FORCOAST

Earth Observation Services For Wild Fisheries, Oystergrounds Restoration And Bivalve Mariculture Along European Coasts

PROJECT DELIVERABLE REPORT

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Executive Summary

This deliverable provides specific descriptions, as well as an overview, of the ForCoast pilot models, and what they could achieve in terms of extension of the marine information available from CMEMS datasets. To the aim of assessing fitness-for-purpose regarding user-requested services, we describe the model's domains and grids, state variables being resolved, numerical engines employed and forecasting capacity. To the aim of opening the roadmap towards the establishment of a centralized ForCoast platform, we present data inputs and storage requirements as well as data infrastructure being currently deployed at a pilot level. Finally, we identify aspects of those models having made the object of specific validation exercises and advocate for a centralized validation protocol.

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1. Introduction

This deliverable provides an overview of the regional models employed within Forcoast. In the Forcoast workflow, regional models are used to extend Copernicus products for the description of marine conditions. This is achieved most of the time by providing local downscaling and/or, embedding models for specific aspects of the environmental dynamics (eg. dispersal). This extension is done in order to reach the relevant information needed to build user-requested services. In this regard, this document should be perceived as an overview of the regional model's current state and foreseen development within the project lifetime.

First, this overview should allow to assess the adequacy of ForCoast modelling capacity in regards to user requests (D2.1). In particular, to ensure that the ensemble of Copernicus products and ForCoast regional models can provide sufficient information to build services adequately meeting user-requests and, where needed, to identify gaps and propose optimal alleviation. Those questions are to be asked specifically per sector, and evaluated for the different corresponding ForCoast Pilot sites.

Second, we gathered here technical requirements of the regional models (eg. external forcing data, computation resources), so as to support the design of a central Forcoast infrastructure, aiming at centralising the ForCoast service provision and commercialisation, sector-wise and across Europe.

Finally, this overview aimed to identify modelling systems, and more precisely state variables, that were specifically validated prior to ForCoast, as a first step towards a ForCoast service quality description and validation.

2. Overview

2.1 Domains and resolutions

Figure 1 provides an European overview, as well as specific maps of the ForCoast Pilot domains. It illustrates the wide geographical distribution of the ForCoast pilot cases, in terms of marine conditions: tidal dynamics, presence of large rivers, bathymetry slope, distance and influence from the open ocean and atmospheric regimes. This diversity is precious to the project in the sense that it denotes a consortium expertise covering a large scope of marine and coastal phenomenons.

The specifications of ForCoast models, that were built prior to the project lifetime and following regional specificities, are relatively heterogeneous. The finest spatial resolution (considering embedded models) reaches below 500 m in four of the ForCoast pilots, and is below 1 km in all cases (Fig. 2). Regarding coastal dynamics, most pilots have their shallower cells above 5 m depth, thus resolving relatively shallow areas, while some (3 pilots) do consider wetting-drying scheme, which is better adapted for coastal simulations in tidally dynamic areas.

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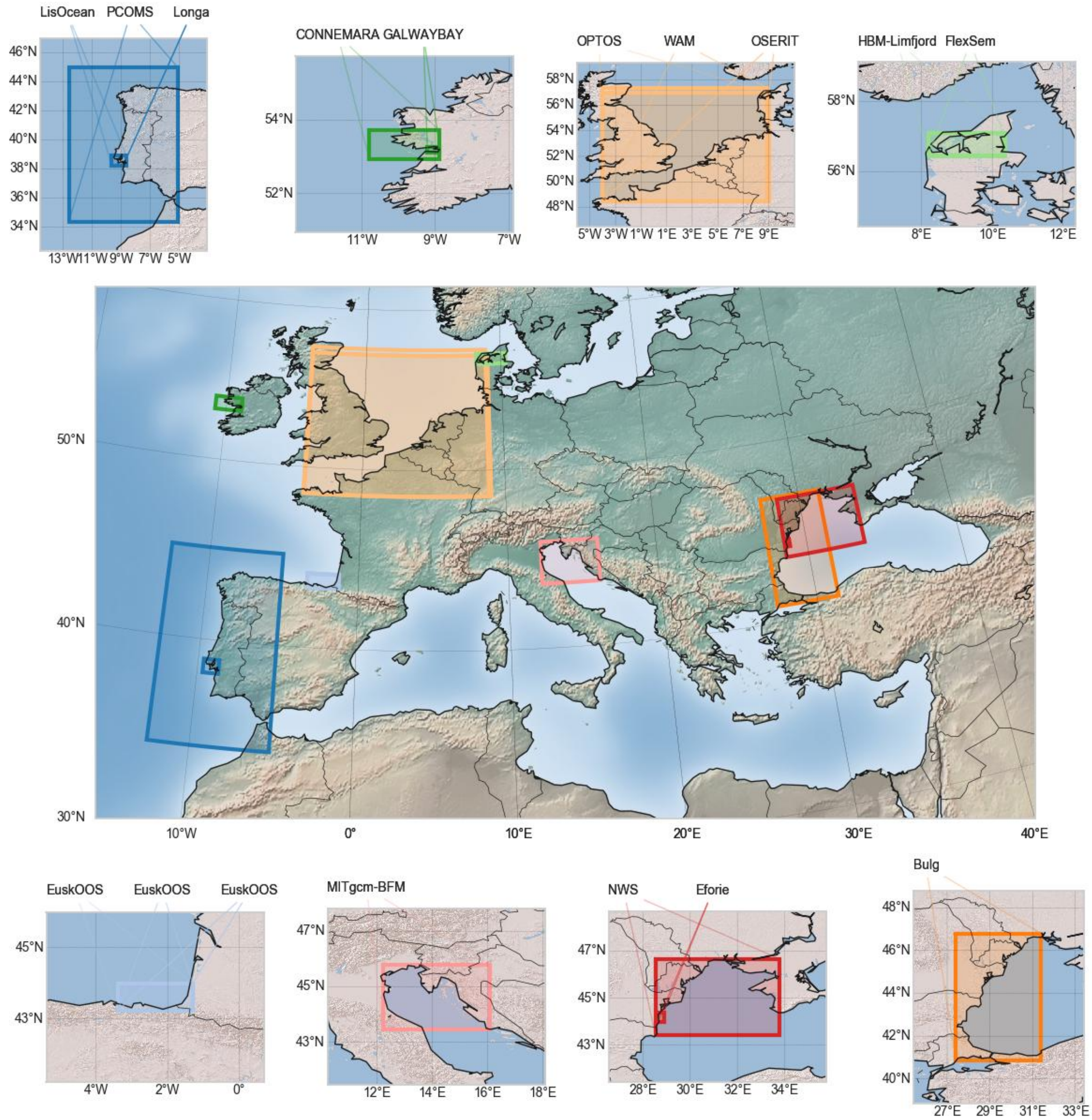

Figure 1.Domains of the ForCoast Pilot models.

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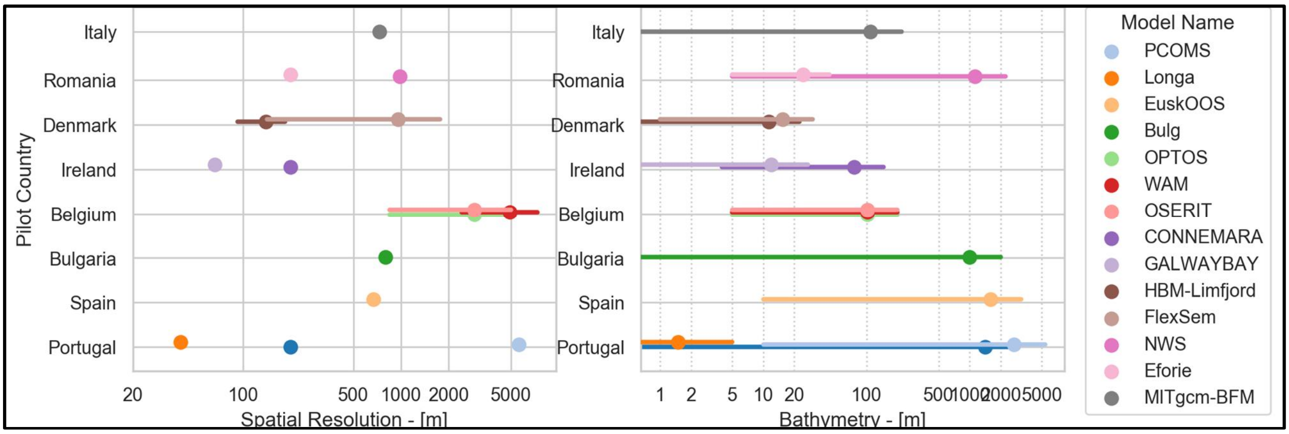

Figure 2. Spatial resolutions and bathymetry ranges covered by the different ForCoast models (for some models, spatial resolution varies across the domain).

2.2 Variables

At present, the ForCoast regional models present an important inhomogeneity in terms of resolved variables. The usual variables of hydrodynamical models (temperature, salinity, currents) are operationally currently available in 4 pilots (Fig. 3), and will be ready for 7 pilots within the years. Biogeochemical models are actually operationally available for 1 pilot, and should be available for 5 pilots by the end of 2020. It will have to be considered, in terms of service design, that no extension of Copernicus biogeochemical products are currently foreseen in the pilots addressing the wild fishery sector. Dispersal modelling modules (used for oil spill, coastal pollution such as bacterial outbreaks, eggs and larvae dispersal) aren't currently available for any pilots, but could be implemented by the end of 2020 for 5 pilots, addressing bivalve mariculture (4) and fisheries (1). Higher trophic levels, be they pelagic or benthic, are only considered in two pilots. Finally, none of the pilots aims at resolving sea-ice or suspended/mineral sediments dynamics within the project. Again, turbidity in estuaries might be an issue relevant to users, and this situation has to be evaluated against D2.1. Specific validation is only rarely available at present, while data assimilation remains exceptional.

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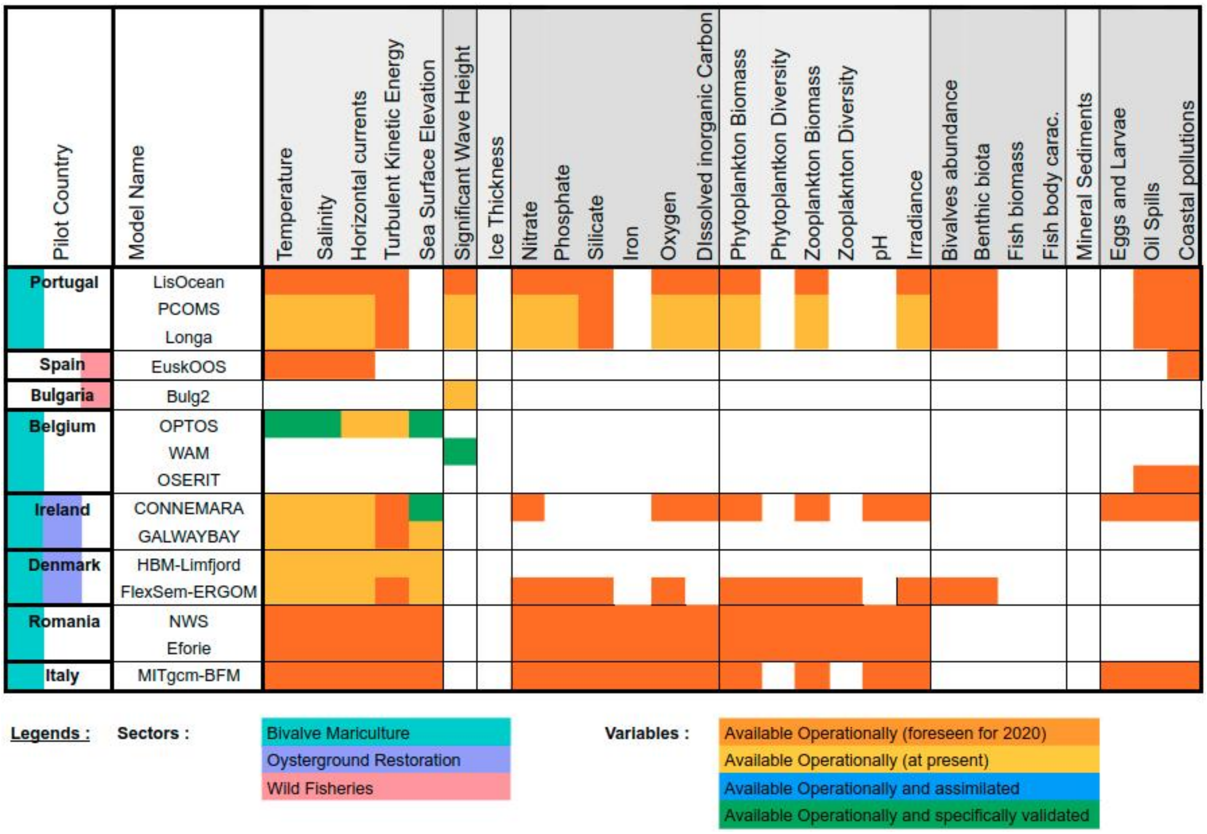

Figure 3. State variables and corresponding operational levels, for the different ForCoast Pilots.

2.3 Resources

2.3.1 Model Engines

A large variety of model engines are used amongst the different ForCoast pilots. Per engine, we mean a given model software. All engines are summarized in Table 1, which provides reference websites or publications. In fact, the only models being used in more than one pilot are used in two pilots only, being those models ROMS (Hydrodynamics and particle drift / dispersal), NEMO (Hydrodynamics) and WAM (Wave). This being stated, the table indicates that the consortium gathers a large expertise in terms of existing marine modelling solutions. In particular, this expertise could be exploited to alleviate, if needed, any stringent information gap preventing to answer a specific user-request.

Table 1. Model engines used by ForCoast partners

Type	Model Engine	Pilots	Website / Reference
Hydrodynamics	ROMS	Spain, Ireland	https://www.myroms.org/
	NEMO	Bulgaria, Romania	https://www.nemo-ocean.eu
	MOHID	Portugal	http://www.mohid.com/
	COHERENS	Belgium	http://odnature.naturalsciences.be/coherens/
	HBM	Denmark	http://ocean.dmi.dk/models/hbm.uk.php

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	Flexsem	Denmark	https://marweb.dmu.dk/Flexsem/
	MITgcm	Italy	http://mitgcm.org/
Biogeochem.	**MOHID**	Portugal	http://www.mohid.com/
	ERGOM-DK	Denmark	https://projects.au.dk/memc/models/
	BAMHBI	Romania	https://doi.org/10.1016/j.ocemod.2016.03.006
	BFM	Italy	http://bfm-community.eu/
Particle Drift / Dispersal	**MOHID**	Portugal	http://www.mohid.com/
	ROMS	Spain, Ireland	https://northweb.hpl.umces.edu/LTRANS.htm
	Ichtyop	Ireland	https://www.ichthyop.org/
	OpenDrift	Bulgaria	https://github.com/opendrift/opendrift/wiki
	NEMO	Romania	https://www.nemo-ocean.eu
	MITgcm -	Italy	http://mitgcm.org/
Waves	**WAM**	Belgium, Bulgaria	https://github.com/mywave/WAM
	WW3/SWIM	Portugal	https://polar.ncep.noaa.gov/waves/wavewatch/manual.v5.16.pdf

2.3.2 External Forcings

Most Pilot models exploit CMEMs products as boundary conditions at their open boundaries (see also ForCoast deliverable D3.1), which are thus available as operational forecasts. Atmospheric conditions are obtained from the UK MetOffice ECMWF services for 7 pilot models. 7 out of the 17 models use outputs from regional atmospheric models. It was not considered while collecting information for this deliverable, to enquire about the delivery time, forecasting extent and available data infrastructures for these atmospheric models but this might be a bottleneck for the operationalization of ForCoast services. Besides, model skill comparison across pilots could be targeted to evaluate the assets of using regional atmospheric models.

As concerns land discharges, climatologies obtained from Perseus Project, or unreported sources are used in most cases, generally for small rivers. Several pilots nonetheless report near real-time riverine data. This concerns all 12 basque rivers (Pilot 2), Corrib river, the most important tributary of the Galway Bay (Pilot 5) and the Po river (Pilot 8). Nutrient loads have not been explicitly described here but may be described when relevant in the pilot specific sections of this deliverable.

Table 2. Atmospheric and land forcings used by ForCoast Pilot models.

Pilot Country	Model Name	Atmospheric	Land
Portugal	LisOcean	AROME(2.5km - IPMA) / WRF3km(IST)	MOHIDLand or climatological monthly average
Portugal	PCOMS	MM5(9km - IST) / WRF (3km - IST)	
Portugal	Longa		
Spain	EuskOOS	WRF model	
Spain	EuskOOS	Meteogalicia (12 km)	
Spain	EuskOOS	Euskalmet (1 km)	
Bulgaria	Bulg		
Belgium	OPTOS	UKMO	weekly climatology of river discharge (fresh water only) computed on period 1990-2010
Belgium	WAM	UKMO or ECMWF	
Belgium	OSERIT	UKMO or ECMWF	weekly climatology of river discharge (fresh water only) computed on period 1990-2010
Ireland	CONNEMARA	ECMWF	The main river NRT discharge data, other rivers monthly climatologies
Ireland	GALWAYBAY	ECMWF	The main river NRT discharge data, remaining rivers monthly to annual climatologies, but under review
Denmark	HBM-Limfjord	DMI-Harmonie atmospheric moder, 2.5km resolution	E-Hype river discharge,https://hypeweb.smhi.se/explore-water/geographical-domains/#europehype
Denmark	FlexSem	DMI-Harmonie atmospheric moder, 2.5km resolution	E-Hype river discharge,https://hypeweb.smhi.se/explore-water/geographical-domains/#europehype
Romania	NWS	ECMWF	PERSEUS
Romania	Eforie	ECMWF	PERSEUS + hidro.ro
Italy	MITgcm-BFM	ECMWF and higher resolution Limited Area Models (~4 to ~2 km)	real-time discharge data for the main river (Po), climatologies (other minor rivers)

2.3.3 Data Storage and Transfer

We indicate in Table 3, for each pilot model, the storage memory requirements for one day of forecast product, including all variables indicated in Fig. 3. Also, we identify the current data delivery systems set prior to ForCoast, to inform on the ForCoast platform deployment strategy. It can be seen that there is no homogeneous preference at present in terms of data distribution platforms.

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Table 3. Memory usage (per day), temporal resolution, data sharing platform and reference websites for the different ForCoast pilot models.

Pilot country	Model Name	Storage /d	Temporal Resolution	Data Delivery System	Website
Portugal	LisOcean	1.2 Gb	Surface - Hourly 3D - every 3h	Thredds, Web platform	http://mycoast.maretec.org/?date=1576459800000&timespan=1d&zoom=9&extent=-1340818.5952277%2C4521987.4107646%2C-753782.21807928%2C4808473.3927376&products=3857_ifado__0m_sea_water_velocity_tagus_vectorfield&opacity=100&stackLevel=120 http://thredds.maretec.org/thredds/catalog/MOHID_WATER/LISOCEAN_0.003DEG_50L_3H/FORECAST/catalog.html
	PCOMS	3.5 Gb	Surface - Hourly 3D - every 3h	Thredds, Web platform	http://forecast.maretec.org/aqua/maps/mapResultDisplay.html?region=BIOPCOMS http://thredds.maretec.org/thredds/catalog/MOHID_WATER/PORTUGAL_0.06DEG_50L_3H/FORECAST/catalog.html
	Longa	0.04 Gb	10 min	Not implemented	
Spain	EuskOOS	0.58 Gb	hourly	THREDDS	www.euskoos.eus, http://thredds.euskoos.eus.
Bulgaria	Bulg	1 Gb		Not implemented	
Belgium	OPTOS WAM OSERIT	0.15 Gb	hourly	ERRDAP	https://erddap.naturalsciences.be/erddap/griddap/BCZ_HydroState_V1.html http://www.marineforecasts.be/ https://oserit.naturalsciences.be/
Ireland	CONNEMARA GALWAYBAY	7 GB 0.8 GB	hourly hourly	THREDDS Not implemented	http://milas.marine.ie/thredds/catalog.html
Denmark	HBM-Limfjord FlexSem-ERGOM	0.65 Gb	hourly (physics) daily (bio)	Not implemented Not implemented	https://www.dmi.dk/ and http://ocean.dmi.dk/ https://marweb.dmu.dk/Flexsem/
Romania	NWS Eforie	1.3 Gb	daily daily	FTP, THREDDS (in prep.) Not implemented	https://www.seamod.ro/thredds.html
Italy	MITgcm-BFM	6 GB	hourly	Not implemented	http://medeaf.inogs.it/adriatic

2.4 Forecasting capacity

All ForCoast pilot models propose 3-days forecasts on a daily update basis. One specific case (lagrangian drifts in the Belgian Pilot) specify "on-demand" delivery, which might be interesting to consider for a wider category of services. If sufficient to user requirements, those specifications (3-days forecast, daily update) could be set as a ForCoast standard for forecast products, without affecting the current operational set-up.

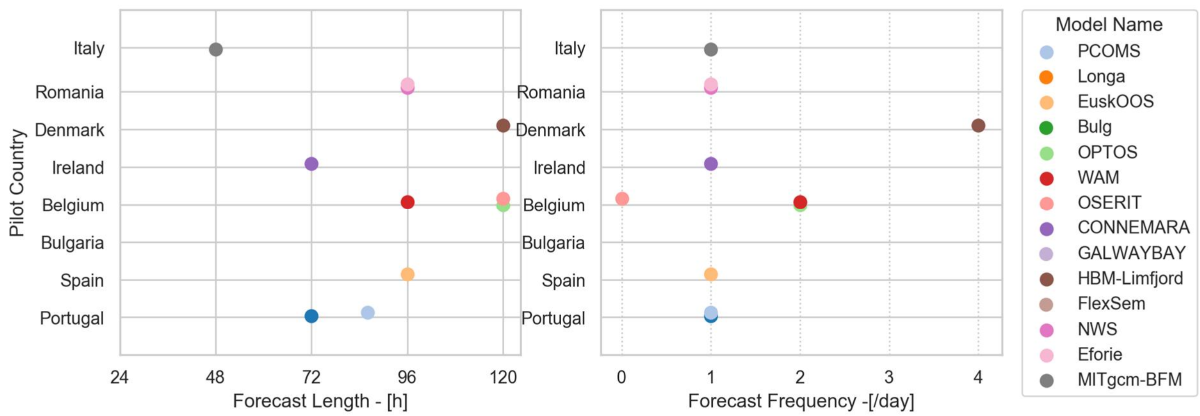

Figure 4. Forecast length and update frequency.

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3. Pilot models

Here follow more detailed descriptions of each specific pilot modelling system.

Pilot 1: Portugal

A) The Western Iberia operational model (PCOMS)

The Portuguese Coast Operational Modelling System (hereafter referred as PCOMS) is the operational modelling system that covers the Western Iberia regional ocean being designed to provide an operational solution for the Portuguese continental coast. This system provides operational hydrodynamics and biogeochemical forecasts for the Western Iberia regional ocean since 2009 and 2012 respectively, being probably the first operational model of its kind covering western Iberia. The PCOMS system has been broadly described in previous publications (Mateus *et al*., 2012; Campuzano, 2018).

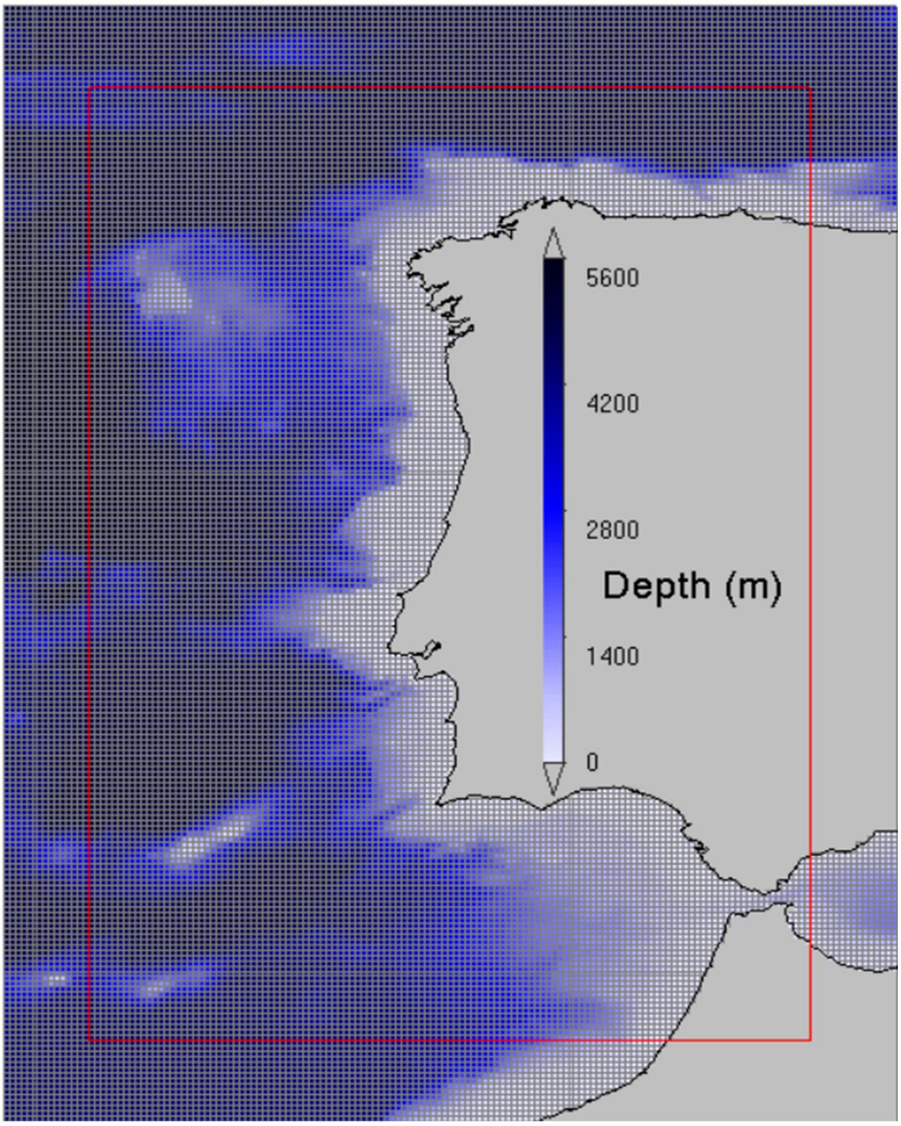

Figure 5. PCOMS regional ocean operational system domains, grids and current bathymetry. The red rectangle indicates the outer limit of the Portugal domain.

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The PCOMS is a 3D full baroclinic hydrodynamic and biogeochemical regional ocean operational model application covering the Iberian Atlantic coast and its adjacent ocean that downscales the Mercator-Océan PSY2V4 (Releases 1-4; hereafter referred as MERCATOR) North Atlantic solution (Drillet *et al.*, 2005). Its performance relies strongly on its core: the MOHID Water model, part of the MOHID Water Modelling System (http://www.mohid.com; Neves, 2013).

The MOHID Water Modelling System is an open source numerical model (https://github.com/Mohid-Water-Modelling-System) which code is continuously improved and updated by the MOHID community. The MOHID Water model is capable of simulating a wide range of processes, i.e. hydrodynamics, transport, water quality, oil spills, in surface water bodies (oceans, coastal areas, estuaries and reservoirs).

The PCOMS system is composed of two nested domains: WestIberia (2D) and Portugal (3D), with constant horizontal spatial resolution of 0.06°, covering the Iberian Atlantic coast and its contiguous ocean. The WestIberia domain covers the area limited to the following range of latitudes (33.48 °N, 45.90 °N) and longitudes (4.20 °W, 13.50 °W) resulting in a grid of 207 x 155 cells with maximum depths around 5600 m. The Portugal domain covers the area comprising the latitudes (34.38 °N, 45.00 °N) and the longitudes (5.10 °W, 12.60 °W) resulting in a grid of 177 x 125 cells and maximum depths around 5300 m. The Portugal domain is located centred in the West Iberia domain leaving 15 cells of difference in every direction. Vertically, the Portugal domain uses a hybrid discretisation consisting of a sigma domain with 7 layers from the surface until 8.68 m depth, with variable thickness decreasing up to 1 m at the surface, on top of a Cartesian domain with 43 layers with thickness increasing towards the bottom. The vertical distribution of the Cartesian domain is inspired by vertical discretisation used by the MERCATOR solution that serves as initial and boundary conditions (Drillet *et al.*, 2005). For the vertical turbulent viscosity, the PCOMS model uses the GOTM (General Ocean Turbulence Model) model (http://www.gotm.net; Burchard *et al.*, 1999) coupled in the MOHID model (Ruiz-Villareal *et al.*, 2005).

The WestIberia domain (2-dimensional) is forced on its open boundary only by astronomical tides provided by the FES2004 version of the FES (Finite Element Solution) global tidal model (Lyard *et al.*, 2006). The Portugal domain (3-dimensional) receives the water levels from the WestIberia domain and merges them at the open boundary with the Mercator-Océan PSY2V4 North Atlantic solution (Drillet *et al*., 2005) daily water levels.

The PCOMS system downscales the Mercator-Océan PSY2V4 North Atlantic solution (Drillet *et al*., 2005; hereafter referred as MERCATOR) for the West Iberian Atlantic coast and its contiguous ocean. The PCOMS system uses the available properties of the MERCATOR solution to initialize the velocity, water level and temperature and salinity fields. Additionally, those fields are used as open boundary conditions (OBCs) being included by nudging so boundary values do not diverge from the general circulation values imposed at the boundary. This is a common practice in ocean regional models especially for long-term integration (Chen *et al.*, 2013).

Since 2012, the PCOMS is coupled to the MOHID WaterQuality module. This module includes inorganic and organic forms of nitrogen and phosphorus on its dissolved and particulate forms as the source of nutrients. Oxygen, nutrient, phytoplankton and zooplankton concentrations are modified based on the phytoplankton growth, respiration and predation by zooplankton limited by the availability of light and nutrients.

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Monthly climatological 3D fields of oxygen, nitrate and phosphate from the World Ocean Atlas 2009 (WOA09; Garcia *et al.*, 2010a and 2010b) are used as initial and boundary conditions, in a similar fashion than the MERCATOR properties. Monthly values are only available for the top 500 meters and 1500 m for oxygen and nutrient concentrations respectively; those values were completed until the seabed using the annual average profile

Since 2011, the PCOMS model application has been continuously in operation. The forecast application runs daily simulating the previous day, to use the best atmospheric forecast available, followed by a 5-day forecast. On a weekly basis, the model simulates the previous fortnight period with the best solution provided by MERCATOR. The readiness, reliability and availability of the PCOMS results allow development of downstream services and they are accessible through the MARETEC Thredds Data Server (http://thredds.maretec.org).

An updated version of the PCOMS is being prepared during the ForCoast project. This new version is more efficient in computing time using MPI parallel processing and replaces the physico-chemical boundary conditions for CMEMS Global Ocean 1/12° Physics Analysis and Forecast updated Daily (GLOBAL_ANALYSIS_FORECAST_PHY_001_024) and CMEMS Global Ocean Biogeochemistry Analysis and Forecast (GLOBAL_ANALYSIS_FORECAST_BIO_001_028). Tidal boundary conditions are updated using the global tide solution FES2014 (Carrère *et al.*, 2016).

B) The Lisbon Metropolitan Area Operational Model (LISOCEAN)

Typical downscaling techniques consist of running simultaneously nested models. In those cases, the running time is defined by the most downstream model which usually has the smallest time step and is the slowest model. In order to surpass this difficulty, a delayed mode (offline) technique has been designed to provide boundary conditions to the local models at the open ocean boundaries. The Window Downscaling Technique consists in saving a 3D window of model results from a Regional model application with a high temporal resolution, around 900 seconds, able to represent the main processes coming from the open ocean (i.e. the tide signal) that serve as boundary conditions to other coastal and estuarine models with higher horizontal resolution. Afterwards, in delayed mode the local model is implemented as a nested model of the window of results. The described technique allows the local model to run independently, saving running time and reducing redundancy, while improving results. This technique also does not increase the running time of the upstream models and allow running several downstream models at the same time. The window downscaling technique is implemented in several estuaries in the Portuguese coast, including the Tagus estuary, which is also able to provide boundary conditions to even more refined local models (i.e. Campuzano *et al*., 2012).

The LISOCEAN model application :

This model application includes both the Tagus and the Sado estuaries as well as the ocean region covering until as far as 120 bathymetric isoline and the Tagus and Sado submarine canyons. Its main objective is to provide high resolution hydrodynamics and biogeochemical information on these highly influenced areas in regards to socio-economics, one of which including a ForCoast Pilot Areas - Sado estuary.

The current implementation of the LISOCEAN domain covers the area limited to the following range of latitudes (33.23 °N, 38.96 °N) and longitudes (8.66 °W, 9.65 °W) resulting in a grid of 285 x 355 cells with maximum depths around 2800 m. Vertically, a hybrid discretisation consisting of a sigma domain with 7 layers from the surface until 8.68 m depth, with variable thickness decreasing up to 1 m at the surface, on

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top of a Cartesian domain with 37 layers with thickness increasing towards the bottom has been implemented, following the same discretization of the PCOMS domain.

Although other boundary conditions are being tested, currently a combination of FES2014 for barotropic fields and IBI daily results for baroclinic fields is in place, and coupled to the MOHID biogeochemical module to provide fields of nutrients and phytoplankton. The open boundary conditions consist of a Flather radiation scheme and a relaxation scheme towards the IBI daily solution - 4 km grid resolution - and temporal decay of 1 day that will downscalle in the next future to PCOMS boundary conditions.

Atmospheric conditions are also being tested, with the current implementation using the IPMA-provided AROME model implementation with 2.5 km grid resolution and a temporal resolution of 1h with forecast of 48 h. Testing will include solutions from WRF computed at IST with grid and temporal resolutions of 3 km and 1 h respectively, with a forecast of 3 days, and also a MeteoGalicia-WRF implementation with grid and temporal resolutions of 1.5 km and 1 h respectively, with a forecast of 3 days. River inputs are being provided for the Tagus River as near-real time observations and for the Sado River as MOHID Land modelled flows.

This domain also generates a window of results for the Longa domain. This window covers the entire region of the Longa domain with a temporal resolution of 720 s.

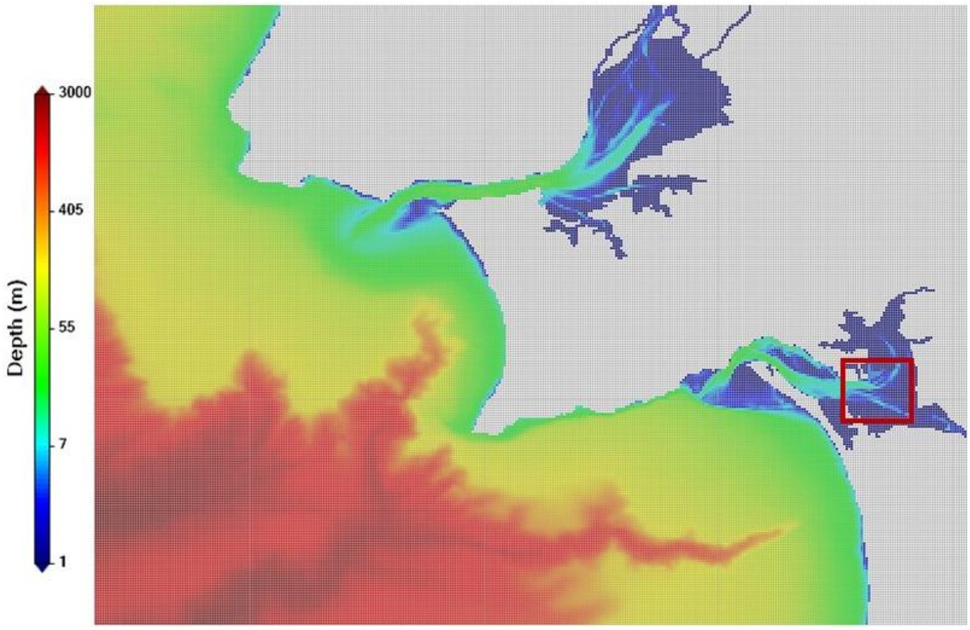

Figure 6. LisOCean operational system domain, grid and current bathymetry. The red rectangle indicates the area covered by the nested Longa domain.

C) The Aquaculture Production Area (Longa)

To improve the solution provided to the aquaculture site located in the “Longa” island inside the Sado estuary, a nested domain with 40 m grid resolution was implemented, covering the area limited to the following range of (38.476 °N, 38.502 °N) and longitudes (8.739 °W, 8.761 °W). Vertically, a hybrid discretisation consisting of a sigma domain with 7 layers from the surface until 8.68 m depth, with variable thickness decreasing up to 1 m at the surface, on top of a Cartesian domain with 3 layers with thickness

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increasing towards the bottom has been implemented, following the same discretization of the LisOcean domain.

Its open boundary condition is set by the LisOcean domain where it is nested, and includes the Flather radiation scheme together with a flow relaxation scheme with a temporal decay of 720 s. Atmospheric forcing is provided by the same solution as that of the LisOcean domain - the IPMA's AROME implementation for the Portuguese coast with 3 km grid resolution and hourly fields.

However, for now only a 2D solution is in place (and operational with forecast of 1 day) in order to meet the need - of the partner EXPORSADO - for high resolution surface elevation fields in forecast mode. However, a 3D implementation will be initialized later in 2020.

Pilot 2: EuskOOS modelling system (southeastern Bay of Biscay, Basque Country, Spain)

The Regional Ocean Modeling System (ROMS) is the hydrodynamic model used to estimate current, temperature and salinity fields in the southeastern Bay of Biscay. ROMS is an evolution of the S-Coordinate Rutgers University Model (SCRUM), as described by Song and Haidvogel (1994). The numerical aspects of ROMS have been described in detail by Shchepetkin and McWilliams (2005). Here we use the ROMS_AGRIF version developed at IRD (Debreu et al., 2012). ROMS has been used to model the water circulation in the study area (e.g., Ferrer et al., 2007, 2009, 2015; Ferrer and Caballero, 2011; Caballero et al., 2014; Laiz et al., 2014; and Legorburu et al., 2015).

The ROMS domain used in the operational system covers the southeastern Bay of Biscay, extending from 43.24º N to 44º N and from 3.4º W to 1.3º W, with a mean horizontal resolution of 670 m. Vertically, the water column is divided into 32 sigma-coordinate levels; these are more concentrated within the surface waters, where most of the variability occurs. The bathymetry was obtained from the European Marine Observation and Data network (Vasquez et al., 2015). This bathymetry was smoothed to ensure stable and accurate simulations (Haidvogel et al., 2000).

The hourly atmospheric forcing inputs used in ROMS are provided by two agencies: MeteoGalicia and Euskalmet (meteorological agency of Galicia and the Basque Country, respectively). These data (with a 12-km and 3-km horizontal resolutions, respectively) are obtained using the Weather Research and Forecasting model (WRF). A more detailed description of this model can be found in Skamarock et al. (2005). The WRF variables used in ROMS are the following: wind and air temperature at 10 and 2 m above sea level, respectively, precipitation rate, relative humidity, and long- and short-wave radiation fluxes. The air-sea heat and momentum fluxes are calculated using the bulk formulae of Fairall et al. (1996, 2003). These two different atmospheric forcing inputs are generating two different ROMS outputs.

At present, the conditions applied to the open boundaries are estimated using the outputs obtained by the Iberian-Biscay-Irish Monitoring and Forecasting Center, IBI-MFC, based on the Nucleus for European Modelling (NEMO). From these outputs, we use the hourly averaged fields for the following variables: velocity, temperature, salinity and sea surface height. These fields are used only at the boundary points to reduce the size of the input files with information of 3D variables. Furthermore, every Thursday, ROMS is initialized in the whole domain with the updated data from NEMO, which include assimilation data of previous days. The objective of this initialization is to correct the possible deviations of ROMS due to the non-use of data assimilation.

The ROMS simulation includes the last daily averaged freshwater discharges (real-time data) from the following rivers: Adour, Barbadún, Nervión, Butrón, Oka, Lea, Artibai, Deba, Urola, Oria, Urumea, Oiartzun and Bidasoa. With the aforementioned information, we obtain 96-h forecasts for the study area. The

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online Lagrangian particle tracking module existing in ROMS is also activated and is generating forecasts of the 96-h evolution of several virtual particles released in the study area at high-temporal resolution (one minute). Several floats are located at the sea surface to forecast the drift of harmful algal blooms, especially towards the Mendexa region (a pilot aquaculture farm), marine litter or other type of pollution, and for search and rescue applications. The storage memory requirement for the 3D and hourly outputs (current, temperature and salinity fields) for one day of forecast is 0.58 Gb. The webpage to see the forecasts, only for the next four days, is located at http://www.euskoos.eus/ and the thredds with the netcdf outputs is located at http://thredds.euskoos.eus.

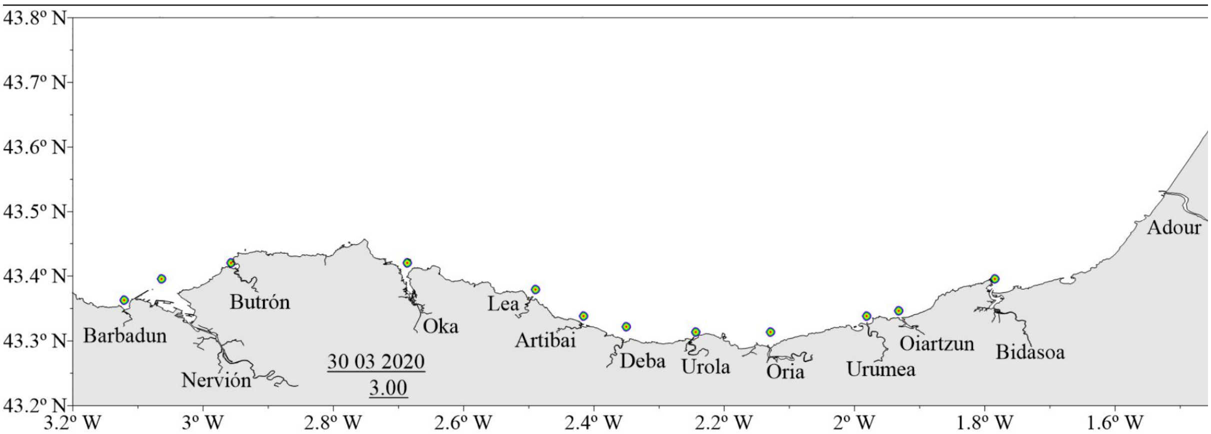

Figure 7. (Pilot 2) Basque rivers whose inclusion is foreseen for the next update of the EUsKOOS model.

Pilot 3: Bulgaria

The Pilot 3 involves implementation of a service in support of wild fishery consisting of three major components, the results of which will be available to users. The service will cover the EEZ zone of Bulgaria and Romania.

A) Implementation of a layer with additional information on the upwelling events in the region of interest, based on the products coming from CMEMS.

The classic oceanographic techniques will be used to evaluate the Ekman transport and the upwelling in the chosen area. The needed information for the estimation will come from the operational CMEMS Black Sea physical modelling system (marine.copernicus.eu). The system is based on the Nucleus for European Modelling of the Ocean v.3.6 (NEMO, Madec at al., 2012). The model horizontal grid resolution is 1/27 x1/36 (~3 km) and 31 z-levels with partial steps and the bathymetry is based on the GEBCO data (www.gebco.net). The assimilation is performed by a three-dimensional variational data assimilation system (3DVAR) that ingests all hydrographic profiles (mostly autonomous profilers ARGO), sea level anomaly data from available altimetry missions and sea surface temperature measurements retrieved from infrared sensors on-board polar-orbiting satellites. The state variables which will be used in the upwelling definition is sea surface temperature and currents from the surface up to the 100 m depth. These variables are regularly monitored by the operational CMEMS team and their quality is evaluated in the relevant Quality Information Document (CMEMS-BS-QUID-007-001).

B) Implementation of a nested wave model

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The wave products are generated using a WAM Cycle 4.6.2 3 km Black Sea model. WAM is based on the spectral description of the wave conditions in frequency and directional space at each of the active grid points of a chosen model area. The energy balance equation, complemented with a suitable description of the relevant physical processes is used to follow the evolution of each wave spectral component. A full description is given by the WAMDI group (1988), Komen et al. (1994), Günther et al. (1992), Janssen (2008) and Bidlot et al. (2007) Staneva et al. (2019).

The basin-scale WAM runs on a model grid situated between 40°51'36" N to 46°48'15" N and 27°22'12" E to 41°57'45" E, with a spatial resolution of about 3 km. It calculates the two-dimensional energy density spectrum at each of the 44699 active model grid points in the frequency and directional space. The solution of the energy balance equation is provided for 24 directional bands at 15° each, starting at 7.5° and measured clockwise with respect to true north, and 30 frequencies logarithmically spaced from 0.042 Hz to 0.66 Hz at intervals of $\Delta f/f = 0.1$. The wave model takes into account depth refraction and wave breaking and is driven by the one-hourly analyzed ERA5-U10-wind fields (spatial resolution 0.25°*0.25°) that are generated by the atmospheric IFS model of the ECMWF. Starting in 2002, the setup (BLKSEA_REANALYSIS_WAV_007_006) includes a continuous data assimilation into the wave model fields using satellite data (wind speed and significant wave height) recorded by the radar altimeters of Jason-1 (2002/01-2013/06), Jason-2 (2013/06-2019/02) and Jason-3 (2019/02-2019/06).

For the Western Black Sea a downscaled high-resolution model is implemented, using at the open boundary the spectral information derived from the basin-scale CMEMS Black Sea Model. The spectral information is extracted at each boundary grid point. The resolution of the western Black Sea wave model is 1 km. The geographical coverage of the nested western Baltic Sea area is: 40.87083 S ==> 46.80416 N and 27.41250 W ==> 31.42083 E.

In addition to the standard CMEMS variables for the Black Sea case study new information that is requested for the fisheries will be provided, namely extreme characteristics (50th, 95th and 99th percentiles) as well as maximum wave high and crest (Hmax and Cmax, Benetazzio et al, 2018)

C) Implementation of a layer with additional information - Fish Suitability Index, based on the biogeochemistry products coming from CMEMS.

The product will integrate the available CMEMS products on essential oceanographic parameters, such as phytoplankton and primary production and downstream services in order to identify the zones favorable for fishing. All available information will be aggregated into a unique product that is more representative for the habitat conditions and easier to interpret than multiple environmental indicators. The layer will be made available to the Individual fishermen, mid-size and industrial fishing. Identification of habitats suitable for specific fish species can be used in order to increase the probability of maximizing the ratio between fishing effort and catches.

Pilot 4: Belgium

OPTOS is the chain of hydrodynamic models used to estimate current, temperature and salinity fields in the southern North Sea and the eastern English Channel. This model is based on COHERENS (COupled Hydrodynamical Ecological model for REgioNal Shelf seas), a multi-purpose modelling system based on a 3D numerical hydrodynamical model. COHERENS is available to the scientific community as a free and well-documented open source code (http://odnature.naturalsciences.be/coherens/.

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WAM is the model used to predict directional spectra along with wave properties such as significant wave height, mean wave direction and frequency, swell wave height and mean direction, and wind stress fields corrected by including the wave induced stress and the drag coefficient at each grid point at chosen output times. The WAM model is a 3rd generation model which integrates the basic transport equation describing the evolution of a two-dimensional ocean wave spectrum without additional unplanned assumptions regarding the spectral shape. There are three explicit source functions which describe the wind input, non-linear transfer and white capping dissipation. There is an additional bottom dissipation source function and refraction terms are included in the finite-depth version of the model. The model runs on a spherical latitude-longitude grid.

Physical models are coupled with two Lagrangian transport models:

- OSERIT (Dulière et al., 2013), already implemented in forecast, is a 3D oil spill drift and fate model accessible through a user-friendly web application. Complex, real-life scenario-based simulations can be set up to fit a wide range of emergency situations that might arise at sea.
- The larval transport model LARVAE&CO (Lacroix et al., 2013) was developed to assess flatfish larval dispersal, recruitment at nurseries and connectivity between spawning grounds and nurseries (Barbut et al., 2019) as well as the impact of climate change on sole recruitment and connectivity in the North Sea (Lacroix et al. 2018). This model has also been used, after some adaptations to other species such as blue mussels and flat oysters, to assess for instance the impact of artificial hard substrates on marine organism's dispersal (project UK-INSITE-UNDINE, Dannheim et al., 2018), or the possibility of oyster bed restoration (BE-Oyster restoration project, De Mesel et al., 2018). The model has not been validated yet due to lack of data. This model should be coupled during the project to forecast models to predict spat arrivals in bivalve farms.

The more recent version of the biogeochemical model MIRO&CO model (Dulière et al., 2019), should be implemented in forecast mode within the frame of the project in support of farming activity. This model is based on the MIRO model, a biogeochemical model that has been designed for Phaeocystis-dominated ecosystems (Lancelot et al., 2005). It integrates 4 modules describing: the dynamics of (i) phytoplankton [diatoms, autotrophic nanoflagellates and Phaeocystis colonies], (ii) zooplankton [microzooplankton and copepods], (iii) bacteria and dissolved and particulate organic matter degradation and, (iv) nutrients [nitrate, ammonium, phosphate and dissolved silica] regeneration in the water column and the sediment. Phaeocystis free-living cells are included in nanoflagellates, while Phaeocystis colonies are described by the sum of 2 components: colonial cells and the polysaccharide matrix in which the cells are embedded, and which serves as a reserve of energy. The MIRO&CO model describes the biogeochemical and ecological dynamics in the English Channel and the southern North Sea. Model results of nutrients (N, P, Si), chlorophyll a concentration, primary production, etc. are available over the period 2000-2010 (grid resolution 5 km x 5 km). A model validation performed by Lacroix et al. (2007) and Dulière et al. (2017) showed that the model is able to capture the geographical distribution of nutrients and in particular the strong coastal gradients, but it underestimates chlorophyll a concentration in the Belgian waters.

Pilot 5: Connemara and Galway Bay models

The Connemara model is based on the Regional Ocean Modelling System (ROMS), a free-surface, hydrostatic, primitive-equation ocean model (Shchepetkin and McWilliams, 2005). It covers the mid-west coast of Ireland and consists of 640 x 440 grid cells, providing a horizontal resolution of approximately 200 meters and 20 layers in the vertical. The model is nested offline in a regional Northeast Atlantic model run operationally at the Marine Institute Ireland. Time series of water levels, 2-D and 3-D momentum, temperature and salinity are provided every hour.

Surface forcing is obtained from the hourly 0.1º ECMWF atmospheric fields. At the open boundaries, clamped boundary conditions have been imposed for 3-D momentum and tracers, whilst a combination of Chapman and Flather conditions have been applied for the free-surface and the barotropic velocity. Heat fluxes are calculated from the bulk formulae and surface freshwater fluxes are obtained from the prescribed rainfall rates and the evaporation rates computed by the model. Near real-time water flux data are provided to simulate freshwater runoff from the main river –the Corrib river, the most important tributary of the Galway Bay–, whereas monthly climatologies are used for smaller rivers, such as Clarin and Dunkellin, also in the inner Galway Bay.

Sea level time series from the Connemara Operational model have been validated against tide gauge data (Nagy et al., 2020).

The Connemara model is undergoing further development that will feed into FORCOAST project, namely the set-up and activation of a biogeochemical module. This module will be the model described in Fennel et al. (2006) and will comprise of the following state variables: chlorophyll a, phytoplankton biomass, zooplankton biomass, small detritus, large detritus, nitrates and ammonia. The initial and boundary conditions will be sourced from CMEMS IBI BIO model and nutrient inputs have been collated from relevant institutions in Ireland.

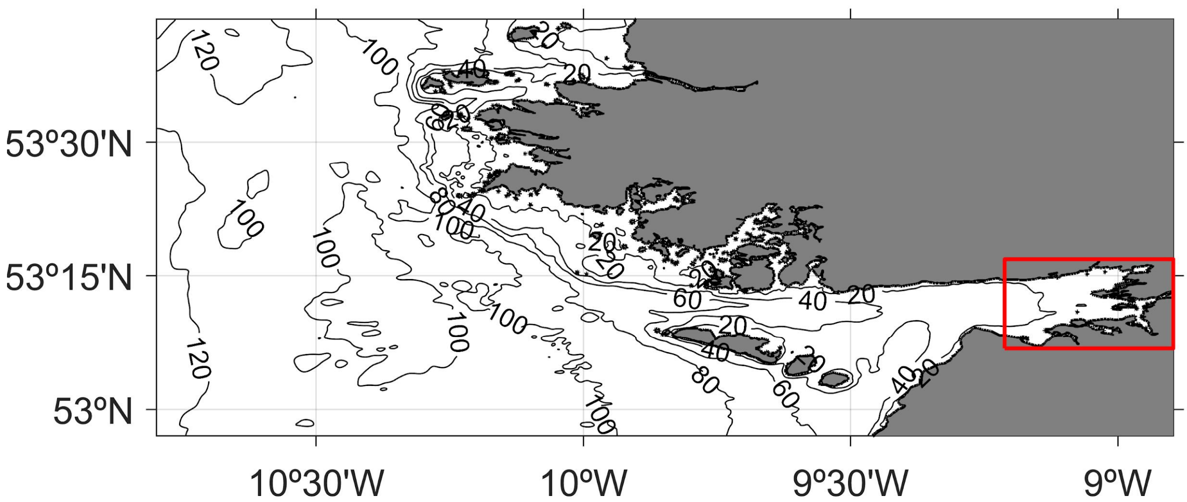

Figure 8. (Pilot 5) Domain of the Connemara Operational model, in the western coast of Ireland. The domain of the nested Galway Bay model is also shown (red).

The Galway Bay model has been recently developed based on a ROMS offline nesting application inside the Connemara Operational model. It is a refinement of the latter by a factor of three, resulting in 336 x 283 grid cells and a horizontal resolution of less than 70 meters. It covers the eastern and innermost part of the Galway Bay and has 8 vertical layers. Similarly, time series of water levels, 2-D and 3-D momentum, temperature and salinity are provided every hour.

Same atmospheric forcing and open boundary schemes have been applied as in the parent model. In addition, a wetting and drying scheme has been introduced to allow for proper representation of intertidal areas. Near real-time freshwater inputs from the Corrib river and monthly climatologies from smaller rivers –Clarin and Dunkellin– have been added to the model. Moreover, freshwater inputs from a

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submarine groundwater discharge occurring at Kinvara Bay (McCormack et al., 2014) have been included as an annual average of 12 m^3/s.

Results from the Galway Bay model will be validated against the tide gauge, ADCP currents and in-situ temperature and salinity records where available.

It is also planned that the Galway Bay model will include lagrangian simulations of the dispersion of particles in the bay from predefined sources as well as either a coliform module or a passive tracer dispersion module that will predict the dispersion and dilution of sewage/coliforms from predefined sources.

Pilot 6: HBM LImfjord and FlexSem-ERGOM

FlexSem is a modular marine modeling framework containing a 3D hydrodynamic model, which easily can be coupled to biogeochemical-, sediment transport- and agent based- modules (Larsen et al. 2020). The setup for the Limfjord has 6686 elements in an unstructured grid, 13 layers and a total of 44456 computational cells. The spatial resolution varies between 142 and 1770 meters and the model is forced on open boundaries by surface height, velocities, temperature and salinity from the HBM model. 2D meteorological forcings of wind speed and temperature affect the surface and 39 fresh water sources contribute fresh water to the model (Thodsen et al. 2018). The biogeochemical model for the Limfjord is under development and is based on the Danish (DK) version of the ERGOM model (Maar et al. 2018). The ERGOM model simulates the cycling of N, P and silicon (Si) (Neumann 2000, Maar et al. 2011, Wan et al. 2012). The 11 state variables describe concentrations of four dissolved nutrients (NO_3, NH_4, PO_4, SiO_2), three functional groups of phytoplankton (diatoms, flagellates, cyanobacteria), micro- and mesozooplankton, detritus and oxygen (Figure 6). The model considers the processes of nutrient uptake, N_2-fixation by cyanobacteria, growth, grazing, respiration, recycling, mortality, settling, nitrification and denitrification. The pelagic ERGOM model is two-way coupled to a sediment biogeochemical model through sedimentation and resuspension of organic matter and diffusive fluxes of nutrients and oxygen (Petersen et al. 2017). Pelagic detritus and diatoms sediment into an organic detritus pool and a dead diatom pool, respectively, in the unconsolidated top layer of the sediment. Organic matter in the unconsolidated sediment can be resuspended, respired or gradually transferred to the consolidated sediment layer. Recycled nutrients (NH_4, PO_4 and SiO_2) in the sediment porewater are exchanged with the bottom water through diffusion and a fraction of the recycled NH_4 is lost in a coupled nitrification-denitrification process. Under oxidized conditions, PO_4 and SiO_2 are retained in the sediment by adsorption to metals and released, when the sediment becomes reduced. Benthic suspension feeders ingest phytoplankton and detritus in the bottom water, whereas deposit feeders ingest freshly deposited diatoms and detritus in the sediment. The pelagic- and benthic model parts were previously validated against monitoring and research data (Maar et al. 2011, Maar et al. 2016, Petersen et al. 2017, Maar et al. 2018).

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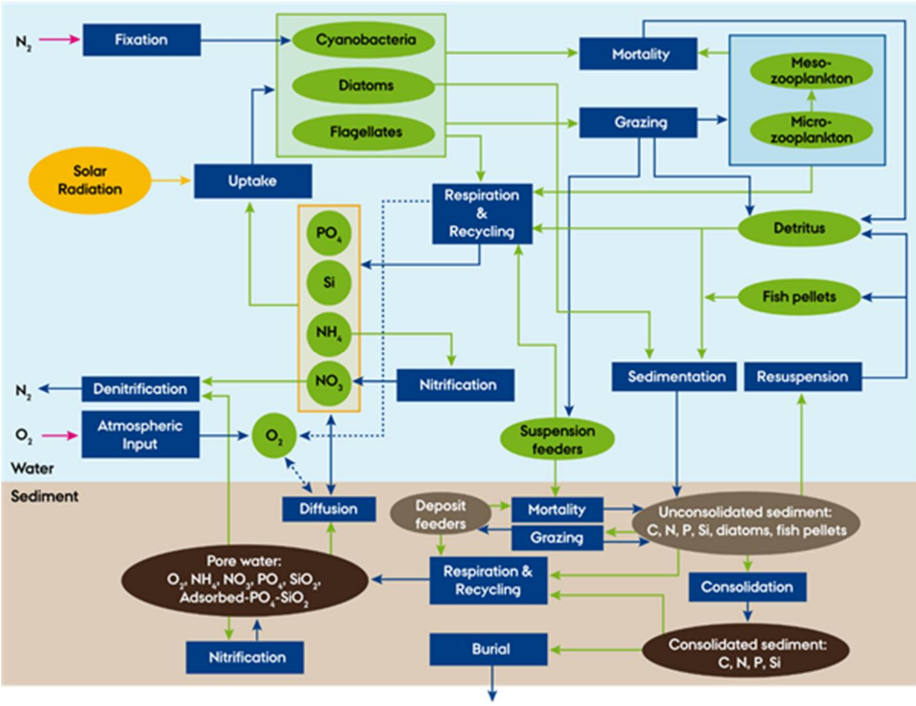

Figure 9. (Pilot 6) Model diagram showing the pelagic (green circles) and benthic (brown circles) state variables and associated fluxes (blue boxes) in the ERGOM-DK model.

Pilot 7: Romania

The forecasting system is composed of a physical model (NEMO 3.6) and a biogeochemical model (BAMHBI), implemented on the north-western part of the Blak Sea at 1km resolution and 59 unevenly distributed vertical layers. The bathymetry is based on GEBCO 2019 with manual adjustments along the coastlines to reflect dams and other coastal infrastructure. The model area comprises the shelf break

Initial conditions and lateral boundary conditions are provided by interpolation of CMEMS Black Sea MFC (Analysis-Forecast product). River data are obtained from SESAME and PERSEUS products. The biogeochemical variables are transported online by the physical model. No data assimilation is performed.

The BAMHBI model describes the food web from bacteria to gelatinous carnivores through 28 state variables. It is conceived with the Black Sea in mind, e.g. it explicitly represents the processes in the suboxic and anoxic layers. Biogeochemical processes in anaerobic conditions have been represented using an approach similar to that used in the modelling of diagenetic processes in the sediments lumping together all the reduced substances in one state variable. In this way, processes in the upper oxygenated layer are fully coupled with anaerobic processes in the deep waters, allowing performing long term simulations. This fully coupling between aerobic, suboxic and anoxic processes is absolutely necessary for performing the long term reanalysis. Processes typical of low oxygen environments like denitrification, anaerobic ammonium oxidation (ANAMMOX), reduced decomposition efficiency have been explicitly represented (Gregoire et al., 2008). Moreover, the model includes a representation of diagenetic processes (Capet et al., 2016) using an efficient and economic representation as proposed by Soetaert et al., 2000. The incorporation of a benthic module allows to represent the impact of sediment processes on important biogeochemical processes such as sediment oxygen consumption (that is responsible for the generation of hypoxic conditions in summer), the active degradation of organic matter that determines the vigour of the shelf ecosystem (~30 % of the primary production produced in shelf waters is degraded in the sediment) and the intense consumption of nitrate by benthic denitrification that filters a substantial

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part (~50 %) of the nitrogen brought by the north-western shelf rivers (the Danube being the most important one) and modulates primary production in the deep basin.

The forecasting system comprises a second level centered on the Constanta-Eforie area. The horizontal resolution is 200m, and the model is nested in the first level using the AGRIF nesting tool. The bathymetry is obtained from local measurements and smoothed toward the GEBCO bathymetry at the model boundaries. This second level is in development.

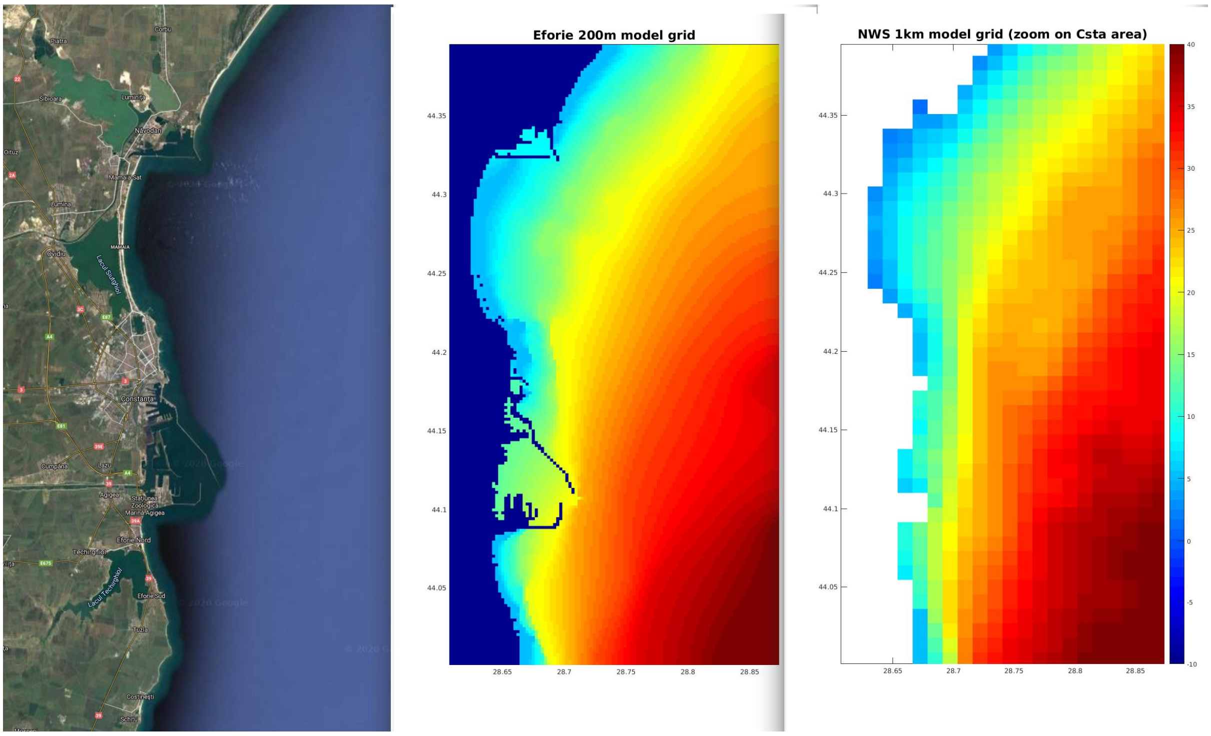

Figure 10. (Pilot 7) Area covered by the Eforie model, (left) Google maps image, (middle) Eforie model bathymetry at 200m resolution, (right) corresponding region in the NWS model at 1km resolution

Pilot 8 : Northern Adriatic Sea

The modelling system is based on the high-resolution MITgcm-BFM coupled model for the northern Adriatic Sea (Cossarini et al., 2017) implemented at OGS. The model is initialized and driven by the downscaling of the nominal products (hydrodynamics and biogeochemistry) of the CMEMS Mediterranean Sea Monitoring and Forecast Centre. Further, in the present hindcast mode, it integrates satellite data and, when available, water quality in-situ measurements by means of nudging algorithms.

The MITgcm hydrodynamic and transport modules are at the core of the MITgcm-BFM coupled hydrodynamic-biogeochemical model (Fig. 8). The biogeochemical processes are included via the BFMcoupler package, and integrated in space and time by the MITgcm. Hydrodynamic and biogeochemical variables can be assimilated by using either native MITgcm modules, or assimilation schemes affecting the coupler, or both.

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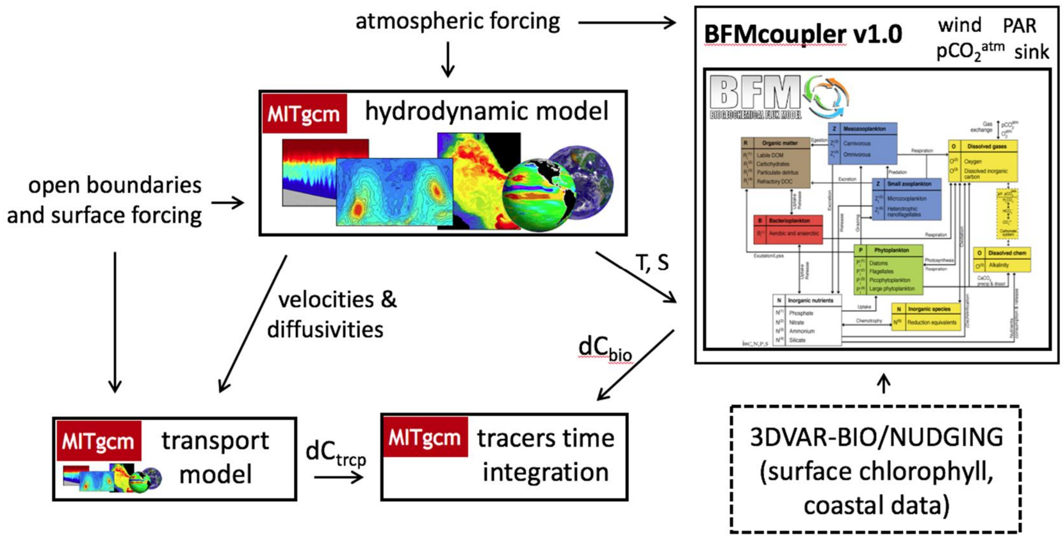

Figure 11. (Pilot 8) The MITgcm-BFM coupled hydrodynamic-biogeochemical model.

The model domain (northern Adriatic Sea) has been discretized with a horizontal resolution of 1/128° (850 × 600 m) and 27 unequally spaced vertical levels. The bathymetry spans north of latitude 43.5° N and explicitly considers the 19 major rivers flowing into the basin. Daily discharge rates are available for the main rivers (e.g., Po), while the other flow rates have been derived from up-to-date climatologies, modulated in order to have the maximum and minimum values in spring/autumn and summer/winter, respectively. The model setup also includes the contribution (in terms of nutrients and pollutants) of the main urban wastewater discharge points along the italian coast.

The meteorological forcing (air temperature, pressure and humidity, wind velocity, heat fluxes and precipitation) is obtained from the ECMWF models, but higher resolution forcing fields from Limited Area Models have already been used in hindcast simulations, and are foreseen in operational applications in the next future. Initial and daily open boundary conditions along the southern side of the domain are derived from the CMEMS modelling system.

Model resolution and set-up guarantee a proper simulation of the main basin and sub-basin scale features of the northern Adriatic Sea, both from the hydrodynamic and biogeochemical point of view.

4. Conclusions

This deliverable serves as an information document of the state of the pilots, providing an overview of ForCoast pilot models, and what they could achieve in terms of extension of the marine information available from CMEMS datasets. It also provides information relevant to the setup of a centralized ForCoast platform.

The fitness for purposes of the set of pilot models will have to be re-evaluated after a close analysis of D2.1 and D3.7. However, we already observe at this stage, a disparity in terms of resolved variables when pilots are gathered sector-wise. For instance, i) none of the pilots addressing wild fisheries resolves biogeochemical variables at regional scales ii) only one of the two pilots addressing oyster grounds restoration proposes a particle drift module, and iii) four pilot addressing bivalve aquaculture do not resolve surface wave dynamics.

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Regarding the development of a centralised ForCoast platform, we observe that there's no redundancy in terms of the model engines being used at the pilots. This means that centralizing the model simulations on a common computation infrastructure would demand a huge effort to install and maintain different softwares. However, we consider that this diversity constitutes a strength of the consortium in terms of marine modelling expertise and proficiency, which benefits knowledge transfer between pilots. Many pilots do not at present have an established FTP, THREDDS or ERDDAP server set operationally. Steps forward would be thus dedicated to the setup of data exchanges protocols between pilot models and a centralised service computation unit.

Furthermore, few of the pilot models are carrying out extensive validation exercise. Based on pan-European datasets normalized validation procedure in a framework will be developed in Task 5.2 and will be documented in Deliverable D5.2.

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