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On the dynamical conditions concomitant with the bottom anoxia in the Northern Adriatic Sea: A numerical case study for the 1977 event

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Summary. — The aim of the present investigation is to explain the dramatic phenomenon of anoxia/hypoxia waters observed in the Northern Adriatic Sea during August 1977 by using the data collected in the DINAS 2 oceanographic campaign and modelling them by means of a three-dimensional numerical model for the whole basin. The model has been forced with ECMWF surface reanalysis data—wind stress, heat fluxes and river discharges. The main result lies in the high temporal and spatial correlation between the observed anoxia areas and the centres of anticyclonic circulation produced by the model. Further investigations seem to be necessary for a better matching between observed and simulated thermohaline fields.

PACS 92.10.Sx – Coastal, estuarine, and near shore processes.
PACS 92.10.af – Thermoaline convection.
PACS 92.20.Cm – Chemistry of the ocean.

1. – Introduction

Although the Adriatic Sea is probably one of the most studied semi-enclosed seas of the world, it is not still made clear how its physical, chemical and biological components interact to produce those particular phenomena, *i.e.* mucilage and bottom hypoxia or anoxia that pose noticeably environmental concern. Particularly hypoxia, observed recursively in the northern areas of the Adriatic during summer and autumn seasons [1-3], seem to be associated, besides with the eutrophic loads of riverine origin, with peculiar wind and surface heat regimes able to determine a well-defined circulation pattern in the above areas. In this context, the Po River outflow plays a special role from the hydrological point of view. In fact, if during spring-summer seasons the Po River discharges a particularly high (with respect to climatic values) volume of fresh waters, then a marked pycnocline is formed and the Po River "fresh" waters spread eastward from Italian coast, sometimes up to Istria peninsula. When such hydrological situation coincides with mild weather, vertical mixing is inhibited for several days. In these conditions the supply of oxygen to the deep layer becomes too scarce compared to its demand to oxidize organic matter accumulated on the bottom thus causing the development of hypoxic or anoxic conditions. Only strong air-sea interactions (occurring sometime in summer too) are capable to mix the water column producing dense waters that ventilate the sea bottom. Although this scenario is qualitatively well known in the Northern Adriatic and in other coastal areas [1-15], it is worth to mention that, for the Northern Adriatic, only a few models have been produced, able to be compared with observations. Examples of these models are represented by the papers of Vested *et al.* [16] and Russo *et al.* [17] addressed to the dense water formation in the Northern Adriatic and the Gulf of Trieste, respectively. Moreover, recent papers have reported the presence of a particular coastal circulation along the Istrian peninsula, the so-called Istrian Coastal Countercurrent (ICCC), in concomitance with hypoxia or anoxia events in 1977, 1988, 1989, 1991, 1997 [18,19]. The formation of closed cyclonic circulation patterns in the Northern Adriatic [20,21] play an essential role in the development of hypoxia/anoxia events both reducing the water exchange with the central Adriatic and increasing the residence time of the eutrophic waters of riverine origin in the northern part. Moreover, the appearance of anticyclonic gyre (eastern part of the gyre is the ICCC) near the Istrian coast enhances those effects turning northwards those nutrient rich coastal waters of Po, Adige and other minor rivers that can be advected till the Istrian coast. It is worth to notice that the Northern Adriatic circulation in spring and summer can be rather complex, including several cyclonic and anticyclonic gyres [19,21]. Analysing the oceanographical data for August Krajcar [22] found that an anticyclonic gyre near the Istrian coast exists as a part of an anticyclonic meander that starts near the Po river delta. It must be pointed out that our model results confirmed the above-mentioned circulation patterns. Moreover, our simulations show another anticyclonic stream flowing along the Italian coast to reach the Istrian one. Thus the semienclosed circulation cell is established in the Northern Adriatic, encompasses a system composed by two anticyclones gyres and a cyclonic one discussed in the following paragraphs. The eastern branch of the eastern anticyclone, that is the ICCC, was particularly intense in 1977, *i.e.* in concomitance with one of the most extended hypoxic events observed in the Northern Adriatic. In fact, during August of that year the daily averaged surface ICCC velocity reached values of $15\,\mathrm{cm\,s^{-1}}$–$23\,\mathrm{cm\,s^{-1}}$ offshore the Istrian coast, *i.e.* the maximum ever observed in the period from 1966-1997 [18]. The development of the ICCC in August indicates the presence of a low-salinity, warm-water pool in the north-eastern open waters representing the core of the two anticyclonic gyres above mentioned [19,23]. It is necessary to mention that this countercurrent (and its anticyclonic meander) results from intricate relationships among different morphological, meteorological and hydrological elements. In this framework, we wish to quote a paper that focuses the basic role of the Po river in determining different patterns for the surface circulation of Adriatic basin [24]. Referring to the 1977 event, the ICCC was likely related to a high Po river discharges in spring coupled with both low barometric pressure and rainfalls that allowed the nutrient rich freshwater to flood the northern part of Adriatic.

Despite the role of this countercurrent, until the present paper no studies have been addressed to model it. The only exception is given by a very recent numerical study showing that the ICCC can be simulated only by a nested model (1.5 km resolution) while its coarser one with 5 km of resolution does not produce ICCC [25]. Differently, the aim of the present paper is to reproduce by the numerical model Princeton Ocean Model—POM [26] the development of the ICCC of the summer 1977, *i.e.* when one of

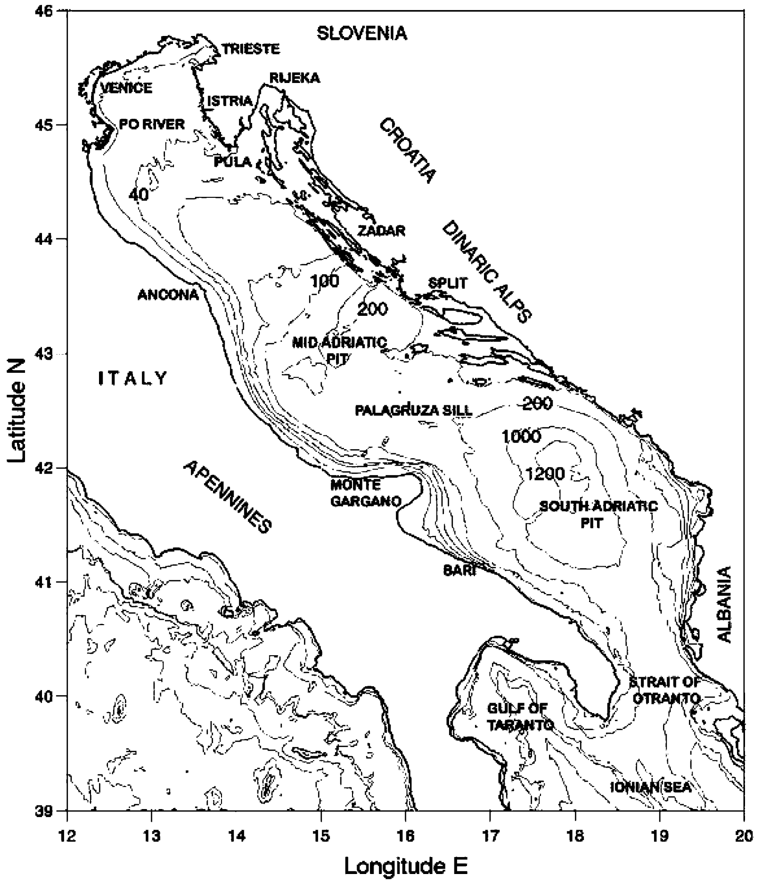

Fig. 1. – Geography and depths of the bathymetry of the Adriatic Sea. Depth contours are in meters (adapted from [21]).

the largest hypoxia events was observed and the ICCC reached the highest value ever recorded. We underline that, although we used the same numerical model chosen by Zavatarelli and Pinardi [25] for their higher resolution simulations (1.5 km), we simulated the ICCC with coarser resolution (5 km) by considering well-defined atmospheric and Po river runoff forcing for a defined case study.

2. – Main characteristics of the Adriatic Sea, the hypoxia event of 1977 as observed, the numerical model and its forcing

2˙1. *Main characteristics of the Adriatic Sea.* – The Adriatic resembles a semi-enclosed rectangular-shaped sea 200 km wide and 800 km long connected with the Mediterranean basin through the Otranto Strait (fig. 1). Its northern part shows a gentle decreasing shelf that reaches its maximum depth in correspondence of the Mid Adriatic Pit (MAP, also called the Pomo or Jabuka Pit). After this depression, the bottom raises in correspondence of the Pelagosa Sill (130 m), then the depth increases until reaching its maximum value at the South Adriatic Pit (1200 m). Finally, the bathymetric profile rises again toward the Otranto Strait up to the depth of 800 m. Many forcings affect the Adriatic Sea: 1) bottom topography; 2) strong air-sea interactions; 3) river runoff (mainly the Po river) and finally, 4) flow exchanges through the Otranto Strait. Regarding the first forcing, we recall that for various theoretical aspects mainly based on the conservation of the potential vorticity [27, 28], the South Adriatic Pit induces a cyclonic circulation in the corresponding sub-basin [29]. The effect of Pomo depression is more subtle. The paper of Carnevale *et al.* [30] poses the mathematical theory for the understanding of such effect. Briefly, the northward current flowing along the Croatian coast bifurcates in a flow directed toward the Italian coast along the southern flank of the Pomo and in a secondary branch directed northward along the eastern Adriatic coast. A confirmation of this theoretical picture is provided by the application of the three-dimensional model DieCAST to the whole Adriatic Sea [29]. We note that the above secondary flow can be considered the main cause for the cyclonic pattern affecting the Northern Adriatic although its bathymetric variations [24], intense air-sea exchanges, and the presence of the Po river runoff strongly modify the basic counter-clockwise circulation above depicted.

The second forcing is given by two main wind regimes, the first coming from south (in details: Libeccio from south-west and Sirocco from south-east) and the second one from east-north-east (Bora), respectively. While the first can induce intense storm surges in the Northern Adriatic with consequent dramatic flooding in Venice (for a review, see the books edited by Cushman-Roisin *et al.* [21] and Fletcher and Spencer [31], respectively), the second one influences deeply both the hydrology and the circulation of surface waters [21, 32-35]. The third forcing, *i.e.* the Po river, while reducing the salinity of surface waters, prevents surface waters from sinking in the northern basin (*i.e.* it opposes the process of the dense water formation). For gentle wind conditions, the Po-river plume forces a density driven current, that flows along the Italian coast, and forms an offshore bulge interesting a large extent of the northern basin. Clearly, the two wind regimes strongly influence the climate of the basin; details on this context are given by the above-mentioned book [21] and recent papers [24]. We underline that the low-salinity riverine waters let in by the Po river in the Adriatic are not important only from the physical oceanography point of view. In fact they can have noticeable impact on the quality of waters of the northern and mid Adriatic coastal areas since the presence of high loads of nutrients in these river-borne surface waters can create the biological conditions fit for the development of dramatic hypoxia/anoxia or mucilage events. Regarding the point 4), the Otranto Strait guarantees the hydrological balance between the dense waters formed in the Adriatic and the compensating flow through surface and intermediate layers of more saline and warmer waters coming from the Eastern Mediterranean. From the numerical point of view, we note that the above balance can be obtained by climatological data or using a nested technique [25, 32, 34].

2·2. *The hypoxia event of 1977.* – The hypoxic crisis of August 1977 in the Northern Adriatic has been reported in several papers [1, 5, 36-40] but, nonetheless, many of the data collected have not yet been completely exploited. The Institute of Marine Sciences (ISMAR) of the Italian National Research Council (CNR) of Trieste carried out a cruise from 4 to 24 August (DINAS 2) that partially covered the zone of Adriatic Sea interested by the phenomenon (fig. 2). Figure 3 shows the stations where the water column was found to be hypoxic (*i.e.* less than 33% of oxygen saturation degree) at least in the deepest layer (usually 2 or 3 m above the sea bottom). These stations outline a rather large hypoxic area surrounding approximately the Po River delta from 45° 15.4′ to 43° 46.3′ N, stretching eastward up to 13° 18.2′ E (*i.e.* station 36), about 25 nautical miles

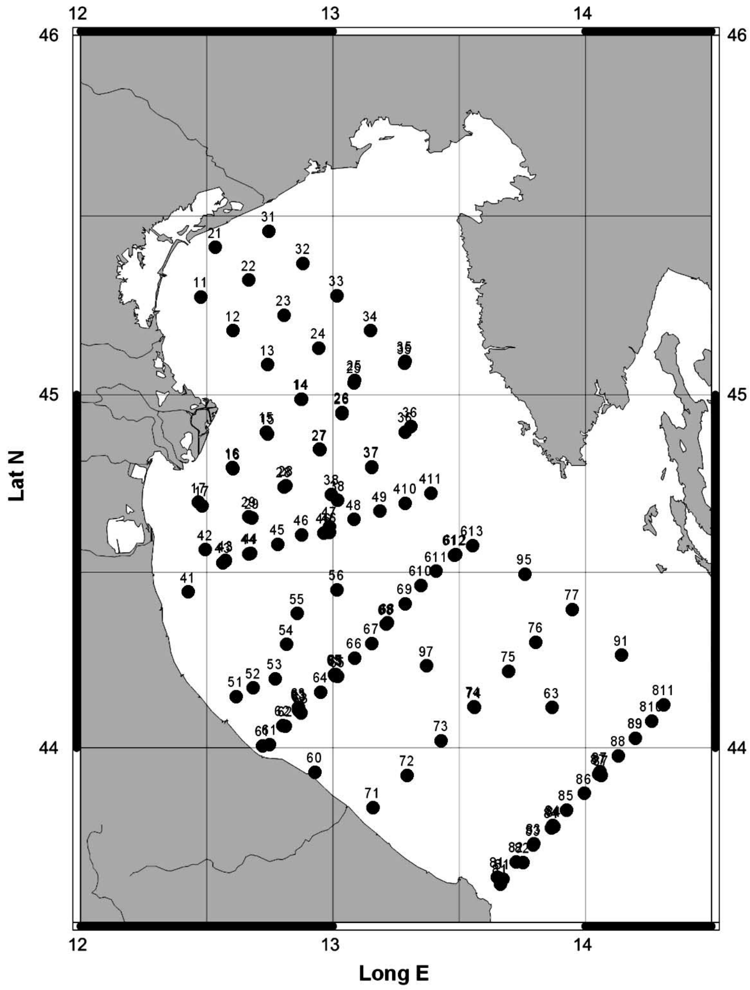

Fig. 2. – Map of the Northern Adriatic with positions of the stations of the DINAS 2 survey carried out during August 1977.

offshore the Istrian coast (fig. 3).

About the duration of the monitoring, the first hypoxic sample has been found in station 53 (fig. 3) on 12 Aug. with 1.29 mL/L of dissolved oxygen (hereafter: DO2) and the last one on 24 Aug. at station 64 with 1.23 mL/L of DO2. The interval of time interested by the phenomenon was therefore of at least 12 days.

On the whole, the DO2 concentration ranged in the deepest layer between 0.75 mL/L (33.5 μM, *i.e.* 12.9% of saturation) at station 37 and 1.88 mL/L (83.9 μM, *i.e.* 32.8% of saturation) at station 23. In the station 37 the hypoxic layer was localized from the depth 30 m down to the bottom (42 m), therefore at least 12 m of water column were interested by the hypoxia.

Although the entire area was hypoxic, two zones were distinguished with the highest levels of hypoxia. The first zone, called SW (fig. 3), closer to the Italian coast, is

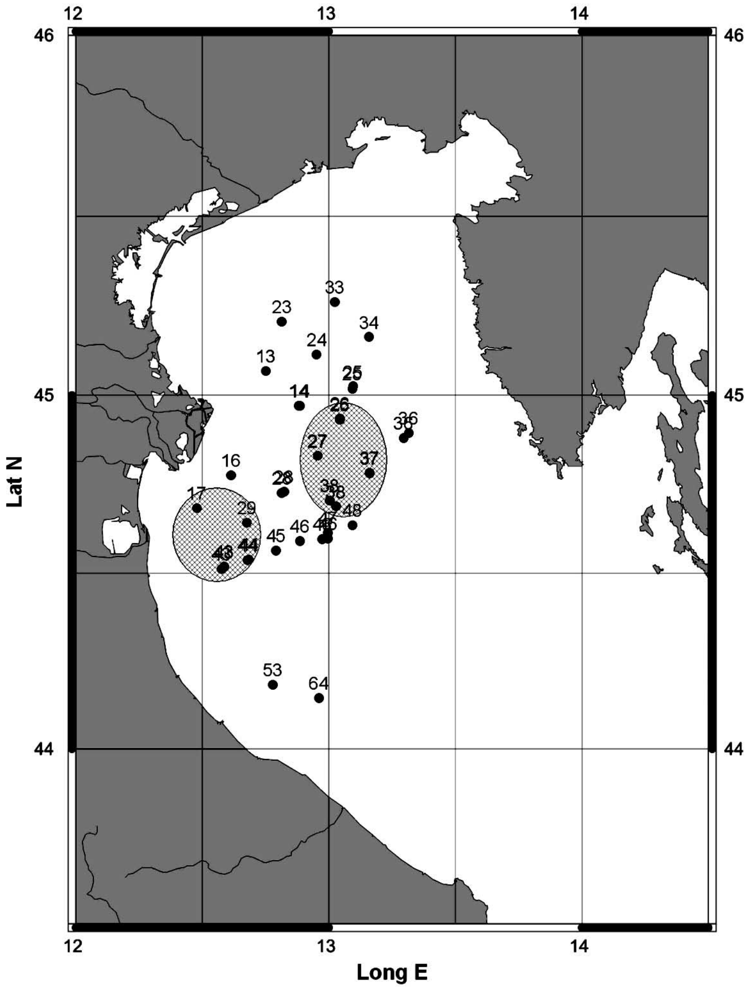

Fig. 3. – DINAS 2 stations having the %DO_2 < 33. The two areas SW and SE are characterized by the highest level of hypoxia (*i.e.* %DO_2 < 20). The area N indicates a centre of lower hypoxia levels.

represented by the cluster of stations 17, 29, 44 and 48, the second, more eastern and called NE, by the 26, 27, 37 and 38 (fig. 3). The two zones were surveyed twice, on 16 and on 20-21 August, and both were found hypoxic, implying that one zone cannot be considered as a spatial-temporal evolution of the other. The absolute minimum degree of oxygenation has been always localized in the NE zone, 15.3% and 12.9% in station 37 on 16 and 20 August, respectively, whereas in the SW zone it was found as low as 18.1% at station 17 and 17.3% at station 29, respectively on 16 and 21 August. These two zones, identified according to these criterions, were more or less centred around 44° 37′ N and 12° 35′ E (the SW zone) and 44° 51′ N and 13° 06′ E (the NE).

In these zones, the water column resulted strongly stratified. During the first survey (16 August), surface density anomaly γ_T was 17.88 (NE) and 17.17 (SW) while γ_T around 30 m depth was 28.58 (NE) and 28.43 (SW). The maximum gradient of density was found between the depths of 5 and 20 m. Such pronounced gradient was due both to the salinity (27.91 psu [41] at surface and 37.68 psu at the bottom in NE zone on 16 Aug. 1977) and temperature (25.90 °C at surface and 13.65 °C at the bottom in zone SW on 20 Aug. 1977).

Another cluster (N) of stations was identified northwards these two zones (st. 13, 14, 23, 24, 25, 33, 34) where hypoxic conditions resulted less severe. The minimum of oxygen, 1.21 mL/L (54.0 μM, *i.e.* 21.0% of saturation) has been observed in the bottom layer of station 13. The most dense water of this cluster of stations ($\gamma_T = 28.54$) has been found at station 24, corresponding to the coldest bottom water ($T = 13.24$°C). This zone results centred around 45° 07′ N and 12° 57′ E (fig. 3). Unfortunately T and S data of surface water of the central station of this zone (st. 24) are not available, but at 5 m depth T, S and γ_T were found to be 22.30 °C, 33.36 psu and 22.91, respectively. Therefore in this cluster also the difference of density between upper and bottom layer can be considered less pronounced than in the previous NE and SW clusters.

2˙3. *The numerical model and its forcing.* – The numerical model here used to perform the simulations is the above-mentioned POM [26]. It is a three-dimensional, free-surface, sigma-coordinate model and for the present simulations was set up with a horizontal grid resolution of 5 km and 20 vertical levels. The model is forced by wind stresses, heat fluxes, river discharges, precipitation-evaporation fluxes, atmospheric pressure and exchanges through the Otranto Strait. The atmospheric forcing is derived from the ECMWF 40 Years Re-Analysis data set (ERA-40). The river runoff is calculated on the base of the climatological data for river discharges rates [42] which was modulated according to the ERA-40 6-hourly runoff data. Water exchange thorough the Otranto Strait is specified by using the Mediterranean Ocean Data Base (MODB), ed. 4 (for details, see `http://modb.oce.ulg.ac.be`). The model is initialized with January temperature and salinity climatological fields (MODB, ed. 6). The bias between observed temperature and salinity values and the corresponding simulated ones and presented in the following should be ascribed to the initial difference between the particular year taken into consideration (1977) and the climatological data set used to initialize the model. The assimilation technique was not used because of the scarcity of temperature (and salinity) data for the whole basin with regard to the 1977. The model runs for 15 days in diagnostic mode with climatological forcing of January [43]. Then, the climatological river discharges [42] are included and the POM runs for another 15 days in prognostic mode, and the initial conditions of January are then obtained. The simulations presented in next paragraph refer to the period January 15, 1977–August 31, 1977 and are obtained by the use of the ERA-40 data set.

About the atmospheric forcing, the ECMWF 40 Years Re-Analysis data set (ERA-40) are 6-hourly and has 2.5 degree of horizontal resolution. They are interpolated to the model grid by using the EMOS software (see `http://www.ecmwf.int/products/data/software/interpolation.html`). Hereafter, we will use the names of the forcing fields used, as they are specified in the catalogue of ECMWF products (see `http://www.ecmwf.int/products/catalogue/` and WMO [44]). The ERA-40 fields used to calculate the heat flux balance at the surface are: sensible, latent heat fluxes, thermal (long-wave) radiation and downward (incoming) solar radiation. To obtain the surface solar radiation (incoming minus reflected) we assume a constant albedo at the sea surface (5%). Some preliminary numerical experiments showed that if the ERA-40 surface solar radiation is used, the heat fluxes in both Northern and Southern Adriatic are underestimated by 20–30%. This is due to the coarse grid of the ERA-40 data. In

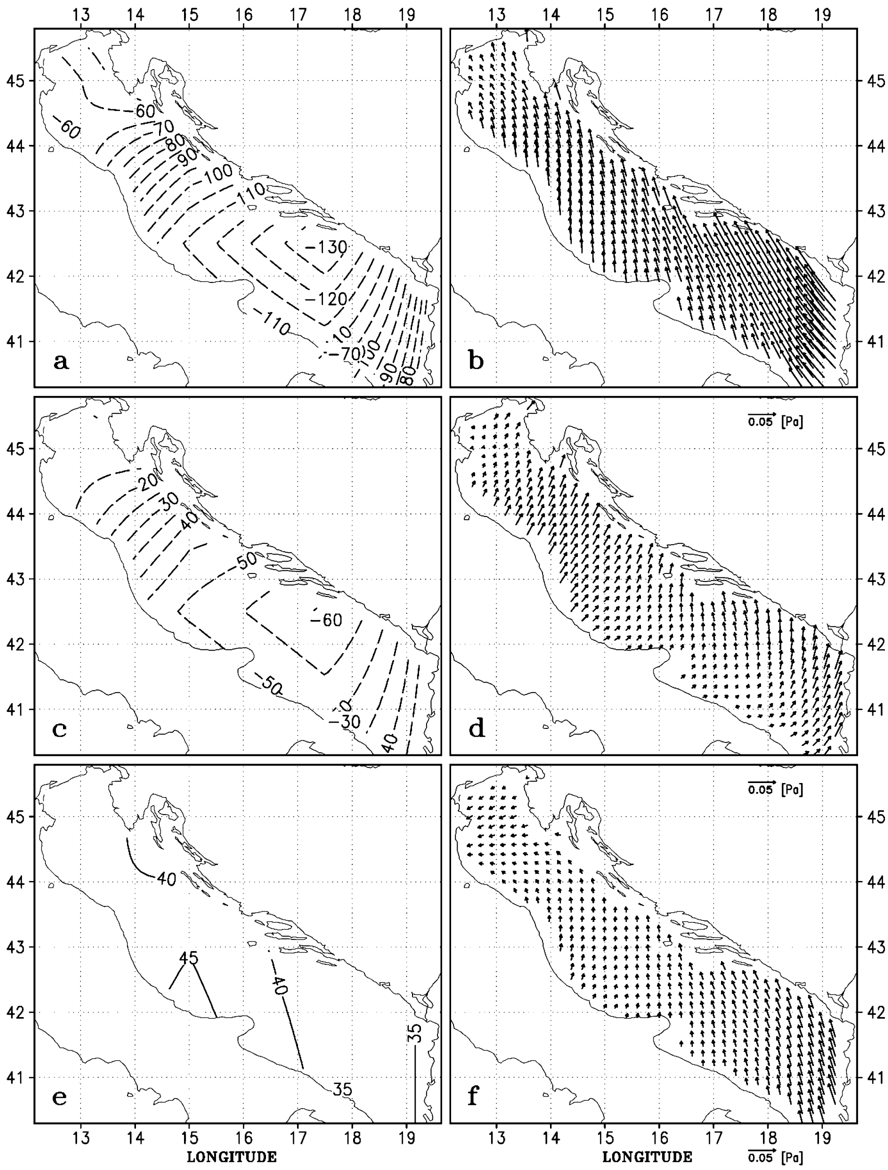

Fig. 4. – Total heat flux ($W\,m^{-2}$) (left column) and wind stress (Pa) (right column) for January (a, b), February (c, d) and March (e, f) 1977, interpolated in the model grid from the ECMWF ERA-40 atmospheric reanalysis data. Contour interval is $5\,W\,m^{-2}$. Dashed lines indicate negative values.

fact, in the above-mentioned regions, the grid boxes cover large land areas and small sea ones, so the estimated surface albedo is unrealistically high—it is well known that for a water surface the albedo is much lower than for a land surface. The ERA-40 data is used for both the East-West and North-South surface stress fields and the fresh-water balance, the latter resulting from total precipitation, evaporation and runoff fields.

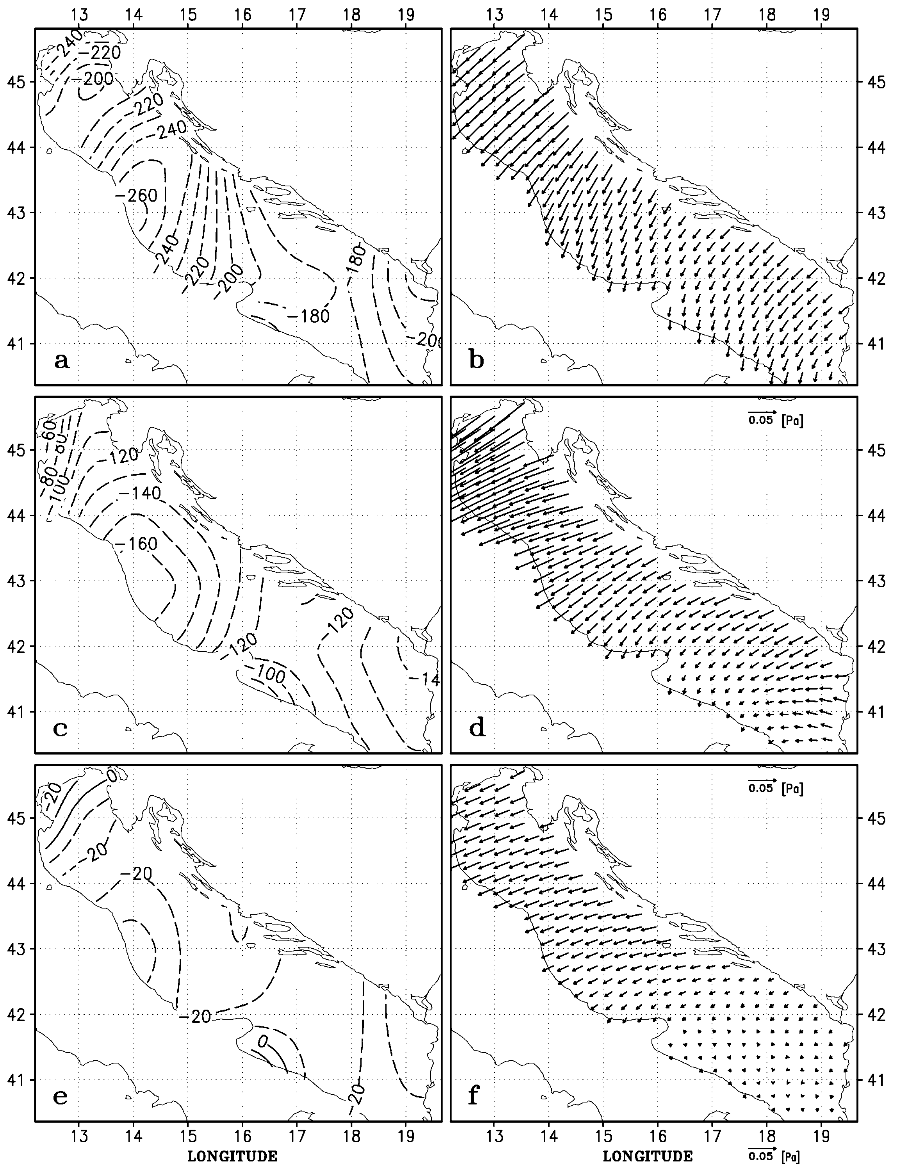

Fig. 5. – Monthly climatological surface heat flux ($W\,m^{-2}$) and wind stress (Pa) for January (a, b), February (c, d), and March (e, f), interpolated in the model grid from May (1982, 1983) data set. Contour interval is $10\,W\,m^{-2}$.

Figure 4 represents the monthly averaged total heat fluxes at the surface and the monthly averaged wind stresses fields for the period January-March, 1977. Figure 5 depicts the same fields, but obtained from May [43, 45] climatological data set. The comparison from the former and the latter data set shows that the 1977 was an anomalous year. The January, February and March heat fluxes were higher than the corresponding climatological values. This can be explained with the few episode of Bora during the first

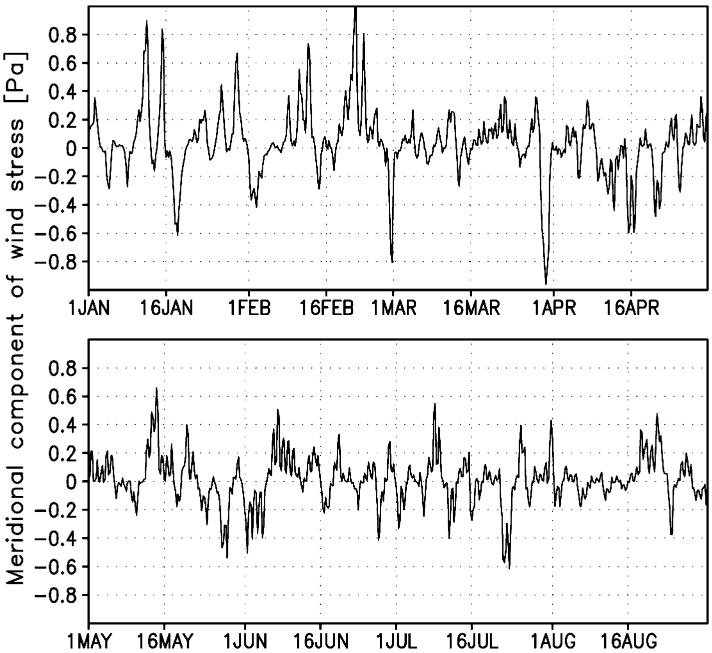

Fig. 6. – Meridional component of wind stress (Pa) for the periods 1 January–30 April 1977 (upper panel) and 1 May–31 August 1977 (lower panel). Data were obtained from ECMWF ERA-40 for the model cell with a centre at 15E, 45N.

four months of the 1977 and the more frequent Sirocco/Libeccio events. Differently, the averaged heat fluxes and wind stresses for May-August 1977 were close to the climatic ones.

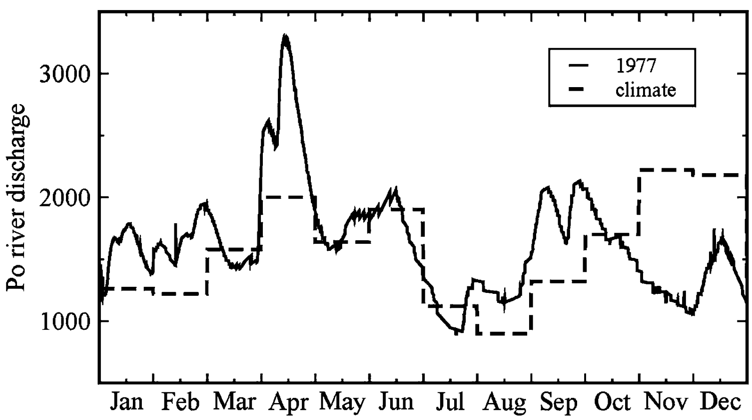

Fig. 7. – Po river discharge rates ($m^3\,s^{-1}$): climatological values (dashed line) obtained from Raicich [42] and; calculated values (solid line) on the base of climatological ones and ECMWF ERA-40 runoff data for the 1977.

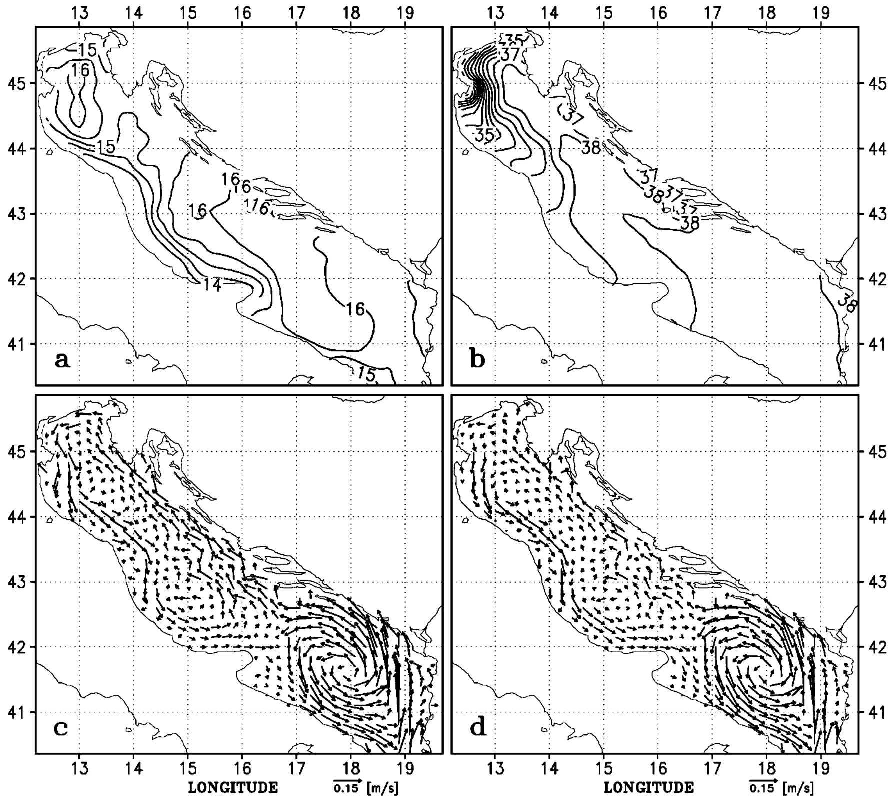

Fig. 8. – Model simulated: (a) temperature; (b) salinity; (c) and (d) velocity fields. The first three plots (a, b, c) are at 1 m depth and the last one (d) is at 10 m depth. All fields are monthly averaged for May 1977. The temperature interval is 0.5 °C and salinity interval is 0.5 psu. Every 9th grid point has been plotted.

The prevalence of the southerly (Sirocco/Libeccio) over northerly (Bora/Maestral) winds during the first months of the 1977 can be seen clearly in fig. 6. The data show the occurrence of 9 episodes of Sirocco and only 3 of the Bora for the period January-February 1977. In comparison, in the same months for the 1975 and 1976 years the Sirocco events were 3 while the Bora ones were 7. The situation is analogous during the period March-August 1977, when episodes with Sirocco/Libeccio winds are well evident. Note that in 2000, another year characterized by establishment of the ICCC, southerly winds prevailed during the major part of the year, also [19].

The other forcing is the river runoff for the whole Adriatic [42]. We note that the first four months of the 1977 were characterized by higher (approximately 20%) than climatic values of the riverine discharge. Moreover, during the same period the difference between precipitation and evaporation was positive. In the remaining period of the 1977 the total river input was close to the climatic average. Therefore when compared with the same period of 1975, the first four months of 1977 are characterized by both noticeably high positive difference precipitation-evaporation and persistence of strong southern winds. Particular mention should be made to the Northern Adriatic where the Po river runoff was extremely high in April with respect to its climatic values (fig. 7) and was higher

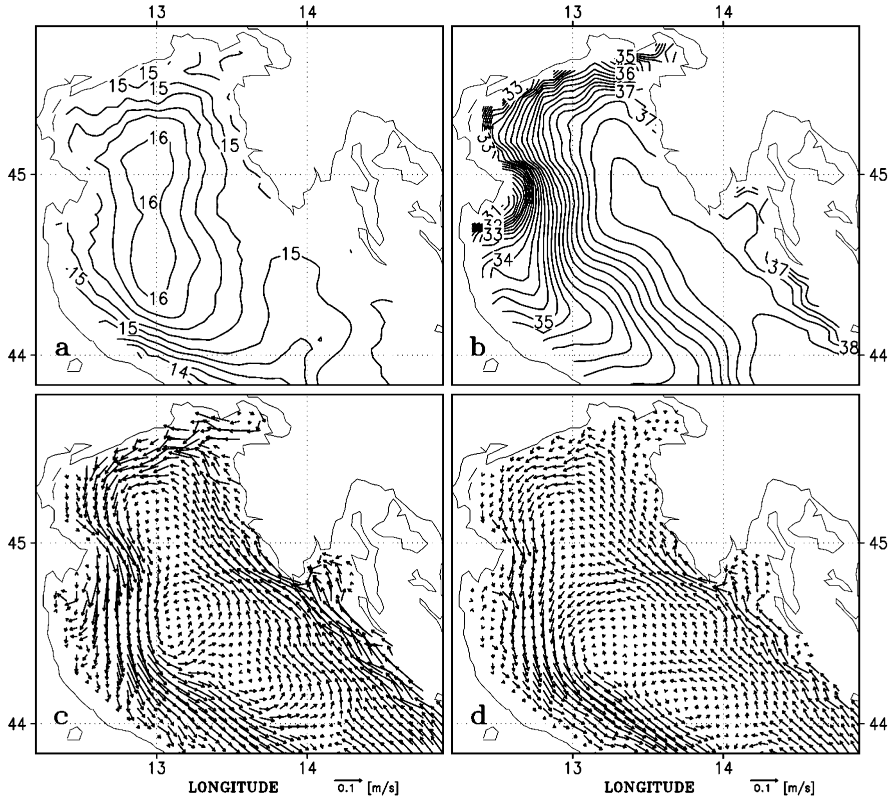

Fig. 9. – Same as in fig. 8 but for the Northern Adriatic. The temperature and salinity intervals are 0.5 °C and 0.5 psu correspondingly.

than the climatological data in January and February 1977, also. To summarize, the Northern Adriatic was characterized, during the first months of 1977, by the prevalence, with respect to the climatological values, of southern winds (Sirocco/Libeccio), higher total heat fluxes and high rate of Po river runoff. These three facts are likely the necessary physical conditions for the formation of the ICCC and consequently for the development of hypoxia/anoxia events because of the spreading of riverine waters in the Northern Adriatic. We remember that the effect of the prevailing southern wind on the Po River plume has been analyzed in a paper of Kourafalou [24] whose results are well in agreement with the present one about the spreading of riverine fresh water in the whole Northern Adriatic.

3. – Model results and discussion

Model results exhibit a good agreement between a flow field reported in the literature [21] and that one simulated and referred to the surface and the 10 m depths. Monthly averaged fields for May 1977 are presented on fig. 8, as an example representative for the circulation during the first five months of 1977. In particular, the southern Adriatic cyclonic gyre is well singled out for all months. This gyre is less intense in August due

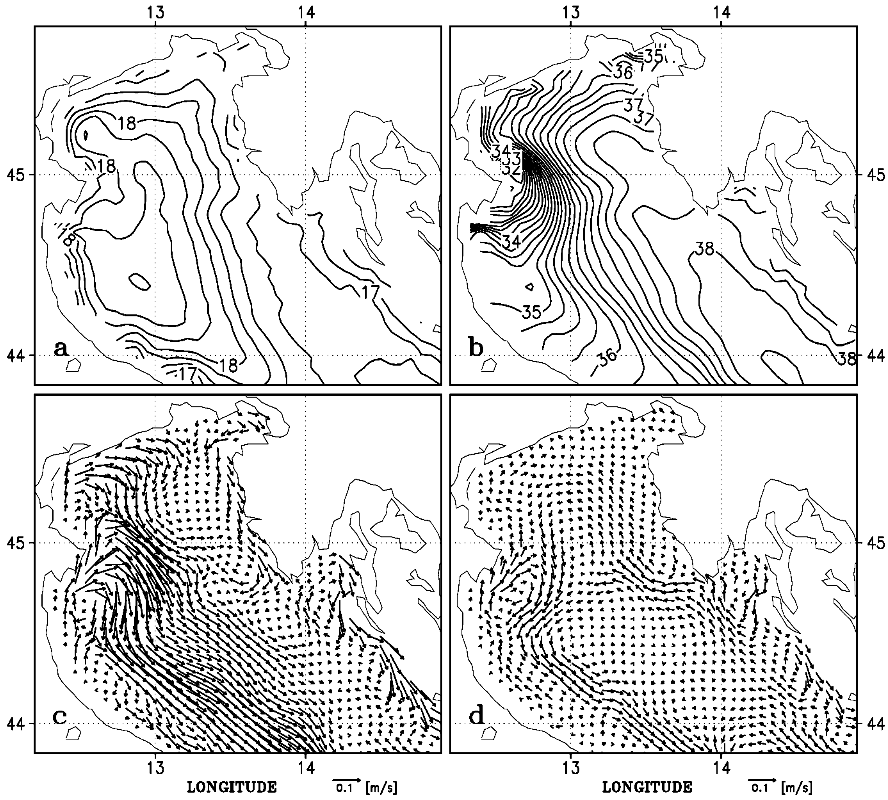

Fig. 10. – Same as in fig. 9 but for June 1977.

to the formation of a narrow and elongated anticyclonic gyre close to the Albanian coast (figures not shown). A similar result has been obtained by quite different numerical model DieCAST after four years of simulations [29]. The model results are in agreement with observations also regarding the reinforcement from winter to summer of the middle Adriatic cyclonic gyre [25]. The simulated surface temperature and salinity fields for the winter and spring months are characterized by the presence of well-marked frontal zones in the northern and middle basin. Colder and less salty water of riverine origin (fig. 8) spread along the western coast in the period January-June 1977. This pattern coincides with the scenario of Lagrangian trajectories for particles released around the Po delta in the case of southern winds [24]. The discrepancy in the observed and simulated thermal fields can be ascribed to the inizialization of the model by means of climatic data instead of those of 1977.

The temperature, salinity fields and the circulation in the Northern Adriatic for the period May-August 1977 are presented in details in figs. 9-12. In May the northern Adriatic circulation is a part of the global Adriatic cyclonic circulation (fig. 9cd). The currents follow the coastal line and their direction is preserved with the depth. Note that, west of Pula (fig. 1) the northern current bifurcates and a part of the flow follows closely the isobath of 40 m in accordance with the principle of conservation of potential vorticity for flow over a variable topography. This is well visible at 10 m depth (fig. 9d).

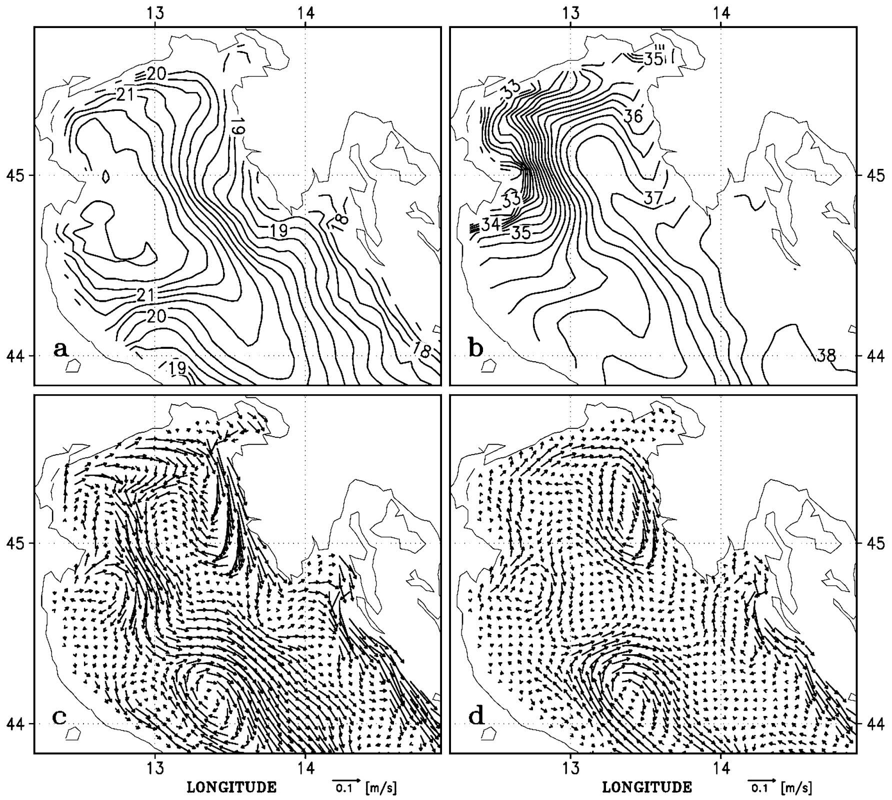

Fig. 11. – Same as in fig. 9 but for July 1977.

The strongest differences between surface and 10 m depth current are present in June (fig. 10cd). While the cyclonic pattern of the circulation at 10 m is preserved, the surface currents are significantly changed: 1) the formation of the ICCC begins, 2) the western coastal current is wider and shifted eastward, 3) the eastern coastal current is weakened, 4) a strong anticyclonic meander in the east of the Po river exists, 5) and a narrow surface density driven current, flowing eastward along the northernmost coast is formed. The existence of some of these circulation features was confirmed by the direct current measurements [18, 19, 22, 23, 46]. In July and August the above-mentioned circulation features evolve and the northern basin results characterized by the presence of centres of opposite vorticity (figs. 11, 12). In particular, four closed circulation gyres are developed in August: anticyclonic gyre north-east of Ancona; anticyclonic gyre close to the Istria whose eastern branch is ICCC; anticyclonic gyre south-east of the Po river; and cyclonic gyre located north-east of the Po river delta. It seems that the formation of the last three gyres is connected with the evolution of the above-mentioned anticyclonic meander east of the Po river [22]. It is well known that different circulation cells are characteristics of the summer circulation of the North Adriatic [47] where the presence of the anticyclonic meander of the ICCC is associated to the advection of freshened waters, mainly originated in the Po area. The most important difference between surface circulation patterns in July and August is the formation of the closed cyclonic gyre north-east of the Po river

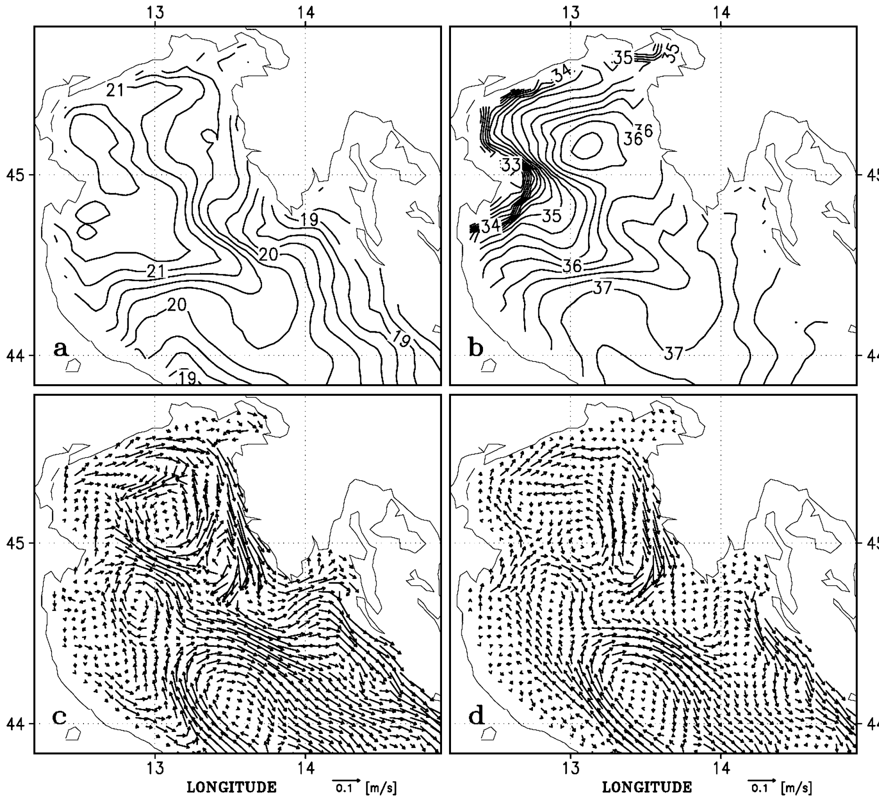

Fig. 12. – Same as in fig. 9 but for August 1977.

in August (fig. 12c). Thus the water exchange between Northern and Middle Adriatic is considerably reduced in August. In July the circulation at that area represents a large cyclonic meander (fig. 11c) and the lower salinity waters, originated in the Po delta area, can leave the Northern Adriatic.

The surface temperature is significantly increased during the last four months of the simulations (figs. 9a-12a) due to the augmented summer solar input. However, the spatial distribution of the temperature is not changed substantially. Regarding the surface salinity field, a few important changes should be pointed out. In May the surface salinity distribution is characterized by strong salinity gradients at the front of the Po river mouth and close to the northern coast (fig. 9b). In June and July these gradients are reduced (figs. 10b, 11b) due to the advection of low salinity waters by the above-mentioned northern current, flowing eastward along the northernmost coast and by the extension of the anticyclonic meander near Po mouth eastward. Less salty waters are spread close to the Istrian coast by the ICCC, also. Thus the frontal zone along the western coast (fig. 9a) is destroyed (except close to the Po river) in August and a new salinity frontal zone is formed along the latitude 44.5N (fig. 12b). Establishment of this zonal front is in direct connection with the formation of the closed circulation in the Northern Adriatic discussed above. In August the salinity gradient close to the west-northern coast (fig. 12b) is stronger than in July due to the intensive precipitations in the second half of August

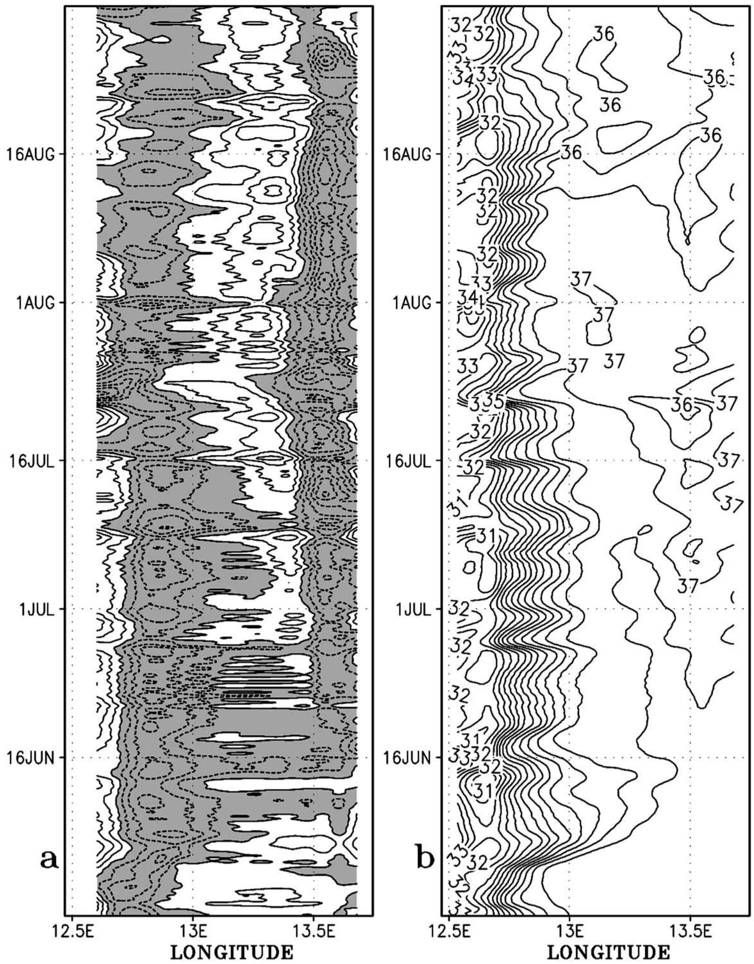

Fig. 13. – Time-longitude plot of the: (a) meridional component of velocity; and (b) salinity at latitude 45N for the period 1 June–31 August 1977. Contour intervals are $5\,\mathrm{cm\,s^{-1}}$ for the velocity and 0.5 psu for the salinity. The 24 hours running mean filter has been used to plot the simulated hourly data. Shaded areas indicate negative (southward) velocities.

and respectively stronger Po river discharge rates (fig. 7). The last feature worth to be mentioned is the isolated pool of relatively saltier waters (36.5 psu) located in the west of Istria (with centre at 13.2E, 45.2N) which coincide with the centre of the closed cyclonic gyre in the Northern Adriatic (fig. 12bc).

The formation of the above-mentioned features in the velocity and salinity fields can be seen in fig. 13, where the surface meridional velocity and salinity at zonal cross-section at latitude 45N are plotted for the period 1 June–31 August 1977. The analysis of the model results show that the rapid circulation change starts in the beginning of June when the formation of the ICCC is underway (fig. 13a). These can be associated with the unusual period of 4 days with Bora wind (1-5 June), followed immediately by 5 days with Libeccio wind (6-11 June) (fig. 3). As a result, a significant eastward transport of

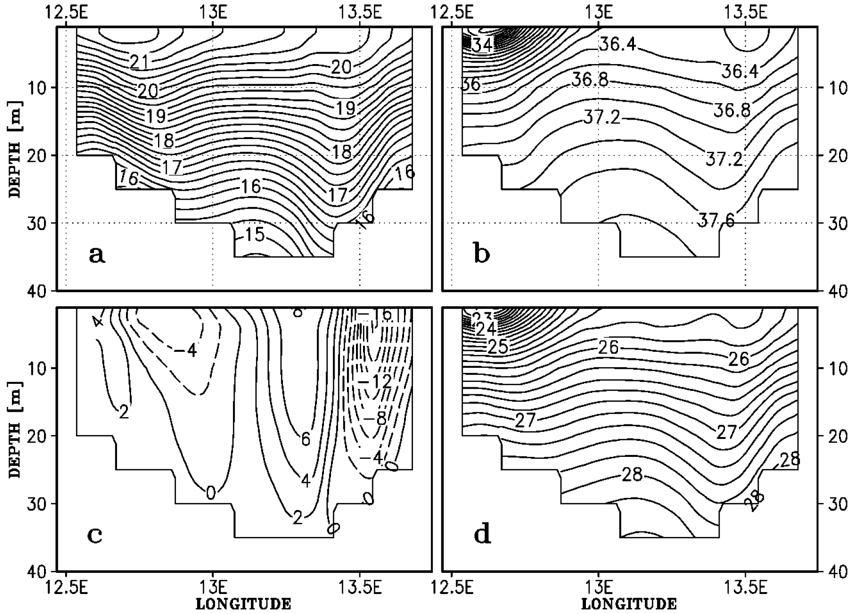

Fig. 14. – Zonal cross-sections at latitude 45° N for August 1977 (monthly averaged): (a) temperature; (b) salinity; (c) meridional velocity; and (d) density (σ_θ). Contour intervals are 0.25 °C, 0.2 psu, $2\,\mathrm{cm\,s^{-1}}$ and $0.2\,\mathrm{kg\,m^{-3}}$, correspondingly.

freshened water is evident after 6th of June (fig. 13b) and consequent development of the ICCC after 15th of June (fig. 13a). This scenario is in good agreement with the results of Kourafalou [24], showed that only with south-westerly winds the particles released at the Po delta can reach the east Adriatic coast. Moreover, the recent study of Supic *et al.* [19] reported that the circulation pattern in the Northern Adriatic changed drastically between 21 February and 17 March 2000, which according to our investigation have been caused by the analogous change in the wind direction (Bora/Sirocco), described above. Finally, we quote the work of Brana and Krajcar [46] in which authors conclude that when the general circulation of the Northern Adriatic is in quasi-stable state, the Bora wind (or some other meteorological disturbance) may have a triggering role and cause the change of general circulation. It is worth to mention that the analogous period of a rapid change of the wind direction (Bora/Libeccio) occurred between 22 and 26 July 1977, followed by 15 days with a week wind in the beginning of August (fig. 6).

Figure 14 presents the vertical distribution of temperature, salinity, meridional velocity and density, respectively, for the cross-section at 45N, in August 1977. These plots confirm the change of the circulation pattern initiated in June with the subsequent maximum intensity of the ICCC in August. In May (not shown) the vertical distributions of the temperature, salinity and density are characterized by well-pronounced zonal gradients, less salty, colder and lower density waters being confined to the Italian coast. There is an inflow of water into the Northern Adriatic in the eastern and central parts of the cross-section and an outflow of water near the western coast. In contrast, the circulation in August is more complex, indicating the occurrence of several cyclonic and anticyclonic gyres/meanders across the section (fig. 14c). The ICCC is well visible

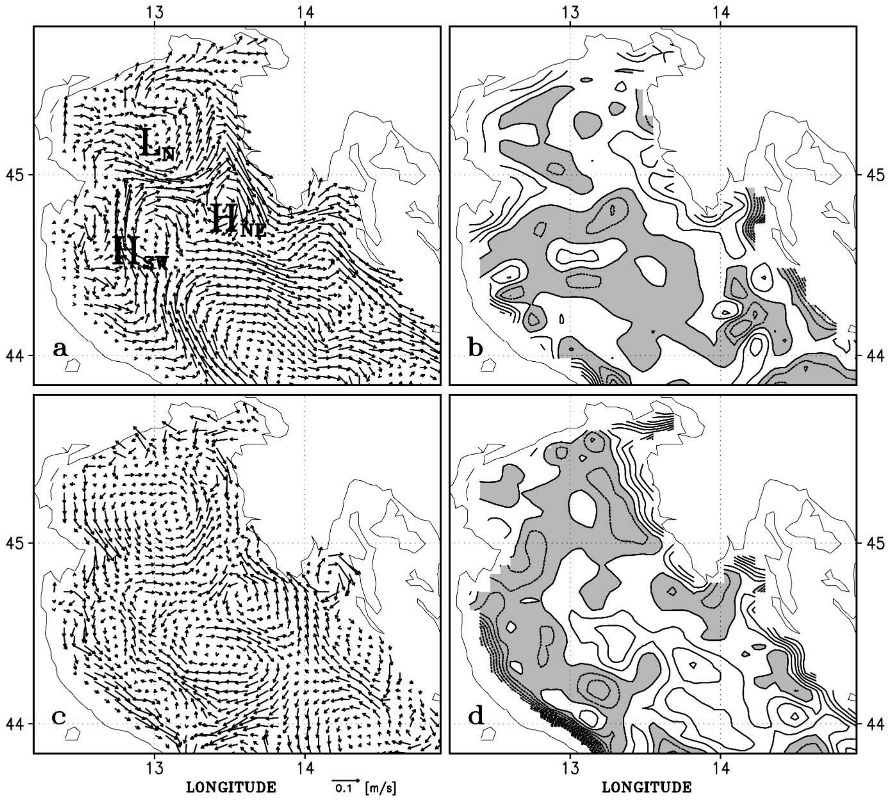

Fig. 15. – Model simulated velocity fields at 10 m depth: (a) horizontal velocity; (b) vertical velocity, averaged for the period 15–17 August 1977; (c) horizontal velocity; (d) vertical velocity on 31 August 1977 instantaneous fields. Contour interval is $3 \times 10^{-6}\,\mathrm{m\,s^{-1}}$ for (b) and $9 \times 10^{-6}\,\mathrm{m\,s^{-1}}$ for (c). Shaded areas indicate negative (downward) vertical velocities. Labels on plot (a) denote the areas of high pressure (H_{SW} and H_{NE}) and low pressure (L_N) correlated with SW, NE and N hypoxia centres (fig. 3), respectively.

with monthly averaged surface velocity of $16\,\mathrm{cm\,s^{-1}}$ (the daily averaged velocity reaches $25\,\mathrm{cm\,s^{-1}}$, fig. 13a). The substantial change can be revealed also in the density vertical profile because of both the propagation of the low salinity surface waters eastward and the increasing of the short-wave radiation, resulting in a significant stratification of the water column (fig. 14).

4. – Final considerations

Even if the phenomenology of the ICCC is known from more than two decades, the present paper gives its first modelling of such a countercurrent for the event of 1977, confirming in the meantime the speculative scenario for its occurrence. Further, the presence of the ICCC has been associated with phenomena of relevant environmental impact for the North Adriatic as hypoxia/anoxia or mucilage events. Therefore the clarification of the physical basis of the ICCC provides the first contribution to the understanding of a phenomenon coupling physical, geochemical and biological aspects which influences the quality of the Northern Adriatic waters. In the present case, we have shown that the process of formation of the ICCC strongly modifies the background cyclonic circulation of the northern basin to form different cyclonic/anticyclonic centres. In particular (fig. 15a), the two anticyclonic gyres (H_{WS} and H_{NE}) developing southward the Po delta seem to be correlated with the above-mentioned two hypoxia areas (SW and NE, fig. 3). However, while the SW is almost perfectly coincident with the corresponding anticyclonic gyre, the NW one turns to be shifted with respect to anticyclonic circulation formed by the ICCC (fig. 15a). This discrepancy can be avoided if we analyse the distribution of the vertical velocity field, presented in fig. 15b. Obviously, the centre of hypoxia area NW (fig. 3) coincides with the zone with stronger downward vertical velocity (fig. 15b), the last one determined by both H_{NE} anticyclonic gyre and a convergent area between H_{WS} and H_{NE} (fig. 15a). Note also that the centre of the H_{NE} is shifted westward in deep layers (fig. 14c).

Coming back to the dynamical aspects, we note that the mechanisms regulating the gyres of the different vorticity results quite similar to that pointed out by Staneva *et al.* [48] for the Black Sea. In fact, the vorticity balance in the Northern Adriatic is maintained by the interplay between the central (cyclonic) and coastal (anticyclonic) circulation in a way that when the former decreases then the latter increases. During such process, the cyclonic gyre is displaced westwards and the local anticyclonic circulation initiates to dominate [48]. We suggest that the persistence of the two cores of most severe hypoxic waters SW and NE (fig. 3) can be ascribed to the presence of the two high-pressure centres H_{SW} and H_{NE} (fig. 15) which, because of their downward vertical motions, enhance the confinement of the hypoxic waters close to the bottom. Moreover, this hypothesis seems to explain the presence of the core of the less hypoxic water N (fig. 3) with the centre of the low pressure in the proximity of the gyre L_N (fig. 15a). We stress that the bottom dissipation associated with high-pressure areas tend to maintain these areas compact for a time interval longer than the low-pressure areas, thus explaining the highest hypoxic level of the SW and NE hypoxia cores. The previous scenario acquires more credibility because of the satisfactory matching between simulated circulation in August 1977 and field observations [18]. In particular, the simulated strong ICCC, has daily averages between 15 and $25\,\mathrm{cm\,s^{-1}}$ (fig. 13a), and results of the same order of magnitude (15 cm/s) of the indirect estimates obtained by the dynamical method near Rovinj for the same year [18]. On the contrary, because of the above-mentioned climatological initialisation of both temperature and salinity fields or the inaccuracy of the atmospheric forcing, the simulated evolution of these parameters does not match the data collected during the DINAS 2 cruise since the latter values differ from the former. For instance, the simulated surface temperature (salinity) on 16 August reaches 23.7 °C (30.5 psu), while the measured one was 2 °C higher (2.5 psu lower). Therefore, the model simulates the water column stratification smoother than that observed during DINAS 2 cruise. Further studies should be addressed to solve this problem by increasing the model resolution, obtaining better initial conditions and adequate atmospheric forcing.

The relationship between the formation of the two closed anticyclonic gyres (H_{SW} and H_{NE}) and the hypoxia event in 1977 become more evident if we look at the process of the hypoxia disappearance at the end of August. After an episode of relatively strong Bora wind on 23 August the northern Adriatic circulation returns to the well-known cyclonic pattern (fig. 15c). Some of the closed circulation features still exist, but the two anticyclones H_{SW} and H_{NE} are almost disappeared and the cyclonic gyre in the northernmost Adriatic is strengthened. The vertical velocities are increased approximately three times and the downward motions over the areas of the most severe hypoxic waters are substituted by upward motions (fig. 15d). All this augments the vertical mixing and the supply of oxygen to the deep layers.

Further studies should be addressed to model dynamical conditions in the Northern Adriatic in the years when anoxia/hypoxia conditions occurred to confirm our hypothesis.

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