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QUARTERLY

Newsletter



Mercator Ocean

Ocean Forecasters



*The MyOcean Ecosystem Models are presented in the present issue, targeting the Marine Resources users.
Credits: myocean.eu*

Editorial – January 2011 – MyOcean Ecosystem Models

Greetings all,

This month's newsletter is devoted to the MyOcean (<http://www.myocean.eu/>) numerical ecosystem models. A focus is here put on the Global Ocean, the Mediterranean Sea, the Black Sea as well as on the Arctic Ocean, with the description of products that are already or will be part of the MyOcean catalogue either in July or December 2011 (<http://operation.myocean.eu/web/24-catalogue.php>).

Scientific articles are displayed as follows: First, Elmoussaoui et al. are describing the Mercator Ocean **Global Ocean multi-nutrient and multi-plankton biogeochemical** model PISCES that is embedded in the operational Mercator Ocean physical systems. Two simulations are carried out in order to evaluate the impacts of physical data assimilation on modeled biogeochemical tracer distributions. Those simulations constitute preliminary versions of the global ecosystem operational product that will be available in the MyOcean December 2011 catalogue. Then, Teruzzi et al. are presenting the operational system for short-term forecast of the **Mediterranean biogeochemistry** implemented in the V0 version of MyOcean project. Their coupled physical-biogeochemical model OPATM-BFM has been used for the operational simulations over a period spanning more than 3 years. The third paper by Dorofeev et al. is displaying the **Black Sea ecosystem** model coupled with the basin dynamics, improved within the MyOcean project. Long term evolution of the Black Sea ecosystem is studied and a regional bio-optical model is developed to reproduce the variability of the water transparency based on sea colour observations. Finally, Samuelsen et al. are presenting the **Arctic Ocean ecosystem model** that will be available from the MyOcean December 2011 catalogue. It consists of a coupling of the NORwegian ECOlogical Model (NORWECOM) to the HYbrid Coordinate Ocean Model (HYCOM) in the TOPAZ system. The variables that will be provided are chlorophyll-a, diffuse attenuation coefficients, nitrate, phosphate, silicate, and oxygen.

The next April 2011 issue will be a special publication with a common newsletter between the Mercator Ocean Forecasting Center in Toulouse and the Coriolis Infrastructure in Brest, more focused on observations.

We wish you a pleasant reading!

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Integration of biogeochemistry into Mercator Ocean systems

By Abdelali El moussaoui¹, Coralie Perruche¹, Eric Greiner², Christian Ethé³, Marion Gehlen³

¹ Mercator Ocean, Toulouse, France

² CLS, Toulouse, France

³ IPSL/LCSE, UMR CEA-CNRS-UVSQ, Saclay, France

Abstract

Understanding marine biogeochemistry in the context of global environmental change is a major scientific challenge, with international initiatives focusing on carbon monitoring and accounting, as well as science-based management of marine ecosystems and resources. The integration of marine biogeochemistry to ocean dynamical models is thus a timely development that Mercator teams have decided to undertake within the framework of the GREEN MERCATOR project. For this purpose, the global configuration of the state-of-the-art multi-nutrient and multi-plankton biogeochemical model PISCES has been embedded in the operational Mercator Ocean systems. Two simulations were carried out in order to evaluate the impacts of physical data assimilation on modeled biogeochemical tracer distributions: (i) a simulation forced by a free physical run (without physical data assimilation) and (ii) a simulation forced by a physical reanalysis (with physical data assimilation). Here we present a first evaluation of the capability of these GREEN MERCATOR simulations to reproduce large scale distributions of biogeochemical tracers. Model output is compared to climatologies and data from one time series station. These GREEN MERCATOR simulations constitute the preliminary versions of the global ecosystem operational product that will be released for MyOcean from December 2011 on.

Introduction

Recent improvements in spatio-temporal coverage of biogeochemical data, advances in biogeochemical modeling and increasing computer power provide the structure for expanding operational systems towards biogeochemistry (Brasseur et al. 2009). This timely development coincides with new international initiatives focused on carbon monitoring and accounting as well as science-based management of marine ecosystems and resources. Yet it remains both a technical and scientific challenge to integrate biogeochemistry into assimilation systems originally designed for operational physical oceanography in order to forecast the biogeochemical state of the ocean. Within the framework of the GREEN MERCATOR project, Mercator Ocean takes up this challenge by aiming at the integration of biogeochemistry and ecology to Mercator Ocean systems.

To this end, the global biogeochemical model PISCES (Aumont and Bopp, 2006) has been used with the Mercator Ocean systems. PISCES is a state-of-the-art multi-nutrient, multi-plankton model, which includes a full representation of the ocean carbon cycle. The choice of this rather complex model is motivated by its proven capability to reproduce the large scale distribution of major biogeochemical regimes (e.g. Schneider et al. 2008). It is also validated for ocean carbon cycle applications (e.g. Roy et al. 2011). While global eddy-resolving (1/12°) ocean general circulation models are used for physical oceanography research (e.g. the French lead international DRAKKAR consortium), as well as by operational oceanography centres (e.g. Mercator Ocean), most coupled physical biogeochemical models are still run at rather coarse resolution (e.g. 1° or 2°). Adding biogeochemistry to high resolution ocean general circulation models increases their computational costs significantly. This problem was tackled by opting at Mercator Ocean for the off-line coupling between ocean physics and biogeochemistry. Output fields produced by the ocean general circulation model at ¼° resolution are averaged in space and time (1° resolution grid; 1 week) and used to force the biogeochemical component PISCES. The combination of spatial degradation of physical forcing fields and off-line coupling between physics and biogeochemistry prepares the ground for future high-resolution (1/12°) reanalysis and near-real time simulations. The GREEN MERCATOR modelling platform opens the possibility for wide ranging applications: e.g. environmental management both at the regional and global scales; carbon monitoring and accounting at the scale of ocean basins; science-based management of marine ecosystems and resources.

This paper presents a status report of ongoing research and development activities focusing on marine biogeochemistry at Mercator Ocean. It discusses model tools and technical choices. The capability of the model to reproduce marine biogeochemical fields is assessed by comparing model output from two simulations – (i) a simulation forced by a free physical run BIOMER_ORCA025 (without physical data assimilation) and (ii) a simulation forced by a physical reanalysis run BIOMER_GLORYS1V1 (with physical data assimilation) - to climatological fields and data from an ocean times series station:

BATS. The comparison of simulated biogeochemical fields provides a first assessment of impacts of physical data assimilation on modeled biogeochemical tracer distributions.

Model tools

The biogeochemical model PISCES

PISCES is a biogeochemical model of intermediate complexity designed for global ocean applications (Aumont and Bopp, 2006). It simulates the biogeochemical cycle of oxygen, carbon and the main nutrients controlling marine biological productivity: nitrate, ammonium, phosphate, silicic acid and iron. The model distinguishes four plankton functional types based on size: two phytoplankton groups (small = nanophytoplankton and large = diatoms) and two zooplankton groups (small = microzooplankton and large = mesozooplankton). For phytoplankton, the prognostic variables are total biomass, iron, chlorophyll and silicon (diatoms) contents. For zooplankton, total biomass is the only prognostic variable. The bacterial pool is not modeled explicitly. PISCES traces three non-living pools for organic carbon: small particulate organic carbon, big particulate organic carbon and semi-labile dissolved organic carbon, as well as biogenic silica and calcite. The model simulates dissolved inorganic carbon and total alkalinity.

The distinction of two phytoplankton size classes, along with the description of multiple nutrient co-limitations allows the model to represent ocean productivity and biogeochemical cycles across major biogeographic ocean provinces (Longhurst, 1998). PISCES has been successfully used in a variety of biogeochemical studies (e.g. Bopp et al. 2005; Gehlen et al. 2006; 2007; Schneider et al. 2008; Steinacher et al. 2010; Tagliabue et al. 2010). Biogeochemical simulations were initialized with corresponding climatologies for nutrients (WOA 2001, Conkright et al. 2002), carbon cycle (GLODAP, Key et al. 2004) and, in the absence of corresponding data products, with model fields for dissolved iron and dissolved organic carbon. A spin-up of three years (year 2002 repeated 3 times) is realized before beginning the PISCES simulation.

The physical configuration

The ocean general circulation model used is NEMO on the horizontal ORCA025 grid (1/4°) and 50 vertical levels. Daily ECMWF operational analyses with CLIO bulk formulation are used as atmospheric forcings. In the system with data assimilation (GLORYS1v1) (Ferry et al. 2010), temperature, salinity and sea level data are assimilated with the SEEK method (Brasseur and Verron, 2006). The Incremental Analysis Update (Bloom et al. 1996; Ourmières et al. 2006) is used to produce a shock-free simulation.

Spatial degradation

The high demand in computing time of online global biogeochemical simulations at increased spatial resolution prompted the choice of off-line coupling between ocean physics and biogeochemistry. With focus on the long term goal of implementing biogeochemistry to the Mercator real-time physical system at 1/12° (analysis), we opted for the spatial degradation of the physical fields with the use of the tool DEGINT (Aumont et al. 1998). The degraded physical model is built from the original (or parent) model by averaging fields of advection, turbulent diffusion, and tracers onto “squares” of four boxes along longitude by four boxes along latitude. The vertical resolution is not degraded. The horizontal resolution of the degraded model has only one sixteenth of the grid cells of the parent model. The degradation procedure is designed to conserve both water fluxes and tracer fluxes at the boundaries of each degraded grid cell, with respect to the corresponding borders for each set of four boxes of the original model. Figure 1 shows the comparison between the non degraded velocity and diffusivity coefficient fields and the degraded ones. Physical structures of the degraded fields are in overall good agreement with those computed by the parent model.

The degradation contributes to reduce the CPU time of simulations and disk space required for the storage of simulation output. Spatial degradation is often considered as going along with a loss of information associated to finer scales. The finite grid model has, however, no relevant signal near the Nyquist frequency and degradation corresponds to an ergodic hypothesis which allows removing the small scale “noise” of the simulation.

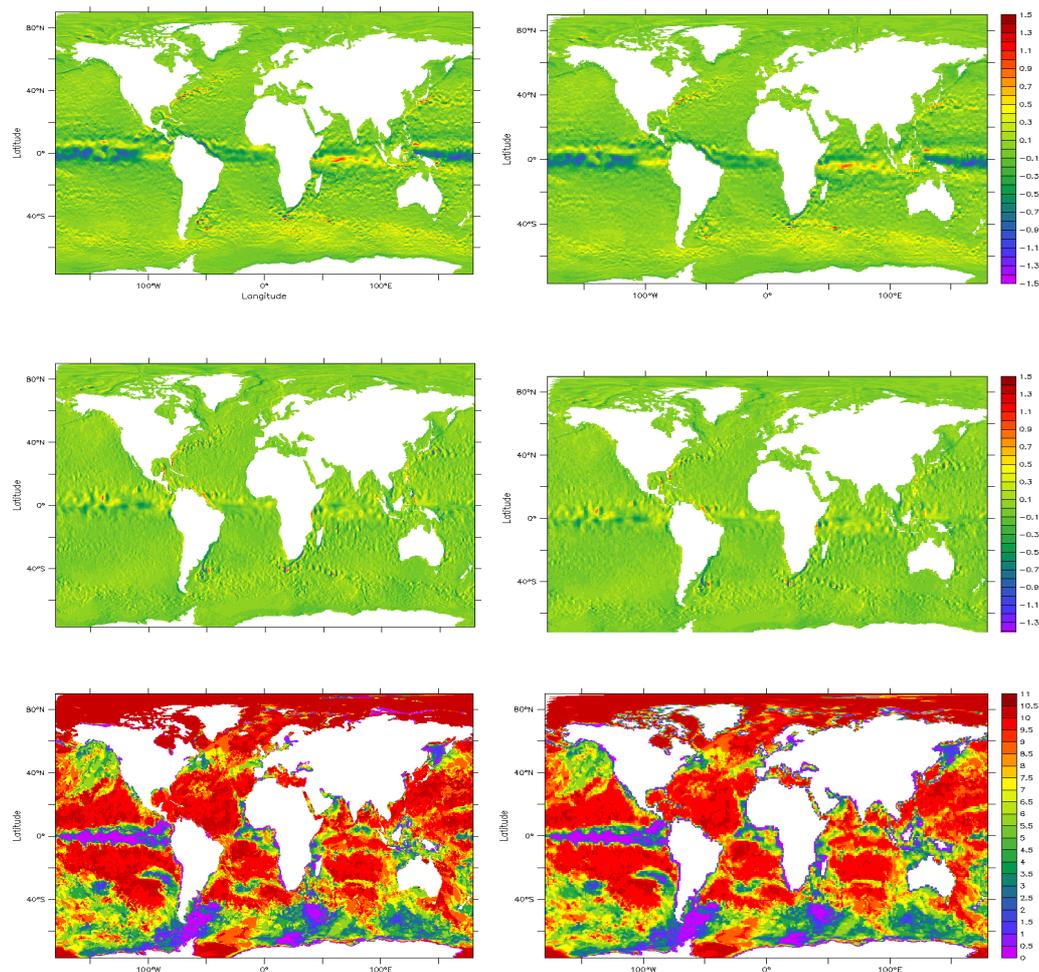


Figure 1: For the physical simulation GLORYS1v1, comparison between non degraded (left) and degraded (right) simulations for the following fields: (top) surface longitudinal velocity ($\text{m}\cdot\text{s}^{-1}$); (middle) surface latitudinal velocity ($\text{m}\cdot\text{s}^{-1}$); (bottom) vertical diffusion at 5 m depth ($\text{m}^2\cdot\text{s}^{-1}$).

Frequency of the physical forcing

The optimal forcing frequency for the biogeochemical model was tested by comparing forcing frequencies of 1, 3 and 7 days. Modelled chlorophyll-a fields were not significantly different and a weekly forcing was adopted as input of PISCES. This time period is in accordance with the time scale of physical processes considered in a simulation at $\frac{1}{4}^\circ$ (“eddy-permitting”). This choice is however not definitive. The forcing frequency needs to be reassessed when moving to higher resolution (“eddy-resolving”) with the objective to reproduce mesoscale processes (eddies, fronts).

Model experiments

Impact of spatial degradation on modeled biogeochemical fields

The impact of spatial degradation of the physical system on biogeochemical fields was assessed by running two simulations:

- a simulation with degradation: BIOMER_GLORYS1V1_BIO1 (physics at $\frac{1}{4}^\circ$ degraded to 1° and biogeochemistry at 1°)
- a simulation without degradation: BIOMER_GLORYS1V1_BIO025 (physics at $\frac{1}{4}^\circ$ and biogeochemistry at $\frac{1}{4}^\circ$)

Figure 2 shows the chlorophyll-a distribution projected by the two above simulations (respectively left and right) for May and September 2002 (respectively top and bottom). Simulated chlorophyll-a fields display a good level of agreement at the global scale. The only differences are located in the most turbulent regions like the Gulf Stream where the mesoscale structures are slightly smoothed in the version with spatial degradation. On average, the simulation without degradation projects higher chlorophyll-a levels in the northern mid and high latitudes (e.g. North Atlantic). This is linked to the greater variance of vertical velocities which results in an increased upwelling of nutrients and hence stronger primary production. Unrealistic high levels of chlorophyll-a are visible along a band across the Arctic Ocean in the model version with degradation in September. They are related to numerical instability (velocity divergence $\neq 0$) along the North folds of the tri-polar model grid (two poles on the continent in the North). This issue is still being investigated.

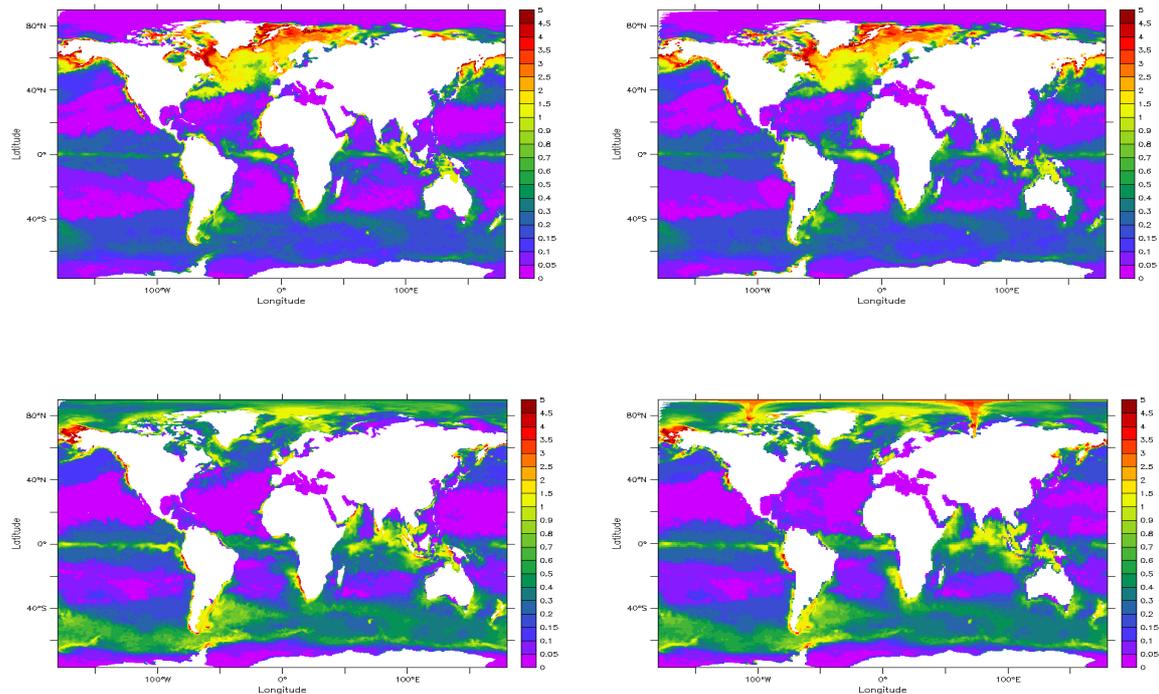


Figure 2: Surface chlorophyll-a (mg Chl.m^{-3}): comparison between the non degraded version BIOMER_GLORYS1V1_BIO025 (left) and the degraded version BIOMER_GLORYS1V1_BIO1 (right). (top) May 2002 ; (bottom) September 2002.

Global simulations

Once these choices about the physical forcing and the spatial degradation were tested and validated, 2 interannual simulations were made:

- a biogeochemical simulation forced by a physical free run (without assimilation) on the period 2002-2007: BIOMER_ORCA025_BIO1 (physics at $\frac{1}{4}^\circ$ and biogeochemistry at 1°)
- a simulation forced by the GLORYS1v1 reanalysis (with assimilation) on the period 2002-2007: BIOMER_GLORYS1V1_BIO1 (physics at $\frac{1}{4}^\circ$ and biogeochemistry at 1°)

The validation and analysis work of these simulations is work in progress.

Comparison to climatologies

Figure 3 illustrates modelled nutrient distribution in the case of phosphate. The annual mean phosphate Log₁₀ concentration near 100m compares model output and climatology. The large scale features of the climatology are reproduced by PISCES in the two simulations BIOMER_ORCA025_BIO1 and BIOMER_GLORYS1V1_BIO1. At the regional level, we note a band of high nitrate levels centered at the Equator spreading across the Pacific and Indian Oceans, which is larger in BIOMER_GLORYS1V1_BIO1 than in BIOMER_ORCA025_BIO1. The non gaussian distributions of the values are reasonably well reproduced.

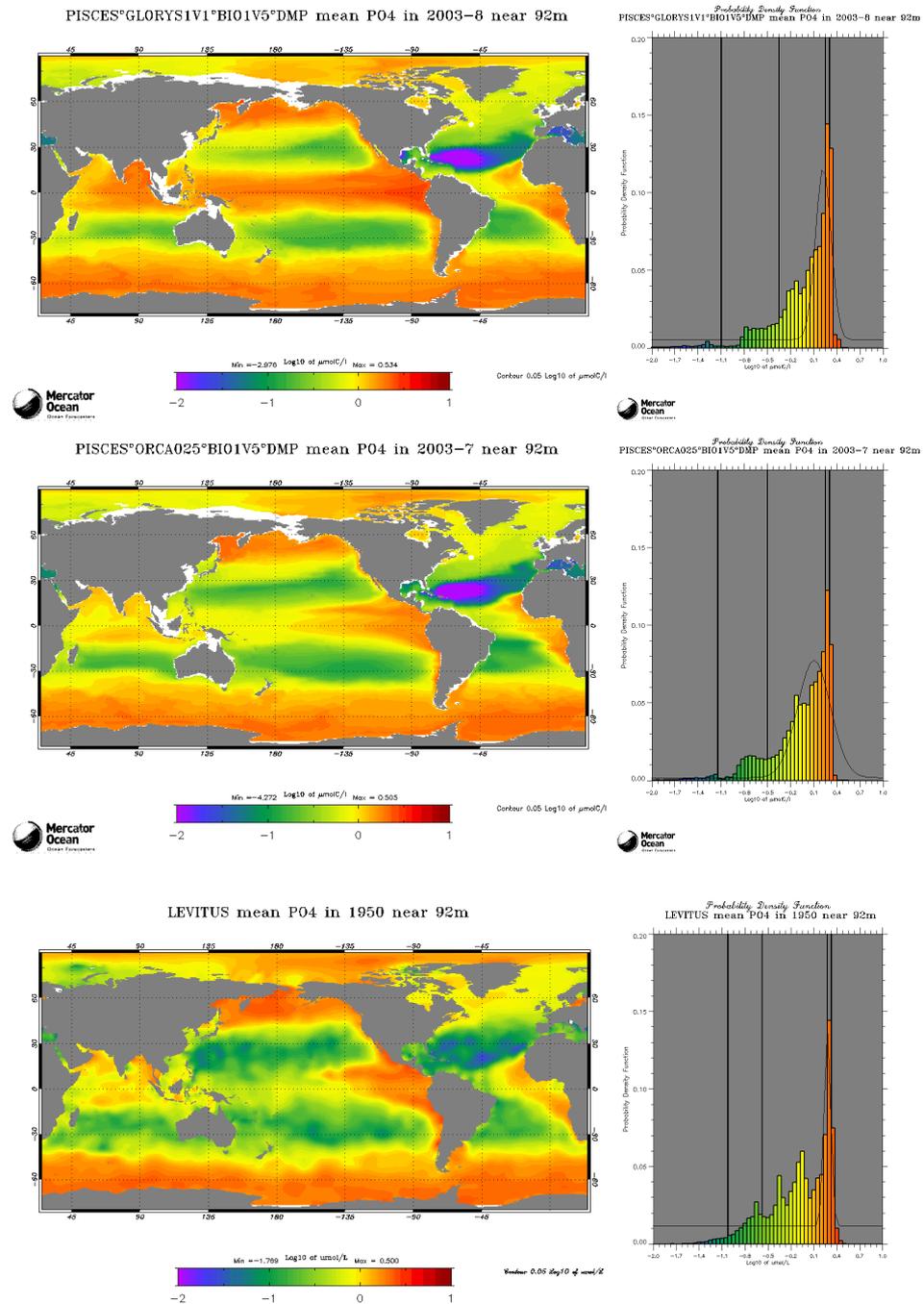


Figure 3: Phosphate concentration (in Log₁₀ units $\mu\text{mol P}\cdot\text{L}^{-1}$) near 92m for the BIOMER_GLORYS1V1_BIO1 simulation (top), the BIOMER_ORCA025_BIO1 simulation (middle) and the LEVITUS climatology, WOA 2005 (bottom). The corresponding probability density function (%) is presented on the right column.

Modelled mean annual chlorophyll-a fields show a good agreement with satellite derived estimates at the global scale (figure 4). The large scale structures are well reproduced (e.g. double-gyres, Antarctic Circumpolar Current). There are, however, significant differences at the Equator with BIOMER_ORCA025_BIO1 and BIOMER_GLORYS1V1_BIO1 overestimating observed chlorophyll-a levels. The representation of the North Atlantic subpolar gyre is improved in the model version with assimilation BIOMER_GLORYS1V1_BIO1, both in terms of chlorophyll a magnitude and the latitudinal position of the transition zone between high productive waters to the North and oligotrophic waters to the South. In the Southern ocean, BIOMER_GLORYS1V1_BIO1 provides an improved estimate of the chlorophyll-a levels south of 40°S.

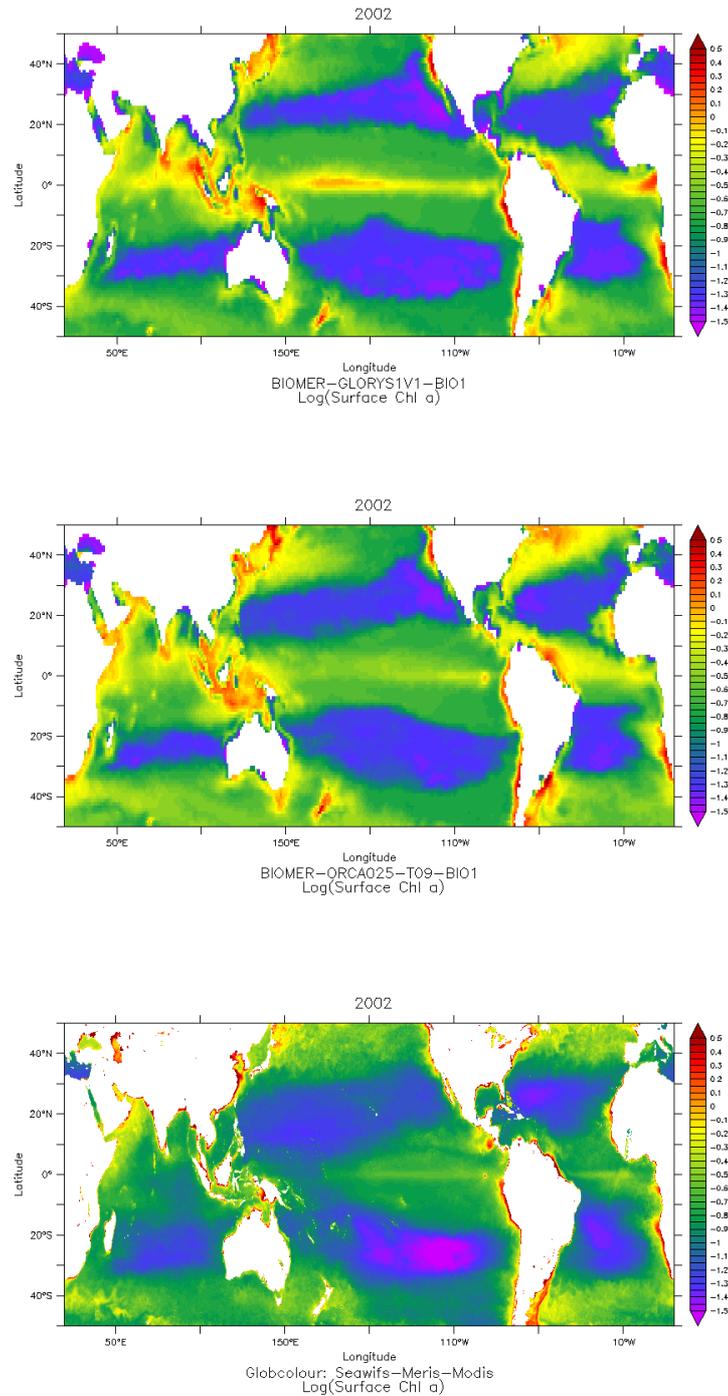


Figure 4: Log₁₀ of the chlorophyll-a concentration (mg Chl.m⁻³): annual mean of year 2002 at sea surface. (top) BIOMER_GLORYS1V1_BIO1; (middle) BIOMER_ORCA025_BIO1; (bottom) Data from SEAWIFS-MERIS-MODIS sensors provided by Globcolour (MyOcean)

Coming back to the overestimation of chlorophyll-a levels simulated by BIOMER_ORCA025_BIO1 and BIOMER_GLORYS1V1_BIO1 at the equator, two potential underlying causes could be identified. (1) The model data misfit can be at least partly attributed to the “CLIO” aerodynamic bulk formulae. The latter is at the origin of a cool bias in surface temperature leading to an overestimation of upwelling and hence nutrient input at the equator. (2) In BIOMER_GLORYS1V1_BIO1, there is moreover a bias introduced by the assimilation scheme, as demonstrated below.

Figure 5 reproduces the nitrate distribution along the equatorial section, averaged over the year 2002 from the two simulations (left and right) and from climatology (bottom). The nitracline shoals from west to east in each ocean basin. In BIOMER_GLORYS1V1_BIO1, it is clearly more intense and reaches shallower layers. Figure 6 shows the corresponding vertical velocities for both simulations. In the Pacific Ocean, these shallow nitrate maxima are correlated to a mean upwelling which does not exist in the free run BIOMER_ORCA025_BIO1. The vertical velocities are the source of anomalous levels of nitrates in equatorial shallow waters.

Preliminary outputs of gravimetric GOCE mission suggest that there are significant errors in the mean sea surface height (MSSH) used to assimilate the satellite altimetry. Regional biases in MSSH are typically of 100km and 5cm (resp. horizontal and vertical scales). The system response to the bias in MSSH is a bias in vertical velocity near the equator, thus introducing anomalous level of nitrate.

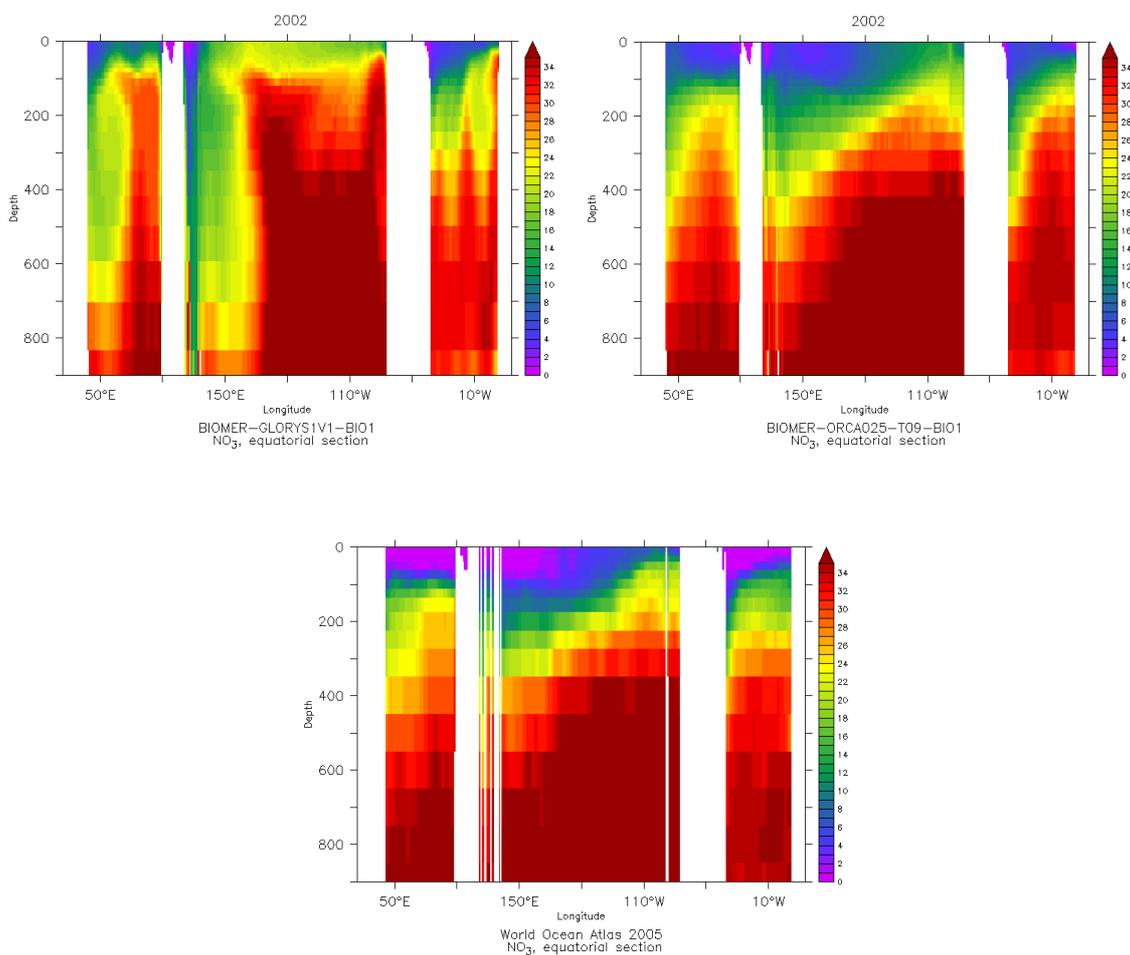


Figure 5: Concentration of nitrates ($\mu\text{mol N} \cdot \text{m}^{-3}$) along the equatorial zonal section, averaged over the year 2002 in the top layer (0-900m). (top left) BIOMER_GLORYS1V1_BIO1; (top right) BIOMER_ORCA025_BIO1; (bottom) Climatology LEVITUS 2005

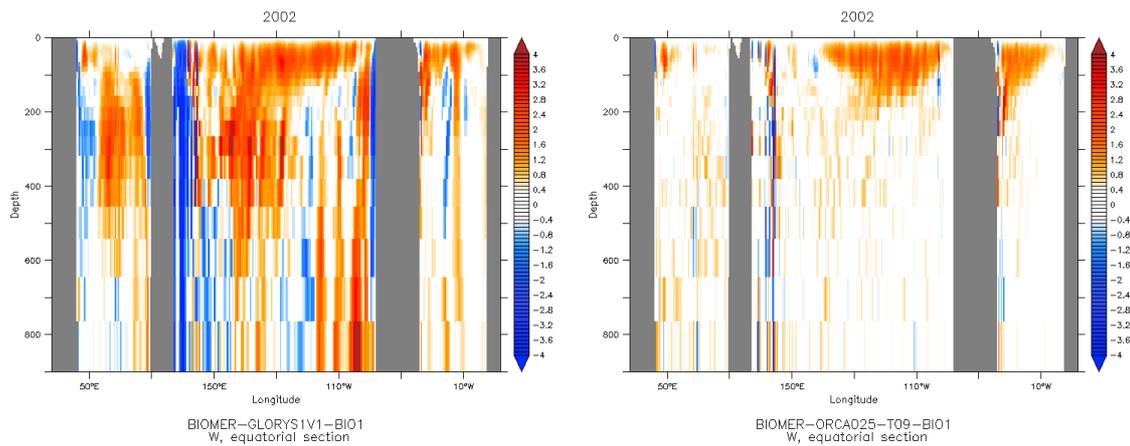


Figure 6: Vertical velocities (m.day⁻¹) along the equatorial zonal section averaged over the year 2002. (left) BIOMER_GLORYS1V1_BIO1; (right) BIOMER_ORCA025_BIO1

Comparison to ocean time series station BATS

The comparison between model output and biogeochemical data from eulerian observatories provides another way to assess the quality of our simulations. In complement with climatologies (e.g. nitrates), observed data time series constitute independent data against which the model can be validated. The BATS (Bermuda Atlantic Time-series Study) station is one of them. It is situated in the Sargasso Sea (31° 40'N, 64° 10'W). At this station, an exhaustive set of biogeochemical, along with physical variables are measured through bottle samples all year round (Steinberg et al. 2001). These sustained data collections are carried out monthly or even biweekly during bloom events. These data open the possibility for assessing the ability of the biogeochemical model to reproduce the seasonal and interannual variability of the ecosystem. Moreover, they give a valuable insight of the ocean biogeochemical state at a given location characteristic of a particular large-scale biogeographic region (Longhurst, 1998).

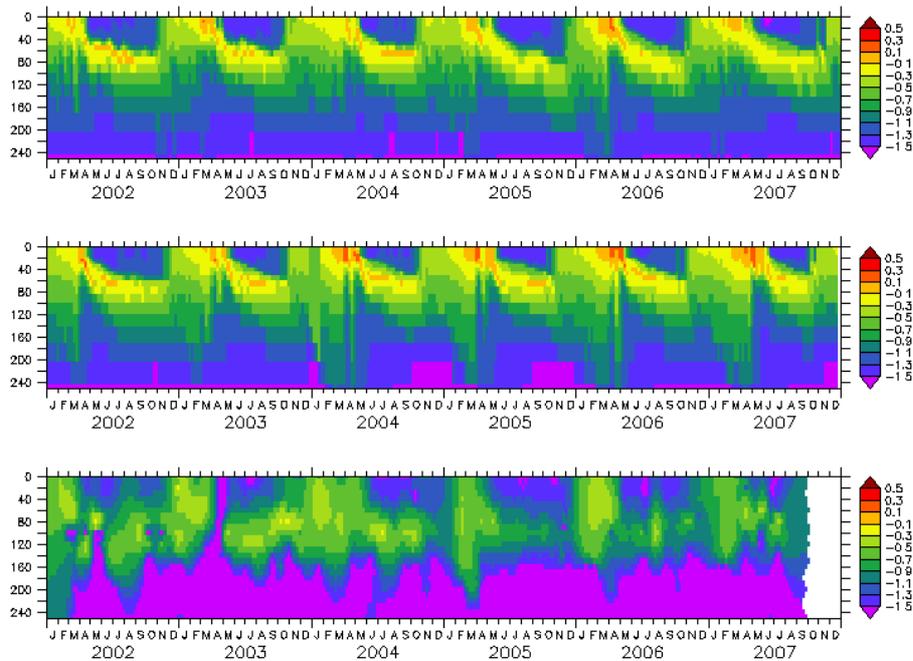


Figure 7: Log₁₀ of the chlorophyll-a (mg Chl.m⁻³) at the BATS station during 2002-2007 period between 0 and 900 m depth ; (top) BIOMER_GLORYS1V1_BIO1; (middle) BIOMER_ORCA025_BIO1; (bottom) bottle data

BATS is situated in the western North Atlantic subtropical gyre, in a highly-turbulent region, between the Gulf Stream (north) and the North Atlantic equatorial current (Steinberg et al. 2001). BATS is characterized by a deep mixed-layer in winter in which nutrients are injected by entrainment and immediately consumed by phytoplankton. In summer, after spring restratification, nutrients are rapidly depleted and phytoplankton declines in the shallow mixed-layer. A subsurface chlorophyll maximum develops at the base of the mixed layer.

Figure 7 (bottom) presents the concentration of chlorophyll-a as a function of depth and time measured at the BATS station between 2002-2007. It illustrates the seasonal cycle of phytoplankton. Figure 7 (top and middle) shows the results of BIOMER_GLORYS1V1_BIO1 and BIOMER_ORCA025_BIO1 respectively. The seasonal cycle is in general well reproduced by the models. BIOMER_GLORYS1V1_BIO1 succeeds well in capturing the interannual variability as demonstrated by the deepening of the mixed-layer in summer 2005. However, the models and in particular BIOMER_ORCA025_BIO1, predict spring blooms that are not present in data. This is due to the too shallow nutricline (valid for nitrates, silicates, phosphates) in our simulations. On figure 8, a scatter plot of nitrate data is superposed to the prediction of BIOMER_GLORYS1V1_BIO1. It shows the shift between model and data nitracline. The underlying causes of this misfit are currently analyzed.

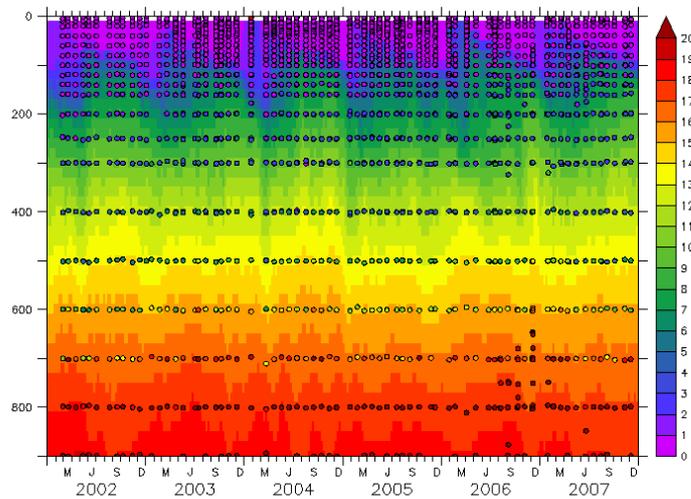


Figure 8: Concentration of nitrates ($\mu\text{mol N.L-1}$) during 2002-2007 period between 0 and 900 m depth at the BATS station (small coloured circles) and in BIOMER_GLORYS1V1_BIO1 (background colour field)

Analysis of trends and variability

With the exception of the Equatorial band, trends are in general weak. The variability is dominated by the seasonal signal. At depth, in some regions, there is a strong inter-annual signal which is questionable in the model. This is illustrated in figure 9 by oxygen levels near 300m. The artefact on the right panel of figure 9 might be related to model drift in response to the short spin-up time of only 2 years (the negative SOI year 2002), as well as the initialization of biogeochemical fields with coarse resolution climatologies. The assimilation does not perturb the overall variability. It does reinforce the ENSO signature, as illustrated by the first EOF mode in chlorophyll-a for the two simulations and the GlobColour data (figure 10). While the phase of the seasonal signal is well reproduced by both simulations, the magnitude is overestimated. The geographical pattern is coherent between model and observations, except the Gulf Stream and Kuroshio broad extensions, and the missing circumpolar signal.

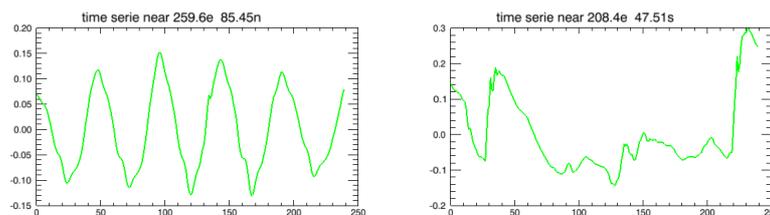


Figure 9: Time series (number of weeks) of oxygen ($\text{mL O}_2\text{.L-1}$) near 300m for BIOMER_ORCA025_BIO1 at 2 locations: (left) 100.4W, 85.45N; (right) 151.6W, 47.51S

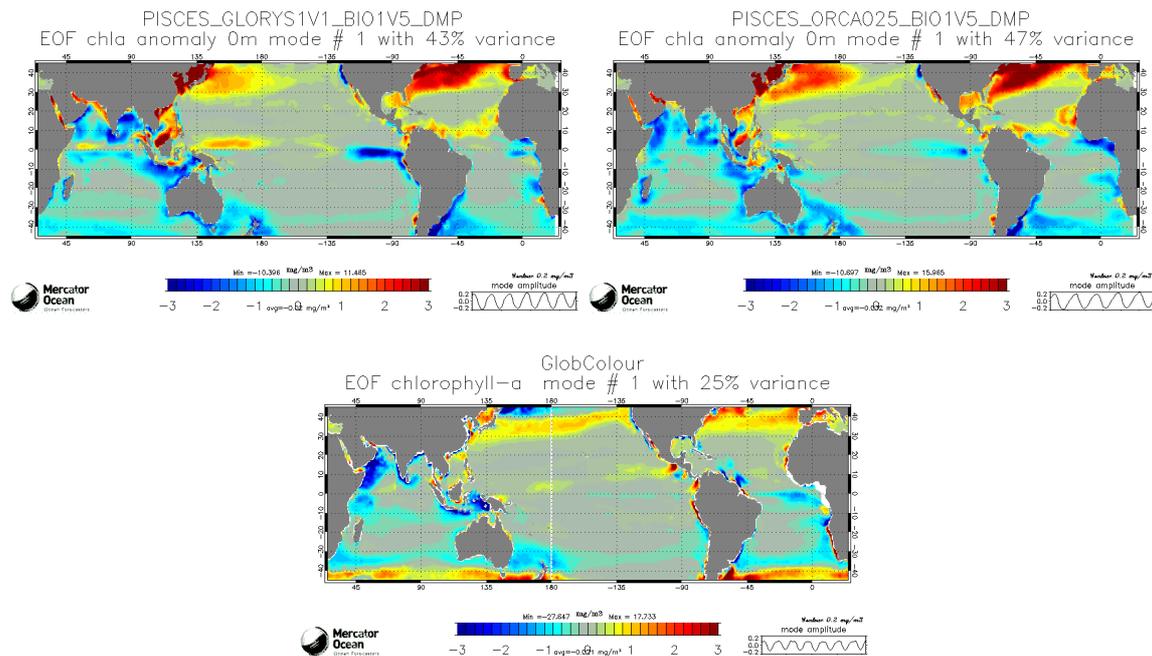


Figure 10: First empirical orthogonal function of chlorophyll-a (mg Chl.m^{-3}) for the BIOMER_GLORYS1V1_BIO1 (top left panel) and BIOMER_ORCA025_BIO1 (top right panel) simulations, and the Globcolour 2002-2008 dataset (bottom panel). The time series of the function appears as an icon at the bottom right of each figure. Monthly averages are used, without Log10 transformation. Data coverage is generally over 80%.

Conclusion

Mercator has implemented a 1° global version of the biogeochemical model PISCES. It is coupled off-line to the global $1/4^\circ$ model in delayed time (forced by ORCA025 simulation or GLORYS1v1 reanalyses) and with the need of a spatial degradation procedure. The later is at the origin of numerical instabilities along the North fold of the tripolar model grid. First analyses of inter-annual simulations demonstrate the capability of both model configurations to reproduce large scale patterns of biogeochemical tracer distributions. Compared to the free simulation BIOMER_ORCA025_BIO1, data assimilation improves the modelled chlorophyll-a distributions in the North Atlantic BIOMER_GLORYS1V1_BIO1. This holds in particular for the transition between high and low productivity zones. Simulated levels of chlorophyll-a are overestimated along the Equatorial band. While this misfit is attributed to atmospheric forcing in BIOMER_ORCA025_BIO1 (which should be improved in the future simulations with new forcing Era Interim 3h and CORE bulk formulation), it is related to unrealistic high vertical velocities introduced by the assimilation scheme in BIOMER_GLORYS1V1_BIO1. With the exception of the Equatorial region, model trends are small and variability is dominated by the seasonal cycle. The time variability shown by EOF decompositions reveals that the assimilation does not perturb the variability simulated by PISCES, except for the ENSO signal which is reinforced through GLORYS1v1.

Looking forward to the future ARGO measurements of oxygen and chlorophyll, the stations like BATS are a first step to validate the biogeochemical parameters across the euphotic and mesopelagic ocean. Moreover, BATS data provide an extensive set of biogeochemical, as well as biological variables (not shown here) which allows to assess the temporal variability of the surface ocean ecosystem (production and export). The systematic comparison between model output and time series data will be extended to the other eulerian observatories such as HOT (oligotrophic gyre, Pacific), PAP (Atlantic subpolar gyre) and ESTOC (Eastern border of Atlantic oligotrophic gyre).

The increasing availability of observational data sets, novel data from autonomous measurement platforms, as well as advances in biogeochemical modelling provide the framework for rapid progress over the coming years. The GREEN MERCATOR simulations presented here constitute the preliminary versions of the global ecosystem product that will be released for MyOcean from December 2011 on.

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Operational forecasts of the biogeochemical state of Mediterranean Sea

By Anna Teruzzi¹, Stefano Salon¹, Giorgio Bolzon¹, Paolo Lazzari¹, Simone Campagna², Federico Ficarella², Cosimo Solidoro¹, Alessandro Crise¹

¹Istituto Nazionale di Oceanografia e di Geofisica Sperimentale-OGS, Sgonico (TS), Italy

²CINECA, Casalecchio di Reno (BO), Italy

Abstract

Preliminary results of the operational system for short-term forecast of the Mediterranean biogeochemistry implemented in the V0 version of MyOcean project are presented. The coupled physical-biogeochemical model OPATM-BFM has been used for the operational simulations over a period spanning more than 3 years (which includes also the MERSEA-IP project), without interruption, while an upgraded version of the model was adopted to carry out a reanalysis simulation over the same temporal range. The analysis of the chlorophyll concentration fields produced by the two simulations, compared with satellite observations, shows the merits and demerits of the upgraded model version, which has been adopted for the MyOcean V1. The chlorophyll concentration is part of the product MEDSEA_FORECAST_BIO_006_002 provided by OGS (Italy) in the MyOcean catalogue (<http://operation.myocean.eu/web/24-catalogue.php>).

Introduction

Operational oceanography constitutes a powerful tool to monitor, analyze and predict the state of the marine environment and the sustainable development of the coastal areas (Flemming et al. 2002). As a consequence, operational oceanography has become in the last decade a major research issues in Europe.

The FP7 MyOcean project (<http://www.myocean.eu/>), which main scope is the deployment of the first integration of the pan-European capacity for ocean monitoring and forecasting, represents the implementation project of the GMES (<http://www.gmes.info/>) Marine Core Service, which was built in particular upon the FP6 MERSEA-IP project (<http://www.mersea.eu.org/>). MyOcean has been conceived to provide a real operational service that supplies top quality ocean information at global and regional scales, coming from space and *in situ* observations that are then assimilated into 3D numerical models. Started on April 2009, the "Version Zero" (V0) of MyOcean was concluded in December 2010, thus giving the opportunity to analyze the results of the preparatory operational phase. The upgrade to the "Version One" (V1), beside substantial improvements concerning the production centers operations (e.g. new models version), now guarantee a unified, regular service to the users via the new web portal.

In the framework of the European research collaborations to operational oceanography, OGS is a MyOcean partner and started its contribution within the MERSEA-IP initiative, developing the first pre-operational system for short-term forecasts of the Mediterranean Sea biogeochemistry, with the OPATM-BFM numerical model. The model was designed to be off-line coupled with an ocean circulation model that provides the physical forcing fields (current velocity, temperature, salinity, eddy diffusivity, wind stress, solar radiation) necessary to drive the temporal and spatial evolution of the biogeochemical state of Mediterranean basin. This system (widely described in Lazzari et al. 2010) was implemented to run weekly during MERSEA-IP, and has been then embedded and extended into the MyOcean Information System during V0. The products are included in the MyOcean catalogue, and consist in 10 days of forecast of 3D chlorophyll concentration of the Mediterranean Sea delivered weekly (V0), upgraded to a twice-a-week delivery (V1) of 3D chlorophyll and nutrients (nitrate and phosphate) concentration. The V1 includes also a new version of the OPATM-BFM model, which details will be described in the following. The OPATM-BFM model had provided pre-operational and then operational results since April 2007 till today without any interruption. The new biogeochemical model has been used for a reanalysis run covering the same period of the operational application of the OPATM-BFM (V0).

Tools and methods

OPATM-BFM is a transport-reaction model that couples the OPA Tracer Model version 8.1 (Madec et al., 1998) with the Biogeochemical Flux Model (BFM) (Vichi et al. 2007a,b) to solve the time evolution of chemical and biological state variables in the marine environment. Its governing equations are formulated as advection-diffusion-reaction equations, one for each of the 51 state variables that are grouped in four types of living functional groups (phytoplankton, mesozooplankton, microzooplankton and bacteria). Further details can be found in Lazzari et al. (2010).

Due to the off-line coupling, the physical fields (3D: zonal, meridional and vertical current velocity, temperature, salinity, vertical eddy diffusivity; surface: solar short-wave irradiance and wind speed) represent an external forcing and are hence computed by an Ocean General Circulation Model (OGCM) before the integration of the transport-reaction equation. The three components of current velocity are necessary to calculate the transport term for each passive tracer; vertical eddy diffusivity is crucial to reproduce the vertical mixing processes of the tracers along the water column. Temperature, salinity, irradiance and wind speed enter in the biogeochemical reaction term which is implemented by BFM.

BFM is based on cycles of carbon and macronutrients (phosphorous, nitrogen and silica), and is targeted on the phytoplankton/nutrients and microbial loop. Key aspects of the BFM are its potential for limitation by macronutrients (nitrogen, phosphate and silicate), the use of adjustable Carbon – Nitrogen – Phosphorus – Silicon (C:N:P:Si) ratios in zooplankton and phytoplankton compartments, and the chlorophyll-to-carbon variable dependency. BFM had already been successfully applied to several areas of the Mediterranean Sea (Allen et al. 2002; Vichi et al. 2003; Polimene et al. 2006; Petihakis et al. 2009).

In MyOcean V0 the OPATM-BFM has been configured following the version employed during MERSEA-IP (Lazzari et al. 2010). The off-line coupling has been designed on the MFS-SYS2b ocean forecasting system managed by INGV (Istituto Nazionale di Geofisica e Vulcanologia, Bologna, Italy), that is based on the OPA model (Madec et al. 1998) version 9.0, implemented on the Mediterranean Sea (Tonani et al. 2008) and includes as assimilation scheme the System for Ocean Forecasting and Analyses (SOFA; Dobricic et al. 2007). MFS-SYS2b has been intensively validated and has evolved to MFS-SYS4b (for detailed information see <http://gnoo.bo.ingv.it/mfs/myocean/description.html>). The V1 version of the biogeochemical Mediterranean forecasting system is off-line coupled with MFS-SYS4b, which is the nominal MyOcean product for the Mediterranean Sea and represents one of the most advanced tools for simulation of circulation in the Mediterranean Sea. Since horizontal resolution of OPATM-BFM is 1/8° while that of the INGV model is 1/16°, an interpolating interface is necessary to reduce the finer grid to the coarser one.

A new version of the OPATM-BFM model has been recently developed and described in Lazzari et al. (in preparation). The upgraded MyOcean V1 model mainly differs with the former in:

- Integration of a phosphorus-nitrogen co-limitation term in the chlorophyll synthesis: this parameterization was chosen to mimic the relevant limitation effects due to phosphorus depletion observed in the Mediterranean Sea (Thingstad et al. 2005).
- Upgraded biogeochemical boundary conditions for all major rivers and runoff inputs distributed along the Mediterranean coast, based on the data of Ludwig et al. (2009) produced in the framework of the SESAME project (<http://www.sesame-ip.eu/>);
- Upgraded biogeochemical boundary conditions for the atmospheric inputs based on the data resumed in Ribera d'Alcalà et al. (2003). Present measurements allow including a total annual input budget of phosphorus and nitrogen for the western and eastern sub-basin.
- Climatological light extinction factor derived by satellite observations SeaWiFS (1998 – 2004), processed by the Satellite Oceanography Group of the Institute of Atmospheric Sciences and Climate – CNR (GOS-ISAC-CNR), in order to include in the model the spatial/seasonal climatological variability dynamics of water inherent optical properties.

All the improvements above have been tested in multi-annual simulations covering the period from 1998 to 2004, and forced by an OGCM with 1/16° horizontal resolution and 43 non uniform levels (see Lazzari et al., in prep.).

Moreover the new version of OPATM-BFM is compliant with the physical external forcing provided by NEMO (Madec, 2008; see also <http://www.nemo-ocean.eu/>).

In order to prepare the restart conditions for the V1, a reanalysis run has been carried out using the new version of OPATM-BFM forced by the physical fields provided by the INGV MFS System between April 2007 and October 2010. The chlorophyll surface concentration from this simulation has been compared with the outputs of the same period covered during pre-operational MERSEA-IP TOP phase (Toward Operational Phase, April 2007 – March 2009) and operational MyOcean V0 (April 2009 – October 2010).

Moreover, two remote observational data sets have been chosen to be compared with the model output:

1. The MODIS-Aqua satellite observations of surface chlorophyll concentration produced by the GOS-ISAC-CNR have been used for the comparison in the period September 2007 – December 2009. The chlorophyll concentrations were computed from Level-2 water leaving radiances, using a validated regional algorithm called MedOC3 that takes into account the particular characteristics of the Mediterranean Sea (Santoleri et al. 2008). These data are available through

MyOcean V1 catalogue starting from November 2010, while the data for the previous period have been provided directly by GOS-ISAC-CNR.

2. The CHL-RAN satellite observation of surface chlorophyll concentration produced in the frame of the GlobColour project (<http://www.globcolour.info/>) and available through the MyOcean catalogue, have been used to qualitatively compare a localized event occurred in March 2010 over the Gulf of Lions. The global merged chlorophyll-a concentration for case 1 water is obtained by the merging of MERIS, MODIS and SeaWiFS data using an advanced retrieval based on fitting an in-water bio-optical model to the merged set of observed normalised water-leaving radiances by the GSM technique (Garver-Siegel-Maritorena bio-optical model; Maritorena and Siegel, 2005).

As already applied to the results of the pre-operational program for the biogeochemistry of Mediterranean Sea developed within MERSEA-IP (Lazzari et al. 2010), statistical assessment methods such as non-Gaussian indicators (median and percentiles) and Jolliff diagrams (Jolliff et al. 2009) have been adapted to the models outputs and the satellite data. The results are discussed in the next section.

Results

The same forecasting system and the same biogeochemical model have been used during the TOP phase of MERSEA-IP (April 2007 – March 2009) and the whole MyOcean V0 (April 2009 – December 2010) without interruption, therefore demonstrating the technical robustness of the OPATM-BFM model. This represents an important result since this is the first numerical experiment for the operational forecast of the biogeochemical state of the Mediterranean Sea. In particular, 79% of the weekly runs has been completed in less than 8 hours (average time is 5 hours), without delay. In view of the V1, the goal is to improve the operational performance, i.e. to reduce the percentage of runs consuming more than 8 hours to be completed.

In Lazzari et al. (2010) the authors compared the outputs of the simulations carried out in the MERSEA-IP pre-operational system with satellite observations between April 2007 and September 2008, concluding that the model was able to satisfactorily reproduce the seasonal cycle of surface chlorophyll concentration in the Mediterranean Sea and capture the intensity and dynamics of phytoplankton bloom events. Some shortcomings were observed in the reproduction of the bloom phase outbreak and in the overestimation of the winter chlorophyll concentration in the Eastern Mediterranean region.

Various simulations and observations used for validation

An upgraded version of the OPATM-BFM model is presently available (see previous section) and is applied in MyOcean V1. Thus three different kinds of data sets are available and will be analyzed in the present section:

1. The outputs produced during pre-operational and operational runs of OPATM-BFM (OPE), obtained with the same operational system and the same model used for MyOcean V0;
2. The outputs produced by the reanalysis simulation carried out with the new version of OPATM-BFM (REA), which is presently used in MyOcean V1;
3. Satellite observations processed by GOS-ISAC-CNR (SAT1) and within the GlobColour project (SAT2).

Seasonal variability of surface chlorophyll concentration

Since the OPATM-BFM model is designed for pelagic areas (here defined as those deeper than 200 m), the statistical analyses consider only the points deeper than 200 m (see Figure 1). Figure 2 shows the comparison between OPE and SAT1 (top) and REA and SAT1 (bottom) of the temporal evolution of surface chlorophyll concentration over the Mediterranean basin in logarithmic scale. Data are geometrically averaged over five days, and the figures show the temporal series of three percentiles (25th, 50th and 75th) and of the minimum and maximum values. The OPE shows the same results as in Lazzari et al. (2010) but for the additional period shown here. OPE is able to reproduce correctly the seasonal cycle of surface chlorophyll concentration in the Mediterranean Sea (Bosc et al. 2004). The OPE run tends to produce the winter bloom earlier than what observed in the SAT1 data, generally overestimating the intensity of the chlorophyll concentration.

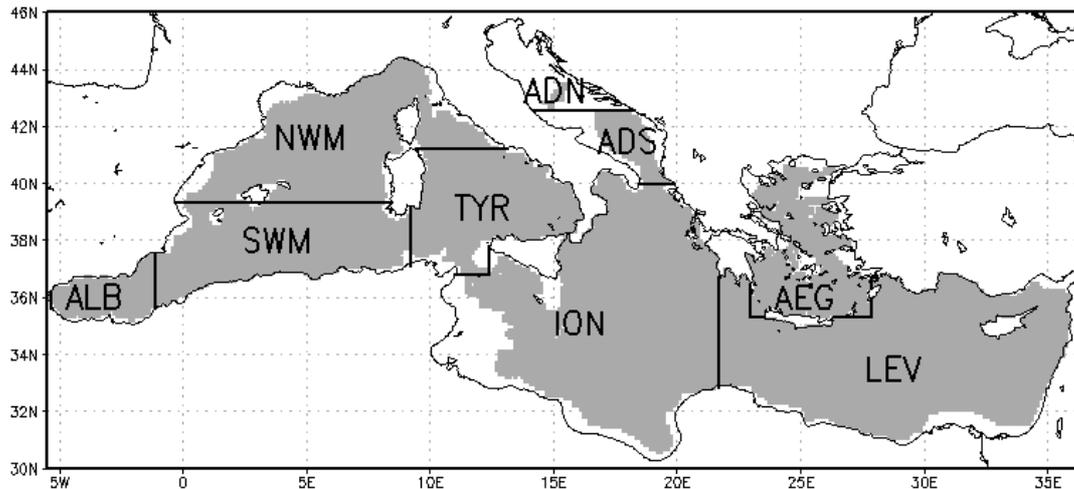


Figure 1: Map of the Mediterranean Sea with selected sub-basins of investigation: ALB = Alboran Sea, SWM = south-western Mediterranean Sea, NWM = north-western Mediterranean Sea, TYR = Tyrrhenian Sea, ADN = northern Adriatic Sea, ADS = southern Adriatic Sea, AEG = Aegean Sea, ION = Ionian Sea, LEV = Levantine basin. Grey shaded area represents grid points deeper than 200 metres.

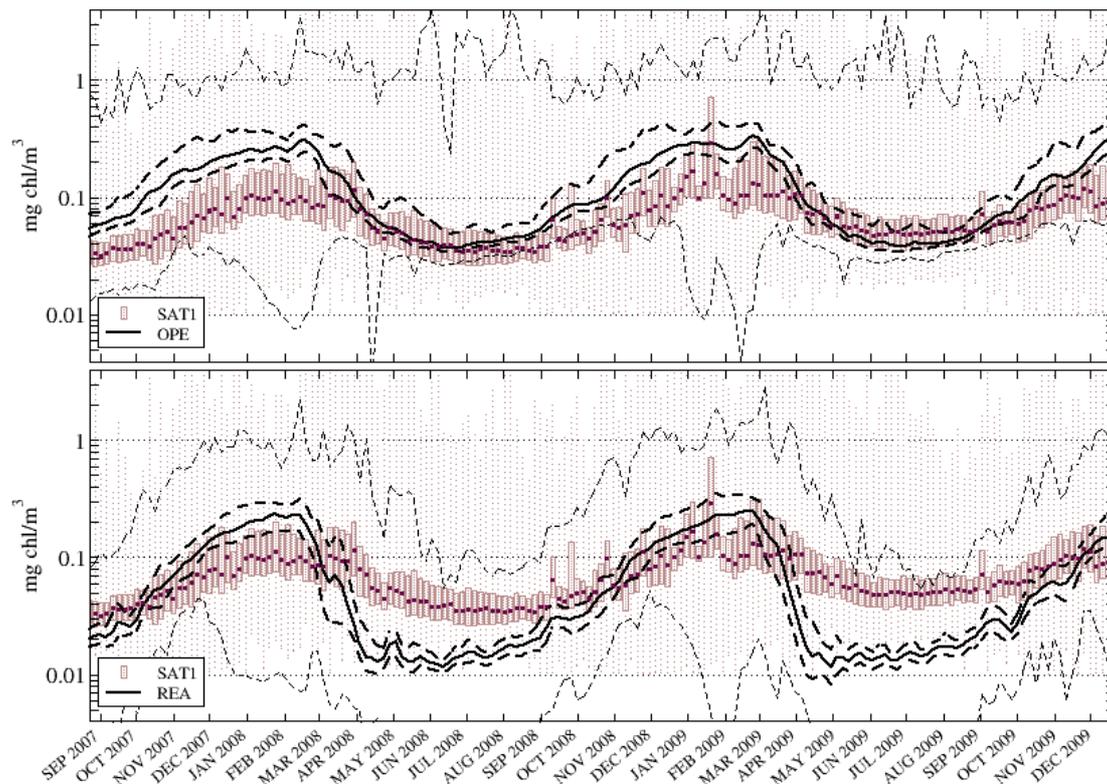


Figure 2: Semilog plot of the temporal evolution of the 5-day mean surface chlorophyll concentration (mg chl/m^3) for the Mediterranean Sea of MODIS-Aqua satellite data (SAT1, box and whisker plot) compared with biogeochemical model results (median, solid line; 25th and 75th percentiles, thick dashed line; minima and maxima, thin dashed line) from operational (OPE, top) and reanalysis (REA, bottom) runs.

The seasonal variability of surface chlorophyll concentration is captured also by the REA run, which seems to be more synchronised with the satellite data (in particular during 2009), showing an increase of the chlorophyll concentration that changes slope around October in 2008 and 2009, and with a smaller overestimation during winter. Moreover, REA underestimates SAT1 during spring and summer 2008 and 2009, but it is relevant to highlight that the effect appears magnified due to the logarithmic scale. Plotting the medians of the three data sets on a linear scale (Figure 3) we observe the general reduction of the difference between REA with respect to OPE, but also the minor impact of the underestimation of REA during spring and summer seasons when compared with SAT1. In any case, both model simulations tend to anticipate the growth and decrease of chlorophyll, with a trend to intensify the decrease in the spring period.

Resuming the effect of the phosphorous co-limitation in the V1 version of the biogeochemical model, we observe an improvement in the simulation results during autumn and winter, reducing the overestimation typical of the V0 version of the model. Conversely, at the same time, it introduces an underestimation of surface chlorophyll concentration during summer. This underestimation can be considered negligible, since during the summer period the biogeochemical activity in the Mediterranean Sea is mostly weak due to the water column stratification and the consequent lack of nutrients in the photic layer. Furthermore it is relevant to note that the algorithm used for the estimation of the chlorophyll concentration from satellite ocean colour observations was developed for the range 0.02-10 mg chl/m³ (Volpe et al. 2007), thus not covering the range of values simulated by the model during summer.

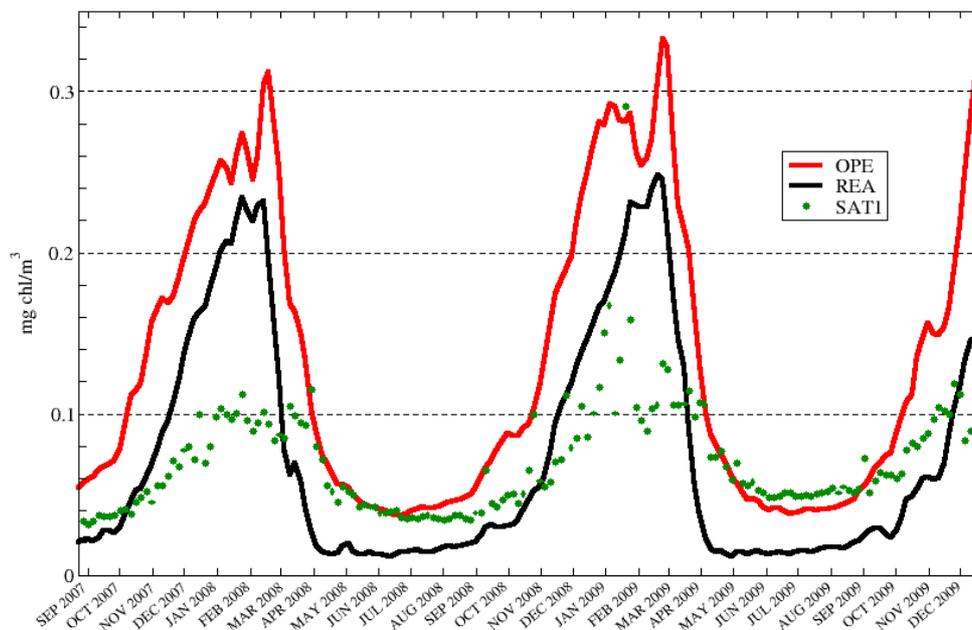


Figure 3: Temporal evolution of the 5-day mean surface chlorophyll concentration (mg chl/m³) for the Mediterranean Sea of MODIS-Aqua satellite data (SAT1, median, green dots) compared with biogeochemical model results (median) from operational (OPE, red line) and reanalysis (REA, black line) runs.

Mediterranean Sea sub-basins analysis

Because of the well-known strongly heterogeneous characteristics of the Mediterranean Sea (Siokou-Frangou et al. 2010) (e.g. western Mediterranean vs eastern Mediterranean), whole basin-averaged statistics represent only a first guess to evaluate the model performance. Therefore, an analysis over sub-basins (as those identified in Figure 1; ALB = Alboran Sea, SWM = south-western Mediterranean Sea, NWM = north-western Mediterranean Sea, TYR = Tyrrhenian Sea, ADN = northern Adriatic Sea, ADS = southern Adriatic Sea, AEG = Aegean Sea, ION = Ionian Sea, LEV = Levantine basin) may give clearer insight into the model capability to reproduce the biogeochemical dynamics of the Mediterranean Sea. We take as an example a couple of sub-basins that notably differ both in physical and biogeochemical dynamics: the north-western Mediterranean (NWM) and Levantine basin (LEV). NWM is characterized as a mesotrophic area influenced by the Rhone river outflow on the coastal area and subjected to intense convection during late winter, while LEV is an oligotrophic area exhibiting a quasi-tropical regime with semi-permanent stratification and chronic shortage of nutrients in the euphotic zone.

Figure 4 shows that REA compares with SAT1 better than OPE from October to March both in 2007-2008 and 2008-2009, while it underestimates the summer chlorophyll depletion more than OPE. Again the effect of the decrease during April-March and the summer underestimation is magnified by the logarithmic scale. Notably, REA seems to reproduce a local event between September and October 2009 that lacks in the OPE simulation (observable also in Figure 2).

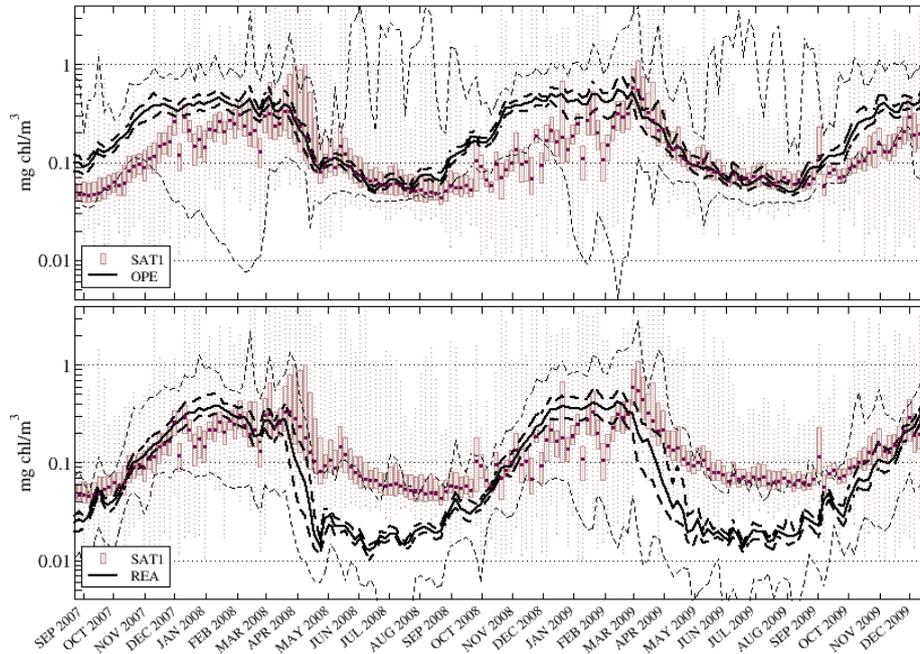


Figure 4: Semilog plot of the temporal evolution of the 5-day mean surface chlorophyll concentration (mg chl/m³) for the north-western Mediterranean Sea (NWM) of MODIS-Aqua satellite data (SAT1, box and whisker plot) compared with biogeochemical model results (median, solid line; 25th and 75th percentiles, thick dashed line; minima and maxima, thin dashed line) from operational (OPE, top) and reanalysis (REA, bottom) runs.

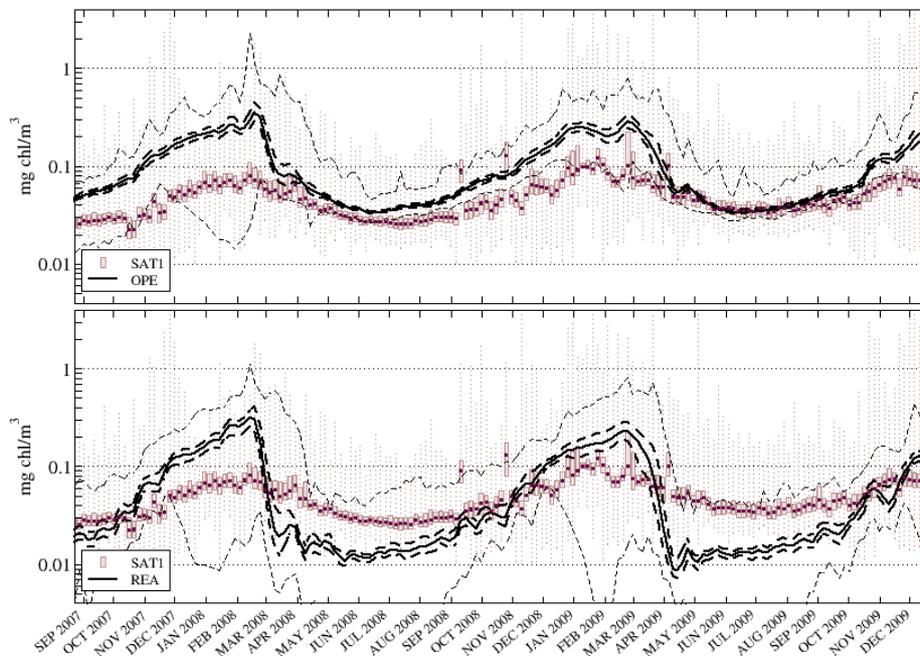


Figure 5: Semilog plot of the temporal evolution of the 5-day mean surface chlorophyll concentration (mg chl/m³) for the Levantine basin (LEV) of MODIS-Aqua satellite data (SAT1, box and whisker plot) compared with biogeochemical model results (median, solid line; 25th and 75th percentiles, thick dashed line; minima and maxima, thin dashed line) from operational (OPE, top) and reanalysis (REA, bottom) runs.

For LEV (Figure 5) the main difference between OPE and REA performances is related to the summer underestimation of REA, since both tend to overestimate the winter-spring bloom (though REA overestimation appears less significant during 2009). It is worth noting that REA data show minima far smaller than SAT1, this aspect being related to the phosphorus-nitrogen co-limitation introduced in the upgraded version of the model. As already commented for Figure 3, the algorithm adopted to evaluate the chlorophyll concentration does not take into account values lower than 0.01 mg/m^3 .

Target diagram analysis

In order to evaluate the performance of REA and OPE in the different sub-basins in the period September 2007 – December 2009, and considering the increased chlorophyll dynamic during autumn and winter seasons, we show in Figures 6 and 7 a graphic representation of model skill compared to SAT1 observations in these periods, using target diagrams (Jolliff et al., 2009). In both figures, the horizontal axis of the target diagram (TD) represents the normalized unbiased root mean square difference (RMSD^{*}) between model (OPE and REA) and SAT1 data, and the vertical axis is the normalized bias B^{*}. In particular, RMSD^{*} is an indicator of the agreement between the amplitude and phase of the temporal patterns of the simulations results and of SAT1 observations, while B^{*} is proportional to the distance between the model and SAT1 mean. Furthermore, in the TD the distance from the origin represents the normalized root mean square difference (RMSD^{*}), which constitutes a measure of the average magnitude of the difference between model and satellite and therefore an indicator of model skill, which improves as the diagram points go toward the origin. For details on the formulation of the statistics used in the TD, please refer to Jolliff et al. (2009) and to Lazzari et al. (2010).

The radius of dots plotted in Figures 6 and 7 is proportional to the number of points used to evaluate the barycentre of the cloud of points (one cloud for each sub-basin) used to calculate RMSD^{*} and B^{*}. It clearly appears that ION and LEV are the sub-basins with the highest number of points (nearly 3600). As a general result, OPE presents a general overestimation (B^{*} > 0) with respect to satellite data in the two seasons. On the other hand, REA results show a significantly reduced bias, which is generally observed in all the sub-basins. The effect is very relevant in autumn (Figure 6) where |B^{*}| < 0.5 for the sub-basins with higher number of points (LEV, ION, NWM, SWM and TYR). The number of points in ADN and ADS (B^{*} < -1) is respectively 40 and 241, since we excluded points with depth lower than 200 m (Figure 1). Furthermore in REA, the phase and temporal patterns (quantified by RMSD^{*}) are slightly larger than OPE in both the seasons considered. As a first conclusion, the skill of OPATM-BFM (related to RMSD^{*}) used in V1 results improved with respect to the V0 version, with better performance in autumn.

Figure 8 shows the comparison between the chlorophyll concentration observed by the satellite (SAT2, top) and that evaluated by the model simulations (both OPE, middle, and REA, bottom) in the Gulf of Lions on selected days of March 2010. It is important to highlight that the SAT2 data set is not obtained with an algorithm specifically designed for the Mediterranean Sea, and we did not use the SAT1, since the SAT1 daily data are available starting from 15 November 2010, since they are available through MyOcean catalogue from 15 November 2010.

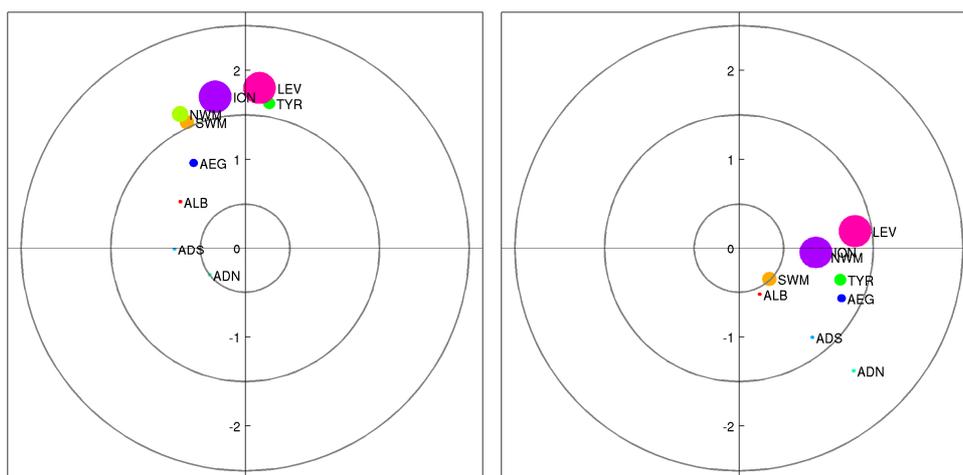


Figure 6: Target diagrams for the Mediterranean sub-basins (see Figure 1) between OPE and SAT1 (right) and REA and SAT1 (left) for autumn (defined as October, November and December) in the period September 2007 – December 2009. Dots represent the average (barycentre) of the points cloud representative of the grid cells, and the size of the dots is proportional to the number of data over which the barycentre is evaluated. The horizontal axis is the normalized unbiased root mean square difference (RMSD^{*}) and the vertical axis is the normalized bias B^{*}.

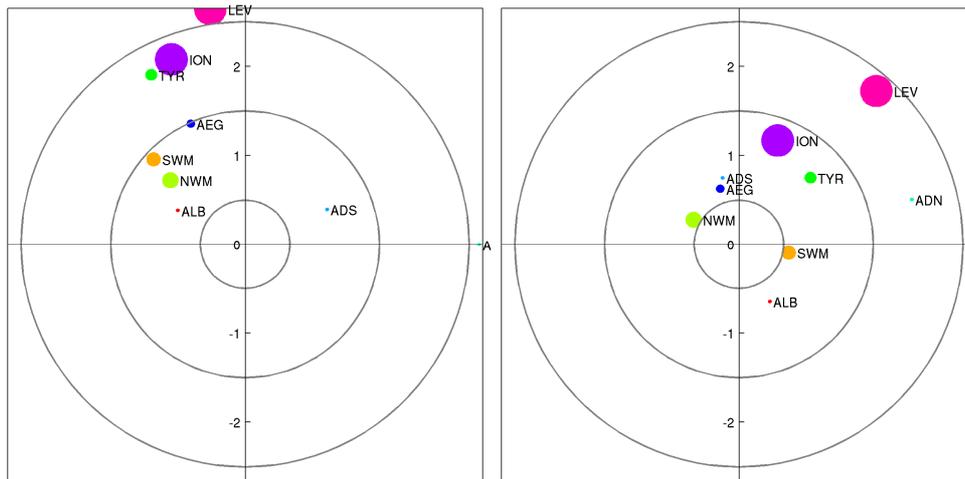


Figure 7: Target diagrams for the Mediterranean sub-basins (see Figure 1) between OPE and SAT1 (right) and REA and SAT1 (left) for winter (defined as January, February and March) in the period September 2007 – December 2009. Dots represent the average (barycentre) of the points cloud representative of the grid cells, and the size of the dots is proportional to the number of data over which the barycentre is evaluated. The horizontal axis is the normalized unbiased root mean square difference (RMSD*) and the vertical axis is the normalized bias B*.

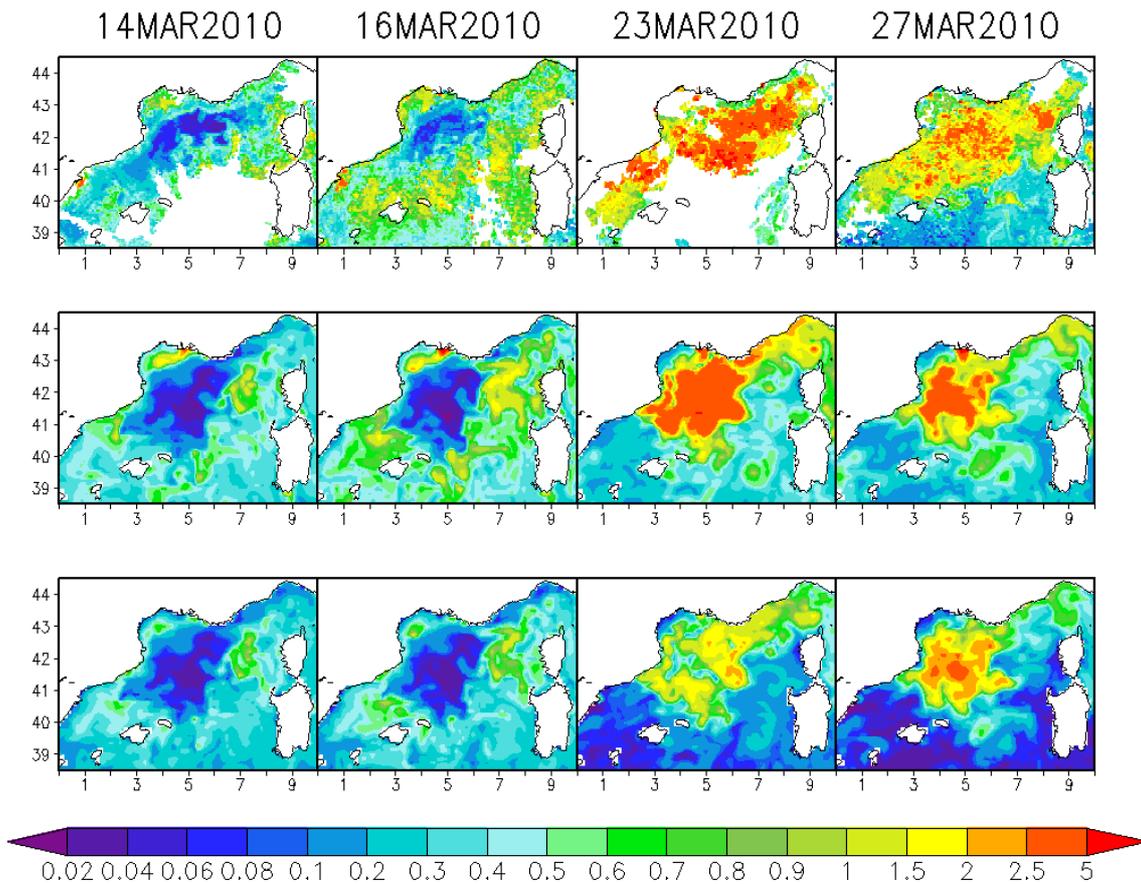


Figure 8: Surface chlorophyll concentration (mg chl/m³) observed during March 2010 in the Gulf of Lions: satellite (SAT2, top), OPE (middle) and REA (bottom).

Satellite data shows the evolution of a spring bloom that develops in the Lions Gyre from values of chlorophyll concentration lower than 0.1 mg/m^3 (14 and 16 March, probably ascribed to a deep convection event in progress causing mixing in the upper layers) to values of patches higher than 2.5 mg/m^3 (on 23 March), then finally reducing in scale at the end of the month.

The dynamic of the event is well reproduced by the OPATM-BFM model, with a better performance in the OPE simulation, except on 16 March when the simulated depleted area is wider than what observed remotely. The simulation is in agreement with the observations also in the second phase of the event (23 and 27 March), that is characterized by a diminishing activity, though the patchiness structure is quite different. The timing and dynamic of the event are satisfactorily reproduced by REA as well, but the simulated fields tend to underestimate the intensity of the whole event, hardly reaching a chlorophyll concentration of 2.5 mg/m^3 on 23 March.

Conclusions

In the present work the operational results of the forecasting system for the Mediterranean biogeochemistry based on the OPATM-BFM model are shown. The OPATM-BFM forecasts provided by OGS are the nominal biogeochemical products for the MyOcean project. In particular, in the V1 version of MyOcean, which started in December 2010, OGS provides 10 days of forecast for 3D chlorophyll and nutrients concentration. The products are delivered twice per week.

In V1 a different model parameterization is applied with respect to the V0 version of MyOcean. In particular, the upgraded OPATM-BFM model adopted in V1 takes into account also the effects of phosphorous co-limitation, and new boundary conditions. The V0 version of the model is the same used during the MERSEA-IP pre-operational project, and it provided an uninterrupted series of forecast since April 2007 until December 2010. A reanalysis with the upgraded version of OPATM-BFM has been run covering the same period.

We analysed the two model series comparing them with sea surface chlorophyll concentration obtained from satellite observations. The results illustrated in the previous sections highlight the effects of the phosphorous co-limitation. Different tools have been used in our evaluation:

- Comparison of temporal evolution of statistics aggregated over the Mediterranean Sea and over selected sub-basins;
- Target diagrams which resume the skills of each Mediterranean Sea sub-basin for different seasons of the year;
- Comparison of satellite and model maps for the Gulf of Lions area, typically interested by local bloom events.

The use of these different approaches allows identifying the improvements (and the drawbacks) related to the V1 model parameterization in terms of model capability to represent the surface chlorophyll concentration. The results of the reanalysis carried out with the V1 version of the biogeochemical model show a skill improvement in the autumn-winter period, which is clearly quantified by means of the target diagrams. Including the phosphorus co-limitation reduces the overestimation of the surface chlorophyll concentration, present in the V0 model version (Lazzari et al. 2010). Furthermore, as for the V0, the model used in V1 is able to simulate local bloom events, well reproducing their time and temporal scales.

During spring and summer the phosphorous co-limitation is related to an underestimation of the surface chlorophyll concentration with respect to satellite data. This occurs in periods when the biogeochemical activity in the Mediterranean Sea is strongly reduced. The very low values produced by the model in the summer period indicate that the phytoplankton activity is significantly damped and this is consistent with the known Mediterranean Sea dynamics. The underestimation has to be evaluated also considering that the simulated summer surface chlorophyll concentration is at the edge of the validity range covered by the algorithm used for the chlorophyll estimation from satellite data (Volpe et al., 2007).

In order to clarify and deeply investigate the capability of the model to adequately simulate the low summer concentrations, it is to be hoped that in the near future also *in situ* data of chlorophyll concentration could be available, especially in the MyOcean operational framework. Since in the V2 version of MyOcean an assimilation scheme will be introduced in the Mediterranean Sea forecasting system based on OPATM-BFM, it will be very profitable to have satellite and *in situ* data operationally available at the same time.

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The MyOcean Black Sea coupling of dynamics and ecosystem

By Victor Dorofeev¹, Temel Oguz², Tatyana Churilova³, Vyacheslav Suslin¹, Aleksandr Kubryakov¹, Gennady Korotaev¹

¹Marine Hydrophysical Institute, Sevastopol, Ukraine

²Institute of Marine Sciences, Turkey

³Institute of Biology of the Southern Seas, Sevastopol, Ukraine

Abstract

The 3D Black Sea ecosystem model coupled with the basin dynamics, which was developed in the framework of the FP6 “Sesame” project and improved within the MyOcean project, is applied to reproduce major stages of the marine biology evolution during the last 40 years. Long-term evolution of the Black Sea ecosystem is accompanied by the transformation of the water transparency. The regional bio-optical model is developed to reproduce the variability of the water transparency based on sea colour observations. It is also used to parameterise spatial and temporal variability of the light absorption in the Black Sea circulation model. Two model runs, one with standard and the other one with regional parameterisations of the light absorption, are compared to show the importance of the correct account of the marine water transparency.

The Black Sea ecosystem and its influence on the basin thermodynamics

The Black Sea ecosystem manifested significant changes during the last few decades. Healthy ecosystem which was observed in the early seventies was altered drastically by the impacts of eutrophication, overfishing and large population growth of gelatinous and opportunistic species in the eighties. The 3D Black Sea ecosystem model coupled with the basin dynamics, which was developed in the framework of the FP6 “Sesame” project and improved within the MyOcean project, is applied to reproduce major stages of the marine biology evolution during the last 40 years. Simulations show reasonable consistency with observed fields.

Long-term evolution of the Black Sea ecosystem is accompanied by the transformation of the water transparency. Whereas the white disk depth achieved 17-20 meters in the early seventies, it decreased to 5-7 meters at the end of the eighties. Such significant changes are able to modulate the upper layer thermodynamics of the Black Sea. The regional bio-optical model is developed to reproduce the variability of the water transparency based on sea colour observations. This model allows including realistic light absorption in the Black Sea circulation model.

Description of the Black Sea ecosystem model

Reconstruction of the Black Sea dynamics during 1971 -1993 by means of assimilation of archive hydrography and after 1993 by means of assimilation of the space altimetry allows considering the Black Sea ecosystem evolution in the 3D ecosystem model coupled with circulation. The biogeochemical model is an extension of the set of one-dimensional models described in Oguz et al. (1999, 2000, 2001) with identical parameters describing interactions between its compartments. The model extends from 0 to 200m depth with 26 z-levels. It includes 15 state variables: two groups of phytoplankton, typifying diatoms and flagellates; microzooplankton (nominally < 0.2mm) and mesozooplankton (0.2 -2mm); the jelly-fish *Aurelia Aurita* and the ctenophore *Mnemiopsis*; omnivorous dinoflagellate *Noctiluca*; nonphotosynthetic free living bacterioplankton; detritus and dissolved organic nitrogen. Nitrogen cycling is resolved into three inorganic forms: nitrate, nitrite and ammonium. Nitrogen is considered as the only limiting nutrients for phytoplankton growth. So all this variables are presented in the model equations in units of mmolN/m³. The other components of the biogeochemical model are dissolved oxygen and hydrogen sulphide.

On the basis of the physical reanalysis simulation from 1971 to 2001 (Demyshev et al. 2010), we carried out a numerical simulation of the long-term evolution of the Black Sea ecosystem. Evident changes of the Black Sea marine biology during this time period were accompanied by modification of the vertical geochemical structure. The most pronounced signature of the geochemical changes is an increase of nitrate concentration in the oxic/suboxic interface zone from 2 to 3 mmol/m³ in the late 1960s to 6–9 mmol/m³ during the 1980s and 90s. Figure 1 illustrates nitrate profiles derived from modelling approximately in the central western gyre for three different years which correspond respectively to early, intense and post-eutrophication phases of the Black Sea ecosystem. Simulated values of nitrate maximum correspond approximately to those measured by cruise vessels at the same times.

Results from the Black Sea ecosystem model

Interannual variability in the Black Sea ecosystem model

Figure 2 presents interannual evolution of the annual-mean phytoplankton biomass in the upper 50m layer for the deep part of the Black Sea basin (left panel) and North Western Shelf (right panel). For the deep part of the basin mean value of the phytoplankton biomass tends to increase from the early seventies to the mid nineties and then decreases. It is caused by the variation of the nitrate concentration in the nitrocline as a result of changes in nutrient supply in the surface layer. However for the shelf region, there is no such an obvious trend in phytoplankton biomass. In this case, phytoplankton stock depends mainly on the volume of nutrients (inorganic nitrogen) supplied by Danube river.

We can see the same tendency in the behaviour of the annual-mean zooplankton biomass (Figure 3). In the deep part of the basin, zooplankton biomass increases as a response to the phytoplankton growth from the early seventies to the late eighties and then abruptly decreases to 0.7 gC/m^2 . In the coastal zone, during the first phase the zooplankton biomass remains approximately constant and then its value drops drastically in 1998. This sharp decrease in zooplankton community in the late eighties is probably associated with Mnemiopsis invasion in the Black Sea.

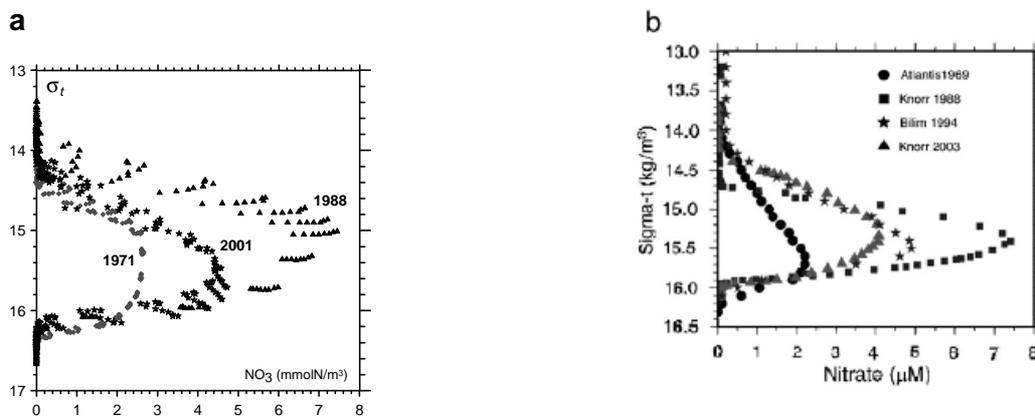


Figure 1: Interannual variability of the Nitrate profiles (in μM) versus potential density (sigma-t) (in kg m^{-3}) for central western gyre in (left panel) the model and (right panel) measured by cruise vessels.

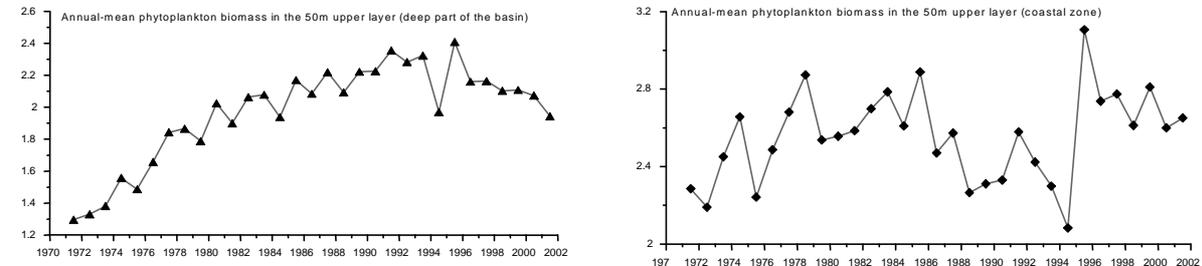


Figure 2: Temporal evolution of the annual-mean phytoplankton biomass (in gC m^{-2}) in the upper 50m layer in the model in (left panel) the deep part of the Black Sea basin and (right panel) the North Western Shelf.

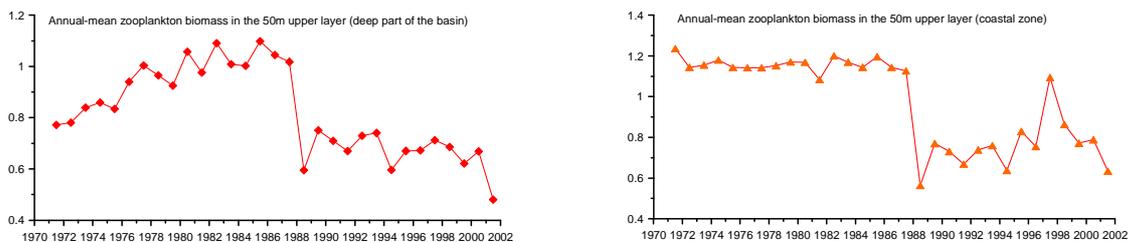


Figure 3: Temporal evolution of the annual-mean zooplankton biomass (in gC m^{-2}) in the upper 50m layer in the model in (left panel) the deep part of the Black Sea basin and (right panel) the North Western Shelf.

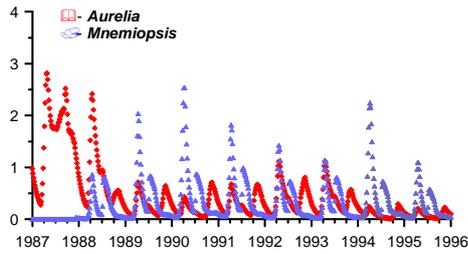


Figure 4: Temporal evolution of the *Aurelia* (red dots) and *Mnemiopsis* (blue dots) biomass (in gC m^{-2}) in the upper 50m layer in the model.

Figure 4 illustrates evolution of the basin-averaged biomass of *Aurelia* and *Mnemiopsis*. Before *Mnemiopsis* invasion *Aurelia aurita* dominated in the carnivorous group of the Black Sea ecosystem. The years 1989–1991 correspond to the phase of pelagic ecosystem evolution in which *Aurelia* blooms were almost replaced by those of *Mnemiopsis* (Figure 8). After its accidental introduction into the Black Sea in ballast waters during the early 1980s, *Mnemiopsis* community quickly dominated the marine ecosystem, because it had no predators in the Black Sea. The sudden increase in the *Mnemiopsis* population caused reduction in the biomass of the zooplankton community.

Seasonal variability in the Black Sea ecosystem model

A good opportunity to compare the results of modelling with measurements is provided by satellite Ocean Colour scanners. Figure 5 displays, as an example, maps of spring-mean surface chlorophyll concentration as a result of numerical modelling (left panel) and those measured with SeaWiFS colour scanner (right panel).

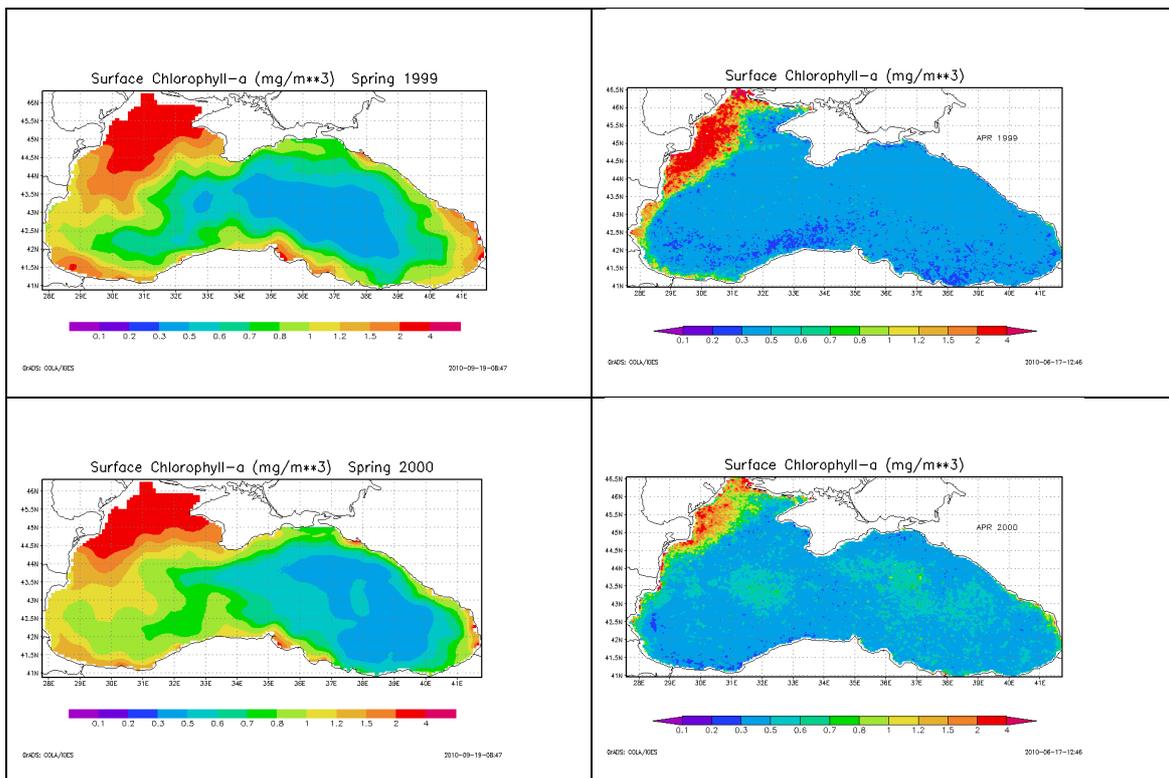


Figure 5: Spring-mean surface chlorophyll-a concentration (mg/m^3) derived from modelling (left panels) and (right panels) satellite data for the two years: 1999 (upper panels) and 2000 (lower panels).

In late winter – early spring, the phytoplankton community produces the main bloom of the year. The highest values of the surface chlorophyll concentration are observed on the north-western shelf. These large concentrations are also present on the periphery of the basin along the coast. It is caused by cyclonic circulation in the Black Sea, which supplies bio-production from north-western shelf to other parts of the basin. In general, simulated surface chlorophyll concentration is higher in spring time than in the SeaWiFS data, although qualitative picture is basically the same. The largest difference can be observed on the north-western shelf and in the western part of the Black Sea. The stripes of high chlorophyll concentration near the western coast are much wider in the results of the modelling than in the observations. It might be due to the relatively poor horizontal resolution of the model (about 8 kilometres).

Description of the Regional bio-optical model

Knowledge of the sunlight penetration into the water column and its spectral composition is important for assessing primary production in the sea, as well as for solutions of different thermodynamic problems. The photosynthesis of organic matter requires radiation in the wavelength range from 400 to 700 nm, which is called photosynthetic available radiation (PAR).

In this paper we consider a semi-empirical spectral model of penetrating irradiance, which takes into account the bio-optical characteristics of the Black Sea. For the past ten years, the light absorption by coloured dissolved and particulate matter on one side, and by phytoplankton and nonliving particulate matter on the other side, have been measured in the Black Sea. The collected data set has enabled to parameterise the light absorption by all optically active components of water and has shown the differences in the equations of parameterisation, reflecting the seasonal and spatial variability (Churilova et al. 2007). The regional approach to the spectral modelling of downwelling irradiance $E_d(z, \lambda)$ is based on the Bedford model (Platt et al. 1991) which was modified using bio-optical characteristics of the Black Sea (Churilova et al. 2009).

In the proposed model, we use several input observed parameters:

- (i) photosynthetic available radiation incident on the sea surface (PAR_0) (SeaWiFS Data);
- (ii) sea-surface temperature (SST) (MODIS-Aqua/Terra Data),
- (iii) normalized water-leaving radiance at wavelengths of 490, 510, and 555 nm: $n_{lw}(490)$, $n_{lw}(510)$, and $n_{lw}(555)$, respectively (SeaWiFS Data), used for the evaluation of the surface concentration of chlorophyll *a* (in sum with pheopigments) and absorption of coloured dissolved organic matter at 490 nm (in sum with non-algal particles) (Suslin et al. 2008).

Validation of the Regional bio-optical model

Comparison of model calculations of the underwater irradiance with the results of in situ measurements showed high accuracy of the model in the spectral and integral solution (Figure 6). Test of sensitivity of the spectral bio-optical model to changes of the light absorption by different optically active components and particles light backscattering showed that the model is more sensitive to variability in the light absorption by coloured dissolved organic matter due to its predominant contribution to total light absorption (Figure 9) (Churilova et al. 2009).

The spectral PAR model was used to analyze depth-dependent variation of the spectrum features of downwelling irradiance and estimate the effect of relative content of light absorbing components on the spectrum of irradiance penetrating to the bottom of the euphotic zone. Non-uniform spectral distribution of light absorption by dissolved, suspended matters and water results in a relatively intense light absorption and scattering at shorter and longer wavelengths of the irradiance spectrum. As a result, the blue-green light penetrates to the bottom of the euphotic zone. In the deep-waters region of the Black Sea, irradiance at wavelengths in the range from 500 - 550 nm penetrates to the euphotic zone bottom (Figure 6). It should be noted that the shorter wavelengths are absorbed mainly by coloured dissolved organic matter and non-algal particles (Figure 9). An increase of their content in water leads to longer wavelengths irradiance penetrating to the bottom of the euphotic zone (Figure 7).

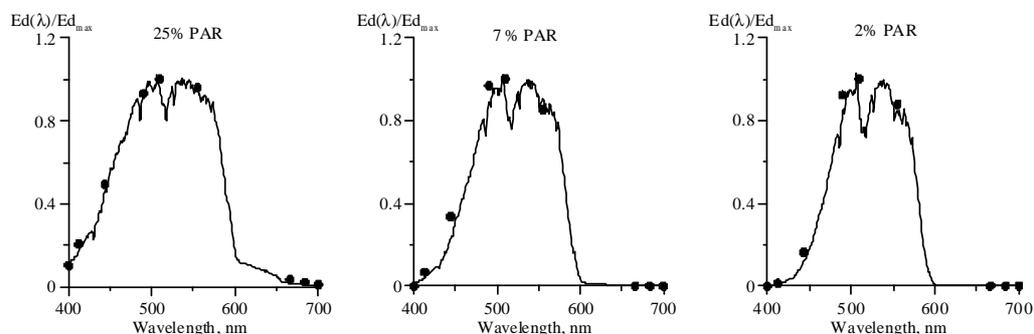


Figure 6: Spectral distribution of downwelling irradiance in relative units ($E_d(\lambda)/E_{d,max}$) in summer in deep-water region of the Black Sea with a surface chlorophyll-*a* concentration of 0.2 mg m^{-3} at the depths with the following percentage of surface solar radiation (PAR): (left panel) 25% of PAR, (middle panel) 7% of PAR and (right panel) 2 % of PAR. Solid lines show the modelled results and circles show the observed ones (according to Churilova et al. 2009).

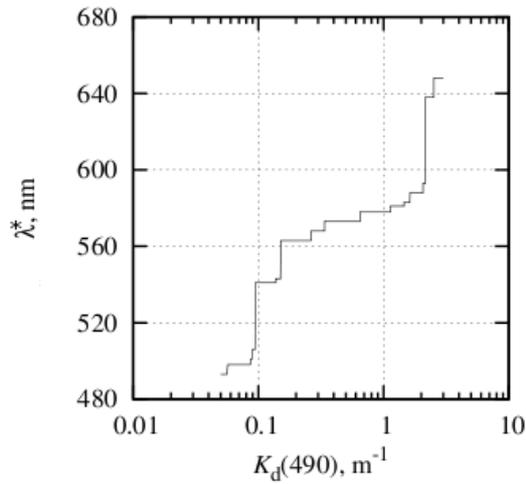


Figure 7: Relationship between light attenuation coefficient at 490 nm ($K_d(490)$, m^{-1}) and wavelength λ^* (nm), at which maximum transparency of water within visible range of solar radiance has appeared .

Application of this model allows evaluating the light field on different space and time scales and could be used for analysis of the spatial and temporal variability of the water transparency. Figure 8 displays the composed maps of the two-week averaged euphotic zone depth (Z_{eu} - the depth of 1 % sea surface radiance) with a spatial resolution of 2.5×3.5 km for year 2007. Pronounced spatial and seasonal variability of Z_{eu} is evidenced on those maps. The water transparency amplitude is doubled during the year from the maximum values in summer to minimum ones in winter. Coastal waters and in particular the north-western shelf waters are characterized by narrower euphotic layer throughout the year in comparison with the deep-waters region.

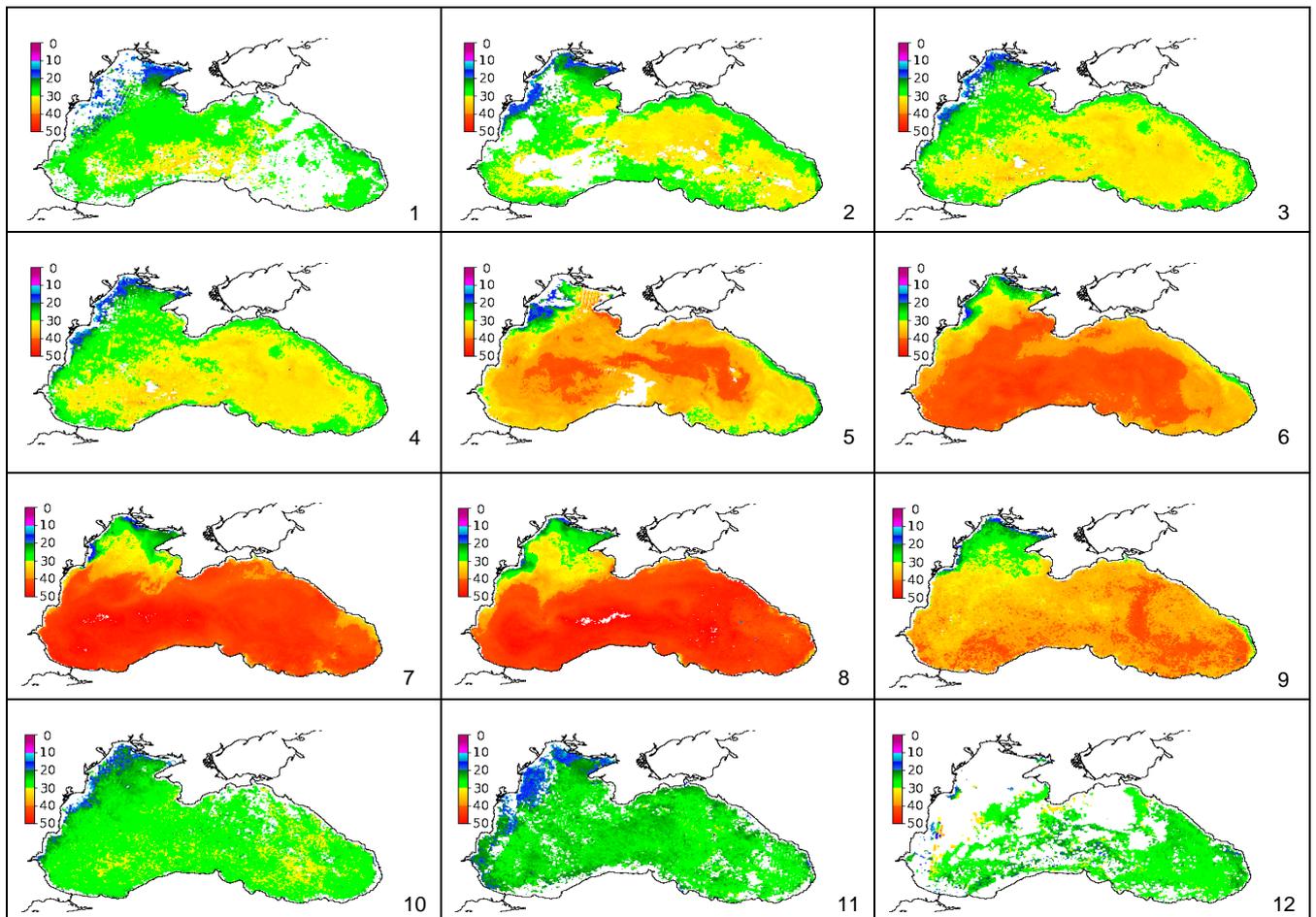


Figure 8: Monthly composed maps of euphotic zone depth (m) in 2007 (with a two-week time average and the second part of the months shown) from (top left panel) January 2007 to (right bottom panel) December 2007.

The photosynthesis zone deepens to 40-50 meters in summer in the deep-waters region. Z_{eu} values decreased in north-western shelf from 35 m near the slope zone to 10 m in the coastal waters at the same time. Almost the entire north-western region is

characterized by relatively shallow euphotic zone (10 - 15 m) in winter, while the deep-waters region of the sea is almost twice more transparent.

The seasonal variations of the euphotic zone are more pronounced in the deep-waters region than on the shelf. Those variations are caused mainly by coloured dissolved organic matter, which contribution to the total light absorption by all optically active components exceeds 50% in the blue-green domain of the visible solar radiation (Churilova et al. 2009). Thus the presented regional spectral bio-optical model which takes into account particulate light back scattering and light absorption by all optically active in-water components is a reliable and suitable tool for careful simulation of the light field which is important for a correct modelling of ecologic and hydrographic fields in the Black Sea.

Improvement of the short-wave radiation absorption.

The commonly used Black Sea general circulation models do not take into account the effect of space and time varying turbidity, caused by the effects of phytoplankton on solar radiation penetration into the sea. Some models, however, do take into account these effects in a very simplified way by considering a constant light attenuation depth. Recently, absorption of solar radiation by phytoplankton has been incorporated into the Black Sea general circulation model to study its dynamic and thermodynamic effects (Kara et al. 2004) on the upper-layer circulation on a climatologic time scales.

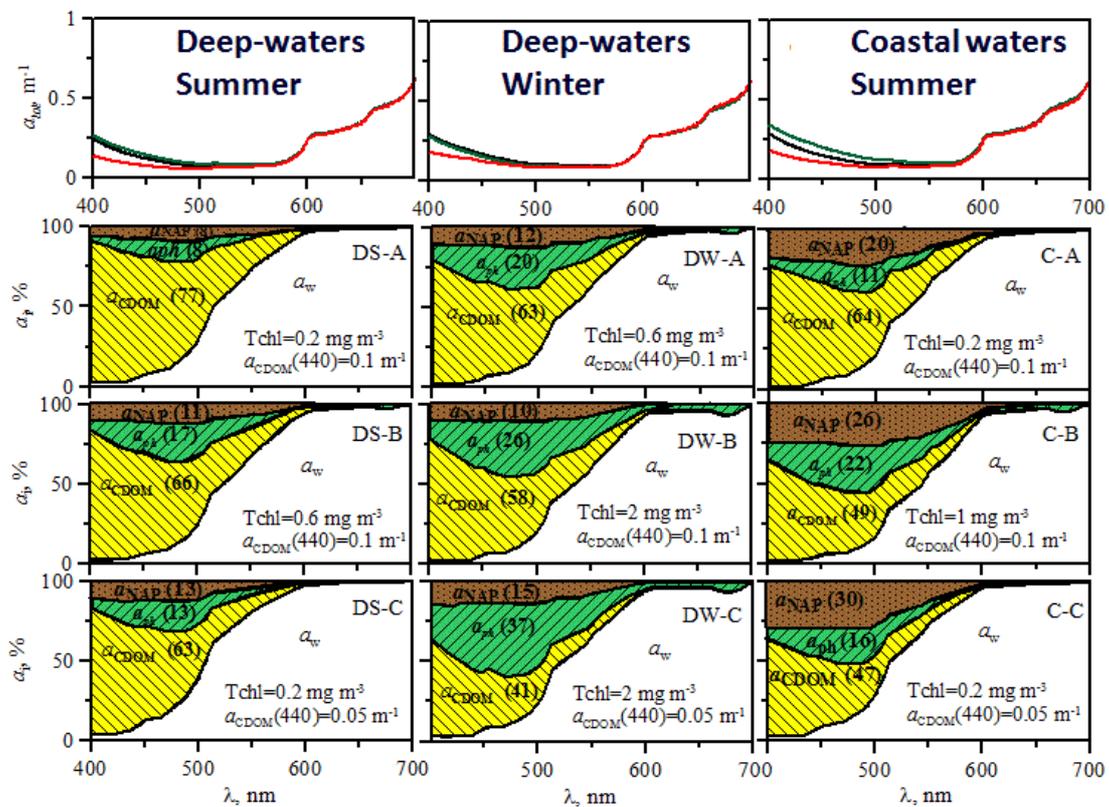


Figure 9: Spectral distributions of the coefficient of total absorption of light a_{tot} (red/green/blue on top panel are -A/-B/-C rows below) in the different parts of the sea for the different seasons and the relative contribution (%) of all optically active components in total light absorption in the surface layer of deep-waters region in warm period (DS - left column, Deep-waters Summer) and cold period of year (DW – central column, Deep waters Winter) and in coastal waters (C – right column, Coastal waters Summer): a_{ph} , a_{NAP} , a_{CDOM} and a_w – light absorption by phytoplankton, non-algal particles – NAP, coloured dissolved organic matter – CDOM; Tchl – surface chlorophyll a concentration in sum with pheopigments. The numbers in brackets correspond to the mean values of the contributions within the range 400–500 nm (according to Churilova et al., (2009)).

Impact of water transparency on the Black Sea currents circulation

We use the above described bio-optical model to show that the realistic account of the spatial and temporal variability of the water transparency in the basin circulation model is extremely important on shorter scales due to the significant biological activity of the Black Sea basin. The simulated mixed layer depth and the sea surface temperature strongly depend on the accuracy of the parameterisation of the short-wave radiation absorption. The contribution of all optically active components in total light absorption is presented on Figure 9. The regional model of light absorption is coupled with the general circulation model to study effects of penetrative radiation on the upper Black Sea thermodynamics. The circulation model is a POM based sigma coordinate model.

The water temperature is calculated in model from the equation:

$$\frac{\partial TD}{\partial t} + \frac{\partial TVD}{\partial x} + \frac{\partial TUD}{\partial y} + \frac{\partial T\omega}{\partial \sigma} = \frac{\partial}{\partial \sigma} \left[\frac{K_H}{D} \frac{\partial T}{\partial \sigma} \right] + F_T - \frac{\partial I}{\partial z};$$

where U, V – are the current velocity component along x and y axis respectively; ρ' – is the relative density of sea water; D – is the full depth of the sea; t – is the time; K_H – is the coefficient of vertical turbulent diffusion; T – is the potential temperature; ω – is the normal velocity to the σ – surface; I – is the penetrating shortwave solar radiation.

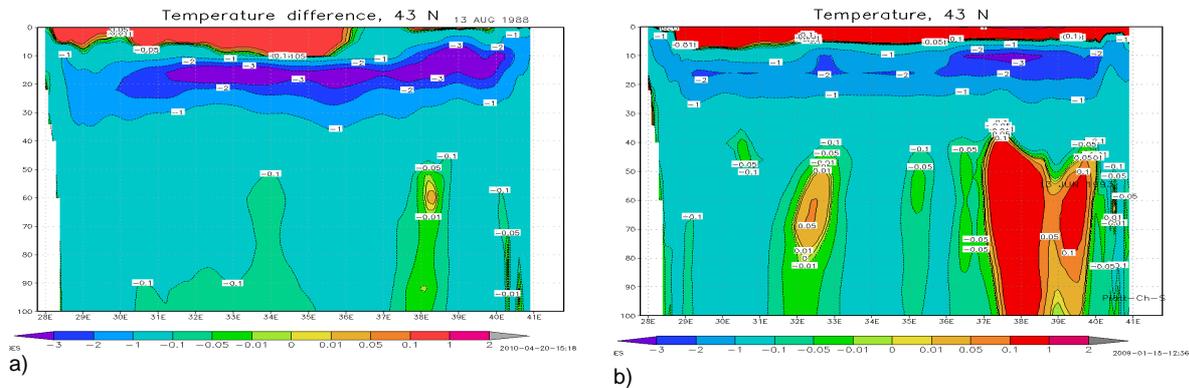


Figure 10: Difference of temperature (°C) between standard and regional parameterisation runs along the zonal section at 43°N in the Black Sea in (a) August 13 1988 and (b) June 13 1993.

The basic equation that describes the penetration of shortwave radiation in the general circulation model of the Black Sea, following (Paulson and Simpson, 1977), is:

$$I/I_0 = R \exp(z/A1) + (1-R) \exp(z/A2)$$

where z – is the depth; I and I_0 – are the values of shortwave radiation at depth z and 0 m respectively; $R, A1$ and $A2$ – are the parameters of the model. The bio-optical model described in the previous section allows determining the three parameters $R, A1$ and $A2$ as functions of time and space. Note that in the standard parameterisation, all parameters are considered as a constant.

Two runs of the circulation model with standard and regional parameterisations of the light absorption are carried out during seven years from 1985 till 2001, covering the period of severe eutrophication in the basin. Both runs are driven by the ERA40 atmosphere forcing. The comparison of simulations with regional parameterisation of the light absorption and control runs shows significant difference in the upper layer thermal structure. Especially large differences occur in the summer seasons. The differences between temperature of the upper mixed layer in summer achieves a few degrees in some years (Figure 10).

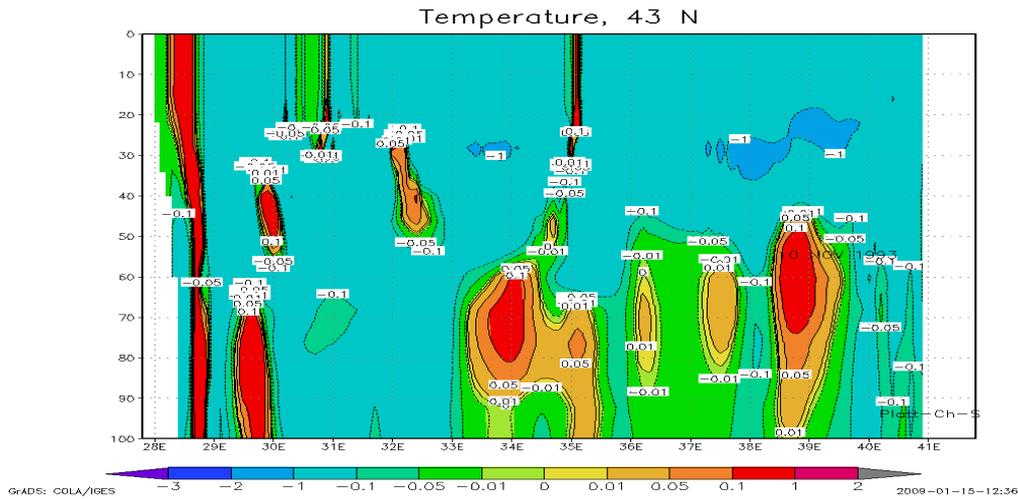


Figure 11: Difference of temperature (°C) between standard and regional parameterisation runs along the zonal section at 43°N in the Black Sea in November 10 1993.

Regional parameterisation of the light absorption changes also the depth of the upper mixed layer up to a few meters against the control run. The difference in the mixed layer depth is reflected in large water temperature difference near the bottom of the layer. During the winter seasons, the differences are smaller and deepen to the 60-70 meters deep layers (Figure 11).

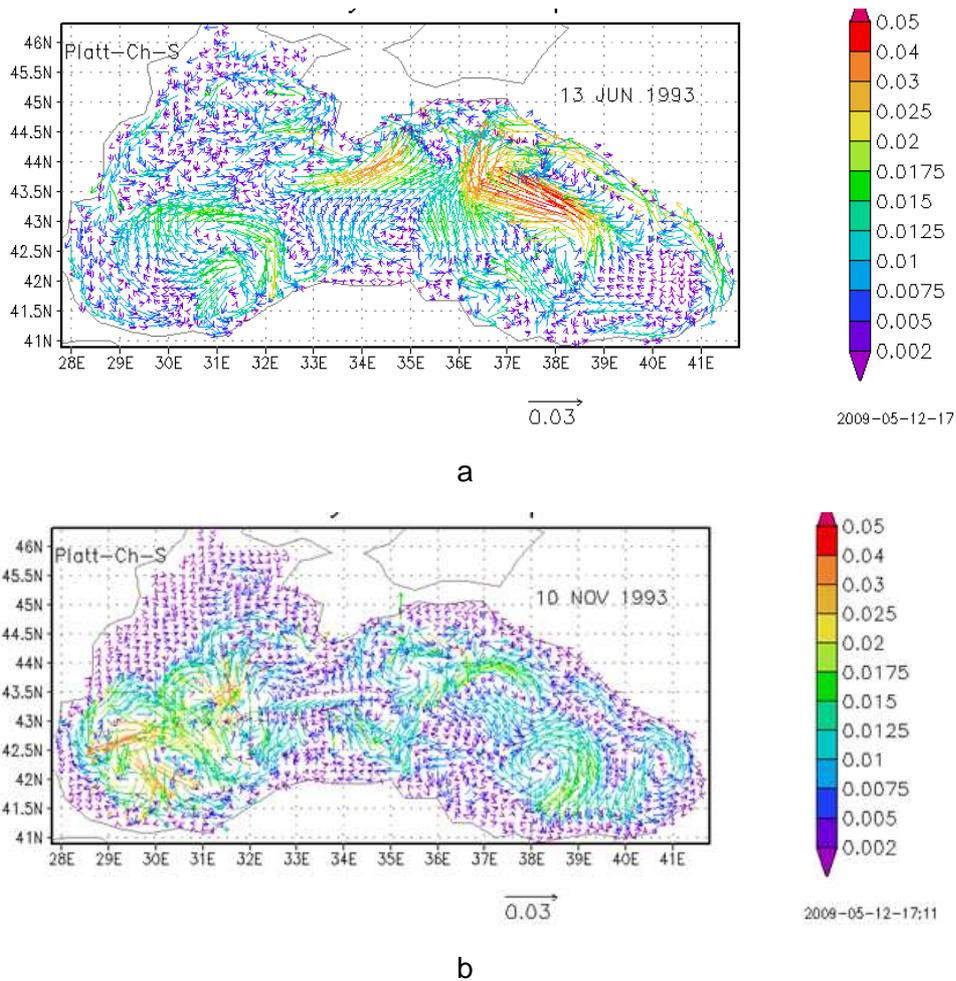


Figure 12. Difference of circulation (m/s) at 10 meters depth between standard and regional parameterisation runs in (a) summer and (b) winter.

The difference between the two runs for the Black Sea currents at 10 meter depth in summer and winter are presented in Figure 12. It shows that the presence of phytoplankton in the upper sea layers plays a significant role in the variability of the circulation and the thermohaline structure of the upper Black Sea. The regional bio-optical model has been developed to take into account the spatial and temporal variability of the attenuation of light radiation in the upper layer which alters the vertical distribution of local heating, and has potential implications for thermal and dynamical processes.

Conclusion

Three-dimensional model of the Black Sea ecosystem coupled with marine dynamics is presented in this paper. A 40-years hindcast simulation of the Black Sea ecosystem shows reasonable consistency between simulation and observations. A bio-optical model of the Black Sea waters is also developed and adjusted using MyOcean Seawifs data. The bio-optical model is able to simulate efficiently the water transparency as well as the upper layer light absorption. Numerical simulation of the Black Sea circulation shows that the regional parameterisation of the light absorption is important both for the correct simulation of upper layer thermodynamics and basin dynamics. The MyOcean project now gives a good opportunity to monitor in the real time and continuously bio-optics and ecosystem in the Black Sea basin.

Acknowledgement

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Arctic Ocean ecosystem modeling in MyOcean

By **Annette Samuelson¹** and **Laurent Bertino¹**

¹Nansen Environmental and Remote Sensing Center, Bergen, Norway

Abstract

By 2012 ecosystem variables will be an integrated part of the forecasting system for the Arctic marine environment that is established within the MyOcean project with the coupling of the NORWegian ECOlogical Model (NORWECOM) to the HYbrid Coordinate Ocean Model (HYCOM) in the TOPAZ system. The variables that will be provided are chlorophyll-a, diffuse attenuation coefficients, nitrate, phosphate, silicate, and oxygen. The two first products can be evaluated in real-time using satellite data, while the latter four may be validated in delayed mode using in-situ data. During the MyOcean project, a number of improvements have been applied to the Arctic physical modelling system, with respect to model resolution, forcing fields, numerical schemes and data assimilation. These improvements should also positively influence the results of the coupled model. Additionally two size-classes of grazers have been added to the ecosystem model and it is currently being tuned with respect to Arctic data. Here we describe the modelling system used and present results from the model prior to the Arctic tuning. We also discuss how the alterations to both the physical and the biological system have affected the simulations compared to previous results.

Introduction

As the physical models improve and computational capacity increases, we have the possibility to issue predictions components of the lower trophic levels of the marine ecosystem such as nutrients and phytoplankton, i.e. the components that are strongly controlled by the physical parameters. The variables predicted by these models can provide valuable input to more specialized models, for example harmful algal bloom (HAB) prediction systems or larvae drift models for certain species of fish. They could also provide the background environment for other types of predictive tools such as spread of mussel/oyster larvae or information about the type of ecosystems that pollutions released in the ocean will interact with. Combined with available data, either in a blended product or through data assimilation, these models will provide our best estimate for the concentrations of nutrients and phytoplankton in the ocean.

Within the MyOcean project forecasting systems are established both in the global ocean and in regional seas around Europe. In the Arctic, forecasts for physical variables are produced operationally (<http://myocean.eu/>), providing model fields and error statistics on a weekly basis. The development and implementation of the forecast system for the Arctic is a joint effort by the Nansen Environmental and Remote Sensing Center (NERSC), the Norwegian Meteorological Institute (met.no), and the Institute of Marine Research (IMR). During 2011, an ecosystem model, the NORWegian Ecological Model (NORWECOM: Aksnes et al. 1995; Skogen, M. and S oiland 1998), will be run together with the operational system (Figure 1). Although data assimilation is only applied to the physical modelling system, adjustments to the physical fields should also influence the ecosystem model. In the Arctic, we expect that the largest improvements will be through a more realistic positioning of the ice-edge, which control the position of ice-edge blooms (Engelsen et al. 2002). Assimilation of salinity- and temperature-profiles from the ARGO-floats should improve water column stratification, an important control-parameter during phytoplankton blooms in light-limited environments, such as the Arctic. The stratification in the marginal ice zone is particularly difficult to model because of the presence of sea-ice, causing the seasonal thermocline to be controlled by both temperature and salinity.

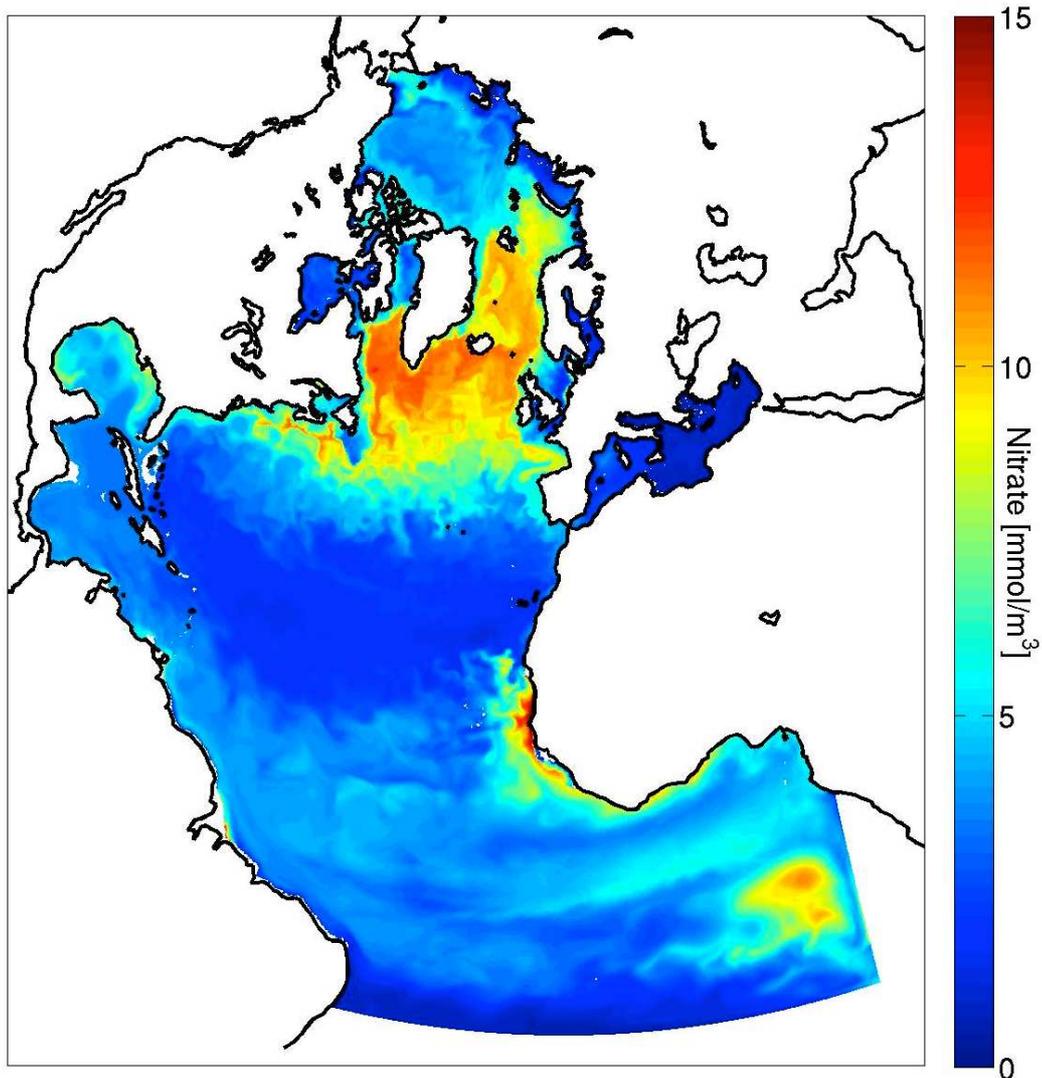


Figure 1: The TOPAZ model region stretches from south of the equator and includes the entire Arctic Ocean. Here, the nitrate concentration (mmol/m^3) in the upper 50 m in March 2006 is shown. Deep mixing throughout the winter causes the high concentrations in the North Atlantic.

Ecosystem models are typically difficult to validate because we lack observations, in addition, a number of model variables and parameter are seldom or never observed. In the Arctic there are few data, but efforts during the International Polar Year and the recent boost in interest for the region may improve this. In real time we can use ocean colour satellite products for validation, and at high latitudes this product can only be used from April to September because of the low solar angle or lack of light in the rest of the year. This is not a great problem as we expect the primary production to be quite low outside this period. In-situ nutrients and chlorophyll must be validated in delayed mode, because they require water samples and laboratory analysis. The operational product will therefore have to be evaluated in two stages; one right after the forecasting period is over and in delayed mode for the in-situ data. Here we present results from a free run in the period 2006 to 2007, where the daily model results have been compared to nutrient and chlorophyll concentration from the ICES database. We also explore how the results compare to the previous model version. As tuning of the model to Arctic data is currently being done, in the present simulation the model was applied as-is and no parameters have been tuned to improve the model performance.

Assimilation of surface chlorophyll data from satellite ocean colour products is also under development for the MyOcean Arctic system. Controlling the strongly non-linear 3D ecosystem dynamics by surface data of limited precision is a very challenging task. Therefore, our focus so far has been on methodological developments able to tackle the non-linear evolution of the errors with an Ensemble Kalman Filter (Natvik and Evensen 2003) and the non-Gaussian nature of ecosystem variables (Simon and Bertino 2009). The Ensemble Kalman Filter has been selected for these developments because it offers a convenient framework for non-

linear extensions and for joint state-parameter estimation (Evensen 2009). Due to large computational costs, the assimilation of ocean colour data will be at first run in reanalysis mode and at coarser resolution than the real-time system, while the real-time forecast ecosystem will be free running, coupled online to the physical TOPAZ4 forecast (MyOcean V1 system). We also expect the assimilation developments to be useful for ocean carbon models.

Model description

The modelling system used is the HYCOM-NORWECOM (Hansen and Samuelsen 2009; Samuelsen et al. 2009), this coupled model uses the HYbrid Coordinate Ocean Model (HYCOM: Bleck 2002) as the physical model and NORWECOM (Skogen and Søiland 1998; Skogen et al. 1995) as the ecosystem model (Figure 2). HYCOM uses a combination of isopycnal and z-coordinates, that allows for both good conservational properties in the deep ocean and high vertical resolution in the upper mixed layer. The present model configuration has 28 vertical layers of which the 5 upper layers are in z-coordinates and the lower 23 layer are hybrid layers. In 2009, the NERSC version of HYCOM was upgraded to the latest version (HYCOM 2.2.12), which carries a number of improvements compared to the previous version. One that may influence the ecosystem is an improved vertical interpolation algorithm that uses a piecewise parabolic interpolation, this reduces artificial mixing caused by the remapping of the isopycnal grid. There is also improved code efficiency and stability in shallow waters (Morel et al. 2008). In addition, a diurnal cycle in the solar irradiance was implemented. The resolution has been increased compared to the model presented in Samuelsen et al. (2009) and the resolution in “European” sector of the Arctic is now about 14 km compared to about 30 km in the previous version.

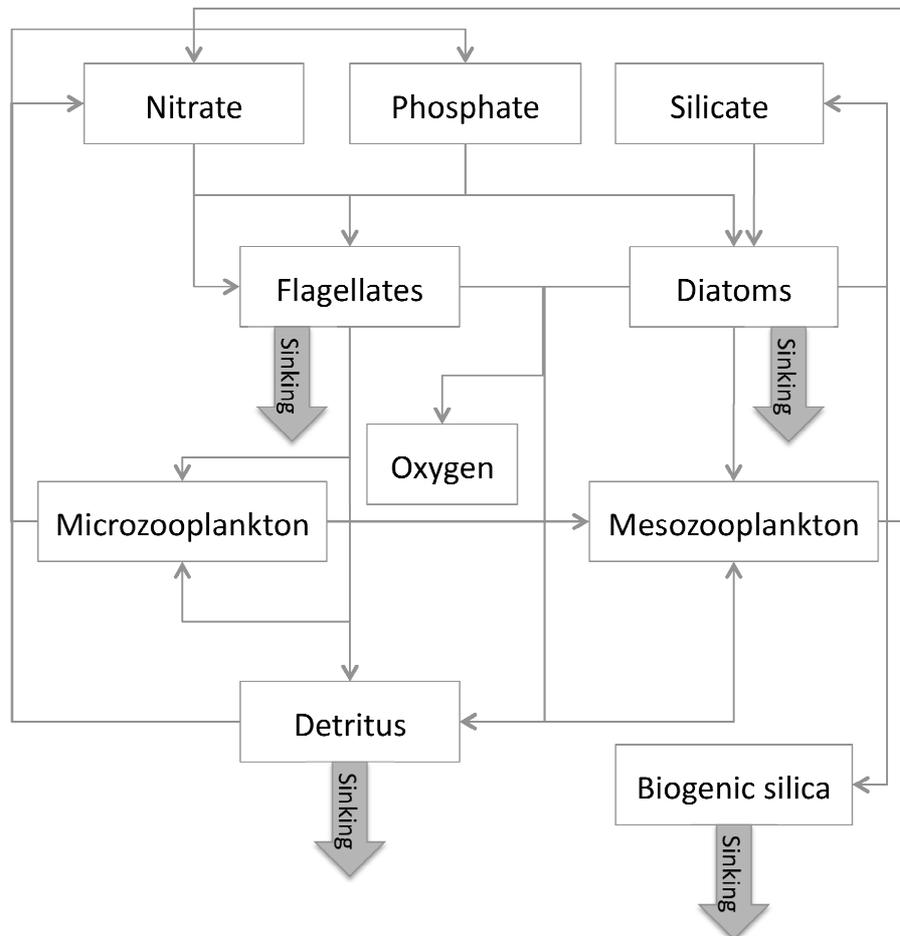


Figure 2: Overview over the components of NORWECOM and how they interact with each other. The zooplankton components were recently added to the model in order to impose more realistic mortality fields on the phytoplankton groups.

Two zooplankton (micro- and mesozooplankton) components were recently added to the model. In the model formulation microzooplankton mostly graze on flagellates, but also ingest detritus. Mesozooplankton preferentially graze on diatoms, but also ingest detritus and prey on microzooplankton with equal preference. The grazing formulation used is from the ECOHAM4 model (Moll and Stegert 2007; Pätsch et al. 2009; Stegert et al. 2009). Excretion by zooplankton is added to the nitrate pool, while the fecal pellet production is added to the detritus pool (Figure 2). With grazers present the background phytoplankton mortality was adjusted down to a low constant rate of 3.5% per day. The oxygen formulation was improved by implementing oxygen exchange with the atmosphere. In addition climatological oxygen concentrations replaced the constant value previously used as initial condition.

The model is forced by the ERA Interim forcing (Simmons et al. 2007), which is a 6-hourly reanalysis product available from 1989 to present. The river forcing is generated using a hydrological model - TRIP (Oki and Sud 1998). The river outflow calculated by TRIP was combined with data from Global Nutrient Export from Watersheds (GlobalNEWS: Beusen et al. 2009; Seitzinger et al. 2005) and used as nutrient river input to the model. Overall, this is an improvement from the previous version of the model where only rivers around Northern Europe included nutrients. Sea surface salinity was relaxed back to climatology with a relaxation timescale of 200 days, while no relaxation is applied to the sea surface temperature. Nutrients and oxygen were relaxed to climatology at the lateral boundaries. The physical model was initiated from climatology in 1973, and the biological model was initialized in 2000. For initialization of NORWECOM climatological values of nutrients and oxygen was used, all other variables were set to a constant low value. Here we consider the years 2006 and 2007 in order to also compare the results to those from the previous model version.

Data

The results have been compared to salinity, temperature, chlorophyll, nutrients and oxygen data downloaded from the ICES database (<http://www.ices.dk/ocean/asp/Chem/HydChem/HydChem.aspx>). We will focus primarily on the biological variables here. In addition we use Ocean Color products from MODIS-Aqua as a reference for the chlorophyll concentrations.

Results and Discussion

As expected the model reproduced the annual cycle with a spring bloom and reduction of the nutrients as described in Samuelsen (2009). An example of a time series is shown in Figure 3. Both the modelled and observed spring bloom starts in April/May earlier in the shallow and southern regions. The timing of the bloom in the model is a little later than what is observed. Diatoms bloom first and have a relatively brief blooming period terminated by the end in supply of silicate (Figure 3). It is then followed by flagellates bloom which blooms over a longer period well into the time when nutrients are seemingly absent, indicating rapid cycling of nutrients during this time.

The diatom bloom has a reasonable magnitude, while the flagellate bloom is overestimated as compared to satellite data (Figure 4). The previous model version also overestimated chlorophyll concentration during the summer, something we speculated could be alleviated by including grazers to keep the population low during the summer (Samuelsen et al. 2009). In this run we have included grazers, yet the summer concentration is still overestimated (Figure 4). Taking a closer look at the grazer-concentrations, we notice that the concentration of micro-zooplankton is very low (Figure 3). Because micro-zooplankton is the only grazer of flagellate, their mortality of flagellates is set by the micro-zooplankton concentration, except for a very small background mortality. This means that with the current parameterization of the model the micro-zooplankton population remains too low to exert sufficient grazing pressure to keep the flagellate concentration on a realistic level.

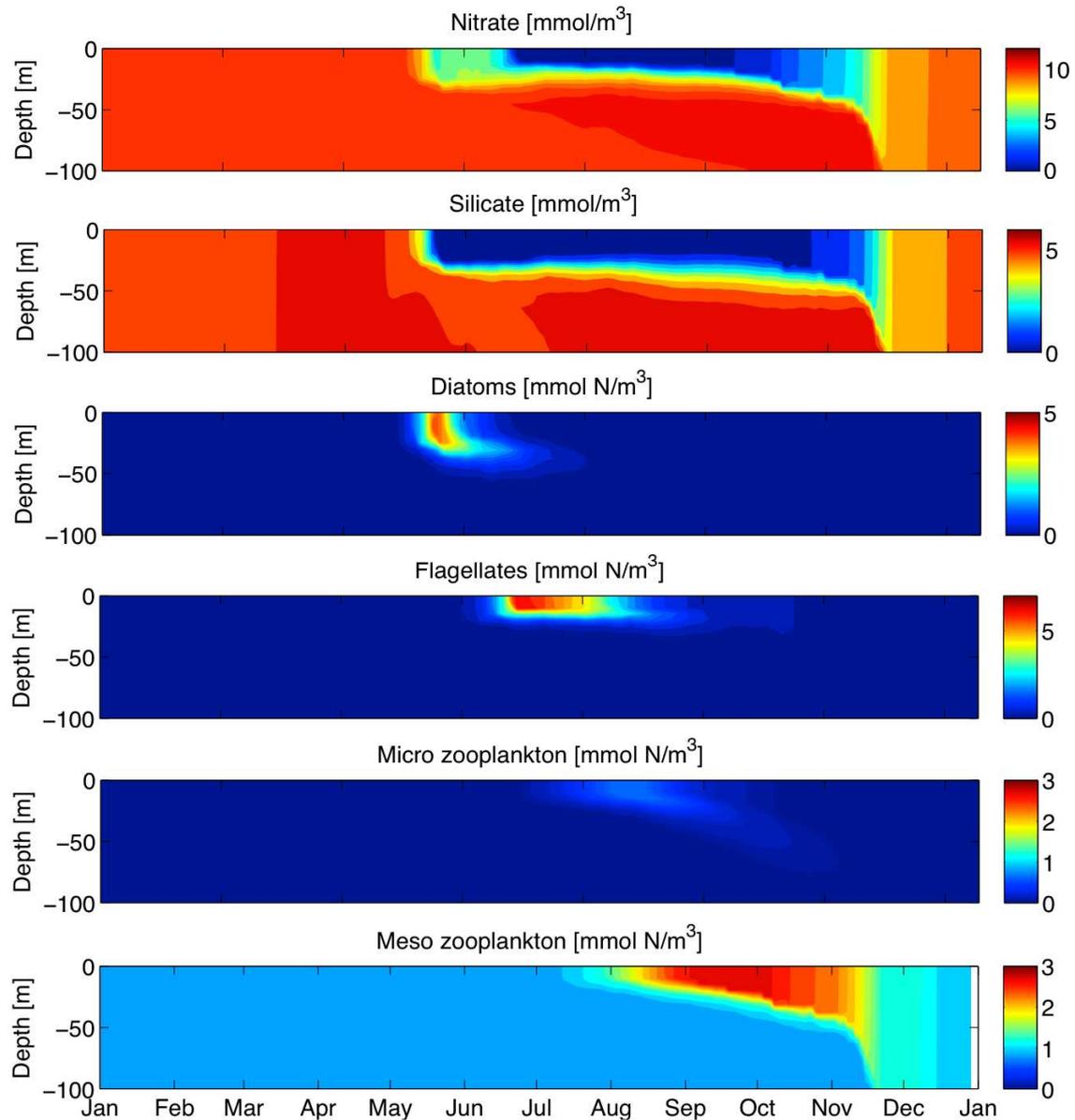


Figure 3: Time-series of two nutrients (nitrate and silicate) (mmol/m^3), the two phytoplankton functional groups (diatoms and flagellates) (mmol N/m^3), and micro- and meso-zooplankton (mmol N/m^3) at 0°E and 70°N , in the central Nordic Seas. Micro- and meso-zooplankton have been plotted on the same colour-scale to emphasize the large difference in concentration between the two zooplankton size-classes.

The higher model resolution may also lead to more mixing of nutrients to the surface than the coarser model. The increased transport of nutrients to the euphotic zone can support higher phytoplankton concentrations throughout the summer. But Hansen and Samuelson (2009) showed that the increased resolution did not lead to a significant increase in primary production unless the resolution reaches the scale of the local Rossby Radius of deformation. At 14 km we still have some way to go before we reach this resolution in the Arctic, further south in the model domain we are resolving eddies and this may lead to higher nutrient-input there which may in turn influence the Nordic Seas and Arctic through advection in the long term.

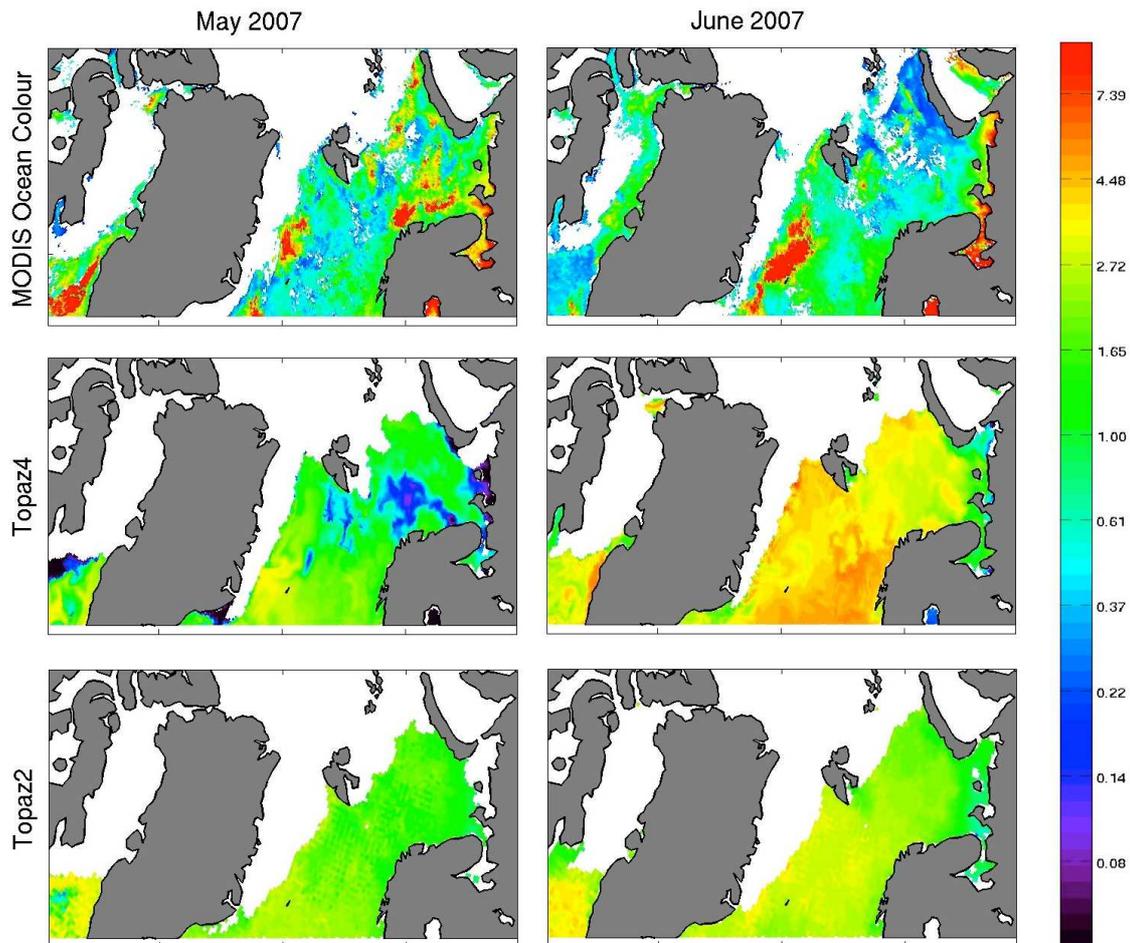


Figure 4: Monthly values of chlorophyll (mg chl/m^3) in May and June 2007 from the MODIS ocean-colour sensor, the current model version (Topaz4) and the previous model version (Topaz2) in the 'European' sector of the Arctic. The rest of the Arctic Ocean is primarily still covered by ice at this time of the year. The ice-covered areas in the model have been masked out.

The higher resolution results in a more patchy distribution that is much more similar to what we observe in satellite images. The influence of the resolution is especially seen in figure 1 at the boundary between the subtropical gyre and the Gulf stream, further North individual eddies are not resolved, but the resulting model fields still have more spatial variability than the previous runs (Figure 4). Specifically notice patches of high productivity along the ice-edge that are completely absent in the previous run, which has very little spatial variability.

We lack observations in the Arctic, but in the Faroe-Shetland channel there is a fairly good data set from October 2006 and May 2007 (Figure 5 and Figure 6). The comparison to in-situ data is more favourable than the comparison to ocean colour chlorophyll; the spread of chlorophyll-values in the surface layer in May 2007 is wider and more similar to observations than in the previous run (Figure 6). There are no large changes in the nutrient values, but the silicate values at mid-depth (400-600 m) seem improved. In May 2007 the observed surface values of all three nutrients are already depleted, while modelled nitrate and phosphate pools remain high. This could be explained by the actual spring phytoplankton assemblage is not as diatom dominated as in the model (Figure 3). Another possibility is that in order to simulate this the model must take into account that the diatom silicate-to-nitrate-uptake ratio is not fixed (Kudo 2003). In October the modelled concentrations of all three nutrients are fairly depleted as in the observations. The largest improvement is seen in the oxygen values (Figure 6), reflecting both improved initial conditions and model formulation.

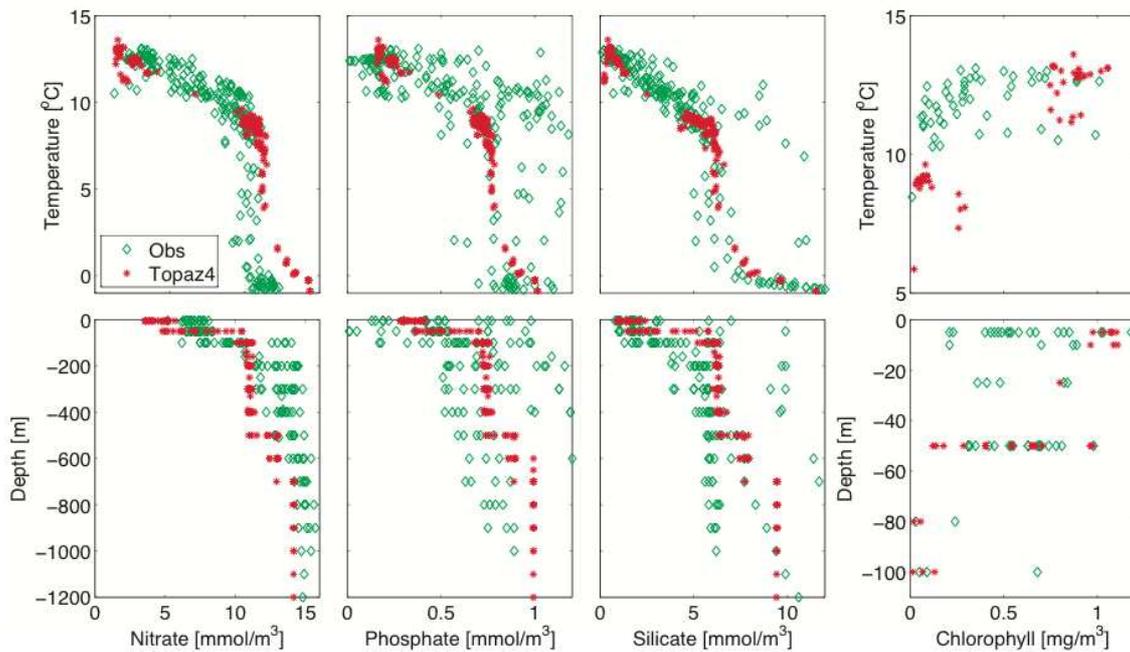


Figure 5: Nutrients (mmol/m^3) and chlorophyll (mg/m^3) in the Faroe-Shetland channel in October 2006, from observations (green diamonds) and the current model run (red stars). The upper row of figures show the variables plotted against temperature and the lower row show the variables plotted against depth.

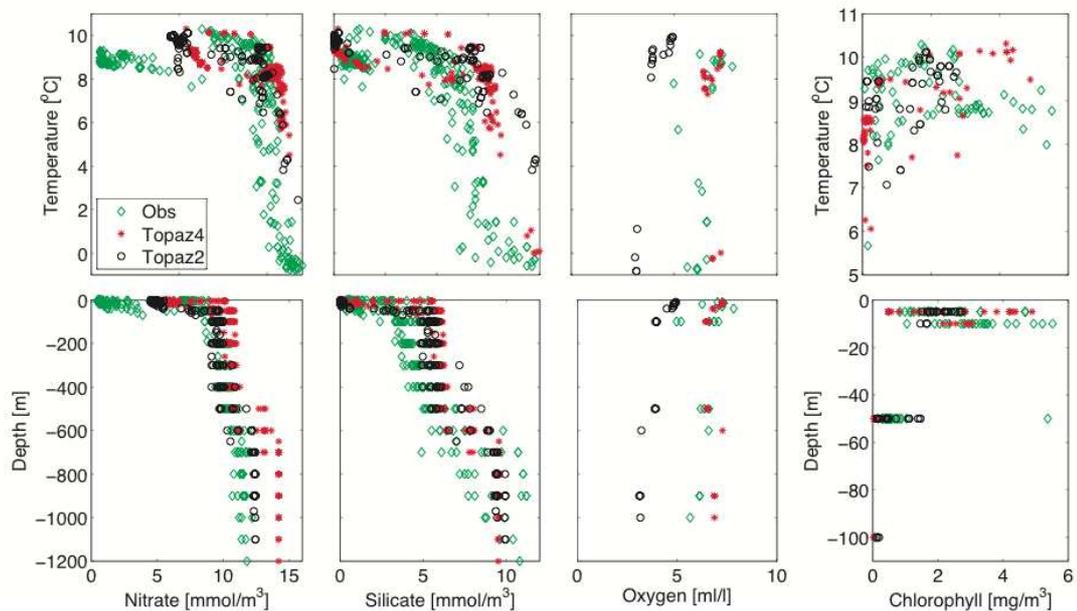


Figure 6: Nutrients (mmol/m^3), oxygen (ml/l) and chlorophyll (mg/m^3) in the Faroe-Shetland channel in May 2007, from observations (green diamonds), the current model run (red stars), and the previous version of the model (black circles). The upper row of figures show the variables plotted against temperature and the lower row show the variables plotted against depth.

Conclusion

The TOPAZ4 system has been set up with the NORWECOM model and run for a longer time in order to test the system before it is run on a regular basis together with the physical operational system for the Arctic. NORWECOM was originally set up and tuned to the North Sea (Skogen et al. 1995), but has also been used in the other regions (Skogen 1999; Zhao and Guo 2010), and the model has here been applied as is without any tuning. Within the MyOcean project, parameter tuning is planned to adjust the model parameters to the Arctic, this effort is currently underway at IMR. A number of improvements have been applied to the system both with respect to the physical model and the input to the biological system through input of river nutrient. In order to provide a more realistic mortality field for the modelled phytoplankton groups, two size classes of grazers were added to the model, however before tuning this did not have the desired effect of reducing summer chlorophyll concentration, because the micro-zooplankton concentration is too low. This bias in the chlorophyll values during the summer causes problems for assimilation of ocean colour data in this model as the assimilation methods assume unbiased models, but perhaps the parameter tuning will alleviate this problem. The nutrient values, on the other hand, are quite good as compared to available data.

With the added biological module, the system takes about twice as much computational time as the run with physics only. In the operational run this is a minor increase in computational need, as only one out of the 100 members will provide the 10-days forecast with the biological module. With validation done on a regular basis as is done for the physical system we will have the necessary information to further improve the modelling system.

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