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MARINE CLIMATOLOGICAL DATASETS FOR THE MALTESE ISLANDS

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ABSTRACT: During the last 25 years of activity, the Physical Oceanography Research Group, previously known as the PO-Unit, and currently established within the Department of Geosciences of the University of Malta, has been promoting the downscaling of broad scope marine core services to higher resolution local scale domains for the Maltese Islands. Several services are delivered either by an intrinsic data elaboration or by making use of and integrating the COPERNICUS Marine Environment Monitoring Service (CMEMS) data to local marine data streams. Local observations are also integrated with higher resolution forecasts for the preparation and provision of dedicated services that address real specific needs of sub-regional and coastal users. This effort has yielded valuable climatological datasets covering the Maltese coastal waters and spanning over several years. This work focusses on the climatologies derived from numerical models and satellites, and compiled within the Interreg MED programme AMAre (Actions for Marine Protected Areas) project.

Keywords: Marine data, Operational Oceanography, Climatology, Numerical Modelling

1 INTRODUCTION

Marine data and information services delivered by operational oceanography have triggered an unprecedented leap in the economic value of meteo-marine data, becoming essential for managing marine resources efficiently, and feeding benefits to the maritime industry and services sectors [1]. Technological development is supporting multiple-purpose *in situ* observing systems with an increasing element of automation, and supported by platforms for remote measurements such as by space-borne sensors. Enhanced numerical modelling tools can identify hydrological and ecological changes within the marine environment down to coastal scales, and are able to simulate the functioning and response of the marine ecosystem to external factors, linking marine data to economic, environmental and social domains. Such systems cater not only for monitoring, but also for research, service provision, security, safety and for policy-formulation purposes. The sharing of data is critical for competitiveness, product development and enhancement of services, and is supporting the implementation of the EU goals encapsulated within the Integrated Maritime Policy, Marine Spatial Planning and Blue Growth [2], [3].

MonGOOS and EuroGOOS are the umbrella associations of national providers of operational oceanography services in the Mediterranean and the European Seas respectively, both contributing to the Global Ocean Observing System (GOOS) and, as of recent, to the COPERNICUS Marine Environment Monitoring Service (CMEMS, http://marine. copernicus.eu/) developed through the GMES (Global Monitoring for Environment and Security) Marine Service programme [4].

These services cover the global ocean and the European regional seas and are freely available to public and private entities in support of applications within disparate fields such as those of climate, maritime transport, aquaculture, marine energy resources (including oil and gas exploration), tourism, coastal engineering and management, amongst many others. However, at the local scale, users have more specific requirements underpinning coastal domains such as shelf areas, gulfs, embayments and ports [5]. Data for these areas is acquired by dedicated observing systems targeting coastal regimes; numerical models are deployed to downscale the regional coarser scale CMEMS data fields to the higher resolution definitions of the coastal sea areas. The merging of national datasets to regional scale marine core data sources is leading to a proliferation of dedicated services, with downscaling to sub-regional and coastal domains, and is steered by the demands of local communities, coastal users and national competent entities.

2 THE MALTA CASE

The Physical Oceanography Research Group (PO-Res.Grp), established in the early 90s as the Physical Oceanography Unit within the Malta Council for S&T and later transposed to the University of Malta, today forms part of the Department of Geosciences. It undertakes oceanographic research, in a holistic perspective, including operational observations and forecasts, specialised data management and data analysis, and the participation in international cooperative research ventures. The overarching research themes of the PO-Res.Grp cover coastal meteorology, hydrography and physical oceanography with a main emphasis on the experimental study of the hydrodynamics of the sea in the vicinity of the Maltese Islands. The Group has mainly endeavoured to promote activities in operational oceanography; this is a branch of oceanography where the sea is observed on a continuous and routine manner through the installation and maintenance of permanent real-time sea monitoring systems, while numerical models are used to provide predictions of meteo-marine conditions that are published daily to serve a wide range of users. Observing systems run by the Group today include atmospheric parameters, sea level, currents and waves in both delayed and operational mode; forecasts for the same parameters are issued daily on the services website www.capemalta.net for the Central Mediterranean area, the Malta shelf area and for marine areas closer to Malta, even as close as the coastal waters inside ports and in embayments. The data is transmitted in real-time not only for research, but primarily to national stakeholders (such as Transport Malta, the Armed Forces of Malta, etc), responsible entities and the general public and private users with an interest to apply such data in their routine operations, or to generate added value through service provision and smart applications.

The PO-Res.Grp has strengthened its activities, know-how and capability through the participation in several EU funded regional and pan-European scientific projects, often with coordinating and leading roles.

2.1 Observing Systems

2.1.1 The longest standing observations made by the PO.Res.Grp are those of sea level which date back to 1993 when the very first data collection station was set up in Mellieha Bay. Real-time collection of sea level data is today done inside the marina at the Malta Hilton Portomaso; since February 2001, this station forms part of the CIESM/IOC Mediterranean regional subsystem of the Global Sea Level Observing System (MedGLOSS) which is a real-time monitoring network for the systematic measurement of the sea level in the Mediterranean and Black Sea. The station collects sea level data (every 15 seconds), seawater temperature and atmospheric pressure. Observations are shared in real-time with updated charts and data listing every two minutes on the Capemalta portal.

2.1.2 A real-time coastal meteorological station on the breakwater of Marsaxlokk harbour delivers operational observations of wind, wind gust, air temperature, air pressure and relative humidity at high sampling intervals. The station provides real-time meteorological information for users in the area, especially for the safer navigation of ships into and out of the port of Marsaxlokk. The data is transmitted by UHF to a control station at the Oil Tanking Malta Ltd. premises, and transferred by FTP to the server at the University where it is quality controlled, elaborated and published on a dedicated web service (http://ioi.research.um.edu.mt/ WeatherStations/index.php/welcome/index) with regular updating of charts and data listing.

2.1.3 The atmospheric heat flux station positioned at the University of Malta measures air temperature, atmospheric pressure, net radiation, solar radiation and relative humidity every 2 minutes. It is intended to accomplish long term monitoring of solar radiation variability at daily, seasonal and annual temporal scales.

2.1.4 The CALYPSO High Frequency radar network (www.capemalta.net/calypso) is the flagship activity, consisting of a permanent and fully operational observing system, capable of recording (in real-time with hourly updates) sea surface currents in the Malta Channel. The system combines data from HF radar installations at selected sites on the northern Maltese and southern Sicilian shores, to elaborate and publish data to users. Collected data, combined to numerical models, are intended to primarily support applications to optimise intervention in case of oil spill response as well as to support search and rescue, security, safer navigation, improved metro-marine forecasts, monitoring of sea conditions in critical areas such as proximity to ports, and the better management of the marine space between Malta and Sicily.

2.2 Forecasting Systems

2.2.1 The ROSARIO Malta Shelf forecasting system (http://www.capemalta.net/MFSTEP/results.html) has been providing routine online marine predictions for the area around the Maltese Islands for the last 15 years. The system operates through the use of an eddy-resolving numerical model with two distinct spatial resolutions of 1/64º or 1/96º (about 1Km) in the area comprising the Maltese Islands and the Malta Channel. The forecasts provide 1-hour and 3-hour averaged colour maps and animations of Temperature, Salinity and Velocity fields at the sea surface and at selected depths, giving daily forecasts of the sea for a 4-day period. This forecasting capability was mainly developed within the MFSPP and MFSTEP projects [6]. The numerical model code used runs with full atmospheric forcing from SKIRON forecast fields. The numerical code used in the model is based on an application of the Princeton Ocean Model (POM) [7] and includes full thermohaline dynamics. POM is a primitive equation, stratified and non-linear numerical ocean model that utilises the Boussinesq approximation and hydrostatic equilibrium. It uses the free surface, potential temperature and salinity, the three orthogonal components of velocity, the turbulence kinetic energy and the turbulence macro-scale as the prognostic variables. The model features a split mode time step and a sigma-coordinate transformation for the vertical grid. The bottom-following sigma layers allow the model to represent accurately regions of high topographic variability. The horizontal grid uses orthogonal coordinates and an 'Arakawa C' differencing scheme. The Mellor and Yamada [8] turbulence closure scheme is used to calculate the coefficients of vertical mixing of momentum, the vertical eddy viscosity and the eddy diffusivity of heat and salt. Density is calculated by an adaptation of the UNESCO equation of state revised by Mellor [9].

The model is run over a domain from 13.80°E to 14.94°E in longitude, and from 35.42°N to 37.21°N in latitude, covering the full shelf area around the Maltese Islands as shown in Fig. 1. The operational

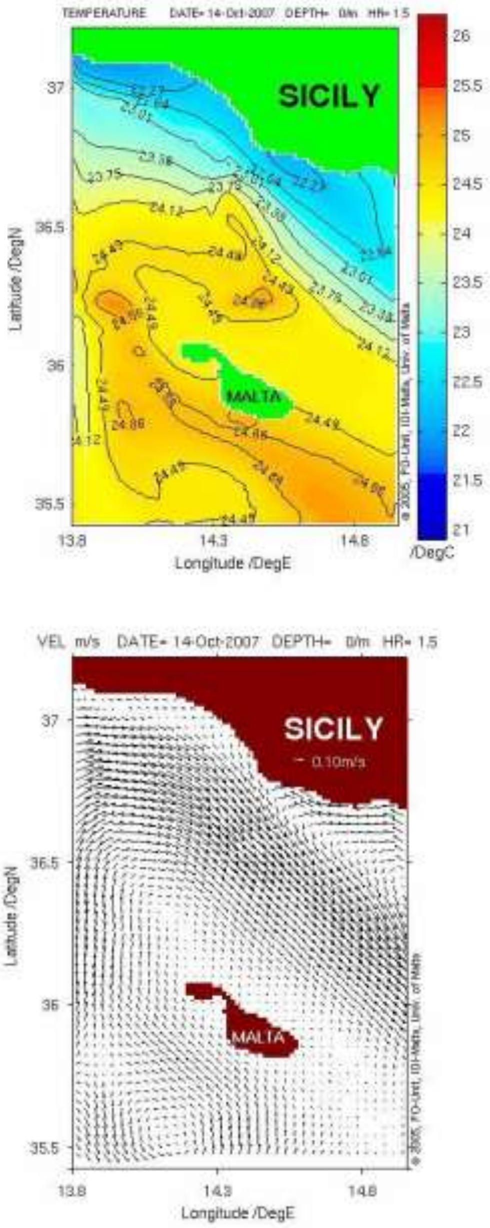

Figure 1: Sample plots of sea surface temperature (upper panel) and currents (lower panel) from the ROSARIO Malta shelf marine forecasting system

runs depend on a hierarchy of embedded models with successive downscaling starting from the basin scale Mediterranean Ocean General Circulation Model run in Bologna and now available through CMEMS, down to the regional model covering the Central Mediterranean area (Sicilian Channel Regional Model, SCRM), and the high resolution

ROSARIO shelf-scale model run by the PO.Res.Grp.

2.2.2 The operational running of the MARIA Malta Atmospheric and Wave forecasting systems consist of a chain of meteo-marine models with downscaling to high resolution sub-domains for the region north of 34º latitude in the Sicilian Channel, and comprising the Maltese Islands. Daily forecasts are published on a dedicated webpage (www.CapeMalta.net/maria/pages/about.html). The atmospheric forecasts are based on the Eta hydrostatic limited area grid point model with a "step-mountain" vertical coordinate system. The downscaling of atmospheric conditions to the sub-regional scale is done by executing the model runs in two nesting steps with successively embedded model configurations down to a resolution of 1/24º (~ 5 Km) over the Central Mediterranean area, and with outputs every 3hours.

The wave forecasting system uses the 3rd generation WAM Cycle 4 spectral wave model. The model is forced by surface wind from the Eta atmospheric model, and runs daily to produce a 72-hour forecast on a high-resolution grid (1/8º) over the Central Mediterranean. The model set-up is based on the following run-time parameters: 30 frequencies (in the range from 0.041772 Hz to 0.66264); 24 directions (every 15 degree); 3 output grids; 4916 sea points; and 3-hour outputs. The main output parameters are: significant wave height; wave direction and mean /peak wave period of total sea.

Both the atmospheric and wave forecasts are presented through a user-friendly visual online interface which allows the flexibility for choice of parameters and forecast times. The interface gives access to maps of the selected parameters, and offers a 2D view of atmospheric/sea state conditions, at both the basin scale for the full Mediterranean, and with greater temporal and spatial detail for the Central Mediterranean area.

2.2.3 More refined wave conditions in the coastal and near-shore areas are predicted at high spatial resolution by using the SWAN model. This is a third-generation wave model using the same formulations of WAM for the source terms and based on the wave action balance equation with sources and sinks [10]. While the WAM model considers problems on oceanic scales, with SWAN the wave propagation is calculated from deep water up to the surf zone. Since WAM makes use of explicit propagation schemes in geographical and spectral spaces, it requires very small grid sizes in shallow water and is thus unsuitable for applications to coastal regions. On the other hand SWAN employs implicit schemes, which are more robust and economic in shallow water.

For the Maltese Islands, SWAN is run on a regular grid over the domain defined by 14.040-14.700º in longitude and 35.665-36.206º in latitude. The spatial resolution of 0.002º is defined by 331 and 271 grid cells in the x- and y-directions respectively. At its lateral boundaries SWAN is nested to the coarser scale WAM model into which it is embedded; boundary conditions are derived from wave spectral information of the best 24 hr Malta MARIA WAM model forecast fields. At the surface it is forced by wind data from the Malta MARIA ETA atmospheric forecasting model; sea currents are prepared from the hydro-dynamical shelf scale eddy-resolving ROSARIO-6420 forecasting model; The SWAN model generates output fields every 3 hours of the following key parameters: Significant Wave Height; Peak Period of the variance density spectrum; Mean Absolute Wave Period; Mean Wave Direction.

2.3 Delivery of marine core services

The PO.Res.Grp was engaged as a historical partner in the MyOcean series of projects that led to the establishment of the COPERNICUS Marine Environment Monitoring Service (CMEMS). As a current member of the COPERNICUS Academy Network, the PO-Res.Grp endeavours to act as a local broker to promote the uptake of CMEMS data by users in Malta and beyond, primarily in the SouthEastern Mediterranean countries. The PO.Res.Grp is however primarily a direct user of CMEMS, especially to derive boundary conditions for its meteo-marine forecasting numerical models, and for the delivery of added value products and downstream services targeted to the local stakeholders and coastal users. CMEMS mainly provides data at the basin and regional scales. On the other hand local users require high resolution data products, especially for applications close to the coast. The PO.Res.Grp is engaged in the integration and enhancement of CMEMS data, with coastal scale observations and high resolution numerical model fields as described above, to close the gap and to address the demands by coastal applications.

Marine data gives invaluable insight on the phenomena occurring in the marine environment, and its ecosystem functioning, including its response to natural and man-induced changes. EU member countries are obliged by the Marine Strategy Framework Directive, (2008/56/EC), to achieve Good-Environmental-Status especially in the coastal seas. The availability of base data extending sufficiently in time and space is crucial to build the core of marine information necessary to interpret trends and changes at different scales. In this perspective, it is necessary to consolidate and enhance local marine observations to fit an overarching national monitoring programme, serving to assess natural variability, to set the ranges and thresholds of expected environmental changes, and to achieve the necessary standards for an integrated management of marine resources. In addition, marine data acquired for research and for environmental monitoring can be further made widely available to recycle its use and re-use by multiple players, beyond the academic and public sector, and including private initiatives to further penetrate industry applications for excellence in green applications in favour of blue growth.

The PO-Res. Grp. has been supporting these targets by enhancing its operational observing platforms and by further performing in the modelling of marine parameters and sea conditions, applying novel techniques to merge different data sources (remote an in situ), as well as by supporting the delivery of new downstream products and operational services, addressing environmental monitoring commitments and the needs of a wide range of users for data applications and exploitation. The PO-Res.Grp invests in research relevant to the production of downstream products in collaboration with stakeholders. The focus is on operational services using real time data, and the merging of different data sources for the delivery of marine information in applications requiring nowcast and forecast fields. Targets lead to the transformation of data into valuable information and knowledge needed for applications such as in coastal engineering, oil spill detection and response, search and rescue, etc. Key priority issues relate to the protection and preservation of natural coastlines as well as for planning of coastal development, and for the efficient and safer use of marine space.

3 CLIMATOLOGICAL DATASETS

Climatologies are compiled from consistent retrospective (often re-analysed) data records made over a number of years. A climatology is a synthesis hinging on long time series of data pertaining to a specific domain, bringing out the characteristic patterns of change in terms of trends and variability through the integration of data over time and space. Climatological datasets are useful to provide background and average expected conditions, serving as a reference and baseline, allowing the setting of thresholds and the ranges of variability of a specific parameter within a particular domain.

This work covers the climatological datasets for the Maltese coastal waters prepared within the Interreg MED programme AMAre (Actions for Marine Protected Areas) project. A main objective of the project is to develop shared methodologies and geospatial tools for multiple stressors assessment, coordinated environmental monitoring, multi-criteria analyses and stakeholders' engagements to launch pilot activities followed by a wider process of capitalization, dissemination and transfer of experiences and results in a number of Marine Protected Areas (MPAs) in the Mediterranean, comprising the North East MPA for the Maltese Islands. Oceanographic data and indicators for MPAs are essential products to support MPAs for environmental assessment and management, and comprise physical parameters coupled with biological time series. These climatologies are based on the Mediterranean Monitoring and Forecasting Centre products provided through CMEMS as well as on the high-resolution data provided by the PO.Res.Grp. They are linked to the AMAre GeoDatabase for their visualization on the project GeoPortal.

Data are derived from both satellite platforms and numerical models. Satellite sensors have advanced significantly in the last two decades and have become a major component of operational oceanography, providing real-time and regular, global, high spatial and temporal resolution observations of key ocean variables that are essential to constrain ocean models through data assimilation and/or to serve downstream applications [11].

The climatological products are delivered as long time series of monthly, seasonal and yearly means of selected surface and bottom sea variables, with different spatial resolution, spanning an area 35.83°N - 36.19°N, 14.13°E - 14.61°E in the case of Malta, and comprising a buffer of an additional 10km to include the ocean dynamics that can affect the sea waters in the MPAs.

The satellite-derived climatologies are all derived from CMEMS datasets as described in [12]. They comprise level 4 data of surface chlorophyll concentrations, water transparency and sea surface temperature with a spatial resolution of 1 km and spanning the period September 1997 to December 2018.

This paper deals with the model-derived climatologies covering sea surface temperature, salinity, currents and nutrients. Dissolved oxygen concentration is given at both the sea surface and bottom.

3.1 Model-derived physical parameters

Forecast fields for sea surface temperature, salinity and currents from the ROSARIO model were used to build a 2D climatology at a resolution of 1/96º (~1 km) and with a temporal step of 3 hours. The ROSARIO forecasting system produces daily forecasts of 4.5 days each. The best 24 hour window of each daily forecast, composed from 5^{th} to the 12^{th} 3h data frames, was extracted from each daily forecast and concatenated to produce the full data series spanning the five years from January 2012 to December 2016.

For each month, parameter values at each respective grid point were averaged to construct 2D monthly averaged fields. In the process other statistical diagnostics like minima, maxima and standard deviation were performed and visualised in 2D plots and time series at selected points to assess

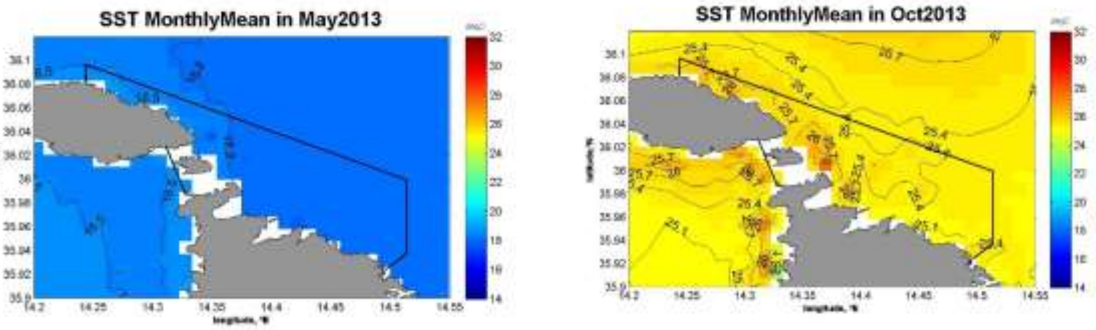

Figure 2: Sample plots of monthly mean sea surface temperature for May 2013 (upper panel) and October 2013 (lower panel) from the ROSARIO Malta shelf marine forecasting system. Black line shows the boundary of the Marine Protected Area.

the variability.

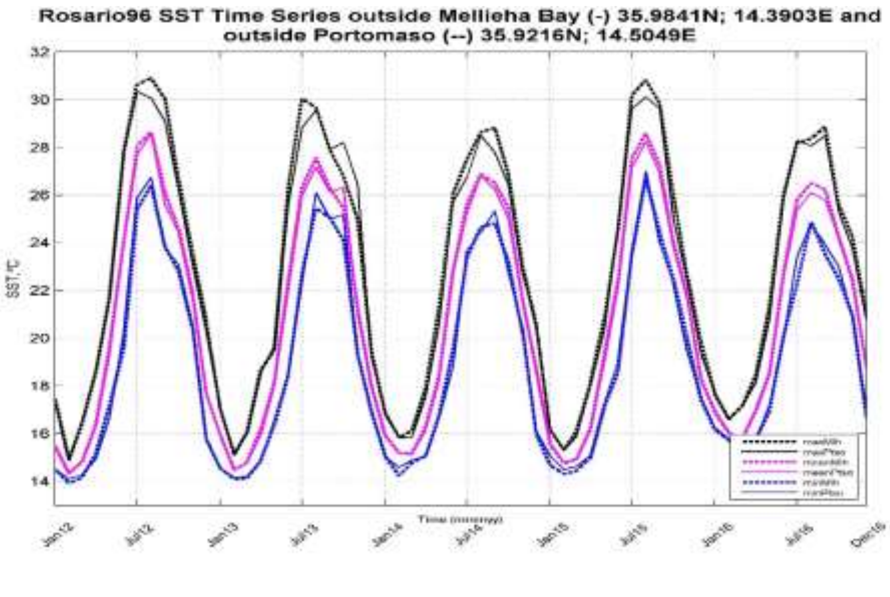

Figure 3: Time series of monthly sea surface temperature at two coastal points outside Mellieha Bay and Portomaso respectively. Mean SST in cyan, minimum SST in blue and maximum SST in black.

also

The monthly mean fields were subsequently combined to calculate seasonal averages over the 3-month periods: Jan - Mar; Apr - Jun; Jul - Sept; and Oct – Dec. In the case of sea currents, both vector and scalar averaging was performed together with a quantification of maximum currents and corresponding directions on a monthly, seasonal and annual basis. This analysis permits thresholds and ranges of variability to be determined.

Fig. 2 shows typical spatial plots for sea surface temperature providing information on the variability in the area on a monthly basis; Fig. 3 shows the seasonal and inter-annual variability at two specific locations.

Sea surface temperature, salinity and currents are derived from the Mediterranean Forecasting System (MFS) re-analysis fields provided by CMEMS for the whole Mediterranean Sea. In this case climatologies cover a longer time span (January 1987 to December 2017), but at a lower horizontal grid resolution: a) of 1/16º (~ 6-7 km) until 2015, and b) of 1/24˚ (~ 4 km) from January 2015 onwards.

Dataset a) comes from the NEMO (Nucleus for European Modelling of the Ocean) hydrodynamic model [13] with a variational data assimilation scheme (OceanVAR) for temperature and salinity vertical profiles and satellite Sea Level Anomaly along track data.

Dataset b) comes from the physical component of the Mediterranean Forecasting System (Med-

Currents) using the NEMO v3.6 hydrodynamic model with solutions corrected by a variational data assimilation scheme (3DVAR) of temperature and salinity vertical profiles and along track satellite Sea Level Anomaly observations.

A detailed description of the calibration and validation activities performed over these datasets is found on the CMEMS web portal.

The two datasets are elaborated for the Maltese Islands as monthly means: 01/1987 – 12/2017; seasonal means: 01/1987 – 12/2017 and yearly means: 1987 -2017.

3.2 Model-derived non-physical parameters

Sea surface nutrient concentration (phosphate and nitrate) at the sea surface together with dissolved oxygen also at the bottom are derived from simulations by the Biogeochemical Flux Model Forecasting System, are provided by CMEMS for the whole Mediterranean Sea and elaborated by CMCC. Two datasets have been considered: a) covering January 1999 – December 2016 at a resolution of 1/16º, and b) from January 2015 to December 2017 at a higher resolution of 1/24º.

Dataset a) comes from the Mediterranean Sea reanalysis fields of the OGSTM-BFM biogeochemical model run by the Istituto Nazionale di Oceanografia e Geofisica Sperimentale (OGS), and comprises data assimilation of surface chlorophyll concentration. Physical forcing fields are provided by the Med-Currents model of the Istituto Nazionale di Geofisica e Vulcanologia (INGV). The ESA-CCI database of surface chlorophyll concentration estimated by satellite and delivered within CMEMS-OCTAC was used for data assimilation. This reanalysis provides monthly means of 3D fields of chlorophyll, nutrients (phosphate and nitrate) and dissolved oxygen concentrations, net primary production, phytoplankton biomass, ocean pH and ocean pCO2. Dataset b) comes from the Mediterranean Sea biogeochemical analysis and forecast fields of the MedBFM model system (the physical-biogeochemical OGSTM-BFM model coupled with the 3DVARBIO assimilation scheme). This is also run by OGS and uses physical forcing fields from the Med-Currents model of INGV. Seven days of analysis/hindcast and ten days of forecast are produced bi-weekly every Wednesday and Saturday, with the assimilation of surface chlorophyll concentration from satellite observations provided by the CMEMS-OCTAC.

A detailed description of the calibration and validation activities performed over these products is found on the CMEMS web portal.

The two datasets are elaborated for the Maltese Islands as monthly means: 01/1999 – 12/2017; seasonal means: 01/1999 – 12/2017 and yearly means: 1999 -2017.

4 CONCLUSIONS

The value of climatological datasets covering the Maltese coastal waters is presented in the paper. Parameters covered include physical data at the sea surface: temperature, salinity and currents; and non-physical data: nutrients at the surface, and dissolved oxygen at the sea surface and at the sea bottom. Datasets are provided from numerical models at different horizontal resolutions and temporal spans, or acquired from satellite observations. Other data fields not included in this work comprise chlorophyll-*a* concentration, significant wave height, wave direction and period as well as atmospheric parameters; they complete the full climatological database that the PO.Res.Grp is endeavouring to maintain and update regularly. This commitment requires substantial effort and carries a price for the support and availability of skilled human resource, and especially to provide and sustain in the long term infrastructure for marine observations and modelling activities that feed the data flow.

Climatologies are essential marine core data and constitute a primary building block in the downstreaming chain to deliver professional marine services to users. In the local scale, and especially for a small island state like Malta, the COPERNICUS scale of coverage is not sufficiently detailed and a complementary national marine core data backbone is needed to provide the coastal scale observations and forecasting services at the temporal and spatial detail that serves the local stakeholders and users. Such a core data service should be delivered by a designated national provider, and where possible, data made available as a public good to ensure uptake and benefits by the widest range of users. The ultimate goal is to serve marine data and information beyond national responsible entities and players, to include the private sector for value addition and in support of blue jobs and investments for excellence in the marine economic sector.

5 ACKNOWLEDGEMENTS

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