ISSN: 0001-5113
AADRAY

ACTA ADRIAT.,
47 (Suppl.): 219 - 245, 2006

UDC: 556.11.081.519876.5(262.3)

Nested modeling of the east Adriatic coastal waters

Mirko ORLIĆ [1], Gordana BEG PAKLAR [2], Zoran PASARIĆ [1], Branka GRBEC [2]
and Mira PASARIĆ [1]

[1]Andrija Mohorovičić Geophysical Institute, Faculty of Science, University of Zagreb,
Horvatovac bb, 10000 Zagreb, Croatia

[2]Institute of Oceanography and Fisheries, P. O. Box 500, 21000 Split, Croatia

The middle Adriatic coastal area was numerically modeled with a 1 km resolution in order to simulate temperature, salinity and currents. The model employed was a modification of the Princeton Ocean Model (POM), forced with surface momentum, heat and water fluxes and discharges from four rivers: Jadro, Žrnovnica, Cetina and Neretva. The coastal model was nested into the whole-Adriatic model having a 5 km resolution, using a simple off-line one-way nesting technique. Results of a three-year long experiment with perpetual atmospheric and river forcing were characterized by a strong annual signal, in reasonable agreement with temperature and salinity data taken at permanent oceanographic stations along the Split-Gargano transect. Current reversal obtained between the islands of Hvar and Vis in summer also agreed with previous measurements. The simulation also revealed the way Dalmatian islands – in particular Lastovo and Vis – influence the East Adriatic Current prevailing in winter, with wakes being formed behind the islands and jets among them. Comparison of an interannual simulation with corresponding measurements showed good agreement for temperature, whereas a discrepancy in salinity was related to the model being forced with climatological water fluxes. Experimental forecasts, produced over a six-month period, enabled some experience to be gained in operational oceanography, but also pointed to an additional problem – the model overmixing when the wind forcing is pronounced. Moreover, low spatial resolution of atmospheric forcing was suspected of reducing the quality of current forecasts for some wind directions.

Key words: nested modeling, temperature, salinity, currents, Adriatic

INTRODUCTION

Systematic investigation of physical properties and processes in the coastal waters off Split began in the 1930s, after the Oceanographic Institute had been established in that town. The first major contribution was made by ERCEGOVIĆ (1934), who carried out weekly or bi-weekly measurements of temperature and salinity throughout one year, at four stations. He found that the annual temperature cycle lags behind the forcing, more so at the deeper levels and at the offshore stations. Moreover, he related the annual salinity cycle to precipitation and river inflows, and commented on the importance of both the wind and buoyancy forcing for the change of stratification.

In the late 1940s a network of permanent hydrographic stations had been established on the transect extending from Split to Gargano, and in the 1950s measurements with classical current meters were initiated. The results began to appear in press a decade later. Thus, it was found that in the vicinity of Split surface salinity peaks two times a year (BULJAN, 1961) and that off the island of Vis there is a single salinity maximum in a year (BULJAN, 1965). Temperature was found to follow the expected annual course, except that a cooling was observed in August and September off Vis at depths of 20-60 m – probably due to upwelling (BULJAN, 1965). Using 24-hour time series of currents recorded on a number of occasions under fair-weather conditions ZORE-ARMANDA (1968) showed that the residual currents in the area change direction: from NW in winter to SW-SE in summer. Later, year-to-year variability of temperature, salinity and currents also received some interest, and in particular it was established that the variability could be related to the air-pressure gradient between the Adriatic and East Mediterranean Seas (ZORE-ARMANDA, 1985), with a relatively high (low) air pressure over the Adriatic supporting an increase (decrease) of salinity.

Occasionally, experiments were organized in some smaller basins in the area. Particular attention was paid to Kaštela Bay. Bi-weekly hydrographic measurements performed over a year at a network of twenty stations enabled reconstruction of current fields related to different winds and various stratification conditions there (ZORE-ARMANDA, 1980).

Acquisition of autonomous current meters in the 1970s made collection of time series over a month or two feasible. The data taken in Mali Ston Bay (VUČAK *et al*., 1981) and Kaštela Bay (GAČIĆ, 1982; GAČIĆ *et al*., 1987; BEG PAKLAR & GAČIĆ, 1997) were used primarily to analyze the response of coastal waters to forcing by the dominant Adriatic winds – bora and sirocco. It was found that in Mali Ston Bay bora drives surface waters into the bay while bottom waters are flushed out of it, and that during sirocco events circulation is reversed. Moreover, it was observed that in Kaštela Bay the surface currents are generally directed downwind, the bottom currents upwind.

Wind-driven currents in Kaštela Bay were also considered by numerical modelers. ORLIĆ *et al.* (1999) developed a model reproducing the influence of the winds on the bay under the homogenous wintertime conditions. It was found that the response of the sea to the forcing depends on the interaction of the wind field with variable bottom topography, that transports are organized in a cyclonic gyre during the bora episodes and in several smaller gyres during the sirocco episodes, and that the surface and bottom currents are oppositely directed. BEG PAKLAR *et al.* (2002) paid attention not only to the homogenous but to the stratified conditions as well. It was established that in winter the currents at a particular level may be more complex than previously believed, and that in summer they are considerably influenced by a reduced exchange of momentum at the pycnocline depth.

It is obvious from the above review that the observations in the coastal waters off Split encompassed a wide range of properties and processes whereas the modeling concentrated on the current field and a single process. Both the experimental and theoretical studies were limited to a few locations. After seven decades of oceanographic investigations the time was ripe for a model that would reproduce temperature, salinity and currents in the wider east Adriatic coastal

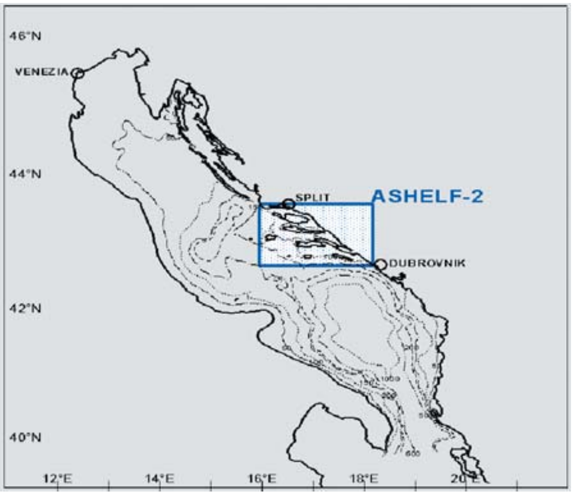

Fig. 1. Map of the Adriatic showing the position of the ASHELF-2 model domain

area. As these parameters depend on meteorological, river and open-sea forcing, the model had to be able to accommodate all of these influences. We have found a modification of the Princeton Ocean Model (POM, BLUMBERG & MELLOR, 1987) suitable for the purpose. The model was applied on a high-resolution grid covering the middle Adriatic coastal waters (Fig. 1), was forced with the air-sea fluxes and river inflows, and was nested into the whole-Adriatic model having a 5 km resolution (AREG, ZAVATARELLI & PINARDI, 2003). The small-scale model was called ASHELF-2 and it was used (1) to simulate average climatological characteristics, (2) to compute interannual variability and (3) to produce the first short-term oceanographic forecasts for the area. The present paper is structured accordingly.

PERPETUAL-YEAR SIMULATION

A three-year long simulation with perpetual atmospheric, river and open-sea forcing was performed in order to reproduce climatological characteristics of the east Adriatic coastal area.

Model setup

Generation of ASHELF-2 mask and bathymetry

ASHELF-2 mask and bathymetry were designed to capture the most important features of the local bathymetry (Fig. 2). Grid generation started from a standard nautical map having a scale of 1:200000. As the first step, the coastline was digitized and represented by a union of segments. Using the special purpose domain

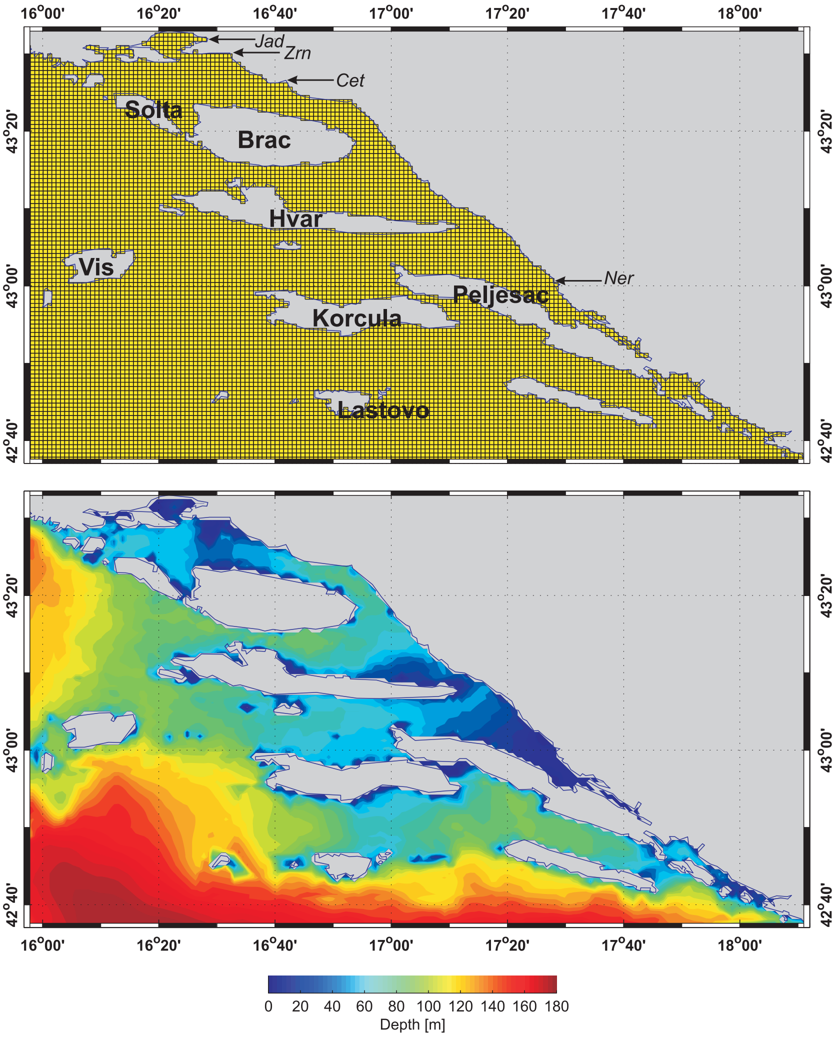

Fig. 2. Mask and bathymetry used in the numerical simulations; horizontal grid step is 1x1 km

processing system the rough mask was produced and subsequently corrected by hand. The proposed grid resolution was 1 km which resulted in a grid of 189 x 106 elements, approximately half of which are wet ones. Special care was taken to ensure that the Split Strait between the islands of Brač and Šolta, the channel between the Pelješac peninsula and the island of Korčula and the channel between the mainland and the island of Hvar have remained opened on the model grid. Bathymetry for the region near the coast and between islands was obtained from an original nautical map using triangular linear interpolation (RENKA, 1984). The outer region was filled by bilinear interpolation from a standard 1 min data set (DBDB-1), the same data from which the AREG bathymetry was produced. Furthermore, in the hope of gaining some benefit for nesting, the AREG bathymetry was improved over the ASHELF-2 region using the ASHELF-2 bathymetry.

Besides the grid with constant horizontal resolution of 1 km, ASHELF-2 used 16 sigma layers along the vertical with finer distribution near the surface and bottom. The COURANT-FRIEDRICHS-LEWY criterion was satisfied with an external time step of 7 s and internal time step of 140 s.

Surface and coastal forcing

The ASHELF-2 model was forced by the monthly values of wind stress and surface heat and water fluxes obtained from products provided by the European Center for Medium Range Weather Forecast (ECMWF) and some measurements as well as by the monthly discharges from four rivers: Jadro, Žrnovnica, Cetina and Neretva.

Monthly wind stress fields (Fig. 3) were obtained from 6 hour ECMWF surface re-analysis results calculated with a spatial resolution of 1.125 deg (i.e. 89 x 125 km) over the 1979-1983 interval, using the HELLERMAN & ROSENSTEIN (1983) formulation (ZAVATARELLI & PINARDI, 2003). The fields reveal that the winds are rela-

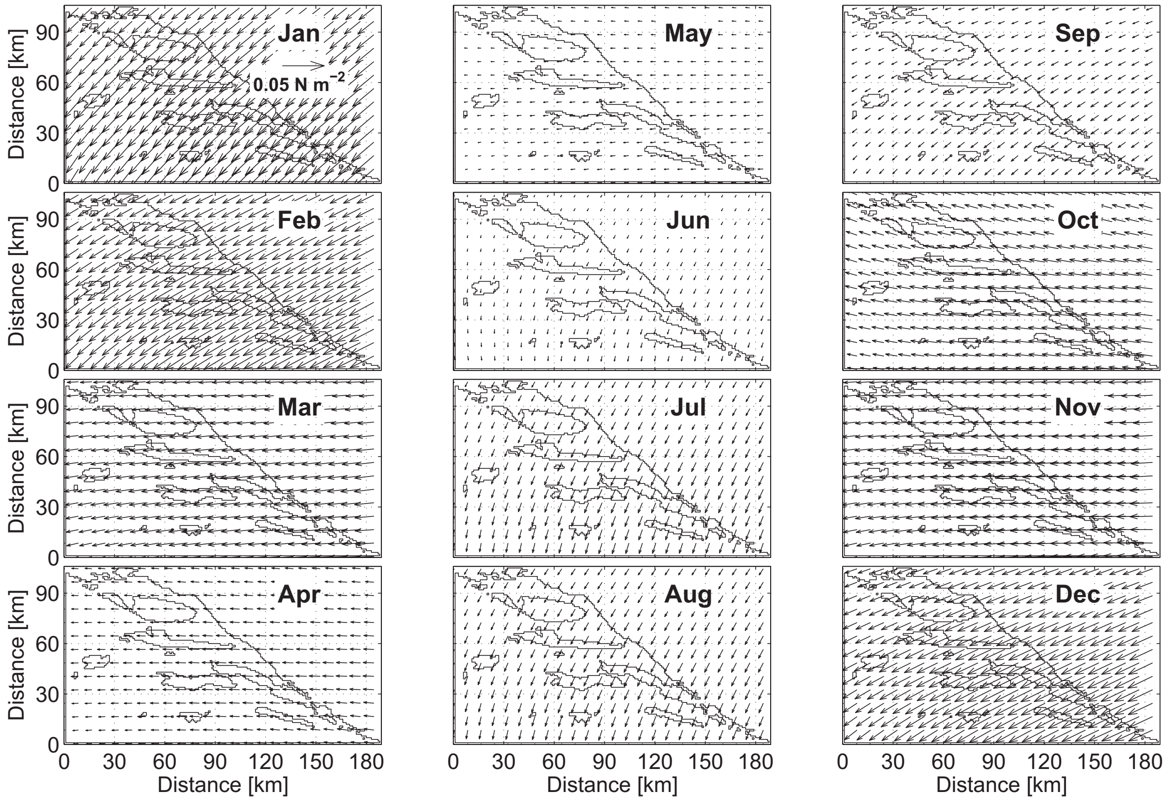

Fig. 3. Original ECMWF monthly wind stress fields interpolated onto the ASHELF-2 grid

tively strong and blowing from the northeast during the colder part of the year, and that they are weaker during the rest of the year. These are well known features of the Adriatic atmospheric conditions, related to the development of monsoons which are felt in the area in winter but not in summer (BARRY & CARLETON, 2001). The monthly fields of wind stress were corrected, following KILLWORTH (1996), before simulation in order to preserve monthly mean values while linearly interpolating between the corrected values during the simulation. The wind stress components were multiplied by a factor of 2.5 according to the findings by CAVALERI & BERTOTTI (1997). Corrected wind stress components were bi-linearly interpolated from the 1.125 deg resolution grid onto the ASHELF-2 grid.

Surface heat fluxes were obtained from the perpetual-year AREG simulation. For the surface forcing of AREG 'level-0' heat fluxes have been used (ZAVATARELLI & PINARDI, 2003). They are monthly averaged heat fluxes obtained from ECMWF surface re-analysis results calculated for the period 1979-1983 with a 1.125 deg resolution. These fluxes have been applied to AREG together with a heat flux correction term having the following form:

$$Q_c = \left(T_o^* - T_o\right)\left(\frac{\partial Q}{\partial T}\right) \tag{1}$$

where T^*_o was the seasonally varying climatological sea surface temperature provided by ARTEGIANI *et al.* (1997), T_o was the model predicted sea surface temperature whereas $\partial Q/\partial T$ equalled 40 W/(m^2 °C). 'Level-1' heat fluxes diagnosed by AREG during the last perpetual year run with the 'level-0' values plus the surface heat flux correction term were used for the atmospheric forcing of ASHELF-2 (Fig. 4). They follow the expected pattern. AREG 'level-1' heat fluxes were bi-linearly interpolated onto the ASHELF-2 grid and corrected according to

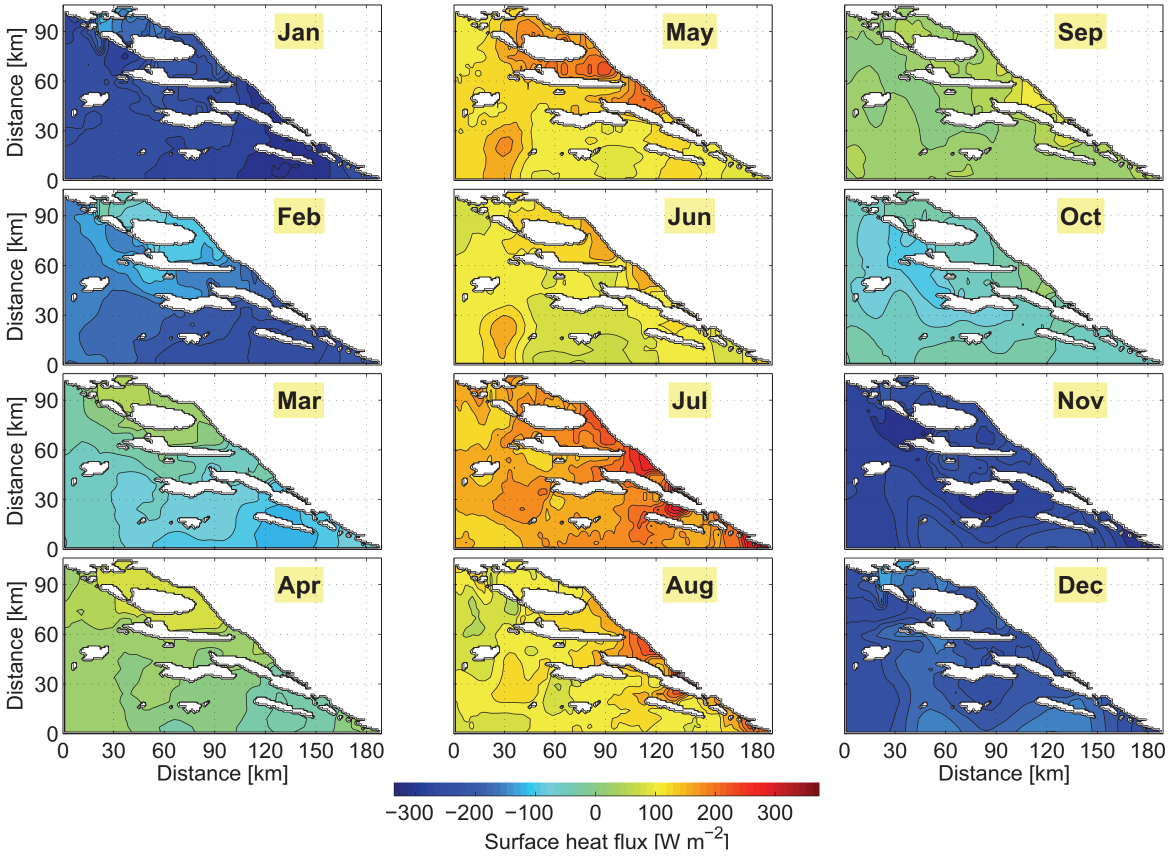

Fig. 4. The same as in Fig. 3, except for the surface heat flux; positive values indicate that the sea is gaining heat from the atmosphere

KILLWORTH (1996) before simulations. During the three-year long ASHELF-2 simulation heat fluxes were corrected in the same way as in the AREG simulation in order to preserve seasonal climatology.

Surface water fluxes were computed from evaporative heat fluxes obtained from ECMWF re-analysis products and LEGATES & WILMOTT (1990) monthly precipitation data were provided with a 0.5 deg resolution (i.e. 39 x 55 km) (Fig. 5). The wintertime maximum in the lower right part of the domain is a well known feature, related to the maximum of precipitation in the southeast Adriatic (PENZAR *et al*., 2001). The monthly water fluxes were corrected according to KILLWORTH (1996) before simulation. During the simulation water fluxes were additionally corrected so as to produce the seasonal sea surface salinity, using:

$$W_c = \left(S^*_o - S_o\right) H / \gamma \qquad (2)$$

where S^*_o was the seasonally varying climatological sea surface salinity provided by ARTEGIANI *et al.* (1997), S_o was the model predicted sea surface salinity, H was the thickness of surface grid cell and γ was the relaxation time chosen to equal 1 day.

Rivers were included in the surface water flux at the grid points that correspond to the location of the four rivers discharging into the ASHELF-2 domain. Jadro, Žrnovnica and Cetina were considered as point sources, whereas Neretva was assumed to be a line source occupying six grid points. In order to determine climatological forcing by rivers in the ASHELF-2 region, monthly mean values of water discharge for the four rivers were collected and analyzed. While determining the mean annual course of the river discharges into the Adriatic, several problems had to be tackled. First, due to tidal influence, river discharge can not be measured at the river mouth. Thus estimates had to be based on measurements made far upstream, which do not account for possible downstream water sources or losses into the karst ground. Second-

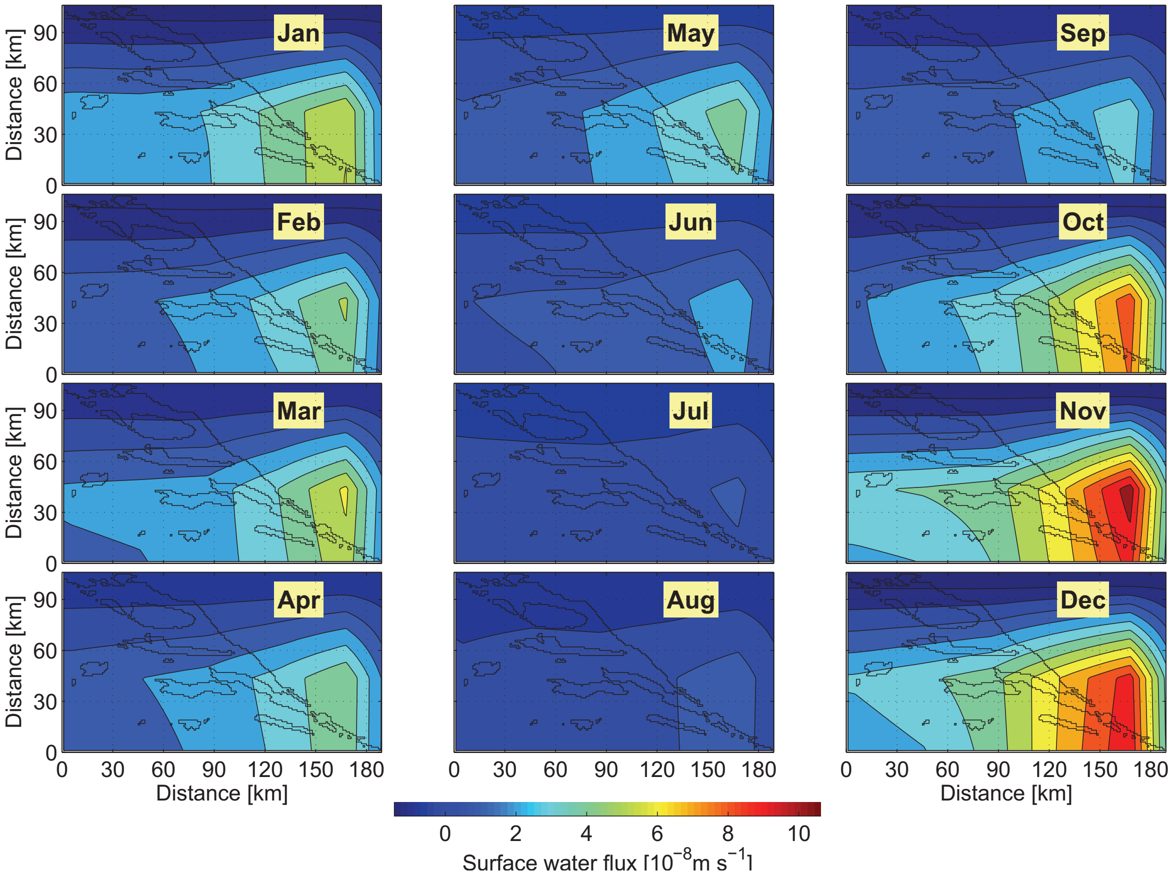

Fig. 5. The same as in Fig. 3, except for the surface water flux (P-E)

ly, some of the time series were inhomogeneous and discontinuous due to strong anthropogenic impact, primarily on the Cetina and Neretva rivers. The construction of numerous hydraulic structures (hydroelectric power plants, water reservoirs) in the last few decades has strongly changed the natural river regime. The redistribution of flow throughout the year – by an increase of low waters and a decrease of high waters – has significantly diminished seasonal variability of water discharge. The estimates obtained for the four rivers are shown in Fig. 6. It may be noticed that the discharges are somewhat smaller than those found in the oceanographic references (thus, for example, our value for the Neretva annual mean discharge is 332 m^3s^{-1} whereas RAICICH (1994) estimates it at 378 m^3s^{-1}). The seasonal cycle of water discharges has two maxima – the primary one in December and a secondary one in April.

Initial and open boundary conditions

Temperature and salinity initial fields for the simulation of the average annual conditions were obtained from the last year of the perpetual three-year integration with the AREG model. The AREG results were averaged over 10 days and the averages corresponding to the last ten December days of the perpetual year were bi-linearly interpolated on the ASHELF-2 grid in order to start the model in January. The initial condition for the current field was a state of rest.

ASHELF-2 was connected to AREG by a simple off-line one-way nesting using 10-day averaged values of velocity, temperature, salinity and elevations from the AREG simulation (ZAVATARELLI & PINARDI, 2003). Time varying ten-day averaged AREG fields were interpolated on the ASHELF-2 model grid and then specified at its western and southern open boundaries

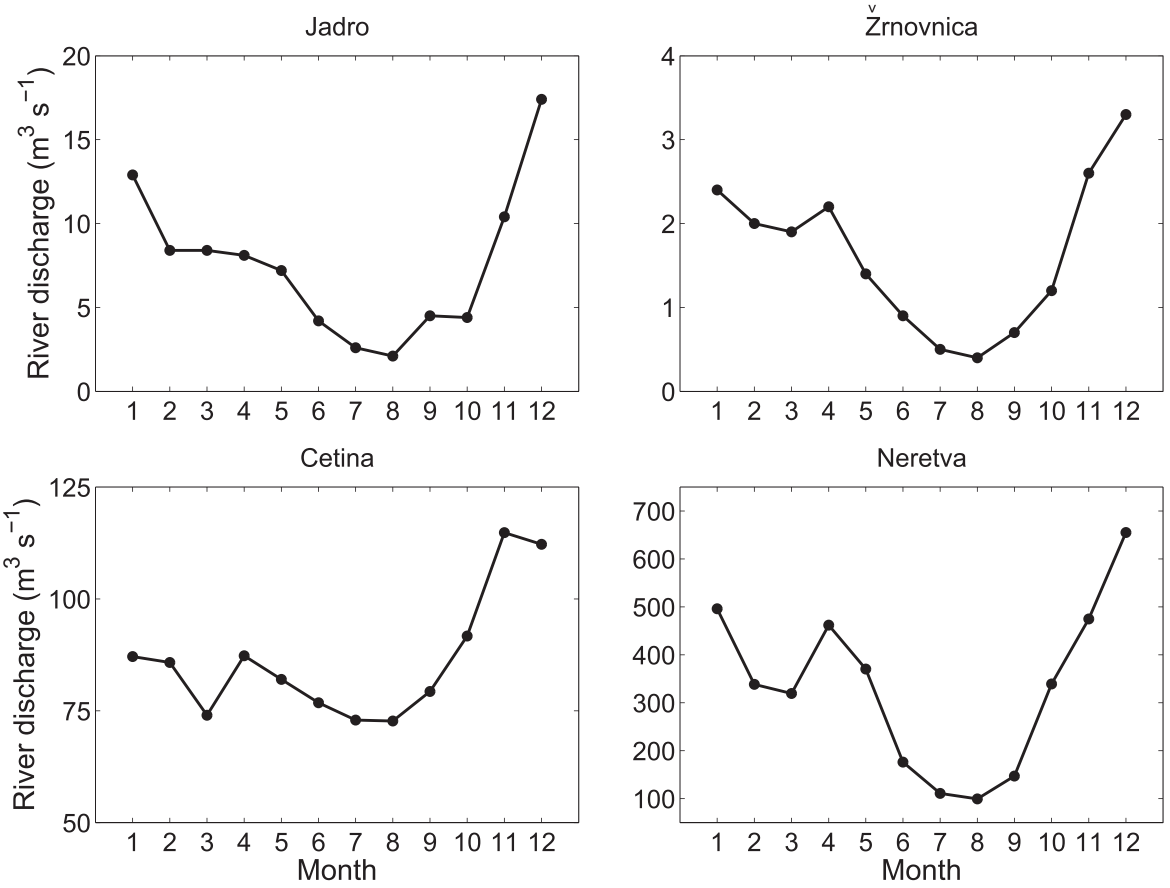

Fig. 6. Annual cycles of four rivers discharging into the ASHELF-2 model domain

(Fig. 7a and b). The fields show that the summertime open-boundary currents differ considerably from those prevailing during the rest of the year which, as will be shown, profoundly influence dynamics of the coastal waters. The nesting procedure followed the one used by ZAVATARELLI & PINARDI (2003), thus ensuring that the volume transport across the ASHELF-2

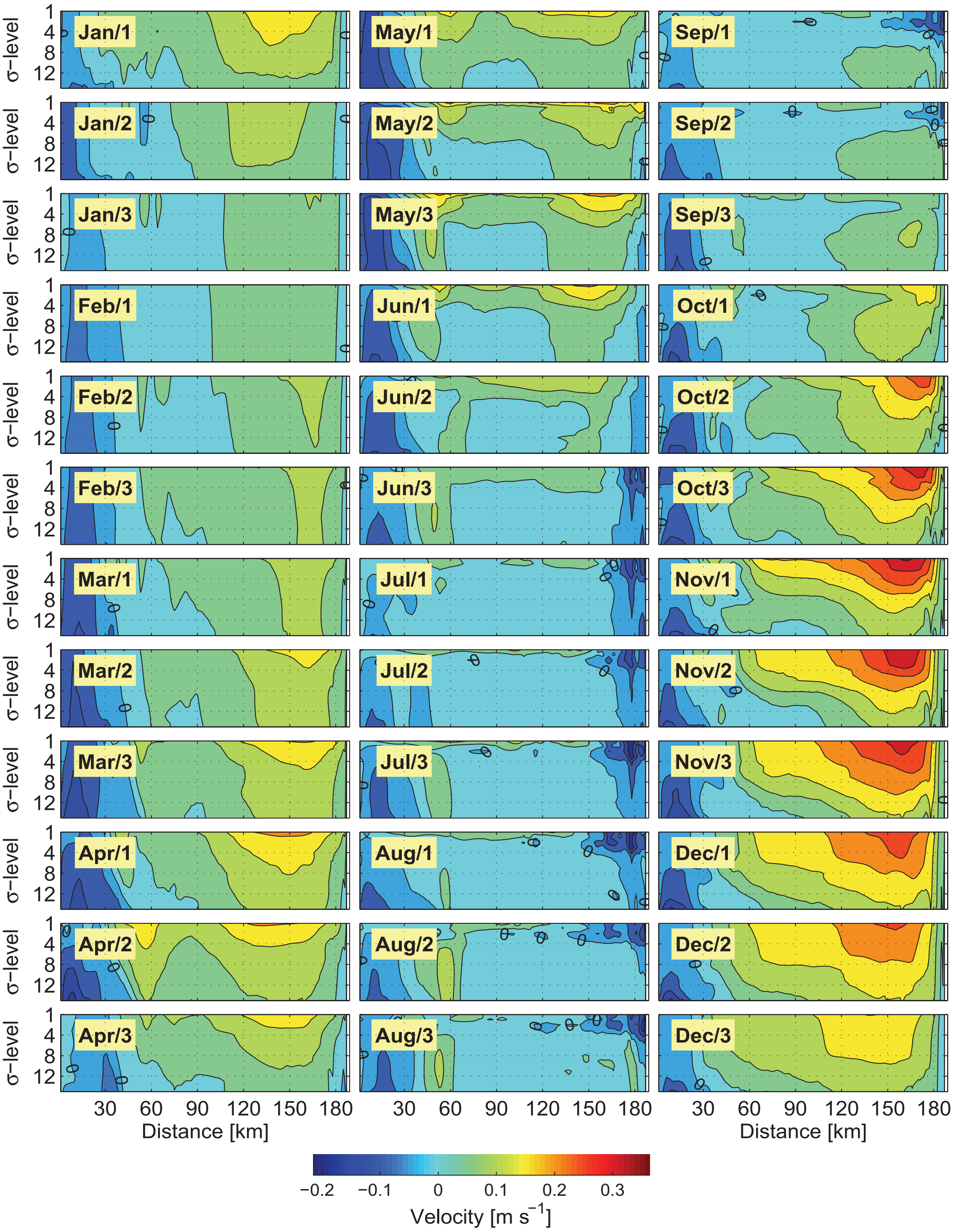

Fig. 7a. Time series of 10-day current fields obtained by an AREG run and used in the nesting procedure for the perpetual-year simulation. Shown are along-Adriatic currents, interpolated onto the ASHELF-2 southern open boundary; numbers on vertical axes refer to σ-levels

open boundaries matches the volume transport across the corresponding section of the AREG model. Temperature and salinity at the outflow boundaries were locally upwinded, whereas at the inflow boundaries they were prescribed from the AREG fields. KILLWORTH correction was applied to all open boundary variables used in the nesting procedure, and linear interpolation between the obtained values was used during the model run.

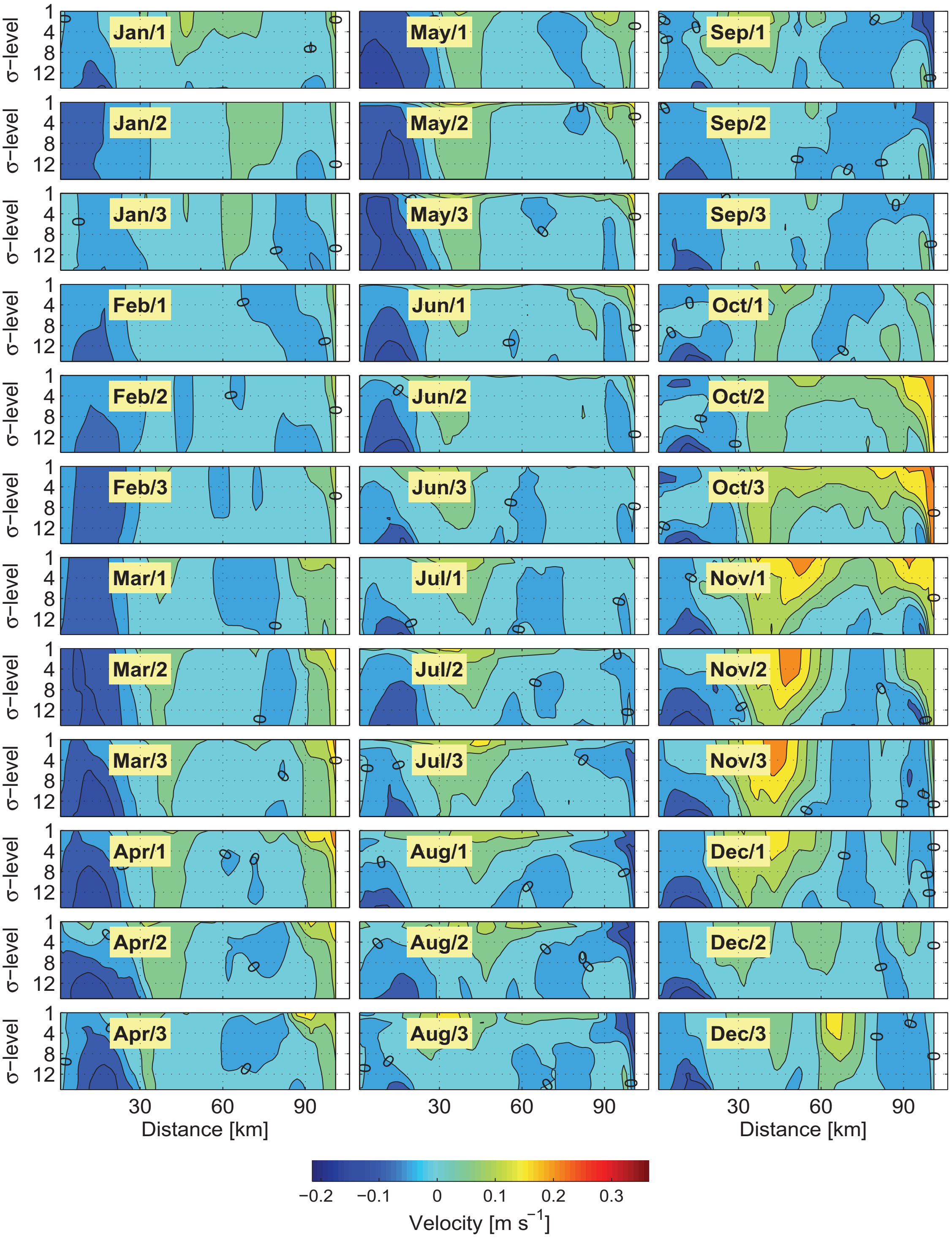

Fig. 7b. The same as in Fig. 7a, except for the western open boundary and cross-Adriatic currents

Results

The results of a three-year long experiment with perpetual atmospheric, river and open-sea forcing reveal a strong seasonal signal which agrees with temperature and salinity data originating from the permanent oceanographic stations distributed along the Split-Gargano transect and with some early current measurements.

Numerical model results indicate that the general flow in the ASHELF-2 domain is northwestward with prominent wakes behind, and jets among, Dalmatian islands occurring during most of the year (Fig. 8). Current reversal obtained between the islands of Hvar and Vis in August agrees with early current measurements at the Split-Gargano transect (ZORE-ARMANDA, 1968), which indicates a strong seasonal signal in the surface current field with oppositely directed alongshore flow in the winter and summer seasons.

The importance of properly imposed open boundary conditions can be seen by comparing current fields modeled with (Fig. 8) and without (Fig. 9) the nesting procedure. In the numerical experiment without nesting, in which a simple radiation condition is applied at the open boundaries, the surface current field shows numerous gyres. In the deepest southern area a cyclonic gyre dominates in February, as is the case further north. In the corresponding numerical experiment with nesting the gyres disappear and the flow is in a dominant northwest direction. Moreover, current reversal, obtained between the islands of Hvar and Vis in August in the experiment with nesting, disappears in the experiment with the radiation condition imposed at the open boundaries, pointing to the importance of the basin-scale dynamics for the reversal.

It is also of some interest to compare current fields obtained by the ASHELF-2 run (Fig. 8) with those resulting from the AREG simulation (Fig. 10). The two models differ not only in the resolution (1 vs. 5 km) but also in the way in which river inflows are taken into

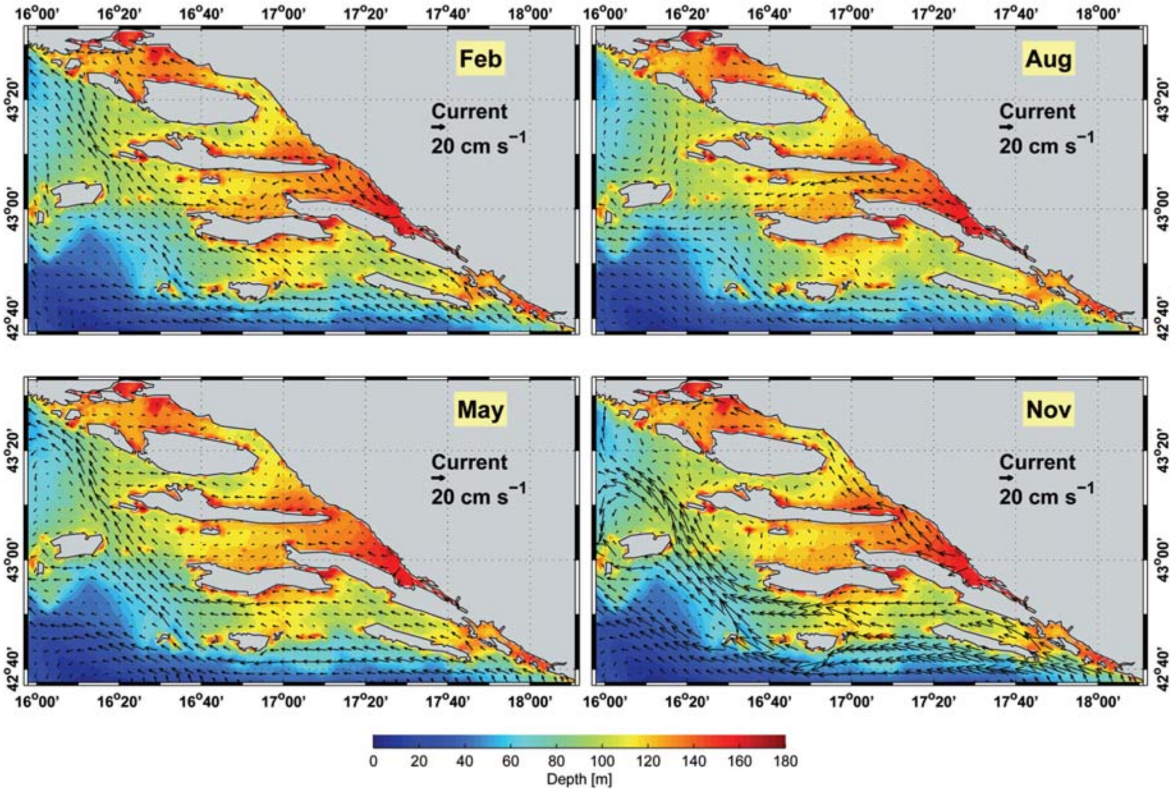

Fig. 8. Monthly current fields for February, May, August and November, obtained in the perpetual-year simulation performed by ASHELF-2 nested into AREG

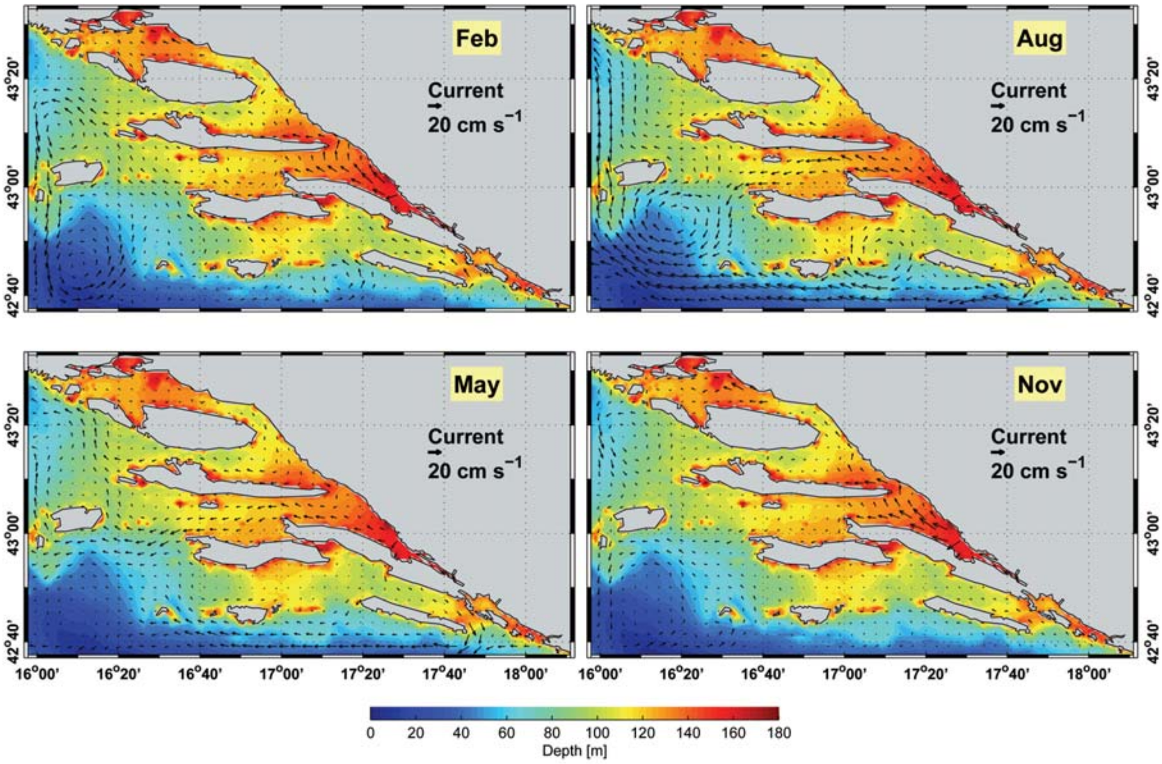

Fig. 9. Monthly current fields for February, May, August and November, obtained in the perpetual-year simulation performed by ASHELF-2 with radiation condition imposed at the open boundaries

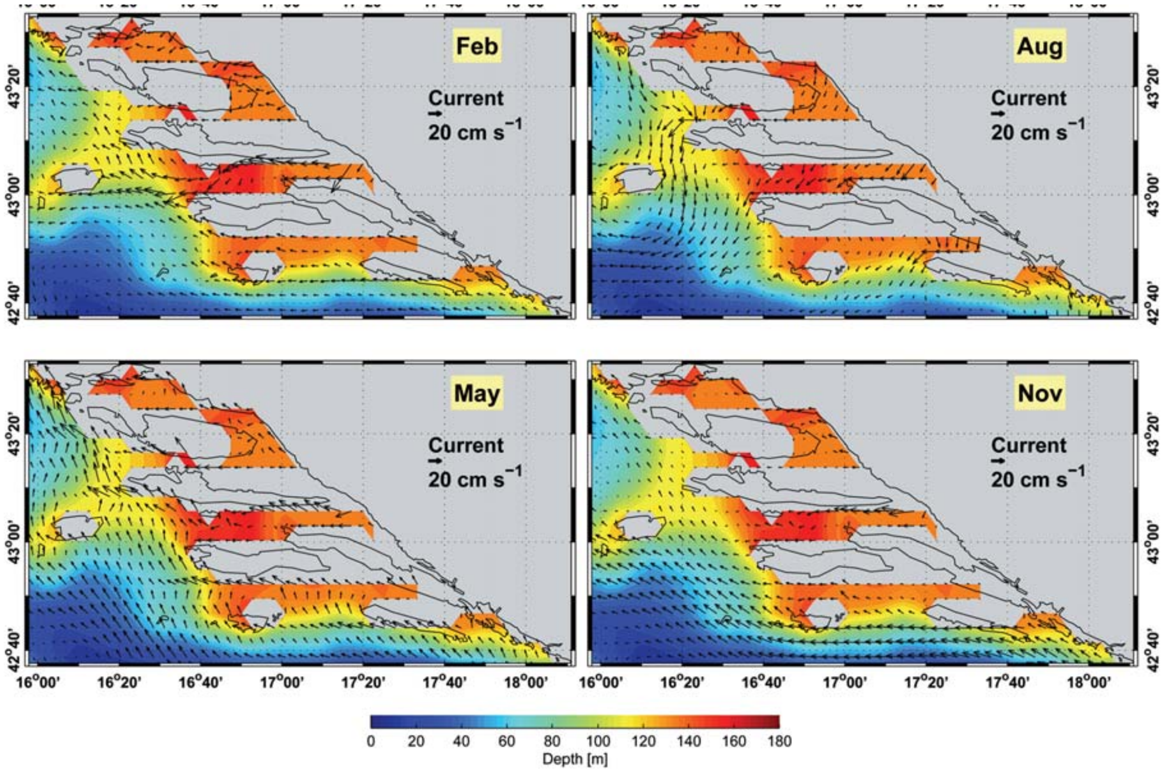

Fig. 10. Monthly current fields for February, May, August and November obtained in the perpetual-year simulation performed by AREG in the ASHELF-2 area

account (concentrated vs. extended sources). The coarser resolution model reproduces annual variability of currents as does the finer resolution one and, in fact, the August current reversal is more pronounced in the AREG fields than in the ASHELF-2 results. On the other hand, the two model runs differ considerably if the influence of Dalmatian islands on the current field is considered. The difference is most striking in November: the AREG simulation does not point to the existence of a jet between the islands of Vis and Hvar nor does it indicate that there are wakes behind smaller islands (e.g. island of Lastovo).

Surface temperature fields obtained by the ASHELF-2 run indicate stronger winter cooling in the shallower areas, whereas surface salinity fields clearly show the influence of the rivers included in the experiment (Fig. 11).

Results of the perpetual-year simulation at the appropriate model points were compared with hydrographic data collected between 1961 and 2000 in the ASHELF-2 area. Two of the permanent stations from the Split-Gargano transect are in the ASHELF-2 model domain and physical parameters measured there could be compared with the model results (Fig. 12). Annual cycles of temperature at both stations show a maximum in August and a minimum in February/March, with temperature amplitudes decreasing with depth (ADRICOSM Group, 2002). The annual cycle of salinity at the station closer to the coast indicates a minimum in May, whereas at the station further offshore an additional minimum in July can be observed (ADRICOSM Group, 2002). The modeled temperature annual cycle at the point that corresponds to the open sea station Stončica shows good agreement with the data, although the modeled annual amplitude is lower than observed (Fig. 13). The difference between temperatures can be explained by the meteorological conditions prevailing during the measurements: the data are usually collected during stable, anticyclonic weather conditions which in the area are characterized by the air temperatures being above the

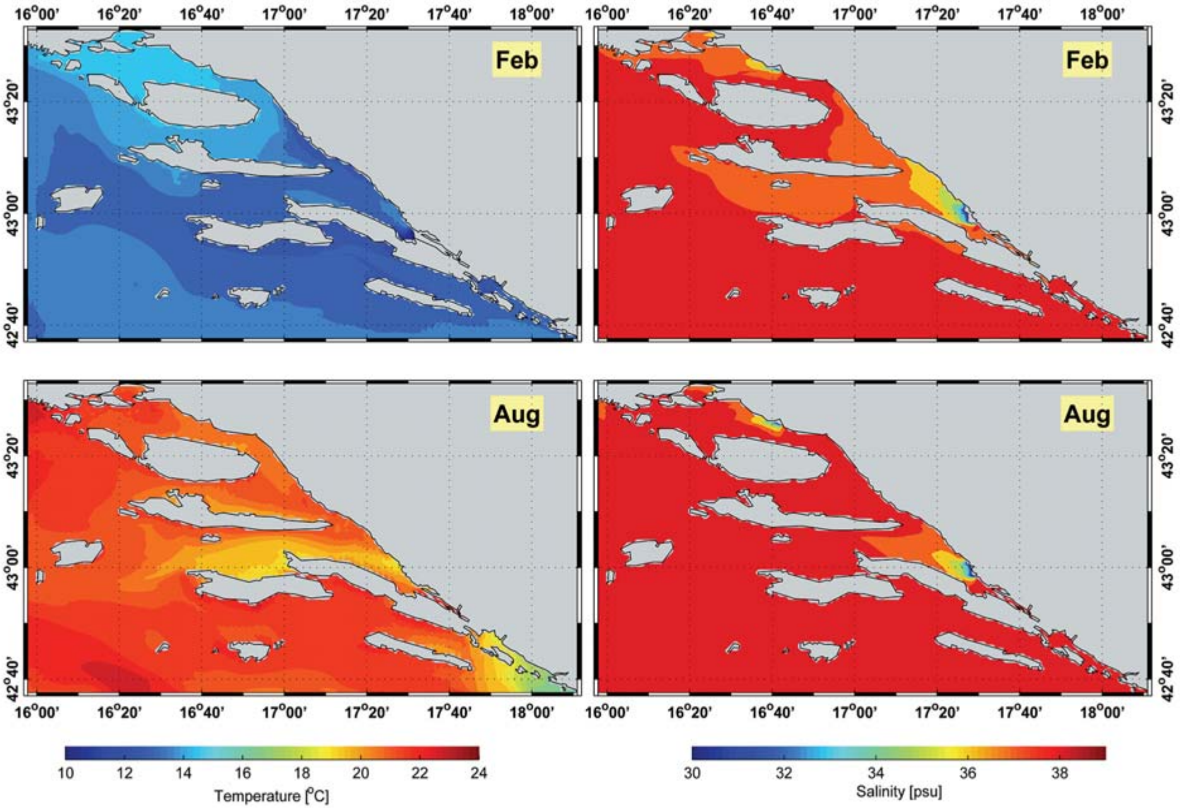

Fig. 11. Temperature and salinity fields for the winter and summer seasons obtained in the perpetual-year simulation performed by ASHELF-2 nested into AREG

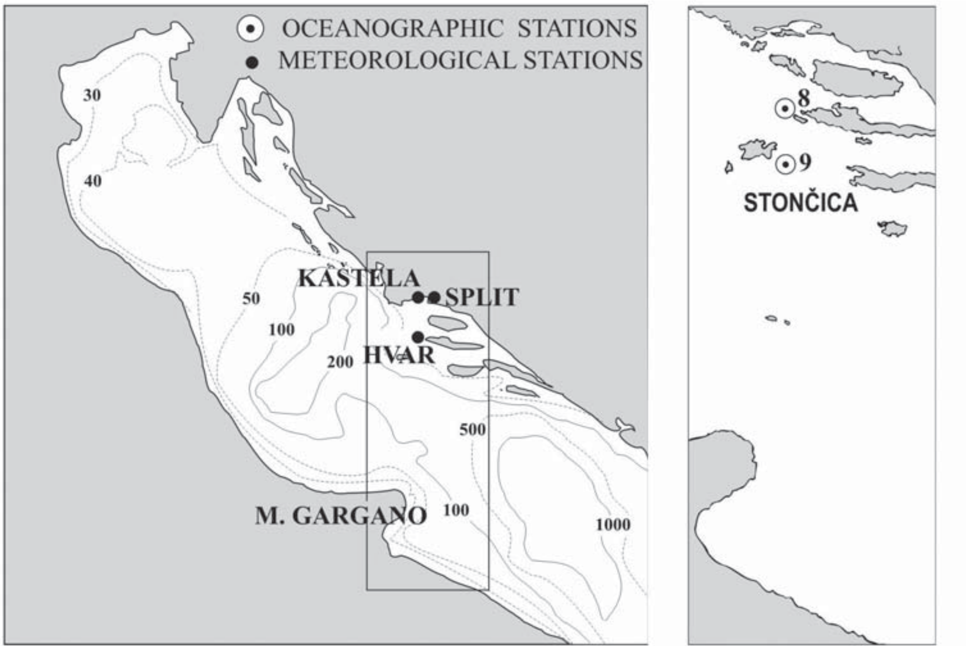

Fig. 12. Position of climatological stations at the Split-Gargano transect

climatological mean during summer and below it during winter. An alternative explanation for the modeled amplitudes that are smaller than the observed ones is that the model is overmixed. Upwelling observed in August and September at Stončica station at depths of 20-60 m by BULJAN (1965) was not reproduced by the model. Further analysis should explore interannual variability of this phenomenon, since BULJAN's investigations were based on data taken between 1948 and 1963 whereas the model was forced with monthly mean meteorological fields recorded between 1979 and 1983. Measured and modeled surface salinities at Stončica show poorer agreement, with a smaller annual amplitude again obtained by the model (Fig. 13). However, the ASHELF-2 simulation did reproduce the spring/summer minimum of salinity. As the minimum was also obtained in the numerical experiment done without nesting (not shown), it would appear that it is primarily related to the influence of local rivers, in particular the Neretva River.

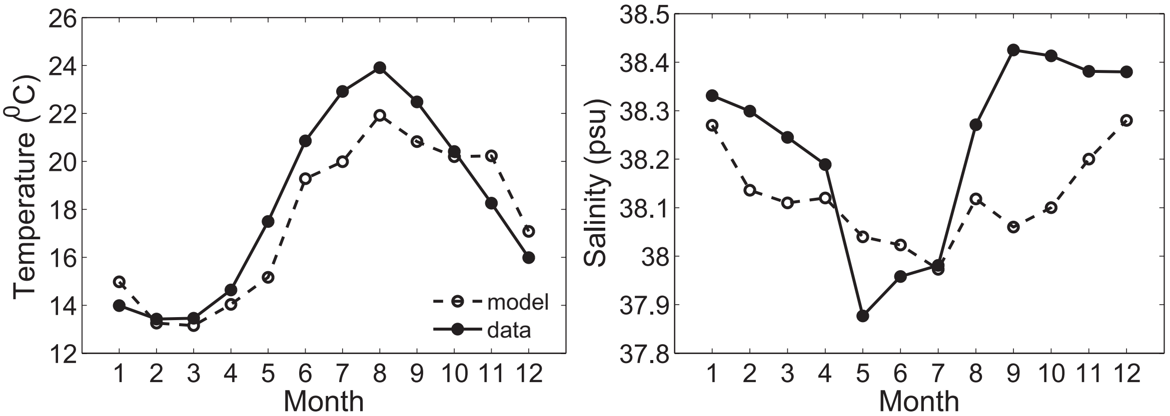

Fig. 13. Observed vs. modeled surface temperature (left) and salinity (right) at the Stončica station and at the corresponding model node. The time series represent long-term averages (1961-2000)

INTERANNUAL SIMULATION

An interannual simulation was performed for the interval extending from 1 January 2000 to 31 March 2003. The model grid and bathymetry used in the perpetual-year simulation were also used for simulating the interannual variability.

Forcing

In the three-year long interannual simulation ASHELF-2 was forced with the surface momentum, heat and water fluxes which were interactively calculated during simulation from 6-hour ECMWF analyses of wind components, air and dew point temperature and cloud cover performed with a 0.5 deg resolution and from instantaneous sea surface temperature obtained by the oceanographic model. Wind stress was calculated according to HELLERMAN & ROSENSTEIN (1983), whereas heat flux components were obtained using standard bulk formulas. The REED (1977) formula was used for solar radiation, longwave flux was calculated according to MAY (1986), while sensible and latent heat fluxes were obtained following KONDO (1975). Monthly fields of the wind stress and surface heat flux show strong interannual variability in the winter and summer seasons, as will be discussed in a subsequent section. Climatological values of the four river discharges (Jadro, Žrnovnica, Cetina and Neretva) and precipitation (LEGATES & WILMOTT, 1990) were used in the water flux calculations, together with interactively calculated evaporative flux.

Initial and open boundary conditions

Temperature, salinity and velocity fields for 31 December 1999, originating from the AREG interannual run, were interpolated on the ASHELF-2 grid and used for initialization.

The ASHELF-2 model, on the western and southern open boundaries, was nested into AREG with daily averaged values obtained from that model. The nesting procedure was the same as in the perpetual-year simulation, the only difference being the averaging frequency of the AREG fields.

Results

Temperature, salinity and current fields obtained during the interannual simulation show strong seasonal and interannual variability. In order to illustrate year-to-year changes, monthly mean fields for various years are intercompared. They may be related to findings by ODDO *et al.* (2005) who performed the simulation for the AREG domain over a three-year interval (2000-2002) and discussed it on a seasonal time scale.

The winter season in the ASHELF-2 area is illustrated by monthly fields for February 2000 and February 2002. NW winds prevailing in February 2000 were significantly stronger than the SW winds dominating in February 2002, and net heat loss was greater in the former year (Fig. 14a). This different forcing resulted in oppositely directed currents. In 2000 the current was aligned with the wind, thus being atypical, whereas in 2002 the current was of the usual, inflowing direction (Fig. 14b). Differences in the spreading of the Neretva plume resulted from different wind conditions (Fig. 14b).

May 2000 was characterized by weak SE winds and relatively large heat gain, whereas during May 2002 weak W winds were combined with a smaller heating (Fig. 15a). In the first situation currents were of NW and of W direction while in the second case NW currents predominated (Fig. 15b). Since the winds were weak, the difference in the prevailing currents was due to the changing overall Adriatic circulation, which affected the modeled area through the open boundary conditions.

The influence of the basin-wide Adriatic circulation is also well illustrated by the comparison of the monthly fields for August 2000 and August 2002 (Fig. 16a and b). In both situations prevailing winds were weak and of NW direction, but the surface currents were oppositely directed. Differences in the current directions resulted from external influence, imposed at the open boundaries through the nesting procedure. Low temperatures obtained in the southern coastal area in August 2000 should likely be ascribed to a larger-scale dynamics and upwelling related to it. They correspond with the findings by BULJAN (1965), but also suggest that

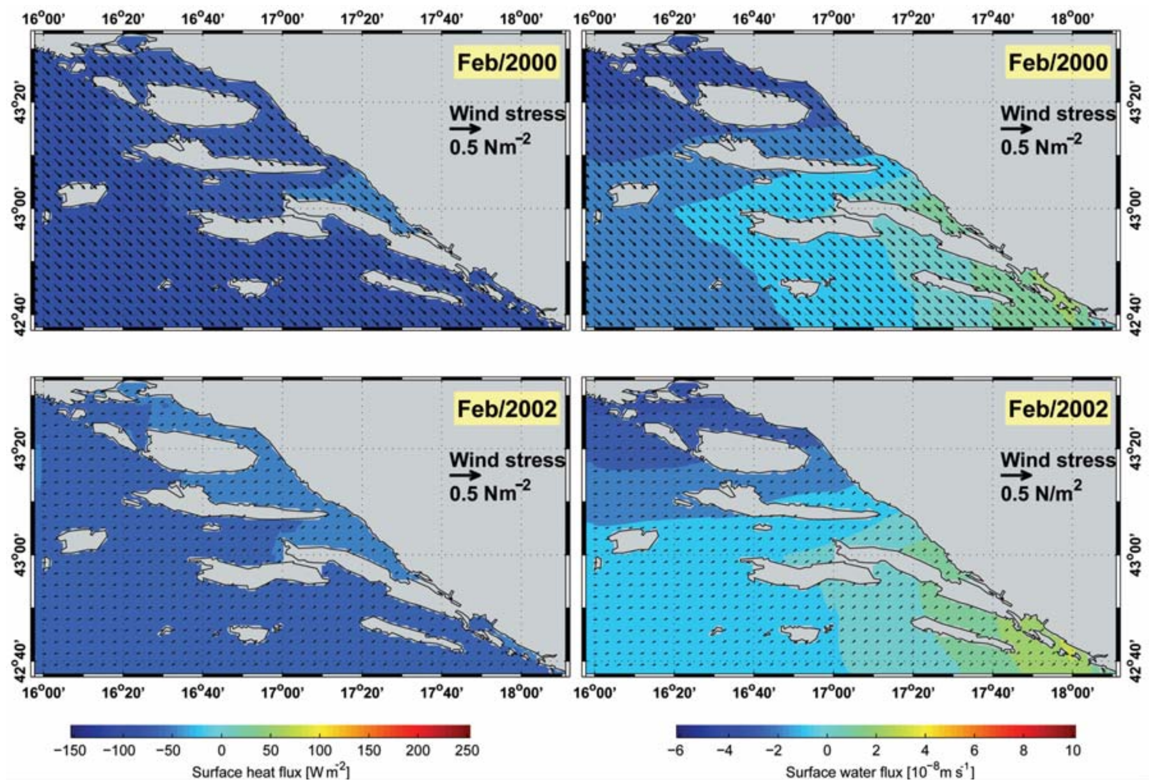

Fig. 14a. Monthly mean forcing fields obtained in the course of interannual simulation for February 2000 (top) and February 2002 (bottom)

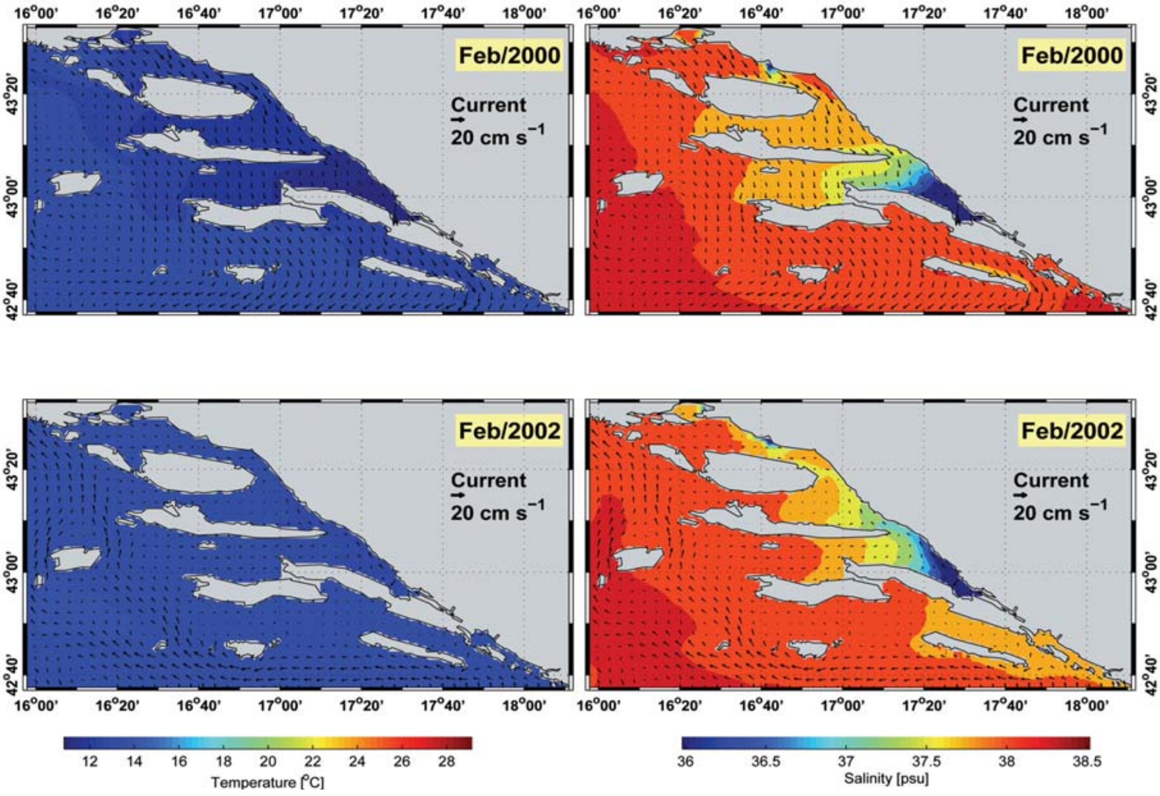

Fig. 14b. Monthly mean surface currents, temperatures and salinities obtained in the course of interannual simulation for February 2000 (top) and February 2002 (bottom)

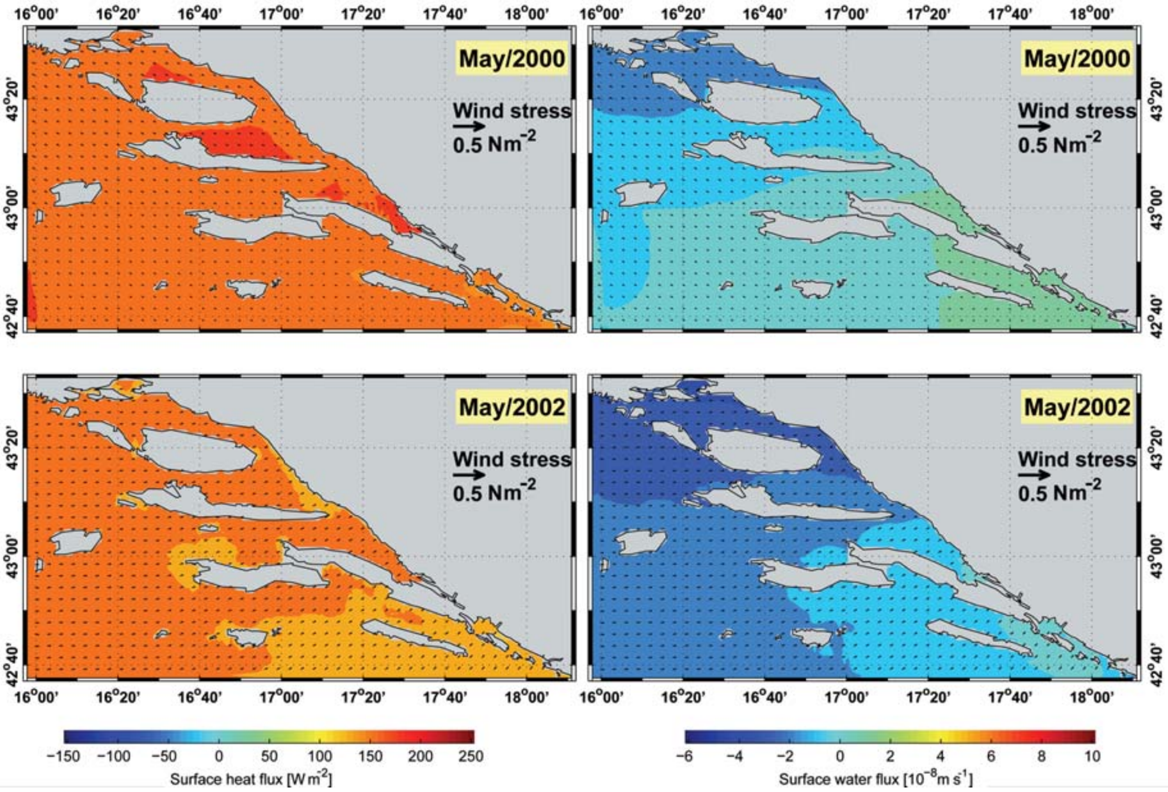

Fig. 15a. The same as in Fig. 14a, except for May

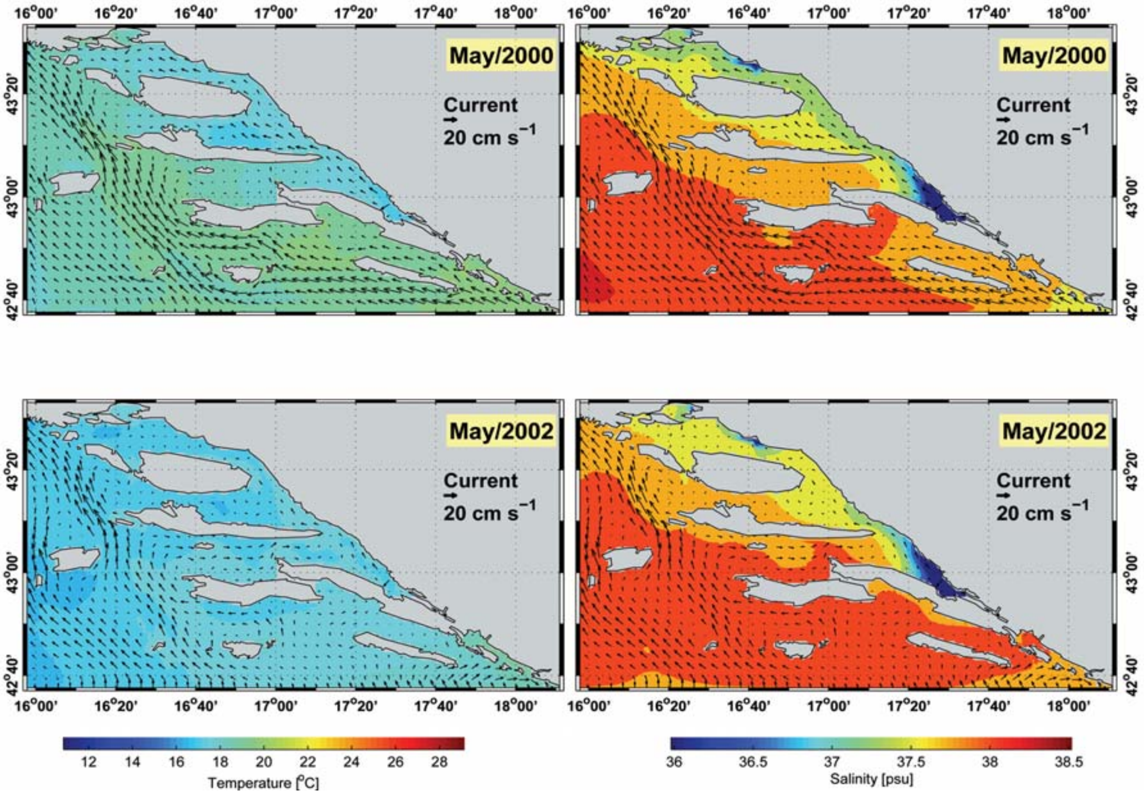

Fig. 15b. The same as in Fig. 14b, except for May

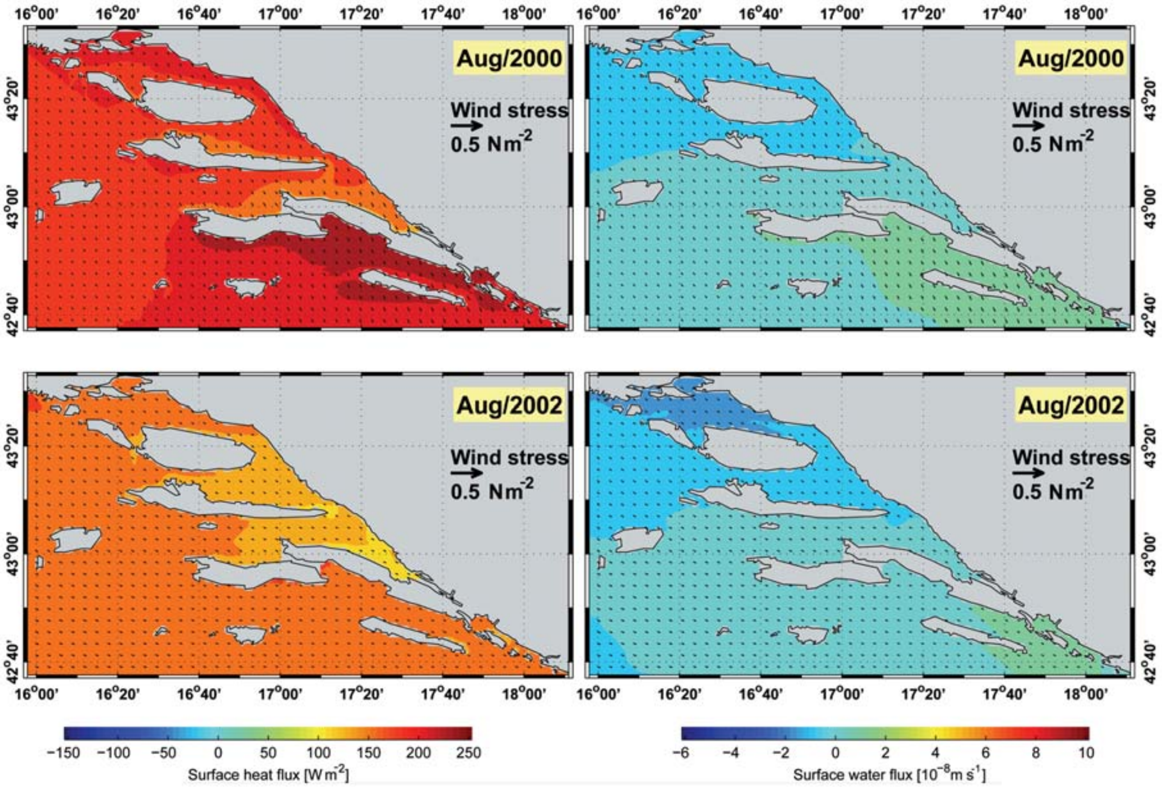

Fig. 16a. The same as in Fig. 14a, except for August

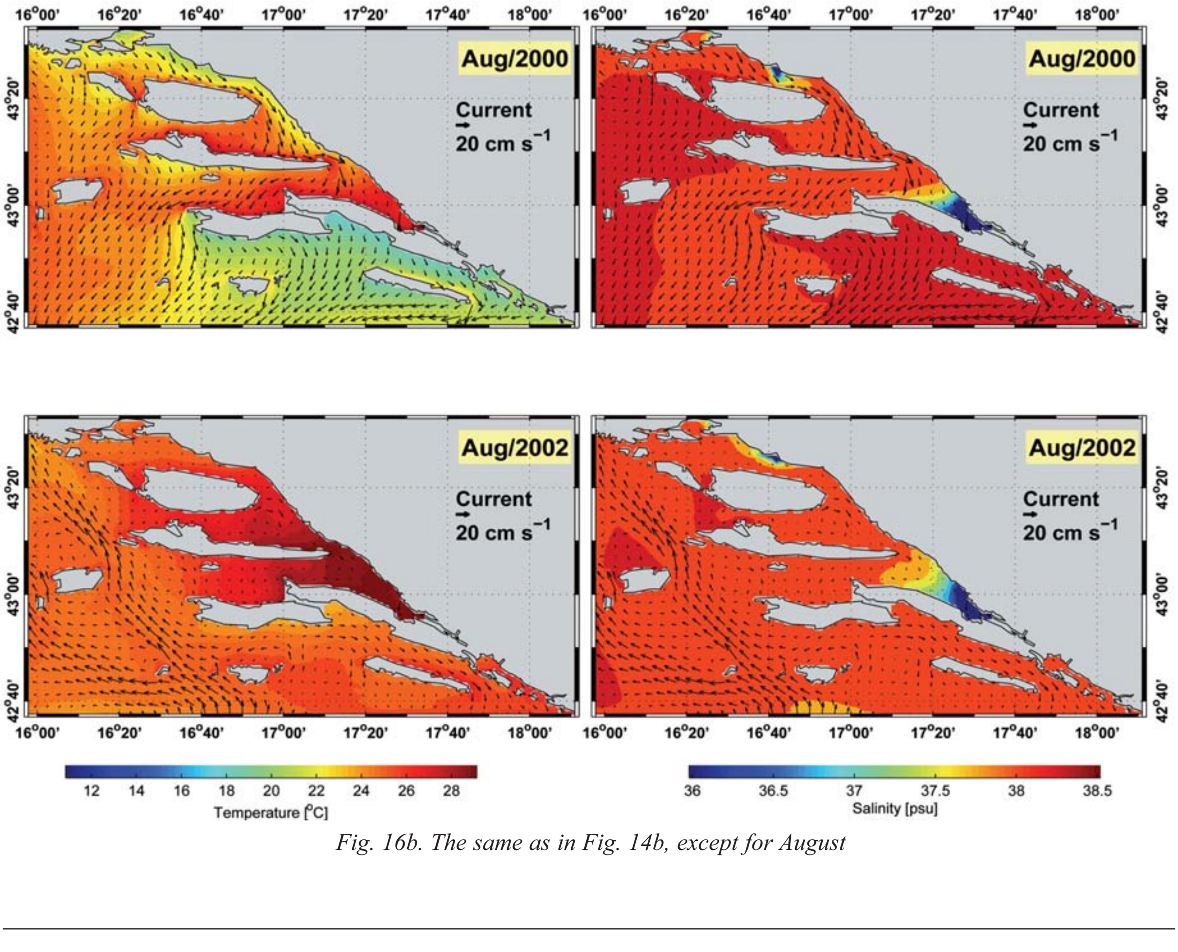

Fig. 16b. The same as in Fig. 14b, except for August

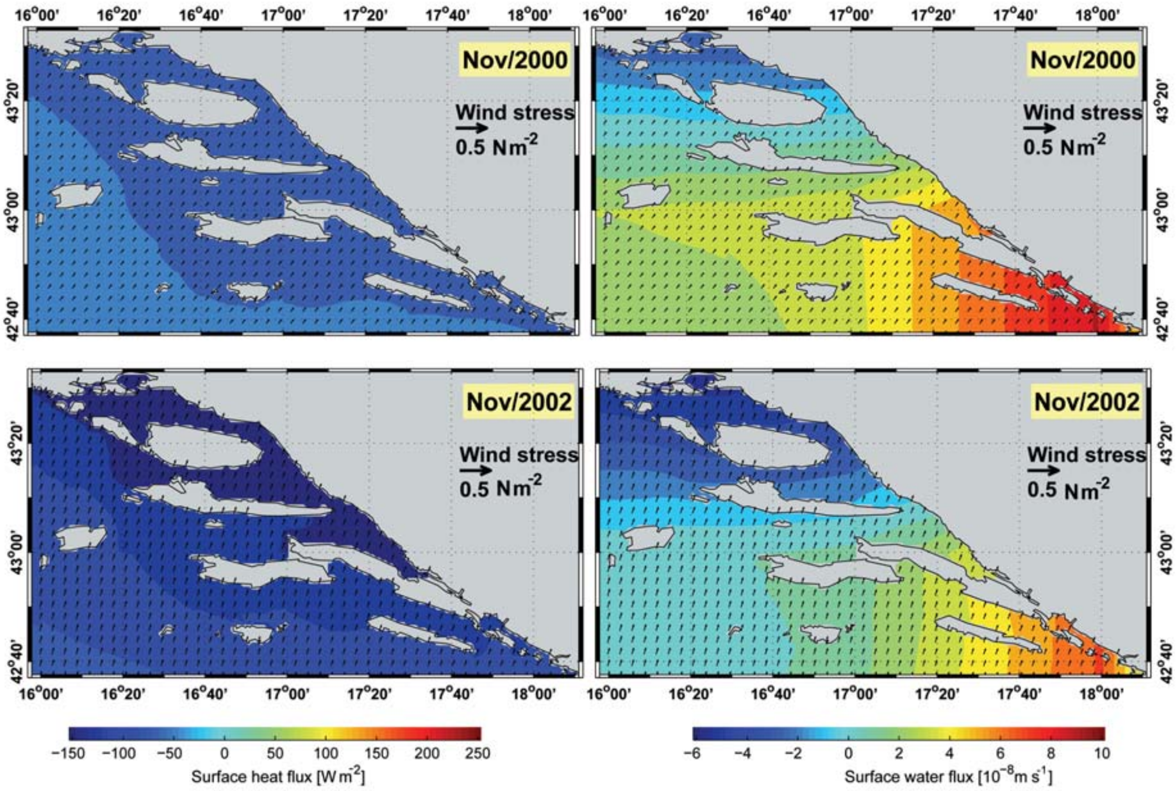

Fig. 17a. The same as in Fig. 14a, except for November

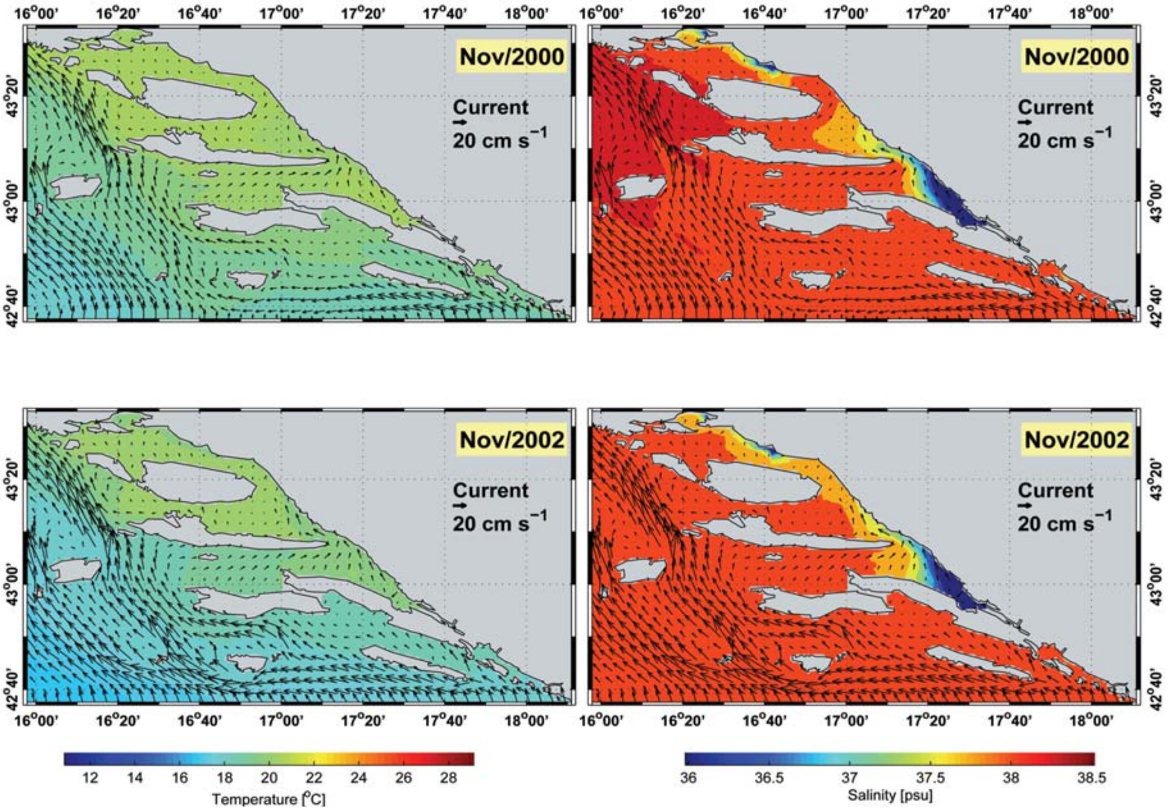

Fig. 17b. The same as in Fig. 14b, except for November

upwelling may strongly depend on conditions in a particular year. The low temperatures of August 2000 supported a relatively large heat gain from the atmosphere while the high temperatures of August 2002 resulted in a relatively small heat gain.

November 2000 was characterized by weaker SW winds and smaller heat loss than November 2002 (Fig. 17a). The forcing resulted in the NW surface current being stronger in November 2002 than in November 2000 (Fig. 17b).

Comparison of the surface heat fluxes used in the perpetual-year simulation with values used in the interannual run shows that the amplitude was greater in the first case (Fig. 18). However, surface heat fluxes employed in the interannual run agree better with the values calculated from measurements at the Hvar meteorological station. Monthly mean temperatures obtained by the three-year interannual run were generally higher than climatological temperatures, with the exception of winter 2000 (Fig. 19). Temperatures measured in 2002 at Stončica station are in good agreement with corresponding values obtained in the interannual run.

Surface water fluxes used in the interannual simulation follow the corresponding perpetual-year cycle due to the use of climatological values for precipitation (Fig. 20). Annual cycles of surface salinity, obtained by the interannual run for the years 2000, 2001 and 2002, agree better with the annual cycle deduced from long-term measurements than with salinities measured at Stončica station in 2002 (Fig. 21). The discrepancy between the measured and simulated values resulted from forcing the model with climatological water fluxes.

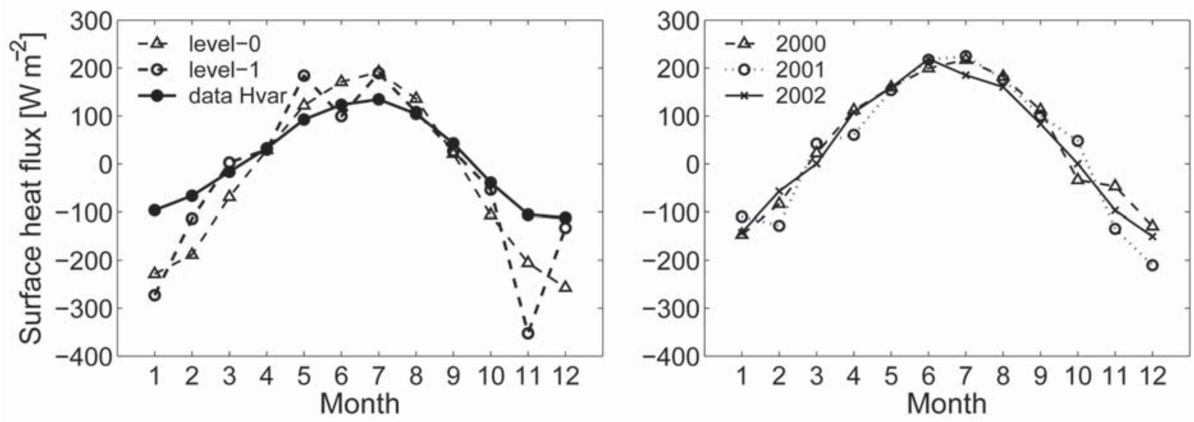

Fig. 18. Climatological surface heat fluxes at Hvar (computed for the years 1961-1980) and corresponding values used in the perpetual-year (left) and interannual (right) run

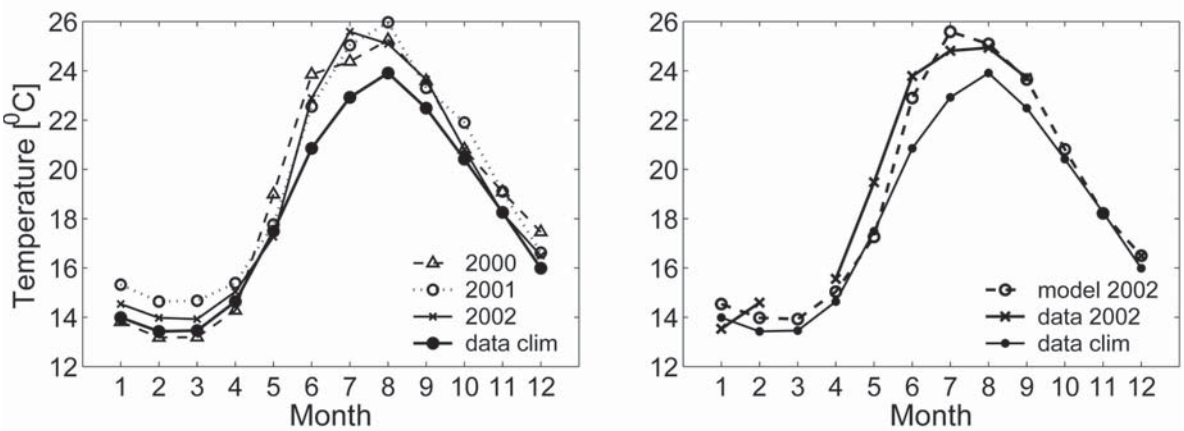

Fig. 19. Temperature at Stončica station: modeled values from the interannual run and climatological values (left); modeled and observed temperatures for 2002 compared with climatological values (right)

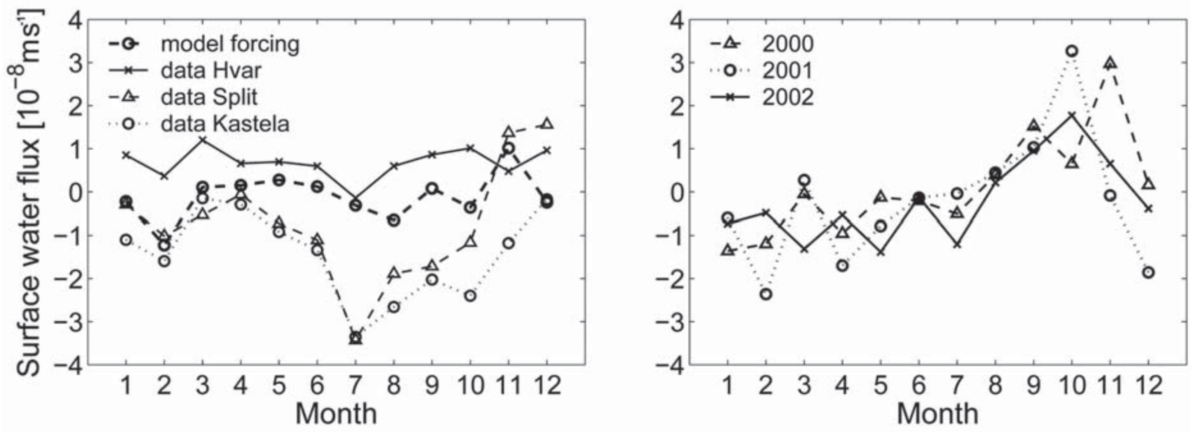

Fig. 20. Surface water flux (P-E): climatological values at three stations (Split and Kaštela – computed for the years 1961-1990; Hvar – computed for the years 1961-1980) compared with values used in the perpetual-year (left) and interannual (right) run

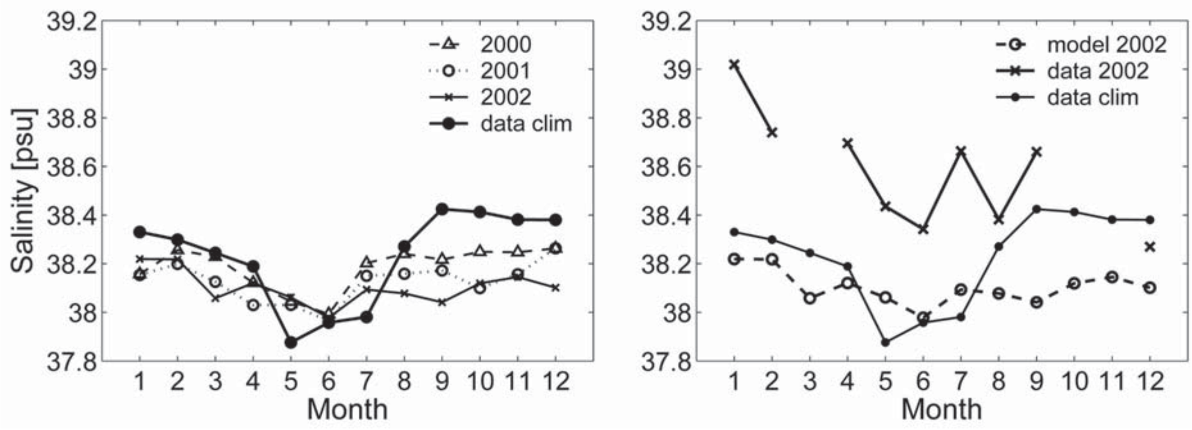

Fig. 21. The same as in Fig. 19, except for salinity

SIMULATION AND FORECASTING

Procedures

Model setup for the simulation and forecasting was almost the same as the one used in the interannual simulation. Wind stress and surface heat fluxes were calculated interactively using ECMWF 6-hour averages provided at a 0.5 deg resolution as well as instantaneous sea surface temperature obtained by the oceanographic model. The same bulk formulas as in the interannual run were also used here. Water fluxes were obtained from the evaporative flux and from the climatological values of precipitation and river discharges.

Between 1 April and 30 September 2003 ASHELF-2 modeling activity comprised of simulations based on analyzed meteorological fields and forecasts based on meteorological predictions. SIMULATIONS had started in April and have lasted until the end of September, resulting in temperature, salinity and current fields in the model domain (Pelješac-Vis-Drvenik area) with a one- or two-week delay. Initial conditions (temperature, salinity and velocity fields) as well as boundary conditions for the nesting were obtained from the corresponding AREG model runs. FORECASTS for the region, produced a week in advance, have been calculated almost regularly, depending on the availability of input information. Initial temperature, salinity and current fields were obtained from AREG model hindcasts, whereas forecasted fields from AREG were used in the nesting procedure. All the modeling results have been disseminated via the web, immediately after the calculations had been finished.

Some results and their comparison with measurements

During the simulation/forecasting period CTD measurements were regularly performed at three transects in the Pelješac-Vis-Drvenik area (Fig. 22). The data collected could be used in a model-to-data comparison. Some preliminary findings on the model performance will be shown here, whereas a thorough analysis is planned for the future. On 20 May 2003 forcing fields showed moderate SE wind and strong heating (Fig. 23). Surface temperatures reached 20 ^{0}C, with lower values being simulated in the deeper area (Fig. 23). Lower salinity values were obtained in the coastal area since the Neretva plume spread widely (Fig. 23). Measured and modeled temperature profiles were found to agree reasonably well at six stations of the first CTD transect, with an RMS error of 0.87 ^{0}C (Fig. 24 shows findings for the first station). Some disagreement in the bottom layer can be

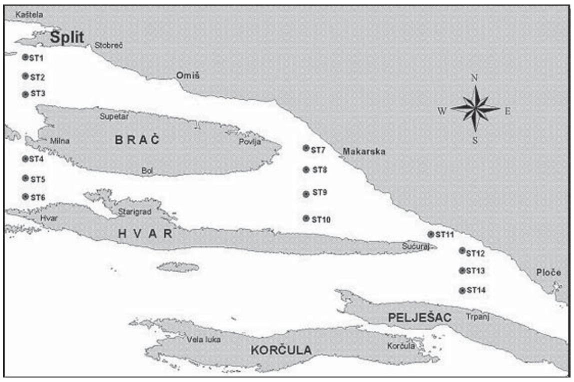

Fig. 22. Position of stations in the Pelješac-Vis-Drvenik area at which CTD data were collected in the framework of the ADRICOSM project

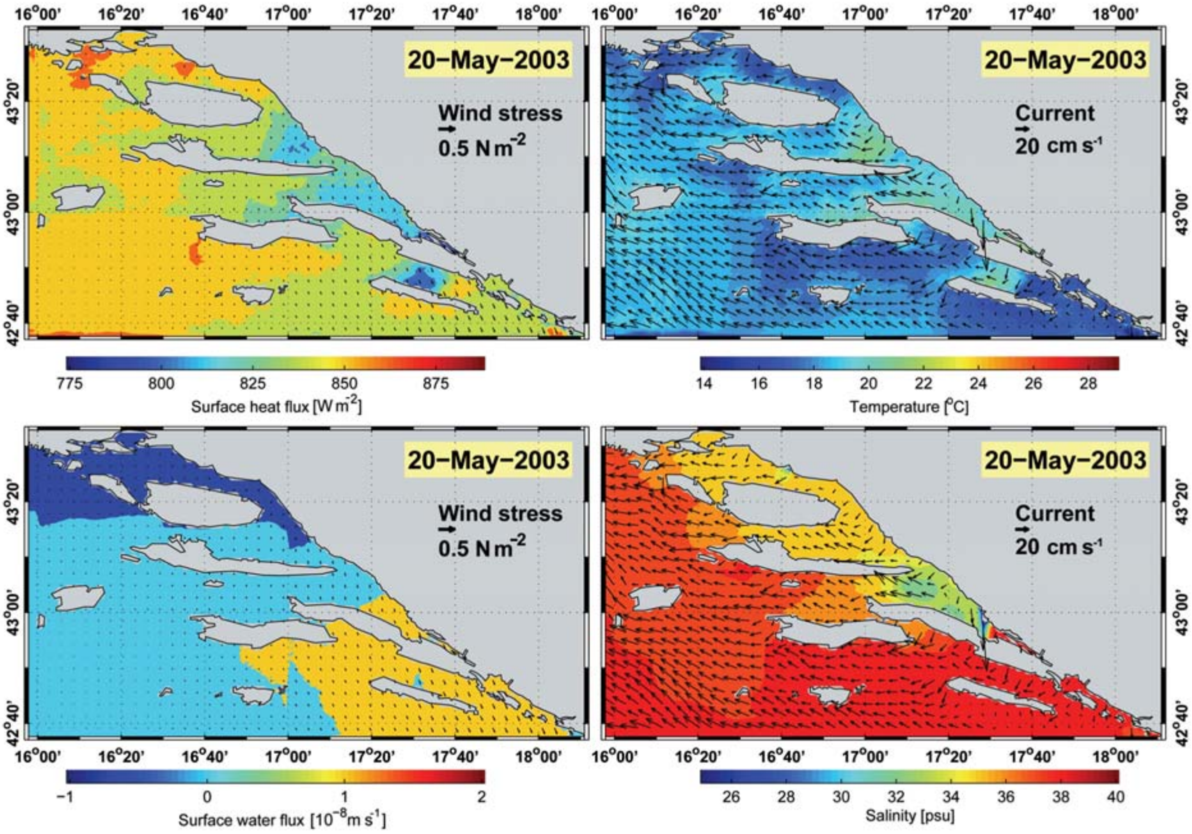

Fig. 23. Simulation for 20 May 2003: mid-day surface wind stress overlaid on the surface heat flux (top left) and surface water flux (bottom left); corresponding surface currents overlaid on the surface temperature (top right) and salinity (bottom right)

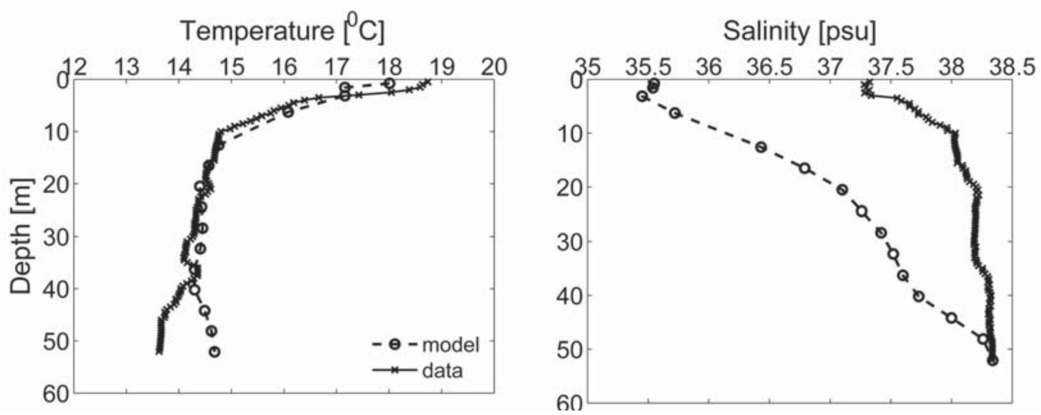

Fig. 24. Modeled vs. measured temperature (left) and salinity (right) profiles on 20 May 2003 at station 1 (shown in Fig. 22)

ascribed to climatological drift. Modeled salinity profiles showed larger deviations from the measured values, especially in the surface layer (Fig. 24), which resulted in RMS error equalling 1.09 at the first CTD transect. Obviously, the use of climatological precipitation and river discharge data was a weak point of the simulation. Spring and summer 2003 were extremely dry and therefore the use of climatological data for calculation of water fluxes resulted in modeled salinities being too low in comparison with measured values. RMS errors for both temperature and salinity increased at the remaining two transects, and consequently the overall values for the 20 May 2003 simulation were 1.23 ^{0}C and 1.39, respectively.

Forcing fields used in the simulation for 28 May 2003 showed prevailing NE (bora) wind with moderate heating (Fig. 25). The wind field was unrealistically uniform due to the low spatial resolution of meteorological forcing. It induced western surface currents in the coastal area and supported offshore spreading of low-salinity river-influenced waters.

On 3 August 2003 pronounced heating was combined with strong NW wind, the latter inducing prevailing downwind currents at the sea surface that were significantly modified in the narrow channels (Fig. 26). The temperature field showed strong upwelling along the northern part of mainland coast and the southern coasts of major islands, whereas the salinity field was uniform since the river-influenced waters were pushed toward the coasts (Fig. 26).

On 14 August 2003 the heating was still strong and the wind was again of NW direction but had lower intensity than in the previous case (Fig. 27). Correspondingly, the upwelling was less pronounced whereas the river plumes spread further offshore (Fig. 27). Comparison of the modeled and measured CTD profiles indicated poorer agreement for temperature, and better for salinity, than in the 20 May 2003 case. RMS errors for temperature and salinity for the first CTD transect were 1.49 ^{0}C and 0.83, and for all the stations visited on 14 August 2003 equalled 1.74 ^{0}C and 0.79, respectively. The temperature profile modeled for the station closest to Split, with values in the surface layer being lower and those in the bottom layer being higher than measured (Fig. 28), indicates that the model mixing was too strong. Overmixing was more pronounced for the 14 August 2003 simulation controlled by stronger wind than for the 20 May 2003 case influenced by weaker wind. Although both the measured and modeled salinity profiles pointed to the existence of a freshened surface layer on 14 August 2003, modeled values were lower than measured in the whole water column (Fig. 28), again due to the use of climatological precipitation and river discharge data in calculating the water fluxes.

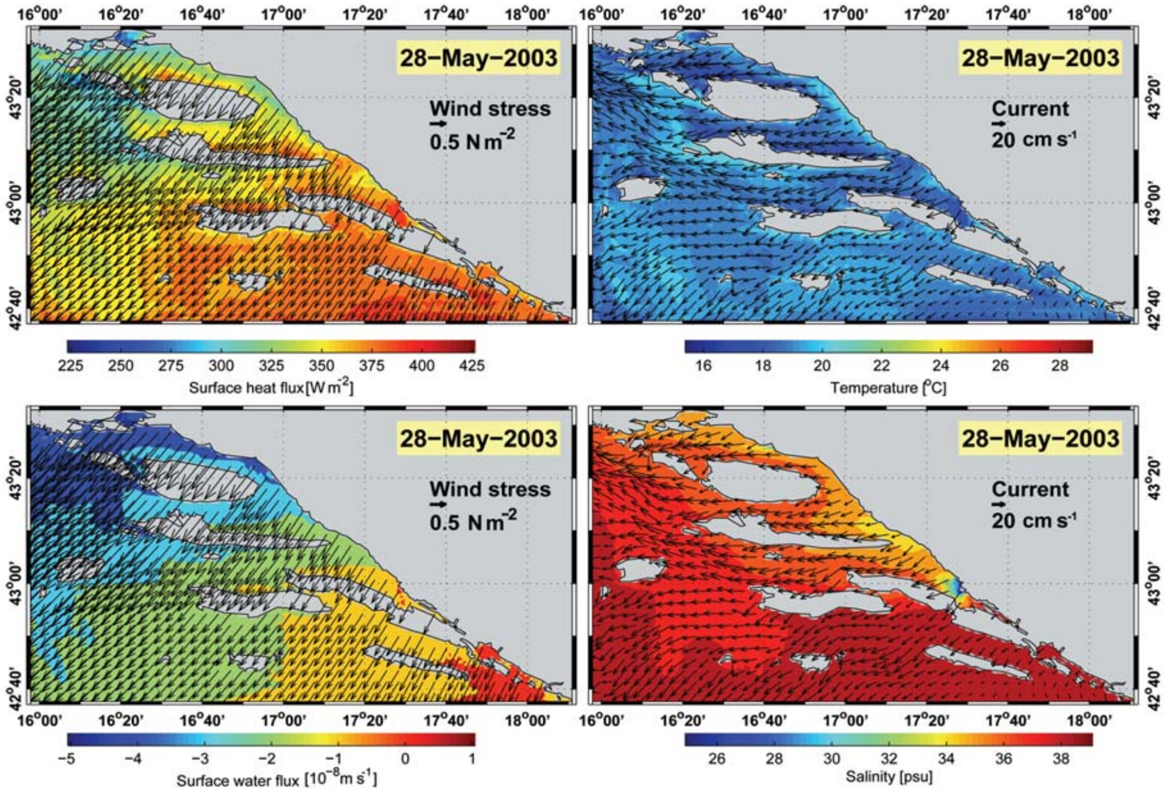

Fig. 25. The same as in Fig. 23, except for 28 May 2003

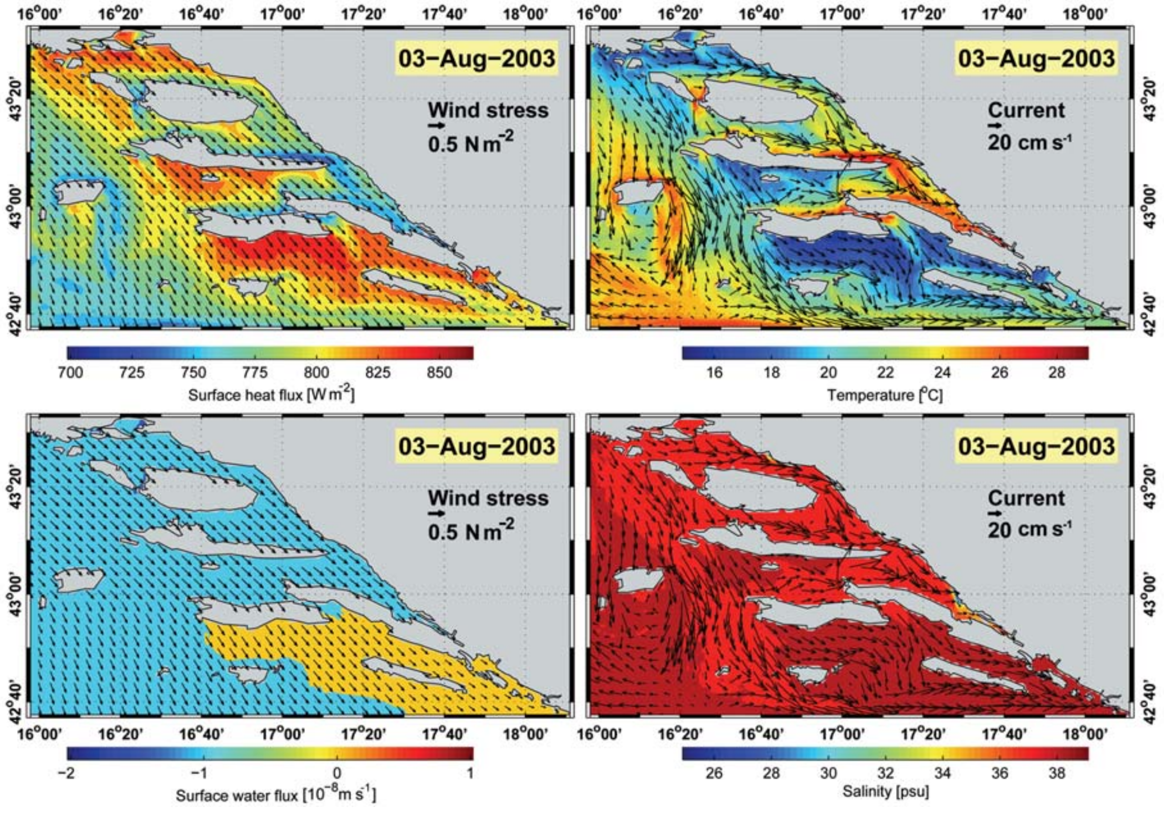

Fig. 26. The same as in Fig. 23, except for 3 August 2003

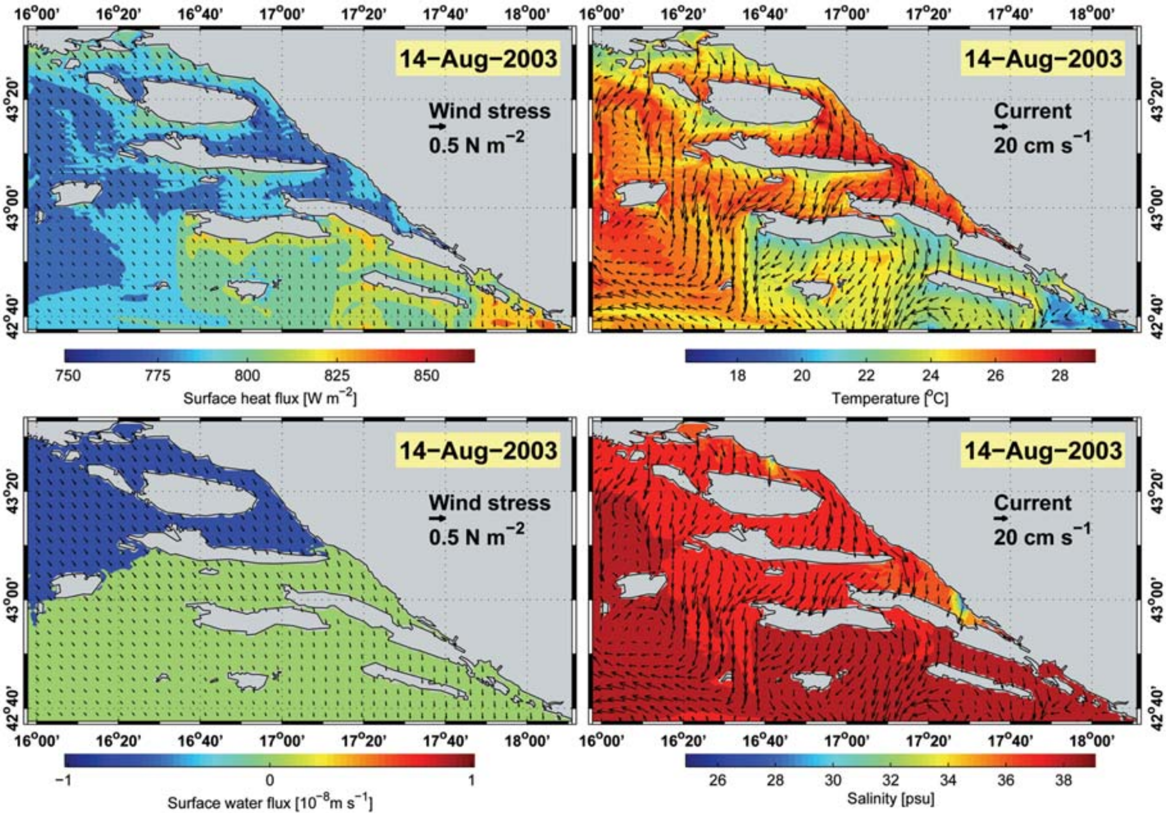

Fig. 27. The same as in Fig. 23, except for 14 August 2003

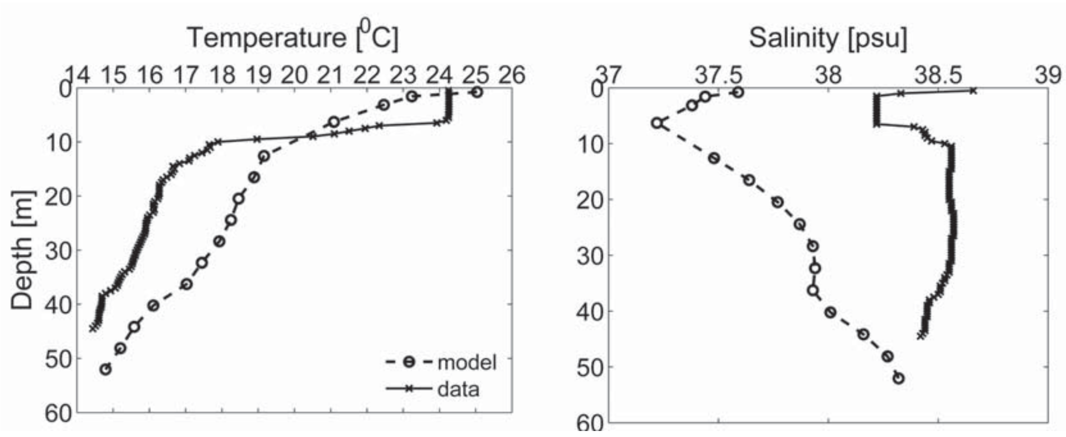

Fig. 28. The same as in Fig. 24, except for 14 August 2003

CONCLUSIONS

The perpetual-year simulation, as described in the present paper, confirmed some previous empirical findings but failed to reproduce some other early experimental results. In particular, modeled and measured annual cycles of temperature and salinity were found to agree in the open sea and close to the sea surface although the amplitudes were underestimated by the model, especially for salinity. The modeling showed that the spring/summer minimum of salinity might be related primarily to the influence of local rivers, the most important being the Neretva River. Moreover, the model realistically reproduced reversal of currents, from

NW in winter to SW-SE in summer, which was previously observed in the area. However, it was not successful at simulating the semiannual cycle of salinity close to the coast or at revealing the upwelling effects in August and September in the open sea. On the other hand, the model provided some results which were previously unsuspected and which may indicate the way future measurement efforts should develop. Particularly interesting are wakes behind, and jets among, Dalmatian islands. They apparently occur over the greater part of the year and, due to their possible importance for biogeochemical processes, should be studied in more detail.

Comparison of the interannual simulation with corresponding measurements showed good agreement for temperature, whereas discrepancies in salinity resulted from forcing the model with climatological water fluxes. Local winds were found to influence the currents when they are strong, otherwise the currents are more dependent on remote forcing represented by conditions imposed at the open boundaries. In one of the years upwelling was obtained in August, thus supporting the early observations but also implying that the phenomenon may strongly depend on conditions in a particular year. The pattern of the Neretva plume was found to be controlled by the local wind conditions.

Forecasts of temperature, salinity and current fields – the first such forecasts produced for the area – enabled some experience to be gained in operational oceanography. Their testing against the field data revealed some problems with the modeling approach employed. An obvious problem is overmixing, which is more pronounced when the wind is stronger. The other problem stems from the water fluxes that were assumed to equal climatological averages: since spring and summer 2003 were characterized by exceptionally dry conditions, simulated salinities were considerably lower than the observed values. Moreover, the low spatial resolution of atmospheric forcing probably reduced the quality of current predictions – especially for some (e.g. bora) wind directions. To summarize, while the forecasting provided an opportunity to develop an operational oceanographic system, it clearly showed that a closer cooperation is needed with meteorologists and hydrologists in order to make the system more successful. The former collaboration should ensure meteorological forcing with a resolution better than 10 km, which is often necessary for the Adriatic, and should also allow for a feedback form the sea to the atmosphere. The latter cooperative effort should result in real-time information on the outflow of all the rivers influencing the sea, but also in the boundary conditions that could be imposed on the hydrologic models. A consequence of these improvements may be a change of forecasting practice. Forecasts described in this paper were given a week in advance. Such a procedure seems reasonable when the open ocean is modeled, since it may be expected to be governed mostly by internal dynamics. In the case of a coastal sea, dominated by wind forcing and by both surface and coastal buoyancy fluxes, a shorter time interval seems more appropriate. Operational high-resolution meteorological models typically do not provide forecasts beyond three days and the river outflows, while usually persisting over a few days, do change on a weekly time scale. Therefore, a possibility of shortening the forecasting interval – with a consequent increase in the frequency of forecasting – should be considered in the future.

ACKNOWLEDGEMENTS

Success of a nesting modeling exercise, as the one described in the present paper, critically depends on the collaboration of people running different models. N. PINARDI, M. ZAVATARELLI and P. ODDO not only provided results of the AREG model runs in a timely fashion but also often helped with advice, thus creating a friendly and productive working atmosphere. Suggestions by two anonymous reviewers helped to improve the original manuscript. The contents of this paper were developed under financial support from the Istituto Nazionale di Geofisica e Vulcanologia, Italy, and funded under the Italian Ministry for the Environment and Territory contract ADRICOSM. Additional financial support was received from the Croatian Ministry of Science, Education and Sports.

REFERENCES

ADRICOSM Group. 2002. First scientific report. Istituto Nazionale di Geofisica e Vulcanologia, Bologna, 134 pp.

ARTEGIANI, A., D. BREGANT, E. PASCHINI, N. PINARDI, F. RAICICH & A. RUSSO. 1997. The Adriatic Sea general circulation. Part II: Baroclinic circulation structure. J. Phys. Oceanogr., 27: 1515-1532.

BARRY, R. G. & A. M. CARLETON. 2001. Synoptic and Dynamic Climatology. Routledge, London, 620 pp.

BEG PAKLAR, G. & M. GAČIĆ. 1997. The wind effect on the Kaštela Bay current field. Acta Adriat., 38: 31-43.

BEG PAKLAR, G., M. ZORE-ARMANDA & V. DADIĆ. 2002. Currents in the Kaštela Bay: empirical analysis and results of a numerical model. Acta Adriat., 43: 33-64.

BLUMBERG, A. F. & G. L. MELLOR. 1987. A description of a three-dimensional coastal ocean circulation model. In: N. S. Heaps. (Editor). Three-dimensional Coastal Ocean Models. AGU, Washington, pp. 1-16.

BULJAN, M. 1961. Temperature and salinity of the sea water in the neighbourhood of Split. Rapp. Comm. int. Mer Médit., 16 (3): 621-624.

BULJAN, M. 1965. Anomalies of temperature and chlorinity of sea water at the Stončica station (Middle Adriatic) (in Croatian), Pomorski zbornik, 3: 949-994.

CAVALERI, L. & L. BERTOTTI. 1997. In search of the correct wind and wave fields in a minor basin. Mon. Weather Rev., 125: 1964-1975.

ERCEGOVIĆ, A. 1934. Investigation of temperature, salinity, oxygen and phosphates in mid-Dalmatian waters of the Adriatic (in Croatian). Prirodoslovna istraživanja Kraljevine Jugoslavije, 19: 1-115.

GAČIĆ, M. 1982. Notes on characteristics of the response of near-shore current field to the onshore wind. Bilješke – Notes. Instit. oceanogr. i rib., Split, 47: 1-6.

GAČIĆ, M., V. DADIĆ, N. KRSTULOVIĆ, I. MARASOVIĆ, T. PUCHER-PETKOVIĆ & N. SVILIČIĆ. 1987. Near-shore transport processes induced by the wind. Est. Coast. Shelf Sci., 24: 35-46.

HELLERMAN, S. & M. ROSENSTEIN. 1983. Normal monthly wind stress over the world ocean with error estimates. J. Phys. Oceanogr., 13: 1093-1104.

KILLWORTH, P. D. 1996. Time interpolation of forcing fields in ocean models. J. Phys. Oceanogr., 26: 136-143.

KONDO, J. 1975. Air-sea bulk transfer coefficients in diabatic conditions. Boundary-Layer Meteorol., 9: 91-112.

LEGATES, D. R. & C. J. WILMOTT. 1990. Mean seasonal and spatial variability in gauge-corrected, global precipitation. Int. J. Climatol., 10: 111-127.

MAY, P. W. 1986. A brief explanation of Mediterranean heat and momentum flux calculations. NORDA Code 332, Naval Oceanographic and Atmospheric Research Laboratory, Stennis Space Center, Mississippi, 5 pp.

ODDO, P., N. PINARDI & M. ZAVATARELLI. 2005. A numerical study of the interannual variability of the Adriatic Sea (2000-2002). Sci. Total Environ., 353: 39-56.

ORLIĆ, M., M. KUZMIĆ & Z. PASARIĆ. 1999. Modeling wind-driven currents in Kaštela Bay (in Croatian), Proceedings 'Kaštela – the Cradle of Croatia', Kaštela, Croatia, pp. 367-372.

PENZAR, B., I. PENZAR & M. ORLIĆ. 2001. Weather and Climate of the Croatian Adriatic (in Croatian), Feletar, Zagreb, 258 pp.

RAICICH, F. 1994. Note on the flow rates of the Adriatic rivers. Technical Report RF 02/94, CNR Istituto Sperimentale Talassografico, Trieste, 8 pp.

REED, R. K. 1977. On estimating insolation over the ocean. J. Phys. Oceanogr., 17: 854-871.

RENKA, R. J. 1984. Algorithm 624: Triangulation and interpolation at arbitrarily distributed points in the plane. ACM Transactions on

Mathematical Software (TOMS), 10: 440-442.

VUČAK, Z., M. GAČIĆ & V. DADIĆ. 1981. Characteristics of the current field in Mali Ston Bay. Proceedings 'Mali Ston Bay – Natural Background and Social Evaluation' (in Croatian), Dubrovnik, Croatia, pp. 41-51.

ZAVATARELLI, M. & N. PINARDI. 2003. The Adriatic Sea modeling system: a nested approach. Ann. Geophys., 21: 345-364.

ZORE-ARMANDA, M. 1968. The system of currents in the Adriatic Sea. Études et revues – Conseil général des pêches pour la Méditerranée, FAO, Rome, 34: 1-48.

ZORE-ARMANDA, M. 1980. Some dynamic and hydrographic properties of the Kaštela Bay. Acta Adriat., 21: 55-74.

ZORE-ARMANDA, M. 1985. Sea water climatic characteristics of Middle Adriatic. Geofizika, 2: 179-193.

Ugniježđeno modeliranje istočno-jadranskih obalnih voda

Mirko ORLIĆ [1], Gordana BEG PAKLAR [2], Zoran PASARIĆ [1], Branka GRBEC [2]
i Mira PASARIĆ [1]

[1] *Geofizički zavod "Andrija Mohorovičić", Prirodoslovno-matematički fakultet Sveučilišta u Zagrebu, Horvatovac bb, 10000 Zagreb, Hrvatska*

[2] *Institut za oceanografiju i ribarstvo, P. P. 500, 21000 Split, Hrvatska*

SAŽETAK

Obalno područje srednjeg Jadrana numerički je modelirano s rezolucijom od 1 km radi simuliranja temperature, saliniteta i struja. Upotrijebljeni model predstavljao je modifikaciju Princetonskog Oceanskog Modela (POM), kontroliranog površinskom izmjenom impulsa, topline i vlage te dotokom četiri rijeke: Jadra, Žrnovnice, Cetine i Neretve. Model obalnog područja povezan je s jadranskim modelom rezolucije 5 km, upotrebom jednostavnog načina gniježđenja. Rezultate trogodišnjeg eksperimenta izvedenog uz ponavljajuće atmosfersko i riječno djelovanje obilježio je jak godišnji signal, u prilično dobrom suglasju s temperaturnim i salinitetnim podacima prikupljenima na stalnim oceanografskim postajama uzduž profila Split-Gargano. Obrat struja dobiven u području između Hvara i Visa tijekom ljeta također je prethodno dokumentiran mjerenjima. Simulacija je uz to pokazala da dalmatinski otoci – napose Lastovo i Vis – utječu na istočno-jadransku struju zimi, dovodeći do pojave brazda iza otoka i mlazeva među njima. Usporedba rezultata simulacije višegodišnje promjenjivosti s odgovarajućim podacima ukazala je na dobro slaganje temperature, dok je relativno veliko odstupanje saliniteta bilo uzrokovano klimatološkim protocima vlage koji su nametnuti modelu. Eksperimentalne prognoze, izdavane za razdoblje od šest mjeseci, omogućile su stjecanje iskustva u području operativne oceanografije, ali su upozorile i na jedan dodatni problem – pretjerano miješanje modelirano u situacijama u kojima je vjetar izražen. Osim toga, niska prostorna rezolucija upotrijebljenih atmosferskih polja po svoj je prilici nepovoljno utjecala na prognoze strujnog polja za neke smjerove vjetra.

Ključne riječi: ugniježđeno modeliranje, temperatura, salinitet, struje, Jadran