A 1/24° RESOLUTION MEDITERRANEAN PHYSICAL ANALYSIS AND FORECASTING SYSTEM FOR THE COPERNICUS MARINE ENVIRONMENT MONITORING SERVICE

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Abstract

This study describes a new model implementation for the Mediterranean Sea that has been achieved in the framework of the Copernicus Marine Environment Monitoring Service (CMEMS). The numerical ocean prediction system, that operationally produces analyses and forecasts of the main physical parameters for the entire Mediterranean Sea and its Atlantic Ocean adjacent areas, has been upgraded by increasing the grid resolution from 1/16o to 1/24o in the horizontal and from 72 to 141 unevenly spaced vertical levels, by increasing the number of fresh water river inputs and by updating the data assimilation scheme. The model has a non-linear explicit free surface and it is forced by surface pressure, interactive heat, momentum and water fluxes at the air-sea interface. The focus of this work is to present the new modelling system which will become operational in the near future and the validation assessment including the comparison with an independent non assimilated dataset (coastal moorings) and quasi-independent (in situ vertical profiles and satellite) datasets. The results show that the higher resolution model is capable of representing most of the variability of the general circulation in the Mediterranean Sea, however some improvements need to be implemented in order to enhance the model ability in reproducing specific hydrodynamic features particularly the Sea Level Anomaly.

Keywords: Mediterranean Sea, Hydrodynamics, Numerical Model, Skill Assessment

1. Introduction

The Mediterranean Forecasting System, MFS, (Pinardi *et al.*, 2003, Pinardi and Coppini 2010, Tonani *et al.*, 2014) is providing since year 2000 numerical analysis and short term forecasts of the main physical parameters in the Mediterranean Sea. The reanalysis started much later (Adani *et al.*, 2011, Simoncelli *et al.*, 2016) and became a routine activity only from 2012. The modelling system has been upgraded during the years in the framework of several national and international projects and, since April 2015, is providing the physical component of the Med-MFC (Mediterranean Monitoring and Forecasting Center) for the Copernicus Marine Environment Monitoring Service (CMEMS) producing every week the analysis of the previous two weeks and providing daily updates of the following 10 days forecast at basin scale, which are freely available through the CMEMS Catalogue (http://marine.copernicus.eu/, Clementi *et al.*, 2017a).

The aim of this study is to provide a description of the recently upgraded Mediterranean Sea forecasting model and data assimilation implementation, which will enter in operation starting from October 2017, and to assess the quality of the new numerical system (namely EAS2) with respect to the previous version (namely EAS1) by comparing with *in situ* and satellite observation datasets.

2. MED-MFC physical modelling system until september 2017: EAS1

The present day Med-MFC numerical hydrodynamic system (so-called EAS1, Clementi *et al.*, 2017a, Oddo *et al.*, 2014) is composed by two elements: an Ocean General Circulation Model (OGCM) and a third generation Wave Model (coupling mechanism is described in Clementi *et al.*, 2017b); the numerical solutions are corrected by a data assimilation scheme based on 3DVAR. The modelling system is implemented in the Mediterranean Sea and its Atlantic Ocean adjacent areas in order to better represent the hydrodynamics at the Gibraltar Strait at 1/16o resolution and 72 vertical levels.

The OGCM code is based on NEMO (Nucleus for European Modelling, Madec 2008) version 3.4 and the model solves the primitive equations using the time-splitting technique, meaning that the external gravity waves are explicitly resolved, and with the linear free surface approximation. The model is forced by momentum, water and heat fluxes interactively computed by bulk formulae using the 6-hours (for the first 3 days of forecast a 3-hours temporal resolution is used), 1/8° 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 Pettenuzzo *et al.*, 2010). The surface water flux is computed as Evaporation minus Precipitation and Runoff. The evaporation is derived from the latent heat flux, the precipitation is provided by ECMWF at the same temporal resolution of the other atmospheric forcing fields, while 7 rivers are considered as volume inputs provided by monthly mean datasets; moreover the Dardanelles Strait is closed but considered as net volume input (Kourafalou and Barbopoulos, 2003) through a river-like parameterization. At the bottom, a quadratic bottom drag coefficient has been used and the model uses vertical partial cells to fit the bottom depth shape. The nesting in the Atlantic Sea is provided by means of daily analysis and forecast CMEMS GLO-MFC (Global Ocean MFC) fields at 1/12° horizontal resolution (the nesting approach is described in Oddo *et al.*, 2009).

The numerical solutions are corrected by a data assimilation scheme based on 3DVAR (Dobricic and Pinardi, 2008), recently modified (Pistoia *et al.*, 2017) to have grid point EOFs and a time dependent observational error evaluated according to Desroziers *et al.*, (2005). The assimilated data include: satellite Sea Level Anomaly (SLA) accounting for atmospheric pressure effect (from CMEMS Sea Level Thematic Assembly Center), and vertical temperature and salinity profiles from Argo, XBT and gliders (from CMEMS In situ Thematic Assembly Center). Objectively Analyzed Sea Surface Temperature (SST) fields (from CMEMS Ocean and Sea Ice Thematic Assembly Center) are used for the correction of surface heat fluxes using a relaxation constant of 40 [Wm-2K-1].

3. MED-MFC physical modelling system form october 2017: EAS2

In October 2017 a new Med-MFC physical model will become operational, so-called EAS2, using the latest available NEMO model version 3.6 with non-linear free surface formulation and time-varying vertical z-star coordinates. The new model resolution is increased to 1/24o uniform in the horizontal and 141 unevenly spaced vertical levels allowing to define the model as an eddy-resolving model for the Mediterranean Sea, since the first internal Rossby radius of deformation is around 10–15km in summer and for most of the Mediterranean subregional seas. The new vertical background viscosity and diffusivity values are set to 1.2e-6 [m2/s] and 1.0e-7 [m2/s] respectively (in EAS1 the values were set as: 1.2e-5 and 1.2e-6 [m2/s]), the horizontal bilaplacian eddy diffusivity and viscosity are set respectively equal to -1.2e8 [m4/s] and -2.e8 [m4/s] (in EAS1 the values were set as: 1.2e-6 and 1.0e-7 [m4/s]). No coupling with wave model is yet operational, it will be re-inserted in April 2018 (corresponding to the end of the 1st phase of the CMEMS service). The data assimilation system is modified with respect to EAS1 implementing the 3DVAR scheme developed by Storto *et al.*, (2015). The surface and open boundary forcing fields are not changed with respect to the previous system, while the freshwater inputs are increased from 7 to 39 river sources evaluated from monthly mean datasets. The new 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 and manually modified in critical areas such as: islands along the Eastern Adriatic coasts, Gibraltar and Messina straits, Atlantic box edge. Fig. 1 shows the model domain and topography as well as the location of the 39 rivers.

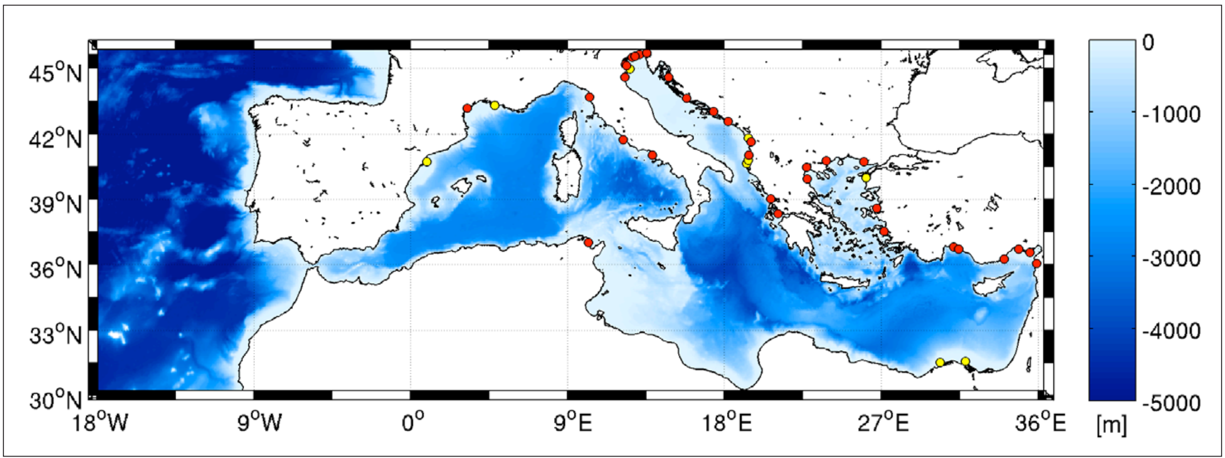

Fig. 1. Model domain, topography and location of river inputs: yellow dots represent the 7 river sources included in both EAS1 and EAS2, red dots represent the 32 additional rivers implemented in EAS2.

4. Model validation

The EAS2 system described in section 3 has been run starting from August 2013, initialized with temperature and salinity climatological fields from WOA13 V2 (World Ocean Atlas 2013 V2, https://www.nodc.noaa.gov/OC5/woa13/woa13data.html), up to present day in order to build a pre-operational dataset which has been validated using *in situ* and satellite observations. We will consider here intercomparison of EAS1 with EAS2 in the period 1st January 2015–31st December 2016. The EAS2 system described in section 3 has been run starting from August 2013, initialized with temperature and salinity climatological fields from WOA13 V2 (World Ocean Atlas 2013 V2, https://www.nodc.noaa.gov/OC5/woa13/woa13data.html), up to present day in order to build a pre-operational dataset which has been validated using *in situ* and satellite observations. We will consider here intercomparison of EAS1 with EAS2 in the period 1st January 2015–31st December 2016.

4.1 Validation datasets

Different datasets have been used to validate the numerical model results.

The first source of data consists of daily averages of in situ observations derived from a fixed coastal buoy network (http://calval.bo.ingv.it/) for temperature, salinity, sea level and currents. This provides an independent validation since moorings are not assimilated by the model. Quasi-independent validation is provided by evaluating temperature, salinity and SLA misfits calculated by the data assimilation system before data are ingested in the system. Moreover maps of numerical SST are compared to satellite daily gap-free SST-L4 maps at 1/16o resolution (Buongiorno Nardelli *et al.*, 2013) and comparison of the volume averaged temperature and salinity properties is done with available WOA13 V2 climatological data sets for the Mediterranean Sea.

4.2 Validation results

The results of the validation procedure are evaluated considering the years 2015-2016 for both the new upgraded system at 1/24° resolution (EAS2) and the previous system at 1/16° resolution (EAS1).

The model independent validation performed using coastal moorings is assessed by considering the Root Mean Square Difference (RMSD) of surface fields for: temperature, salinity, sea level and currents. Table I shows that the skill of the two systems in terms of temperature, salinity and currents is similar, while the new system is able to better predict the coastal sea level with a reduced error of about 0.7cm in 2015 and 0.3cm in 2016.

Table I. RMSD of Temperature, Salinity, Sea Level, Zonal and Meridional Currents for systems EAS1 and EAS2 compared to surface coastal mooring observations for the years 2015 and 2016. The number of available buoys used to validate the model solutions is also provided.

VARIABLE	YEAR 2015			YEAR 2016		
	N. BUOY	RMSD		N. BUOY	RMSD	
		EAS1	EAS2		EAS1	EAS2
Temperature [oC]	15	0.84	0.89	16	0.67	0.66
Salinity [PSU]	8	0.57	0.57	8	0.39	0.40
Sea Level [cm]	51	6.11	5.39	49	4.81	4.51
Zonal Vel. [cm/s]	5	12.85	11.72	6	11.35	12.13
Merid. Vel. [cm/s]	5	13.31	12.91	6	12.60	13.33

A check on the daily volume averaged salinity is provided by comparing the two systems with available WOA13 V2 datasets (used to initialize EAS2 system) and represented in Fig. 2 showing that the new system (blue line) is much closer to the climatological dataset (black dashed line) with respect to EAS1 (red line), also assessing the ability of the model to not diverge from its initial status.

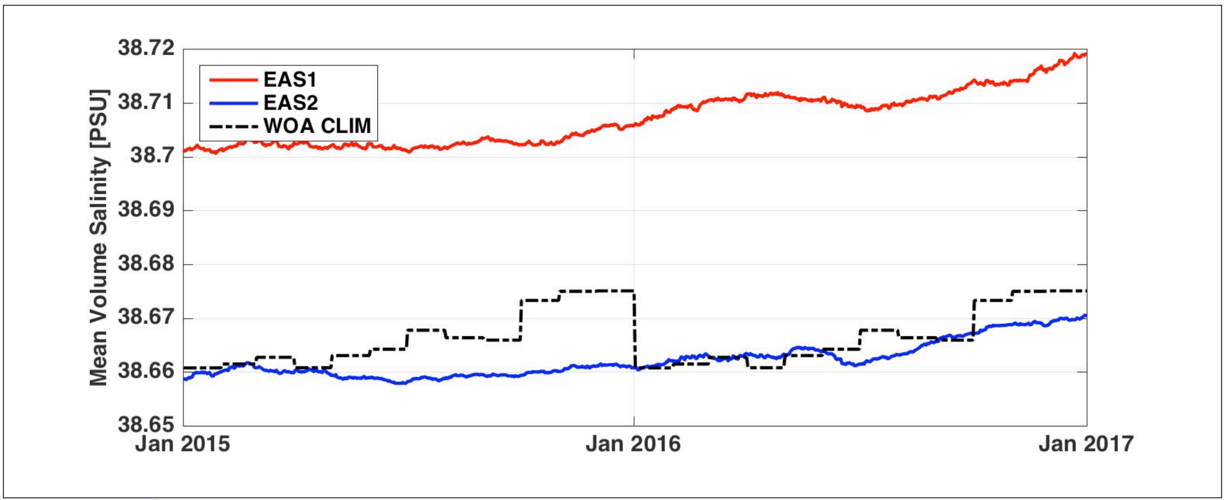

Fig. 2. Time series of daily volume averaged salinity evaluated for systems EAS1 (red line), EAS2 (blue line) and compared to monthly climatological values from WOA13 V2 datasets.

A quasi-independent validation assessment has been carried out by evaluating the *RMS* misfits in the open ocean: RMS of observation minus model value transformed at the observation location and time. Numerical temperature and salinity fields are compared to *in situ* datasets and SLA is compared to satellite observations. Results are presented in Table II for temperature and salinity at different depths showing that the new system always presents an enhanced skill with lower error with respect to the previous one, while it is characterized by a larger SLA error. This issue could be related to the updates in the data assimilation scheme and the need of a new estimate of the background error covariance matrix with Empirical Orthogonal Functions evaluated from a longer assimilation run.

Table II. RMS misfits of temperature and salinity at various depths for systems EAS1 and EAS2 averaged in the year 2015-2016.

DEPTH [M]	EAS1		EAS2	
	TEMP. *RMS* MISFIT [OC]	SAL. *RMS* MISFIT [PSU]	TEMP. *RMS* MISFIT [OC]	SAL. *RMS* MISFIT [PSU]
8	0.51	0.19	0.46	0.17
30	0.84	0.18	0.78	0.17
150	0.28	0.09	0.27	0.09
300	0.22	0.05	0.21	0.04
600	0.13	0.04	0.10	0.03
	SLA *RMS* MISFIT [CM]		SLA *RMS* MISFIT [CM]	
	3.31		4.22	

In order to assess the quality of the predicted SST, a comparison with satellite daily gap-free SST maps (L4) at 1/16° horizontal resolution is presented in Fig. 3 showing maps of satellite SST averaged in the period 2015-2016 (left panel) and the difference between the predicted and observed SST for system EAS1 (central panel) and EAS2 (right panel). The numerical SST is in good agreement with the satellite data with maximum differences of ±1°C and showing a general slightly warmer pattern with respect to the Satellite data.

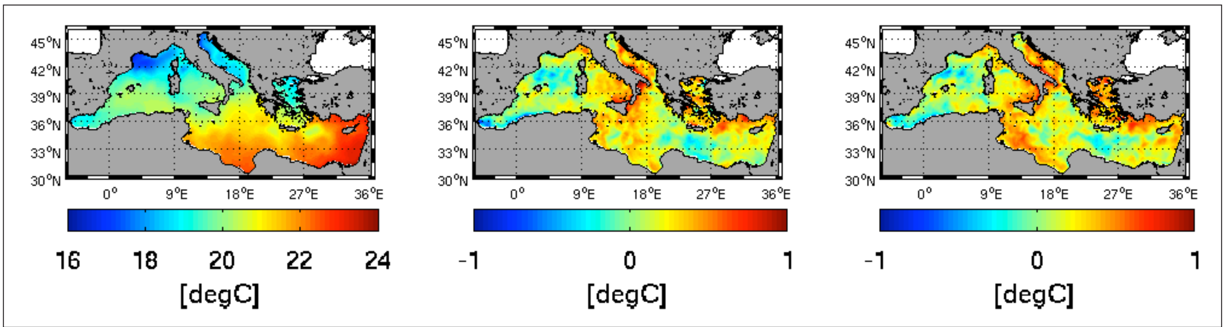

Fig. 3. SST Maps averaged in the period 2015-2016. Left: Satellite SST [degC]; Central: SST. Difference between EAS1 and Satellite [degC]; Right: SST. Difference between EAS2 and Satellite [degC].

5. Conclusions

A new numerical modeling system implemented in the Mediterranean Sea at 1/24o horizontal resolution and 141 vertical levels has been described and compared to the previous version at lower resolution (1/16° in the horizontal and 72 vertical levels). The differences between the two systems also include an update of the OGCM with a non-linear free surface formulation, z-star time varying vertical coordinates, an increased number of river inputs and an upgrade of the data assimilation scheme. A validation assessment performed for the years 2015-2016 has been carried out by comparing the new system, that will become operational from October 2017, with the previous one using insitu, satellite and climatological datasets. This study shows that the 2 numerical systems perform well in reproducing *in situ* as well as satellite measured physical parameters and are capable of representing most of the variability of the general circulation in the Mediterranean Sea. The new system presents an enhanced skill considering temperature and salinity model misfits along the entire water column, while some improvements should be carried out in the next future to enhance the representation of the SLA misfit using a new estimate of the background error covariance matrix for the SLA. The validation using independent coastal moorings shows similar performances between the two systems with an increased skill of the new system in predicting the sea level; moreover the overall model performance in coastal areas is lower with respect to open ocean and this issue will be considered in future improvements.

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References

Adani, M., Dobricic, S. and Pinardi, N. (2011). Quality Assessment of a 1985–2007 Mediterranean Sea Reanalysis. *Journal of Atmospheric and Oceanic Technology*, 28, 569–589, doi: 10.1175/2010JTECHO798.1

Buongiorno Nardelli, B., Tronconi, C., Pisano, A. and Santoleri, R. (2013). High and Ultra-High resolution processing of satellite Sea Surface Temperature data over Southern European Seas in the framework of MyOcean project. *Remote Sensing of Environment*, 129, 1-16.

Clementi, E., Pistoia, J., Fratianni, C., Delrosso, D., Grandi, A., Drudi, M., Coppini, G., Lecci, R. and Pinardi, N. (2017a). Mediterranean Sea Analysis and Forecast (CMEMS MED-Currents 2013-2017). [Data set]. doi: https://doi.org/10.25423/MEDSEA_ANALYSIS_FORECAST_PHYS_006_001.

Clementi, E., Oddo, P., Drudi, M., Pinardi, N., Korres, G. and Grandi A. (2017b). Coupling hydrodynamic and wave models: first step and sensitivity experiments in the Mediterranean Sea. *Ocean Dynamics*. doi: https://doi.org/10.1007/s10236-017-1087-7.

Desroziers, G., Berre, L., Chapnik, B. and Poli, P. (2005). Diagnosis of observation, background and analysis-error statistics in observation space. *Quarterly Journal of the Royal Meteorological Society*, 131, 3385–3396.

Dobricic, S. and Pinardi, N. (2008). An oceanographic three-dimensional variational data ssimilation scheme. *Ocean Modelling*, 22, 3-4, 89-105.

Kourafalou, V.H. and Barbopoulos, K. (2003). High resolution simulations on the North Aegean Sea seasonal circulation. *Annales Geophysicae*, 21, 251–265, doi: http://www.ann-geophys.net/21/251/2003/.

Madec, G. (2008). NEMO ocean engine. *Note du Pole de modélisation, Institut Pierre-Simon Laplace (IPSL), France, Note 27*, ISSN 1288-1619, pp 209.

Oddo, P., Adani, M., Pinardi, N., Fratianni, C., Tonani, M. and Pettenuzzo, D. (2009). A nested Atlantic-Mediterranean Sea general circulation model for operational forecasting. *Ocean Science*, 5, 461-47.

Oddo, P., Bonaduce, A., Pinardi, N. and Guarnieri, A. (2014). Sensitivity of the Mediterranean sea level to atmospheric pressure and free surface elevation numerical formulation in NEMO. *Geoscientific Model Development*, 7, 3001-3015.

Pettenuzzo, D., Large, W.G. and Pinardi, N. (2010). On the corrections of ERA-40 surface flux products consistent with the Mediterranean heat and water budgets and the connection between basin surface total heat flux and NAO. *Journal of Geophysical Research*, 115, C06022, doi: 10.1029/2009JC005631.

Pinardi, N., Allen, I., Demirov, E., De Mey, P., Korres, G., Lascaratos, A., Le Traon, P-Y., Maillard, C., Manzella, G. and Tziavos C. (2003). The Mediterranean ocean Forecasting System: first phase of implementation (1998-2001). *Annales Geophysicae*, 21, 3-20, doi:10.5194/angeo-21-3-2003.

Pinardi, N. and Coppini, G. (2010). Operational oceanography in the Mediterranean Sea: the second stage of development. *Ocean Science*, 6, 263-267.

Pistoia, J., Clementi, E., Delrosso, D., Mattia, G., Fratianni, C., Drudi, M., Grandi, A., Padeletti, D., Di Pietro, P., Storto, A. and Pinardi., N. (2017). Last improvements in the data assimilation scheme for the Mediterranean Analysis and Forecast system of the Copernicus Marine Service. *Extended abstract to the 8th EuroGOOS Conference, Bergen.*

Simoncelli, S., Masina, S., Axell, L., Liu, Y., Salon, S., Cossarini, G., Bertino, et al. (2016). MyOcean regional reanalyses: overview of reanalyses systems and main results. *Mercator Ocean J. 54. Special Issue on Main Outcomes of the MyOcean2 and MyOcean Follow-on projects.* Available from: https://www.mercator- ocean.fr/wp-content/uploads/2016/03/JournalMO-54.pdf.

Storto, A., Masina, S. and Navarra, A. (2015). Evaluation of the CMCC eddy-permitting global ocean physical reanalysis system (C-GLORS, 1982-2012) and its assimilation components. *Quarterly Journal of the Royal Meteorological Society*, 142, 738–758, doi: 10.1002/qj.2673.

Tonani M., Teruzzi, A., Korres, G., Pinardi, N., Crise, A., Adani, M., Oddo, P., et al. (2014). The Mediterranean Monitoring and Forecasting Centre, a component of the MyOcean system. *Proceedings of the 6th International Conference on EuroGOOS.* Eurogoos Publication n°. 30, ISBN 978-91-974828-9-9