Project	NECCTON No 101081273	**Start / Duration**	Jan 2023 - Dec 2026
Dissemination	Public	**Nature**	Report
Date	27 February 2026	**Version**	1.0

NECCTON

NEW COPERNICUS CAPABILITY FOR TROPHIC OCEAN NETWORKS

Deliverable D9.1

Synthesis of the performance of the integrated modelling systems and recommendations on all 25 products for use by the Copernicus Marine Service

Deliverable Contributors:	Name	Organisation	Role / Title
Deliverable Leader	Susan Kay	UKMO	T9.1 lead
Contributing Author(s)	Stefano Ciavatta	MOi	Project lead
	Olivia Fauny	MOi	Data management lead
	Verena Trenkel	IFREMER	WP7 lead
	Carolina Amadio	OGS	Hindcast producer
	Ken H. Andersen	DTU	Hindcast producer
	Damiano Baldan	OGS	Hindcast producer
	Olivier Beauchard	NIOZ	Hindcast producer
	Johannes Bieser	HEREON	Hindcast producer
	Giulia Bonino	CMCC	Hindcast producer

This project has received funding from Horizon Europe RIA under Grant Number 101081273

	Federica Braga	CNR	Hindcast producer
	Giuliana Profeti	CNR	Hindcast producer
	Momme Butenschön	CMCC	Hindcast producer
	Donata Canu	OGS	Hindcast producer
	Igor Celić	OGS	Hindcast producer
	F. Chisci	OGS	Hindcast producer
	Mathurin Choblet	ULIEGE	Hindcast producer
	Anna Conchon	CLS	Hindcast producer
	Gianpiero Cossarini	OGS	Hindcast producer
	Ute Daewel	HEREON	Hindcast producer
	Lee de Mora	PML	Hindcast producer
	Daniel van Denderen	DTU	Hindcast producer
	Michael Denes	UU	Hindcast producer
	Ilya Drozd	ULIEGE	Hindcast producer
	Giovanni Galli	OGS	Hindcast producer
	Thanos Gkanasos	HCMR	Hindcast producer
	Jean-François Grailet	ULIEGE	Hindcast producer
	Marilaure Grégoire	ULIEGE	Hindcast producer
	Josefine Hahn	BSH	Hindcast producer
	Martin Huret	IFREMER	Hindcast producer
	Maurizio Ingrosso	OGS	Hindcast producer
	Nis Sand Jacobsen	DTU	Hindcast producer
	Paolo Lazzari	OGS	Hindcast producer
	Patrick Lehodey	MOi	Hindcast producer
	Simone Libralato	OGS	Hindcast producer
	Anja Lindenthal	BSH	Hindcast producer
	Svitlana Liubartseva	CMCC	Hindcast producer
	Tomas Lovato	CMCC	Hindcast producer
	Loïc Macé	ULIEGE	Hindcast producer
	Clara Menu	IFREMER	Hindcast producer
	Laurène Merillet	CLS	Hindcast producer
	Rebecca Millington	PML	Hindcast producer
	Quentin Misi	MOi	Hindcast producer
	Quinten Mudde	NIOZ	Hindcast producer
	S. Nicol	Pacific Community	Hindcast producer
	Diego Panzeri	OGS	Hindcast producer

	Sergi Pérez-Jorge	IMAR	Hindcast producer
	George Petihakis	HCMR	Hindcast producer
	Maria Inês Pinheiro da Silva	IMAR	Hindcast producer
	Helen Powley	PML	Hindcast producer
	Andrea Rochner	UKMO	Hindcast producer
	Ginevra Rosati	OGS	Hindcast producer
	Kenneth A. Rose	NIOZ	Hindcast producer
	Annette Samuelsen	NERSC	Hindcast producer
	Inna Senina	Pacific Community	Hindcast producer
	Karline Soetaert	NIOZ	Hindcast producer
	Ioannis Tamvakis	HCMR	Hindcast producer
	Olivier Titaud	CLS	Hindcast producer
	Morgane Travers-Trolet	IFREMER	Hindcast producer
	Kostas Tsiaras	HCMR	Hindcast producer
	Luc Vandenbulcke	ULIEGE	Hindcast producer
	Polina Verezemskaya	ULIEGE	Hindcast producer
	Vijith Vijayakumaran	HEREON	Hindcast producer
	Haolin Yu	ULIEGE	Hindcast producer
	Veli Çağlar Yumruktepe	NERSC	Hindcast producer
Reviewer(s)	Stephanie Guinehut	Mercator	Internal reviewer
	Diego Macias	Joint Research Centre	External reviewer
	Paul Snelgrove	Memorial University	External reviewer
Final review and approval	Stefano Ciavatta	Mercator	Project lead

Document History:

Release	Date	Reason for Change	Status	Distribution
1.0	20 Feb 2026	Initial document, reviewed	Released	Internal

To cite this document

Kay, S., Ciavatta, S., Fauny, O., Trenkel, V., Amadio, C., Andersen, K. H., Baldan, D., Beauchard, O., Bieser, J., Bonino, G., Braga, F., Profeti, G., Butenschön, M., Canu, D., Celić, I., Chisci, F., Choblet, M., Conchon, A., Cossarini, G., … Yumruktepe, V. Ç. (2026). Synthesis of the performance of the integrated modelling systems and recommendations on all 25 products for use by the Copernicus Marine Service (9.1). Zenodo. https://doi.org/10.5281/zenodo.18663056

TABLE OF CONTENTS

1. Executive Summary

The NECCTON project has developed an integrated modelling system to deliver new variables and products to the Copernicus Marine Service. The system is based on the models of the lower trophic levels (LTL) of the marine ecosystem which are already used in Copernicus Marine Service production, coupled to new models that increase the range of available variables to include marine species and stressors. NECCTON has created a set of multi-decade model runs to demonstrate the capability of the modelling system and the quality and technological readiness level of the 27 thematic variables (originally 25 products) proposed. This report summarises the validation and recommendations for each variable produced in the NECCTON hindcasts. The datasets themselves, with validation information, can be found on the NECCTON data portal https://data.neccton.eu.

Each regional dataset has been assigned a technology readiness level (TRL) ranging from 4 (tested in a laboratory environment – the model has run successfully and produced a dataset) to 5 (validated in a relevant environment – the dataset has an acceptable match to observations). NECCTON will apply many of the hindcast outputs in the case studies now in progress, and successful completion of a case study will move them to TRL 6 (technology demonstrated in relevant environment).

The following thematic variables have reached TRL 5 for at least one region and are recommended for consideration by the Copernicus Marine Service:

- LTL: mesozooplankton, particulate organic matter, reflectance
- Benthic: bottom oxygen, pH and light, macrozoobenthos and benthic flora
- HTL: small pelagics, large pelagics, demersal fish and unspecified fish biomass, ideally using an ensemble of models
- Pollutants and stressors: plastics, organophosphate esters, mercury, fisheries pressure and climate change stressor indices.

Further recommendations include testing these variables in a wider range of regions and taking steps to address the shortage of observational data.

2. Glossary

Abbreviation	Definition
ARC	Arctic region
AUC	Area Under the Receiver Operating Curve
BAL	Baltic Sea region
BS	Black Sea region
DOM	Dissolved Organic Matter
EcoBM	Ecosystem Biomass Model
FABM	Framework for Aquatic Biogeochemical Modelling
FEISTY	FishErIes Size and functional TYpe model
GLO	Global ocean domain
HTL	High (or Higher) Trophic Levels
IBI	Iberia-Biscay-Ireland region
LTL	Low (or Lower) Trophic Level

MED	Mediterranean Sea region
NECCTON	New Copernicus Capability for Trophic Ocean Networks (project name)
NWS	North West Shelf Domain
POM, POC	Particulate Organic Matter, Particulate Organic Carbon
POPs	Persistent Organic Pollutants
RMSD	Root Mean Square Difference
ESD-MED	Ensemble of species distribution models
SpDM	Species Distribution Model
SPM	Suspended Particulate Matter
SpPM	Species Population Model
TRL	Technology Readiness Level

3. Introduction

The NECCTON project has developed an integrated modelling system to deliver new variables and products to the Copernicus Marine Service. The system is based on models of the low trophic levels (LTL) of the marine ecosystem which are already used in the Copernicus Marine Service to provide operational forecasts of European seas and the global ocean, coupled to new models which increase the range of available variables to include marine species and stressors. The LTL models have been developed to provide new and improved candidate variables for Copernicus Marine including, for the first time, variables describing the sea bottom and benthic environments. The Framework for Aquatic Biogeochemical Modelling (FABM) has been extended to include all six of the Copernicus Marine LTL models, enabling easy transfer of developments in one regional model to others. In addition, the NECCTON integrated modelling system includes models of high trophic levels (HTL), which would give the Copernicus Marine Service the capability to offer new, biodiversity-focussed variables and products. A further suite of models has been brought into the system to produce variables focussed on pollutants and other anthropogenic stressors that affect marine ecosystems. Details of the model developments introduced during NECCTON can be found in deliverables D5.2, D6.2, D6.3, D7.2, D8.2 and D8.3.

A set of multi-decade model runs has been created to demonstrate the capability of the modelling system and the quality and technological readiness level (TRL) of the proposed variables, enabling us to assess whether they offer the accuracy and reliability required by users, as well as their maturity for future, possible transfer to the Copernicus Marine Service operational systems. This report summarises the results of this work and makes recommendations about which products and variables are ready for adoption by the Copernicus Marine Service and which need further development. The hindcast products themselves are available from the datacube at https://data.neccton.eu, along with validation information provided by the hindcast creators.

A note on the terminology used in the report

To ensure full alignment with the Copernicus Marine Service data management, the initial NECCTON data architecture was revised by updating both the nomenclature and the definitions of the terms *product*, *dataset* and *variable*.

This change, compared to the original project design, reflects a deliberate long-term strategy aimed at preparing NECCTON data as early as possible for seamless future integration into the Copernicus Marine Service. It also guarantees harmonisation across all NECCTON products regardless of their original producer.

Under this revised structure two complementary sets of definitions can be distinguished: those related to the scientific description of NECCTON outcomes (Figure 1), and those related to the organisation of the catalogue within the datacube and its associated viewer (Figure 2).

From a scientific perspective:

- A **thematic variable**, formerly referred to as a "NECCTON product," denotes one of the 27 broad families of variables addressed by NECCTON, such as mesozooplankton, large pelagic fish, carbon flux to the bottom, marine mammal habitat, or oil spill. For convenience, thematic variables are grouped into four **classes**: low-trophic-level, benthic, high-trophic-level, and pollutants & stressors.
- A **variable** is an instance of a thematic variable. For example, "skipjack tuna" and "bigeye tuna" are two variables within the broad thematic variable "large pelagic fish."

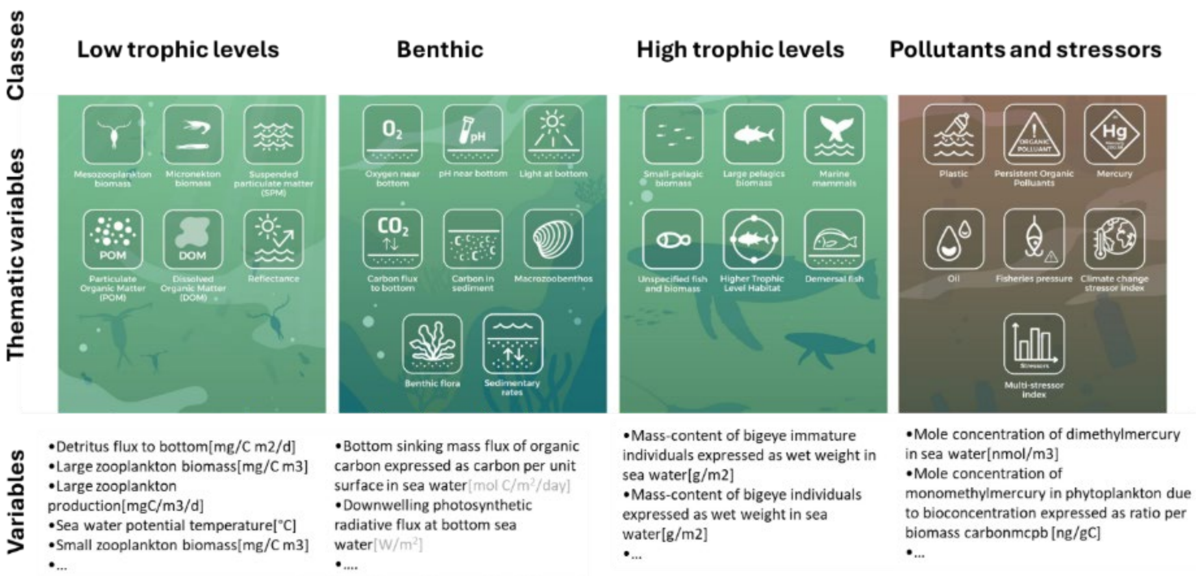


Figure 1. The 27 thematic variables delivered by NECCTON, grouped into four broad classes of the marine environment. Each thematic variable (e.g. large pelagic fish) is further subdivided into specific variables simulated by the NECCTON models (e.g. bigeye tuna biomass and skipjack tuna biomass).

From a catalogue and datacube architecture perspective:

- A **product** represents a class of thematic variables for a specific region and comprises one or more datasets (for example, "High Trophic Levels in the Global Ocean").
- A **dataset** corresponds to one or more thematic variables within a region produced by a single model or data provider. In practice, a dataset represents the contents of an individual NetCDF file and includes one or more variables sharing the same spatio-temporal resolution.

- A **variable** is consistent with the previous definition and, in this context, represents an instance within a dataset. In the data portal, a variable corresponds to a single layer displayed in the data viewer. Each variable is assigned a CF-compliant standard name, in accordance with CF conventions.

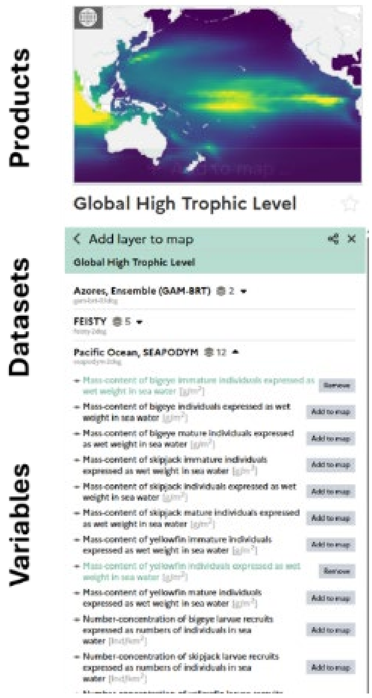


Figure 2. Example of the “Global High Trophic Level” product in the NECCTON data portal (https://data.neccton.eu/viewer/expert?view=catalogue). This product belongs to the High Trophic Level (HTL) class for the global ocean. It comprises three datasets produced by the GAMB-BRT model (IMAR), the FEISTY model (DTU), and the SEAPODYM model (MOi). The SEAPODYM model generates multiple variables (e.g. bigeye tuna mass content, skipjack tuna mass content) corresponding to the thematic variables targeted by NECCTON (e.g. large pelagic fish in Figure 1).

The NECCTON proposal put forward 25 candidate products. We added two further items as a result of stakeholder consultation. Therefore the 25 products referred to in the title of the report are now 27 thematic variables.

The NECCTON integrated modelling system

A key goal of NECCTON was to produce a fully integrated modelling system that can represent the functioning of the whole marine ecosystem better than current isolated models, which focus on single marine components. To achieve this goal, we have taken the suite of models that are used to simulate low trophic levels for the Copernicus Marine Service and linked them to a wide range of models that represent a variety of aspects of high trophic levels, using a variety of approaches. Both one-way and two-way coupling methods have been tested and developed, and this is described in full in D7.2.

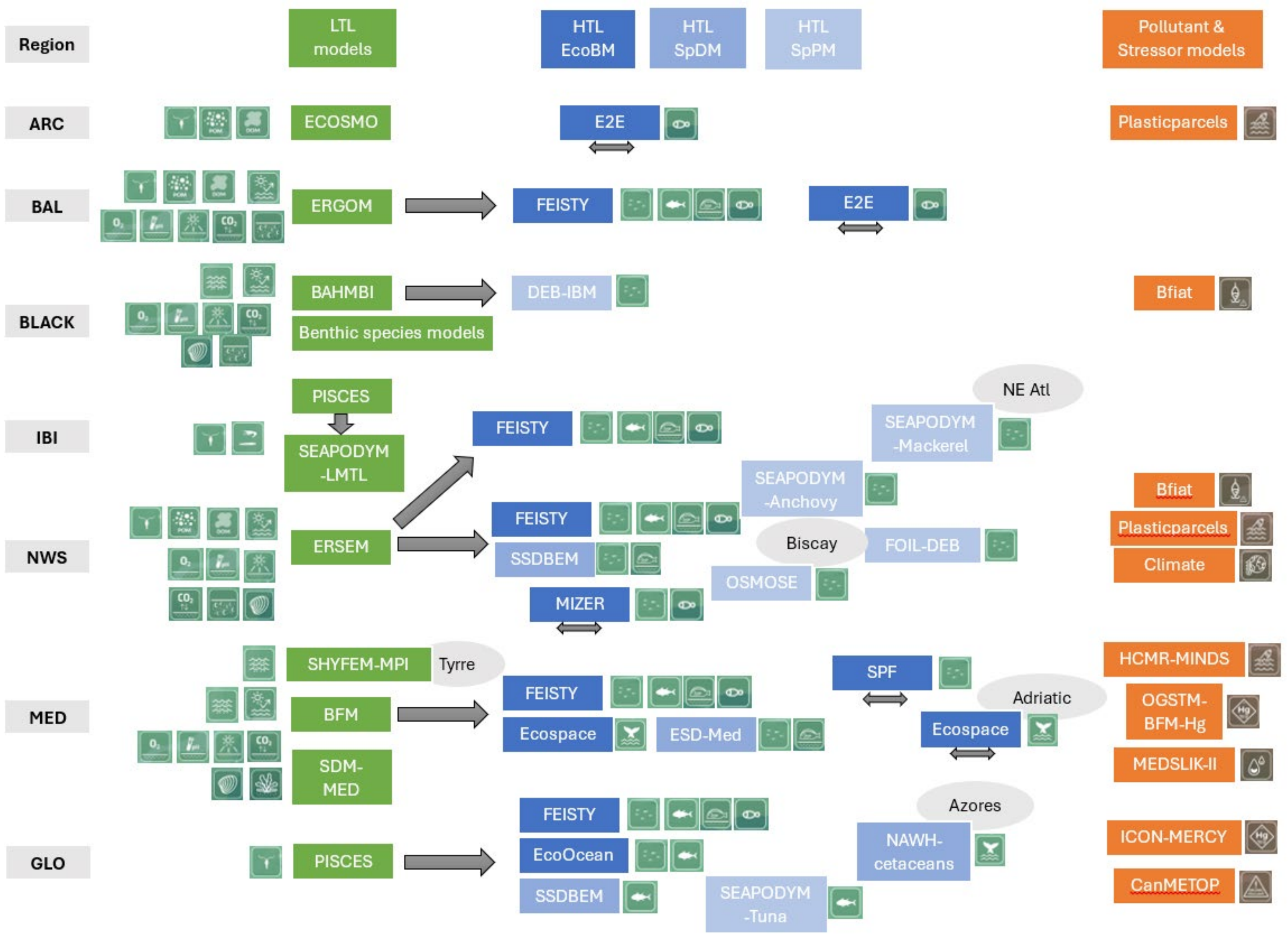
In cases where one-way coupling was used to link low and high trophic levels, HTL and LTL modellers worked together to ensure that appropriate data was generated to drive the HTL models – variables such as zooplankton biomass, net primary production, temperature, pH and the carbon flux to the seabed. The LTL models yielded multi-decade-long hindcasts and their outputs were used to run the HTL models, with a few fully two-way coupled models also included in the NECCTON set. The pollution/stressor models used physical and biogeochemical variables as inputs, many of them taken from the Copernicus Marine Service but not specifically from the NECCTON models. The models and their linkages, along with the variables that each produced, are summarised in Figure 3.

4. Method for producing recommendations

The producers of all the hindcasts have written a one-page summary for each variable (namely Quality Sheets), following the approach of the Synthetic Quality Overviews provided by the Copernicus Marine Service (see Milestones 6.2 and 8.3). All the sheets were documented internally in the project repository, and will be made publicly available to users via the data portal.

The quality sheets give a brief outline to describe what the variable represents, summarise how the model was calibrated and the outputs validated, and provide a recommendation about usage and take-up by the Copernicus Marine Service and/or further development. Previous deliverables present validation of the NECCTON model developments in more detail; the quality sheets aimed to provide a summary focussed specifically on the hindcast datasets. Quantitative assessments have been made wherever possible, using agreed metrics such as bias, correlation and root mean square difference, but in some cases there was insufficient observational data available for comparison, even after efforts within NECCTON to gather all available data and process into a suitable form. We developed recommendations from the validation using expert judgement. The Appendix includes a few of the quality sheets, to illustrate the approach and the kinds of information made available.

The quality sheets form the basis of this report. The table below (section 5) summarises validation outcomes for all the NECCTON variables produced by the hindcasts, along with recommendations for further development or adoption as a Copernicus Marine Service product. Consistent with the NECCTON work plan, most variables have been produced for several but not all of the Copernicus Marine Service regions: the discussion (section 6) gives a conclusive synthesis for the four groups of NECCTON products (LTL, benthic, HTL and pollutants/stressors) across regions.



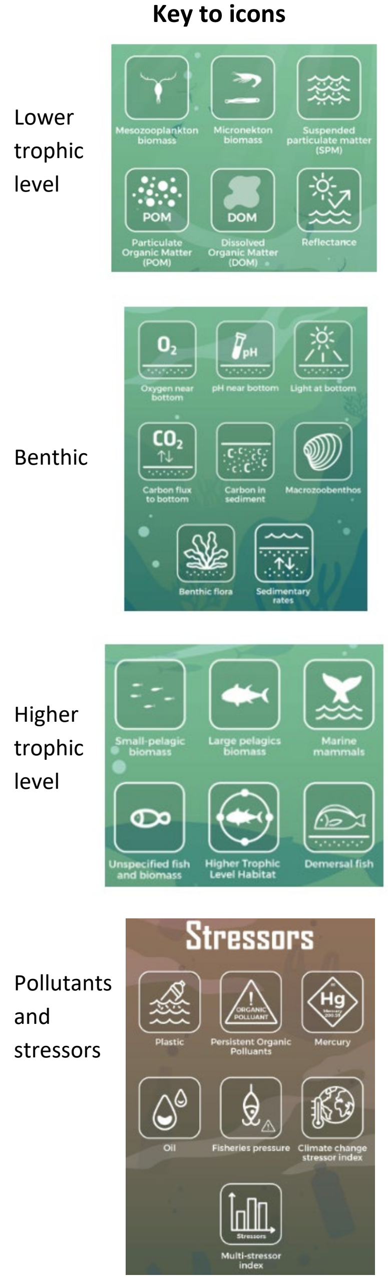


Figure 3. The NECCTON models and variables, showing the linkages between them and the variables produced for each region. The variables are shown as icons, with the key to the right giving their meanings. The higher trophic level models are colour coded to show ecosystem biomass models (EcoBM), species distribution models (SpDM) and species population models (SpPM). The grey arrows show information transfer by one-way ⟹ or two-way ⟺ coupling.

5. Listing of variables and recommendations

A note on Technology Readiness Levels (TRLs): NECCTON aims to move the thematic variables from TRL 4 to TRL 5 or 6. Variables considered ready for take-up at this point in the project are considered to be at TRL 5 (validated in a relevant environment). NECCTON will apply many of the hindcast outputs to case studies now in progress, and successful completion of a case study will move them to TRL 6 (technology demonstrated in relevant environment). In the table below colour codes indicate the current status: green shows TRL 5, yellow TRL 4, pale green intermediate between TRL 4 and 5, red TRL 3, grey not yet available.

Thematic Variable	Region and model	Producer	Validation outcome	Estimated TRL	Recommendation
Mesozoo-plankton biomass	ARC ECOSMO	NERSC	Model results averaged over four regions show good agreement to an observation-based climatology.	5	Ready for use at regional scale and monthly/seasonal resolution, but the uncertainty would be greater for higher temporal or spatial resolutions.
	NWS ERSEM	UKMO	Only surface observational data is available. The model broadly captures spatial and temporal patterns, though with biases in some areas.	5	Could be used cautiously as an input for simulations, though users should be aware of the biases.
	IBI SEAPODYM-LMTL	CLS	Model outputs agree well with the observed population structure in the summer but tend to overestimate the spatial extent of high zooplankton biomass in the spring and autumn.	5	Could be used with caution, though further validation is advised – NECCTON case study 7 will help with this.
	BAL ERGOM	BSH	NECCTON developments have improved the variable, but model results still tend to be higher than observations.	4	Further model development is needed before it is ready for take-up by the Copernicus Marine Service.
	GLO PISCES	MOi	The model represents the observed spatial distribution of mesozooplankton, particularly at the surface	5	Could be used with cautions for driving higher trophic level (HTL) models and initializing climate projections, but further calibration effort is recommended to reduce uncertainty.

Thematic Variable	Region and model	Producer	Validation outcome	Estimated TRL	Recommendation
Micronekton biomass	IBI SEAPODYM-LMTL	CLS	Direct validation is not possible, owing to lack of observations. Some comparison to sites in the Southern Ocean has validated that the model reproduces the seasonal cycle.	4	Further validation is recommended, when survey data become available.
Suspended Particulate Matter (SPM)	NWS ERSEM-SPM	UKMO +PML	It was not possible to produce a stable working model in the timeframe of the project.	3	Further work is needed, building on testing and development done in NECCTON
	Tyrrhenian Sea SHYFEM-MPI	CMCC	The model successfully reproduces spatial patterns and magnitudes of inorganic SPM. RMSD is in the range 0.8-2.8 g m^{-3} for the surface layer, with better agreement near the coast.	5 (Tyrrhenian Sea), 4 (MED)	The model is successful in this small area but further development would be needed to make it suitable for a wider area.
	BS BAHMBI-SPM	ULIEGE	Compared to satellite estimates, the model outputs are consistently smaller but show some agreement in spatial and temporal variation. The match is better for coastal than for deep water areas.	4	The model is promising, especially for coastal areas, but needs further development before it is ready for take-up by the Copernicus Marine Service. Better validation data is needed – satellite data has high uncertainty and may include bloom products not considered by the SPM model.
Particulate organic matter (POM), total and detrital	ARC ECOSMO	NERSC	The model captures regional patterns well in the top 200m but underestimates BGC-Argo observations of POM in deeper water	5 (4 for subsurface)	Recommended for operational and climate applications in the surface ocean (0-200m). Values at lower depths could be used cautiously, with awareness of bias.
	NWS ERSEM	UKMO +PML	Observations are sparse so total POM was validated at the surface for March-September only, and detrital POM could not be validated. Model outputs have comparable magnitude and spatial distribution to observations, though with biases in some regions.	4/5	The variable has broad agreement to observations and could be taken up by the Copernicus Marine Service, but it would have high uncertainty

Thematic Variable	Region and model	Producer	Validation outcome	Estimated TRL	Recommendation
	BAL ERGOM	BSH	Model outputs show broad agreement with observations at monitoring stations, with mainly positive correlation and RMSD 5-21 mmol m^{-3} depending on depth.	5	Validation quality is acceptable and this variable is recommended for take-up by the Copernicus Marine Service, with appropriate quality information.
	MED BFM	OGS	Accuracy is comparable to that of other ecosystem modelling variables, with RMSD about 0.15-0.5 mmol m^{-3}. Performance is better in the open sea than near the coast.	5	The variable is recommended for take-up once tested in an operational modelling system.
Dissolved organic matter (DOM)	ARC ECOSMO	NERSC	Model outputs have low bias and RMSD about 10-20 mmol m^{-3} for the Atlantic (Atl) part of the region but much lower skill for the Eastern Arctic (EA).	4 EA/ 5 Atl	Regional and monthly average DOM could be provided for the Atlantic part of the Arctic, but the Eastern Arctic needs further development.
	NWS ERSEM	UKMO +PML	Model outputs broadly agree with the (sparse) observations but show some strong biases and relatively low correlations.	4	Further development is needed, building on the improvements made in NECCTON.
	BAL ERGOM	BSH	Model results show some correlation to observations, but the RMSD is quite large at 50-80 mmol m^{-3}.	4	The variable could provide useful information for regional applications, but the uncertainty would be large.
Reflectance (modelled)	NWS ERSEM	UKMO +PML	The variable generally shows good agreement with observed temporal and spatial patterns, though it is higher than observed in the shallower regions and temporal correlation is poor in deep regions at 490 and 510 nm.	5	The variable could be adopted by the Copernicus Marine Service, with appropriate quality information, but further work should be done to understand and reduce biases.
	BAL ERGOM	BSH	The hindcast was delayed by technical issues and validation has not yet been completed.		
	MED BFM	OGS	Model outputs agree well with satellite values, although they are larger than observed in winter. The RMSD is higher in the	5	The quality is satisfactory and this variable could be adopted by the Copernicus Marine Service.

Thematic Variable	Region and model	Producer	Validation outcome	Estimated TRL	Recommendation
			eastern Mediterranean basin than in the western basin at shorter wavelengths, with the opposite pattern at longer wavelengths.		
	BS BAHMBI	ULIEGE	The variable provides a good depiction of the observed seasonal variability but tends to underestimate blooms and misses the summer coccolithophore bloom.	5	Can be used with caution for all applications.
Reflectance (satellite-observed)	MED, BS, NWS	CNR	Satellite-derived reflectance from the PRISMA hyperspectral mission is assessed in D4.2. Outputs processed using the POLYMER atmospheric correction algorithm gave good agreement to in situ observations at 443-620 nm wavelengths. Shorter wavelengths tend to be overestimated and agreement for longer wavelengths is currently poor.	5	PRISMA reflectance validates well at many wavelengths and will be valuable for model validation and development of modelling systems which assimilate reflectance rather than chlorophyll. It is recommended for take-up by the Copernicus Marine Service, though quality improvement at the shorter and longer parts of the wavelength range is desirable.
Oxygen near bottom	NWS ERSEM	UKMO +PML	The variable has comparable accuracy to current Copernicus Marine Service oxygen, with bias averaging 9 mmol m^{-3}, and correlation 0.85.	5	Oxygen is already delivered by the Copernicus Marine Service. Bottom level oxygen would be helpful for users specifically interested in sea-floor conditions.
	BAL ERGOM	BSH	NECCTON developments have reduced the RMSD compared to in situ observations, especially at 80-100 m depth.	5	Oxygen is already delivered by the Copernicus Marine Service. Bottom level oxygen would be helpful for users specifically interested in sea-floor conditions.
	MED BFM	OGS	The model reproduces oxygen with an RMSD on the order of 10 mmol m^{-3} and correlation values 0.5-0.9 (better for deeper water).	5	Oxygen is already delivered by the Copernicus Marine Service. Bottom level oxygen would be helpful for users specifically interested in sea-floor conditions.
	BS BAHMBI	ULIEGE	The model outputs match well to the mean values and seasonal variation in observations, but tend to underestimate the variability. In	4(hyp)/5(overall)	Oxygen is already delivered by the Copernicus Marine Service, but the NECCTON work has shown that deep-water hypoxia may be under-estimated. Further testing and model development is recommended.

Thematic Variable	Region and model	Producer	Validation outcome	Estimated TRL	Recommendation
			particular, the model does not reproduce the lowest observed values.		
pH near bottom	NWS ERSEM	UKMO +PML	Model outputs have a small negative bias in most months, positive bias in winter. Validation is limited by sparse data.	5	pH is already delivered by the Copernicus Marine Service. Bottom level pH would be helpful for users specifically interested in sea-floor conditions.
	BAL ERGOM	BSH	Model outputs have a small negative bias and RMSD about 0.3.	5	pH is already delivered by the Copernicus Marine Service. Bottom level pH would be helpful for users specifically interested in sea-floor conditions.
	MED BFM	OGS	pH was validated for all depths, with RMSD about 0.02 and correlation in the range 0.4-0.9 (higher for deeper water).	5	pH is already delivered by the Copernicus Marine Service. Bottom level pH would be helpful for users specifically interested in sea-floor conditions.
	BS BAHMBI	ULIEGE	pH through the water column follows the same trend as composite profiles of in situ data. Values are in line with observations in the upper layer, but lower than observed by about 0.4 in the oxycline zone.	5	pH is already delivered by the Copernicus Marine Service. Bottom level pH would be helpful for users specifically interested in sea-floor conditions.
Light at bottom	NWS ERSEM	UKMO +PML	Direct validation is not possible, owing to lack of observations. Attenuation is larger than observed by satellite so values are likely to be too low.	4	Given the high uncertainty this variable is not ready for take-up by the Copernicus Marine Service. More observations are needed.
	BAL ERGOM	BSH	Model outputs are close to observations for depths below 30 m, but turbidity and cloud effects cause higher errors nearer the surface, and especially at depths less than 5 m.	5	This variable is ready to be adopted by the Copernicus Marine Service. Users should be made aware of the higher uncertainty in very shallow waters.
	MED BFM	OGS	Direct validation is not possible, owing to lack of observations. Comparison to light attenuation coefficient shows good agreement.	5	The variable could be adopted by the Copernicus Marine Service, though with some uncertainty because of the lack of in situ observations.

Thematic Variable	Region and model	Producer	Validation outcome	Estimated TRL	Recommendation
	BS BAHMBI	ULIEGE	Comparison to BGC-Argo observations in deep water shows excellent correlation and a small negative bias. Observations are not available for the shelf area.	4 (shelf) /5 (deep water)	This variable could be taken up by the Copernicus Marin Service, though there would be higher uncertainty for shallower waters, including the northwestern shelf.
Carbon flux to bottom	NWS ERSEM	UKMO +PML	The modelled annual mean flux is the same order of magnitude as reported rates of organic carbon accumulation in the North Sea.	4	Observations are very limited and so the model cannot be reliably assessed. It may be useful, but would have high uncertainty.
	BAL ERGOM	BSH	The modelled annual range falls within the variability reported from long-term sediment-trap observations in the central Baltic Sea.	4	Observations are very limited and so the model cannot be reliably assessed. It may be useful, but would have high uncertainty.
	MED BFM	OGS	Observations of carbon flux are not available so the model values for the concentration of particulate organic carbon in deep water were validated to give an indication of accuracy. The values have the correct order of magnitude but show consistent bias, positive in the north west Mediterranean, negative elsewhere.	4	Flux of organic carbon cannot be validated directly and POC values show some bias. Carbon flux may be a useful variable, but would have high uncertainty.
	BS BAHMBI	ULIEGE	Carbon flux was validated indirectly by comparison to observed benthic-pelagic fluxes of oxygen and nutrients on the northwestern shelf. The model generally captures the direction and magnitude of agreed fluxes.	4	The comparison to oxygen and nutrient fluxes gives some confidence in the use of the model, but it might be difficult for non-expert users to assess. Carbon flux may be a useful variable, but it would have high uncertainty.
Carbon in sediment	NWS ERSEM	UKMO +PML	Very little data is available to validate the model. Some estimates of organic carbon exist, but they represent long-term standing	4	Given the high uncertainty this variable is not ready for take-up by the Copernicus Marine Service. It might be

Thematic Variable	Region and model	Producer	Validation outcome	Estimated TRL	Recommendation
			stocks rather than carbon involved with short-term biogeochemical processes.		useful as an input for simulations, but it would need to be clear to users what carbon pool it represents.
	BAL ERGOM	BSH	Very few observations are available. Model outputs are the same order of magnitude as the observations, but with higher maximum values.	4	Due to the low number of observational data, validation options for this product are very limited, resulting in high uncertainty, and the model skill cannot be reliable assessed.
	BS BAHMBI	ULIEGE	Carbon in sediment was validated indirectly by comparison to observed benthic-pelagic fluxes of oxygen and nutrients on the northwestern shelf. The model generally captures the direction and magnitude of agreed fluxes.	4	The comparison to oxygen and nutrient fluxes gives some confidence in the use of the model, but it would be difficult for non-expert users to assess. Carbon in sediment would have high uncertainty.
Macrozoobenthos	NWS ERSEM	UKMO +PML	The model broadly reproduces the spatial patterns seen in a 1986 North Sea survey, with lower values than observed in the south, higher elsewhere.	4	Further development is needed, and a better observational dataset for comparison, before it is ready to be adopted by the Copernicus Marine Service
	MED SDM-MED	OGS	This variable is derived from species distribution models for presence/absence of main species and this validates well against observations. The conversion from presence/absence to carbon biomass introduces an uncertainty which is difficult to quantify.	5	This variable could be taken up the Copernicus Marine Service, with information about the uncertainty in presence-biomass conversion.
	BS Individual physiological model	NIOZ	The variables provided are biomass and density for mussels (*Mytilus galloprovincialis*). Model outputs are in line with field observations, though with some tendency to overestimate in the lower part of the range of biomass and density.	5	The variables could be useful and are tentatively recommended for the Copernicus Marine Service, however users would need clear information about the high uncertainty for small biomass and density values.

Thematic Variable	Region and model	Producer	Validation outcome	Estimated TRL	Recommendation
Benthic Flora	MED SDM-MED	OGS	Data is provided for two species *Cymodocea nodosa and Posidonia oceanica*, based on species distribution models. Both models have acceptable performance (e.g. AUC>0.7), though with some additional uncertainty introduced in the conversion to carbon biomass.	5	This variable could be taken up the Copernicus Marine Service, with appropriate information about uncertainty.
	BS Macroalgae model	NIOZ	Data is provided for the macroalga *Phyllophora.* Very little observational data is available so the model skill cannot be reliably assessed, but model outputs appear to be the same order of magnitude as the limited observations.	4	Given the high uncertainty this variable is not ready for take-up by the Copernicus Marine Service. Further validation data is needed.
Sedimentary rates	BS	ULIEGE	Sedimentary rates is a new thematic variable, added after the start of the project in response to user requests. An estimate will be produced by the end of the project.		Not yet available
Small pelagics (anchovy and sardine)	MED SPF	HCMR	The model successfully reproduces the spatial and some of the temporal stock variability of anchovy and sardine in the Mediterranean Sea, when compared to acoustic survey data. Some regions are better simulated than others.	5	The variable can be used for climate projections and fisheries scenario simulations and can be upgraded into an operational hindcast model for anchovy and sardine in the Mediterranean Sea, with appropriate information about uncertainty.
Small pelagics (anchovy, sardine, mackerel,	Biscay OSMOSE	IFREMER	The size of catches is well represented and simulated biomass is the right order of magnitude compared to available estimates. Spatial distribution has not been calibrated nor validated and should be considered with caution.	4	The OSMOSE model and its outputs are suitable for research purposes, for example trophic interactions, climate change and alternative fishing scenarios. However spatial information has high uncertainty and needs further development. Integration in a model

Thematic Variable	Region and model	Producer	Validation outcome	Estimated TRL	Recommendation
horse mackerel)					ensemble will help further assess the validation of outputs
Small pelagics (anchovy and sardine)	Biscay FOIL-DEB	IFREMER	Model outputs show good agreement with survey data magnitude. Modelled adult spatial distribution is largely constrained by average observed distribution, so the model cannot predict interannual variability.	4	Simulations made using FOIL-DEB are suitable for research purposes (larval connectivity patterns, recruitment, growth, interannual variation of biomasses), but further model development and a higher level of maturity is needed before take-up by the Copernicus Marine Service.
Small pelagics (anchovy)	Biscay SEAPODYM-Anchovy	MOi	The simulated biomass and catch by fisheries agree with the magnitude and interannual variation seen in survey data and catch statistics. The results converge with stock assessment estimates	4	Initial quantitative estimation (2010-2023) and its validation (1998-2023) are promising, but the resolution of fishing data used for parameter optimisation is too coarse for fine scale validation. Some very high catch events close to the Spanish coast cannot be predicted. Key forcing variables (e.g. zooplankton) had to be corrected in shallow waters and need further evaluation.
Large pelagics (skipjack, yellowfin and bigeye tuna)	Pacific SEAPODYM-Tuna	MOi	The model captures the spatial distribution of key exploited tuna species, as observed in spatially disaggregated catch data (catch and size structure). Outputs are consistent with those from stock assessment models used by the Western Central Pacific Fisheries Commission.	5	The model can be used for testing fishing scenarios including spatial planning measures and the variables are ready for adoption by the Copernicus Marine Service. Similar products in Atlantic and Indian Oceans should be proposed.
Small pelagics (all species), unspecified fish biomass	NWS MIZER	PML	Averaged across the shelf, modelled and observed fish landings agree well, both for small pelagics and for unspecified fish. However, spatial variation is less well reproduced. Calibration and validation data are not independent.	4	MIZER outputs are suitable for use as part of an ensemble but further development is needed before they are ready to be offered as a separate product.

Thematic Variable	Region and model	Producer	Validation outcome	Estimated TRL	Recommendation
Small pelagics, large pelagics, demersal, unspecified	NWS FEISTY	DTU	Biomass levels are very good, but the model overestimated catches for the first half of the simulated period.	5	The model is almost ready for use, though an additional calibration step is recommended to improve simulations of catches.
Small pelagics, large pelagics, demersal, unspecified	IBI FEISTY	DTU	Biomass levels are very good, but the model overestimated catches for the first half of the simulated period.	5	The model is almost ready for use, though an additional calibration step is recommended to improve simulations of catches.
Small pelagics, large pelagics, demersal, unspecified	GLO FEISTY	DTU	Modelled and observed catches agree well when averaged over appropriate regions, such as Large Marine Ecosystems.	5	The model is ready for use after further limited development and calibration.
Small pelagics (mackerel)	Natl SEAPODYM-Mackerel	CLS	The magnitude of the total biomass is in line with the stock assessment report. The model simulates the seasonal migration but cannot reproduce the expansion to the Nordic Seas since the mid-2000s.	4	The SEAPODYM mackerel model is promising and could be a useful product, but requires more work on calibration and a stronger validation before the hindcast, and climate projections, are ready to be used for management advice.
Small pelagics (anchovy, sardine), demersal (hake, red mullet, deep-water shrimp, red	MED ESD-MED	OGS	This ensemble statistical model shows acceptable levels of RSMD when outputs are compared to observational data, and the ensemble approach allows uncertainty to be assessed.	5	The ESD-MED product is considered a robust representation of the spatial patterns of the included species. It is recommended for take-up by the Copernicus Marine Service, with annual updates.

Thematic Variable	Region and model	Producer	Validation outcome	Estimated TRL	Recommendation
giant shrimp)					
Small pelagics (anchovy)	BS DEB-IBM	ULIEGE	The model captures spatial and temporal patterns of anchovy distribution but is not able to represent populations for particular years.	4	The model outputs are suitable for research purposes such as scenario testing and comparing seasonal patterns, hotspot dynamics, and large-scale distribution shifts, but they are not intended for operational forecasts or for year-specific predictions.
Unspecified fish biomass	ARC E2E	HEREON	The modelled spatial and temporal distribution of planktivorous fish matches observed distribution of herring and blue whiting seen in survey data.	4	The model outputs are ready to be included as part of an ensemble, but further validation is required before they are suitable as an operational, stand-alone product.
Unspecified fish biomass	BAL E2E	HEREON	The modelled spatial distribution of planktivorous fish matches the observed distribution of pelagic fish inferred from acoustic survey data.	4	Further validation is required before this is suitable as an operational product.
Marine mammals (all species)	Adriatic Ecospace	OGS	Ecospace outputs broadly reproduce spatial and temporal trends of observed functional groups data. Further work will involve comparison of maps for particular species to species distribution models.	4/5	Maps of marine mammals as a whole functional group can inform conservation and management programmes and are ready for take-up by the Copernicus Marine Service. Maps for individual species can follow after further validation.
Marine mammals (common dolphin, Atlantic spotted dolphin)	Azores NAWH-cetaceans	IMAR	Cross-validation shows good performance at capturing seasonal and spatial patterns, but limited skill at reproducing interannual variability. Model validation across the entire study area was limited by the absence of independent observational data from offshore areas.	4	The NAWH-cetaceans outputs are suitable for trends across multi-decadal climate change projections in the study region but the model needs further development to provide a robust operational hindcast with accurate interannual variation or for use across a wider area.
Plastic	ARC	UU	The model processes have been validated, however validation of the model outputs is	4	The NECCCTON product should be considered a proof-of-concept, to explore the usefulness and usability of

Thematic Variable	Region and model	Producer	Validation outcome	Estimated TRL	Recommendation
	Plasticparcels		exceptionally difficult owing to lack of observations and high uncertainty about the inputs.		such a product for end users. Lack of observations limits assessment of the model outputs: further validation and collection of observations is recommended.
	NWS Plasticparcels	UU	The model processes have been validated, however validation of the model outputs is exceptionally difficult owing to lack of observations and high uncertainty about the inputs.	4	The NECCCTON product should be considered a proof-of-concept, to explore the usefulness and usability of such a product for end users. Lack of observations limits assessment of the model output: further validation and collection of observations is recommended.
	MED HCMR-MINDS	HCMR	The model reproduced observed size distributions and captured spatial patterns, with correlation 0.1-0.3. Performance is better in some regions than others.	5	The variable can be taken up by the Copernicus Marine Service, with quality information setting out the model limitations.
POPs: OPE	GLO	HEREON	Organophosphate esters (OPE) were compared to observations across the global ocean, giving good agreement (R^2=0.72). Observations are sparse in some areas, particularly the Southern Ocean.	5	This variable is ready to be taken up by the Copernicus Marine Service, with appropriate quality documentation.
Mercury	MED OGSTM-BFM-Hg	OGS	Two variables are provided: total mercury and methylmercury. For total mercury, the model outputs have low bias but do not capture the high variability of surface observations and hence have low correlation. Methylmercury shows fair agreement with observations, but is overestimated at the surface and has lower variability than observed.	5	Both variables could be taken up by the Copernicus Marine Service, but would need to be well documented so that users can assess whether they are suitable for their application.
	GLO ICON-MERCY	HEREON	The model correctly reproduces the magnitude and spatial distribution of total and elemental mercury but does not capture the full variability. Observed high values in	5	This variable is ready to be taken up by the Copernicus Marine Service, with appropriate quality documentation.

Thematic Variable	Region and model	Producer	Validation outcome	Estimated TRL	Recommendation
			polar regions are underestimated by the model.		
Oil	MED MEDSLIK-II	CMCC	Comparison to one past oil spill event show good agreement between the modelled and observed track of the oil, and modelled coastline deposition was consistent with which beaches were affected by the spill.	4-5	This variable could be taken up by the Copernicus Marine Service, following validation against more events.
Fisheries pressure	NWS Bfiat	NIOZ	The model was calibrated based on a meta-analysis of observations for a range of gear penetration depths. Predictions and confidence intervals consistently lie within the observational range.	5	Following calibration, the model outputs give a good match to observed community depletion and are considered ready for take-up by the Copernicus Marine Service.
	BS Bfiat	NIOZ	The model was calibrated based on a meta-analysis of observational observations for a range of gear penetration depths. Predictions and confidence intervals for the considered gear penetration depth in the Black Sea (2.5 cm) lie within the observational range but exceed the mean.	5	The model outputs tend to overestimate community depletion compared to observations. They could be taken up by the Copernicus Marine Service but should be considered to have some uncertainty.
Climate change stressor indices, including multi-stressor index	NWS	PML	Four indices of climate stress are provided, along with a multi-stressor index that assesses their combined effect. These indices were applied to four fish species (cod, herring, sea bass and sea bream), cold water corals, blue mussels and seaweed. Validation focusses on the suitability of each index for the species considered.		
			Aerobic Growth Index (AGI) is an established metric for motile species but not shown to be applicable to sessile organisms or non-vertebrates.	5	AGI for fish species would be a useful addition to the Copernicus catalogue. It is not appropriate for other species without further work.
			Heat Wave Hazard Index (HWHI) is very sensitive to the choice of depth etc so must be calculated separately for each species. It	4/5	HWHI could be provided for selected organisms, provided it is calculated carefully and information on uncertainty is supplied.

Thematic Variable	Region and model	Producer	Validation outcome	Estimated TRL	Recommendation
			may not be appropriate for motile organisms which can move to cooler waters.		
			Aragonite Saturation is based on climate model outputs for the carbonate system, which are less reliable than temperature and oxygen. The index is based on the minimum value for the water column so may be less relevant for bottom-living organisms.	5	Aragonite Saturation from past observations is already provided by the Copernicus Marine Service. It could be extended as an indicator of future climate stress, provided that users have good information about its uncertainty and applicability.
			The Hypoxia Index indicates occasional low-oxygen events in the Skagerrak and Bay of Biscay but not in the rest of the NWS region: this is consistent with observations.	5	Hypoxia index could be a useful indicator in regions which are prone to low-oxygen events.
			Multi-stressor index (MSI) for climate stressors is calculated separately for each species, depending on its susceptibility to different stressors. The weighting of each stressor depends on multiple assumptions, adding some uncertainty to the index.	4/5	The MSI could be useful to help understand the combined effect of multiple climate stressors, but the method of calculation and the base assumptions must be clear and available to users.
Multi-stressor index	all	PML	NECCTON has developed a methodology for producing a multi-stressor index that includes pollutants and stressors beyond climate change. However, it has not been possible to produce a demonstration product because the datasets have only recently become available.	4	Further development and testing of the methodology is needed before the full multi-stressor is ready to be adopted by the Copernicus Marine Service.

6. Synthesis

Low-trophic-level (LTL) water column variables

The LTL variables were created in NECCTON by using models that are already in operational use by the Copernicus Marine Service MFCs, though with modifications and updates during the project. These developments included diel vertical migration and light-dependent mortality of mesozooplankton, improved modelling of dissolved and particulate organic matter, new or extended spectral radiative transfer modelling and the first attempt to introduce inorganic suspended particulate matter into Copernicus Marine Service models. The hindcasts were produced without any assimilation of physical or biogeochemical observations and so any final decision on delivery of new variables to the Copernicus Marine Service would depend on testing in a full operational-like environment, including data assimilation of observations that could affect the NECCTON variables, directly or indirectly. We make the following recommendations on that basis, i.e. where appropriate the variables are recommended for pre-operational testing and possible delivery.

The **mesozooplankton** variable has evaluated well in several regions. It could be adopted by the Copernicus Marine Service: the NECCTON hindcasts are suitable for the expected use case of running higher trophic level models. Regional and monthly averages would have higher confidence than a variable at the grid resolution and at daily resolution, although users asked for the higher resolution. As an additional benefit from NECCTON, the model developments made during the project will contribute directly to improving the total zooplankton variable already delivered by several forecasting centres.

Micronekton The Copernicus global product has been evaluated and calibrated with a limited number of observations. At regional scale, including shallow waters, it is known to likely overestimate biomass due to the lack of representation of the flux of energy towards the benthic system. The NECCTON product is for the IBI region. It is difficult to validate directly because observations for this region are limited or difficult to access. As a next step the IBI regional results could be compared to any available acoustic transects (38 kHz), at least to evaluate the seasonal cycle, interannual variability and spatial distributions. NECCTON has demonstrated the utility of micronekton as a new variable to model the anchovy spawning habitat and population dynamics in the Bay of Biscay. It is recommended for adoption as a Copernicus Marine Service product once its validation—and, if necessary, correction—have been completed for the continental slope and shelf ecosystem.

Models of inorganic **suspended particulate matter** were developed for an area in the Tyrrhenian Sea (Mediterranean) and the Black Sea. Both models are able to reproduce observed spatial patterns, though the magnitude of the Black Sea model outputs is smaller than satellite observations (which themselves have quite high uncertainty). The models perform better in coastal areas than in deeper waters, which is positive because coastal areas are where they are likely to be most useful. A 1D model was developed for the North West Shelf but despite considerable work it was not possible to

This project has received funding from Horizon Europe RIA under Grant Number 101081273

move it to a functional working model in the timeframe of NECCTON. Successful modelling of SPM across a wide area is difficult and further investment will be needed to develop a fully-functioning NWS model or to extend the Tyrrhenian Sea model to the wider Mediterranean.

Total particulate organic matter (POM) validates well against BGC-Argo data in the Mediterranean Sea and Arctic regions, and against station data in the Baltic Sea, and could be offered as a Copernicus Marine Service variable with appropriate quality information. Validation is more problematic for the North West Shelf, because BGC-Argo does not operate at the 0-200 m depths of the shelf and other data is sparse in both time and space. There is enough support from the validation to offer this variable, given that there was high interest from users in a POM variable for this region, but the high uncertainty should be made clear. Detrital POM comprises only the non-living part and excludes phytoplankton and zooplankton: this cannot be validated in any region owing to lack of observational data. The Copernicus Marine Service could offer this variable based on the validation of linked variables – total POM, zooplankton and chlorophyll (for phytoplankton), however the basis for validation, and the uncertainty, should be made clear to users.

Dissolved organic matter (DOM) was produced for the Arctic, Baltic Sea and North West Shelf regions but only validated well enough in the Atlantic part of the Arctic to recommend take-up without further development. However the NECCTON work has shown the potential for this relatively new variable, and strong interest from users – further development is recommended to improve model skill. As well as improvements within the models, better modelling of rivers is likely to be important for improving DOM: this is indicated by results in the Eastern Arctic and the coastal North West Shelf. The NECCTON models include the labile but not refractory component of DOM. The labile fraction represents organic carbon which interacts with living organisms and hence changes at daily time-scales but does not include the long-term, relatively stable refractory carbon which is seen in observations: this should be clearly communicated to users of any future product.

NECCTON has developed two new sets of **remote sensing reflectance** variables: satellite-derived values using the PRISMA hyperspectral sensor and model-derived values for four regional seas. Reflectance is a promising variable for delivery by the Copernicus Marine Service, having validated well for the regions where it was tested. Further evaluation is recommended of model outputs produced with assimilation of ocean colour data, as used in most of the Copernicus Marine Service forecasting systems: it is likely that this will bring the ecosystem more in line with optical satellite observations and hence give a better agreement with values of reflectance observed by satellite. NECCTON has enabled centres to progress their capability in optical modelling and there is potential for this to lead to improvements in the quality of existing variables given further development.

Benthic variables

The Copernicus Marine Service does not currently offer any variables specifically describing the sea bottom and seabed and NECCTON has developed a range of candidates. These include two kinds of dataset: (1) outputs from process-based benthic ecosystem models linked to the water-column models used to produce LTL variables and (2) mapped datasets developed by using statistical and machine learning methods to interpolate between observations or to link environmental conditions to species distributions.

Oxygen and pH are already delivered by the Copernicus Marine Service, however a bottom-specific product can be helpful to users specifically interested in conditions at the seabed, who would otherwise need to calculate bottom values from the depth-resolved product. Oxygen values are comparable to existing Copernicus Marine Service products or, in the case of the Baltic Sea, improved by NECCTON developments. The only caveat is that hypoxia in the Black Sea is underestimated, which may be a limitation for some users. pH validates well, although data is limited in some areas which might affect confidence in the validation. Overall, bottom level oxygen and pH are clearly recommended for the Copernicus Marine Service.

Validating **light at the bottom level** is difficult in most regions as there are limited observations. Data from observing stations is available in the Baltic Sea and the model-observation agreement is good except in shallower waters; the relatively poor performance in shallow waters might make it less suitable for users interested in growth of benthic flora so depth-dependent quality information will be important. In the Black Sea the model validates well against observations from BGC-Argo floats but these are not available for the northwestern shelf so accuracy is less certain there. Comparison of Mediterranean model outputs for surface light attenuation to satellite values shows good agreement and supports the recommendation of this product. Surface attenuation is a less reliable proxy indicator for the more complex waters of the North West Shelf, and so the uncertainty of this variable is high.

Lack of observational evidence is also a problem for **carbon flux to the bottom** and **carbon in sediment**. At best, the modelled regions have a handful of data points and it is not clear that the carbon pool included in those studies is the same as that considered by the models. In the Black Sea there are observations of oxygen and nutrient fluxes at the sea bed which give some information about model performance, but users would need clear information about how this information can be translated into uncertainty about carbon variables. These products could be useful as input to other models, in the absence of other data, but they would have high uncertainty.

NECCTON has produced several benthic flora and fauna model outputs, mainly from dedicated statistical or species-specific process-based model. The exception is ERSEM, where the benthic component has been used to produce a 30-year daily time series of **macrozoobenthos** (suspension and deposit feeders). A single survey is available for comparison, which gives some support and suggests that further development is worthwhile. The other macrozoobenthos regional model outputs, Black Sea mussels and Mediterranean total carbon biomass, do not have the same time resolution but are easier to validate and both are recommended for take-up. The Mediterranean **benthic flora** modelling uses the same approach as the benthic fauna and these variables are similarly recommended as giving useful spatial information, though they do not include temporal variation. For the Black Sea macroalgae, NECCTON has developed a functional model but there is not enough observational data to provide a confident evaluation.

Higher trophic level variables

NECCTON has used several types of fish models to create multiple hindcasts for different regions, species and groups of fish. These “ensembles of convenience” enable users to compare a number of outputs relating to their variable of interest, assess the degree of agreement between them and hence judge the level of confidence they can have in the model outputs. The models used fall into three categories: ecosystem biomass models (EcoBM), which use simplifying assumptions to model complex ecosystem processes and interactions; species distribution models (SpDM), which estimate the location of species based on known correlation to environmental conditions, and species population models (SpPM), which simulate a range of processes acting on a particular species, including population dynamics, trophic interactions between fishes and lower-trophic levels, and eventually fishing mortality.

Many of the models give outputs for **small pelagics**, either particular species or for the group as a whole, when considering individuals within a certain size or weight range. Most models give biomass values of the right order of magnitude when compared to independent data and some are able to reproduce observed spatial and/or temporal patterns. The Bay of Biscay has particularly good coverage, with this area covered by an ensemble of outputs from ecosystem biomass, species distribution and species population models run for the IBI, North West Shelf and global regions.

Fewer hindcasts have been created for **large pelagics** and for **demersal fish**, but there are outputs for at least one of each type of model (ecosystem biomass, species distribution and species population models).

Unspecified fish biomass comes from ecosystem biomass models, both one-way coupled to LTL models (FEISTY) and two-way coupled (MIZER, E2E). These models generally do well at capturing the overall fish biomass, though the distribution may have more uncertainty.

In several instances, fish variables are close to being ready for operational production, though some further calibration/validation is still recommended. Examples of relatively high TRL include small and large pelagics in the global ocean simulated by different types of models, and small pelagics in the Mediterranean, the Iberian-Biscay-Irish seas including the Bay of Biscay, and the North West Shelf seas.

Many of the hindcast producers feel that their model outputs are ready to use for research purposes, such as testing scenarios of climate change or fishing pressure, but not for operational delivery. Even where the models have a high TRL some further calibration/validation is recommended. It is worth noting that fine-resolution observations are not available for all HTL species, preventing a robust validation of the simulations. Providing a group of models as an ensemble makes the results more robust than for an individual model, but the hindcasts vary widely in their ability to capture different aspects of fish biomass and distribution. In any future Copernicus Marine Service product, it will be important to document the different strengths and weaknesses of the hindcasts, based on quantitative validations, and make sure that users are aware of the variation in the methods used to create them.

For **marine mammals**, NECCTON has developed candidate models for two regions, the Azores and the Adriatic Sea. The Azores results are obtained from a statistical model based on sightings corrected for sampling effort, which performs well in capturing seasonal patterns but is less effective at representing interannual variability. The approach requires high resolution environmental and biological variables that are not available for climate change projections. Adriatic Sea results are obtained from a food web model which provides information on marine mammal biomass distribution within a spatio-temporal framework and will be developed to give estimates for individual species. Both these models are promising but need further development. It would also be desirable to cover a wider area, by extending these models or by developing new ones, though this may need more observational data than is currently available.

Pollutants and anthropogenic stressors

NECCTON has brought together a range of leading models to develop and test candidate variables that describe pollutants and anthropogenic stressors identified by users as being of key importance for the marine environment.

Plastics variables have been produced for the Mediterranean using the HCMR-MINDS model and for the Arctic and North West Shelf using the plasticparcels model. Both models include processes of transport, breakdown and biofouling to give concentration of five size classes of microplastics in the water column; the Mediterranean model also includes surface macroplastics. The Mediterranean model is considered mature and its outputs could be adopted as a Copernicus Marine Service variable, with documentation describing the model limitations and uncertainty. However, the plasticparcels take-up is limited by the lack of validation data: NECCTON has shown proof of concept, but more observational data is needed.

One **persistent organic pollutant (POP)** has been produced as a NECCTON variable, organophosphate esters (OPE). Model outputs for this variable validate well and it is recommended for take-up by the Copernicus Marine Service. It would be desirable to include other POPs as well.

Mercury variables have been modelled for the Mediterranean Sea and the global ocean through the coupled models OGSTM-BFM-Hg and ICON-MERCY. Both models validate well, though they do not capture the full observed variability. These variables are ready to be taken up by the Copernicus Marine Service, with appropriate uncertainty information.

Oil spill tracking has been tested for the Mediterranean Sea, with two hazard indices proposed: the probability of the coastline oiling and the probability of the sea surface oiling. The model validated well when results were compared to one well-documented oil spill and it is a promising candidate for the Copernicus Marine Service, though further validation is advised. In the longer term, models for other regional seas could also be developed.

Four potential **indicators of climate change stress** have been demonstrated for the North West Shelf, along with a multi-stressor index that combines them using weightings suitable for particular species. These indicators are considered ready for adoption by the Copernicus Marine Service, as long as clear information is provided about the uncertainty associated with each index and the species it is applicable to, as well as validation information about the climate model outputs which are used to calculate the index. It would be straightforward to extend the methodology to other Copernicus Marine Service regions.

7. Conclusion

NECCTON has produced validated datasets for 25 thematic variables, with several of them covering more than one of Copernicus Marine Service regions. We created these datasets using an integrated modelling system which links models of many different types, representing marine trophic levels from the lowest to the highest, including fisheries in some cases, and a range of stressors and pollutants that can adversely affect marine ecosystems. Some of the models were already used to provide products to the Copernicus Marine Service: they have been revised and extended, and brought together under a common framework, FABM, enabling developments to be easily shared. Other models have been tested in the Copernicus Marine Service framework for the first time.

Table 7.1 summarises the results from validation of these datasets. TRL 5 denotes that the thematic variable is ready for take-up by the Copernicus Marine Service in a given region, in some cases after a limited amount of further calibration or validation; all will need testing in an operational-like environment. NECCTON recommends the following thematic variables for at least one region:

- LTL: mesozooplankton, particulate organic matter, reflectance.
- Benthic: bottom oxygen, pH and light, macrozoobenthos and benthic flora.
- HTL: small pelagics, large pelagics, demersal fish and unspecified fish biomass, ideally using an ensemble of models.
- Pollutants and stressors: plastics, organophosphate esters, mercury, fisheries pressure and climate change stressor indices.

Two thematic variables will follow for a total of 27 thematic variables eventually. A methodology for the multi-stressor index has been developed and demonstrated using the climate change stressors and this can be tested more widely now that a larger range of stressor datasets is available. Sedimentary rate was added after the commencement of the project and a method for estimating it is in progress.

The NECCTON case studies will demonstrate the use of many of the thematic variables in practical applications, giving potential to move them to TRL 6 by the end of the project.

Further development beyond NECCTON can include testing the TRL 5 variables in other regions or, in the cases marked with an asterisk (*) in Table 7.1, extending them from a limited area to the whole region. In cases that use one of the LTL models shown in Figure 3, the FABM coupler will simplify moving new capability from one model to another. Experience in NECCTON has highlighted the lack of observational data to support model development and validation, particularly for the benthic variables. New technologies such as marine gliders and automated imaging systems are beginning to make it easier and cheaper to collect observations of marine ecosystems: we recommend that Copernicus Marine encourages the collection of such data and ensures that it is accessible and useful to modellers. We also recommend dialogue with users to explore whether some model outputs can still be useful in the absence of quantitative validation data.

The NECCTON developments represent a significant step forward in capability for marine environmental modelling, with 17 new variables recommended for the Copernicus Marine Service.

All the outputs are publicly available on the NECCTON data portal, and we will seek stakeholder feedback through the case studies, conferences and other available opportunities.

*Table 7.1 TRLs for each thematic variable for each region where a hindcast was created. * indicates that the variable was produced for part of the region only. Colour codes indicate current status: green shows TRL 5, yellow TRL 4, pale green intermediate between TRL 4 and 5, red TRL 3, grey not yet available; white shows regions where NECCTON did not propose model runs. Multiple entries show regions where multiple models were run; the numbers give the TRL for each model.*

	Thematic variable	ARC	BAL	BS	IBI	NWS	MED	GLO
LTL	Mesozooplankton	5	4		5	5		5
LTL	Micronekton				4			
LTL	Suspended Particulate Matter			4		3	5*	
LTL	Particulate organic matter	4/5	5			4/5	5	
LTL	Dissolved organic matter	4/5	4			4		
LTL	Reflectance (model)			5		5	5	
LTL	Reflectance (satellite)			5*		5*	5*	
Benthic	Oxygen near bottom		5	5		5	5	
Benthic	pH near bottom		5	5		5	5	
Benthic	Light at bottom		5	4/5		4	5	
Benthic	Carbon flux to bottom		4	4		4	4	
Benthic	Carbon in sediment		4	4		4		
Benthic	Macrozoobenthos			5		4	5	
Benthic	Benthic flora			4			5	
HTL	Small pelagics			4	4*,4*, 4*,5,4	4,5	5,5	5,4
HTL	Large pelagics				5	5		5*,5,4
HTL	Unspecified fish				5	4,5		5
HTL	Demersal fish				5	5	5	5,4
HTL	Marine mammals						4/5*	4*
Pollut.	Plastic	4				4	5	
Pollut.	POPs							5
Pollut.	Mercury						5	5
Pollut.	Oil						4/5	
Pollut.	Fisheries pressure			5		5		
Pollut.	Climate change stressor indices					4,5		
Pollut.	Multi-stressor index (climate stressors only)					4		

8. Appendix: sample validation summary sheets.

Product technical name: Mesozooplankton	Author: Mokrane Belharet Date: 10/2025

Global Mesozooplankton validation

This product represents the temporal mean mesozooplankton concentration in seawater over the period 2000–2020, derived from the global configuration of the NEMO-FABM-PISCES model. The simulations explicitly account for diel vertical migration (DVM) processes through the NERSC DVM model. The fraction of mesozooplankton assumed to migrate is fixed at 30% (Gorgues et al. 2009) and is considered spatially and temporally constant. Model outputs were evaluated against observational data from the MAREDAT database. These observations correspond to zooplankton concentrations sampled at various vertical intervals (0–10 m, 0–50 m, 0–100 m, 0–200 m, etc.). Each observed value was compared with the corresponding model estimate, computed as the vertical mean of simulated concentrations extracted from the 3D model grid at the same spatial coordinates and vertical level as the observation. Overall, the model results show good agreement with the observations, particularly in surface waters (0–10 m depth), where sampling uncertainties are minimal due to the limited thickness of the sampled water column. As the sampled depth range increases, the uncertainties associated with concentration estimates also increase, making the validation process more challenging. To the best of our knowledge, this is the first time that a biogeochemical model explicitly and mechanistically represents zooplankton vertical migration at the global scale. Although the current results are already satisfactory and can be considered a robust basis for driving higher trophic level (HTL) models and initializing climate projections, the prescribed fraction of migrating zooplankton remains a major source of uncertainty, as it likely varies spatially and temporally in response to several biotic and abiotic factors (e.g., light availability, primary production, predator abundance, etc.). Dedicated calibration efforts are therefore recommended to improve consistency with observations and to reduce uncertainties in future projections.

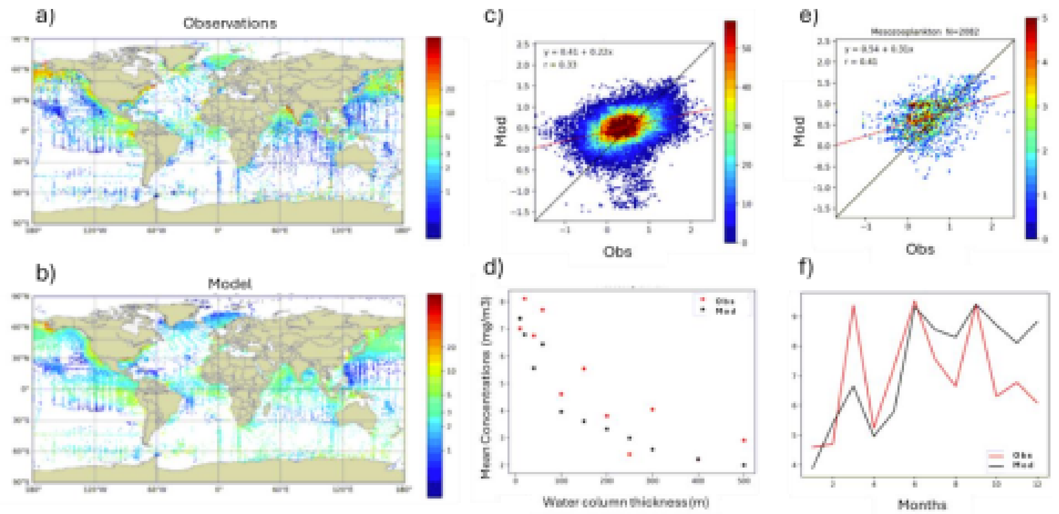


Fig 1: ***Comparison between observed and modeled mesozooplankton concentrations.*** ***a)*** *Spatial distribution of the observed mean concentrations, including all sampling dates and all sampled layers with a water column thickness shallower than 500 m.* ***b)*** *same as panel (a) but for the modeled mean concentrations.* ***c)*** *Scatterplot comparing observed and modeled concentrations for all data points shown in panels (a) and (b).* ***d)*** *Spatial mean of observed and modeled concentrations as a function of the sampled water column thickness (from the surface).* ***e)*** *Same as panel (c), but limited to surface waters (0–10 m).* ***f)*** *Time series of observed and modeled spatially averaged concentrations in surface waters (0–10 m).*

Product technical name: Sedimentary organic carbon content	Author: BSH (Anja Lindenthal and Josefine Hahn) Date: December 2025	NECCTON

11.3 Carbon in bottom

This new product represents the sedimentary organic carbon content. The NEMO4.2-ERGOM1.2 model covers the Baltic Sea with a horizontal resolution of 1nm and a non-equidistant vertical resolution of 56 levels. The product provides daily mean bottom maps for the years 2018 to 2020.
Measurements of total organic carbon in sediment were taken in wintertime of 2018 and 2020 by IOW[1].
Carbon content in sediment is highest in the deeper layers of the Baltic Sea. Sedimentary carbon is lower in the Western Baltic compared to the Eastern Baltic. Values range from 5.2 to 1740.7 mol C m^{2} (5th to 95th percentile). Observations range from 3.8 to 66.9 mol C m^{2}.
Due to the low number of observational data, validation options for this product are very limited, resulting in high uncertainty, and the model skill cannot be reliable assessed.

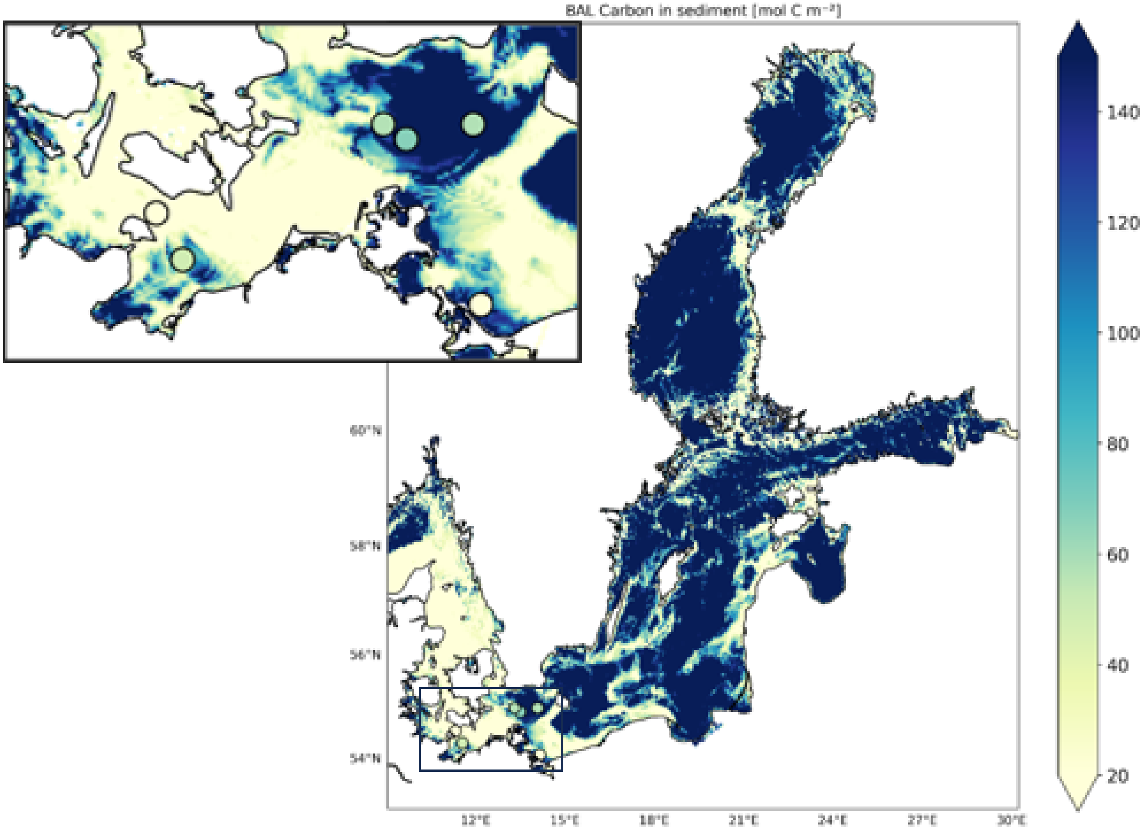


Figure 1: Annual mean sedimentary carbon content in mol C m^{2} in the Baltic Sea. Observations are displayed as color-coded dots. The box is enhanced in the upper left corner.

(1) Odin database: Data originator: Leibniz Institute for Baltic Sea Research Warnemünde (IOW), Germany

Product technical name: Marine mammal habitat (habitat spotted dolphin and habitat common dolphin)	Author: IMAR (Sergi Pérez-Jorge and Maria Inês Pinheiro da Silva) Date: 22/12-2025	NECCTON neccton@mercator-ocean.fr

NAWH-cetaceans

The product represents the monthly probability of occurrence of common dolphin (*Delphinus delphis*) and Atlantic spotted dolphins (*Stenella frontalis*) within the Azores region (Central North Atlantic) for the period 2001-2015. It is derived from an ensemble of two species distribution models based on sighting data obtained by the Azores Fisheries Observer Program. Additionally, NAWH-cetaceans integrates fishing vessel tracking data to account for spatial and temporal biases due to uneven sampling effort. This product offers a significant advancement over previous SDM models for cetacean in the region by incorporating survey effort and by capturing complex and non-linear patterns (Tobeña et al., 2016).

The predictive performance of the product was assessed using the original sightings dataset through three validation strategies: 1) 75/25% training – testing data split; 2) “Leave one-out” cross-validation; and a 3) five folds cross-validation). Overall, the predictions capture the seasonal patterns of the target species reasonably well, including a clear latitudinal pattern (Figure 1; Pinheiro da Silva et al., 2025). However, the model is only available from May to August (coverage of the existing sightings dataset), and it shows limited skill in capturing the interannual variability, as indicated by the LOO validation results.

Independent validation of the model is currently not possible due to the lack of existing cetacean dataset having a similar spatio-temporal coverage. The product can be used for climate change projections as part of the case study of the NECCTON project due to the identified overall patterns, but it would appreciate further validation with data from offshore areas to provided robust operational hindcast by CMEMS.

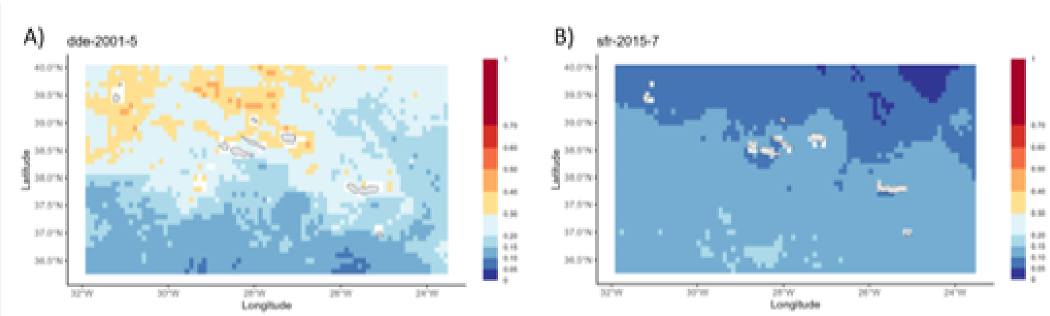


Figure 1. Marine mammal habitat product examples. A) Probability of occurrence for common dolphin in May 2001. B) Probability of occurrence for spotted dolphin in July 2015. Probability of occurrence ranges from 0 (low probability of occurrence of the target species) to 1 (high probability).

References

Pinheiro da Silva et al., (2025). Global Ecology and Conservation, 62, e03769

Tobeña et al., (2016). Frontiers in Marine Science, 3, 202

Product technical name: **MED_MULTIYEAR_BGC_POLLUT_006_104**	Authors: Ginevra Rosati, Donata Canu Date: 12/19/2025

Total mercury (HgT) in the Mediterranean Sea

This product is validated by comparing the sum of all modeled mercury (Hg) species in seawater (HgII, Hg0, MMHg, and DMHg) to in situ observations of total mercury (HgT). It was simulated using the OGSTM-BFM-Hg model (Rosati et al., 2022) over the Mediterranean Sea domain from 2005 to 2020. This product offers monthly output at a horizontal resolution of approximately 4.5 km.

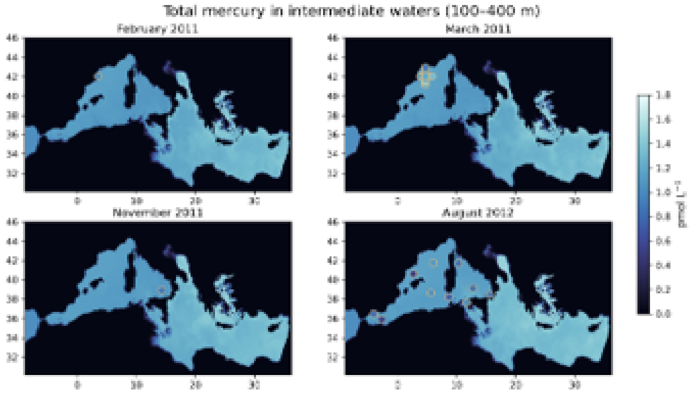


Figure 1. Spatial distribution of HgT in the intermediate waters of the MED simulated for different months of 2011 compared with observations (Cossa et al., 2017, Kotnik et al., 2017).

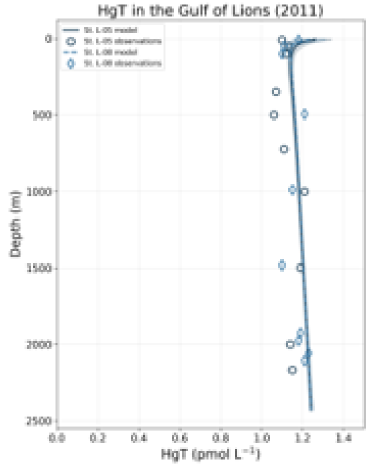


Figure 2. Vertical distribution of HgT concentrations at two stations in the Gulf of Lions. The dots represent observations sampled in February and March 2011 (Cossa et al., 2017), the lines shows the model averages for the same period with their standard deviation (shaded

Validation was carried out through comparison with data (Figures 1, 2, and 3) sampled at different depths of the water column from published and unpublished sources (Cossa et al., 2022, 2017, 2009, Jiskra et al., 2021, Kotnik et al., 2017, 2015, 2007, Rosati et al., 2018). The bias, RMSE, and correlation coefficient (Table 1) were computed by comparing each observation data point with the model average of the corresponding month at the nearest location on the domain. The model bias is very low and the RMSE is about 50% of the average concentration, indicating a good agreement with observations. However, the correlation is low due to the high variability of the observations in the surface water which is not fully captured by the model. This product can be used in projection simulations and operational hindcasts.

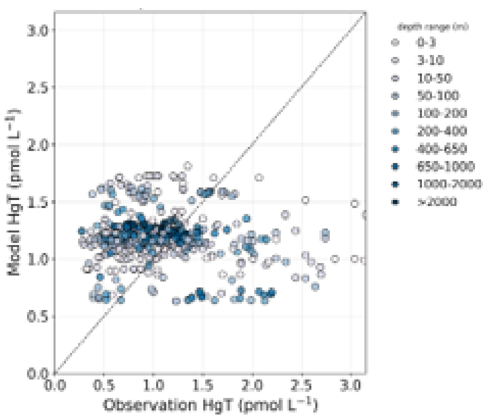


Figure 3. Comparison between observed and modeled HgT concentrations in the MED (# obs = 613).

Bias	0.09	pmol L⁻¹
RMSE	0.55	pmol L⁻¹
r	-0.09	-

Table 1. Model bias, root-mean-squared-error, and correlation coefficient of modeled HgT against observations.

Cossa et al., 2022, ES&T, 56(7), 3840–3862. https://doi.org/10.1021/acs.est.1c03044
Cossa et al., 2017, GCA, 199, 222–237. https://doi.org/10.1016/j.gca.2016.11.037
Jiskra et al., 2021, Nature, 597(7878), 678–682. https://doi.org/10.1038/s41586-021-03859-8
Kotnik et al., 2017, Mar. Chem., 193, 8–19. https://doi.org/10.1016/j.marchem.2017.03.002
Kotnik et al., 2015, Mar. Poll. Bull., 96(1–2), 136–148. https://doi.org/10.1016/j.marpolbul.2015.05.037
Kotnik et al., 2007, Mar. Chem., 107(1), 13–30. https://doi.org/10.1016/j.marchem.2007.02.012
Rosati et al., 2022, Biogeosciences. 19(February), 3663–3682. https://doi.org/10.5194/bg-19-3663-2022
Rosati et al., 2018, GBC, 32,529–550. http://doi.org/10.1002/2017GB005700