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The Adriatic Basin forecasting system

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A regional ocean forecasting system has been implemented in the framework of the ADRIatic sea integrated COastal areaS and river basin Management system Pilot Project (ADRICOSM). The system is composed of a 5 km horizontal resolution model and an observing system collecting coastal and open ocean hydrological data. The numerical model is based on the Princeton Ocean Model using a SMOLARKIEWICZ iterative advection scheme, interactive air-sea flux computation, Po and other Adriatic rivers flow rates and is one-way nested to a general circulation model of the Mediterranean Sea. In this study the data from the observing system are used only for model validation. The results of the first operational year are shown and the model performance has been assessed based on root mean square (RMS) criteria.

Key words: forecasting system, general circulation model, Adriatic Sea

INTRODUCTION

Physical ocean processes play an important role in governing and/or constraining marine acoustical, biological and sedimentological dynamics. Therefore, forecasting physical ocean fields can greatly contribute to the understanding of the functioning of marine sub-systems, as well as providing an efficient support tool for marine environmental management.

Numerical ocean models for forecasting started being developed at the beginning of the nineteen-eighties (PINARDI *et al*., 2002). The progress in computer power and efficient/accurate numerical techniques led to a progressive increase in numerical ocean models spatial resolution and overall quality, which now allows for the simulation of mesoscale and coastal dynamics.

Within the ADRICOSM (ADRIatic sea integrated COastal areaS and river basin Management system) Pilot Project, a near real time monitoring system and a near real time basin-shelf marine forecasting system has been implemented and is now being used in operational mode for the Adriatic Sea.

The semi-enclosed Adriatic Sea (Fig. 1) is a particularly challenging environment for the development of such a system (ZAVATARELLI *et al*., 2002) as the bottom morphology, the surface forcing functions (highly variable at the interannual and seasonal scales) and the exchanges with the Mediterranean Sea through the Otranto Channel define a variety of oceanographic dynamical regimes, ranging from coastal (the northern part of the basin is entirely epi-continental and affected by strong riverine freshwater input) to open sea (the southern Adriatic basin is 1200 m deep and interacts strongly with the Ionian open ocean waters). Moreover, the basin is also a well known site of dense water formation occurring, with different dynamics, in the northern and in the southern sub-basins (ARTEGIANI *et al*., 1989; OVCHINNIKOV *et al*, 1997; MANCA *et al.,* 2002). A forecasting system capable of dealing with these characteristics must include four interacting components (PINARDI *et al*., 2002): an atmospheric component, providing surface forcing functions from operational atmospheric analyses and forecasts; a remotely sensed and *in situ* ocean observing system capturing both the coastal and the open sea variability; a numerical ocean circulation model and a proper data assimilation scheme allowing for an efficient melding of the observations into the initial condition for the forecast.

In this paper we concentrate on the numerical model component of the forecasting system and we show results from the operational forecasting activity of the model, obtained without the data assimilation, and compare the forecast/simulations with independent observations in order to provide a first quantitative assessment of the model forecast skill. Preliminary considerations on the performance of the model with the active data assimilation procedure are instead described in GREZIO & PINARDI (2005).

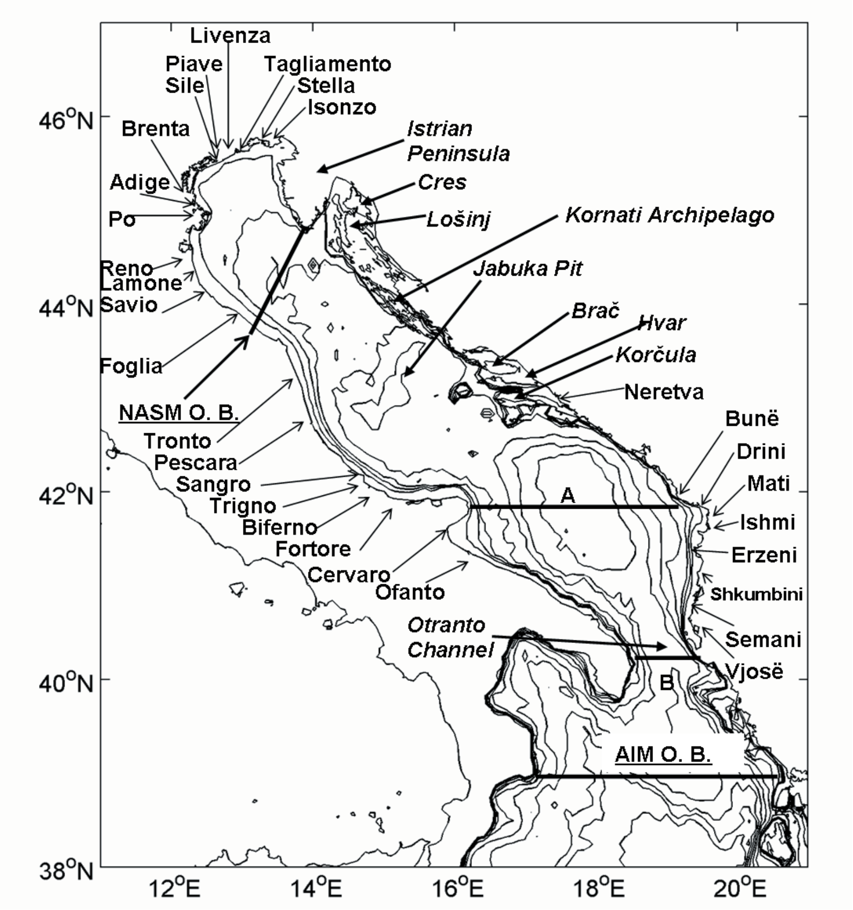

Fig. 1. The Adriatic Sea coastal and bottom morphology. The figure also shows the locations of the river mouths discharging into the basin, the islands retained in the AREG model geometry, the track of the VOS XBT observational program and the location of the open boundary (AREG O.B.). Redrawn with modifications from ZAVATARELLI & PINARDI (2003)

METHODOLOGY AND SYSTEM DESCRIPTION

The Adriatic REGional model, hereafter called AREG, covers the entire Adriatic Sea basin and extends into the Ionian Sea (Fig. 1). The horizontal resolution is approximately 5.0 km, while 21 σ (bottom following) layers define the vertical resolution (Fig. 2). The model is based on the Princeton Ocean Model, POM (BLUMBERG & MELLOR, 1987) as implemented in the Adriatic Sea by ZAVATARELLI & PINARDI (2003). The model contains an embedded second order turbulence closure scheme providing vertical exchange coefficients (MELLOR & YAMADA, 1982). Horizontal diffusion is parameterized following the scheme of SMAGORINSKY (1993), as coded into POM by MELLOR & BLUMBERG (1985). The current implementation makes use of an iterative advection scheme for tracers (SMOLARKIEWICZ, 1984) implemented into POM following SANNINO *et al.,* (2002).

Surface boundary conditions are computed through standard bulk formulae (see table 1 for details) parameterizations previously applied to the Adriatic (MAGGIORE *et al*., 1998; ZAVATARELLI *et al.*, 2002; ZAVATARELLI & PINARDI, 2003; ODDO *et al*., 2005) and Mediterranean Seas (CASTELLARI *et al*., 1998; DEMIROV & PINARDI, 2002). The surface fluxes computation has been carried out interactively, as the sea surface temperature (SST) field required by the bulk formula is provided, for every time-step, by the model simulation.

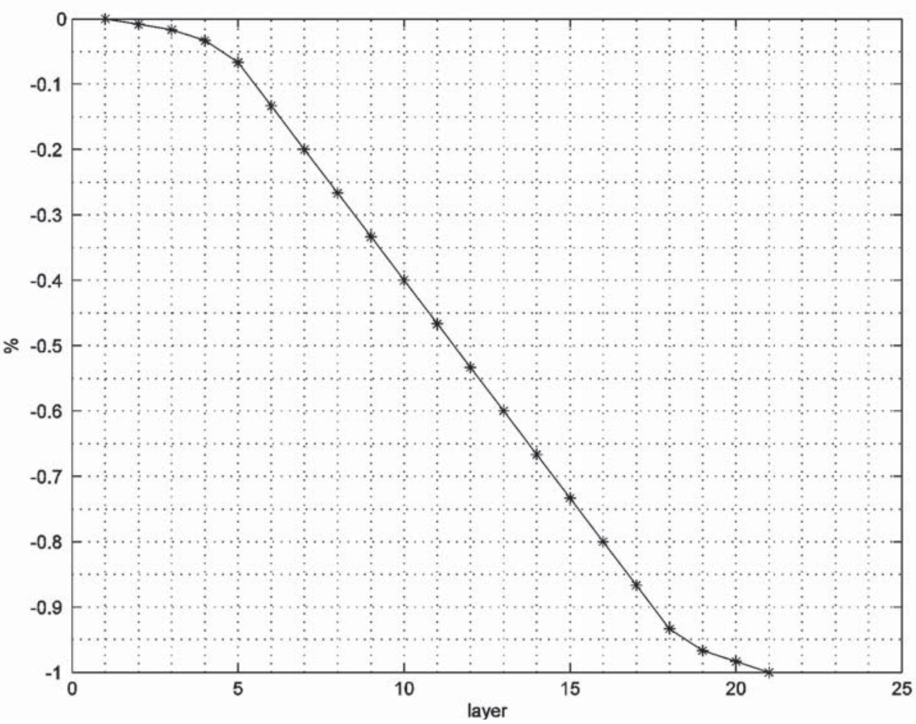

Fig. 2. Vertical sigma layers distribution

Table 1. Bulk formulae used for surface fluxes interactive computation. Sensible heat flux and latent heat flux are computed by classical bulk formulae parameterised according to KONDO (1975)

Solar radiation	REED (1975, 1977)
Net long-wave radiation	MAY (1986)
Sensible heat flux	KONDO (1975)
Latent heat flux	KONDO (1975)
Wind stress drag coefficients	HELLERMAN & ROSENSTEIN (1983)

The atmospheric data (air temperature, relative humidity, cloud cover and both wind components) used to compute the surface heat and momentum fluxes have 0.5° horizontal resolution and 6 hrs frequency and are provided by the European Centre for Medium Range Weather Forecast (ECMWF).

The water flux resulting from the equilibrium between evaporation minus precipitation and river runoff has been parameterized as a salt flux. The evaporation flux has been estimated from the interactively computed latent heat flux, while precipitation values have been obtained from the global climatological monthly means of LEGATES & WILMOTT (1990). The use of climatological precipitation dataset, instead of ECMWF data, is due to the low quality of this field especially after the second forecast day.

The crucially important river runoff data for all the Adriatic Sea rivers have been taken from the RAICICH (1994) compilation of climatological monthly means (in Fig. 1. the mouth location of all the Adriatic rivers considered in the model setup is reported), with the sole (and important) exception of the Po River discharge. The Po runoff is specified daily taking the values at the closing point of the drainage basin (Pontelagoscuro) and partitioned over six grid points approximately representing the proportion of the fresh water discharge through the mouth of the delta (PROVINI *et al.*, 1992).

At the lateral open boundary (Fig. 1) the model is one-way nested with the operational 1/8° resolution model of the entire Mediterranean (PINARDI *et al.*, 2003) through the specification of daily averaged temperature, salinity and velocity fields. The definition of the nested open boundary conditions is based on ZAVATARELLI & PINARDI (2003), to which a nudging term for the scalar properties has been added in a limited area of the model domain immediately adjacent to the open boundary. The relaxation time for the nudging varies from 30 days, at the open boundary points, to 10 years in the innermost area corresponding to the 10th grid point. The forecasting system is operational since April 2003 and it releases 7 day forecasts and hindcasts every week. This paper evaluates the hindcast/forecast products for the period January 1st 2003 – December 31st 2003 in order to provide a first assessment of the model forecasting skill when used without any data assimilation. The climatological temperature, salinity and velocity fields originating from the simulation of the Adriatic Sea circulation of ZAVATARELLI & PINARDI (2003) have been used as the initial conditions (January 1st 1999 at 00:00 GMT).

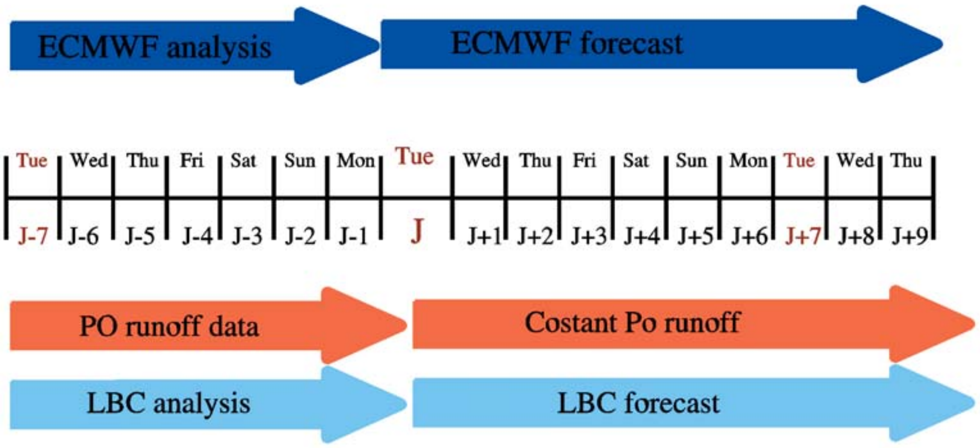

Fig. 3. Time line of hindcast-forecast procedure. The arrows indicate the external data collected on Tuesday (J) and used for the model simulations. 'LBC' indicates the large scale model data used for Lateral Open Boundary conditions. The analysis data span the period starting from noon of the previous Tuesday (J-7) to noon of the current Tuesday (J). The forecast data span the period from 6.00 p.m. of the current Tuesday (J) to Thursday of the next week

The operational forecasting sequence is shown in Fig. 3. Every week the model is integrated for 7 days in hindcast mode from noon of the previous Tuesday (J-7) up to noon of the current week Tuesday (J), the starting time of the forecast. The numerical model is then integrated in forecast mode for 9 days (from J to J+9) using as an initial condition the fields from the hindcast. The hindcast is forced by the ECMWF atmospheric analyses, uses the Mediterranean Forecasting System (MFS) analyses as lateral boundary conditions (LBC) and the observed daily Po runoff is imposed. For the forecast the model is forced instead by the atmospheric and lateral data from ECMWF and MFS forecasts.

Po runoff sensitivity studies

During the forecast, the most recent Po runoff daily value is used since no forecasts of the runoff are presently available. This choice is motivated by the results of a sensitivity study done with simple forecasting methods of the Po runoff. This study has been performed with the Po River data for the year 2002. A 7 day forecast of the Po river discharge has been attempted using three different methods: persistence of the last available value, use of a climatological trend corrected on the basis of the last available data and a forecast based on statistical extrapolation. For the second method a daily climatology has been previously obtained using a time series of daily Po runoff values spanning the period from 1991 to 2001. The result of such computation has been corrected on the basis of the anomaly between the last available data and the corresponding climatological value.

For the runoff forecast based on extrapolation, the coefficients of a polynomial of degree *n* are determined by linear methods from the fit of the observed data in a pre-defined TIME WINDOW. Different sensitivity experiments were carried out using different values for *n* and the TIME WINDOW. For all the tested cases a simple extrapolation gives high values of root mean square (RMS) error. For instance, using n=1 the obtained constant trend does not adequately predict the runoff because the natural variability of the Po River discharge is large even over a few days. Using *n* greater than 2, the resulting polynomial is not sufficiently constrained and the runoff forecast gives unrealistic extrapolated values.

In order to avoid extrapolation similar tests have been performed, expanding the Po runoff time-series (with constant or climatological values) for the forecast period.

The best results have been obtained by fitting the coefficients of a polynomial of degree 3 (*n*) using a series of 22 values, where the first 15 values (TIME WINDOW=15) are the observations and the remaining data have been obtained as those persisting from the last available value. An example of these computations is shown in Fig. 4.

The performance of the different Po forecast procedures has been assessed based on the RMS error between predicted and observed values. The time series of the RMS obtained using a constant value, a corrected climatology and the results of the polynomial approach are shown in Fig. 5 together with the variance of the Po runoff. The results of the three different approaches show similar RMS values and time evolution. Moreover, the “CONSTANT” approach has the lowest annual mean RMS error.

ANALYSIS OF HINDCAST QUALITY AND FORECAST ACCURACY

A detailed description and analysis of the 1999-2003 hindcast simulation, focusing on the interannual variability of the Adriatic Sea general circulation and on a comparison of the simulation results with *in situ* observations can be found in ODDO *et al*., (2005).

In Fig. 6 the hindcasted seasonally averaged mean surface circulation for year 2003 is shown in order to provide an overall picture of the model behaviour. We note that the model successfully reproduces the well-known large scale circulation structure of the Adriatic Sea as well as its seasonal variability. Following the naming scheme proposed by ARTEGIANI *et al*., (1997 a), the model simulates a well defined

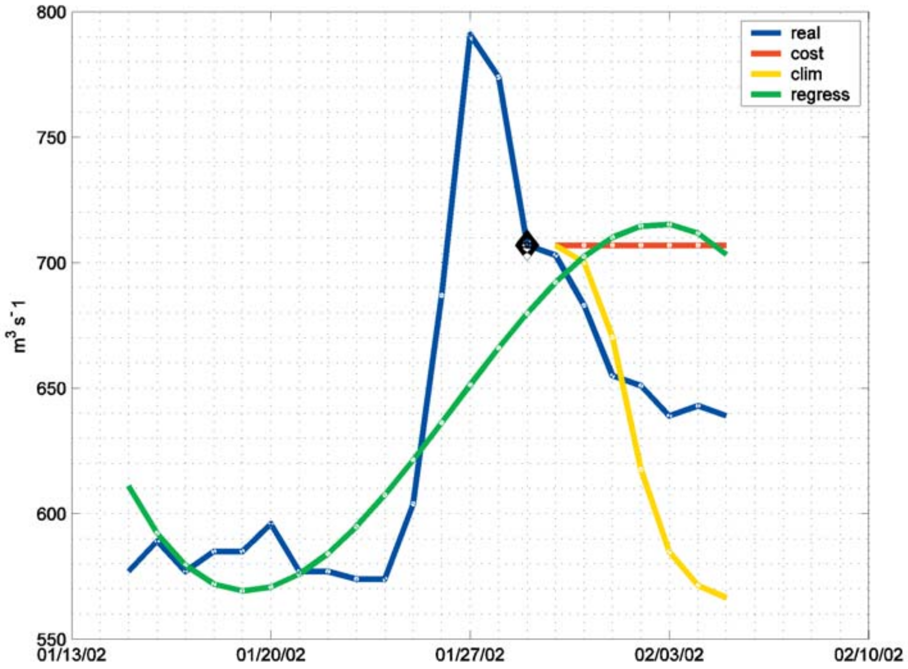

Fig. 4. Example of Po runoff forecasts for the week from January 29th 2002 to February 5th 2002. The diamond indicates the last available Po data. In blue the observed runoff is reported. Green, red and yellow indicate the results of the different forecast methods tested

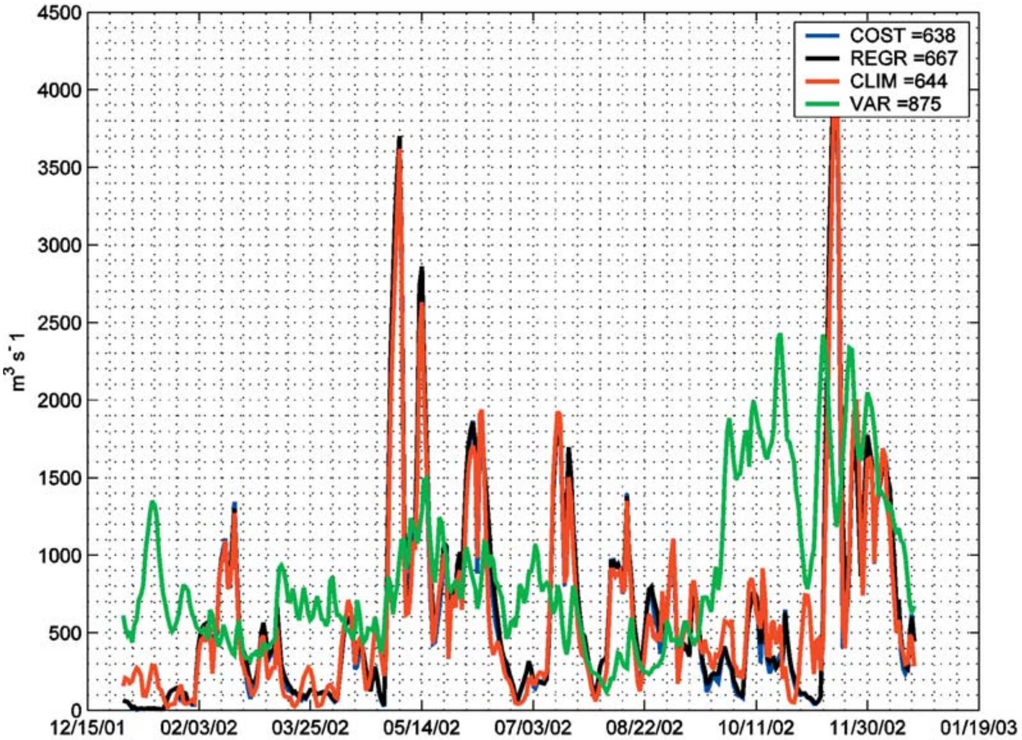

Fig. 5. Time series of the RMS error computed between observed Po runoff values and different forecast methods. The variance of the Po runoff computed using 10 years of daily data is also given (green line). In the legend the annual mean RMS for each forecast method is given

Western Adriatic Coastal Current (WACC) along the Italian coasts and the Eastern Southern Adriatic Current (ESAC), the intensity of which is seasonally modulated. The two coastal currents border the cyclonic gyres in the middle and southern Adriatic (middle, MAd, and southern, SAd, Adriatic gyres respectively), which are intensified in summer and autumn in accordance with the results of previous studies (ARTEGIANI *et al.*, 1997 b; POULAIN, 2001). The Northern Adriatic gyre is also well reproduced in the model results and its centre position shifts from season to season.

Hindcast quality

In Fig. 7A the comparison between the hindcasted basin-averaged sea surface temperature (SST) and the corresponding averages from remotely sensed observations is shown. The sat-

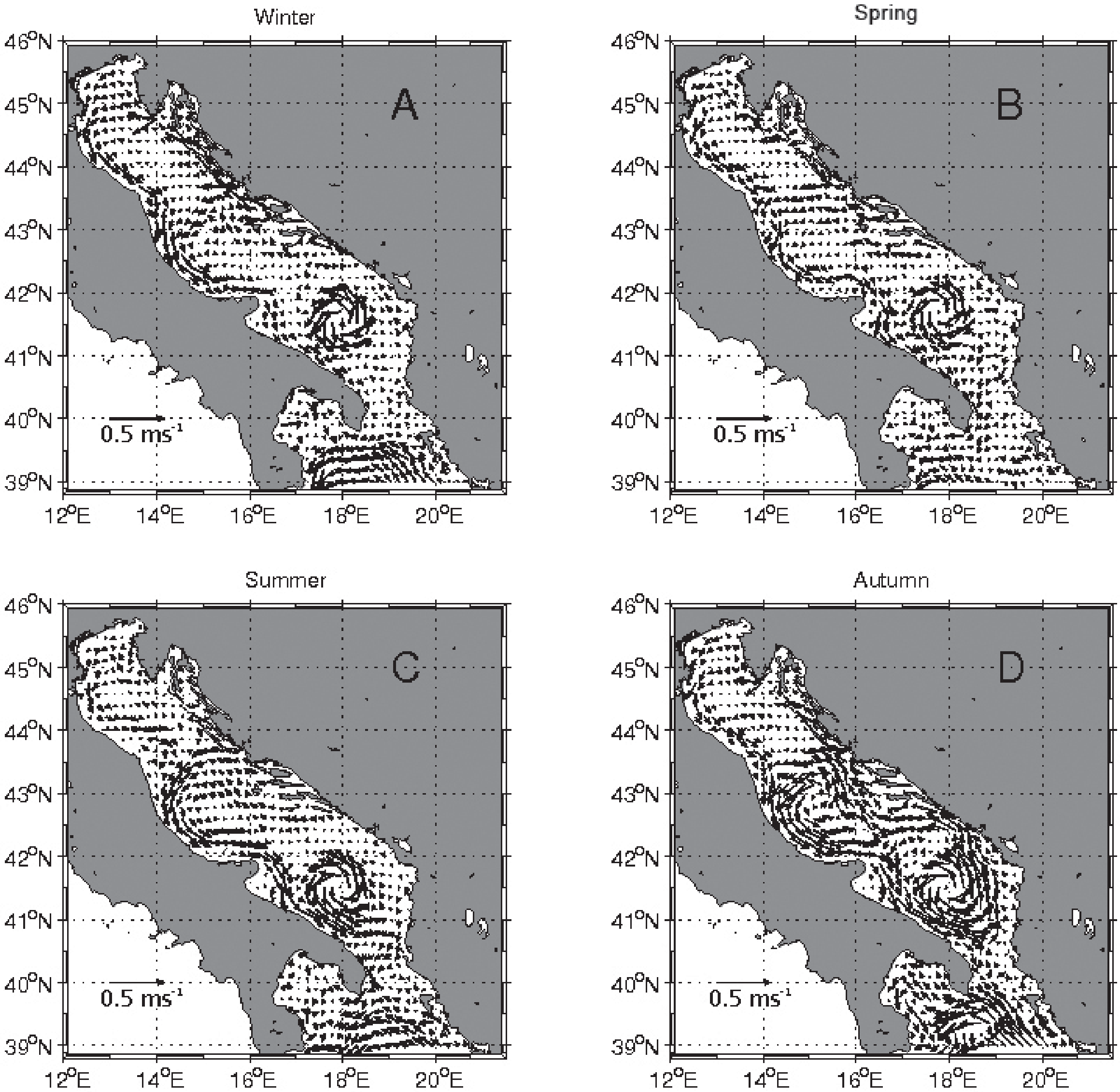

Fig. 6. Seasonally averaged (for year 2003) near surface (2m depth) velocity field. Winter from January to April (panel A); Spring from May to June (B); Summer from July to October (C); Autumn from November to December (D). The seasons definition was first proposed by ARTEGIANI et al., (1997 a,b)

ellite based SST daily fields are computed with a space/time objective interpolation scheme (SANTOLERI *et al.*, 1991) on the AREG model grid, filling also the cloud-covered areas. The comparison denotes a good overall qualitative and quantitative agreement between the hindcast and the remotely sensed SST for a large part of the annual cycle, with the notable exception of the summer period, during which the model seems to underestimate the surface temperature. A possible reason for this discrepancy has been discussed in ODDO *et al.*, (2005) and tentatively identified with overestimation of the vertical mixing processes occurring in summer, causing a lower model surface temperature through mixing with subsurface water.

Moreover it has to be pointed out that summer differences between model and observed surface temperatures could also derive from the missing numerical resolution due to the thickening of the first sigma layer in deep regions and the bulk formulas inaccurate physics. In winter due to greater mixing the vertical resolution has less impact and sea surface temperature can be approximated by the first depth level temperature.

The accuracy and quality of the hindcast and forecast results have been studied by using Root Mean Square (RMS) error indices. The model error, $E_{(i,j)}$, is defined as the difference between the predicted, $P_{(i,j)}$, and the observed, $O_{(i,j)}$, value:

$$E_{(i,j)}=P_{(i,j)}-O_{(i,j)}$$

The correspondent RMS error is therefore:

$$RMS=\left[\left(\frac{1}{N}\right)\sum E^2\right]^{\frac{1}{2}}$$

where N is the total number of available data.

The RMS errors of the AREG hindcast and forecast are shown as horizontal maps and as

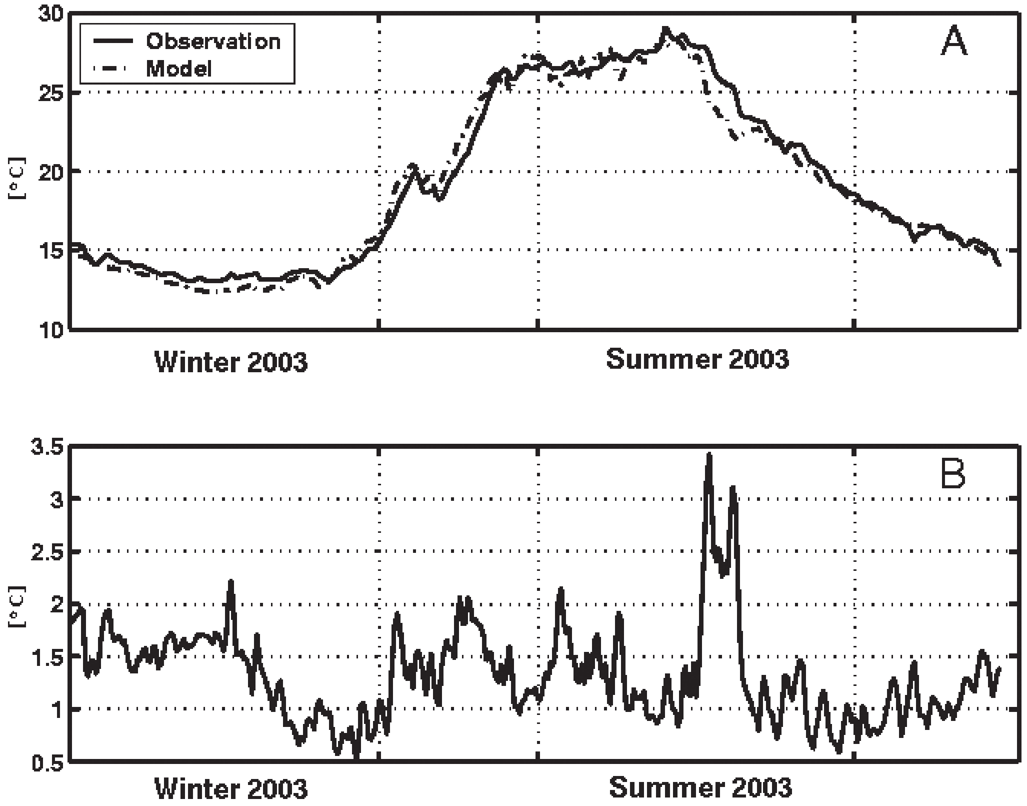

Fig. 7. A: 2003 annual cycle of the basin averaged SST. The dashed line indicates the model hindcast; the solid line indicates the mean of satellite SST observations. B: Time series of the basin averaged hindcast RMS error computed using the observed SST

time series. The former have been obtained by averaging temporally the RMS error values for each grid point, the latter by averaging spatially the RMS error calculated for each day. For the quality assessment, the RMS error has been computed using hindcast and observations (so-called RMS hindcast error), while for the forecast accuracy the RMS error is computed as the difference between forecast and hindcast (so-called RMS forecast error). The time series of the RMS error is shown in order to obtain a time varying synthetic index of the model results, while the horizontal error maps highlight the areas where the major model deficiencies are located.

In Fig. 7B the time series of the horizontally averaged RMS hindcast error for SST using satellite data for all of 2003 is shown. The time series reaches the minima in late winter and summer. It is characterized by a well marked maximum in summer and has a mean bias of about 1.3 °C. We also argue that the main reason for the high values of RMS hindcast error is the misplacement of the spatial structures and probably related to the low horizontal resolution of the atmospheric forcing. The horizontal structure of the same RMS error is shown in Fig. 8. The distribution clearly indicates that the main model deficiency is located in the shallow water areas, in particular in the regions affected by river runoff (Fig. 1). This might be due also to the fact that we do not consider temperature effects for entering Po and other Adriatic river waters in addition to forcing inaccuracies. Furthermore the SST satellite estimates have the lowest accuracy in the shallow coastal areas and therefore the discrepancies might not be entirely due to the model imperfections.

During 2003 Expendable Bathythermograph (XBT) temperature profiles were collected as part of the ADRICOSM monitoring program for the open ocean areas of the southern Adriatic by means of Voluntary Observing Ships (VOS). Temperature data have been collected monthly along a track joining Bari and Dubrovnik and crossing the whole Southern Adriatic (Fig. 1). These data also allowed the computation of the hindcast error for subsurface water properties.

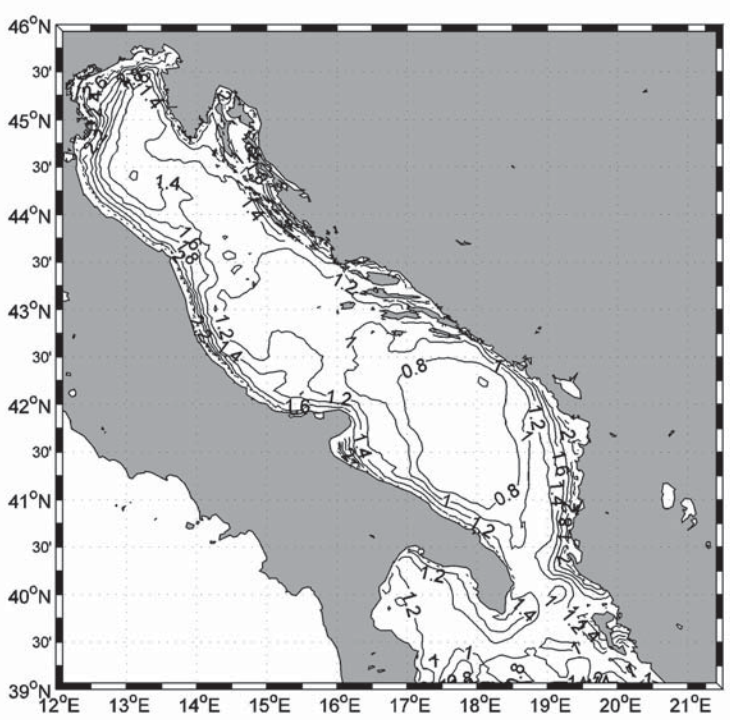

Fig. 8. Spatial distribution of the annually averaged (from 1st January to 31st December 2003) hindcast RMS error computed using the (remotely) observed and hindcasted SST. Units are °C

The RMS hindcast error computed between model results and XBT data is presented as a scatter plot and as vertical profiles in Fig. 9. The time evolution of the hindcast error (Fig. 9A) confirms that higher values are achieved in the summer period. The seasonal averaged vertical profiles of the hindcast temperature error reported in Fig. 9B indicate a good agreement between predicted and observed values below depths of 150 m for all seasons (autumn is missing because the VOS monitoring stopped). The winter profiles are characterised by a relative maximum at a depth of 400 m, probably related to an inexact vertical location of the Levantine Intermediate Water (LIW) intruding into the Adriatic through the Otranto Channel. In spring and summer the high values at the surface and the subsurface maxima confirm the problems in the vertical mixing affecting the upper layers.

Forecast accuracy

In Fig. 10 we show forecasted 2 m temperatures for the second (2nd April 2003), fourth (4th April 2003) and seventh (7th April 2003) day of the forecast together with the corresponding hindcast and their differences (hindcast - forecast). Fig. 10 indicates that the main differences are in the frontal regions of the WACC and in the Po plume. It is interesting to notice that the differences reach a maximum at day 4 and then decrease due to the non-linear dynamics of the regions, which amplify the errors in the forcing functions of the forecast (atmospheric forecast and Po runoff held constant) with a non-exponential law.

The first forecast accuracy index is given by the RMS forecast error for the surface temperature and salinity fields from April 1st to December 31st 2003. In addition we show the so-called RMS persistence error where the forecast to be made with the persistent use of the initial condition and then differences are computed with the hindcast. The RMS forecast and persistence errors are shown in Fig. 11.

The RMS forecast temperature error (Fig. 11A) is always significantly lower than the corresponding RMS persistence error and this

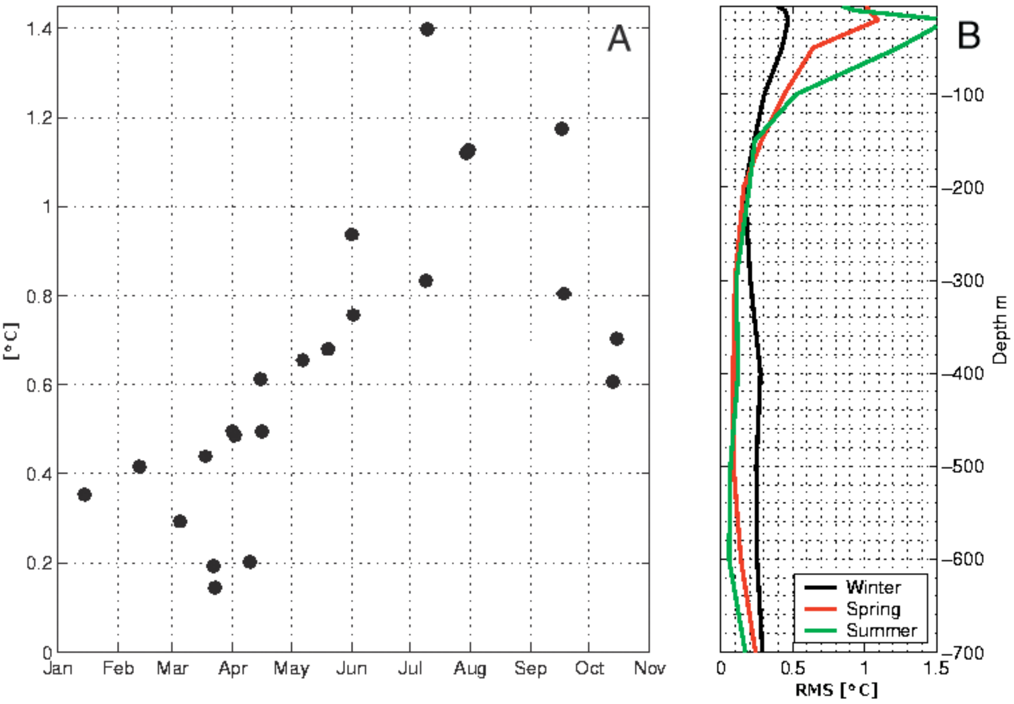

Fig. 9. RMS error computed using the VOS XBT data collected during 2003 along the track indicated in fig. 1 and the corresponding hindcasted temperature. A: Vertically averaged RMS error. B: Seasonally averaged vertical profiles of RMS error

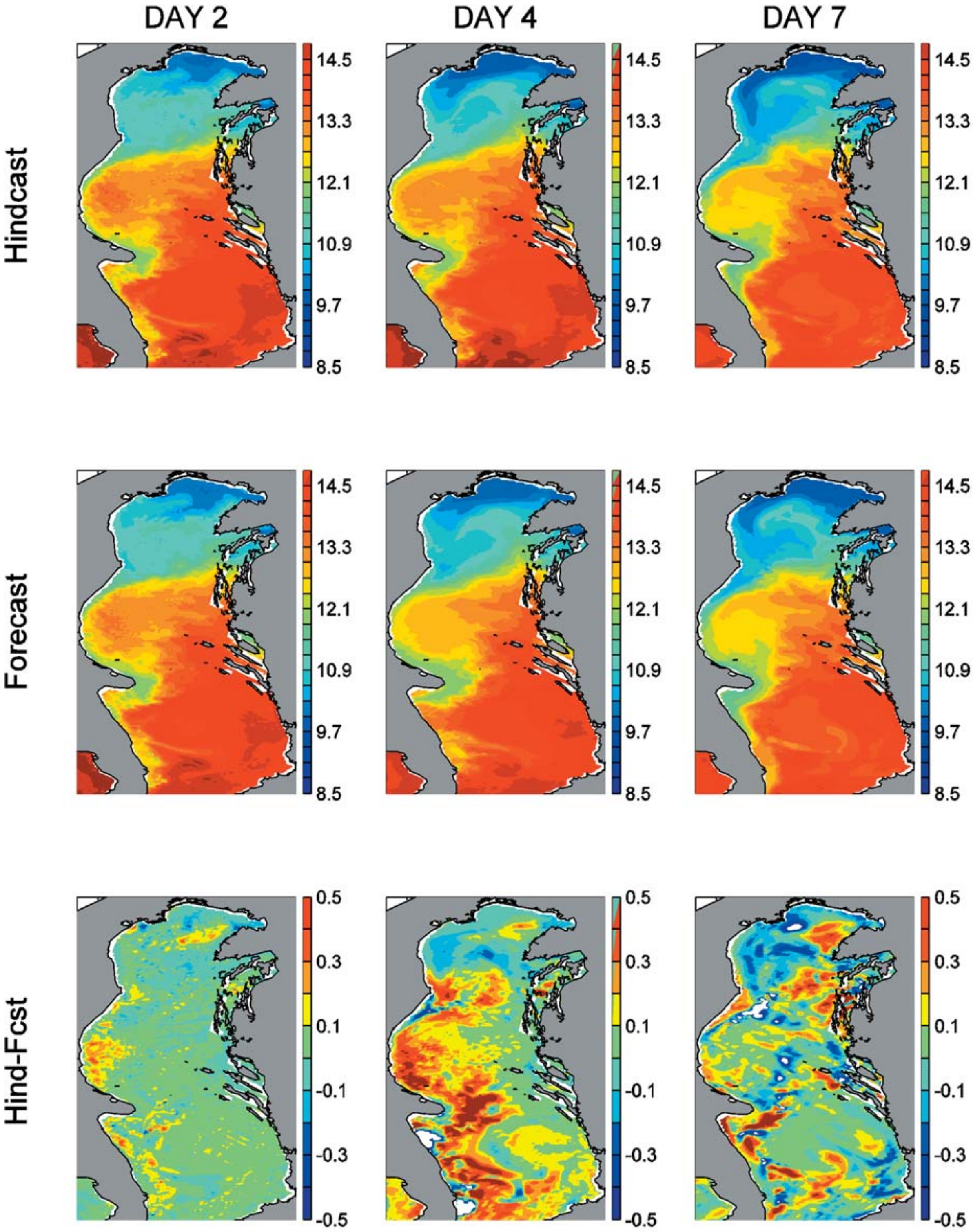

Fig. 10. Horizontal maps of near surface (2m depth) hindcasted and forecasted temperature and their differences. The two simulations (hindcast and forecast) started on 1st April 2003. The second, fourth and seventh days of the simulations are shown. Units are °C

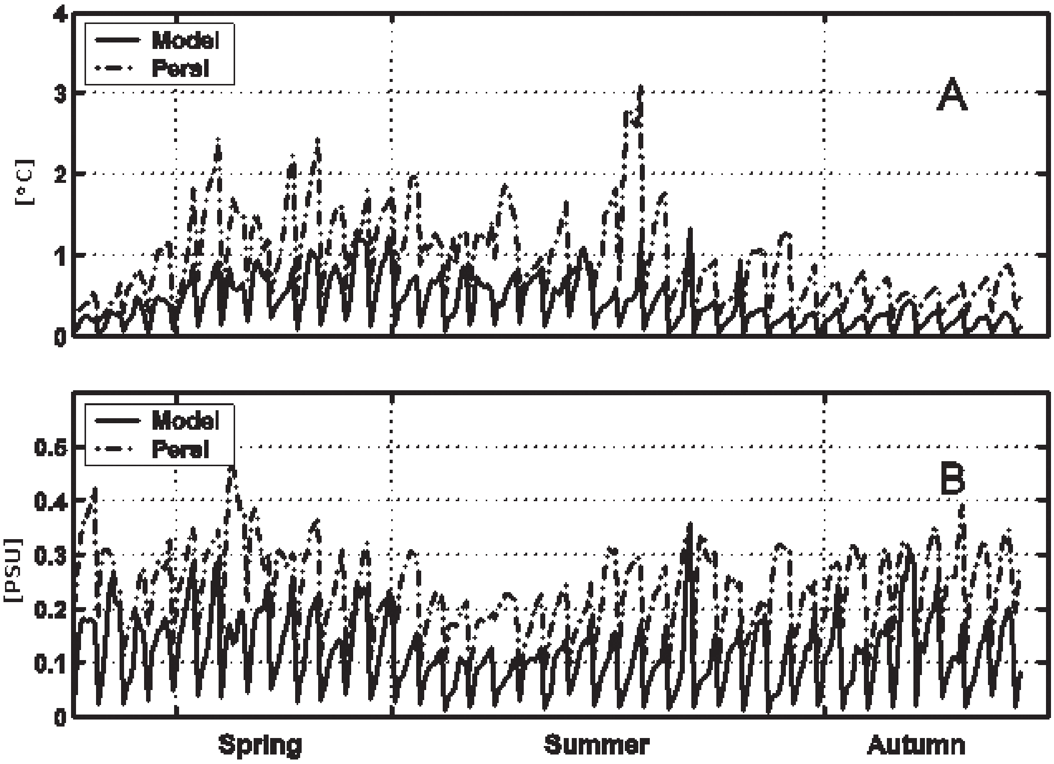

Fig. 11. A: 2003 time series of the RMS forecast and SST persistence error; B: 2003 time series of the RMS forecast and SSS persistence error

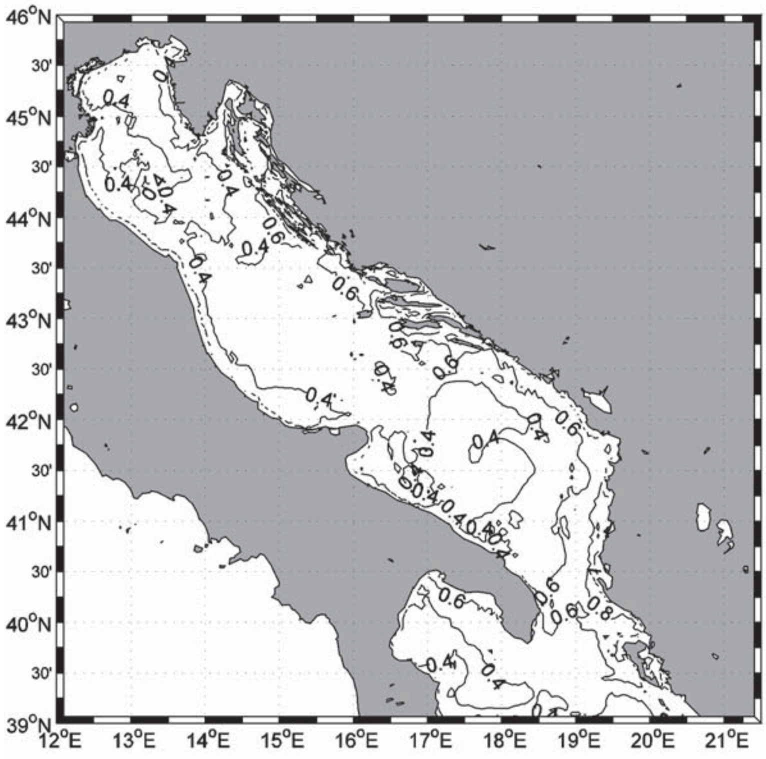

Fig. 12. Horizontal map of the time averaged (from 1st April to 31st December 2003) RMS error between hindcasted and forecasted SST. Units are °C

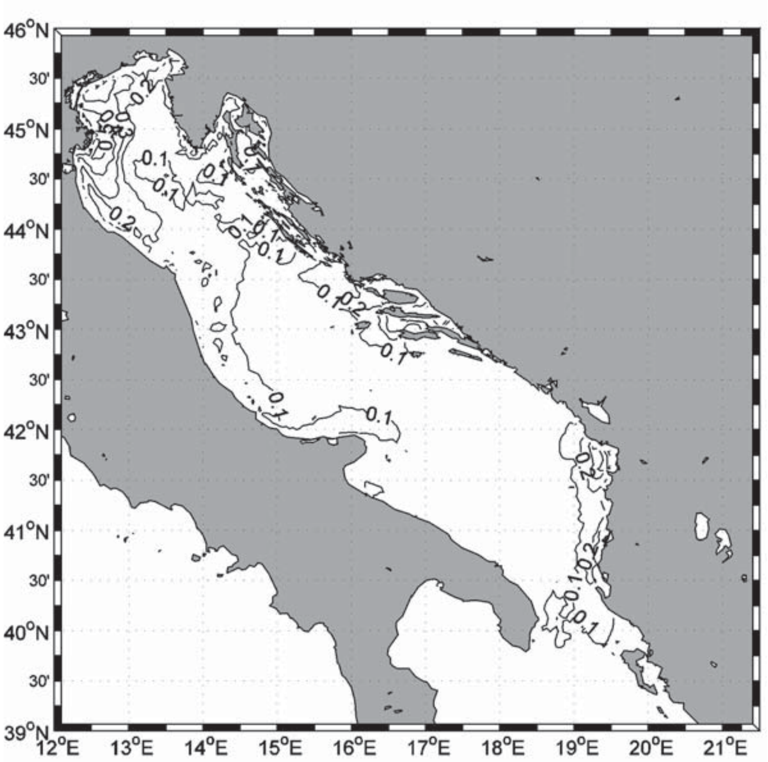

Fig. 13. Horizontal map of the time averaged (from 1st April to 31st December 2003) RMS error between hindcasted and forecasted Sea Surface Salinity. Units are PSU

gives a general motivation for the necessity of a numerical forecast system. In terms of temperature the accuracy of the forecast decreases in spring and early summer, whilst being practically constant in autumn. On the other hand, the forecast error in the surface salinity (Fig. 11B) reaches the minimum values in summer and generally shows lower variability with respect to the error for temperature time series. The summer minima are obviously a consequence of the low Po runoff variability (Fig. 5 green line).

The horizontal map of the time averaged RMS forecast error for surface temperature and salinity are shown in Fig. 12 and Fig. 13 respectively. The surface temperature RMS forecast error has an east-west gradient with the maxima along the east coast. The pattern of the salinity RMS forecast error has an extended maximum in front of the Po Delta, obviously related to the Po forecast errors, and other maxima closer to the east coast. We argue that the higher forecast error in temperature and salinity along the eastern Adriatic side is mainly due to atmospheric forcing inaccuracies, whilst the salinity forecast error is dominated by the Po runoff uncertainties.

CONCLUSIONS

The AREG forecasting system has been developed to predict the hydrodynamic conditions of the Adriatic Sea. The choices made during the implementation phase make the system stable and robust, and allow long time integration without significant drift.

The model forecast accuracy, as well as hindcast quality, have been evaluated for the year 2003, the intensive data collection period for the ADRICOSM project.

The hindcast quality evaluation carried out using XBT data indicates a good agreement between observed and simulated temperature below a depth of 100 m in all seasons. RMS hindcast error variability is particularly evident only in the upper layers, reaching the maximum value in summer. Moreover, the major hindcast deficiencies seem to be related to the inaccurate parameterisation of the vertical mixing processes that mainly affect the hindcast quality during the stratified period. Further hindcast quality investigations have been carried out using satellite sea surface temperature. This study confirmed the previous results and also indicated rivers temperature effects (actually neglected) as a possible source of errors. Moreover, as already pointed out, it is difficult to accurately quantify the model error using satellite images given the low accuracy of this kind of observations in the coastal areas and the possibility during summer of large skin effects.

The choice of a constant Po runoff value during the forecast obviously affects the forecast results in front of the Po Delta and along the WACC. It is found that the Po runoff forecast and the inaccurate atmospheric forecast are the major source of errors in the northern Adriatic area as well as along the western and eastern sides of the Adriatic. However, the RMS forecast error is always lower than the RMS persistence error and this justifies the usage of a numerical prediction system in the Adriatic Sea for short term forecasts.

From an analysis of the horizontal distribution of the system RMS error, and in agreement with the results of previous numerical studies in the Adriatic Sea (ZAVATARELLI & PINARDI, 2003), we can conclude that in the northernmost part of the basin, where the horizontal and vertical processes have smaller space-time scales, there is a need for higher horizontal resolution in the model.

A data assimilation scheme suitable for the area is under development and will be soon implemented in the operational scheme (GREZIO & PINARDI, 2005).

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Jadranski prognostički sustav

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SAŽETAK

U okviru projekta “Integralno upravljanje obalnom zonom Jadranskog mora (ADRICOSM)” uspostavljen je regionalni oceanografski prognostički sustav. Sustav se sastoji od oceanografskog modela horizontalne rezolucije 5 km i sustava prikupljanja hidrografskih podataka u priobalnom području i na otvorenom moru. Numerički model je temeljen na Princetonskom Oceanskom Modelu (POM) uz korištenje iterativne SMOLARKIEVIČEVE advekcijske sheme, interaktivnog računanja protoka na granici mora i atmosfere, protoka rijeke Po, kao i drugih jadranskih rijeka, te gniježđenja s mediteranskim modelom. U ovom radu podaci iz sustava mjerenja korišteni su samo za ocjenu rezultata modela. Prikazani su rezultati dobiveni tijekom prve godine operativnog sustava, a procjena ponašanja modela i njegovih rezultata dobivena je na temelju RMS (root mean square) pogreške.

Ključne riječi: prognostički sustav, model opće cirkulacije, Jadransko more