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THE NEW COPERNICUS BLACK SEA MONITORING AND FORECASTING CENTRE: TOWARDS BLACK SEA OPERATIONAL OCEANOGRAPHY

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Елисавета Пенева, Емил Станев, Атанас Палазов. НОВИЯТ ЧЕРНОМОРСКИ ЦЕНТЪР ЗА МОНИТОРИНГ И ПРОГНОЗА ПО ПРОГРАМА „КОПЕРНИК": КЪМ ОПЕРАЦИОННА ЧЕРНОМОРСКА ОКЕАНОГРАФИЯ

Целта на статията е да представи новият Черноморски център за мониторинг и прогноза (ЧМ-ЦМП), създаден през април 2016 г. в рамките на Морските услуги по Програма „Коперник" на Европейската комисия. Оперативната работа на ЧМ-ЦМП стартира през октомври 2016 г. с издаване на регулярна информация за действителното състояние и 10-дневна прогноза на физическите и био-геохимичните параметри на Черно море. Качеството на издаваните продукти се осигурява чрез постоянно сравнение с данни от спътникови и in-situ измервания. Системата за анализ и прогноза се състои от 3 компоненти: 1) физичен модел на морето – BS-currents, базиран на числения модел за океанска циркулация NEMO (Nucleus for European Modelling of the Ocean): 2) био-геохимичен модел – BS-biogeochemistry, базиран на числения модел Biogeochemical Model for Hypoxic and Benthic Influenced areas (BAMHBI); 3) модел на вълнението – BS-Waves, базиран на числения модел WAM, за когото е предвидено съвместно интегриране с физичния модел на по-късен етап.

Elisaveta Peneva, Emil Stanev, Atanas Palazov.THE NEW COPERNICUS BLACK SEA MONITORING AND FORECASTING CENTRE: TOWARDS BLACK SEA OPERATIONAL OCEANOGRAPHY

The aim is to present the new Black Sea Monitoring and Forecasting Centre (BS-MFC) which was established in April 2016 as a part of the Copernicus Marine Environment Monitoring Service (CMEMS). The objective of BS-MFC is, starting from October 2016, to release regularly information about the actual state and 10-days forecast of the Black Sea physical and biological parameters. The good quality of the products is ensured by continuous comparison with data from in-situ and satellite measurements. The analysis and forecast system consists of 3 modules: 1) a physical model, BS-currents, based on тхе модел Nucleus for European Modelling of the Ocean (NEMO): 2) a biogeochemical model, BS-biogeochemistry, based on is the Biogeochemical Model for Hypoxic and Benthic Influenced areas (BAMHBI); 3) a wave model, BS-Waves, based on WAM will be coupled with the physical model at later stage.

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1. INTRODUCTION

The objective of the European Earth observation Programme Copernicus is to provide up-to-date information on how our planet and its climate are changing and to help the right actions, decision making, businesses and citizens. Copernicus services address six main thematic areas (Land Monitoring, Emergency Management, Marine Monitoring, Atmosphere Monitoring, Security, and Climate Change) which have reached different degrees of maturity and are expected to evolve continuously (http://copernicus.eu).

Presently, Copernicus Marine Environment Monitoring Services (CMEMS) provides regular information on the basic characteristics of the global ocean and European regional seas with high scientific quality. This is done combining satellite, in-situ observations and numerical simulations and special efforts are devoted to the estimation of the product quality and its improvement. The services are grouped in 4 Thematic Assembly Centres (TACs: ocean and sea ice, sea level, ocean colour and In-situ) and 7 Monitoring and Forecasting Centres (MFCs: Global Ocean, Arctic Ocean, Baltic Sea, European North-West Shelf seas, Iberia-Biscay-Ireland regional seas, Mediterranean Sea and Black Sea) (http://marine.copernicus.eu). These operational services are created through competitive procedures and unite the expertise of leading marine physicist and biogeochemists for the respective basins: the Global Ocean MFC is led by the Mercator Ocean (www.mercator.fr); the Arctic MFC is led by the Norwegian Meteorological institute (www.met.no); the Baltic Sea MFC is led by Danish Meteorological Institute (www.dmi.dk) and German Hydrographic Service (www.bsh.de); the European North-West Shelf Seas MFC is led by UK Meteorological Office (http://www.metoffice.gov.uk); the IBI regional seas MFC is led by the Spanish State Ports Service; the Mediterranean MFC is led by the Euro-Mediterranean Center for climate change (www.cmcc.it); and Black Sea MFC Is led by the Institute of Oceanology in Bulgarian Academy of Science.

The Black Sea is one of the largest inland basins of the world with a surface area of ~4.2×10^5 km^2 (zonal and meridional dimensions ~1000 km and ~400 km) and a maximum depth of ~2200 m. It is almost completely isolated from the world oceans; it is connected to the Sea of Azov via the Kerch Strait in the North and to the Marmara Sea (which is connected to the Aegean Sea through Dardanelles Strait) via the Bosporus in the southwest. The other characteristic of the Black Sea is the large river catchment area and the great amount of fresh water discharge in the sea (coming from the basic rivers Danube, Dniepr and Dniestr). The fresh water input and the Mediterranean inflow through the Bosporus Straits are the main reasons to form extremely strong density stratification, which leads to limited ventilation and anoxic conditions under ~100 m depth. Thus the Black Sea is unique environment both from physical and biogeochemical point of view, and very difficult to be numerically simulated in realistic way [1].

The model to represent adequately the Black Sea hydrodynamics has to take into account the following points:

- To permit eddy resolving resolution.
- Good representation of vertical processes in order to represent adequately the stratification and the permanent pycnocline. The second problem is the existence of a layer of cold intermediate water (CIL) that persists during the summer. In general the applied models are to diffusive, so that this cold intermediate water had the tendency to disappear during the summer.
- Various bathymetries: rather small and shallow continental shelf, which rapidly falls to about 2000 m depth.
- Representation of fresh river input in northern part and the Bosporus plume of Mediterranean saline water.
- Flexible to put in the operative chain, fast enough to perform the simulations in due time.

Since October 2016 the Black Sea Monitoring and Forecasting Centre is operational (BS-MFC), with the main objective to produce regular information on the Black Sea physical and biogeochemical state with quality evaluation. The consortiums unite the 6 scientific organisations: Institute of Oceanology in Bulgarian Academy of Science, Sofia University “St. Kliment Ohridski”, Euro-Mediterranean Centre of climate change, Helmholtz Zentrum Geeststadt, University of Liege, and Technical University of Istanbul. This paper describes the components of the forecasting system and gives more details on the validation of the physical component comparing model simulations to satellite and in-situ data.

2. BS-MFC ANALYSIS AND FORECASTING SYSTEM

2.1. PHYSICAL MODEL

The Black Sea Forecasting System BSFS is the physical component of the BS-MFC and is providing since October 2016 analysis and forecast for the Black Sea within CMEMS [2].

The hydrodynamic state is supplied by the Nucleus for European Modeling of the Ocean (NEMO, v 3.6, [3]). The theoretical bases of NEMO are the Navier-Stokes equations along with a nonlinear equation of state are coupled with the two active tracers (temperature and salinity) to the fluid velocity. The model uses the following additional assumptions made from scale considerations:

- Spherical earth approximation: the geopotential surfaces are assumed to be spheres so that gravity (local vertical) is parallel to the earth's radius.
- Thin-shell approximation: the ocean depth is neglected compared to the Earth's radius.
- Turbulent closure hypothesis: the turbulent fluxes (which represent the effect of small scale processes on the large-scale) are expressed in terms of large-scale features.
- Boussinesq hypothesis: density variations are neglected except in their contribution to the buoyancy force
- Hydrostatic hypothesis: the vertical momentum equation is reduced to a balance between the vertical pressure gradient and the buoyancy force (this removes convective processes from the initial Navier-Stokes equations and so convective processes must be parameterized instead).
- Incompressibility hypothesis: the three dimensional divergence of the velocity vector is assumed to be zero.

The model solves six equations, namely the momentum balance (1), the hydrostatic equilibrium (2), the incompressibility equation (3), heat (4) and salt (5) conservation equations:

$$\frac{\partial U_h}{\partial t} = -\left[(\nabla \times \mathbf{U}) \times \mathbf{U} + \frac{1}{2}\nabla(\mathbf{U}^2)\right]_h - fk \times \mathbf{U}_h - \frac{1}{\rho_0}\nabla_h p + D^{\mathbf{U}} + F^{\mathbf{U}}, \quad (1)$$

$$\frac{\partial p}{\partial z} = -\rho g, \quad (2)$$

$$\nabla . \mathbf{U} = 0\,, \quad (3)$$

$$\frac{\partial T}{\partial t} = -\nabla . (T\nabla\mathbf{U}) + D^T + F^T, \quad (4)$$

$$\frac{\partial S}{\partial t} = -\nabla . (S\nabla S) + D^S + F^S, \quad (5)$$

where **U** is the vector velocity, $\mathbf{U} = \mathbf{U}_{h+w}$ (horizontal and vertical parts), T – the potential temperature, S – the salinity, p is the pressure, ρ – the in-situ density and it is related to the other variables by the equation of state

$$\rho = \rho\,(T, S, p). \tag{6}$$

Additionally, D is the diffusion term and F is the friction term, which describes the processes of diffusion and friction with various parameterizations schemes.

The model resolves the entire Black Sea with horizontal grid resolution 1/36° in zonal resolution, 1/27° in meridional resolution (~ 3 km) and has 31 unevenly spaced vertical levels. Fig 1. shows the bathymetry of the model domain, it is based on the General Bathymetric Chart of the Oceans GEBCO 1'ocean bathymetry (www.gebco.net).

The model initial condition comes from climatological data for 3D fields of temperature and salinity [4] and a spin-up period of 2 years of integration is applied.

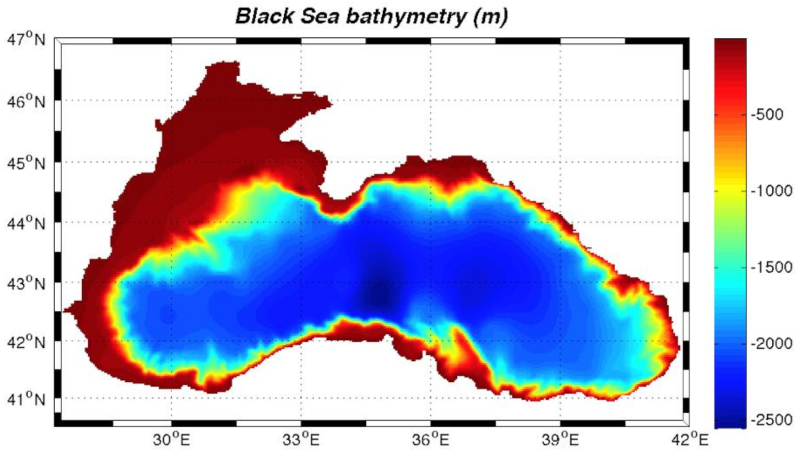

Fig. 1. Model domain bathymetry based on GEBCO data set (www.gebco.net)

As for the atmospheric boundary conditions at the sea surface the model uses the data of the European Centre for Medium-range Weather Forecast (ECMWF) analysis and forecast at 1/8° spatial resolution: for forecast, 3 h time resolution fields are used for the first three days while 6 h time resolution fields are used for the remaining 7 days. In particular, the atmospheric fields used are: zonal and meridional components of 10 m wind [m s^{-1}], total cloud cover [%], 2 m air temperature [K], 2 m dew point temperature [K] and mean sea level pressure [Pa]. Precipitation fields over the basin are from GPCP rainfall monthly data [5, 6].

The atmospheric fields are used for computing the momentum, heat and water fluxes at the air-sea interface based on the Black Sea bulk formulae [7].

Concerning the land forcing, in particular the river runoff contribution, an estimate of the inflow using monthly mean dataset provided by SESAME project [8] is used.

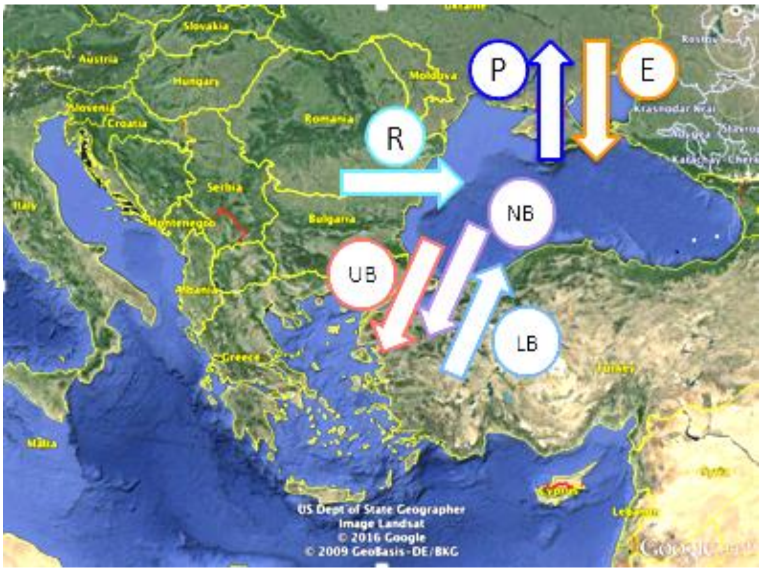

Fig. 2. Schematic representation of the fresh water balance and the exchange with Mediterranean through Bosporus Straits

The rivers in the model are given as surface boundary conditions in several points where the river mouth lies. In similar way the Bosporus Strait two-way exchange is parameterized: the net transport consists of upper (Q_U) and lower (Q_L) currents and the barotropic transport $Q_B = Q_U - Q_L$ is calculated as a residual from the fresh water balance equation

$$S_{BS}\frac{\partial \eta}{\partial t} = Q_R + Q_P - Q_E - Q_B, \quad (7)$$

where S_{BS} is the Black Sea surface, Q_R – the summary river runoff, Q_P – the summary precipitation, Q_E – the summary evaporation, and η is the free sea surface.

The equation is closed assuming that on monthly basis $\frac{\partial \bar{\eta}}{\partial t} = 0$, which allows to calculate the barotropic Bosporus transport Q_B. This method is described in more details in [9] and [10]. Fig. 2 shows the schematic picture of the fresh water balance components including the barotropic Bosporus transport.

The current nominal CMEMS product of the Black Sea Physical Analysis and Forecasting system is composed by: 3D, daily mean and hourly mean fields of Potential Temperature, Salinity, Zonal and Meridional Velocity; by 2D, daily mean and hourly mean fields of Sea Surface Height, and Mixed Layer Depth.

2.2. BIOGEOCHEMICAL MODEL

The current CMEMS nominal product of the Black Sea Biogeochemistry Analysis and Forecasting system is composed by: 3D, daily mean fields of chlorophyll, phosphate, nitrate, primary production, dissolved oxygen, phytoplankton biomass and 2D fields of bottom oxygen.

The biogeochemistry component of the BS-MFC is based on the Biogeochemical Model for Hypoxic and Benthic Influenced areas (BAMHBI, [11], [12] and [13]). It describes the food web from bacteria to gelatinous carnivores through 24 state variables including three groups of phytoplankton: diatoms, small phototrophic flagellates and dinoflagellates, two zooplankton groups: micro- and mesozooplankton, two groups of gelatinous zooplankton: the omnivorous and carnivorous forms, an explicit representation of the bacterial loop: bacteria, labile and semi-labile dissolved organic matter, particulate organic matter. The model simulates oxygen, nitrogen, silicate and carbon cycling. In addition, an innovation of this model is that it explicitly represents processes in the anoxic layer.

The atmospheric forcing is identical to the one described for BS-MFC physical component. Rivers nutrients loads data are issued from the SESAME and PERSEUS projects [8] and are introduced into the 6 main river entrances represented in the model domain, which are the Danube, Dniepr, Dniestr, Rioni, Sakarya and Kizilirmak. These river loads consist of annual loads modulated by repeated seasonal distribution. For the forecast, the climatological mean values computed over the last 5 years are used. The Bosporus Strait is open and the boundary condition is described in details in [9] and [10].

2.3. WAVE MODEL

The information on waves will be available after April 2017. The wave model code is based on WAM Cycle 4.5.4, a state of the art third generation wave model successfully used for the last 20 years by various institutes and operational centres worldwide for wave hindcasting and forecasting. WAM model cycle 4.5.4 is a modernized and improved version of the standard WAM Cycle 4 with high-grade modular composition and interfaces for parallelization purposes. WAM solves the wave transport equation explicitly without any presumptions on the shape of the wave spectrum. The basic physics and numerics of the WAM Cycle 4 wave model, which is described in [14]. In WAM 4.5.4, the source function integration scheme of [15] and the reformulated wave model dissipation source function [16].

Depth-induced wave breaking [17] has been included as an additional source function. Depth and/or current fields can be non-stationary. Grid points can fall dry and refraction due to spatially varying current and depth is accounted for. It calculates the two-dimensional energy density spectrum at each of the 44 699 active model grid points in the frequency and directional space. The solution of the energy balance equation is provided for 36 directional bands at 10° each, starting at 5° and measured clockwise with respect to true north, and 30 frequencies logarithmically spaced from 0.042 Hz to 0.66 Hz at intervals of $\Delta f / f = 0.1$.

The following basic wave physics are accounted for in the WAM Cycle 4.5.4 code:

- Wave propagation in time and space.
- Wave generation by the wind.
- Shoaling and refraction due to depth.
- Refraction due to currents.
- White-capping and bottom friction.
- Quadruplet wave-wave interactions.

The Black Sea WAM implementation will use the shallow water mode with shoaling and refraction due to bathymetry and surface currents provided in off-line mode by the Black Sea physical system. The regional wave model for the semi-enclosed Black Sea runs in shallow water mode on a model grid same as the one shown in Fig. 1.

WAM calculates the two-dimensional energy density spectrum at each of the 44699 active model grid points in the frequency and directional space. The solution of the energy balance equation is provided for 36 directional bands at 10° each, starting at 5° and measured clockwise with respect to true north, and 30 frequencies logarithmically spaced from 0.042 Hz to 0.66 Hz at intervals of $\Delta f / f = 0.1$.

The driving force for the wave model are the ECMWF data, same as the described in 2.1 atmospheric data.

3. DATA ASSIMILATION IN THE MODEL

The data assimilation system of the physical component of BS-MFC is based on a three-dimensional variational (3DVAR) assimilation scheme, originally developed for the Mediterranean Sea [18] and later extended for the global ocean [19], [20]. The system is called OceanVar. The variational cost function is solved with the incremental formulation [21]. The pre-conditioning of the cost function minimization is achieved through a change-of-variable transformation.

In the BS-MFC system implementation of the OceanVar, the control vector in physical space is formed by the three-dimensional fields of temperature and salinity. The assimilation frequency is daily, with a 1-day assimilation time-window.

Background-error covariances are decomposed in vertical covariances and horizontal correlations. The former are modelled through 15-mode multi-variate Empirical Orthogonal Functions (EOFs). EOFs were calculated from a dataset of anomalies with respect to the long-term mean of a model simulation without data assimilation, using the full model resolution. Horizontal correlations are modelled through a third-order recursive filter [22], with spatially inhomogeneous correlation length-scales [23] specified as a function of the distance from coast, ranging approximately from 9 to 27 km.

The assimilation of sea level anomaly (SLA) is performed by imposing local hydrostatic adjustments as multi-variate balance between the sea level innovation and vertical profiles of temperature and salinity [19].

The observations assimilated in the BS-MFC include: i) in-situ hydrographic profiles of temperature and salinity (mostly Argo floats) from CMEMS. If profiles are disseminated at high vertical resolution, a vertical thinning is applied to the profile before ingestion in OceanVar; ii) along-track sea level anomalies, currently from AltiKa, Cryosat-2 and Jason-2, pre-processed and distributed by CMEMS. The mean dynamic topography for the assimilation of SLA is computed from a 4-year (2011–2014) model mean sea surface height, rescaled through gridded sea level products from CMEMS to match the reference period for altimetry (1993–2012); iii) gridded sea surface temperature (SST) observations provided by CMEMS. The assimilation of SST assumes that satellite observations are co-located with the first model level.

4. MODEL RESULTS VALIDATION FOR PHYSICS PARAMETERS

A largely discussed and cited in the literature problem about the Black Sea is lack of systematic data to be used for the near-real time model validation. The quality of the BS-MFC model results is evaluated against satellite SST data and in-situ Argo profiler’s measurements. As mentioned above in Section 3, these are data assimilated in the model, thus the validation is against semi-independent data. The physical component of BS-MFC is run over a 17 years period (1999–2015) overlapping two periods of different spatial resolution of the atmospheric forcing: from January 1999 until September 2008, ECMWF at 50 km resolution has been used, while from September 2008 until December 2014 – at 25 km. Fig. 3 shows the averages at the sea surface quantities of temperature, salinity and height. The graphics shows good representation of the seasonal cycle.

The interannual variability is also adequate: it is known that 2006 and 2012 winters were extremely cold and freezing along the coast in the northern part were observed. From the plot it is seen that the SST in 2006 and 2012 winters are lowest for the decade.

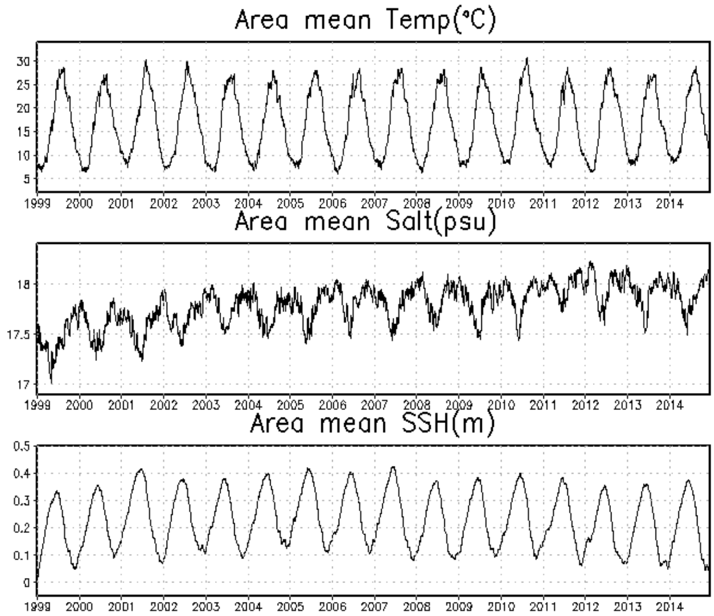

Fig. 3. Mean sea surface temperature, salinity and height over the period 1999–2014

The first two years (1999–2000) are considered a spin-up period for the model, thus the evaluation of the SST is done for the later period 2001-2015. The CMEMS product SST_BS_SST_L3S_NRT_OBSERVATIONS_010_013 is used for the validation.

Table 1. BIAS and RMSE from SST misfits over the whole basin for the period 2001–2008 and 2009–2015

Variable	BIAS 2001-2008	RMS 2001-2008	BIAS 2009-2015	RMS 2009-2015
SST [˚C]	-1	1.3	-0.8	1

The Table 1 summarizes the results for two separated periods when ECMWF switched to finer horizontal resolution of the analysis and forecast product (from ~50 km to ~25 km). In general the model at the sea surface is colder than the observations with RMSE ~1˚C.

The interesting fact is that one can reveal the influence of the atmospheric forcing data: the better spatial resolution in the second period has decreased the RMS error with ~20%.

Evaluation of the thermohaline fields is performed for the last two years of the period 2014–2015 against available data for temperature and salinity from the Argo autonomous profilers and the results are summarized in the Tables 2 and 3 for different layers.

Table 2. BIAS and RMSE of the model Temperature relative to the Argo measurements over the whole basin for the period 2014-2015 given for different depth layers

Layer [m]	BIAS [˚C]	RMS [˚C]
0-10	-0.48	1.24
10-20	0.75	2.38
20-40	-0.03	1.58
40-60	-0.16	1.12
60-80	-0.12	0.47
80-100	-0.06	0.29
100-200	0.11	0.20
200-500	0.08	0.10
500-1000	-0.04	0.05

Table 3. BIAS and RMSE of the model Salinity relative to the Argo measurements over the whole basin for the period 2014-2015 given for different depth layers

Layer [m]	BIAS [psu]	RMS [psu]
0-10	-0.69	0.74
10-20	-0.68	0.71
20-40	-0.67	0.68
40-60	-0.42	0.57
60-80	0.13	0.61
80-100	0.52	0.79
100-200	0.79	0.87
200-500	0.29	0.33
500-1000	0.11	0.12

The temperature is accurate with a RMS error of about 1ºC. Higher errors in the first 0–60 m layer, decreasing in the deepest layers. This is undoubtfully related to the Cold Intermediate Layer (CIL) formation. The salinity is accurate with RMS error ~ 0.7 psu in the layer 0–200 m, where the permanent halocline lies. That could be due to very schematic representation of the Bosporus Strait, modeled as surface boundary condition. Overall, the system presents a satisfactory accuracy regarding the SST and 3D fields of the temperature and salinity.

4. BS-MFC ON-LINE PRODUCTS

Fig. 4 presents a snapshots of the CMEMS website for the Black Sea products provided by BS-MFC and available on-line and updated every day (http://marine.copernicus.eu). Below is given the list of product nomenclature and short description of included variables and fields.

- BLKSEA_ANALYSIS_FORECAST_PHYS_007_001

Analysis and 7-days forecast for the daily and hourly mean 3D fields of currents velocity, potential temperature and salinity as well as 2D fields of the sea surface height and mixed layer for the period 2014 until present at ~3 km spatial resolution.

- BLKSEA_REANALYSIS_PHYS_007_004

Reanalysis of the daily-, monthly- and seasonal- mean 3D fields of currents velocity, potential temperature and salinity as well as 2D fields of the sea surface height and mixed layer for the period January 2005–December 2015 at ~3 km spatial resolution.

- BLKSEA_ANALYSIS_FORECAST_BIO_007_002

Analysis and 7-days forecast for the daily mean 3D fields of phytoplankton, NO_3, Chlorophyll, O_2, PO_4 and Primary Production for the period 2014 until present at 0.05 deg spatial resolution.

- BLKSEA_REANALYSIS_BIO_007_005

Reanalysis of weekly mean 3D fields of phytoplankton, NO_3, Chlorophyll, O_2, PO_4 for the period January 1980–December 2005 at 0.14 deg spatial resolution.

- BLKSEA_REANALYSIS_BIO_007_007

Reanalysis of weekly mean 3D fields of phytoplankton, NO_3, Chlorophyll, O_2, PO_4 for the period January 2006–December 2015 at 0.14 deg spatial resolution.

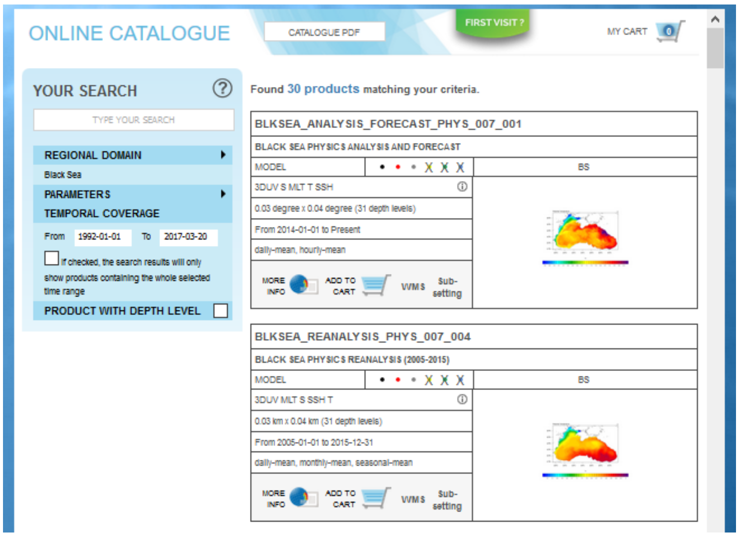

Fig. 4. Snapshots of the CMEMS website (marine.copernicus.eu) regarding BS-MFC products

5. CONCLUSIONS

This article aims to present the work done to establish the new Black Sea Monitoring and Forecasting Centre (BS-MFC) as a part of the Copernicus Marine Environment Monitoring Service (CMEMS). The BS-MFC is operational since October 2016 and gives daily information about the actual state and 10-days forecast of the Black Sea physical and biological parameters. Starting in April 2017 Black Sea waves will be also predicted. The analysis and forecasting system consists of 3 components: 1) a physical model based on Nucleus for European Modelling of the Ocean (NEMO): 2) a biogeochemical model, based on is the Biogeochemical Model for Hypoxic and Benthic Influenced areas (BAMHBI); 3) a wave model based on WAM will be coupled with the physical model at later stage. The physical component assimilates in near-real time the information from satellite observations of the Sea Surface Temperature and Height, as well as in-situ vertical profiles of the Temperature and Salinity, mostly coming from the Argo autonomous floats.

The good quality of the products is ensured by continuous comparison with data from in-situ and satellite measurements. These are semi-independent data for the model, as the independent data at present are very difficult to obtain. Overall, the system presents a satisfactory accuracy regarding the SST and 3D fields of the temperature and salinity. In general the model at the sea surface is colder than the observations with RMSE ~1˚C.

The highest RMS error for the temperature in the deep part is in the first 0–60 m layer (~1˚C), decreasing in the deepest layers. The salinity is accurate with RMS error ~ 0.7 psu in the layer 0–200 m, where the permanent halocline lies. The evolution of the BS-MFC foresees progressively to improve the model simulations including better representation of the exchange with Mediterranean Sea through the Bosporus Strait and parameterization of the vertical diffusion which maintains the strong stratification.

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