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Data assimilation of temperature and salinity profiles in the Adriatic Sea regional model

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Temperature and salinity data collected during the October 2002 - October 2003 period have been assimilated into a version of the Princeton Ocean Model implemented over the entire Adriatic Sea. The scheme used is SOFA (System for Ocean Forecast and Analysis, DE MEY & BENKIRAN, 2002) and this is the first coastal application of this scheme. The CTD data were collected in 4 coastal areas (Emilia-Romagna coastal strip, the Gulf of Trieste, the Rovinj and Pelješac-Vis-Drvenik coastal strips) while temperature profiles were acquired with XBT in the southern Adriatic Sea deep ocean areas. The analysis skill scores are examined in order to evaluate the assimilation performance. The results of the assimilation are first compared with independent analyses of satellite Sea Surface Temperature (SST) and it is found that assimilation of profiles improves the SST model estimate. Furthermore, the Root Mean Square (RMS) difference between model and temperature and salinity profiles before data insertion is analysed. The range of RMS temperature error is less than 1 ^{0}C for the entire area and decreases with time, indicating a positive impact of the assimilation. The RMS of salinity is less than 1 psu and it also shows a decreasing trend during the assimilation period.

Key words: data assimilation, Adriatic Sea, optimal interpolation

INTRODUCTION

The ADRIatic sea integrated COastal areaS and river basin Management system Pilot Project (ADRICOSM) implemented, for the first time, components of a forecasting-analysis system for the Adriatic Sea (CASTELLARI *et al.*, 2006). On the basis of the Mediterranean Forecasting System (MFS) experience (PINARDI *et al.*, 2003), forecasting activities have been demonstrated to also be applicable in this critical shelf area (ODDO *et al.*, 2006). An important aim of the project was to develop a data assimilation scheme for the coastal and large scale data collected in Near Real Time (NRT) in order to produce sequential estimates of the state of the ocean and prepare initial fields for forecasts.

Data assimilation methods produce best estimates of the state of the physical system, given observations and a prognostic model.

Over the past few decades many data assimilation methods have been developed for the atmosphere and the ocean based on Kalman Filter, Adjoint Variational Methods and Optimal Interpolation (OI) (EVENSEN 2003; CARTON & HACKERT, 1989; DERBER & ROSATI, 1989). In this study we used an OI scheme called SOFA (System for Ocean Forecasting and Analysis, DE MEY & BENKIRAN, 2002) where observations are assimilated into the model at the exact time they are available (DALEY, 1991), closely following a previous application of the same method in the Mediterranean Sea (DEMIROV *et al.*, 2003).

The Adriatic Sea is a regional sub-basin of the Mediterranean Sea where intense and complicated processes can occur such as deep water formation, convection and spreading. The convection in the Adriatic Sea is localized: a) in the northern Adriatic due to intense surface cooling (VILIBIĆ, 2003), with water sinking along the continental shelf and b) in the southern Adriatic due to open sea-like vertical convection (ARTEGIANI *et al.,* 1997a, 1997b). The circulation in the basin is characterized by three cyclonic gyres: the North-Adriatic Gyre (observed only in autumn), the Middle-Adriatic Gyre (observed in spring, summer and autumn), the South-Adriatic Gyre (observed in summer and autumn), and two shelf-coastal currents: one on the eastern coast from the Otranto Strait to the northern Adriatic and the other one on the western coast from the north Adriatic to the south Adriatic, which is particularly affected by the Po River run off (ZAVATARELLI & PINARDI, 2003). Thus the Adriatic Sea contains both open ocean and shelf processes with a strong interaction between them.

For the first time, data assimilation is tried for both large scale and coastal data sets in order to produce optimal estimates of the state of the ocean. Temperature and salinity profiles were collected during the October 2002-October 2003 period in several Adriatic coastal areas and in the deep southern Adriatic open ocean areas. The assimilation system is the one normally used in open ocean estimation problems and we try to show here that it can work also in both open ocean and coastal areas. This system will be used in the future to augment the quality of initial conditions for the daily forecasts that have started to be produced during the project (ODDO *et al*., 2006).

The paper is organized as follows. In the second section we describe the components of the data assimilation system in the Adriatic Sea. Results from the data assimilation analysis are discussed in the third section and conclusions are presented in fourth section.

MATERIALS AND METHODS

The Data Assimilation System used in the ADRICOSM project is based on three components: an Ocean General Circulation Model (OGCM), an observing system (composed of networks collecting temperature and salinity profiles), and SOFA.

The numerical model

The OGCM is based on the POM code (Princeton Ocean Model, BLUMBERG & MELLOR, 1987) which has been implemented in the Adriatic Sea by ZAVATARELLI & PINARDI (2003) and ODDO *et al*. (2005). The model has 5 km resolution and 21 sigma layers in the vertical with the minimum depth set to 10 m (Fig. 1). The lateral open boundary conditions are nested within the Mediterranean OGCM, which is now operational (PINARDI *et al*., 2003). The interface between the Mediterranean and the Adriatic Sea model is accomplished with a one-way nesting method (ODDO & PINARDI, submitted). The atmospheric forcing is provided by the European Centre for Medium-Range Weather Forecasts (ECMWF) 6 hour surface fields that are converted into heat, water and momentum fluxes with interactive bulk formulas (ODDO *et al*., 2006). The Po River runoff uses daily flow rates while all the other rivers have monthly mean runoff values.

The observing system

The ADRICOSM observing system is composed of two parts: one for the open ocean, encompassing the southern Adriatic deep regions, and the second one focusing on the shelf/coastal areas. The time resolution of the two observing

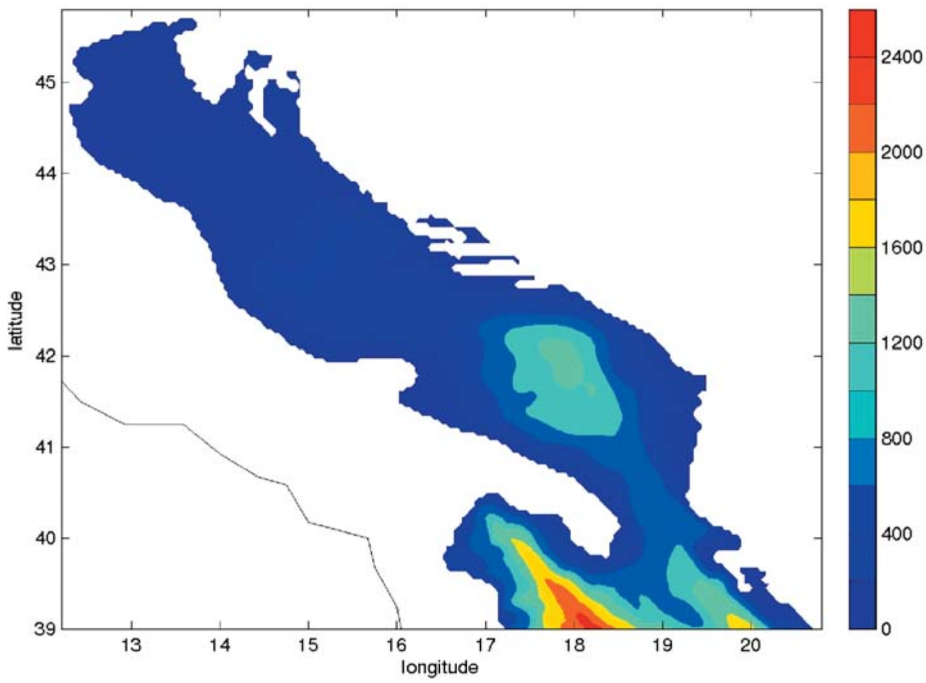


Fig. 1. Bathymetry of the Adriatic Sea used in the numerical model (depths are in meters)

components is quite different: the deep ocean network is done on monthly time scales while the shelf on a weekly scale. In this way both datasets try to take into account the variability of the deep and coastal parts of the basin.

The deep basin monitoring system in the southern Adriatic is composed of eXpendable Bathy-Thermographs (XBT) deployed on Voluntary Observing Ships (VOS) tracks (Fig. 2a). Temperature profiles down to 700 m depth were collected along two VOS tracks with an along-track spatial resolution of 12 nm. Adria-VOS-1 is a transect between Ploče and Malta while Adria-VOS-2 is between Dubrovnik and Bari, repeated twice a month from October 2002 to October 2003.

The ADRICOSM shelf scale observing network is localized in 4 different coastal regions: the Emilia-Romagna coastal strip, the Gulf of Trieste, the Rovinj and Pelješac-Vis-Drvenik coastal strips. In these regions, transects of temperature and salinity (measured by Condutcivity-Temperature-Density instruments, CTD) were carried out and the data were transmitted in near real time. The spatial resolution of the data is of the order of 10 km. In Fig. 2b, the exact locations of the CTD network are shown.

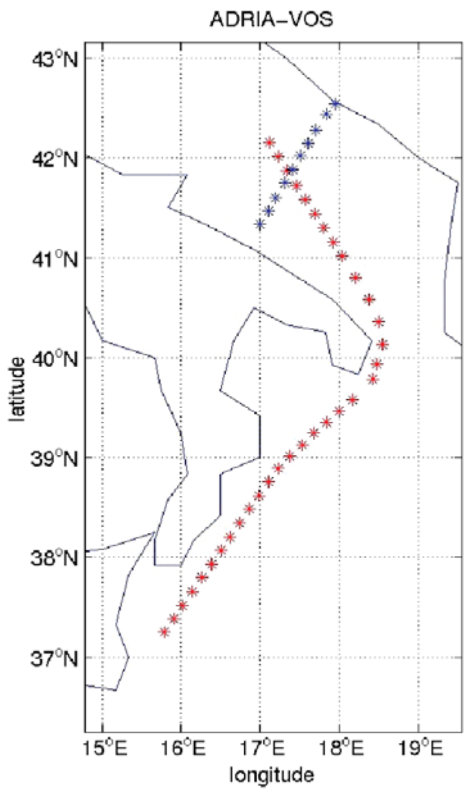


Fig. 2a. ADRIA-VOS 1 (red dots) and ADRIA-VOS 2 (blue dots) tracks. Dots indicate the approximate locations of XBT casts with nominal spatial resolution of 12 nm

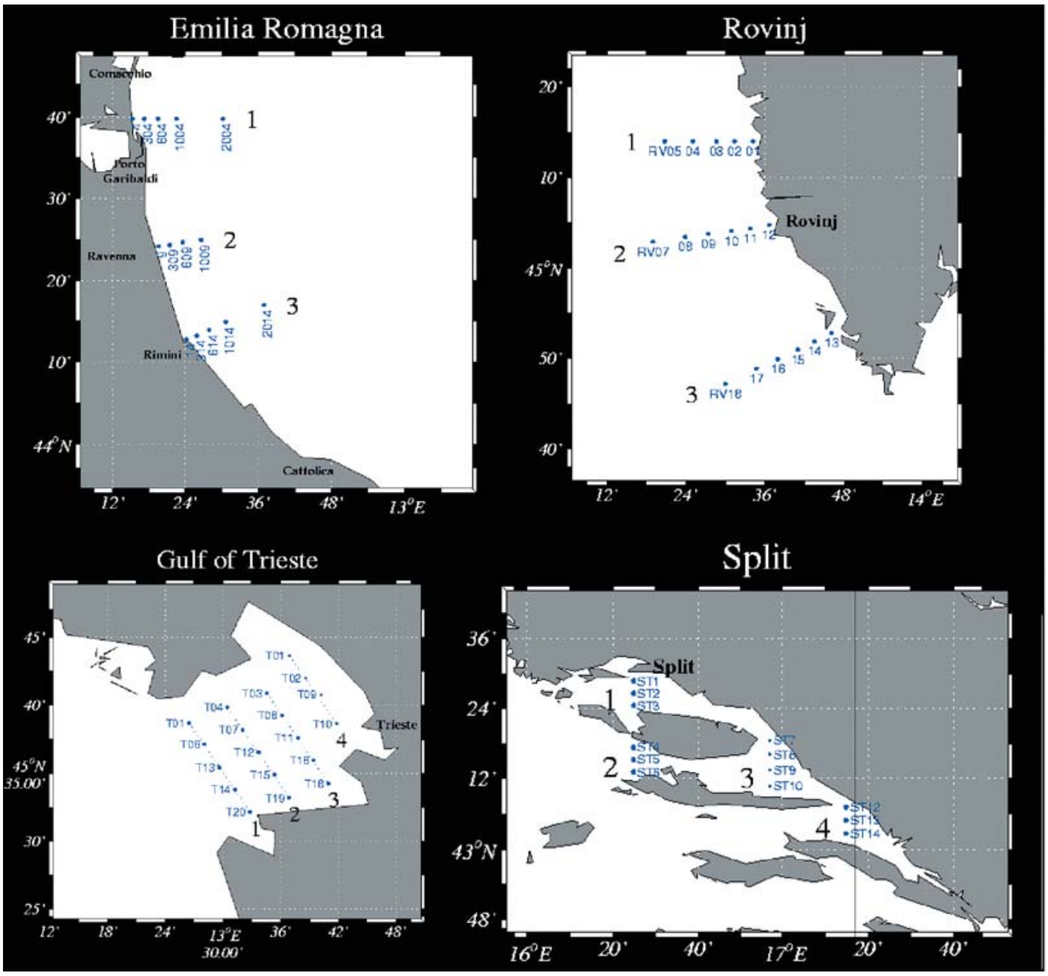


Fig. 2b. Coastal monitoring system in the 4 target regions of the Adriatic Sea (Emilia-Romagna and Rovinj coastal strips, Gulf of Trieste and Pelješac-Vis-Drvenik coastal strip). Dots indicate the CTD stations nominal positions

The coastal data sets were available in near real time from the central data dissemination centre for ADRICOSM. The CTD data were interpolated in the vertical on a reference grid which is composed of 22 levels located at different depths (1 m, 2 m, 3 m, 4 m, 5 m, 6 m, 7 m, 8 m, 9 m, 10 m, 15 m, 20 m, 25 m, 30 m, 40 m, 50 m, 60 m, 70 m, 80 m, 90 m, 100 m and 125 m). The deepest levels are chosen because the coastal network of the Split area has stations deeper than the other coastal networks. The interpolated data are used in the data assimilation procedure.

The XBT temperature profiles were pre-processed in order to remove spikes following the procedure established within the MFS project (MANZELLA *et al.*, 2003). After this pre-processing the XBT data were interpolated to the levels of the Mediterranean Ocean Model (5 m, 15 m, 30 m, 50 m, 70 m, 90 m, 120 m, 160 m, 200 m, 240 m, 280 m, 320 m, 360 m, 400 m, 440 m, 480 m) before they were used in the assimilation system.

The data assimilation system

The data assimilation scheme

In this study the SOFA type of data assimilation was applied, specifically multivariate Reduced-Order Optimal Interpolation method (DE MEY & BENKIRAN, 2002). This system combines the model fields with the observations at the time and location that they were available and produces an analysis every week.

SOFA was initially implemented by DEMIROV *et al.* (2003) for the Mediterranean OGCM. In ADRICOSM the innovative part of this system is the assimilation of CTD data in coastal areas and the use of a sigma layer model.

Following IDE *et al.* (1997) and notation for the Extended Kalman Filter (EKF, GELB, 1974), we consider that the observations $\mathbf{y}^O$ are linked to the true state $\mathbf{x}^t$ by the stochastic equation

$$\mathbf{y}^O = H(\mathbf{x}^t(t)) + \varepsilon \tag{1}$$

where H is the non-linear observation operator and ε is the observation noise process which is assumed to have a covariance matrix $\mathbf{R}$. Thus $\mathbf{y}^O$ is an estimate of the true state. Another estimate of the true state of the ocean is given by the numerical model $\mathbf{M}$ that is used to produce a forecast state vector $\mathbf{x}^f$ at successive time steps, i.e.:

$$\mathbf{x}^f(t+dt) = \mathbf{M}(\mathbf{x}^a(t)) \tag{2}$$

where $\mathbf{x}^a$ is the analyzed estimate and dt is the model time step. The analyzed state of the system at time $t+dt$ (also called analysis) is given by

$$\mathbf{x}^a(t+dt) = \mathbf{x}^f(t+dt) + \mathbf{K}(\mathbf{y}^O - H(\mathbf{x}^f)) \tag{3}$$

where $\mathbf{K}$ is the Kalman Gain and $(\mathbf{y}^O - H(\mathbf{x}^f))$ is the misfit. The Kalman gain for Optimal Interpolation is formally written as

$$\mathbf{K}^{OI} = \mathbf{B}^f\,\mathbf{H}^T(\mathbf{H}^T\mathbf{B}^f\mathbf{H}^T + \mathbf{R})^{-1} \tag{4}$$

where the observational operator $\mathbf{H}$ is now a tangent linear observational operator. The OI is a particular EKF where the Kalman gain is approximated by a specific background error covariance matrix $\mathbf{B}^f$. The simplification of the background error covariance is one of the major issues in atmospheric and oceanic data assimilation. One solution was found by introducing the Empirical Orthogonal Functions (EOFs) and a separation between the vertical and horizontal structure of $\mathbf{B}^f$. Because the background error covariance matrix $\mathbf{B}^f$ is defined as positive and symmetric it can be decomposed in eigenvalues and eigenvectors, i.e.:

$$\mathbf{B}^f = \mathbf{V}\,\Delta\,\mathbf{V}^T \tag{5}$$

where $\mathbf{V}$ is the matrix whose column are 3-D eigenvectors (3-D EOFs) of $\mathbf{B}^f$ and Δ is a diagonal matrix whose diagonal elements are the eigenvalues. The use of EOFs in atmospheric and oceanographic studies allows the reduction of the dimensionality of the problem, i.e., to reduce the order to the assimilation problem.

For the ocean case, it has been shown that the ocean large scale state variables can be separated into vertical and horizontal modes. DE MEY & BENKIRAN (2002) wrote the covariance model error matrix as

$$\mathbf{B}^f = \mathbf{S}^T\,\mathbf{B}_r^f\,\mathbf{S} \tag{6}$$

where $\mathbf{S}$ is a matrix containing only vertical multivariate eigenvectors or v-EOFs and $\mathbf{B}_r$ contains the eigenvalues and the horizontal covariance structures associated with each v-EOF. This special decomposition can make $\mathbf{B}^f$ singular since (6) is not a perfect equality.

The detailed explanation of the background error covariance matrix decomposition for SOFA can be found in DE MEY & BENKIRAN (2002). The Kalman Gain re-written with (6) is:

$$\mathbf{K}^{OI} = \mathbf{S}^T\mathbf{B}_r^f\,\mathbf{H}_r^T(\mathbf{H}_r^T\mathbf{B}_r^f\,\mathbf{H}_r^T + \mathbf{R}_r)^{-1} \tag{7}$$

where $\mathbf{H}_r = \mathbf{HS}$ is the tangent linear observation operator projected onto the vertical modes and $\mathbf{R}_r$ is the reduced order observational error covariance matrix referred to the vertical modes. The order reduction of the scheme is reached by choosing only a limited number of vertical modes in $\mathbf{S}$, which we now indicate with $\widetilde{\mathbf{S}}$. This is allowed because in the ocean the representative vertical modes are fewer than the number of vertical levels chosen for the numerical model. The ocean is "low order" in the vertical and this allows the order reduction. Then, the reduced order $\mathbf{K}^{OI}$ is

$$\mathbf{K}^{ROOI} = \widetilde{\mathbf{S}}^{-1}\,\mathbf{B}_r^f\,\widetilde{\mathbf{H}}_r^T(\widetilde{\mathbf{H}}^T\,\mathbf{B}_r^f\,\widetilde{\mathbf{H}}^T + \mathbf{R}_r^*)^{-1} \tag{8}$$

and the analysis is

$$\mathbf{x}^a = \mathbf{x}^f + \mathbf{K}^{ROOI}(\mathbf{y}^O - H(\mathbf{x}^f)) \tag{9}$$

The order reduction procedure defined above considers the vertical error covariance matrix $\widetilde{S}$ with a limited number of vertical EOFs, considered as 10 for the Mediterranean Sea open ocean (SPARNOCCHIA *et al.*, 2003) and considered appropriated for the Adriatic Sea open ocean areas as well. In our case the EOFs are bi-variate i.e. they consider only the covariance between the *T* and *S* error fields, so that the corrected or analyzed fields are always *T* and *S*.

We apply (9) in a transformed space where the model and the observations are interpolated. This allows us to use v-EOF that is computed in physical space (see section later). This pre-processing does not affect the general results of the assimilation scheme. We proceed as follows:

1) interpolate the $\mathbf{x}^f$ onto a reference vertical interpolation grid in *z*-space from σ-layers;
2) interpolate the observations to the same reference vertical interpolation grid;
3) use H_r to interpolate spatially the model grid point to the observational point.

In other words the analysis step is done in *z*-space and both $\mathbf{y}^O$ and $\mathbf{x}^f$ are first interpolated on "reference analysis *z*-grids" (Fig. 3). The correction or analysis cycle is then carried out and the analysed fields $\mathbf{x}^a$ are interpolated back to σ-levels only in the region where the correction is done trying to reduce the noise due to interpolation between the two vertical grids.

Multivariate vertical EOFs

The choice of v-EOFs is crucial for the analysis step since they compose the error covariance matrix written in (6). As said before, our v-EOFs consider only the *T,S* error correlations, i.e., they consider the error associated with the water mass variability.

The bivariate v-EOFs isolate the primary mode of combined variance of temperature and salinity profiles (SPARNOCCHIA *et al*., 2003; GAVART & DE MEY, 1997). The procedure to calculate them is as follows. The generic *T* and *S* profiles are transformed into a state vector **X**

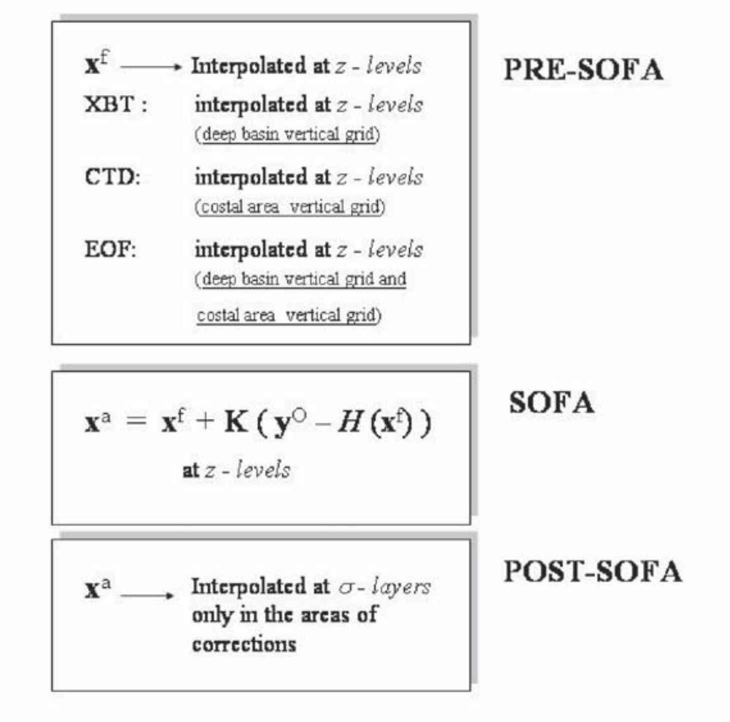


Fig. 3. Schematic of a three step scheme to implement SOFA in the open ocean and coastal areas of the Adriatic Sea. In the PRE-SOFA step the model, the v-EOFs (see text) and the observational data sets are interpolated on a reference z-grid where the assimilation is carried out. The reference vertical interpolation grid is different in the 7 regions of Fig. 4. In the SOFA step the analysis $\mathbf{x}^a$ *is calculated by using the reduced order Kalman filter gain given in equations (8) and (9) in the text. In the POST-SOFA step the analysis* $\mathbf{x}^a$ *is interpolated back to the model s-layers considering only the areas with non zero corrections of T and S fields*

containing (j) realisations of the 2 state variables at M levels:

$$\mathbf{X} = [x^{(j)}_1, \ldots, x^{(j)}_k, \ldots, x^{(j)}_M, \ldots, x^{(j)}_{M+k}, \ldots, x^{(j)}_{2M}] = \left[\frac{\delta T^{(J)}_1}{\sigma^T_1}, \ldots, \frac{\delta T^{(J)}_M}{\sigma^T_M}, \frac{\delta S^{(J)}_1}{\sigma^S_1}, \ldots, \frac{\delta S^{(J)}_M}{\sigma^S_M}\right] \quad (10)$$

where $\delta T^{(J)}_k = (T^{(J)}_k - T_{clim})$ and $\delta S^{(J)}_k = (S^{(J)}_k - S_{clim})$, with $k = 1, \ldots, M$, are the profile departures from the model climatology at each vertical level. The (j) realisations are offered by the number of daily model field values available each season and the number of grid points in each region. These quantities are normalized by the standard deviation from the model climatology σ^T_k and σ^S_k

$$\sigma^T_k = \sqrt{\frac{1}{n}\sum_{j=1}^{n}(T_{kj} - T_{\mathrm{clim}})^2}, \quad \text{and}$$

$$\sigma^S_k = \sqrt{\frac{1}{n}\sum_{j=1}^{n}(S_{kj} - S_{\mathrm{clim}})^2}, \; k = 1, \ldots, M \quad (11)$$

where n is the number of model vertical profiles in each region, for the given averaging time. The v-EOFs are the eigenvectors of the vertical covariance matrix, i.e.:

$$\mathbf{XX}^{\mathrm{T}} = \mathbf{S}^{\mathrm{T}}\mathbf{OS} \quad (12)$$

where O is a diagonal matrix containing the v-EOF eigenvalues.

We identified 7 regions in the Adriatic Sea where different vertical EOFs were calculated (Fig. 4). Region 1 is the region where there are no data, thus no T and S corrections are calculated. The 4 coastal areas (region 2, 3, 4 and 7) have been chosen taking into account the availability of the CTD data collected during the project. Region 5 and 6 are the XBT data regions.

The v-EOFs are calculated from two different data sets: the first one is a long time series of model simulation profiles and the second is based on historical XBT data, already calculat-

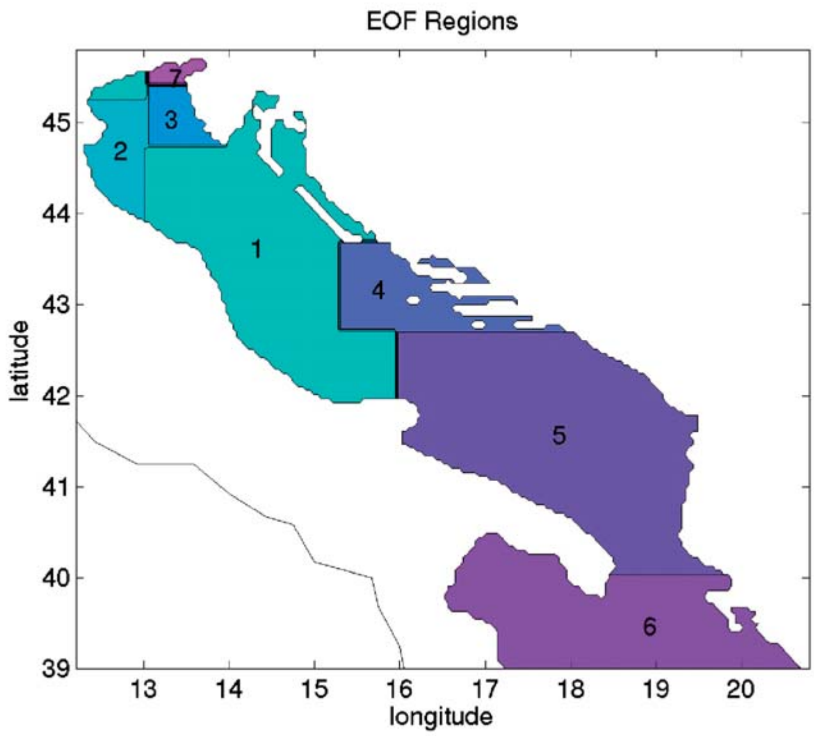


Fig. 4. The 7 regions where the EOFs and the reference interpolation grid for the assimilation are shown. In region 1 no assimilation is actually carried out because there are no data. In regions 2, 3, 4 and 7 the data assimilation utilizes different model-calculated v-EOFs and a coastal area reference vertical grid. In regions 5 and 6 the data assimilation utilizes the Mediterranean Forecasting System v-EOFs (DEMIROV et al., 2003) and a deep basin reference vertical grid

ed by SPARNOCCHIA *et al.* (2003). The former data base is used for the coastal areas while the latter is used for the open ocean areas of the southern Adriatic.

For the coastal areas the v-EOFs are calculated from the model simulation as departures of the *T* and *S* profiles from the model seasonal climatology. They are computed as a time and regional space ensemble average. The time variability of the v-EOF is seasonal, i.e., we compute a different set of EOFs for each season and coastal region. The Adriatic Sea seasons are considered following ARTEGIANI *et al.* (1997a): winter (January-February-March-April), spring (May-June), summer (July-August-September-October), autumn (November-December). In the coastal areas, the bi-variate vertical EOFs are calculated on a reference vertical grid different from the open ocean deep areas. Each region has a different mean depth so that we consider a different number of levels in each region.

For the deep parts of the Adriatic basin the seasonal vertical EOFs are the same as the MFS data assimilation system. SPARNOCCHIA *et al.* (2003) demonstrated that for the Mediterranean open ocean areas 10 v-EOF modes were sufficient to properly represent the vertical correlation matrix. On the other hand it has been demonstrated that the first modes take into account the largest Percentage of Explained Variance

$$PEV = \frac{100\lambda_i}{\sum_{k=1}^{M}\lambda_k}$$

where λ_i is the eigenvalue relative to the eigenvectors contained in **S**. Table 1 and Table 2 show the PEV for each eigenvector calculated in regions 2 and 7, with the first 4 modes accounting for the largest variance in the water column in spring and autumn with similar results occurring in winter and summer and in the other coastal areas. Fig. 5 shows the v-EOF calculated for the four seasons in region 2 and 7, respectively. They show a low modal structure in the vertical and the zero crossing is present only at mode 3.

Table 1. The eigenvalues λ, the percentage of the explained variance(PEV) and the standard deviation σ^T and σ^S of the first 10 modes of the vertical EOFs in region 2 in autumn

Mode	λ	PEV %	σ^T (°C)	σ^S (psu)
1	15.4253	50.9586	3.1169	0.6583
2	11.8880	39.2729	3.1140	0.6096
3	2.6014	8.5940	3.1098	0.5679
4	0.2564	0.8470	3.1017	0.5365
5	0.0655	0.2165	3.0882	0.5137
6	0.0192	0.0633	3.0689	0.4987
7	0.0085	0.0279	3.0426	0.4889
8	0.0032	0.0105	3.0113	0.4825
9	0.0012	0.0039	2.9758	0.4771
10	0.0010	0.0032	2.9358	0.4709

Table 2. The eigenvalues λ, the percentage of the explained variance(PEV) and the standard deviation σ^T and σ^S of the first 10 modes of the vertical EOFs in region 7 in spring

Model	λ	PEV %	σ^T (°C)	σ^S (psu)
1	15.7446	65.2422	2.7655	0.6833
2	8.0182	33.2257	2.7229	0.6702
3	0.2413	1.0001	2.7097	0.6626
4	0.0884	0.3664	2.7145	0.6590
5	0.0227	0.0943	2.7270	0.6575
6	0.0103	0.0429	2.7407	0.6566
7	0.0046	0.0190	2.7531	0.6548
8	0.0013	0.0052	2.7627	0.6515
9	0.0006	0.0025	2.7681	0.6463
10	0.0003	0.0012	2.7678	0.6386

The analysis cycle in the Adriatic Sea

The analysis cycle in the Adriatic Sea is shown in Fig. 6. Each Wednesday (day *J*) an analysis is carried out by assimilating the XBT T profiles and the CTD T, S profiles available during the 14-day period centred at day *J* (from day *J-7* up to day *J+7*). Dur-

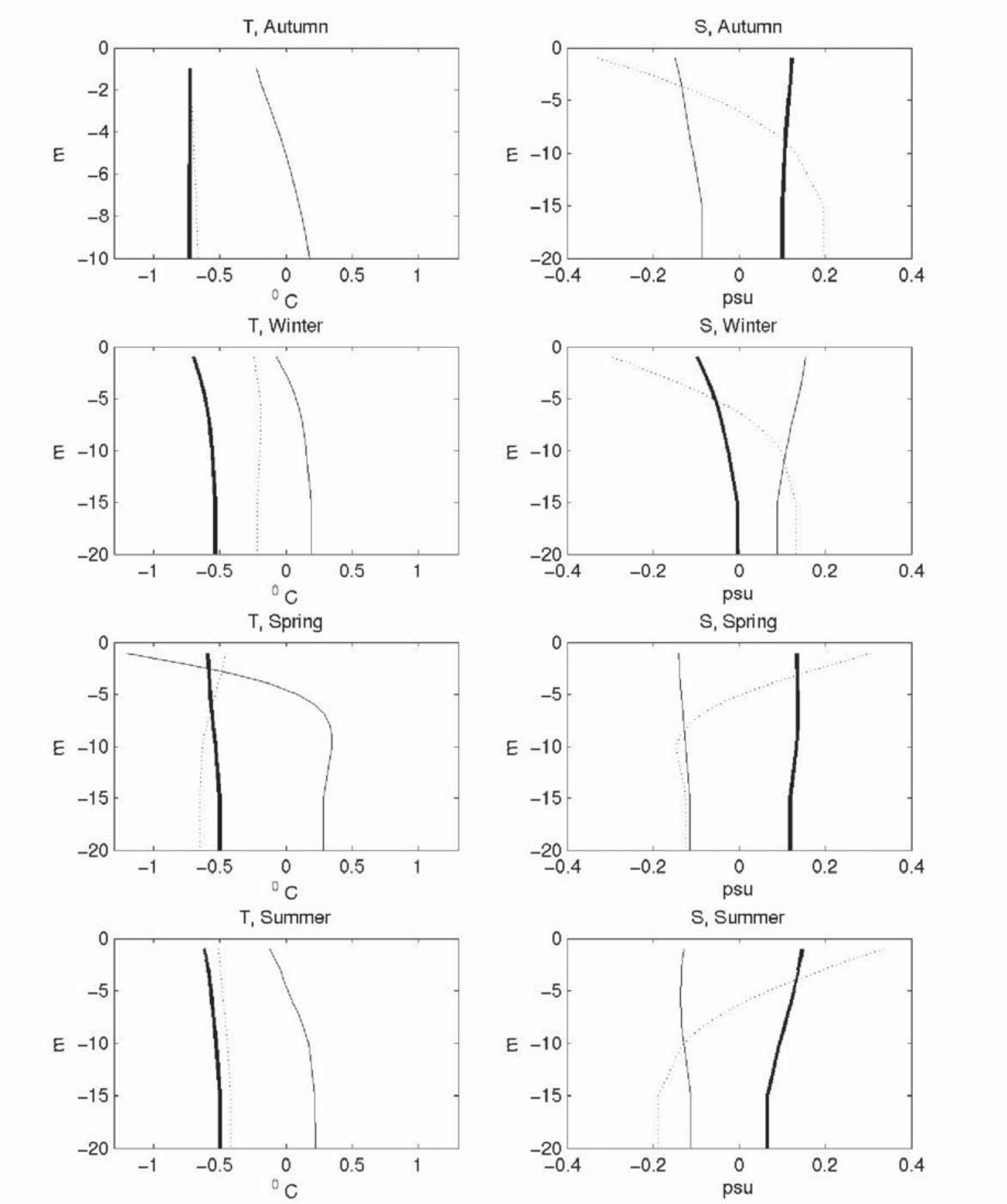


Fig. 5. First 3 v-EOF modes (thick line: first mode, black line: second mode, dotted line: third mode) for temperature and salinity in region 7 calculated for the four seasons (indicated at the top of the respective panels)

ing the assimilation the model is forced by the ECMWF fields and the lateral boundary conditions provided by the Mediterranean OGCM. The update is done only once at day J but the misfits are calculated at the precise time each observation is taken.

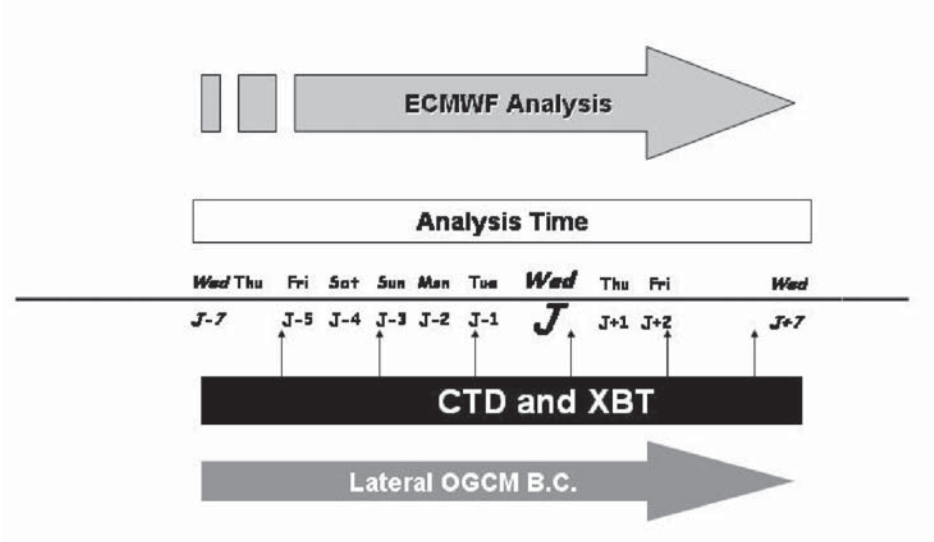


Fig. 6. The analysis cycle in the Adriatic Sea: each Wednesday (day J) an analysis is computed by assimilating the XBT T profiles and the CTD T, S profiles collected during plus or minus 7 days around the central analysis day. The model runs using the forcing provided by the ECMWF (European Centre for Medium-Range Weather Forecasts) analyses and the lateral boundary conditions (b. c.) are provided by the Mediterranean OGCM (Ocean General Circulation Model)

RESULTS AND DISCUSSION

In this section we show the results of the assimilation of *in situ* data from October 2002 until October 2003, the Targeted Operational Period of the project. We discuss the validation of the analyses to point out the quality of the assimilated fields.

The approach for the validation of the analysis follows the work of DEMIROV *et al*. (2003) and MURPHY (1988). It consists of:

a) qualitative checks of the analysis against observations, so called Consistency, and

b) statistic indices, so called Accuracy tests.

Thereafter, the simulated fields (without assimilation) will be called SF while the assimilated or analysis fields, AF.

Consistency

Consistency checks were carried out by comparing the AF monthly mean Sea Surface Temperatures *(SST)* and monthly mean salinity AF with available independent data. For surface temperature we used the satellite *SST* values (SCIARRA *et al*., 2006) collected during the ADRICOSM project while for salinity the Med-Atlas climatology (MEDAR Group, 2002).

In Fig. 7 we show the qualitative comparison between the satellite monthly mean *SST* (Fig. 7A), and monthly mean AF *SST* during the winter months (Fig. 7B).

The model temperatures are in the expected range compared with the *SST* observations. However, in the northern Adriatic Sea and the southern Adriatic the AF temperatures are about 1-2 degrees warmer than the observed *SST*. In the Middle Adriatic Sea the AF *SST* does not present significant differences from the satellite *SST* (Fig. 7C).

In order to understand the effect of data assimilation we show the difference between the AF and SF (Fig. 7D). First of all, the AF *SST* are generally colder than the corresponding SF, thus closer to the satellite *SST* observations. The tongue of warm water coming from the Ionian into the Adriatic Sea is the most important. The extension of this tongue in the Adriatic basin is reduced in the AF of January 2003 in agreement with the satellite observations.

The second reference dataset comes from the climatological salinity fields of Med-Atlas

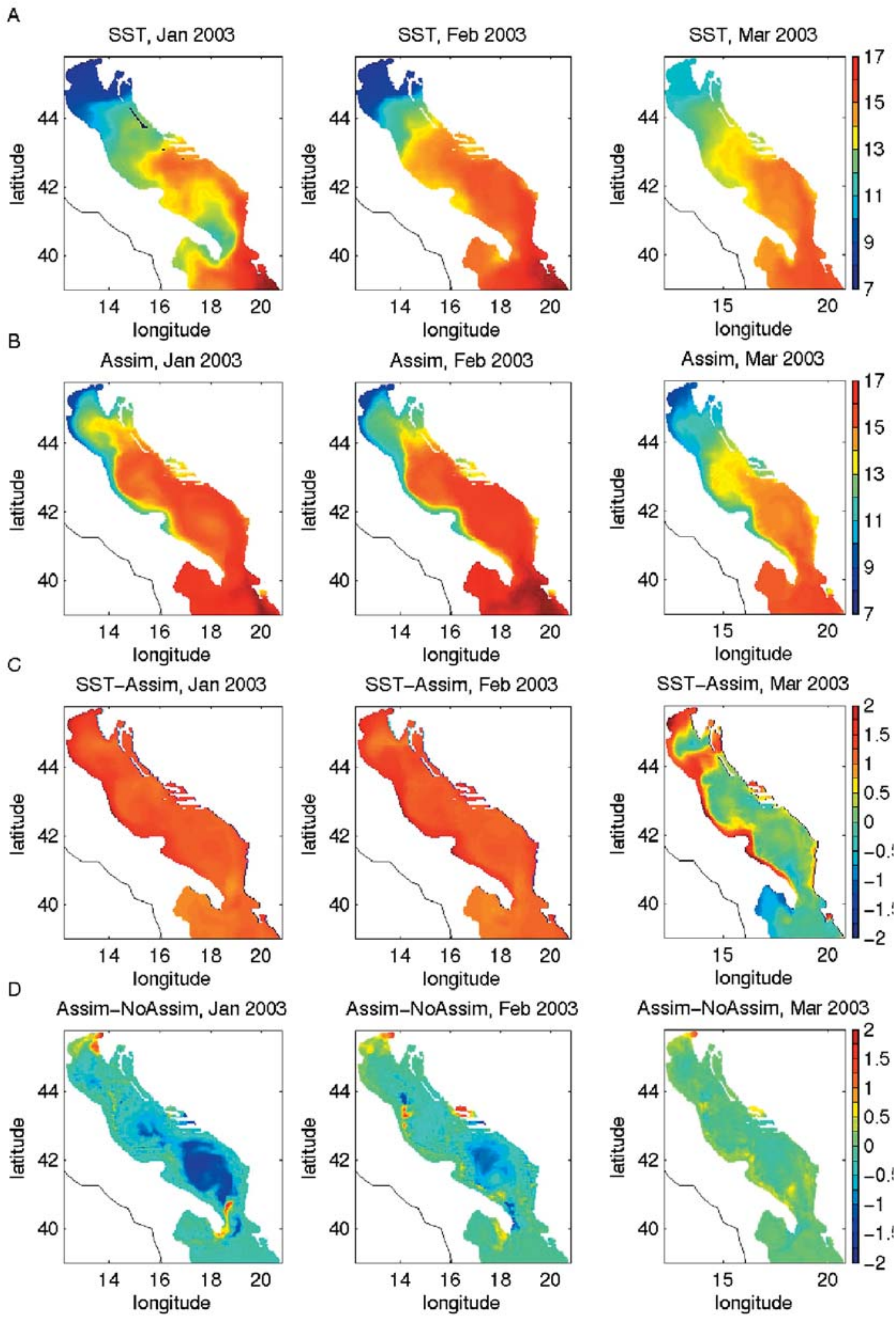


Fig. 7. Monthly mean Sea Surface Temperature (SST in °C) in winter 2003, for the months of January, February and March: (A) satellite SST from GOS.ISAC.CNR data centre for ADRICOSM, (B) SST analysis (AF), (C) difference between (A) and (B) and (D) difference between the AF and SF estimates (analysis and simulation fields)

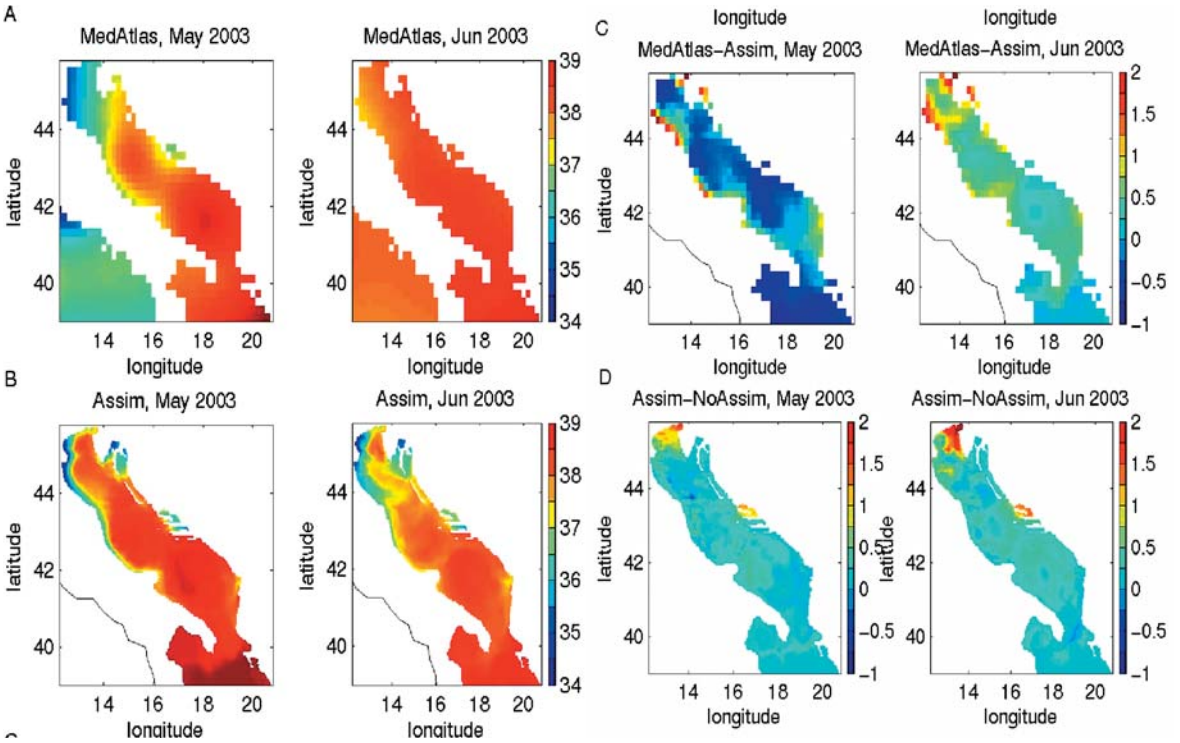
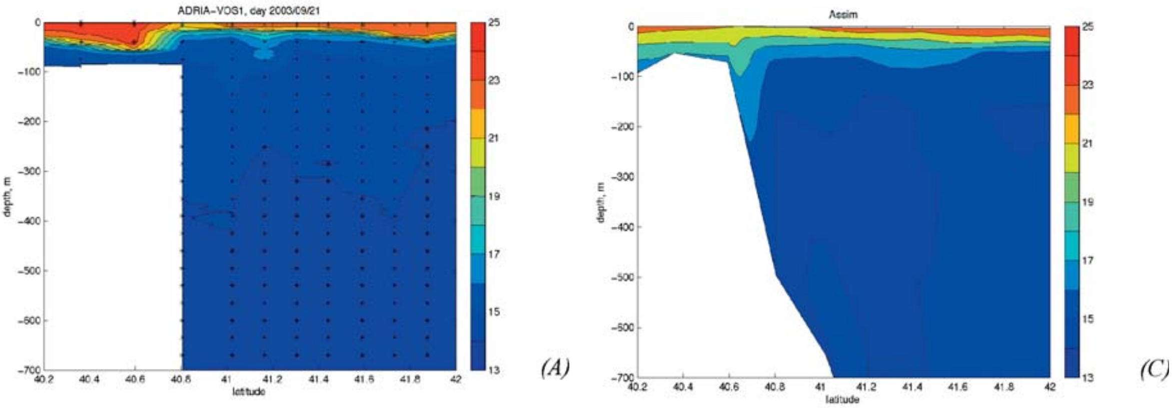


Fig. 8. Monthly mean salinity at 5 m depth (in psu) for May and June: A: MedAtlas climatological means for May and June, B: salinity AF for May and June 2003, C: difference between A and B and D: difference between B and SF salinity



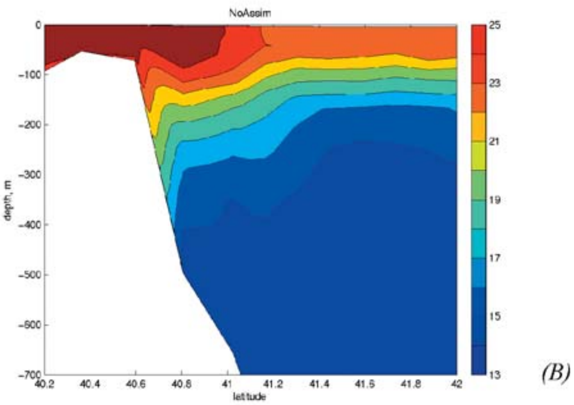


Fig. 9. A: Temperature section (in °C) on 21–09–2003 from the ADRIA-VOS 1 XBT data. The dots indicate the profile points interpolated to the reference grid and used for the assimilation. B: SF of temperature for the same section (in °C): model bottom topography is indicated by the white area. C: AF of temperature for the same section (in °C)

(MEDAR Group, 2002) (Fig. 8A). Spring and summer 2003 were highly atypical (Fig. 8C) with surface salinity in the Adriatic highly above the climatology. This means that climatology is not a good first guess for assimilation. Fig. 8D indicates the difference between the AF and SF with the major differences localized along the eastern coast of the Adriatic Sea. The AF surface salinity for the north-eastern Adriatic Sea is more saline than in the SF since the assimilation of CTD profiles in the Pelješac-Vis-Drvenik area have corrected the model SF.

Finally, a qualitative comparison between XBT data collected along the Adria-VOS track 1 (Fig. 2) and the AF is carried out to show the effect of the assimilation. This is not an independent data set but it shows the overall positive impact of the assimilation on the structures of the dynamical fields.

In Fig. 9A a summer snapshot for 21-09-2003 is presented. Fig. 9C shows the section with the AF and Fig. 9B shows the corresponding SF. Fig. 9B and Fig. 9C show important qualitative differences. The assimilation is capable of modifying the vertical extension of the thermocline in a substantial way as well as improving the deep temperature values.

The same qualitative analysis of the impact of the assimilation is shown here for the coastal data set. In Fig. 10a, 10b, 10c and 10d the profile before and after assimilation is shown together with the observed profile for regions 2, 3, 4 and 7 respectively. The profiles after assimilation are between the SF profiles and the observed data. This means that in the coastal areas the data assimilation system is capable of correcting the model, "bringing" the model closer to the observations.

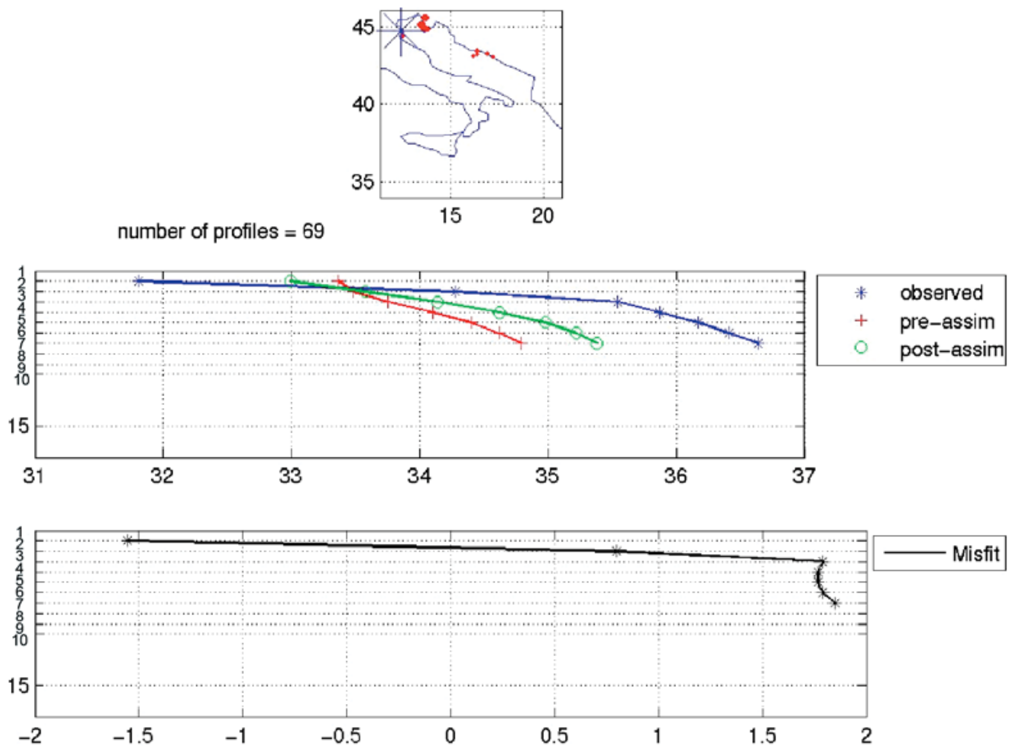


Fig. 10a. The upper panel shows the density of the data (red dots) available in the Adriatic Sea during the period 13 -27 May 2003 and the profile selected (blue star) in region 2 for 20 May 2003. The intermediate panel shows the observed S profile (blue), the SF for salinity (red) and the AF (green). Vertical and horizontal axes are depth (in metres) and salinity (in psu), respectively. The lower panel show the vertical salinity misfit, i.e. the difference between SF and the observed profile before assimilation on the same vertical axis as in the intermediate panel

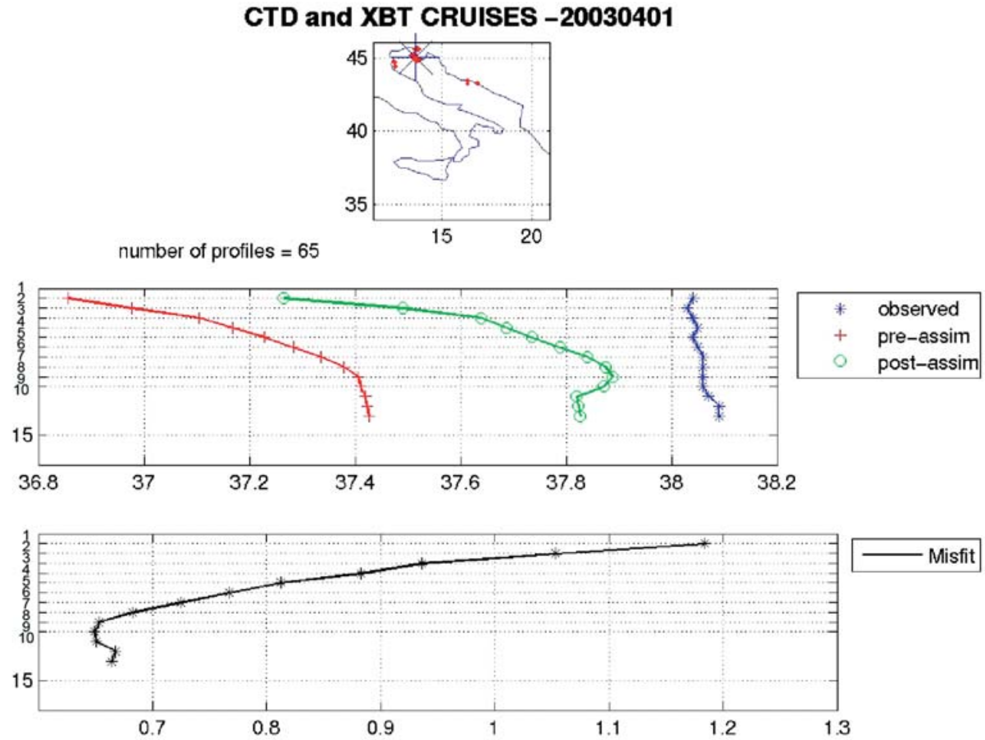


Fig. 10b. As in (a) but for a profile located in region 3 and for 1 April 2003

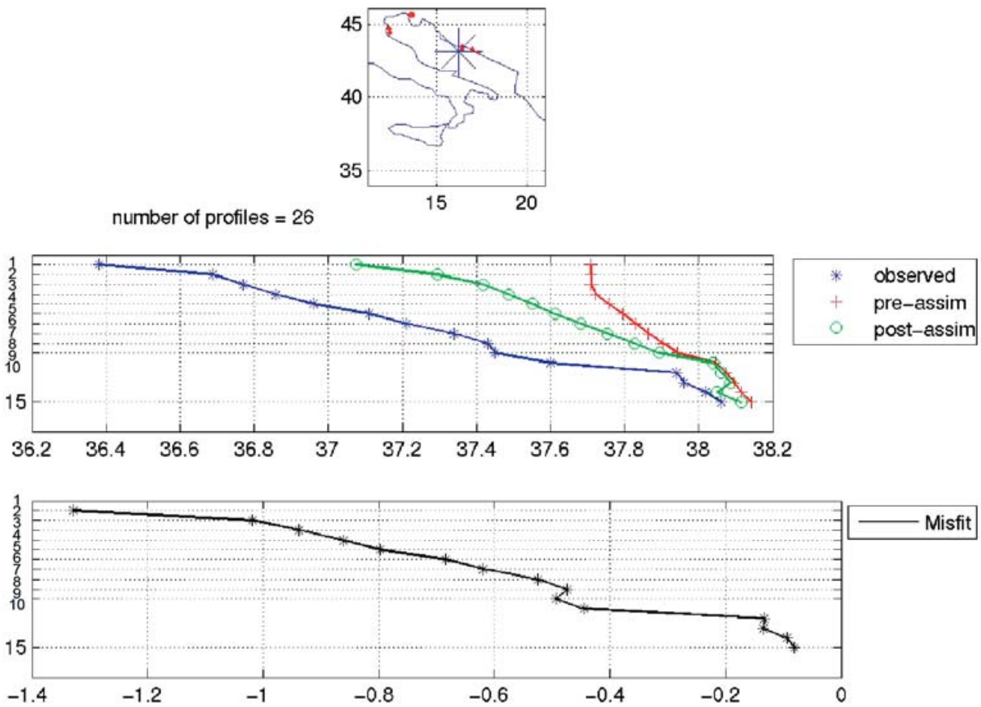


Fig. 10c. As in (a) but for a profile located in region 4 and for 11 February 2003

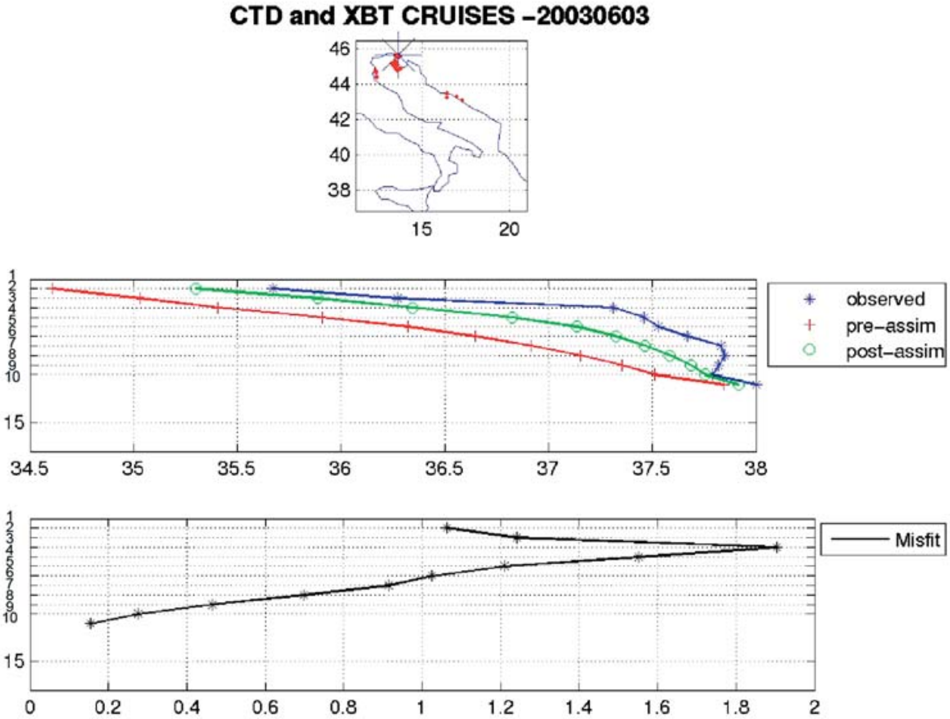


Fig. 10d. As in (a) but for a profile located in region 7 and for 3 June 2003

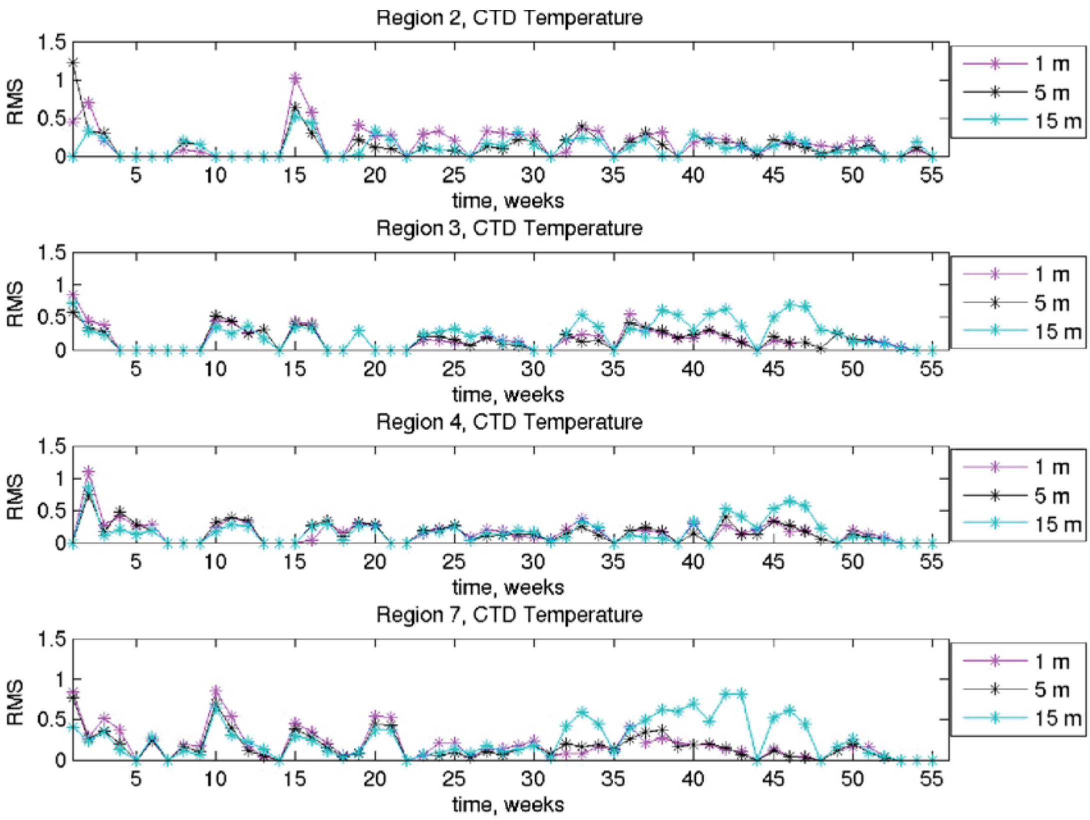


Fig. 11. RMS misfit error (see formula 13) for temperature (in ^{o}C) during the CTD data assimilation year (October 2002-October 2003, time=weeks) at 1 m, 5 m and 15 m depth in the four coastal areas (regions 2, 3, 4 and 7)

Accuracy

We analyse here the so-called misfit error, that is the difference between the SF and the observations before the latter are assimilated. This statistical index is not a check of the assimilation and model performance by independent data but it can show the improvement of the model solution due to the regular assimilation of data.

The *RMS* misfit error between the SF values φ_m (before inserting the data) and the observed values φ_o is defined by:

$$RMS = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(\varphi_m - \varphi_o)^2} \qquad (13)$$

where φ_m and φ_o are *T* or *S, n* is the number of observations during the assimilation cycle.

In Fig. 11 and Fig. 12 we show the *RMS* misfit error for temperature and salinity calculated in each Adriatic coastal areas, where the CTD data were available. The *RMS* temperature and salinity errors are shown at 1 m, 5 m and 15 m for the period of the present study (October 2002-October 2003). The temperature RMS error misfits are generally in the range of 0.5 ^{0}C to 1 ^{0}C at 1 m, 5 m and 15 m depth. The salinity RMS error misfits are generally confined in the range of 0.5 psu to 1 psu at 1 m, 5 m and 15 m depth.

In Fig. 13 we show the *RMS* misfit error for XBT temperature profiles. The error is again less than 1 ^{0}C during the year of assimilation.

It is important to note that all the RMS misfit errors decrease with time showing the beneficial impact of assimilation on the SF.

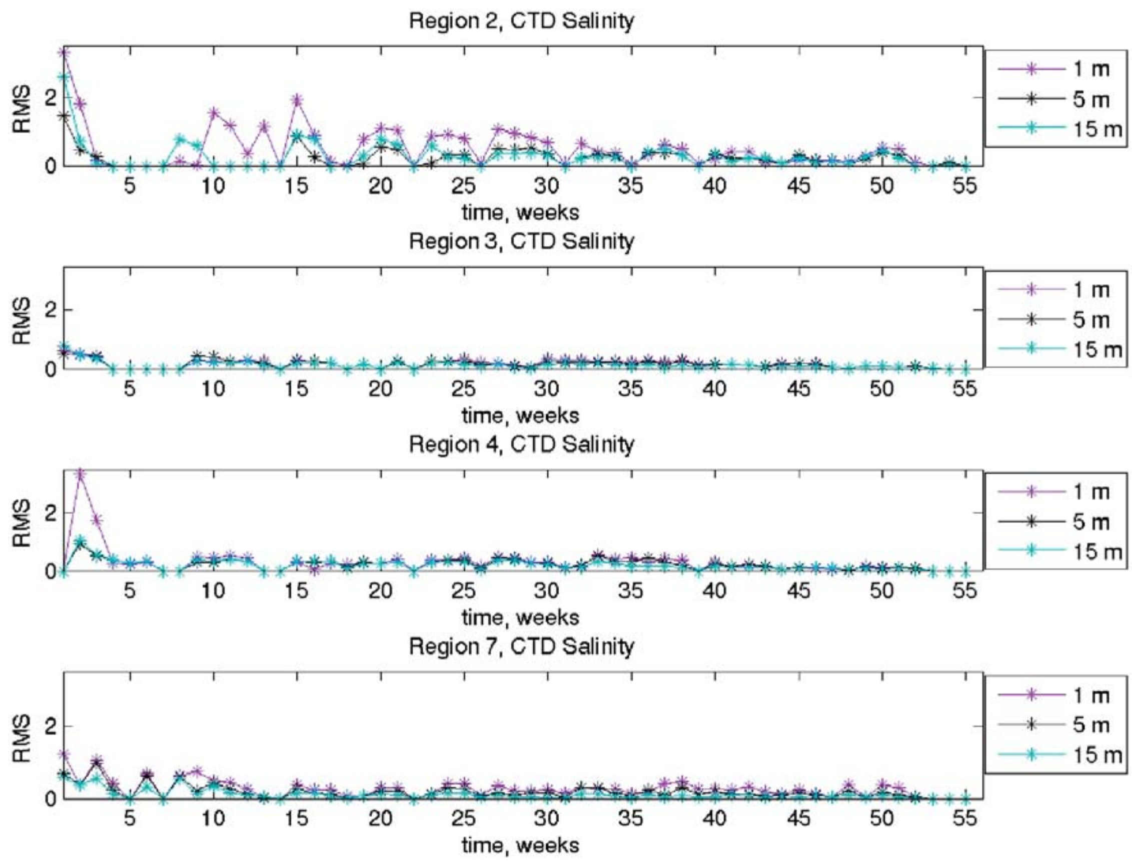


Fig. 12. RMS misfit error (see formula 13) for salinity (in psu) during the CTD data assimilation year (October 2002-October 2003, time=weeks) at 1 m, 5 m and 15 m depth in the four coastal areas (regions 2, 3, 4 and 7)

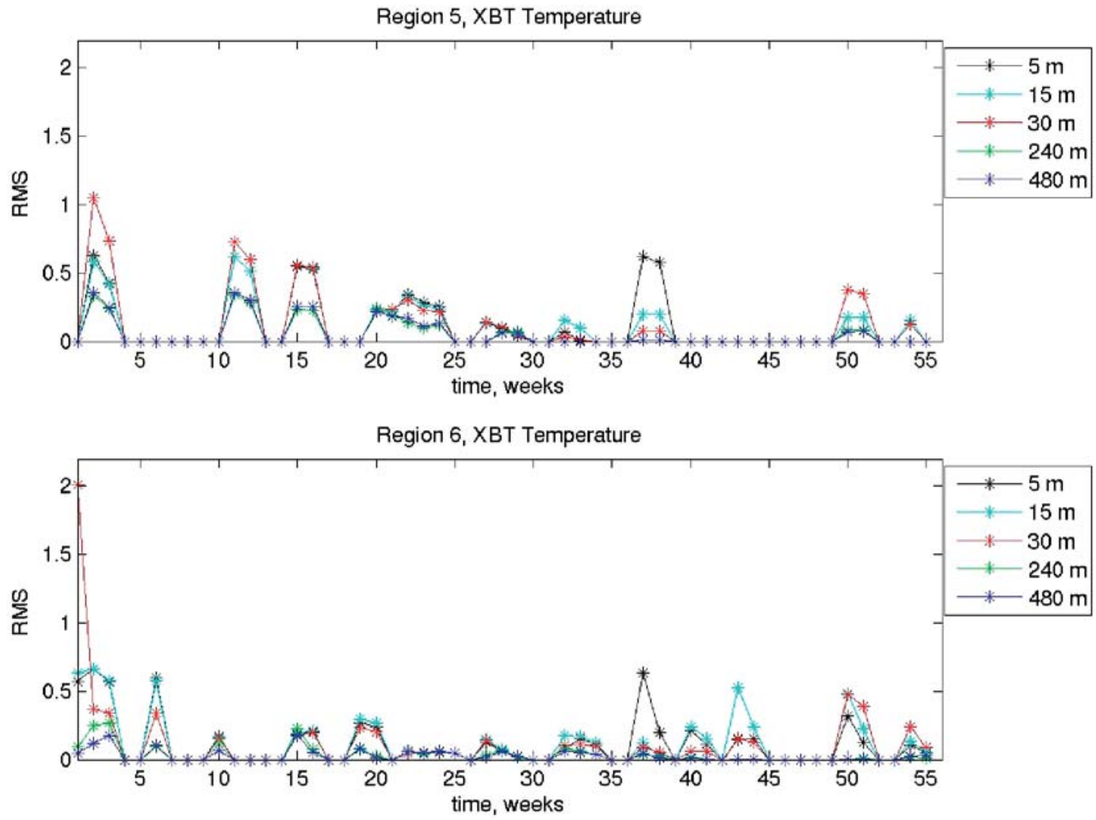


Fig. 13. RMS misfit error (see formula 13) for temperature (in °C) during the XBT data assimilation year (October 2002-October 2003, time=weeks) at 5 m, 15 m, 30 m , 240 m and 480 m depth in the southern Adriatic Sea (regions 5 and 6)

CONCLUSIONS

In this paper we presented the implementation of a data assimilation system in the open and coastal areas of the Adriatic Sea. The system is based on a Reduced Order Optimal Interpolator Method (SOFA) adapted for the multivariate assimilation of *T* and *S* observations from CTD in the Adriatic coastal areas and *T* profiles from XBT in the deep parts of the domain. The reduced order of the data assimilation is achieved through vertical Empirical Orthogonal Functions, which define the vertical structure of the model error. Seasonal model v-EOFs are computed in the coastal regions (Emilia Romagna coastal strip, Gulf of Trieste, Rovinj and Pelješac-Vis-Drvenik coastal strips) from model simulations.

The *T* and *S* profiles are assimilated into the Adriatic OGCM for the period from October 2002 to October 2003. Results demonstrated a beneficial impact of the assimilation both in the Adriatic Sea coastal and deep ocean areas.

The analysis skill scores were further examined. The analysis produced by the data assimilation has been validated against independent observations (*SST* from satellite) and climatology monthly means. In all the regions, the data assimilation system is capable of "bringing" the model closer to the observations. Moreover, temperature sections along VOS-1 tracks indicate that the temperature profiles from XBT improve the vertical stratification of the model.

Statistical indexes indicate that the *RMS* misfit error for temperature is less than 1 °C in the southern Adriatic Sea. The range of *RMS* misfit temperature error is similar near the coasts where the temperature data from CTD are assimilated. The *RMS* misfit salinity error is less than 1 psu.

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Asimilacija podataka o temperaturi i salinitetu u jadranskom regionalnom modelu

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SAŽETAK

Podaci temperature i saliniteta, prikupljeni u razdoblju listopad 2002. - listopad 2003., su asimilirani u Princeton oceanski model koji je primijenjen na cijeli Jadran. Upotrijebljena shema je bila SOFA (System for Ocean Forecast and Analysis, DE MEY & BENKIRAN, 2002), što je prva primjena ove sheme na obalno more. CTD podaci su prikupljeni na četiri obalna područja (obalni pojas Emilia–Romagna, Tršćanski zaljev, obalno područje kod Rovinja i obalno područje Pelješac-Vis-Drvenik) dok su podaci XBT-a prikupljeni u dubokim područjima južnog Jadrana. Ispitane su modelske analize, kako bi se procijenila uspješnost asimilacije. Rezultati asimilacije su najprije uspoređeni s nezavisnim analizama površinske temperature mora (SST) iz satelita te je nađeno da asimilacija profila poboljšava procjenu površinske temperature iz modela. Nadalje je analiziran kvadratni korjen razlike (RMS) između modela te profila temperature i saliniteta prije uključivanja podataka. Raspon RMS pogreške temperature je ispod 1 ^{0}C na čitavom području i opada s vremenom, ukazujući na pozitivni utjecaj asimilacije. RMS razlika saliniteta je ispod 1 psu i pokazuje trend opadanja za vrijeme razdoblja asimilacije.

Ključne riječi: asimilacija podataka, Jadransko more, optimalna interpolacija