on ways to constrain the larval mortality in OSMOSE. An alternative could be to link larval mortality to certain environmental variables. This may allow the model to simulate more efficiently the strong interannual variability of the HHCS in a mechanistic way. In the next stage of the project, a calibrated configuration will be applied to evaluate the model response, and the potential ecosystem response, to increased fishing pressure. It may also be coupled in a two-way fashion to CROCO-BioEBUS to explore the two-way bottom-up and top-down interactions between biogeochemistry, including plankton, and the organisms modelled by OSMOSE.

4.7.4 Lower trophic level ecosystem response to change in higher trophic level production: a modelling study in the Northern Atlantic/Arctic ocean

Presented by Ute Daewel

Here we implement a functional group type ecosystem model HYCOM-ECOSMO E2E for the North Atlantic/Arctic ecosystem with the aim to understand the feedback mechanisms between lower (LTL) and higher trophic level (HTL) production on multiyear time-scales. The advantage of the model is that fish and macrobenthos are implemented generalized and consistently into the NPZD type model ECOSMO, however, at the expense of trophic complexity. Here, we specifically explore the role of migration strategies for changes in higher trophic level production and compare those to findings from more specialized fish models available in the literature. Fish migrates based on environmental gradients. Here we chose the predator to prey ratio to account for food availability and competition. This spatio-temporal variable closure term strongly impacts the outcome of simulated LTL ecosystem dynamics both in space and time. It also alters the ratio between small and large zooplankton, and induces a top-down effect chain (compared to the reference simulation without fish) that even changes the nutrient dynamics and seem to improve the seasonality in simulated nutrient concentrations in the Norwegian Sea area. Key process formulations identified as important to better constrain the spatial and temporal variability are feeding parameters and preferences, larval mortality (recruitment), swimming speed, and underlying environmental gradients.

4.7.5 Modelling fish migration to evaluate survey strategies using an end-to-end ecosystem model

Presented by Erik Askov Mousing

Fish stock assessments are dependent on scientific surveys and a large amount of resources are spent every year to ensure good estimates. An important part of these surveys is the survey design which is planned prior to the survey, usually based on expert knowledge. In Holmin et al (2020) we have investigated the possibility of simulating survey cruises by coupling the stock assessment software StoX to the end-to-end ecosystem model NORWECOM.E2E. IBM modules for Norwegian spring-spawning herring and Atlantic mackerel were used to simulate stock dynamics and distributions in the Nordic seas for 2010 and 2012. Several different survey strategies were then simulated based around the 2012 IESNS, IESSNS and NASSHS surveys. In addition, data from the commercial fishing fleet was incorporated and used to redistribute effort in order to assess the potential added knowledge from the fisheries. Output from NORWECOM.E2E was converted to resemble acoustic and trawl survey and input into StoX to estimate fish biomass. The results showed that in general, the survey designs used in 2012 led to estimates close to the real biomass. Some simulations showed sensitivity to survey timing and direction. Reallocation of survey effort based on fisheries data generally led to an underestimation of total fish biomass and should be used with caution. We conclude that the results are proof-of-concept that ecosystems models are a good tool to test potential survey designs and can serve as a new planning tool for fisheries management.

4.7.6 Hypotheses and mechanisms related to mackerel migration

Presented by Erik Askov Mousing

The summer feeding distribution of Northeast Atlantic mackerel has expanded northwards and westwards in recent years. Several hypotheses have been presented to explain this expansion including increasing temperature, changes in prey distributions and an increase in the spawning stock biomass. Mousing et al (in prep) test these hypotheses using an individual based model (IBM) for adult mackerel. The distribution of mackerel was simulated for the years 2011-2016, forced by a high-resolution physical circulation model. Mesozooplankton biomass and production fields were generated from the same physical forcing using the NORWECOM.E2E model, and quasi two-way coupled to the IBM. A new, habitat suitability based, migration routine was developed where the mackerel follow horizontal gradients in the environment considering temperature and prey availability. Simulated distributions were compared to observed distributions from the IESSNS survey. It was found that the observed distribution is more northern than the modelled but, but a general mechanistic migration routine based on local gradient search can “to some extent” lead to the observed pattern. Random search cannot lead to observed large-scale patterns, changes in size structure, temperature and mesozooplankton modify the distribution, while the increase in stock size is the primary factor leading to the expansion (density-dependence).

5 Assessment of model skill evaluation methods (ToR d)

5.1 Comparison of existing “guidelines” and metrics of skill assessment using existing examples and applying these methods to models used by the group to conclude on the feasibility of the currently existing approaches and identifying possible weakness

To make marine ecosystem models more relevant to management and policy, transparency about model limitations and uncertainties is necessary. However, standardized protocols and metrics are still under development within ecosystem modelling, and a reflection on how to objectively select the criteria (metrics and outputs) to consider when assessing model skill is crucial and must be conducted in relation with the model purpose. WGIPEM group members have been active in developing several different model skill evaluation methods and practical techniques and guidelines for verifying and validating simulation models. For coastal ocean models, a quality assessment metrics developed within the FORCOAST project is available. Very relevant to ecosystem models, Planque et al (2020) provides a first version of a standardized protocol for ecosystem model evaluation (the OPE-protocol). The OPE protocol provides a set of guidelines for reporting model evaluation, which helps ecological modellers in performing comprehensive model evaluations that are concerned with predefined ecological patterns and oriented towards specific objectives. The application of the OPE protocol on several case studies is required to test it and eventually improve it, through a learning-by-doing approach. Another approach is the key run procedure as developed by WGSAM (presented by shared member Sigrid Lehuta), illustrated with the case of the Ecopath with Ecosim model of the Irish Sea. Key runs are standardized simulations and output reviewed along established review criteria and agreed among members of WGSAM. Keyruns can serve as quality-assured inputs for ICES advice (e.g. natural mortality estimates in single species assessment models).

Two examples show how biological questions can be elucidated based on model simulations. Firstly, Lehuta et al (2020) uses three alternative formulations of the ISIS-Fish model for sole in the eastern English channel representing three alternative stock structures, The study demonstrate the existence of three populations in the eastern English channel. Secondly, Hansen et al (in press) simulate several different cruise designs to assess different monitoring strategies for a set of ecological indicators as defined in the Norwegian Barents Sea management plan. Hansen et al (in press) concludes that the inter annual variability of these indicators is very sensitive to the cruise design (time and space), but that good monitoring programs can be designed based on virtual samplings in models.

5.2 Investigating uncertainty analysis (structural, parameters, scenarios) including model ensemble

Evaluated and reduced uncertainty in marine ecosystem models will strengthen the modelling capability. Piroddi et al (2021) and Friedland et al (2021) demonstrate the added value of using a model ensemble instead of a single model to study the potential impacts of riverine input

reductions. The method is illustrated by two Pan-European, multi-model assessments in support of the Marine Strategy Framework Directive. There was a high gain of following an ensemble approach, as the robustness and reliability of the derived model results were increased, but the number of participating model systems should be increased wherever possible. The WGIPEM group members were invited to join with their models. Another example of the strength of ensemble modelling is shown by Spence et al (2018), who using an ensemble modelling approach that synthesizes numerous modelling and empirical studies, are able to predict, with quantifiable uncertainty, how multiple indicators will respond to multiple fisheries management strategies in the North Sea. This approach is also used on a synthesis of empirical and model predictions of past and future primary production in the North Sea. An example of Management Strategy Evaluation is shown in Hollymann et al (2021), using the Norwegian and Barents seas Atlantis model. The trade-offs of selected management procedures were evaluated while assessing the impacts of uncertainties for achieving management goals.

Model-observation comparisons are often restricted by both data availability and unknown representation errors. Synergy between validation procedures and assimilation is a field that could be further explored, as assigning uncertainties to different kinds of observations is an issue when setting up assimilation system. Two examples of recent application where parameters and the model state were jointly estimated by assimilating remotely sensed chlorophyll and nutrients from in situ observations had good results with respect to obtaining improved parameters.

Representation errors in both models and observations are discussed in a recent joint WGIPEM paper (Skogen et al 2021), concluding that using models and observations generates synergy and allows us to support science better and thereby increase our knowledge and understanding of marine ecosystems to disclose the truth. A subgroup with the working title « Representativeness/ what Observations do Modellers need? » was formed to work on a continuation of this paper.

5.3 Publications

Skogen, M.D., Ji, R., Akimova, A., Daewel, U., Hansen, C., Hjøllø, S.S., van Leeuwen, S.M., Maar, M., Macias, D., Mousing, E.A., Almroth-Rosell, E., Saille, S.F., Spence, M.A., Troost, T., van de Wolfshaar, K. (2021) *Disclosing the truth: are models better than observations?*, Marine Ecology Progress Series, DOI: 10.3354/meps13574

5.4 Scientific highlights

Highlights under ToR d include:

- First version of OPE presented, a standardized protocol for ecosystem model evaluation.
- An ISIS-Fish study supports the existence of three populations of sole in the eastern English channel, which were previously thought to be (and managed as) one population.
- Inter annual variability of indicators is very sensitive to cruise design (time and space), but good monitoring programs can be designed based on virtual samplings in models.
- Models and observations are both a necessary part of the evidence base for marine management, and should not be seen as mutually exclusive. If a model does not correspond to observations it mainly says something about the ecosystem state on different spatial and temporal scales, rather than being an indication one of them is wrong.

5.5 Abstracts

5.5.1 Assessment of ocean model performance within H2020 FORCOAST project

Presented by Diego Pereiro

In this work, standard or common methods are provided to validate the FORCOAST coastal models, indicating which procedures should be followed for different ocean platforms. This is important in the context of a project like FORCOAST aimed at producing services to end-users, which makes it necessary to provide stakeholders with an unambiguous measure of how reliable the new services are. Different quality assessment metrics are proposed: Mean Error (ME), Root Mean Square Error (RMSE), Correlation Coefficient (CORR), Adjusted Relative Mean Absolute Error (ARMAE) and Receiver Operating Characteristic (ROC) curve. Then, methods to be followed for hindcast, forecast and process-oriented validation are specified as well. Assessment of coastal model performance following the standards described in this deliverable will result in the production of a final coordinated pilot model evaluation report within FORCOAST.

Performance	Range of ARMAE
Excellent	< 0.2
Good	0.2 – 0.4
Reasonable	0.4 – 0.7
Poor	0.7 – 1.0
Bad	> 1.0

Figure 22: Using ARMAE number to provide an objective assessment of the model performance.

5.5.2 A standard protocol for describing the evaluation of ecological models

Presented by Benjamin Planque

In Planque et al (2020), we aim to provide support for modellers so that they can report model evaluation in a transparent, comprehensive and standardized manner. We have developed a standardized protocol organized around 3 blocks: Objectives, Patterns and Evaluation (OPE). Each block is decomposed into a set of questions (total 26) that guide modellers through the reporting of their model evaluation. The protocol is generally applicable to all (simulation) models, species and ecosystems. The protocol has a non-prescriptive approach: it doesn't tell what to do, but explain what to report. The goal is to make model performance evaluation transparent to end-users, but also to guide the researcher in improving the model, by reporting how the model has improved. The application of the OPE protocol on several case studies is required to test it and eventually improve it, through a learning-by-doing approach.

Overview	Objective(s) of the model application
	Specific model setup
Patterns	Ecological patterns
Evaluation	Data used for evaluation
	Evaluation methodology
	Sensitivities

Figure 24: The three main blocks of the OPE protocol and the corresponding main groups of questions that guide the reporting on model evaluation.

5.5.3 Disclosing the truth: Are models better than observations?

Presented by Morten Skogen

Skogen et al (2021) discuss representation errors in both models and observations. The aphorism, ‘All models are wrong, but some models are useful’, originally referred to statistical models, but is now used for scientific models in general. When presenting results from a marine simulation model, this statement effectively stops discussions about the quality of the model, as there is always another observation to mismatch, and thereby another confirmation why the model cannot be trusted. It is common that observations are less challenged and are often viewed as a ‘gold standard’ for judging models, whereas proper interpretations and the true value of models are often overlooked. Models are not perfect, and there are many examples where models are used improperly to provide misleading answers with great confidence, but to what extent does an observation represent the truth? (see figure). The precision of the observational gear may be high, but what about representativeness? The interpretation of observations is simply another model, but this time not coded in a computer language but rather formed by the individual observer. We submit that it would be more productive to initiate a process where the norm is that models and observations are joined to strengthen both. In the end, neither method is the goal, but both are useful tools for disclosing the truth. Biased views on either observational or modelling approaches would limit us from achieving this goal.

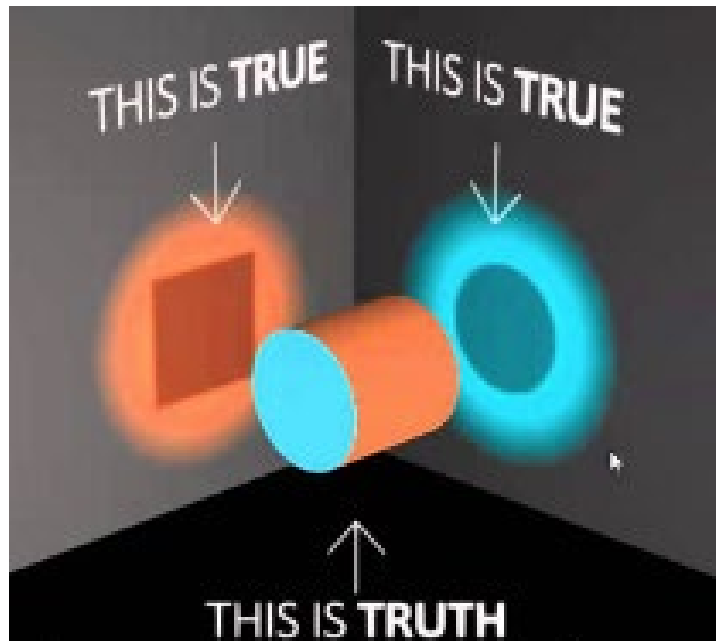


Figure 25: Truth depends on the eye that sees. Source: <https://medium.com/the-ascent/it-can-all-be-true-e59bacf132b8>.

5.5.4 Exploring the impacts of uncertainty on model results: an exercise conducting simulations for Management Strategy Evaluation with an Atlantis model of the Norwegian and Barents Seas

Presented by Holly Perryman

Management Strategy Evaluation (MSE) is a process that uses simulation models to evaluate the trade-offs of candidate management procedures while assessing the impacts of uncertainties for achieving management goals. Simulations for MSE have traditionally been under a single-species context but conducting simulations for MSE under an ecosystem-based context (i.e. using marine ecosystem models to conduct simulations) will likely become more frequent over time to support Ecosystem-Based Management (EBM). Ecosystem-based simulations for MSE should include scenarios for assessing the impacts of key model uncertainties. Things to keep in mind moving forward with ecosystem-based simulations for MSE should include i) key uncertainties and errors of the ecosystem-based simulation models, ii) scenarios for exploring the impacts of these key uncertainties and errors, and iii) metrics for evaluating the performance of the utilized model – in addition to metrics for evaluating the performance of the candidate management procedures.

5.5.5 Predicting management effects on ecosystem indicators

Presented by Michael Spence

Adaptive management of marine fisheries within the Ecosystem Approach requires information about how indicators of good environmental status will respond to fishing, both now and into the future. Ecosystem models are frequently used to gain this information, however despite sharing a common objective, to project the effect of different management strategies on ecosystem dynamics, these models often produce differing results. Such differences make any decision

sensitive to the choice of model, leading to diminished confidence and a restricted uptake of ecosystem models at the management-level. In Spence et al (2018), we overcome this issue, using an ensemble modelling approach that synthesizes numerous modelling and empirical studies, to predict, with quantifiable uncertainty, how multiple indicators will respond to multiple fisheries management strategies in the North Sea. Specifically, we predict continued improvement of fish communities, with indicators of size-structure and absolute demersal biomass demonstrating healthy recovery rates. These trends are consistent across all fishing scenarios considered, with indicator values peaking under no fishing and recovery rates under MSY and NASH equilibrium being comparable. We are more uncertain about recovery in lower (zooplankton biomass) and higher (biomass of birds and mammals) trophic levels. This uncertainty highlights how deficient current ecosystem models are in resolving these ecological components and provides a clear avenue for future work. This work demonstrates how we can integrate information from a range of studies, both empirical and modelling, to support the Ecosystem Approach to management and inform on the use of fishing strategies to meet environmental objectives and fisheries goals.

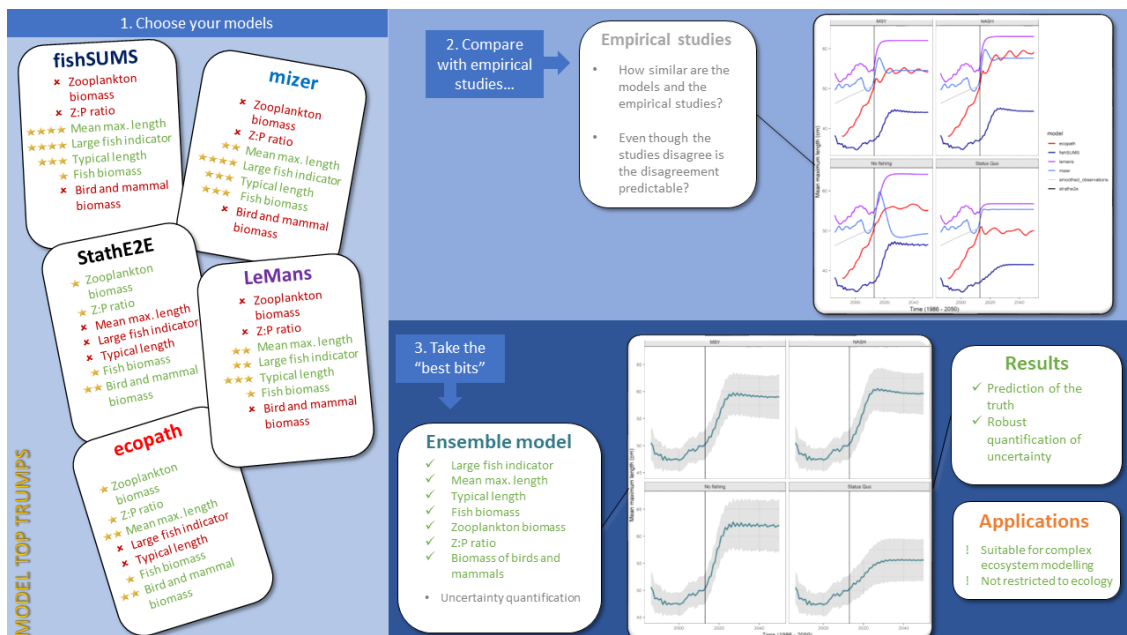


Figure 26. Flow diagram.

5.5.6 Synthesising empirical and modelling studies of predictions of past and future primary production in the North Sea

Presented by Michael Spence

IPCC models are able to describe future primary production in the North Sea, but there exist also empirical studies. A synthesis of all the information can be performed, but based on the evidence it cannot be stated what will happen to primary production in future (lower or higher than at present). Spence et al (2018) have developed a framework (figure) which allows models fitted to different data and describing the system in different ways to be combined. The framework does not assume one of the simulators is 'correct', it is robust to the addition of new simulators and maximizes information from simulators.

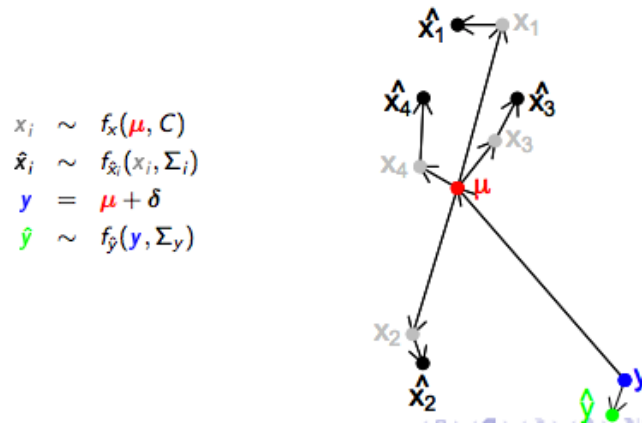


Figure 27. A schematic that shows an example of the ensemble model at time t . In this example, we have four simulators that are all able to predict the elements of $y(t)$.

5.5.7 Effects of nutrient management scenarios on the marine environment – two Pan-European, multi-model assessments in support of the Marine Strategy Framework Directive

Presented by Rene Friedman

The potential impacts of riverine input reductions on the lower trophic levels (dissolved nutrients and phytoplankton) and the higher trophic levels, and how these are related to selected eutrophication and food web indicators used by the MSFD, are explored by a multi-model assessment in Friedland et al (2021) and Piroddi et al (2021). The LTL models provided the change of primary production to the HTL ensemble. In all European waters eutrophication indicators showed an improvement, although the intensities and reaction speeds differed between the regions, e.g. in the Baltic Sea only small changes near the river mouths were achieved, while in the North Sea strong and fast decreases in dissolved nutrients and chlorophyll-a got visible. There was a high gain of following an ensemble approach, as the robustness and reliability of the derived model results were increased. However, the studies identified several knowledge gaps: A critical number of ensemble members is needed to gain robust results, and there is a strong need for model systems, which cover several connected MSFD regions. It seems necessary to apply an analogue ensemble approach also on land, e.g. by applying more than 1 catchment model.

5.5.8 Eliciting population spatial structure through calibration and validation?

Presented by Sigrid Lehuta

Sole is one of the most valuable commercial species in the Eastern Channel. Evidences are accumulating to suggest that there is little connectivity between three areas of the channel either at early or adult stages. However, the population is still managed as a single stock with possible risks of overexploitation of one component. Improving the knowledge on population spatial structure and assessing the consequences of ignoring it in management is therefore crucial to its sustainability. As an example of how we can elucidate biological questions using mechanistic inference based on model skill assessment, 3 alternative formulations of the ISIS-Fish model for sole in the eastern English Channel, were set up. The formulations ranged from a unique stock

to three independent populations and an in-between situation with an intermediate level of exchanges of adult fish between zones. The goal was to calibrate and validate all three models and assess if one is more plausible with regard to the data. The main conclusion was that most of the variables and skill metrics converged to demonstrate that data support the existence of three populations in the eastern English Channel (Figure). The study proves the interest of model skill evaluation methods to highlight model (and data) strength and weaknesses and reflect on the limits of our understanding of system functioning. It shows how it can serve hypotheses testing beyond model evaluation but warns about complementarity/redundancy of observations and metrics.

5.5.9 Evaluation of ecological indicators. Best practice to observe

Presented by Morten Skogen

A set of ecological indicators is proposed for the Norwegian Barents Sea management plan. An ecosystem model, NORWECOM.E2E, is used to simulate several of these forced by a physical downscaling of a global climate model (NORESM) for the period 2006-2070. Several different cruise designs are simulated to assess different monitoring strategies for monitoring of these indicators. Hansen et al (in press) concludes that the inter annual variability of these indicators is very sensitive to the cruise design (time and space), but that good monitoring programs can be designed based on virtual samplings in models. An example of identifying where and when is optimal for monitoring, given limited resources to estimate these indices from observations are shown in the figure below.

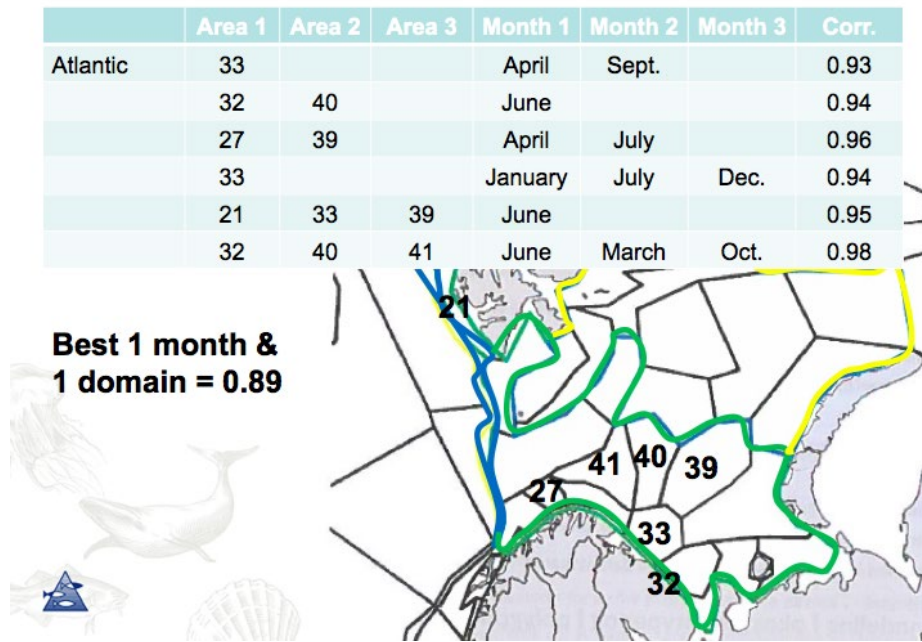


Figure 28: Best results from two and three polygon monitoring programs for temperature in the Atlantic region of the Barents Sea from the NORWECOM.E2E model.

5.5.10 Parameter estimation in a lower-trophic level model by ensemble-based data assimilation

Presented by Annette Samuelsen

In the context of operational oceanography and with the purpose of producing forecast and reanalysis of lower trophic levels, we have tested different approaches for estimating both state and parameters in our coupled physical biogeochemical model. The main assimilation method is the ensemble Kalman filter, and the work ranges from twin experiments to production of a biogeochemical reanalysis. Two examples of recent application where parameters and the model state were jointly estimated by assimilating remotely sensed chlorophyll and nutrients from in situ observations were presented. One example is a 4-year reanalysis where parameters were allowed to vary both in space and time (Simon et al., 2015). Improved states were obtained, but it was found that in certain regions parameters estimates are outside what is considered biologically reasonable. The parameter estimation could also not compensate for errors coming from the physics. The second example is a tuning of a 1D model at station M in the Norwegian Sea (Gharanti et al., 2017). This study was primarily to test different assimilation methods and whether assimilation of nutrient observation can help correct the model state. This study had good results with respect to obtaining improved parameters. Currently a new reanalysis is under production applying our experiences from the two studies presented above. Assigning uncertainties to different kinds of observations is an issue for setting up the assimilation system, it is also very relevant when doing validation.

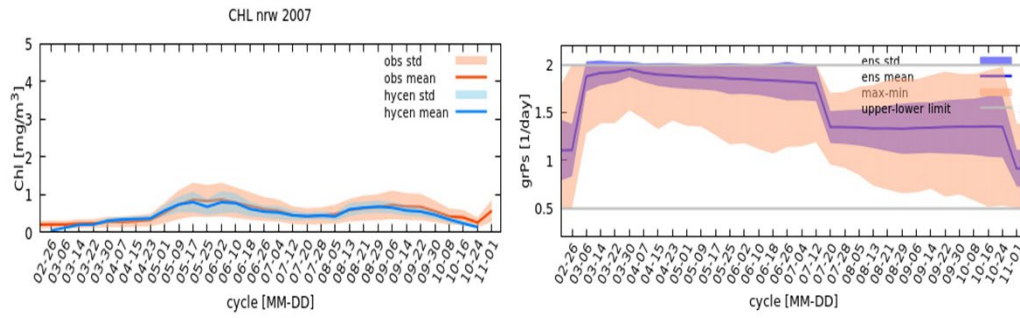


Figure 29: Results from the Norwegian Sea from the latest biogeochemical reanalysis assimilating both chlorophyll from satellite and in-situ nutrients. Left: Chlorophyll observations mean and standard deviation and model mean and standard deviation after assimilating chlorophyll. The associated change in one of the parameters estimated: grazing on small phytoplankton temporary increases during the spring bloom period and reduces the chlorophyll overestimation that was present before the assimilation of observations.

6 Collaborations and outreach

6.1 Joint session with WGBIOP: What type of information do the modellers need?

Chaired by David Maxwell (WGBIOP) and Solfrid Hjøllø (WGIPEM), summarized by Anna Akimova

1) What type of biological parameters do you use in your models?

- **Lower trophic level models:** growth rates, mortality rates, grazing, nutrient uptake rates, particle remineralization, sinking, sediment exchange rates
- **Fish early-life stage models:** growth and mortality rates, movement, duration of the egg and pelagic larval stages, prey preference
- **Higher trophic level models and E2E:** growth and mortality rates, food consumption, length, weight, gape size, swimming speed, temperature tolerance, reproductive strategy, environmental cues for seasonal migration

2) Where do you find this information?

- Literature reviews
- Field data (own data or databases, like ICES, FAO, Copernicus, satellite data)
- Laboratory experiments
- Other models (e.g. ECOSIM)

3) What type of biological parameters you miss information of in your models?

- Life-history parameters for non-commercial but highly abundant fish species
- Biological parameters for fish early-life stages (e.g. growth, mortality, feeding rates, settlement, diel migration, swimming speed)
- Feeding related parameters: consumption rates, diet preferences (size preference, nutrition), food assimilation rates
- Spawning behavior (seasonality, interannual changes, homing effects, spawning season duration)
- Vertical distribution, diel migration and swimming speed of zooplankton and fishes
- Information on the uncertainty of measured parameters is required for model sensitivity analyses and estimates of the model uncertainty

4) Potential changes in biological processes?

Potentially, yes, particularly due to external stressors (pollutants, extreme temperatures, etc). Changes due to the organism adaptation to various stressors are of interest as well.

5) How can we improve knowledge transfer?

- Data archives
- Joint seminars and workshops
- Meetings in the annual science conference

6) Questions?

- There is a mismatch between parameters measured in field and utilized in the ecosystem models. Where can we find conversion factors between wet and dry biomass of marine organism, carbon content of phyto- and zooplankton organisms, etc.?
- What data are available to parameterize mortality rates at various trophic levels? How can we improve existing mortality parameterizations (both due to predation and starvation)?

6.2 WGSAM: New criteria for consistent model skill assessment of multispecies and ecosystem models

Presented by Sigrid Lehuta on behalf of ICES WGSAM

WGSAM has built a strategy in order to deal with the consideration of an increasing number of demands for key-run reviews and validation by the group. Key-runs are standardized model runs and output that can serve as quality-assured inputs for ICES advice (e.g. natural mortality estimates for single species assessment models). The standardized procedure and key run review criteria are based on previous experience by the group and on literature. The procedure focuses on the step where the model is used in a model life cycle. Any keyrun review deals with six general topics: 1. Appropriateness of the model for the problem, 2. Assumptions (scientific basis, computational infrastructure; adequacy of conceptual model), 3. Input data quality, 4. Comparison with observations, 5. Uncertainty/sensitivity analysis, 6. Final recommendations. The review is performed in course of the meeting week and involves an interactive process between the review group and the modellers. The process is illustrated with the case of the Ecopath with Ecosim model of the Irish Sea. The review work along the agreed criteria is published as an ICES WGSAM report (e.g. ICES WGSAM 2019) and a paper describing the general concept behind the WGSAM keyrun procedure is in preparation (Kempf et al. (in prep)).

6.3 WGSPF modelling activities

Presented by Martin Huret

The new working group on small pelagic fish introduced themselves, their objectives, and the task forces they set up at their 2021 WGIPEM annual meeting. Links with WGIPEM are found in activities 2, 5, 7 and 11.

Task Force on Ecological Process Knowledge

1. Critical review, evaluation & testing of classic hypotheses (Myron Peck (NL), Akinori Takasuka (Japan)Activity)

2. **Life cycle closure - bottlenecks & gaps in knowledge (IBM):Noelle Bolwin (USA), Ignacio Catalan (Spain)Activity**
3. Drivers of spatial distribution & phenology (Rebecca Asch (USA), Marta Moyano (Norway)Activity)
4. Food-web dynamics (Susana Garrido (Portugal))Activity)
5. **Internal and external drivers of growth, reproduction, & survival (LTL+bioenergetics):Martin Huret (France), Martin Lindegren (Denmark), Florian Berg (Norway)**

Task Force on Translating Process Knowledge

6. Survey design & monitoring: Matthias Kloppmann (Germany), Chris Rooper (Canada)
7. **Improving short-term forecasts &/or long-term projections:Ryan Rykaczewski (USA)**
8. Management improvement: Salvador Lluch-Cota (Mexico), Richard Nash (UK), Andres Uriarte (Spain)

Task Force on Social-Ecological Approaches

9. Activity 9: Vulnerability & opportunities of dependent human communities: Myron Peck (Netherlands)
10. Activity 10: Quantifying trade-offs in goods & services: (Cecilie Hansen (Norway), Isaac Kaplan (USA))
11. **Activity 11: Bio-economic modelling: Myron Peck (The Netherlands) – place holder**

6.4 Human dimensions

WGIPEM has invited social scientists to their last two annual meetings, see section 2.4. At the last meeting an interactive session was held, which ended with the overview provided by Luisetti et al (2014) (Figure 26). We will continue to discuss ways to include human dimensions within ecosystem modelling with the group.

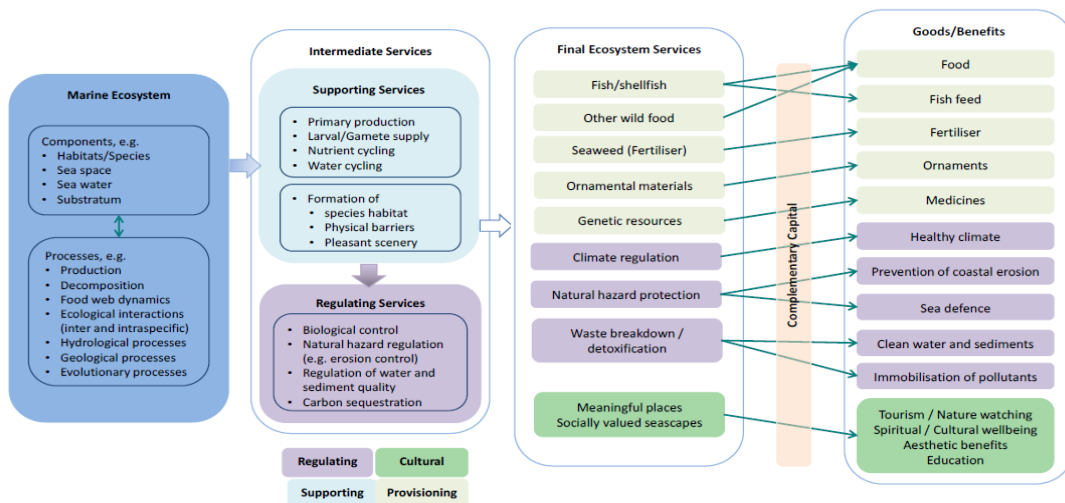


Figure 30 Overview of marine ecosystem services, divided into regulating, supporting, cultural and provisioning services. From Luisetti et al (2014) and shown for discussion to WGIPEM members.

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List of participants present at WGIPEM meeting in Bergen 2019 and online in 2021. Chairs are in **bold**. For a full list of all members see <https://www.ices.dk/community/groups/Pages/Members.aspx?Acronym=WGIPEM>

Annex 2: Resolutions

ToR	Description	Background	Science Plan Codes	Duration	Expected deliverables
a	Improve model interactions between trophic levels by:	Fundamental science lying behind the structural and parametric needs for these types of model.	2.2, 2.5	Annual	Report or paper on how human activities affecting marine ecosystems can be described in models.
	<ul style="list-style-type: none"> - investigating the importance of spatiotemporal scales for trophic match– mismatch - assessing human activities effects on ecosystems, including cumulative impacts 	<p>Important for IEA groups and WKEWIEA.</p> <p>Linked to Marine Ecosystem Research Program</p>			<p>Report on knowledge gaps related to improving lower-to-higher trophic level model coupling.</p> <p>Seek to establish contact to the social science EG's.</p> <p>Where appropriate peer reviewed publications are endorsed.</p>
b	Improve lower trophic level models by investigating:	More research is needed to improve model description of diversity, adaptation and traits in lower trophic level models.	1.3, 1.9	Annual	Collaborative paper on productivity and drivers across models and ecosystems.
	<ul style="list-style-type: none"> - parametrization of functional diversity (community structure, traits) and adaptations - patterns and drivers of plankton phenology and productivity across models and ecosystems - benthic-pelagic coupling in models 	<p>The benthic-pelagic coupling is important for nutrient and energy fluxes and should be better described in the models.</p> <p>IEA groups, WGZE and BEWG</p>			<p>Where appropriate peer reviewed publications are envisioned.</p>
c	Improve higher trophic level models by investigating:	Understanding the connectivity between networks of MPAs under influence of climate change is vital. Connectivity is also essential to defining the spatial structure of stocks and better understanding of the recruitment process.	1.3, 1.4	Annual	Collaborative report or paper on the influence of climate on connectivity
	<ul style="list-style-type: none"> - effects of connectivity, climate and habitat on emerging species distribution, to support management and fisheries 				Collaborative report or paper on movement algorithms used in modelling
	<ul style="list-style-type: none"> - key process formulation (mortality, physiological rates. ..) - movement algorithms 	<p>Fundamental research is needed to improve the description of key physiological processes in models.</p>			Appropriate peer reviewed publications are envisioned

		<p>Important for IEA EG's, spatial planning EG's, BWEG, WGBIOP and for advice.</p> <p>In E2E models movement is essential and there is a need to assess the characteristics and impacts of each algorithm in different environments (theoretical and/or realistic).</p>			
d	<p>Assessment of model skill evaluation methods by:</p> <ul style="list-style-type: none"> - comparison of existing "guidelines" and metrics of skill assessment using existing examples and applying these methods to models used by the group to conclude on the feasibility of the currently existing approaches and identify possible weakness - investigating uncertainty analysis (structural, parameters, scenarios) including model ensemble 	<p>The lack of systematic evaluation of ecosystem model performance and sensitivity currently limits their use in an operational and management context.</p> <p>Evaluation is challenged by the complexity of the models themselves, as well as model vs sparse dataset comparisons, where characterizing different types of variability (mean or trend; interannual or seasonal; rare or extreme events etc.) are needed.</p> <p>Links to all EGs using multi-species and ecosystem modelling (e.g. WGSAMS, WGIMM, working groups on integrated assessments).</p>	1.3, 5.3	Annual	<p>Review paper on model skill assessments methods together with WGSAM</p> <p>Appropriate peer reviewed publications are envisioned</p>

Annex 3: List of models used by the group

Spatial coverage	Model name	Pressures addressed				Model compartments	Output available	Contact person(s)
		Climate change	Fishing	Eutrophication	Others			
Global or region of choice								
global or any chosen region	APECOSM	YES	YES			Generic communities (epipelagic, mesopelagic, migratory, bathypelagic) + focus species		
global or region of choice	FEISTY	YES	YES	No, but can be included		Forage fish, Large pelagic fish, and Demersal fish functional types with 3 size classes	Published output available upon request	Colleen Petrik
Baltic Sea and Greater North Sea								
North Sea-Baltic Sea from -4.08E to 30.42E and 48.55N to 65.85N	HBM-ER-GOM	YES		YES	zooplankton mortality	pelagic lower trophic level food web, sediment model, Calanus stage-structured models, plus forcing by SPM, fish consumption	Upon request	
Local area set-ups e.g. Limfjorden, Belt Sea, Kattegat	Flexsem	YES	YES (mussel fishery)	YES	aquacultures, resuspension from dredging	pelagic lower trophic level food web, sediment model, blue mussels	Upon request	
Eastern English Channel	ISIS-Fish		YES (fisheries)		management	commercial fish, fleets, management		

Spatial coverage	Model name	Pressures addressed				Model compartments	Output available	Contact person(s)
		Climate change	Fishing	Eutrophication	Others			
Baltic Sea and Greater North Sea								
European Shelf or any chosen region	ERSEM-BFM	YES		YES	Acidification through forcing with atmospheric $p\text{CO}_2$ concentrations. Dredging effects can be included.	Lower trophic level biogeochemical model: 6 phytoplankton, 5 zooplankton groups, pelagic bacteria and archaea in pelagic part and 5 benthos groups plus 2 benthic bacteria and archaea in benthic part. Three dynamic sediment layers. Two benthic groups have a pelagic part: resuspended benthic diatoms and filter feeder larvae. Diatoms produce TEP. Cycling of C, N, P, Si, O ₂ .	Upon request	Sonja van Leeuwen, NIOZ, NL (sonja.van.leeuwen@nioz.nl)
Eastern English Channel	OSMOSE coupled to ECO-MARS 3D	YES	YES			main fish species + forcing by phytoplankton, zooplankton, benthos	no	
Southern North Sea	GPM-GETM	YES		YES		pelagic lower trophic level food web, 0-D benthic early diagenesis, + forcing by SPM	upon request (2000-2014)	Onur Kerimoglu (kerimoglu.o@gmail.com)
global or any chosen region	PML-ERSEM	YES		YES	ocean acidification,	Four phytoplankton, three zooplankton and one bacteria + cycling of carbon, nitrogen, phosphorous, silicon and oxygen through pelagic and benthic ecosystems	upon request	

Spatial coverage	Model name	Pressures addressed				Model compartments	Output available	Contact person(s)
		Climate change	Fishing	Eutrophication	Others			
Baltic Sea and Greater North Sea								
English Channel and North Sea	LARVAE&CO	Climate change and interannual variability			Impact of offshore wind farms	Hydrodynamics – particle tracking module. Individual-based model for flatfish and hard-substrate species.	Upon request	
Baltic Sea and North Sea	NEMO-NORDIC-SCOBI	YES				Hydrodynamics - biogeochemical model. In the water column: Nutrients (NO ₃ , NH ₄ , PO ₄ , dissolved silica), phytoplankton (diatoms, flagellates and others, cyanobacteria), zooplankton. Benthic nutrient pools.	upon request	Elin Almroth-Rosell (elin.almroth.rosell@smhi.se)
English Channel and southern North Sea	MIRO&CO	Interannual variability		YES		Hydrodynamics -biogeochemical model. In the water column: Nutrients (NO ₃ , NH ₄ , PO ₄ , dissolved silica), phytoplankton (diatoms, autotrophic nanoflagellates, <i>Phaeocystis</i> colonies), microzooplankton, copepods, bacteria, dissolved and particulate organic matter. In benthic layer: diagenetic module.	Upon request	

Spatial coverage	Model name	Pressures addressed				Model compartments	Output available	Contact person(s)
		Climate change	Fishing	Eutrophication	Others			
Barents Sea and Norwegian Sea								
Barents Sea	NDND: Non Deterministic Network Dynamics model	YES	YES			Phytoplankton, Herbivorous zooplankton, Omnivorous zooplankton, Benthos, Pelagic fish, Demersal fish, Marine mammals, Birds.		Benjamin Planque
Barents Sea and Fram Strait	ECOSMO-E2E coupled to SCHISM	YES	No yet but planned	NO		Hydrodynamics + sea-ice module Biogeochemical model: Nutrient (N-P-Si) – Phytoplankton (2) – Zooplankton (2) – Detritus (2) – Macrobenthos – Fish (2) Sea-ice biogeochemistry (Ice algae-nutrient-detritus)	Partly Upon request	Déborah Benkort Ute Daewel
Norwegian and Barents Sea and North Sea	NORWECOM.E2E	YES	YES		ocean acidification, contaminants, pollution, specific human activities	Nutrient-Phytoplankton-Zooplankton-Detritus, pelagic fish (mackerel, herring, blue whiting), Calanus finmarchicus, Calanus hyperboreus, mesopelagic fish, ongoing work to include capelin, krill and fishing vessels.	Upon request	Morten D Skogen, Erik Mousing, Solfrid Sætre Hjøllø
Norwegian and Barents Sea	NoBa-Atlantis	yes	yes				Upon request	Cecilie Hansen, Ina Nilsen

Spatial coverage	Model name	Pressures addressed				Model compartments	Output available	Contact person(s)
		Climate change	Fishing	Eutrophication	Others			
Bay of Biscay and the Iberian Coast								
Bay of Biscay and Marroco coast + finer resolution for the Portuguese coast and estuaries	MOHID Water Modelling System	YES (short term weather change)		YES	Pollution and specific human activities (oil spills, changes in the estuaries and coastal area morphology,)	hydrodynamics, nutrient- primary production-detritus; simple benthos model in the sediment compartment; possibility for macroalgae, seagrass and shelfish DEB individual based population model		
Bay of Biscay centered, but covers also the English Channel	IBM-DEB + ECOMARS-3D	YES				hydrodynamics, phytoplankton (3), zooplankton (2), fish population + DEB compartments (reserve, structure and reproduction buffer on the individual level) <i>+ forcing by fishing mortality</i>		
Canary Current LME								
North West-Africa continental shelf from 10°N to 31°N	Evol-DEB	x	x			small pelagic fish schools <i>+ forcing by ocean currents, temperature, salinity, phyto- and zooplankton (from ROMS-PISCES)</i>		