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Assimilation experiments for the Fishery Observing System in the Adriatic Sea

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ABSTRACT

An impact assessment of a Fishery Observing System (FOS) network in the Adriatic Sea was carried out with an ocean circulation model fully-coupled with a data assimilation system. The FOS data are single point vertical values of temperature collected in 2007. In this study, we used the Observing System Experiment (OSE) and Observing System Simulation Experiment (OSSE) methodologies to estimate the impact of different FOS design and sensors implementation. OSEs were conducted to evaluate real observations and they show that the FOS network improves the analysis significantly, especially during the stratification season. Root mean square (RMS) of temperature errors are reduced by about 44% and 36% in the upper and lower layers respectively. We also demonstrated that a similar impact can be obtained with a reduced number of vessels if the spatial coverage of the data points does not change significantly. In the OSSE, the impact of the implementation of a CTD (conductivity–temperature–depth) sensor in place of the existing temperature sensor was tested with identical twin approaches between January and April 2007. The results imply that the assimilation of salinity does not improve the analysis significantly during the winter and spring seasons.

1. Introduction

Integrating new types of coastal observing systems into high resolution shelf and coastal ocean models is important for forecasting and obtaining best estimates of the essential marine variables in the shelf and coastal areas of the world's oceans. Since the real time global ocean observing system has become a reality in support of ocean forecasting in the open ocean regions (Dombrowski et al., 2009), the challenge is now to define the strategy of the observing system for shelf and coastal areas.

There are various methods to analyze the impact of observing systems (Oke and O'Kane, 2011) on ocean dynamical field reconstructions. One of these is the Observing System Experiment (OSE) which is widely used in the atmospheric and oceanic community. It is a data-denial approach evaluating the impact of the excluded set of observations with a reference to a best estimate that assimilates all the data.

Another methodology is the Observing System Simulation Experiment (OSSE). The rationale is similar to the OSE but the OSSE evaluates the possible impact of a future observing system or various design strategies of the existing system together with new ones. In atmospheric research, the OSSE methodology has been used for the last three decades (Arnold and Dey, 1986; Masutani et al., 2010). For the Mediterranean Sea, Raicich (2006) used an 'identical twin' approach in which a model simulation was used as the 'truth' or 'nature' run from which the synthetic observations are generated, and a perturbed model simulation is generated that differs from the nature run. Synthetic observations are assimilated in the perturbed model simulation and the estimated field variables are intercompared with the nature run. Masuda (2014) studied the effectiveness of concentrated observations for an ocean state estimation in a region remote from the observation site in the North Pacific with the same approach. On the other hand, Alvarez and Mourre (2014) studied the design of a glider network with a 'fraternal twin' approach, in which the nature run and the forecast model are the same but with different physical configurations. Finally, Halliwell et al. (2014, 2015) used the fraternal twin approach and extensively validated their OSSE by comparing it with the reference OSEs.

We focus on the Adriatic Sea where a Fishery Observing System (FOS) has been developed to collect in-situ environmental data using fishing vessels (Falco et al., 2007). The FOS is one of the most notable

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vessels of opportunity networks along with the RECOPESCA program (Leblond et al., 2010). Designing a ship-of-opportunity optimal network is challenging and alternative strategies for collecting vertical temperature profiles on fishing vessels in the coastal and open ocean are being evaluated (Kourafalou et al., 2015).

In this study, we use a high-resolution ocean circulation model coupled to a data assimilation system in order to assess the impact of specific FOS observations. In our case, FOS data are single vertical point measurements rather than profiles, and it is important to evaluate their impact on quality analyses since this ship-of-opportunity measurement system is cheap and does not impact on fishing activities. We performed Fishery Observing System Experiments (FOSE) to evaluate the impact of the geographical network and the temperature measurement depth distribution. We then designed a Fishery Observing System Simulation Experiment (FOSSE) to estimate the impact of the implementation of a CTD sensor instead of the temperature-only sensor that currently exists.

The paper is organized as follows: Section 2 introduces the model and data assimilation system and the FOS observations provided in 2007 are detailed. Section 3 presents the FOSE design and results. Section 4 is devoted to FOSSE, and the overall results are discussed in Section 5.

2. Materials

2.1. Model description

The model configuration is described in detail by Gunduz et al. (2013) and will only be outlined here. The model uses the NEMO (Nucleus for European Modeling of the Ocean, Madec, 2008) code in its explicit free surface, linear formulation. It has a constant horizontal grid resolution of 1/48° corresponding to 1.8 and 2.3 km in longitudinal and latitudinal directions, respectively, and 120 unevenly spaced z-levels with partial cells at the bottom. The vertical grid is 1 m in the top 60 m, increasing to 9 m at a depth of 100 m and to 50 m at the deepest point in the Adriatic Sea. The largest spacing of 70 m is in the Ionian Sea at the deepest point (2800 m, Fig. 1).

Atmospheric surface momentum, heat and water fluxes are computed using European Centre for Medium-Range Weather Forecasts (ECMWF) ERA-Interim surface fields and bulk formulas. However, precipitation is taken from the Merged Analysis of Precipitation (CMAP) observational dataset (Xie and Arkin, 1997). The ERA-Interim atmospheric forcing fields are available at a 6-hour frequency and horizontal resolution of 0.25°.

The model domain has one open boundary that communicates with the Mediterranean Sea positioned south of the Otranto Strait (Fig. 1). The boundary conditions for temperature, salinity, sea surface height, zonal and meridional currents are provided daily from the large-scale MFS (Pinardi and Coppini, 2010).

The initial conditions of the model were taken from the simulation by Gunduz et al. (2013) in order to coincide with 1 January 2007, and the simulation period is up to December 2007.

2.2. Data assimilation scheme

The OceanVar data assimilation scheme (Dobricic and Pinardi, 2008) is implemented in the Adriatic Sea using a new description of the vertical background error covariances. As described in Dobricic et al. (2005), part of the background error covariance is represented by vertical multivariate Empirical Orthogonal Functions (EOFs) for temperature and salinity. In our study the vertical EOFs were calculated at each model grid point and monthly, using a 10 year-long simulation (Gunduz et al., 2013), and the salinity and temperature variances as a departure from a monthly mean seasonal climatology.

The horizontal part of background error covariance is assumed to be Gaussian isotropic, depending only on distance. It is modeled by the successive application of the recursive filter in longitudinal and latitudinal directions, which provides a high computational efficiency in each iteration of the algorithm. The rapidly evolving part of the background error covariance, consisting of the sea level and the barotropic velocity components, is modeled using a barotropic model forced by the vertically-integrated pressure innovations resulting from temperature and salinity variations. The assimilation scheme of Dobricic and Pinardi (2008) is multivariate, i.e. temperature, salinity and sea surface height observations produce corrections not only in the corresponding state variables but also in the vertically correlated state variables, in particular the velocity fields. The assumption that the horizontal error correlation structure is homogeneous and isotropic is an important limitation of the scheme. This correlation structure is not adequate for strongly anisotropic flow fields as they exist along the western boundary of the

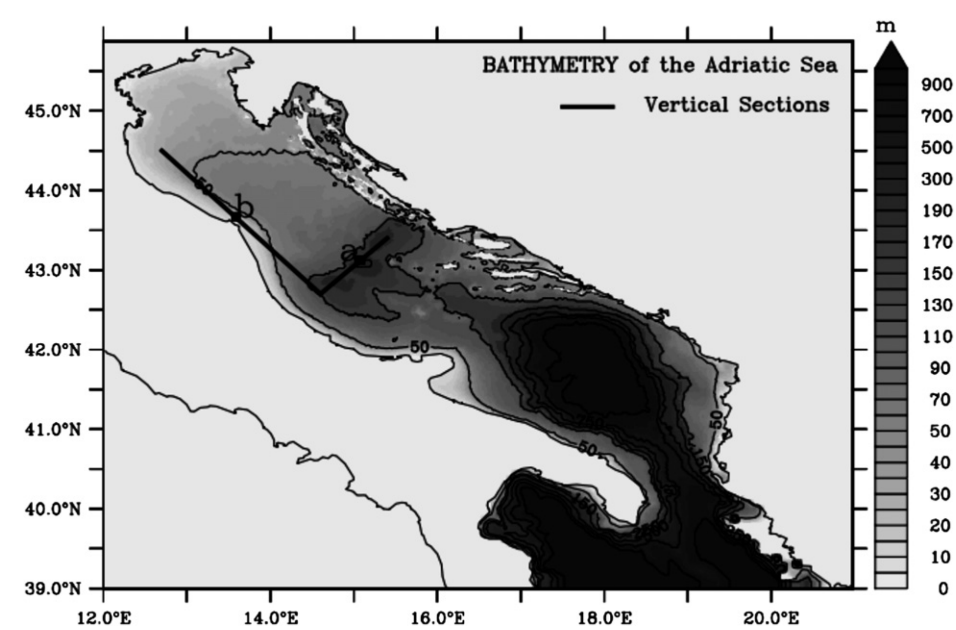

Fig. 1. Bathymetry of the Adriatic Sea. The section indicated with the line segments are used for studying vertical structure of the water column. The locations (a) and (b) are the reference points for the black and green lines, respectively, in the vertical cross-sections.

Adriatic Sea and this might be responsible for some reduced impact of observations in the analysis quality.

2.3. The Fishery Observing System

The FOS data used in this study consists of seven different vessels from five different fleets (Falco et al., 2007). The fleets are located in Chioggia, Rimini, Ancona, San Benedetto del Trento and Giulianova from north-west to mid-west Adriatic Sea, respectively (Fig. 2). StarOddi sensors are installed on the nets of the pelagic pair trawlers and purse seine fishing vessels. Sensors measure the temperature with an accuracy of ± 0.1 °C. The depth is calculated from the pressure with a minimum accuracy of approximately ± 0.2 m. Profiles taken during the release and hauling of the net were excluded due to a stabilization problem of the sensor. Only the measurements taken at the fishing depth were used. This means that temperature is measured at a specific single vertical point. The sensor remains at that depth for approximately 2–3 h along the vessel track for the pelagic pair trawlers. The temperature doesn't change significantly along the track once the sensors get stabilized at depth as shown in Fig. 3 (upper panel). Thus the observations used in the assimilation are the average of the temperature values measured during the vessel drifting time. The result is the dataset of single vertical point measurements illustrated in Figs. 2 and 3 (lower panel).

The measurement points reach a maximum depth of 160 m however most stay within the first 100 m. The largest amount of data was collected by the Ancona and Rimini fleets (Fig. 3) because two vessels were used for these fleets whereas only one vessel was available in each of the other three fleets. The least amount of data was collected in August due to the restrictions in fishing activities.

3. Fishery Observing System Experiments (FOSEs)

3.1. Design of the FOSEs

The FOSEs were designed to show the impact of the FOS measurements described in Section 2.3 on the quality of analysis with respect to simulations and to check the impact of a lower number of fishing vessels on the quality analysis. All the experiments are listed in Table 1.

It would be interesting to see the impact of the FOS along with other observations but given the specific area we decided not to consider complementary satellite observations. To our knowledge FOS is the only systematic large scale in situ observing system for the Adriatic Sea shelf areas. Only satellite data could be considered at the same level, in particular altimetry and sea surface temperature (SST). However, in shelf areas of the Adriatic Sea satellite altimetry consists only of few tracks and, due to the closeness of coastlines, the accuracy of the retrieved signal is low. For SST, accuracy is also low due to the low seawater coastal temperatures which interfere with the cloud detection algorithm. Thus it was decided to concentrate only on FOS observations which are at the moment the only systematic in situ observing component for the Adriatic Sea shelf areas with a reasonable accuracy.

The control run was performed without assimilation as a reference experiment to assess the impact of the assimilation. All of the observations were then assimilated to produce an analysis or 'best estimate'. Two other experiments were designed: the first, OSE01, used the observations only from four of the vessels, while OSE02 completely neglected the Ancona fleet.

In OSE01 the observations collected by one of the two fishing vessels from Ancona and Rimini fleets were excluded (AN2 and RN2 in Fig. 3, respectively). The observations from the San Benedetto fleet were not used since the fleet was close to the Giulianova fleet. OSE01 was performed with four vessels to assess the impact of observations covering all regions but with fewer vessels (see Table 2).

Most of the data collected by the Ancona fleet, which amounts to 45% of the total data, was under a depth of 30 m which is approximately the depth of the surface Ekman layer and also the T,S mixed layer (Artegiani et al., 1997). OSE02 was therefore performed without using the Ancona data in order to evaluate the impact of the shallower observations alone.

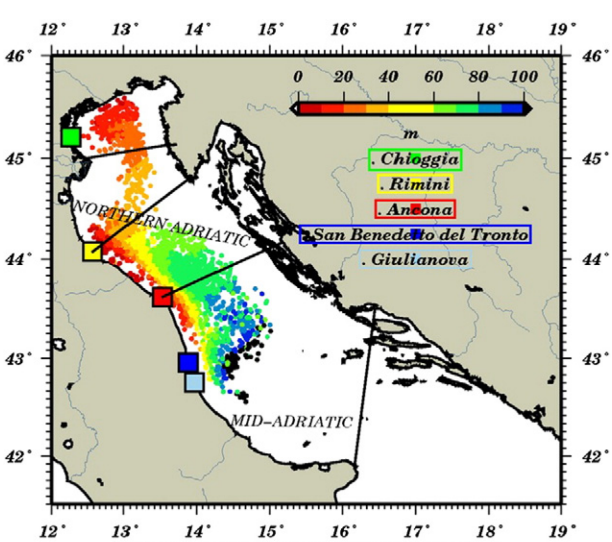

Fig. 2. FOS observations distribution and their nominal depth for the year 2007. The squares show the locations of fleets in the Adriatic Sea involved in collecting the data.

3.2. Evaluation methodology for the FOSEs

The FOSEs were compared using misfits and analysis residuals. The misfit, also called innovation, is the difference between the observation and the background state at the location of the observation. It can be written as $m = y - Hx_b$ where x_b is the background state, H is the observation operator mapping the background from model space to the observation space and y is the observation. The root mean square of the temperature misfits (hereafter, RMS error) are calculated weekly in two different layers of the water column as follows:

$$RMS = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(y-Hx_b)_i^2} \tag{1}$$

where N is the number of observations in a week in the averaging layers, chosen to be 0–40 m and 40–100 m. Since the misfits are calculated before the assimilation of the FOS data, they can be considered as quasi-independent observations.

The RMS of misfits are evaluated by using the entire FOS data set regardless of the excluded observations in OSEs. The impact of data is considered to be positive if the RMS error is reduced in the assimilation experiments compared to the control run.

3.3. Results of the FOSEs

In Fig. 4, the RMS of temperature misfits are shown for all the FOSEs. In the control run, the RMS error shows a significant seasonality in the upper 0–40 m layer reaching up to 2.5 °C during the stratification season and then decreasing again in autumn. On the other hand, in the 40–100 m layer the maximum error is achieved in autumn due to the deepening of the surface mixed layer after the summer (Artegiani et al., 1997). The mean control run RMS temperature error throughout the year is 1.3 °C for the upper layer and 0.5 °C for the lower layer.

When we assimilate all the FOS observations in the 'best estimate' experiment, the RMS error falls significantly and does not exceed 2 °C throughout the year. During the stratification season, when the misfit between the data and model is higher, the reduction in the RMS error is bigger than the annual mean. The mean RMS error of the best

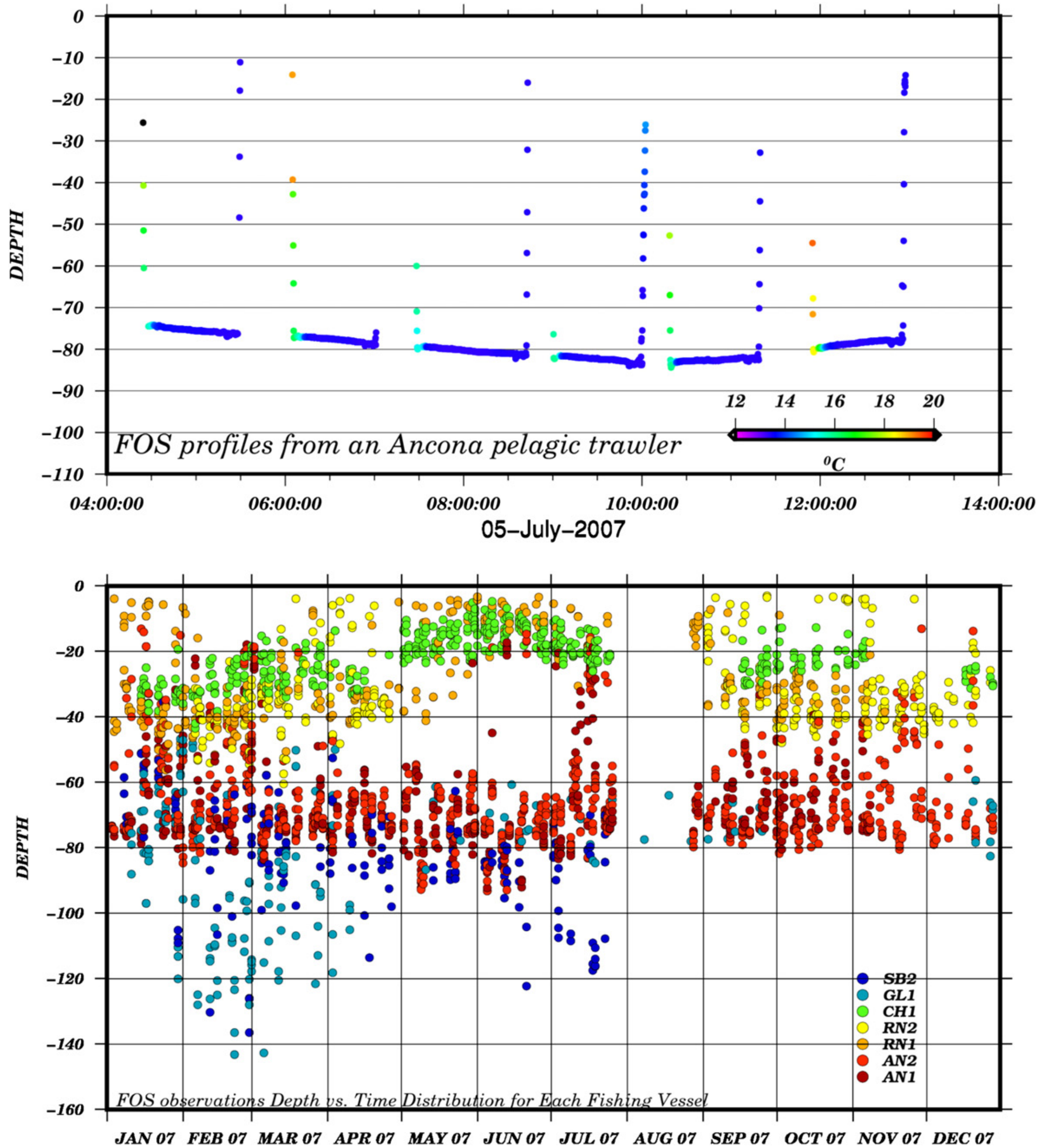

Fig. 3. Temperature of sample profiles from an Ancona pelagic trawler in 5 July, 2007. Time axis shows the hour of the day (upper panel). Distribution of FOS observations with depth and months of 2007 (lower panel). The data collected by each vessel are shown with a different color. The vessels from Ancona, Rimini, Chioggia, Giulianova and San Benedetto del Tronto are plotted as red, yellow, green, light blue and blue circles, respectively.

estimate throughout the year is 0.74 °C in the upper layer, which corresponds to a reduction of 44% compared to the control run. In the lower layer, it is 0.3 °C which means a 36% reduction in the error. In addition to the improvement in the RMS error, the bias in the best estimate is 79% and 88% less than the control run in the upper and lower layers, respectively (Table 3).

In the best estimate, 76% of the data passed the quality check of the data assimilation system, i.e. the difference between the model and the observations was less than 5 °C and the depth is less than the bathymetry. The amount of assimilated data decreased by about 40% in OSE01 and 50% in OSE02. The decrease of data in the different experiments is given in Table 4: we present only March and July because they are

Table 1
Fishery Observing System Experiment (FOSE) design.

Experiment	Type	Assimilation
Control run	Simulation	NO
Best estimate	Assimilation	ALL FOS
OSE01	Assimilation	Four vessels
OSE02	Assimilation	All vessels except Ancona

Table 2
Number of fishing vessels used in experiments from each fleet.

Experiment	Chioggia	Rimini	Ancona	Guilianova	S. Benedetto
Control run	0	0	0	0	0
Best estimate	1	2	2	1	1
OSE01	1	1	1	1	0
OSE02	1	2	0	1	1

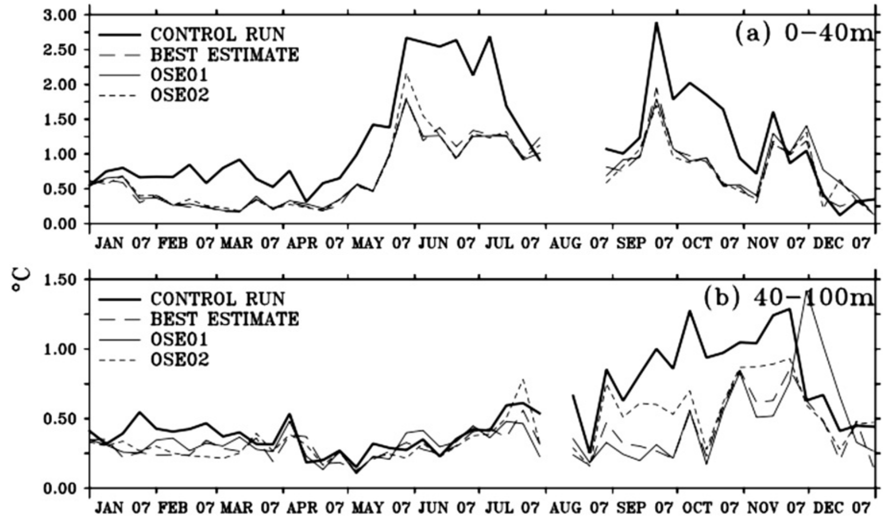

Fig. 4. Time series of weekly RMS of temperature misfits for all the FOSEs, the control run, the best estimate, OSE01 and OSE02 for a) the 0–40 m layer and b) 40–100 m layer. Symbols corresponding to each experiment are shown in the legend.

representatives of the mixing and stratification seasons. In both OSEs, the denial of a subset of data doesn't degrade significantly the solution in terms of temperature misfit RMS error (Fig. 4). The OSE01 shows that the impact of decreasing to four fishing vessels is negligible because the four vessels chosen sample almost the same horizontal areas as the full fleet, only with fewer repeated measurements. If we exclude the Ancona fleet, in OSE02 the impact is again similar to the best estimate for most of the time. Since the samples provided by the Ancona vessels were mostly below a depth of 40 m, we conclude that fewer data are sufficient to increase the deep layer quality analysis with respect to the simulation. However, there is a degradation of RMS in both OSE01 and OSE02 at the end of November and in December. Similarly, OSE02 shows a larger RMS during the whole September. We think that these larger RMS values are caused by the same dynamics will be discussed at the end of this section.

In Fig. 5, the spatial distribution of errors are shown. In Fig. 5a and b, the RMS of temperature misfits and RMS of temperature analysis are compared. Moreover, the analysis RMS of OSE01 and OSE02 are presented in Fig. 5c and d, respectively. The RMS of misfits for the best estimate are higher in the north-western part of the basin, mainly due to the impact of PO river. The errors exceed 3 °C along the coast of Rimini. On the other hand the errors are reduced in that area as well as the other regions in the analysis. (Fig. 5b). In the OSE01 and OSE02, the analysis errors are larger in the areas where we decreased the number of assimilated observations, as expected (Fig. 5c and d). Beside that the analysis RMS are similar where we assimilate in all experiments such as the northern-most Adriatic Sea.

The variational data assimilation algorithm produces a correction that is added to the background state variables. In Fig. 6, we show the vertical structure of the temperature corrections due to the assimilation of the FOS data for March and July. It is evident that the best estimate has the largest corrections to the background field with respect to OSE01 and OSE02 but the shape is largely the same since it is due to the vertical structure of the error covariance matrix. Fig. 6 shows that the single point vertical observations can correct the whole water column during the well-mixed season, while during the stratification season, the corrections are centered around the measurement layer that coincides with the seasonal thermocline.

In Fig. 7, we show the standard deviation around weekly mean temperature calculated by the background temperature values for all the experiments. The standard deviations in the assimilation experiments are getting smaller when the water column is well-mixed between January and May. However, following the thermocline formation during the summer, the standard deviation gets higher in the upper layer when the data is assimilated. Moreover, the deepening of the surface mixed-layer in September carries higher standard deviation to the lower layer. Therefore, we conclude that the assimilation of FOS increases the variance around the thermocline.

In order to show the impact of temperature assimilation experiments on the other non-observed variables, the mean SSH time series for the region between 42N–46N and 12E–16E and for all the experiments assimilating only FOS temperature is shown. In Fig. 8 the SSH is reproduced for all the experiments and the difference is small but visible and it is larger in the November and December periods where it was shown that OSE1 and OSE2 has a larger RMS error.

We compared the model mean sea surface temperature for each experiment with the OISST (Optimum Interpolation Sea Surface Temperature) 1/4° daily analysis product of NOAA. The analysis is constructed by combining observations from different platforms such as satellites, ships and buoys on a regular global domain (Reynolds et al., 2007). We used only the AVHRR-only product which involves satellite SST only from AVHRR.

The assimilation-free control run SST (not shown) already agrees with the OISST except in June and July. The free-model overestimates the SST in these two months as well as December. In the assimilation experiments, the impact of FOS on the SST seems very small. That is not surprising since the FOS is by design a subsurface observing system

Table 3
Estimates of yearly mean RMS temperature errors and bias for the control run and the best estimate experiments. The last column shows the reductions in RMS error and bias after the assimilation in the best estimate are also listed.

	RMS error			Bias		
	Control run	Best estimate	Reduction %	Control run	Best estimate	Reduction %
0–40 m	1.3	0.7	44	−0.5	−0.1	79
40–100 m	0.5	0.3	36	−0.2	−0.03	88

Table 4
Number of assimilated observations for March and July in each of best estimate, OSE01 and OSE02. Ratios of the assimilated observations to the whole dataset are given in percentages.

	Best estimate	OSE01	OSE02
March	340	191 (57%)	207 (62%)
July	292	174 (60%)	129 (44%)

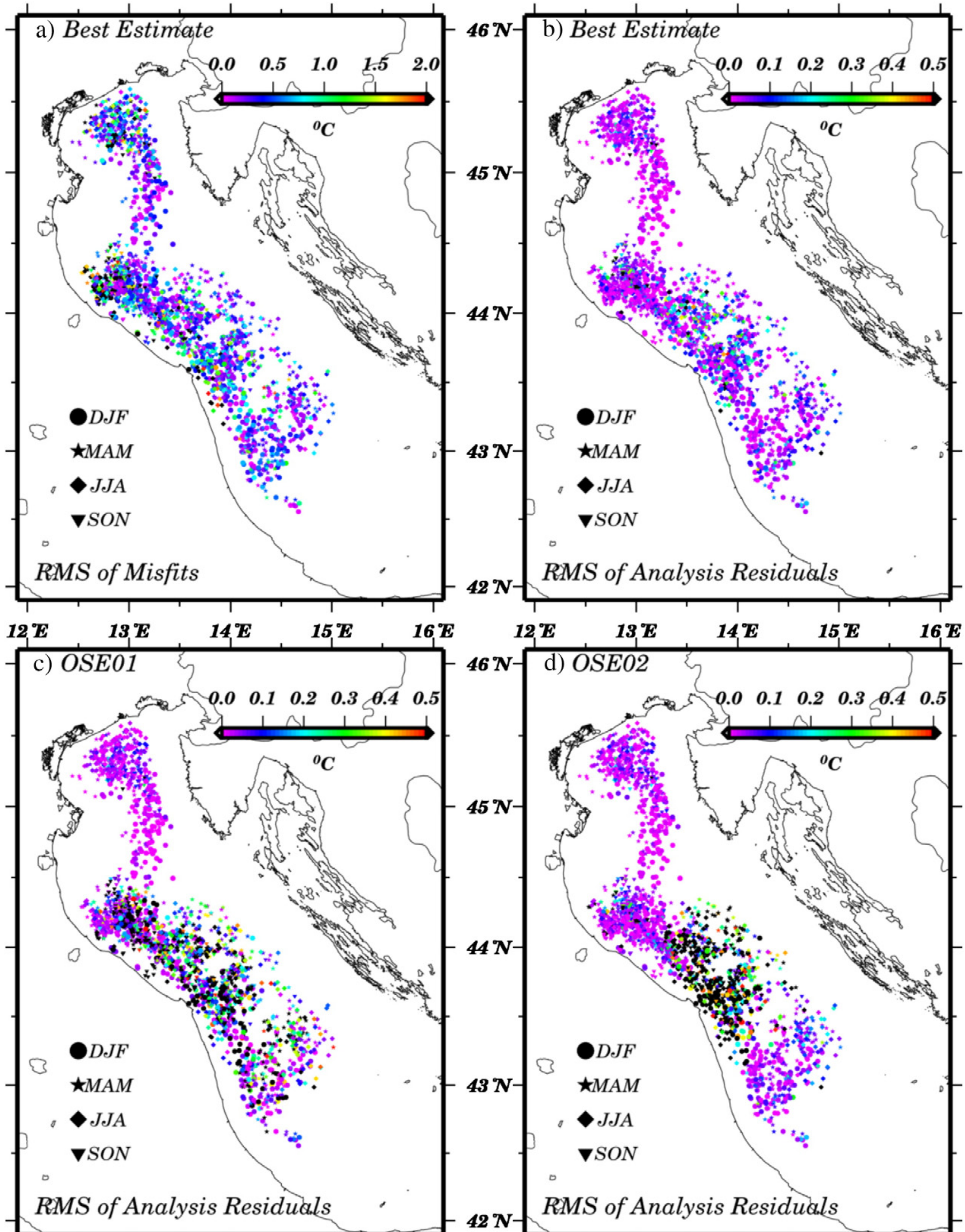

Fig. 5. Spatial distribution of temperature a) misfits and b) analysis residuals for the best estimate (top two panels). The bottom two panels illustrate the analysis residuals for c) OSE01 and d) OSE02. The data of different seasons are represented by different symbols such that circles for DJF, stars for MAM, diamonds for JJA and inverted triangles for SON months of 2007. Color scales are different for each figure.

and the SST is generally restricted by the heat fluxes forcing the ocean model at the surface boundary.

The time series of RMS of misfits in Fig. 4 and mean temperature in Fig. 7 show a temperature minimum in OSE01 which is significantly different from the other experiments at the end of November 2007. We believe that this error is a result of the western Adriatic dynamics related to the Po river discharge and the jet along the western coast. As we described in Section 3.1, the OSE01 excludes the data from RN2 and AN2 vessels (see Fig. 3). When the data is assimilated, the temperature in the Po river impact area is corrected and decreases as compared to

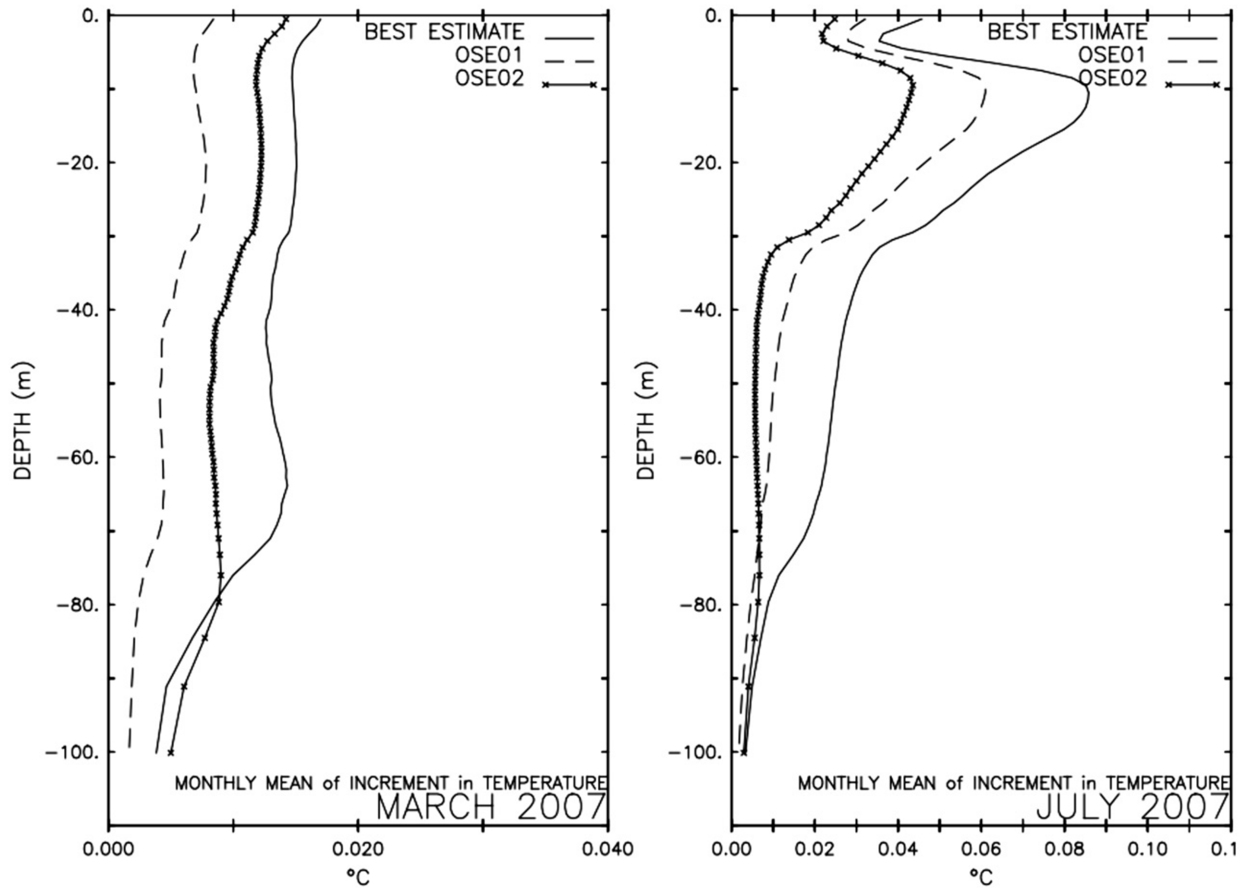

Fig. 6. Monthly basin mean of increments in the best estimate (full line), OSE01 (dashed line) and OSE02 (crossed line). In March (left), the profiles are almost uniform until 70 m whereas in June (right) the correction is larger around the seasonal thermocline.

the control run in the subsurface layers. The resulting cold water masses are transported southward by the Western Adriatic Coastal Current (Artegiani et al., 1997) towards Ancona. If we stop to assimilate the data, as in the case of OSE01, the water reaching Ancona will be still cold (see Fig. 9) and will lead to larger errors. If we continue to assimilate as in the best estimate (RN2 and AN2 are assimilated) and OSE02 (RN2 assimilated) we correct the fields and the RMS statistics become better compared to the control run. In the control run, however, since we never assimilate the path of the jet is already warmer than the other experiments, therefore the error is smaller compared to OSE01. As a result, we conclude that a FOS design with fewer observations as in OSE01 or OSE02 may perform similar to the available FOS network. However, the deficit of data along the Western Adriatic Coastal Current for some period may degrade the analysis. Therefore, continuous

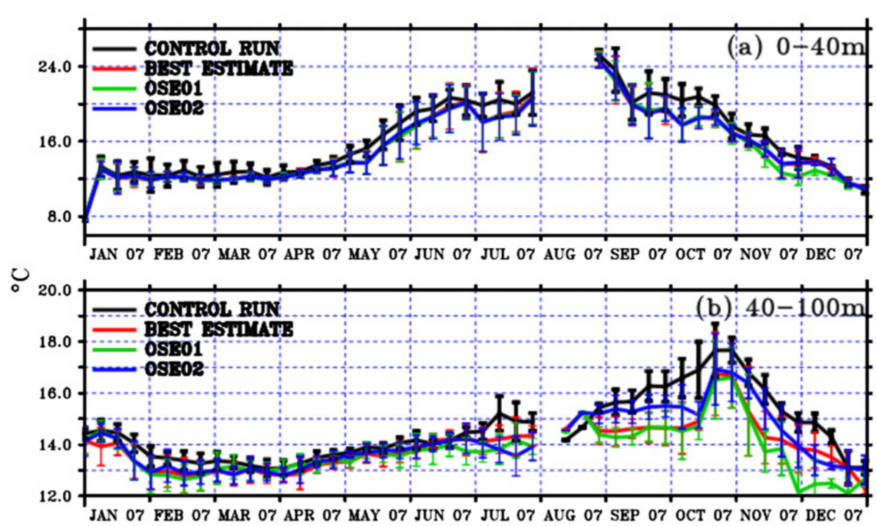

Fig. 7. Time series of weekly mean temperature calculated by the background values for the FOS dataset for all the FOSEs. The Control run, the best estimate, OSE01 and OSE02 are represented by black, red, green and blue lines, respectively a) for the 0–40 m depth layer and b) 40–100 m layer. Error bars show the standard deviation around mean.

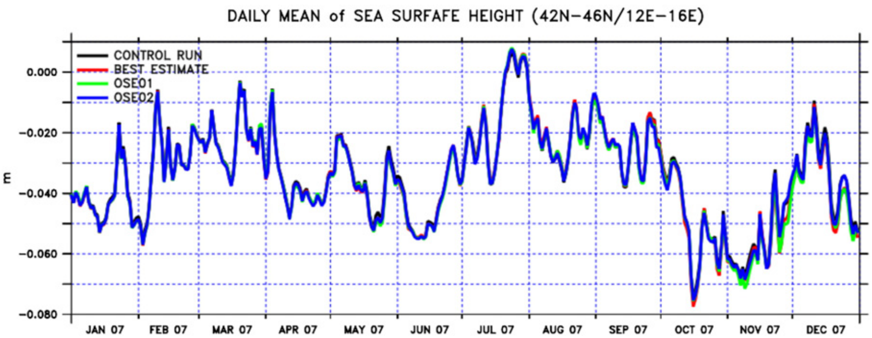

Fig. 8. Time series of daily mean sea surface height between the region 42N–46N and 12E–16E for all the FOSEs. The control run, the best estimate, OSE01 and OSE02 are represented by black, red, green and blue lines, respectively.

monitoring in time may be more crucial than repeated observations in the same area.

Thus in conclusion, the assimilation of FOS temperature observations improves the analysis especially during the stratification season, despite being single point measurements. OSE01 also shows that the quality of the analysis does not change dramatically provided that the geospatial data coverage stays similar, while the number of observations is reduced given that a continuous data in time is provided. Finally, a similar improvement in the analysis below the seasonal thermocline can be achieved with fewer data.

4. Fishery Observing System Simulation Experiments (FOSSEs)

4.1. Design of the Fishery Observing System Simulation Experiments (FOSSE)

FOSSE uses the identical twin methodology, considering two experiments, one called truth and the other, the perturbed experiment. The control run outlined in Section 3.3 is chosen to be the truth from which to sample synthetic temperature and salinity observations.

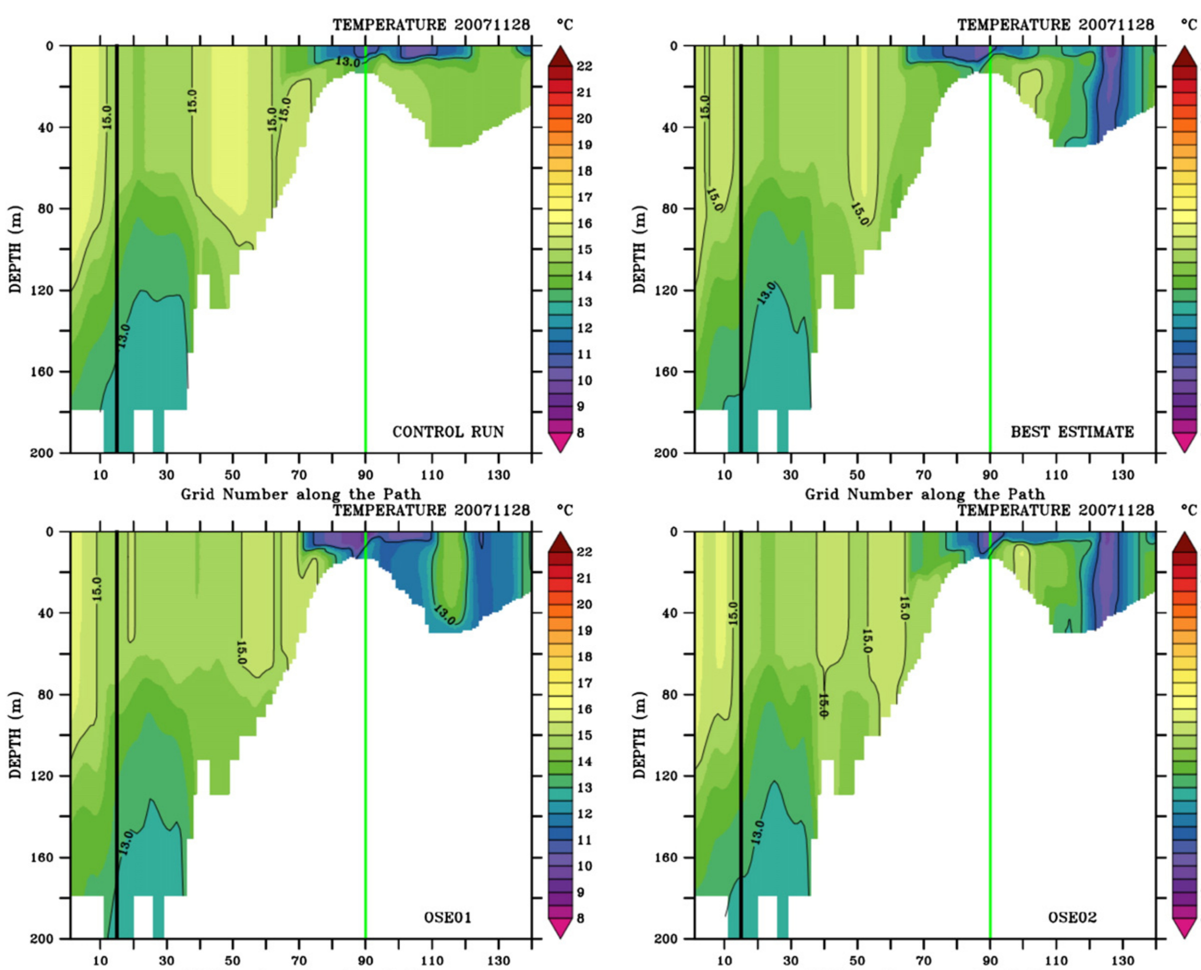

Fig. 9. Vertical structure of the water column following the section represented in Fig. 1 for 28 November 2007. Black and green lines correspond to the locations of the grid points (a) and (b), respectively shown in Fig. 1. The control run, the best estimate, OSE01 and OSE02 are shown from top left to bottom right, respectively.

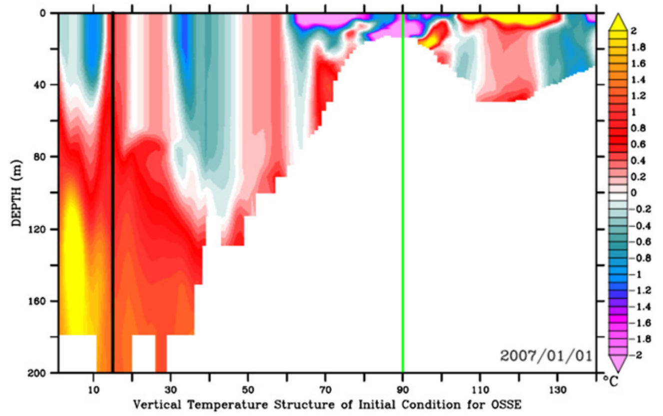

Fig. 10. Vertical structure of the temperature field differences between the initial conditions of the truth and the perturbation run along the section shown in Fig. 1. Black and green lines indicate the vertical sections below the reference points (a) and (b), respectively shown in Fig. 1. Horizontal axis is the number of grid points along the transect. The depth is in meters.

The perturbed experiment is produced by adding a perturbation to the temperature and salinity fields and then letting it grow due to flow field nonlinearities. The perturbation was applied on June 1, 2006 using the thermocline intensified random perturbation (TIRP) method introduced by Pinardi et al. (2008):

$$\begin{aligned} T_p(\mathrm{x,y,z}) &= \mathrm{T_0(x,y,z)} + \mathrm{p(x,y)}\sum_{\mathrm{i=1}}^{N} e_i f_i(z) \\ S_p(\mathrm{x,y,z}) &= \mathrm{S_0(x,y,z)} + \mathrm{p(x,y)}\sum_{\mathrm{i=1}}^{N} e_i g_i(z) \end{aligned} \tag{2}$$

where T_0 and S_0 are the unperturbed temperature and salinity fields; p(x, y) is a random number between (0,1.8) for temperature and (0,0.4) for salinity; and f_i and g_i are 20 vertical empirical orthogonal functions computed from the model statistics and e_i are their eigenvalues.

The perturbed run uses the 2005 wind fields until December 31, 2006 in order to increase the perturbation growth. The difference between the truth and the perturbation run on January 1, 2007 is shown in Fig. 10. The perturbation is large particularly on the shelf areas of both the Croatian and Italian coasts where the nonlinear dynamics of the Western Adriatic coastal current (Zavatarelli and Pinardi, 2003) and the northward flowing eastern Adriatic current are capable of amplifying the initial perturbations. Starting from January 1, 2007 synthetic observations were inserted into the perturbation run.

Two FOSSEs were designed using this perturbation run (Table 5). In OSSE01 we only assimilated the synthetic temperature observations, while in OSSE02 both temperature and salinity synthetic observations were assimilated.

4.2. Synthetic observations and evaluation methods

The distribution of the synthetic observations from January to April 2007 is shown in Fig. 11 for all the existing fishing vessels. The horizontal coverage of the measurements for this period is similar to the whole year distribution (Fig. 2). The temperature and salinity values were sampled from the truth run at the realistic FOS positions using a random instrumental error parametrization. For the temperature, a random error is added to the samples by fitting a Gaussian distribution with mean equal to 0 °C and a std. of 0.1 °C. For salinity errors, a random Gaussian distribution is used with mean equal to 0 psu and a std. of 0.04 psu.

In order to evaluate our FOSSE results, we compare the misfit RMS error with FOSE best estimate error statistics. This highlights whether the perturbed run produces errors that are statistically similar to the real observation assimilation case, so that the FOSSE results will be credible. In FOSSE, we only use the period between January 2007 and April 2007 because after this time, the perturbation run converges to the truth and the impact of the assimilation is not similar to the corresponding FOSEs.

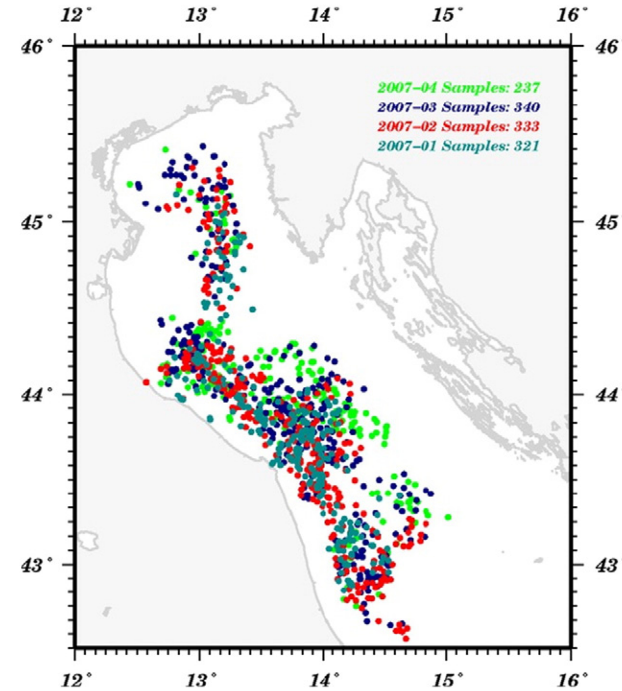

Fig. 11. Monthly distribution of the synthetic observations from January to April 2007.

4.3. FOSSE results

The RMS temperature error in this period is less than 1 °C for all the experiments (Fig. 12). The control run reaches 0.9 °C RMS errors in the upper layer in March, whereas the maximum error in the perturbation run is 0.65 °C. The mean RMS error of the control run in this period is 0.68 °C in the upper layer, and 0.46 °C for the perturbation run (Table 6). In the lower layer, the mean RMS temperature errors are 0.34 °C and 0.27 °C for the control run and the perturbation run, respectively. The mean RMS error of the best estimate is 0.31 °C and for the OSSE01 is 0.35 °C in the upper layer. For the lower layer, this is 0.27 °C

Table 5
Fishery Observing System Simulation Experiment (FOSSE) design.

Experiment	Type	Assimilation	Variable
Truth	Nature run	No	–
Perturbation	Simulation	No	–
OSSE01	Assimilation	All synt. FOS#1	Temp
OSSE02	Assimilation	All synt. FOS#1	Temp + Salt

Table 6
Comparison of mean RMS temperature error of FOSE and FOSSE in January–April 2007. Upper 0–40 m and lower 40–100 m are considered separately. Error reductions after temperature assimilation are also listed.

	FOSE			FOSSE		
	Control run	Best estimate	Reduction %	Perturbation	OSSE01	Reduction %
0–40 m	0.68	0.3	54	0.46	0.35	24
40–100 m	0.34	0.27	21	0.27	0.23	15

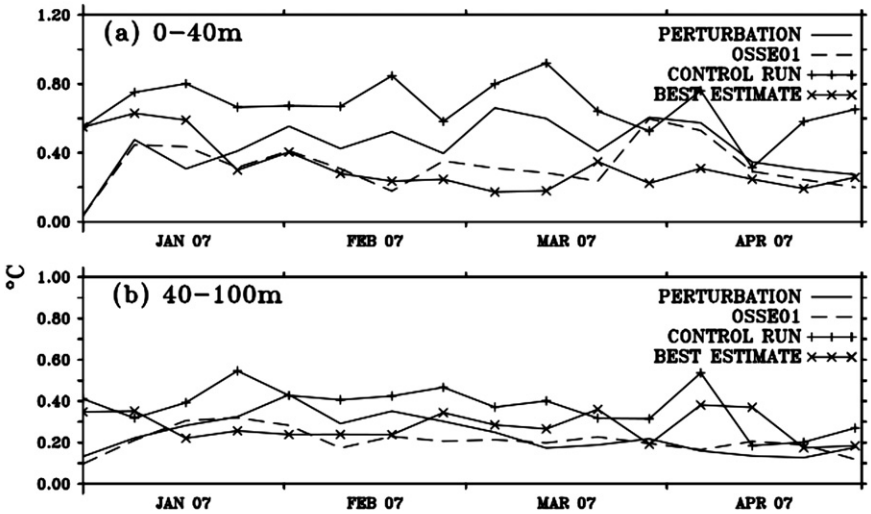

Fig. 12. RMS of temperature misfits comparison of the OSE and the OSSE. The perturbation run in OSSE corresponds to the control run of OSE. Similarly, OSSE01 corresponds to the best estimate of OSE since we assimilated all the temperature data between January and April 2007.

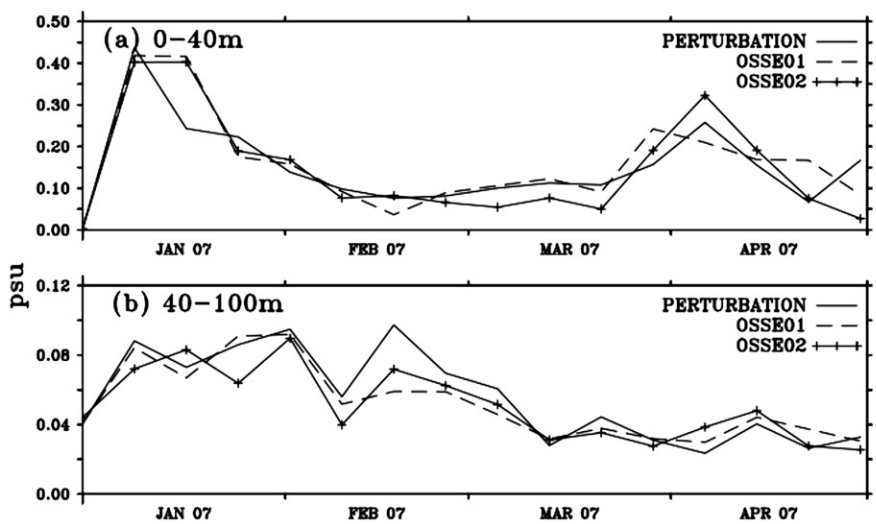

Fig. 13. The RMS salinity error comparison of perturbation run, the OSSE01 and the OSSE02 (a) 0%u201340 m depth (b) 40%u2013100 m depth. The scales are different in the upper and lower layer.

and 0.23 °C for the best estimate and the OSSE01, respectively. Thus in synthesis, the error statistics between FOSE and FOSSE experiments are similar, and thus the OSSE experiments are a credible experimental tool to evaluate new characteristics of the observing systems.

The OSSE02 is designed to test the possible impact of installing a CTD sensor on the fishing vessels in place of the existing one. The synthetic salinity observations are assimilated in addition to the synthetic temperature observations. Fig. 13 compares the OSSE02 with the perturbation run and OSSE01.

In both layers, the impact of salinity assimilation is negligible as shown in Table 7. The mean RMS salinity errors in the upper and lower layers are practically equal in all the experiments.

Table 7
The mean RMS salinity error for the perturbation run, the OSSE01 and the OSSE02 in the 0–40 m depth and the 40–100 m depth.

	Perturbation Run	OSSE01	OSSE02
0–40 m	0.16	0.18	0.16
40–100 m	0.06	0.06	0.05

In Fig. 13a, the biggest errors appear in January and April when there are few data in the first 20 m of the water column (Fig. 3). These observations are generally in the coast of Rimini where there is the highly dynamic western Adriatic coastal jet. When the RMS salinity error is calculated in the 20–40 m depth, excluding those misfits in the first 20 m, although the performance of the analysis does not improve (Table 8), it is not degraded (Fig. 14).

Several publications in the past have shown that the data assimilation system used in this paper has been successful to assimilate temperature and salinity observations from different observing systems such as XBT (Dobricic and Pinardi, 2008), gliders (Dobricic et al., 2010) and Argo (Nilsson et al., 2011) in the Mediterranean Sea and its sub-basins.

The difference of our study case is that we apply the large scale data assimilation scheme to a shelf and rapidly evolving coastal area. Our

Table 8
The mean RMS salinity error for the perturbation run, the OSSE01 and the OSSE02 in the 20–40 m depth.

	Perturbation run	OSSE01	OSSE02
20–40 m	0.08	0.09	0.07

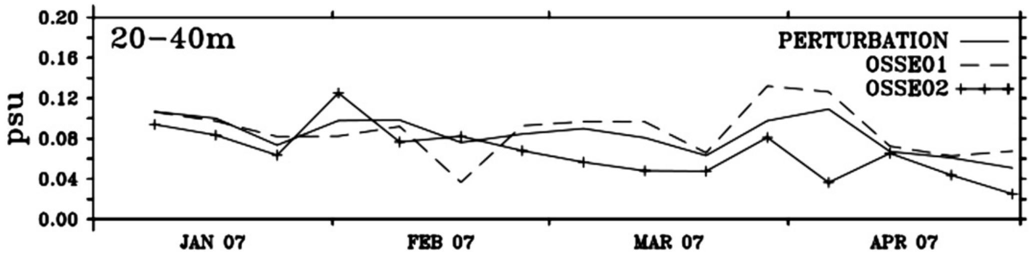

Fig. 14. Same as Fig. 13 but RMS salinity errors are calculated between 20 and 40 m.

results show that corrections are rapidly advected towards the Southern Adriatic Sea by the rapidly flowing western Adriatic coastal current thus impacting negatively the quality of the field downstream of the assimilation. Therefore, we argue that for narrow coastal jet streams we may not be able to assess the real impact of the assimilation of salinity data.

In conclusion, we believe that the net gain for CTD single vertical value measurements near coastal areas might be of limited benefit to the quality of analysis during winter and spring seasons, although our experiments are not conclusive in this respect.

5. Summary and discussion

The paper examines a special fishery vessel of opportunity observing system in the Adriatic Sea using the OSE and OSSE methodologies. The FOS observations used are only single value temperature measurements averaged over the fishing net hauling period and covering all of 2007. FOSE experiments tested the impact of the number of fishing vessels used, while the FOSSE tested the impact of introducing CTD salinity and temperature measurements.

The FOSE results indicate that decreasing the number of vessels by leaving the coverage unaltered, and decreasing the number of measurements does not have a critical impact on the quality of the analyses. Our work shows that FOS improves the RMS of temperature misfits by a factor of 35–43% with respect to the simulation RMS error. The impact is bigger during the stratification season around the thermocline where the errors are larger.

We designed an identical twin FOSSE system to assess the possible impact of salinity in addition to temperature observations.

Our results demonstrate that the salinity assimilation does not change the quality of the analysis significantly. We argue that this is because our data assimilation scheme is not suitable for the fast advecting dynamics of the coastal flow field that requires nonhomogeneous and non-isotropic horizontal correlation function. This is a limitation of our data assimilation system and thus we believe that our FOSSE experiments are not conclusive. More work and a different assimilation scheme would be required to finally establish the impact of CTD single value measurements in the FOS.

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