Modelling in the Mediterranean Sea

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Contents

Data provider

A suite of models have been developed by Istituto Nazionale di Oceanografia e di Geofisica Sperimentale (OGS) an independent national research institute in Italy

Regional summary

The Mediterranean Sea (MS) is a semi-enclosed sea, characterised by an inverse estuarine circulation with the Atlantic Ocean. Morphologically, the MS can be divided in two sub-regions (the Strait of Sicily separates the western and eastern Mediterranean), and it is characterized by the presence of a narrow continental shelf and two marginal sub-regions (the Adriatic Sea and the Aegean Sea). The major inflow into the Mediterranean is nutrient-poor, oxygenated Atlantic surface water through the Strait of Gibraltar. The western sub-basin is seasonally stratified and large parts of the open ocean eastern sub-basin are permanently stratified.

Physical processes create a dynamic and complex system in which mesoscale, thermohaline and wind driven circulations interact at different scales, resulting in a dominant west to east surface transport partially compensated by east to west transport at intermediate depths (Pinardi and Masetti, 2000).

The MS is considered an oligotrophic region and it exhibits low productivity (generally <150 gC m-2 yr-1), with the highest levels occurring in the open ocean convection areas (mainly in north-western sub-region), along the coasts, near major cities and at river estuaries. The lowest productivity levels occur in the southe-astern Mediterranean Sea.

These spatial trophic patterns are reflected in the deep chlorophyll maximum (DCM), a quasi-permanent structure (absent during the winter mixing period) in the MS, which is characterised by a zonal gradient: shallower in the west and deeper in the east (Lazzari et al., 2012; Siokou-Frangou et al., 2010).

Despite its oligotrophic features, the MS maintains high levels of biodiversity (Bianchi and Morri, 2000; Coll et al., 2010) and some hot spots for fisheries (Caddy et al., 1995). In fact, estimation of the catch statistics is of 1 million tons in the last decade. Clupeoids (herrings, sardines and anchovies) represent the most important target group comprising 35% of catch on average (data 2000-2008; see FAOStatJ, 2012)

Justification of model selection

The Mediterranean OGS model system consists of the following components:

- LTL: OPATM-BFM transport-biogechemical model;
- DA: 3D-variational scheme
- HTL: Ecopath with Ecosim

The OGS model system has been developed after a more than a decadal experience in 3D biogeochemical and ecosystem modelling of the Mediterranean Sea within a series of Italian and European projects.

The present version of OPATM-BFM model is part of the MyOcean Mediterranean Forecast System

(MFS). The hydrodynamic model of MFS, based on NEMO, is run by INGV (Italy) which provides the physical fields for the transport-biogeochemical OPATM-BFM model. The coupled system is run operationally twice a week at the CINECA supercomputer facility (Italy) to produce 7 days of hindcast and 10 days of biogeochemical forecast. The operational products are 3D daily averaged fields of chlorophyll-a, phosphate, nitrate, dissolved oxygen Net Primary Production and Phytoplankton Biomass.

Within MyOcean and OPEC the system has been upgraded by adding a 3D variational assimilation scheme. The assimilation scheme use satellite MODIS surface chlorophyll to update the phytoplankton groups.

The Ecopath with Ecosym modeling approach has been widely used to represent HTL groups dynamics as it allows for a representation of the food web in terms of functional groups and permits representation of exploitation activities. We take advantage of OGS experience in the field of EwE modeling which has been already applied to both coastal ecosystems (e.g., Lagoon of Venice) and open water ecosystems (e.g., Adriatic Sea) in the frame of several national and international projects, as well as of results of SESAME project for development of End-to-end models.

Technical overview of models used in this region

Hydrodynamic model

The transport model is a modified version of the OPA 8.1 transport model (Foujols et al., 2000), which resolve the advection, the vertical diffusion and the sinking terms of the tracers (biogeochemical variables).The meshgrid is based on 1/8° longitudinal scale factor and on 1/8°cos(ϕ) latitudinal scale factor. The vertical meshgrid accounts for 72 vertical z-levels: 25 in the first 200m depth, 31 between 200 and 2000 m, 16 below 2000 m.

The temporal scheme is an explicit forward time scheme for the advection and horizontal diffusion terms, whereas an implicit time step is adopted for the vertical diffusion. The sinking term is a vertical flux, where the sinking velocity is fixed for particulate matter and dependent on nutrients for two phytoplankton groups (diatoms and dinoflagellates).

The physical dynamics that are coupled with biogeochemical processes are pre-computed by an high resolution ocean general circulation model (OGCM MFS) run by INGV (Italy). This circulation model supplies the temporal evolution of the fields of horizontal and vertical current velocities; vertical eddy diffusivity; potential temperature; salinity, in addition to surface data for solar shortwave irradiance and wind stress (see section on boundary and forcing for further details).

Lower Trophic level model

The Lower Trophic level (LTL) model is the Biogeochemical Flux Model, BFMv2. This model’s features has been chosen targeting the energy and material fluxes through both “classical food chain” and “microbial food web” pathways (Thingstad and Rassoulzadegan, 1995), and to take into account co-occurring effects of multinutrient interactions. Both of these factors are very important in the Mediterranean Sea, wherein microbial activity fuels the trophodynamics of a large part of the system for much of the year and both phosphorus and nitrogen can play limiting roles (Krom et al., 1991; Bethoux et al., 1998). The model presently includes nine plankton functional types (PFTs). Phytoplankton PFTs are diatoms, flagellates, picophytoplankton and dinoflagellates. Heterotrophic

PFTs consists of carnivorous and omnivorous mesozooplankton, bacteria, heterotrophic nanoflagellates and microzooplankton.

BFM model describes the biogeochemical cycles of 4 chemical compounds: carbon, nitrogen, phosphorus and silicon through the dissolved inorganic, living organic and non-living organic compartments. Nitrate and ammonia are considered for the dissolved inorganic nitrogen.

The non-living compartments consist of 3 groups: labile, semilabile and refractory organic matter. The last two are described in terms of carbon, nitrogen, phosphorus and silicon contents.

Within OPEC project the BFM model has been coupled to a carbonate system module, which consists of two prognostic state variables: alkalinity (ALK) and dissolved inorganic carbon (DIC). DIC evolution is driven by biological processes (photosynthesys and respiration), exchanges at air-sea interface. Alkalinity evolution is affected by biological processes (nitrification, denitrification, and uptake and realease of nitrate, ammonia and phosphate by plankton cells). DIC exchange at the air-sea is resolved by computing the seawater pH, pCO2 and gas transfer formula (OCMIP II model, Orr et al., 1999),

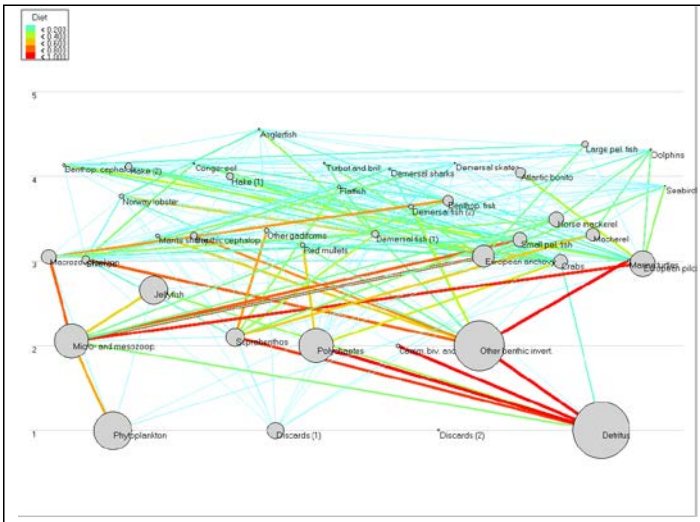
Several others improvements have been implemented within OPEC project as well. The chlorophyll synthesis parameterisation of phytoplankton functional types has been improved by the introduction of a multi-nutrient (nitrogen and phosphorus) limitation in the chlorophyll synthesis equation has improved this situation. Furthermore, the model dynamics have been constrained by a satellite-based light extinction coefficient. Following Geider et al. (1997), the BFM parameterisation describes gross primary production (gpp) in terms of PAR, temperature, carbon quota in plankton cells, chlorophyll content per unit of carbon biomass, and silicate concentrations in the case of diatoms. In the previous BFM version, chlorophyll synthesis rate was proportional to the carbon synthesis rate which, in turn, was limited only by internal nitrogen quotas.

Higher trophic level models

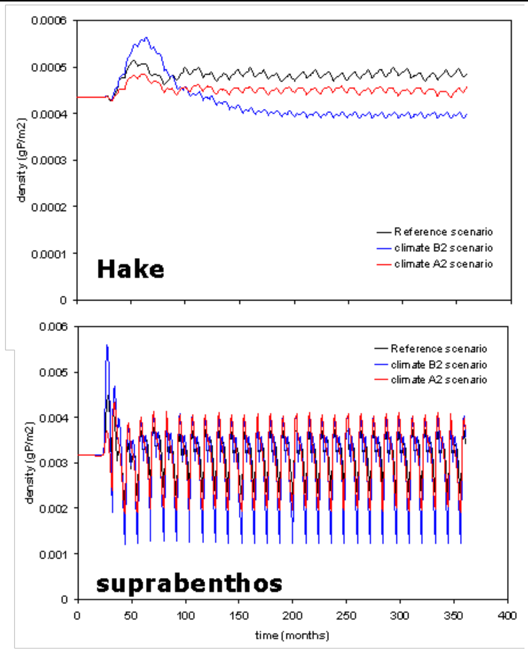
The HTL model for the Adriatic Sea is a deterministic time-dynamic model of the food web developed with Ecopath and Ecosim (EwE; Christensen and Walters, 2004), which has been previously analysed and calibrated (Coll et al., 2009; Libralato et al., 2010). The model domain is the North-Central Adriatic Sea, i.e. the GSA 17 (Geographical Sub-Area) as defined by FAO-GFCM, but excludes the very shallow areas (within 3 nm from the coast or shallower 10 m depth) and the eastern part of the basin (12 nm from the eastern coast). Overall the model covers a total area of 55500 km^2, with a mean depth of 75 m.

State variables of the model are the biomass of the food web components. Namely, the food-web biological articulation is represented through 40 functional groups of species or groups of species with ecological similar traits (i.e., turnover ratio, feeding and habitat preferences) or commercial importance for fisheries. The model variables, therefore, include 3 plankton groups (Phyto-, Micro and Mesozoo- and Macrozoo –plankton), 11 invertebrates (Jellyfish, Suprabenthos, Polychaetes, Scallops and gastropods, Benthic invertebrates, Shrimps, Norway lobster, Mantis shrimp, Crabs, Octopus, Squids), 18 finfish, 2 elasmobranches, dolphin, seabird and marine turtles living functional groups. Other variables comprise non living groups such as detritus, by-catch and fisheries discard. All variables are described through differential equation of their biomass (wet weight) density and rates are on yearly basis. Thus units of the model are t km^{-2} years^{-1} wet weight organic matter for flows and t km^{-2} for biomasses.

The model is forced with fishing pressure described in the model by using specific fleet dynamics: bottom trawling (named Strascico), beam trawling (Rapido), mid-water trawling (Volante), purse seine (Lampara) and tuna fisheries. Fishing effort for each fleet and fishing mortality for sardine and anchovy are used as fishing forcings (1975-2002). Changes in primary productivity were obtained as environmental anomaly during the fitting of the model biomasses to available biomass data, as well as the vulnerability parameters for trophic interactions that were tuned to have best fit. Catch statistics from 1975 to 2002 were compared with modelled catches from the calibrated model run (1975-2002).



Food web representation of the of EwE model of the Adriatic Sea ecosystem.



Example of output for two selected groups of the EwE model for a scenario (30 years) simulation.

Data Assimilation

The 3D-VAR scheme iteratively minimizes the cost function [*Weaver et al.*, 2003]:

$$J\left(\mathbf{x}_k^a\right)=\frac{1}{2}\left(\mathbf{x}_k^a-\mathbf{x}_k^f\right)^T\mathbf{B}_k^{-1}\left(\mathbf{x}_k^a-\mathbf{x}_k^f\right)+\frac{1}{2}\left(H_k(\mathbf{x}_k^a)-\mathbf{y}_k\right)^T\mathbf{R}_k^{-1}\left(H(\mathbf{x}_k^a)-\mathbf{y}_k\right), \quad (3.1)$$

where $\mathbf{x}_k^f$ is the model forecast, $\mathbf{y}_k$ is the set of observation and H_k is the observational operator. The two terms in the cost function Eq. (3.1) are related to the distance of the analysis $\mathbf{x}_k^a$ from the forecast fields and from the observations weighted by the accuracy of the forecast ($\mathbf{B}_k$) and by the accuracy of the observations ($\mathbf{R}_k$), respectively.

Given some assumption and mathematical development, (Teruzzi et al. (2013) , Dobricic and Pinardi (2006)), equation (1) can be rewritten as following:

$$J(\mathbf{v}) = \mathbf{v}^{\mathrm{T}}\mathbf{v} + (\mathbf{d} - \mathbf{HVv})^{\mathrm{T}}\mathbf{R}^{-1}(\mathbf{d} - \mathbf{HVv}),$$

where $\mathbf{d}_k = \mathbf{y}_k - H_k(\mathbf{x}_k^f)$ represents the linearization of the misfit. A new control variable **v** is defined as function of innovation vector $\delta\mathbf{x}_k = \mathbf{x}_k^a - \mathbf{x}_k^f$ and an appropriate decomposition of the background error covariance matrix $\mathbf{B} = \mathbf{V}^T\mathbf{V}$. The innovation is then computed by $\delta\mathbf{x} = \mathbf{Vv}$.

The solution **v** is iteratively computed by using the quasi-Newton L-BFGS minimizer [*Byrd et al.*, 1995], which requires the computation of the cost function gradient and the adjoint operators of V and H.

The core part of this approach is the definition of the matrix **V**, which, using the method proposed by Dobricic and Pinardi, (2008), is decomposed as following:

$$\mathbf{V} = \mathbf{V}_{\mathrm{b}}\mathbf{V}_{\mathrm{H}}\mathbf{V}_{\mathrm{V}}$$

The linear operators $\mathbf{V}_i$ describe the vertical error covariance of the chlorophyll fields ($\mathbf{V}_{\mathrm{V}}$), the horizontal error covariance ($\mathbf{V}_{\mathrm{H}}$) and the state variable error covariance ($\mathbf{V}_{\mathrm{b}}$). The information on the surface chlorophyll innovation provided by the solution **v** is transformed into the three-dimensional innovation by $\mathbf{V}_{\mathrm{V},}$ subsequently $\mathbf{V}_{\mathrm{H}}$ acts as an a horizontal filter propagating the innovation to grid points where observations are not available; and $\mathbf{V}_{\mathrm{b}}$ provides innovations for the four types of phytoplankton in terms of their content of chlorophyll, nitrogen, phosphorous and carbon.

$\mathbf{V}_{\mathrm{V}}$ is defined by a set of synthetic profiles that are evaluated by means of an Empirical Orthogonal Function (EOF) decomposition. EOF has been applied to a validated multi-annual -1997-2004 - OPATM-BFM run [*Lazzari et al.*, 2012] considering 12 months and 9 sub-regions in order to account for the variability of 3D chlorophyll fields.

Vh is built using a Gaussian parameterization whose correlation radius modulates the smoothing intensity and the horizontal spatial areas influenced by the operator (Dobricic and Pinardi, 2008). A radius of 15 km has been chosen as the optimal criteria that increases the coverage of innovation in points where there is no observation and avoids excessively smoothing of the solution.

Vb operator maintains the ration among the phytoplankton groups and preserves the physiological status of the phytoplankton cells: in particular the internal ratios of chlorophyll-carbon and chlorophyll-nutrient are preserved, and the innovations are proportionally applied to all of the components of the phytoplankton functional types. This constrains is relaxed for particular ambient conditions: positive innovation at depths with no light and nutrients available are not applied, and positive innovation is limited for starvation stage of phytoplankton groups (nutrient internal ratio very far from optimal ratios)

The assimilation scheme has been implemented as part of the OGS MyOcean forecast system providing updated initial conditions every week, and consists of a sequence of five steps:

1. chlorophyll maps are downloaded, temporally averaged and spatially interpolated on the model grid.
2. The misfit is evaluated as the difference between the satellite chlorophyll and the daily mean value of the sum of the four phytoplankton type chlorophylls.
3. The 3D-VAR provides the innovation for the four phytoplankton group variables.
4. The new initial conditions (analysis) are produced, and the setup for the simulation of the next five days is prepared.
5. A new forecast is simulated using the new initial conditions and the physical and boundary conditions described downloaded from MFS-MyOcean.

Forcing and Boundary Conditions

The physical forcing fields for the 20-year hindcast simulation for the targeted LTL indicators and ECVs for the Mediterranean Sea are provided in the frame of MyOcean pan-European infrastructure for Ocean Monitoring and Forecasting. The hindcast simulation will be composed by a reference run of 10 years without data assimilation and a reanalysis run of 10 years with 3DVAR data assimilation scheme.

The forcing data are produced by means of the Mediterranean Forecasting System running at INGV, which uses an OGCM (Ocean General Circulation Model) and the OCEANVAR data assimilation scheme. Data consist in 3D zonal and meridional current velocity, temperature, salinity, vertical eddy viscosity, short-wave radiation and wind stress interpolated on the OPATM-BFM model mask grid at 1/8 deg x 1/8 deg.

The OGCM code is NEMO-OPA (Nucleus for European Modelling of the Ocean-Ocean PArallelise) version 3.2 (Madec et al., 2008), which has been implemented in the Mediterranean at 1/16 deg. x 1/16 deg. horizontal resolution and 72 unevenly spaced vertical levels (Oddo et al., 2009).

The Digital Bathymetric Data Base Variable Resolution (DBDB-V) has been used to make the model coast line and bathymetry. The model covers the entire Mediterranean Sea and also extends into the Atlantic in order to better resolve the exchange with the Atlantic Ocean at the Strait of Gibraltar (see details in Oddo et al., 2009). The model uses vertical partial cells to fit the bottom depth shape.

The model is forced by momentum, water and heat fluxes interactively computed by bulk formulae using the 6-h, 0.5 or 0.25 deg. horizontal-resolution operational analyses from the European Centre for Medium-Range Weather Forecasts (ECMWF) and the model predicted surface temperatures (details of the air-sea physics are in Tonani et al., 2008).

For full details on boundary and forcing conditions in this region please refer to http://marine-opec.eu/downloads/OPEC_D2.4.pdf

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