LAST IMPROVEMENTS IN THE DATA ASSIMILATION SCHEME FOR THE MEDITERRANEAN ANALYSIS AND FORECAST SYSTEM OF THE COPERNICUS MARINE SERVICE

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Abstract

The Mediterranean Forecasting System (MFS) is a numerical ocean prediction system that produces analyses, reanalyses and short term forecasts for the entire Mediterranean Sea and its Atlantic Ocean adjacent areas. The system is now part of the Copernicus Marine Environment Monitoring Service (CMEMS) providing regular and systematic information about the physical state and dynamics of the Mediterranean Sea through the Med-MFC (Mediterranean Monitoring and Forecasting Center).

MFS has been implemented in the Mediterranean Sea with 1/16o horizontal resolution and 72 vertical levels and is composed by the hydrodynamic model NEMO (Nucleus for European Modelling of the Ocean) 2-way online coupled with the third generation wave model WaveWatchIII (Clementi et al., 2017a) and forced by ECMWF atmospheric fields at 1/8° horizontal resolution. The model solutions are corrected by the data assimilation system (3D variational scheme, Dobricic and Pinardi, 2008) with a daily assimilation cycle of along track satellite Sea Level Anomaly (SLA) and vertical profiles of Temperature and Salinity from ARGO and gliders. In this study we present a new estimate of the background error covariance matrix with vertical Empirical Orthogonal Functions (EOFs) that are defined at each grid point of the model domain in order to better account for the error covariance between temperature and salinity in the shelf and open ocean areas. Moreover the Observational error covariance matrix is z-dependent and varies in each month. This new dataset has been tested and validated for more than 2 years against a background error correlation matrix varying only seasonally and in thirteen sub-regions of the Mediterranean Sea (Dobricic et al. 2005).

Keywords: Data assimilation, EOFs, model error, observational error

1. Introduction

Since year 2000, the Mediterranean Forecasting System, MFS, (Pinardi *et al.*, 2003, Pinardi and Coppini, 2010, Tonani *et al.*, 2014) is providing numerical analysis and forecast of the main physical parameters in the Mediterranean Sea. In the framework of several national and international projects this system has been kept updated and, since April 2015, it provides 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 daily providing 10 days forecast at basin scale, that are freely available through the CMEMS Catalogue (http://marine.copernicus.eu/, Clementi *et al.*, 2017b). Currently the CMEMS Med-MFC system operationally uses a 3DVAR scheme that assimilates in situ observation of temperature and salinity by ARGO, Gliders and XBT, and along track satellite SLA. In this work we present the upgrade in the background and observational error covariance matrix from the system CMEMS Med MFC V1 (operational up to April 2016), hereafter EAS0, which used EOFs estimated from a climatological model simulation in 13 geographical regions and constant observational errors in vertical, to CMEMS Med MFC V2 (operational since May 2016), hereafter EAS1, in which EOFs are defined at each grid point and the observational error is depth dependent.

The paper is organized as follows: in section 2 the pre-conditioning in the Background Error Covariance Matrix is described, while in section 3 the impact of the different Background Error Covariance Matrixes will be shown and in section 4 the conclusions are presented.

2. Vertical part of the background error covariance matrix

3DVAR finds the minimum of the cost function, J, written as:

$$J = \frac{1}{2}\delta\mathbf{x}^T\mathbf{B}^{-1}\delta\mathbf{x} + \frac{1}{2}[\mathbf{H}(\delta\mathbf{x}) - \mathbf{d}]^T\mathbf{R}^{-1}[\mathbf{H}(\delta\mathbf{x}) - \mathbf{d}]$$

$$\delta x = x - x_b \qquad \mathbf{B} = \mathbf{V}\mathbf{V}^T \qquad \mathbf{d} = y - H(x_b) \qquad \text{Eq 1}$$

In Eq. 1 **δx** is the analysis increments, the difference between the background state, x_b, and the truth, *x*. **H** is the linear interpolation operator that brings the model information on the observation grid, **d** is the misfit, i.e. the difference between the background and observation, B is the Background Error Covariance Matrix and **R** is Observational Error Covariance Matrix. Pre-conditioning in **B** is modelled through a sequence of linear operators composing **V** (Dobricic and Pinardi, 2008):

$$\mathbf{V} = \mathbf{V_D}\mathbf{V}_\eta\mathbf{V_H}\mathbf{V_V} \qquad \text{Eq 2}$$

where $\mathbf{V_D}$ applies a divergence-damping filter on the correction field, $\mathbf{V}_\eta$ calculates the sea surface height error covariance from three-dimensional fields of temperature and salinity with a barotropic model, $\mathbf{V_H}$ applies horizontal covariances on fields of temperature and salinity, $\mathbf{V_V}$ contains multi-variate vertical Empirical Orthogonal Functions (EOF). The multivariate vertical EOFs consider sea level, temperature and salinity profile anomalies. The temperature and salinity EOFs include the information about the cross-variance between temperature and salinity and thus a water-mass type analysis.

In order to create a more accurate representation of the horizontal variability in the water mass representation in the background error covariance matrix, we decided to compute the vertical EOFs in each grid point of the model domain. EOFs are calculated with a Singular Value Decomposition algorithm applied to a state vector containing temperature, salinity at model levels and sea surface elevation anomalies, for each grid point of the Mediterranean Sea deeper than 75m. The basic model variables are extracted from twelve years of reanalysis (Adani *et al.*, 2011) for the period 2000 to 2011. The temperature and salinity anomalies entering the state vector are calculated as monthly mean deviations and a EOF-box of 10 x 10 grid point profiles is used for each central grid point of a EOF-box since not all model grid point represent independent dynamical states. The EOF-box will naturally involve different depths grid points and only grid points deeper than the target point are considered to build the state vector. This sampling allows us to account for the different bottom shape maintaining the EOF-box smoothing approach, and the resulting state-vector will be very different for shelf or deep-water area.

The daily averaged model field anomalies in each grid point resulted in a minimum dataset of more than 600 multi-variate profiles. The state vector *X* can then be represented as follows:

$$X = \left(\frac{\delta\eta}{\sigma_\eta}, \frac{\delta T_1}{\sigma_T}, \dots, \frac{\delta T_m}{\sigma_T}, \frac{\delta S_1}{\sigma_S}, \dots, \frac{\delta S_m}{\sigma_S} \right) \qquad \text{Eq 3}$$

where σ_η, σ_T and σ_S represent the standard deviation of corresponding fields, and δ indicates the difference between the daily averaged value and temporal mean for each month. Each vector composing Eq.3 is a time series of daily values. As in Dobricic *et al.*, (2006) in order to create EOFs independent from the number and thickness of vertical levels, Dobricic *et al.*, (2016) used to multiply the state vector *X* by a metric factor matrix *g* (North *et al.*, 1982) where the diagonal elements are:

$$g = diag\left(1, \frac{\Delta z_1}{H}, \dots, \frac{\Delta z_m}{H}, \frac{\Delta z_1}{H}, \dots, \frac{\Delta z_m}{H} \right) \qquad \text{Eq 4}$$

where the Δz are the model layer thicknesses and *H* is the model depth of the target point.

The structure of the vertical covariance matrix for the Gulf of Lyon region in winter and March for the EAS0 and EAS1 system respectively, are shown in Fig. 1. Temperature and salinity are correlated with the surface elevation, and the maximum of autocorrelation is in the upper water column. Largest correlation between T and S fields are found at the same levels.

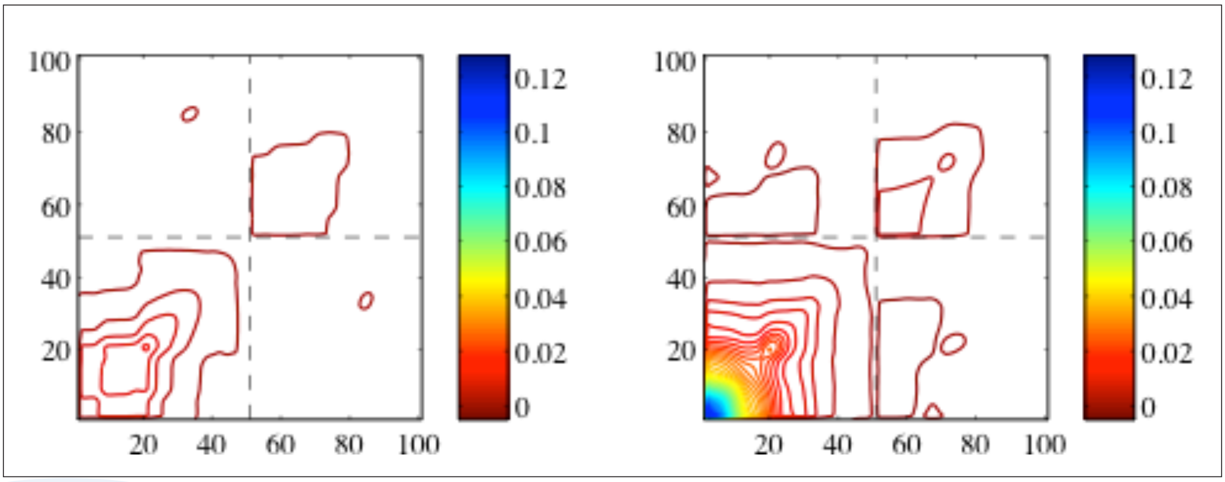

Fig. 1. Vertical Background Error Covariance Matrix for EAS0 (left) and EAS1(right). In the left panel the Vertical Background Error Covariance Matrix is given for a large region in the Gulf of Lyon (northern Mediterranean Sea, Dobricic et al., 2006) during wintertime. In the right panel the matrix corresponds to a central grid point in the Gulf of Lyon valid for the month of March with a depth of 50 levels. The matrix horizontal and vertical dimensions are given by the number of variables in the state vector of Eq. (3), i.e. the sea level anomaly, the first 50 levels of temperature anomalies and the first 50 levels of salinity anomaly profiles. The matrix is composed of 101 x 101 elements and the diagonal corresponds to the sea level variance, temperature and salinity variances at each level that is considered to be the background error. The colorbar is proportional to the background error variance.

2.1 Estimation of the observational error correlation matrix

It is well known that the background and observational error matrices are not completely independent and that the observational error is dominated by representativeness errors. Desrozier's relation (Desrozier *et al.*, 2005) indicates a semi-empirical algorithm to calculate an optimal balance between the background error, **B**, the observational error **R** and the expected variance of the misfits, $\mathbf{E}(d^{o}_{b}\ d^{OT}_{b})$

$$\mathbf{E}\left(d_b^o d_b^{OT}\right) = \mathbf{R} + \alpha \mathbf{HBH}^T \qquad \text{Eq 5}$$

In Eq. 5, The α coefficient in Eq. 5 is an empirical coefficient and different choices can be tried tested on the basis of sensitivity experiments that gave as best guess the value of 0.5. In this way we are implicitly stating that model and observation errors contribute equally to the analysis error. Once the value of α is decided and the expected variance of misfit is calculated from the reanalysis data, we estimate R as a function of the depth and time (the months). We consider **R** to be uniform in horizontal because of the lack of sufficient data to detect grid point changes in **R**.

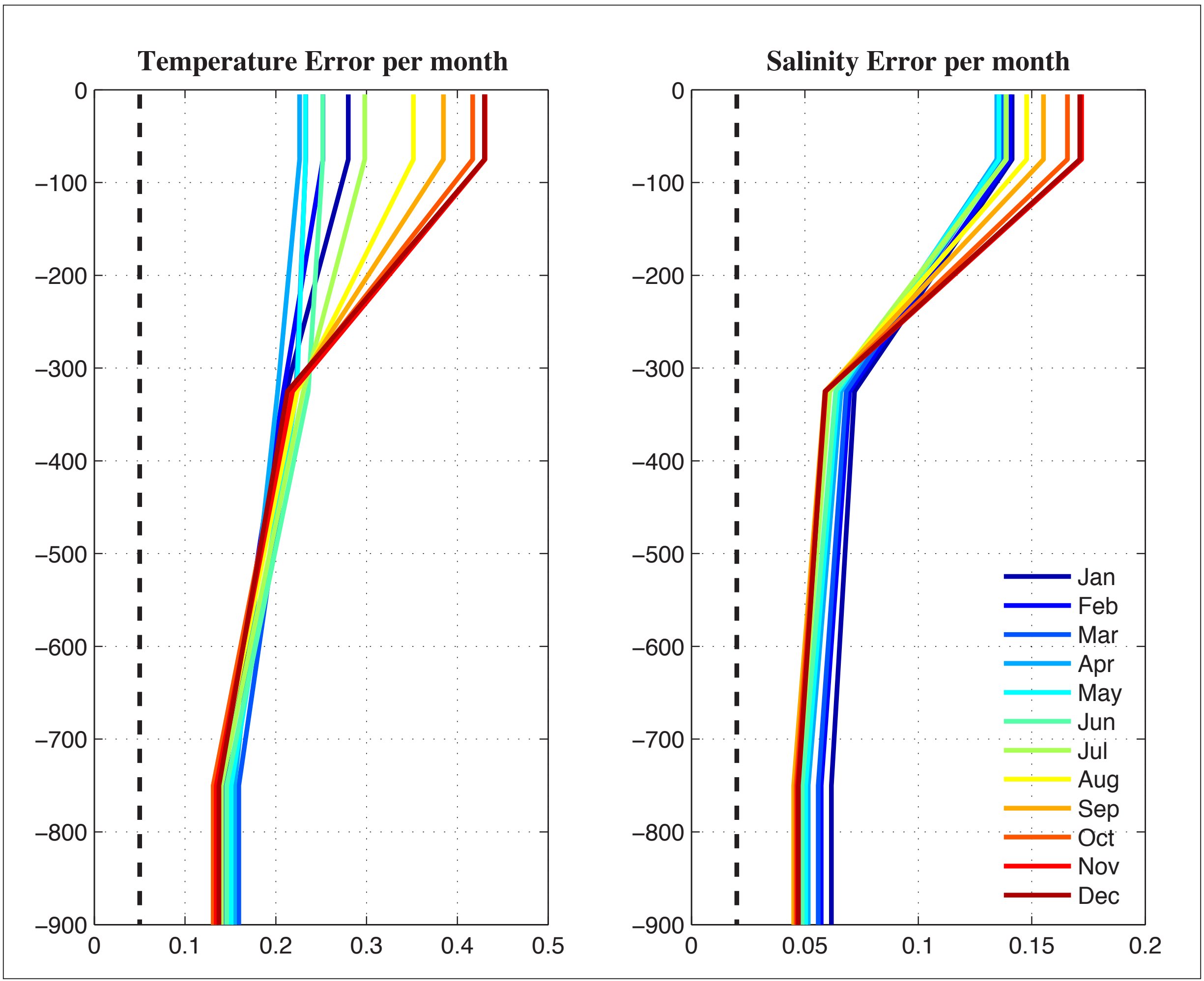

Fig. 2. Observational vertical error profiles for temperature (left panel, [°C]) and salinity (right panel, [PSU]) estimated using Eq. . Black dotted line was is the constant value set for EAS0, while the full continuous coloured lines represent profiles stand for the vertical error profiles varying according for each the month. The vertical axis represents the depth expressed in m.

3. Sea level anomaly data assimilation sensitivity experiments

Along track sea level anomalies have been assimilated together with the *in situ* salinity and temperature data in the MFS systems EAS0 and EAS1 for a sensitivity test of one year period (from the 1st May 2014 to 30th April 2015) and results are shown in Fig. 3 in terms of weekly Root Mean Square (RMS) of misfits over the entire Mediterranean Sea. The grid point **B** and the variable **R** structure (in EAS1 experiment) improve the RMS misfit of about 0.3cm, i.e. 10% of the average RMS misfit. On the other hand, the RMS misfit for temperature and salinity (evaluated but not shown here) highlights that EAS1 has an enhanced skill in representing the salinity below the mixed layer depth, while temperature performance in the two systems is similar.

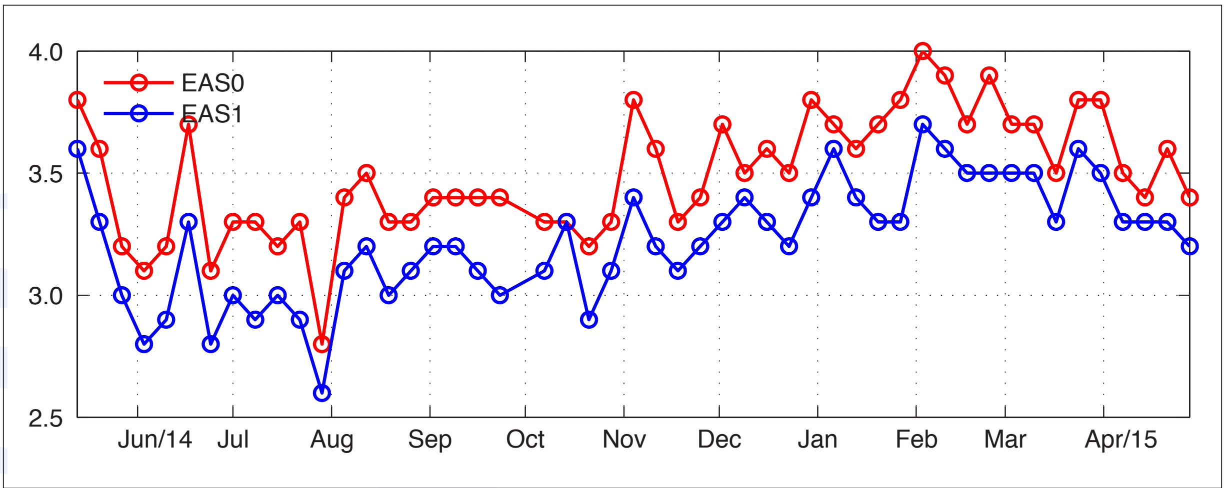

Fig. 3. The weekly RMS of SLA misfits (background-observation) for the assimilation experiment using regional EOF, EAS0 (red line), and the one using the new grid point EOFs (blue line) during the testing period: 1st May 2014 to 30th April 2015. All values are expressed in cm.

4. Conclusions

A new background error covariance matrix has been evaluated to improve the assimilation scheme of the MFS numerical ocean prediction system in the Mediterranean Sea in the framework of the CMEMS Med-MFC. The upgraded system takes into consideration monthly mean values and water mass variability at each grid point of the model domain. In addition, a new observational error matrix has been computed that is vertically and monthly varying, accounting for different representativeness of the *in situ* dataset. Based on one-year sensitivity experiments, the improved assimilation scheme has proved to increase the predicted SLA skill by reducing the RMS misfit of the order of 10% considering an average error of about 3cm.

We are currently investigating the application of the same methodology to a new version of the modelling system with increased resolution of 1/24 degree in horizontal and 141 vertical levels.

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