# National Report – Italy

# CMCC – Global Ocean Forecasting System (GOFS16) and Mediterranean Forecasting System (MedFS) physics

# OGS - Mediterranean Forecasting System (MedBFM) biogeochemistry

**Summary**

## Background

CMCC (Euro-Mediterranean Center for Climate Change) is providing a specific Italian effort on operational oceanography with focus on short-range ocean forecasting and model reanalysis covering the Global Ocean and the Mediterranean Sea.

OGS (National Institute of Oceanography and Applied Geophysics) is providing a specific Italian effort on operational oceanography, with focus on short-range ocean forecasting and model reanalysis covering the Mediterranean and the Adriatic Sea (i.e., a marginal basin of the Mediterranean Sea).

The **Global Ocean Forecasting system (GOFS16)** at 1/16° degree resolution has been producing forecasts operationally since July 2017.

GOFS16 was developed by marrying the CMCC expertise in developing both regional operational modelling systems and data assimilation systems for global ocean reanalyses. The former expertise has been achieved within several European Projects mainly dedicated to the Mediterranean and Black Sea forecasting systems (MyOcean, MyOcean2, CMEMS Mediterranean-MFC, CMEMS Black Sea-MFC, etc.). The latter expertise is proven by the continuous production and development of global ocean Reanalyses at eddy-permitting resolution since 2008 (Storto et al. 2016a, Storto et al. 2016b, Masina et al. 2017). Such Reanalyses have been employed in several inter-comparison projects (ORAIP, etc.) and funded in the framework of several projects: MyOcean, MyOcean2, till the last CMEMS GLORAN that is an ensemble of Reanalyses from four institutions freely available from the CMEMS catalogue.
The ocean component of GOFS16 is based on the global ocean-sea ice NEMO-LIM2 model that has been set up following an eddy-resolving configuration (GLOB16) developed at CMCC and described in Iovino et al. 2016. The data assimilation (DA) component is a 3dvar system (Storto et al., 2011) called OceanVar, already employed at ¼ resolution (Storto et al., 2016a) and recently adapted to bear large amount of data through a hybrid-parallelization scheme (Cipollone et al.,2020).
The 6-day-long forecast product of GOFS16 has hourly/daily frequency for the temperature, salinity, sea surface height, meridional/zonal velocity. Maps of GOFS16 forecasts are available from the following webpage (http://gofs.cmcc.it/) in almost near-real-time (daily update). A validation tool of the analysis fields is also available online at http://evalid.cmcc.it/evaluation/gofs/, where in-situ temperature and salinity profiles from CMEMS catalogue are compared with model equivalent values.

GOFS16 is fully developed and coordinated within CMCC. Two departments are involved: the Ocean Prediction and Application division (OPA) and the Ocean Modeling and Data Assimilation one (ODA). The former is responsible for the operational maintenance and monitoring of the forecasting system, the latter has the duty of developing the different components.

The **Mediterranean Forecasting System, MedFS,** (Pinardi et al., 2003, Pinardi and Coppini 2010, Tonani et al 2014) has been producing forecasts operationally since September 1999 and is continuously updated and improved.

The MedFS system was developed in the frame of several European projects: MFSPP (Mediterranean Ocean Forecasting System Pilot Project), MFSTEP (Mediterranean Ocean Forecasting System Toward Environmental Predictions), MERSEA (Marine Environment and Security for the European Area), BOS4GMES (Building Operational Sustainable Services for GMES), MyOcean, MyOcean2 and MyOceanFollowOn. The Italian project RITMARE has some research activities linked to the development of the MedFS system.

Several Mediterranean national marine forecasting systems are nested into MedFS in the so-called MONGOOS (Mediterranean Oceanography Network for the Global Ocean Observing System) subsystems network, see www.mongoos.eu.

Since May 2015 the MedFS system represents the Mediterranean physical component of the

European Copernicus Marine Environment Monitoring Service (CMEMS) namely the Mediterranean Monitoring and Forecasting Centre (MED-MFC) providing a service available 24 hours a day, 365 days a year.

The CMEMS MED-MFC is coordinated by CMCC and is composed by three Production Units (PUs): Med-PHY, Med-BIO and Med-WAV, the latter are off-line coupled to the Med-PHY. Med-PHY is now developed and maintained by CMCC, Med-BIO is developed and operate by OGS (Istituto Nazionale di Oceanografia e Geofisica Applicata), Med-WAV is developed and operate by HCMR (Hellenic Centre of Marine Research). All the CMEMS MED-MFC products are available at the CMEMS website catalogue: http://marine.copernicus.eu.

CMCC has also developed and run operational the Southern Adriatic Northern Ionian coastal Forecasting System (SANIFS) providing short-term forecasts. The SANIFS system provides very-high resolution downscaled modelling with unstructured grid model SHYFEM (Figure 4). SANIFS is nested in the Copernicus MED-MFC system. SANIFS provides every day 5 days hourly forecast. The horizontal resolution is 100 meters along all the Italian coasts of the domain and reaches 10 meters resolution in the main harbours (e.g. Taranto, Bari, Brindisi) and selected areas of interest (MPA, touristic areas). Ocean forecasting products visualization is available http://sanifs.cmcc.it

The **Mediterranean Biogeochemical Forecasting System, MedBFM,** (Teruzzi et al., 2018; Cossarini et al., 2019; Salon et al., 2019) has been producing biogeochemical forecasts operationally and biogeochemical reanalysis since 2013 and it is continuously updated and improved.

The **MedBFM** system was developed in the frame of several European projects: MERSEA (Marine Environment and Security for the European Area), OPEC (Marine ecosystem forecasting tools for European Regional Seas), MEDSEA (Mediterranean Sea Acidification in a changing climate), MyOcean, MyOcean2 and MyOceanFollowOn.

Since May 2015 the MedBFM system represents the Mediterranean biogeochemical component of the European Copernicus Marine Environment Monitoring Service (CMEMS) namely the Mediterranean Monitoring and Forecasting Centre (MED-MFC) providing a service available 24 hours a day, 365 days a year.

The MedBFM, developed and operated by OGS, is part of the CMEMS MED-MFC and it is off-line coupled with the physical Mediterranean Forecast System (MFS).

The northern Adriatic model is a higher-resolution downscaling of MedBFM, and capitalized on the experience of the OGS modelling group in the framework of several Adriatic monitoring and short-term forecasting projects (ECOMADR, ADRIANE, TOSCA, Vector, HV/QCBS/LAB-C1, Ritmare). In particular, the coupled model configuration is borrowed from the CADEAU project (http://www.bio.isprambiente.it/cadeau/).

# 1. Input data

Links to the corresponding datasets are provided in the dedicated section:

## 1.a Global Ocean Forecasting system

**- In-situ observation input data:**

Vertical profiles of temperature and salinity from Argo, XBTs and CTDs, Gliders floats from CMEMS INSITU TAC product (INSITU_GLO_NRT_OBSERVATIONS_013_030)

**- Satellite observation input data:**

- Satellite Sea Level L3 along-track data from global near-real-time product (SEALEVEL_GLO_PHY_L3_NRT_OBSERVATIONS_008_044) disseminated by CMEMS SL-TAC

- Satellite Sea Surface Temperature dataset: L3 Advanced Very High-Resolution Radiometer (AVHRR) from NOAA, L3 Advanced Microwave Scanning Radiometer 2 (AMSR2) from OSI-SAF, NOAA Optimum Interpolation ¼° Daily SST

- Sea surface salinity data: from EN4 (MET-OFFCE) monthly objective analyses

- Sea ice concentration data: L4 SIC Optimal interpolation from NOAA.

**- Forcing:**

- The atmospheric fields are extracted from the National Centers for Environmental Prediction (NCEP) operational datasets. The CORE bulk formulae forcing method is adopted. The method requires as input fields the following atmospheric parameters: 6-hourly turbulent variables (10 meters winds and 2 meters temperature and specific humidity); daily radiative fluxes (downward short-wave and long-wave radiations); daily freshwater fluxes (total precipitation and snow)

- Land forcing: coastal and river runoff (Dai and Trenberth, 2002) which uses 99 major rivers and coastal runoff estimates, with a global annual discharge of ~1.32 Sv.

### 1.b Mediterranean Forecasting System - physics

**- In-situ observation input data:**

Vertical profiles of temperature and salinity from Argo, XBTs and Gliders floats from CMEMS INSITU TAC products:

INSITU_GLO_NRT_OBSERVATIONS_013_030,
INSITU_MED_TS_NRT_OBSERVATIONS_013_035

**- Satellite observation input data:**

- Satellite Sea Level along track data from CMEMS SL-TAC products SEALEVEL_EUR_PHY_ASSIM_L3_NRT_OBSERVATIONS_008_043 and SEALEVEL_EUR_PHY_L3_NRT_OBSERVATIONS_008_059

- SST satellite data from CMEMS SST-TAC product: SST_MED_SST_L4_NRT_OBSERVATIONS_010_004

**- Forcing:**

- Atmospheric forcing: 1/10° horizontal-resolution operational analysis and forecast fields from the European Centre for Medium-Range Weather Forecasts (ECMWF) at 6-hours resolution (1-hour for the first 3 days of forecast, 3-hours for the following 3 days of forecast and 6-hours for the last 4 days of forecast).

- Lateral forcing from CMEMS Global Analysis and Forecast system: GLOBAL_ANALYSIS_FORECAST_PHY_001_024 at 1/12° horizontal resolution, 50 vertical levels.

- Land forcing: 39 rivers climatological inflow from PERSEUS project dataset.

### 1.c Mediterranean Biogeochemical Forecasting system

**- In-situ observation input data:**

Vertical profiles of chlorophyll, nitrate and oxygen from BGC-Argo float (Coriolis/Ifremer) and insitu cast of scientific (Emodnet).

**- Satellite observation input data:**

- Satellite chlorophyll L3 from Near Real Time products (i.e., Copernicus OCEANCOLOUR_MED_CHL_L3_NRT_OBSERVATIONS_009_040 from marine.copernicus) and from reprocessed products (i.e., OCEANCOLOUR_MED_CHL_L4_REP_OBSERVATIONS_009_078 from marine.copernicus);

**- Forcing:**

- The daily physical forcing fields (current, temperature, salinity, vertical eddy viscosity, SSH) and atmospheric (short wave radiation and wind stress) provided by the MFS.

- open boundary conditions in the Atlantic Ocean from World Ocean Atlas 2018 (Sanchez et al., 2018; data from https://www.nodc.noaa.gov/OC5/woa18) and from GLODAP v2 dataset (Olsen et al., 2016, 2019; data from https://www.nodc.noaa.gov/ocads/oceans/GLODAPv2_2019/)

- Atmospheric forcing: 1/8° horizontal-resolution operational analysis and forecast fields from the European Centre for Medium-Range Weather Forecasts (ECMWF) at 6-hours resolution (for the first 3 days of forecast a 3-hours temporal resolution is used).

- Atmospheric deposition rates of inorganic nitrogen and phosphorus (Ribera d'Alcalà et al., 2003)

- Atmospheric pCO2 concentration is set equal to the annual averages measured at the Lampedusa station (Artuso et al., 2009) between 1999 and 2018 (data from http://cdiac.ess-dive.lbl.gov/ftp/trends/co2/lampedus.co2).

- Land forcing: 39 rivers climatological phosphate and nitrate loads inflow from PERSEUS project dataset.

## 2. Data serving

### 2.a Global Ocean Forecasting system

The GOFS16 products consist in Analyses and Forecasts described hereafter.

The Physical Analyses and Forecasts system produces daily and hourly 3D mean fields of Potential Temperature, Salinity, Zonal and Meridional Velocity, and 2D mean fields of Sea Surface Height and Sea Ice Concentration. The model outputs are produced at the resolution of 1/16° horizontally and 98 vertical levels.

The Physical Analyses and Forecasts system has a daily re-initialization. Every day the analysis date is integrated twice, respectively without and with corrections from the DA system to provide the best initial condition for nowcast and forecasts. The DA assimilates all the observations (listed in the data section) for the analysis date. A weekly re-initialization from 7 day before at least, is planned in order

to include late-coming observations and satellite data corrections. The forecast cycle produces 8-days forecast fields that is initialized every day by an analysis field.

- **Dissemination systems**

  The GOFS16 products are disseminated through the CMCC Dissemination Unit.

- **Delivery mechanisms**

  The GOFS16 products are delivered through ftp service.

- **Services**

  The GOFS16 dataset are operationally produced and available on demand 24 hours a day, 365 days a year.

### 2.b Mediterranean Forecasting System

The MedFS products consist in an Analyses and Forecasts product and a Reanalysis product. Hereafter the Analyses and Forecasts product is described, while the Reanalysis product will be described in Section 9.

The Physical Analyses and Forecasts product of the CMEMS Med-MFC MEDSEA_ANALYSIS_FORECAST_PHYS_006_013 (Clementi et al. 2019, DOI: https://doi.org/10.25423/CMCC/MEDSEA_ANALYSIS_FORECAST_PHY_006_013_EAS5) produces monthly, daily and hourly 3D mean fields of Potential Temperature, Salinity, Zonal and Meridional Velocity, and by 2D mean fields of Sea Surface Height, Mixed Layer Depth, Sea Bed Temperature. The model outputs are produced at 1/24° horizontal resolution and 141 vertical levels.

The Physical Analyses and Forecasts product of the Med-MFC is produced with two different cycles. The Analysis cycle is done weekly, on Tuesday, for the previous 15 days, because a shorter analysis cycle would not allow getting enough observations into the assimilation, for both in situ and satellite data. The forecast cycle is daily and it produces 10-days forecast fields starting each day at 12:00:00 UTC. The forecast is initialized by a background field every day except Tuesday, when an analysis is used.

- **Dissemination systems**

The MedFS products are disseminated through the central CMEMS Dissemination Unit.

- **Delivery mechanisms**

The MedFS products are delivered through the CMEMS Website Catalogue http://marine.copernicus.eu/services-portfolio/access-to-products/.

- **Services**

The MedFS dataset are operationally produced and available 24 hours a day, 365 days a year.

### 2.c Mediterranean Biogeochemical Forecasting System

The MedBFM products consist of an Analyses and Forecasts product. The Biogeochemical Analyses and Forecasts product of the CMEMS Med-MFC (MEDSEA_ANALYSIS_FORECAST_BIO_006_014 (Bolzon et al. 2019, DOI:

https://doi.org/10.25423/CMCC/MEDSEA_ANALYSIS_FORECAST_BIO_006_014_MEDBFM3) produces monthly and daily 3D fields of chlorophyll, biomass of phytoplankton, nitrate, phosphate, oxygen, primary production and 2D fields of surface pCO2 and CO2 flux at the air-sea interface. The model outputs are produced at 1/24° horizontal resolution and 125 vertical levels.

The Biogeochemical Analyses and Forecasts product of the Med-MFC is produced with two different cycles. The Analysis cycle is done weekly, on Tuesday, for the previous 7 days with the assimilation of both in situ and satellite data. The forecast cycle is daily and it produces 10-days forecast fields starting each day at 15:00:00 UTC.

- **Dissemination systems**

The MedBFM products are disseminated through the central CMEMS Dissemination Unit.

- **Delivery mechanisms**

The MedBFM products are delivered through the CMEMS Website Catalogue http://marine.copernicus.eu/services-portfolio/access-to-products/.

- **Services**

The MedBFM dataset are operationally produced and available 24 hours a day, 365 days a year.

# 3. Models

## 3.a Global Ocean Forecasting system

The oceanic equations of motion of GOFS16 system are solved by an Ocean General Circulation Model (OGCM) based on NEMO (Nucleus for European Modelling of the Ocean) version 3.4. The code is developed and maintained by the NEMO-consortium.

The configuration used is called GLOB16 and described in Iovino et al., 2016. GLOB16 is considered a global, eddying configuration of the ocean and sea ice system with a horizontal resolution of 1/16 degree at the Equator, corresponding to 6.9 km, that increases poleward as cosine of latitude, leading to 5762 × 3963 grid points and roughly 3 km in the polar region. Two distinct poles are introduced at the North Pole to avoid the convergence of meridians that could lead to singularities following the ORCA grid format.

The NEMO code solves the primitive equations using as prognostic variables: 3D temperature, salinity, meridional and zonal velocities and 2D sea-surface height. In the current version a linearized free-surface formulation is used (Roullet and Madec, 2000) and a free-slip lateral friction condition is applied at the lateral boundaries. Tracer advection follows a total variance dissipation (TVD) scheme (Zalesak, 1979) while vertical mixing is achieved using the turbulent kinetic energy (TKE) closure scheme (Blanke and Delecluse, 1993). Unresolved vertical mixing processes are represented by a background vertical eddy diffusivity of $1.2 \times 10^{-5}$ $m^2$ $s^{-1}$ and a globally constant background viscosity of $1.2 \times 10^{-4}$ $m^2$ $s^{-1}$. A classical quadratic bottom friction is used, with a drag coefficient of $1e^{-3}$ $m^2/s^2$ without specific amplification in straits.

The model interactively computes air-surface fluxes of momentum, mass, and heat. Forcing fields are provided from NOAA operational system with 0.25 degree spatial resolution. The turbulent variables are applied at a 6 hourly frequency and radiative and freshwater fluxes are daily fields. The surface boundary conditions are prescribed to the model using the bulk formulae proposed by Large and Yeager (2004). The water balance is computed as Evaporation minus Precipitation and Runoff. The

evaporation is derived from the latent heat flux, precipitation is provided by NCEP as daily averages, while the runoff is a monthly climatology of coastal and river runoff (Dai and Trenberth,2002) which uses 99 major rivers and coastal runoff estimates, with a global annual discharge of ∼1.32 Sv. The fresh water is added to the surface only assumed to be fresh (0 psu) and at sea surface temperature.

The topography is created from three separate products: 1) The 2-minute Etopo2 bathymetry of the National Geophysical Data Center (NGDC), used for the deep ocean (below 300m). 2) The 1-minute GEBCO is used on shelf areas shallower than 200m; 3) Bedmap2 is used for the Antarctic region, south of 60◦S.

The ocean component is coupled to the Louvain-la-Neuve sea Ice Model (LIM2) that includes the representation of both the thermodynamic and dynamic processes. The elastic–viscous–plastic formulation by Hunke and Dukowicz (1997) is used.

### 3.b Mediterranean Forecasting System - physics

The oceanic equations of motion of MedFS system are solved by an Ocean General Circulation Model (OGCM) based on NEMO (Nucleus for European Modelling of the Ocean) version 3.6 (Madec et al., 2016). The code is developed and maintained by the NEMO-consortium.

NEMO has been implemented in the Mediterranean at 1/24° x 1/24° horizontal resolution and 141 unevenly spaced vertical levels (Clementi et al., 2017a) with time step of 240sec. The model covers the whole Mediterranean Sea and also extends into the Atlantic in order to better resolve the exchanges with the Atlantic Ocean at the Strait of Gibraltar.

The NEMO code solves the primitive equations using the time-splitting technique that is the external gravity waves are explicitly resolved with non-linear free surface formulation and time-varying vertical z-star coordinates.

The advection scheme for active tracers, temperature and salinity, is a mixed up-stream/MUSCL (Monotonic Upwind Scheme for Conservation Laws, Van Leer 1979), originally implemented by Estubier and Lévy (2000) and modified by Oddo et al. (2009). The vertical diffusion and viscosity terms are a function of the Richardson number as parameterized by Pacanowsky and Philander (1981).

The model interactively computes air-surface fluxes of momentum, mass, and heat. The bulk formulae implemented are described in Pettenuzzo et al. (2010) and are currently used in the Mediterranean operational system (Tonani et al. 2015). A detailed description of other specific features of the model implementation can be found in Oddo et al. (2009, 2014).

The vertical background viscosity and diffusivity values are set to $1.2e^{-6}$ [$m^2/s$] and $1.0e^{-7}$ [$m^2/s$] respectively, while the horizontal bilaplacian eddy diffusivity and viscosity are set respectively equal to $-1.2e^{8}$ [$m^4/s$] and $-2.e^{8}$ [$m^4/s$]. A quadratic bottom drag coefficient with a logarithmic formulation has been used according to Maraldi et al. (2013) and the model uses vertical partial cells to fit the bottom depth shape.

The hydrodynamic model is nested in the Atlantic within the Global analysis and forecast system GLO-MFC daily data set (1/12° horizontal resolution, 50 vertical levels) that is interpolated onto the Med-Currents model grid. Details on the nesting technique and major impacts on the model results are in Oddo et al., 2009. The Dardanelles Strait is also implemented as a lateral open boundary condition by

using GLO-MFC daily Analysis and Forecast product and daily climatology derived from a Marmara Sea box model (Maderich et al., 2015).

The model is forced by momentum, water and heat fluxes interactively computed by bulk formulae using the 6-hours (higher temporal resolution is used for the first 6 days of forecast), 1/10° horizontal-resolution operational analysis and forecast fields from the European Centre for Medium-Range Weather Forecasts (ECMWF) and the model predicted surface temperatures (details of the air-sea physics are in Tonani et al., 2008). The water balance is computed as Evaporation minus Precipitation and Runoff. The evaporation is derived from the latent heat flux, precipitation is provided by ECMWF as daily averages, while the runoff of the 39 rivers implemented is provided by monthly mean climatological datasets.

The coupling between the hydrodynamic model (NEMO) and the wave model (WW3) is achieved by an online hourly two-way coupling and consists in exchanging the following fields: NEMO sends to WW3 the air-sea temperature difference and the surface currents, while WW3 sends to NEMO the neutral drag coefficient used to evaluate the surface wind stress. More details on the model coupling and on the impact of coupled system on both wave and circulation fields can be found in Clementi et al. (2017b).

The topography is created starting from the GEBCO 30arc-second grid (http://www.gebco.net/data_and_products/gridded_bathymetry_data/gebco_30_second_grid/), filtered (using a Shapiro filter) and manually modified in critical areas such as: islands along the Eastern Adriatic coasts, Gibraltar and Messina straits, Atlantic box edge.

### 3.c Mediterranean Biogeochemical Forecasting system

The biogeochemical component of the Mediterranean forecasting system at 1/24° horizontal resolution (Med-BIO) is produced by means of the MedBFM model system which is off-line coupled with the NEMO3.6-WW3-Oceanvar hydrodynamic model (Med-PHY component).

MedBFM version 3 includes the transport model OGSTM v4.0 coupled with the Biogeochemical Flux Model BFM v5 and the data assimilation 3DVarBio v2.1 scheme (Salon et al., 2019). The data assimilation is performed weekly using the satellite chlorophyll (i.e., a composite average of 7 days) from CMEMS OC product. The off-line physical-biogeochemical coupling consists a daily update of the 2D/3D field physical output (i.e., velocity, temperature, salinity, diffusivity, and solar radiation and wind at surface from the physical forecast system) that forces the transport processes, the biogeochemical model (e.g., kinetic rates of chemical reactions depend on temperature) and the energy and matter fluxes at the air-sea interface (e.g., photosynthetic available radiation (PAR) depends on incoming solar radiation, CO2 and O2 gas exchanges depends on wind and surface water conditions).

The OGSTM 4.0 transport model is a modified version of the OPA 8.1 transport model (Foujols et al., 2000), which resolves the advection, the vertical diffusion and the sinking terms of the tracers (biogeochemical variables). The OGSTM resolves the free surface and variable volume layer effects on the transport of tracers being fully consistent with NEMO3.6 vvl output provided by Med-PHY. The meshgrid is based on 1/24° longitudinal scale factor and on 1/24°cos(ϕ) latitudinal scale factor. The vertical meshgrid accounts for 141 vertical z-levels (125 active in the Mediterranean domain): 35

in the first 200 m depth, 60 between 200 and 2000 m, 30 below 2000 m. The temporal scheme of OGSTM is an explicit forward time scheme for the advection and horizontal diffusion terms, whereas an implicit time step is adopted for the vertical diffusion.

The sinking term is a vertical flux, which acts on a sub-set of the biogeochemical variables (particulate matter and phytoplankton groups). Sinking velocity is fixed for particulate matter and dependent on nutrients for two phytoplankton groups (diatoms and dinoflagellates).

The daily mean physical dynamics are off-line coupled with the transport-biogeochemical processes, and are pre-computed by the Med-PHY forecast model system, which supplies the temporal evolution of the fields of horizontal and vertical current velocities, vertical eddy diffusivity, potential temperature, salinity, sea surface height in addition to surface data for solar shortwave irradiance and wind stress (see section on upstream data and boundary conditions for further details).

The features of the biogeochemical reactor BFM (Biogeochemical Flux Model) have been chosen to target the energy and material fluxes through both “classical food chain” and “microbial food web” pathways (Thingstad and Rassoulzadegan, 1995), and to take into account co-occurring effects of multi-nutrient interactions. Both of these factors are very important in the Mediterranean Sea, wherein microbial activity fuels the trophodynamics of a large part of the system for much of the year and both phosphorus and nitrogen can play limiting roles (Krom et al., 1991; Bethoux et al., 1998).

BFMv5 model (i.e., the official version released by www.bfm-community.eu) describes the biogeochemical cycles of 4 chemical compounds: carbon, nitrogen, phosphorus and silicon through the dissolved inorganic, living organic and non-living organic compartments. The model includes nine plankton functional types (PFTs). Phytoplankton PFTs are diatoms, flagellates, picophytoplankton and dinoflagellates. Heterotrophic PFTs consists of carnivorous and omnivorous mesozooplankton, bacteria, heterotrophic nanoflagellates and microzooplankton. Nitrate and ammonia are considered for the dissolved inorganic nitrogen. The non-living compartment consists of 3 groups: labile, semilabile and refractory organic matter. The first two are described in terms of carbon, nitrogen, phosphorus and silicon contents. The model is fully described in Lazzari et al. (2012, 2016), where it was corroborated for chlorophyll, primary production and nutrients in the Mediterranean Sea for a 1998-2004 simulation. The BFM model is also coupled to a carbonate system model (Cossarini et al., 2015, Melaku Canu et al., 2015), which consists of three prognostic state variables: alkalinity (ALK) and dissolved inorganic carbon (DIC) and particulate inorganic carbon (PIC) which are driven by biological processes (i.e. photosynthesis, respiration, precipitation and dissolution of $CaCO_3$, nitrification, denitrification, and uptake and release of nitrate, ammonia and phosphate by plankton cells) and physical processes (exchanges at air-sea interface and dilution-concentration due to evaporation minus precipitation process). In particular, PIC precipitation occurs in correspondence of phytoplankton mortality and grazing by zooplankton (Orr et al., 2017). Dissolution of PIC occurs for oversaturated calcite conditions according to Berner and Morse (1972). $pCO_2$ and pH (expressed in total scale) are calculated at the in-situ temperature and pressure conditions using Mehrbach et al. (1973) refit by Lueker et al. (2000). Formulations for the kinetic constants of thermodynamic equilibrium of carbon acid dissociation as prescribed in Orr and Epitaloni (2015). $CO_2$ air-sea gas exchange formulation is computed according to updates provided by Wanninkhof (2014).

# 4. Assimilation method

The data assimilation for both the Global and the Mediterranean physical forecasting systems is the 3DVAR scheme called OceanVar developed by Dobricic and Pinardi (2008) and modified by Storto et al. (2016a), while the 3DVARBIO variational scheme is used by the Mediterranean biogeochemical system (Teruzzi et al., 2018; Cossarini et al., 2019).

## 4.a Global Ocean Forecasting system

The data assimilation system for global ocean application has been recently massively parallelized to bear global high-resolution grid (Cipollone et al., 2020). The system assimilates in-situ temperature and salinity profiles, sea level anomaly and SST satellite data. Sea level anomaly data are covaried with temperature and salinity profile by means of the dynamic height formulation (Storto 2011, Cooper and Haines 1996) and the background errors exploits multivariate EOFs (Empirical Orthogonal Functions) for vertical covariances and recursive filters for horizontal correlation (Storto et al. 2014). Observational error covariances have been improved by means of Desroziers et al. (2005) relationship. SST data are assumed to be located at the shallowest model level. The assimilation is performed at the same resolution of the model to include most of the corrections coming from high-resolution satellite dataset.

The assimilated data include:

**SST:** The system assimilates two different kind of near real time SST data: Advanced Very High-Resolution Radiometer (AVHRR) from NOAA and Advanced Microwave Scanning Radiometer 2 (AMSR2) from NASA. The dataset can reach 1km of resolution in several areas. Only SST retrievals acquired during night-time are assimilated to reduce the impact of the diurnal cycle on the SST measurements. The data are also sub-sampled to lower the stress on thinning routines.

**SLA:** The set of data assimilated for SLA comes from CMEMS catalog and corresponds to the in near-real time along-track observations belonging to Cryosat2, Jason3, Sentinel 3a and Altika satellite and Sentinel 3b.

**In-situ Profiles:** Near-real-time in-situ observations coming from moorings, Argo floats, Expand-able Bathy Termographs (XBTs), and Conductivity-Temperature-Depth (CTDs) gathered together in the CMEMS catalog, are assimilated by the system.

The analysis of GOFS16 includes a nudging scheme to correct the heat and freshwater surface fluxes. The dataset employed to constraint the Heat flux is the gridded sea-surface temperature analyses provided by NOAA (Reynolds et al., 2007). This product uses infrared retrievals from AVHRR instruments, drifter and buoy in-situ measurements to provide an optimal interpolation. The relaxation time scale is of 15 days. Alongside, the fresh-water flux is corrected through the sea-surface salinity product of the UK MetOffice EN4 (v4.1.1) objective analyses with a relaxation time scale of 300 days. GOFS16 implements a data assimilation scheme to ingest sea-ice concentration observations from satellites. The sea-ice analysis uses in particular data from Optimal-interpolation daily field from NOAA that are delivered together with the SST-OI field. The assimilation scheme consists of a nudging to the sea-ice analysis with an 8-hour relaxation time-scale.

## 4.b Mediterranean Forecasting System - physics

The 3DAVAR background error correlation matrices of the Mediterranean Sea configuration vary monthly for each grid point in the discretized domain of the Mediterranean Sea. Observational error covariance matrix is evaluated with Desroziers et al. (2005) relationship.

The assimilated data include: along track Sea Level Anomaly (a satellite product accounting for atmospheric pressure effect is used) from CMEMS SL-TAC, and in-situ vertical temperature and salinity profiles from VOS XBTs (Voluntary Observing Ship-eXpandable Bathythermograph) and ARGO floats. Objective Analyses-Sea Surface Temperature (OA-SST) fields from CMEMS SST-TAC are used for the correction of surface heat fluxes close to observational time (midnight) with a relaxation constant of 110 $Wm^{-2}K^{-1}$.

### 4.c Mediterranean Biogeochemical Forecasting system

The data assimilation of the surface chlorophyll concentration and of the vertical insitu profiles of chlorophyll and nitrate is performed through a variational scheme (3DVarBio) during the 7 days of analysis (see details on 3DVarBio in Teruzzi et al., 2014, 2018, 2019 and Cossarini et al., 2019). The surface chlorophyll concentration is provided by satellite observations produced by the OCTAC; the insitu vertical profiles of chlorophyll and nitrate are provided by BGC-Argo floats data made available by CORIOLIS and LOV. The data assimilation corrects the four phytoplankton functional groups (17 state variables including carbon, chlorophyll, nitrogen phosphorus and silicon internal quotas) and two nutrients (i.e., phosphate and nitrate) of the BFM. The 3DVarBio scheme decomposes the background error covariance matrix using a sequence of different operators that account separately for the vertical covariance (Vv), the horizontal covariance (Vh) and the covariance among biogeochemical variables (Vb). Vv is defined by a set of synthetic profiles that are evaluated by means of an Empirical Orthogonal Function (EOF) decomposition applied to a validated multi-annual 1998-2015 run (Teruzzi et al., 2018). EOFs are computed for 12 months and 30 coastal and open sea sub-regions in order to account for the variability of 3D chlorophyll and nitrate anomaly fields. The assimilation is performed from 0 to 600 meters for chlorophyll and nitrate profiles, and from 0 to 200 meters for satellite chlorophyll. Vh is built using a Gaussian filter whose correlation radius modulates the smoothing intensity. A non-uniform and direction-dependent correlation radius has been implemented (Teruzzi et al., 2018, Cossarini et al., 2019). Vb operator consists of monthly and sub-region varying covariances among the biogeochemical variables. Further, Vb operator maintains the ratio among the phytoplankton groups and preserves the physiological status of the phytoplankton cells (i.e. preserve optimal values for the internal chlorophyll and carbon nutrients quota).

## 5. Systems (operational)

### 5.a Global Ocean Forecasting system

The GOFS16 production is composed by several steps:

1. Upstream Data Acquisition, Pre-Processing and Control of: NCEP atmospheric forcing (Numerical Weather Prediction), Satellite (SLA, SST, SIC) and in-situ (T and S) data.

2. Forecast: NEMO-LIM2 coupled modelling system is run to produce 6-day-long forecast.

3. Analysis: NEMO is combined with our DA system called OceanVar in order to produce the best estimation of the sea state (i.e. analysis). Each daily production (say production of day T) starts with a first integration of the sole model between T-48h and T-24h. Corrections are then calculated by the DA system for the same time-range and applied to a second model integration between the same date. This leads to the best initial conditions at T-24h that are used to generate the nowcast (T-24,T) and a 6-day-long forecast.

4. Post processing: the model output is made CF-compliant and transformed in different formats (binary, netcdf, etc.)

5. Output Delivery.

### 5.b Mediterranean Forecasting system - physics

The MedFS production in the framework of the CMEMS Med-MFC is composed by several steps:

1. Upstream Data Acquisition, Pre-Processing and Control of: ECMWF atmospheric forcing (Numerical Weather Prediction), Satellite (SLA and SST) and in-situ (T and S) data.

2. Forecast/Hindcast: NEMO-WW3 coupled modelling system is run to produce one day of hindcast and 10-day forecast.

3. Analysis/Hindcast (only on Tuesday): NEMO is combined with the OceanVar assimilation scheme in order to produce the best estimation of the sea (i.e. analysis). The NEMO+WW3+OceanVar system is running for 15 days into the past in order to use the best available along tack SLA products. The latest day of the 15 days of analyses produces the initial condition for the 10-days forecast.

4. Reanalysis (updated once a year): NEMO code is combined with a DA scheme called OceanVar (3DVAR). The NEMO+OceanVar system is run for the previous year.

5. Post processing: the model output is processed in order to obtain the products for the CMEMS catalogue.

6. Output Delivery.

### 5.c Mediterranean Biogeochemical Forecasting system

The MedBFM production in the framework of the CMEMS Med-MFC is composed by several steps:

7. Upstream Data Acquisition, Pre-Processing and Control of: MFS physical output (3D daily fields of currents, temperature, salinity, SSH and atmospheric), Satellite (CHL) and in-situ BGC-Argo (CHL, O2, NO3, pH, bbp700) data.

8. Forecast/Hindcast: OGSTM-BFM coupled modelling system is run to produce one day of hindcast and 10-day forecast.

9. Analysis/Hindcast (only on Tuesday): OGSTM-BFM-3DVarBio coupled modelling system with assimilation produces the best estimation of the sea (i.e. analysis). The OGSTM-BFM-3DVarBio system is running for 7 days into the past.

10. Post processing: the model output is processed in order to obtain the products for the CMEMS catalogue.

11. Output Delivery.

## 6. Link to observations (e.g. Argo, GHRSST, etc.)

Links to observational datasets are provided below

### 6.a Global Ocean Forecasting system

- GHRSST L3 SST from the Advanced Very High-Resolution Radiometer (AVHRR) currently produced by OSI SAF:

  ftp://ftp.nodc.noaa.gov/pub/data.nodc/ghrsst/GDS2/L3C/GLOB/AVHRR_SST_METOP_B_GLB/OSISAF/v1

- GHRSST Level SST from the Advanced Microwave Scanning Radiometer 2 (AMRS2)

  ftp://ftp.nodc.noaa.gov/pub/data.nodc/ghrsst/GDS2/L3U/AMSR2/REMSS/v8a

- Reynolds Sea Surface Temperature-OI from NOAA:

  https://www.ncei.noaa.gov/data/sea-surface-temperature-optimum-interpolation/access/avhrr-only/

- Sea Ice Concentration L4 from NOAA:

  https://www.ncei.noaa.gov/data/sea-surface-temperature-optimum-interpolation/access/avhrr-only/

- Sea Surface salinity from EN4 OA (MET-OFFICE):

  http://hadobs.metoffice.com/en4/data/en4-2-1/

- INSITU data from CMEMS catalogue:

  http://marine.copernicus.eu/services-portfolio/access-to-products/?option=com_csw&view=details&product_id=INSITU_GLO_NRT_OBSERVATIONS_013_030

- Along-track sea-level-anomaly from CMEMS catalogue:

  http://marine.copernicus.eu/services-portfolio/access-to-products/?option=com_csw&view=details&product_id=SEALEVEL_GLO_PHY_L3_NRT_OBSERVATIONS_008_044

### 6.b Mediterranean Forecasting system - physics

All the observational datasets assimilated by the system are provided by CMEMS.

- Vertical profiles of temperature and salinity from Argo, XBTs and Gliders floats from CMEMS INSITU TAC product INSITU_GLO_NRT_OBSERVATIONS_013_030: https://resources.marine.copernicus.eu/?option=com_csw&view=details&product_id=INSITU_GLO_NRT_OBSERVATIONS_013_030
- Vertical profiles of temperature and salinity from Argo, XBTs and Gliders floats from CMEMS INSITU TAC product INSITU_MED_NRT_OBSERVATIONS_013_035: https://resources.marine.copernicus.eu/?option=com_csw&view=details&product_id=INSITU_MED_NRT_OBSERVATIONS_013_035
- Satellite Sea Level along track data from CMEMS SL-TAC product SEALEVEL_EUR_PHY_ASSIM_L3_NRT_OBSERVATIONS_008_043: https://resources.marine.copernicus.eu/?option=com_csw&view=details&product_id=SEALEVEL_EUR_PHY_ASSIM_L3_NRT_OBSERVATIONS_008_043
- Satellite Sea Level along track data from CMEMS SL-TAC product SEALEVEL_EUR_PHY_L3_NRT_OBSERVATIONS_008_059:

https://resources.marine.copernicus.eu/?option=com_csw&view=details&product_id=SEALEVEL_EUR_PHY_L3_NRT_OBSERVATIONS_008_059

- SST satellite data from CMEMS SST-TAC product SST_MED_SST_L4_NRT_OBSERVATIONS_010_004: https://resources.marine.copernicus.eu/?option=com_csw&view=details&product_id=SST_MED_SST_L4_NRT_OBSERVATIONS_010_004

### 6.c Mediterranean Biogeochemical Forecasting system

- Surface chlorophyll from CMEMS catalogue:

  http://marine.copernicus.eu/services-portfolio/access-to-products/?option=com_csw&view=details&product_id=OCEANCOLOUR_MED_CHL_L4_REP_OBSERVATIONS_009_078

- Insitu data of chlorophyll, nitrate, oxygen, ph, bbp700 from BGC-Argo datacenter:

ftp://ftp.ifremer.fr/ifremer/argo

## 7. Internal metrics and Inter-comparison plans

### 7.a Global Ocean Forecasting system

The Validation/Verification process of the GOFS16 is provided at different time scales and is performed using semi-independent analysis.

The metrics refer to the "misfits" that are calculated by the data assimilation system as differences between observations and model outputs transformed at the location and time of the observations. Misfits are calculated before the data are inserted via data assimilation and can be considered as semi-independent since data are mostly sparse in time and space. The metrics are composed of:

- Root Mean Square Errors (RMSE) of temperature and salinity using misfits with ARGO-CTD and XBT (only for temperature) collected from CMEMS INS TAC. A validation webpage is available online for the analysis (http://evalid.cmcc.it/evaluation/gofs/)

- RMSE of Sea Level Anomaly using misfits with satellite along track sea level anomalies from CMEMS SL TAC.

- RMSE and BIAS of Sea Surface Temperature (SST) using AVHRR and AMRS2 retrievals or AVHRR-OI.

Daily RMSE/BIAS timeseries and spatial RMSE/BIAS maps for SST and SLA are also calculated for the first 6 days of the forecasts.

### 7.b Mediterranean Forecasting system - physics

MedFS product visualisation, validation and system description is available at the following link: http://oceanlab.cmcc.it/mfs-evaluation/.

The Validation/Verification process of the MedFS is provided at different time scales and is performed using both semi-independent and independent data.

The metrics calculated using the semi-independent data refer to the "misfits" that are calculated by the data assimilation system as differences between observations and model outputs transformed at the location and time of the observations. Misfits are calculated before the data are inserted via data assimilation and can be considered as semi-independent since data are mostly sparse in time and space. The metrics are composed of:

- Root Mean Square Errors (RMSE) of temperature and salinity using misfits with ARGO-CTD and XBT(only for temperature) collected from CMEMS INS TAC, at depth of 8, 30, 150, 300 and 600 m.

- RMSE of Sea Level Anomaly using misfits with satellite along track sea level anomalies from CMEMS SL TAC.

- RMSE and BIAS of Sea Surface Temperature (SST) using CMEMS SST TAC dataset.

In addition, the Mean Square Error (MSE), the MEAN values of observations and model outputs, the variance of the model outputs and of the observations and the correlation are evaluated for the analysis, first, third, fifth and ninth day of forecast and observations. These metrics are defined for all the Mediterranean Sea and for 16 sub-basins for nine different layers (0-10, 10-30, 30-60, 60-100, 100-150, 150-300, 300-600, 600-1000, 1000-2000 m). The observations used are: ARGO, XBT and GLIDERS (from INS TAC), satellite along track SLA (from SL TAC) and SST (from SST TAC). These metrics are calculated every month and are published in the CMEMS Validation webpage (http://marine.copernicus.eu/services-portfolio/scientific-quality/).

The metrics calculated using the independent data (moored buoys, tide gauges and ADCP) from INS TAC and MonGOOS partners are time series of daily mean values and averaged RMSE and BIAS of the difference between the analysis and third day of forecast.

### 7.c Mediterranean Biogeochemical Forecasting system

MedBFM product visualisation, validation and system description is available at the following link: medeaf.inogs.it

Near Real Time validation skill metrics are calculated (and visualized in the medeaf.inogs.it:/nrt-validation webpage) every Tuesdays. They consists of:

The Validation/Verification process of the MedFS is provided at different time scales and is performed using both semi-independent and independent data.

The metrics calculated using the semi-independent data refer to the "misfits" that are calculated by the data assimilation system as differences between observations and model outputs transformed at the location and time of the observations. Misfits are calculated before the data are inserted via data assimilation and can be considered as semi-independent since data are mostly sparse in time and space. The metrics are composed of:

- Root Mean Square difference (RMSD) of surface chlorophyll using misfit with Satellite L3 data

- Root Mean Square difference (RMSD) of chlorophyll, nitrate, oxygen using misfit with BGC-Argo float

- Root Mean Square difference (RMSD) of process-based metrics (DCM, nitracline, depth of maximum of oxygen; Salon et al., 2019) using BGC-Argo data

Summary of these metrics are calculated every month and are published in the CMEMS Validation webpage (http://marine.copernicus.eu/services-portfolio/scientific-quality/).

# 8. Targeted users and envisioned external metrics

MedFS users downloading data from CMEMS Catalogue are around 150 each month. 55% are scientific users, while the remaining 45% is covered by users from commercial sectors, public service, PhD-Training-Teaching.

# 9. Reanalysis and Hindcasting activities

## 9.a Global Ocean Reanalysis system

CMCC has a long experience in the development of global ocean Reanalysis at eddy-permitting resolution, testified by several works and international inter-comparison exercises (Storto et al. 2016a, Storto et al. 2016b, Masina et al. 2017, Storto et al. 2019). The development is continuous: a new global Reanalysis is scheduled for the next year based on the new atmospheric forcing ERA5 from ECMWF. The latest ocean reanalysis is called C-GLORSv7 and is freely available from CMEMS catalogue in the ensemble reanalysis product (GLOBAL_REANALYSIS_PHY_001_031). The Reanalysis system includes four components:

1. The three-dimensional variational data assimilation scheme (OceanVar), presented in the dedicated section, that assimilates Hydrographic profiles and along-track altimetry observations in FGAT (First Guess at Appropriate Time) configuration;
2. The NEMO ocean model v3.6, configured at 1⁄4 degree using a tripolar grid, with 75 vertical depth levels with partial steps and coupled to the LIM2 sea-ice model;
3. A large-scale bias-correction scheme that corrects the model tendencies to limit the large-scale biases induced by the model and the atmospheric forcing.
4. A nudging scheme that assimilates space-borne sea-surface and sea-ice observations;

The large-scale bias correction (LSBC) is performed during the model integration to avoid spurious model biases and drifts. The LSBC scheme of C- GLORS relaxes the temperature and salinity towards large-scale monthly univariate objective analyses from hydrographic profiles (EN4, Good et al., 2013). The nudging schemes, presented in the dedicated section, includes also a 10-day relaxation to PIOMAS Arctic sea-ice thickness (Zhang and Rothrock, 2003) in order to avoid that the sea-ice concentration assimilation prejudices the sea-ice volume conservation and variability in the Northern Hemisphere.

The dataset ingested by OceanVar are taken from the following reprocessed observation dataset: i) the insitu observations extracted from the EN4 dataset (Good et al., 2013) and distributed by the UK MetOffice Hadley Center; ii) The dataset of SLA from AVISO along-track delayed-mode dataset (SEALEVEL_GLO_PHY_L3_REP_OBSERVATIONS_008_045) from CMEMS. A variational quality control of hydrographic profiles that allows to assimilate data with non-Gaussian errors through a Huber-like norm method, is included.

The ocean component is the OGCM NEMOv3.6 coupled to sea-ice model LIM2 and forced by ERA-interim atmospheric forcing (ECMWF) through bulk formulas. A detailed description of the

configuration ORCA025 employed is in Storto et al. (2016a). Outputs consist of 3D daily mean fields of Potential Temperature, Salinity, Zonal and Meridional Velocity, and of 2D daily mean fields of Sea Surface Height, Sea Ice Concentration, Sea ice Thickness and several other fields.

The Reanalysis timeseries cover the satellite altimetry era, from 1993-2017. A longer timeseries is available from a previous product, called C-GLORSv5, that includes the full meteorological satellite era from 1980 to 2017 and is available upon request.

### 9.b Mediterranean Reanalysis system - physics

A new Mediterranean Reanalysis time series has been produced in 2020 and the new product (MEDSEA_MULTIYEAR_PHY_006_004) will be available on the CMEMS web catalogue from 15 December 2020. The new reanalysis has been produced using the OGCM NEMO model version 3.6 implemented in the Mediterranean Sea at 1/24°x 1/24° horizontal resolution and 141 unevenly spaced vertical levels (Clementi et al., 2017a) with time step of 240sec. The topography is created starting from the GEBCO 30arc-second grid filtered and interpolated on the model grid. The model covers the whole Mediterranean Sea and also extends into the Atlantic (where it is nested to the CMCC CGLORS-v5 daily reanalysis fields) in order to better resolve the exchanges with the Atlantic Ocean at the Strait of Gibraltar. On the other side, the Dardanelles inflow is parameterized as a river. The model is forced by momentum, water and heat fluxes interactively computed by bulk formulae using the ERA5 reanalysis dataset (30 km horizontal resolution and hourly time frequency, Hersbach et al, 2020) and the model predicted surface temperatures (details of the air-sea physics are in Tonani et al., 2008). The water balance is computed as Evaporation minus Precipitation and Runoff. The evaporation is derived from the latent heat flux, precipitation is provided by ERA5, while the runoff of the 39 rivers implemented is provided by monthly mean datasets:

Objective Analyses-Sea Surface Temperature (OA-SST) fields from CNR-ISA SST-TAC are used for the correction of surface heat fluxes with the relaxation constant of 110 W.m-2.K-1 applied close to midnight since the observed dataset corresponds to the foundation SST (~SST at midnight).

The data assimilation system is the OceanVar scheme developed by Dobricic and Pinardi (2008) and modified by Storto et al. (2015). The background error correlation matrices vary monthly for each grid point in the discretized domain of the Mediterranean Sea. Observational error covariance matrix is evaluated with Desroziers et al. (2005) relationship. EOFs have been evaluated from a previous 30 years reanalysis run. The EOFs, evaluated at each grid point, are corrected with a vertical localization. The assimilated data include: CMEMS along track Sea Level Anomaly and in-situ vertical temperature and salinity profiles from a combination of CMEMS and SeaDataNet datasets. The assimilation cycle is daily and both in-situ and satellite data are jointly assimilated to estimate the initial condition for numerical model for the next day.

The new MedFS reanalysis product (MEDSEA_MULTIYEAR_PHY_006_004, DOI: https://doi.org/10.25423/CMCC/MEDSEA_MULTIYEAR_PHY_006_004_E3R1, Escudier et al., 2020) consists of 3D daily mean fields of Potential Temperature, Salinity, Zonal and Meridional Velocity; by 2D daily mean fields of Sea Surface Height, Mixed Layer Depth and by 2D hourly mean fields of Sea Surface Height and Sea Surface Currents. The model outputs are produced at 1/24° horizontal resolution and 141 vertical levels. The aim of the Mediterranean Reanalysis is to provide an integrated

set of information consistent across space-time dimension, using both observations and model, covering the period 1987-2019. The reanalysis product is extended every 6 months.

### 9.c Mediterranean Biogeochemical Reanalysis system

A new Mediterranean Reanalysis time series has been produced in 2020 and the new product (MEDSEA_MULTIYEAR_BIO_006_008) will be available on the CMEMS web catalogue from May 2021. The new reanalysis has been produced using the MedBFM model system version 3.1 implemented in the Mediterranean Sea at 1/24°x 1/24° horizontal resolution and 141 (125 active) unevenly spaced vertical levels. The MedBFM system includes the transport model OGSTM v4.0 coupled with the biogeochemical flux model BFM v5 and the variational data assimilation module 3DVARBIO v2.1 for surface chlorophyll. The biogeochemical BFM model (Biogeochemical Flux Model) describes the energy and material fluxes through both “classical food chain” and “microbial food web” pathways and takes into account co-occurring effects of multi-nutrient interactions. BFM features the biogeochemical cycles of 4 chemical compounds: carbon, nitrogen, phosphorus and silicon through the dissolved inorganic, living organic (i.e., 9 plankton functional types: diatoms, flagellates, picophytoplankton, dinoflagellates, carnivorous and omnivorous mesozooplankton, bacteria, heterotrophic nanoflagellates and microzooplankton) and non-living organic compartments. MedBFM3 is offline coupled with the physical reanalysis (model OGCM NEMO model version 3.6 run by CMCC; CMEMS product MEDSEA_MULTIYEAR_PHY_006_004) that provides daily forcing fields (i.e., currents, temperature, salinity, diffusivities, wind and solar radiation). The model covers the whole Mediterranean Sea and also extends into the Atlantic (boundary at 9°W using WOA and GLODAP climatological profiles for nutrients, oxygen and carbonate system variables) in order to better resolve the exchanges with the Atlantic Ocean at the Strait of Gibraltar. On the other side, the Dardanelles inflow is parameterized as river loads for nutrients and carbonate system variables. Nutrients and carbonate system variables terrestrial loads from 39 rivers (and input from the air deposition) are included with interannual variability.

The data assimilation of surface chlorophyll concentration is performed once a week through a variational scheme (3DVARBIO, Teruzzi et al., 2018). The surface chlorophyll concentrations consist of satellite observations produced by CMEMS OCTAC based on the ESA-CCI data. The data assimilation corrects the four phytoplankton functional groups (17 state variables including carbon, chlorophyll, nitrogen phosphorus and silicon internal quotas) of the BFM. The 3DVarBio scheme decomposes the background error covariance matrix using a sequence of different operators that account separately for the vertical covariance (Vv), the horizontal covariance (Vh) and the covariance among biogeochemical variables (Vb).

The Mediterranean biogeochemical reanalysis (CMEMS MEDSEA_REANALYSIS_BIO_006_008 product) covers the period 1999-2019 and includes 3D fields at 1/24° horizontal resolution (which for the Mediterranean basin is about 4 km) of ten variables (chlorophyll, phytoplankton carbon biomass, phosphate, nitrate, ammonia, oxygen, primary production, pH (reported on Total Scale), dissolved inorganic carbon and alkalinity) and two 2D surface variables (surface partial pressure of CO2, surface CO2 flux).

## 10. Computing resources

CMCC implements a Physical Architecture (HW/SW resources) to guarantee the NRT and Reanalysis production and product delivery.

Both the Global Ocean and the Mediterranean systems activities are based on HPC facilities located at the CMCC Supercomputing Center. The ZEUS HPC systems are used to produce the products, the internal archiving facilities use the Hierarchical Storage System (HSS) associated with a Data Life cycle Management (DLM) system, OKEANOS HPC system is used for archiving.

OGS uses the Italian national HPC Center (CINECA) to guarantee the NRT and Reanalysis production and product delivery.

| System name | GOFS16 Analysis and Forecast System |
|---|---|
| **Ocean Models** | |
| **OGCM** | NEMO v3.4 |
| **Domain** | GLOBAL |
| **Horizontal resolution** | 1/16° |
| **Vertical sampling** | 98 vertical levels |
| **Atmospheric Forcing** | 6-h,daily with 0.25° horizontal-resolution NCEP |
| **Assimilation characteristics** | |
| **Assimilation Scheme** | OceanVar (3dvar) |
| **SST** | L3 AVHRR and AMRS2 data. Heat flux correction (SST Reynold OI) |
| **SSH** | SLA Satellite along track data are assimilates |
| **SSS** | Correction to fresh-water flux (SSS EN4 OA) |
| **SIC** | Relaxation to SIC OI field from NOAA |
| **T/S** | T/S Vertical profiles are assimilated |
| **System Set-ups** | |
| **Forecast range** | 8 days |
| **Update frequency** | Daily |
| **Analysis length** | 1 day |
| **System website links** | |
| **General information** | https://www.cmcc.it/data-services-and-products/forecasting-systems |
| **Technical description** | |
| **Viewing service** | http://gofs.cmcc.it/<br>http://evalid.cmcc.it/evaluation/gofs/ |
| | |
| **System name** | **C-GLORSv7 Reanalysis System** |
| **Ocean Models** | |
| **OGCM** | NEMO v3.6 |
| **Domain** | GLOBAL |
| **Horizontal resolution** | 1/4° |
| **Vertical sampling** | 75 vertical levels |

| | |
|---|---|
| **Atmospheric Forcing** | 6-h, 0.75° horizontal-resolution ERA-Interim |
| **Assimilation characteristics** | |
| **Assimilation Scheme** | OceanVar (3dvar) |
| **SST** | Nudging to the SST is performed |
| **SIC** | Nudging to the SIC is performed |
| **SIT** | Nudging to the SIT is performed |
| **SSH** | SLA Satellite along track data are assimilates |
| **T/S** | T/S Vertical profiles are assimilated |
| **System Set-ups** | |
| **Forecast range** | N.A. |
| **Update frequency** | yearly |
| **Hindcast length** | Reanalysis length: 1993-2019 |
| **System website links** | |
| **General information** | http://marine.copernicus.eu/services-portfolio/access-to-products/?option=com_csw&view=details&product_id=GLOBAL_REANALYSIS_PHY_001_031 |
| **Technical description** | http://marine.copernicus.eu/services-portfolio/access-to-products/?option=com_csw&view=details&product_id=GLOBAL_REANALYSIS_PHY_001_031 |
| **Viewing service** | http://marine.copernicus.eu/services-portfolio/access-to-products/?option=com_csw&view=details&product_id=GLOBAL_REANALYSIS_PHY_001_031 |

| System name | MedFS Analysis and Forecast System |
|---|---|
| **Ocean Models** | |
| **OGCM** | NEMO v3.6 |
| **Domain** | Mediterranean Sea extended in the Atlantic Ocean |
| **Horizontal resolution** | 1/24° |
| **Vertical sampling** | 141 vertical levels |
| **Atmospheric Forcing** | 1/3/6-h, 0.1° horizontal-resolution ECMWF |
| **Assimilation characteristics** | |
| **Assimilation Scheme** | OceanVar (3dvar) |
| **SST** | Nudging to the SST is performed |
| **SSH** | SLA Satellite along track data are assimilated |
| **T/S** | T/S Vertical profiles are assimilated |
| **System Set-ups** | |
| **Forecast range** | 10 days |
| **Update frequency** | daily |
| **Hindcast length** | 1 day (2 weeks analysis) |
| **System website links** | |
| **General information** | http://medfs.cmcc.it<br>http://marine.copernicus.eu/services-portfolio/access-to-products/ |
| **Technical description** | http://medfs.cmcc.it<br>http://marine.copernicus.eu/services-portfolio/access-to-products/ |
| **Viewing service** | http://medfs.cmcc.it<br>http://oceanlab.cmcc.it/mfs-evaluation/<br>http://marine.copernicus.eu/services-portfolio/scientific-quality/ |

| System name | MedFS Reanalysis System |
|---|---|
| **Ocean Models** | |
| **OGCM** | NEMO v3.6 |
| **Domain** | Mediterranean Sea extended in the Atlantic Ocean |
| **Horizontal resolution** | 1/24° |
| **Vertical sampling** | 141 vertical levels |
| **Atmospheric Forcing** | 1-h, 0.25° horizontal-resolution ERA5 |
| **Assimilation characteristics** | |

| | |
|---|---|
| **Assimilation Scheme** | OceanVar (3dvar) |
| **SST** | Nudging to the SST is performed |
| **SSH** | SLA Satellite along track data are assimilated |
| **T/S** | T/S Vertical profiles are assimilated |
| **System Set-ups** | |
| **Forecast range** | N.A. |
| **Update frequency** | 6 months |
| **Hindcast length** | Reanalysis length: 1987-2019 |
| **System website links** | |
| **General information** | http://marine.copernicus.eu/services-portfolio/access-to-products/ |
| **Technical description** | http://marine.copernicus.eu/services-portfolio/access-to-products/ |
| **Viewing service** | http://marine.copernicus.eu/services-portfolio/access-to-products/ |

| System name | MedBFM Analysis and Forecast Biogeochemical System |
|---|---|
| **Biogeochemical Models** | |
| **Biogeochemical model** | OGSTM-BFM (offline coupled with MFS system) |
| **Domain** | Mediterranean Sea |
| **Horizontal resolution** | 1/24° |
| **Vertical sampling** | 141 (125 active) vertical levels |
| **Atmospheric Forcing** | 3/6-h, 0.125° horizontal-resolution ECMWF |
| **Assimilation characteristics** | |
| **Assimilation Scheme** | 3DVarBio |
| **Surface CHL** | Surface satellite L3 map |
| **Profiles of CHL and NO3** | Vertical profiles from BGC-Argo data |
| **System Set-ups** | |
| **Forecast range** | 10 days |
| **Update frequency** | daily |
| **Hindcast length** | 1 day (1 week analysis) |
| **System website links** | |
| **General information** | http://medeaf.inogs.it<br>http://marine.copernicus.eu/services-portfolio/access-to-products/ |
| **Technical description** | http://medeaf.inogs.it<br>http://marine.copernicus.eu/services-portfolio/access-to-products/ |
| **Viewing service** | http://medeaf.inogs.it<br>http://marine.copernicus.eu/services-portfolio/scientific-quality/ |
| **System name** | **MedBFM Reanalysis System** |
| **Biogeochemical Models** | |
| **Biogeochemical model** | OGSTM-BFM (offline coupled with MedFS Reanalysis) |
| **Domain** | Mediterranean Sea |
| **Horizontal resolution** | 1/24° |
| **Vertical sampling** | 141 (125 active) vertical levels |
| **Atmospheric Forcing** | 3/6-h, 0.125° horizontal-resolution ECMWF |
| **Assimilation characteristics** | |
| **Assimilation Scheme** | 3DVarBio |
| **Surface CHL** | Surface satellite L3 map from ESA-CCI |
| **System Set-ups** | |

| | |
|---|---|
| **Forecast range** | N.A. |
| **Update frequency** | once |
| **Hindcast length** | Reanalysis length: 1999-2019 |
| **System website links** | |
| **General information** | http://marine.copernicus.eu/services-portfolio/access-to-products/ |
| **Technical description** | http://marine.copernicus.eu/services-portfolio/access-to-products/ |
| **Viewing service** | http://marine.copernicus.eu/services-portfolio/access-to-products/ |
| | |

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