GEOFIZIKA VOL. 8 1991

Original scientific paper
UDC 551.465

Ten-day variability of the summer circulation in the North Adriatic

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Received 3 April 1991, in final form 12 July 1991

Current, temperature and salinity data, collected during the ASCOP experiment that was carried out in the eastern part of the North Adriatic in summer 1989, have been analysed together with related meteorological and hydrologic data. After dividing the current series into three nearly equal subintervals, residual currents have been calculated for each of them. The major feature this exercise revealed was a variability at a time scale of about ten days. A similar phenomenon has been observed by Italian researchers in the northwestern part of the Adriatic during several summers.

It has been shown in the paper that the wind episodes registered during the experiment, although inducing remarkable changes in temperature and salinity records, did not directly generate the observed current variability. The changes in the Po River outflow have also been ruled out as the cause of the observed current reorientation.

Temperature data collected in the area have pointed to stratification as the factor controlling the observed current variations. The stratification itself was influenced by buoyancy fluxes and wind forcing. However, further theoretical and empirical work is needed to establish conclusive evidence and elaborate dynamics of the observed phenomenon.

Desetodnevna varijabilnost ljetne cirkulacije u sjevernom Jadranu

U radu su analizirani podaci o strujama, temperaturi i salinitetu izmjereni ljeti 1989. godine u istočnom dijelu sjevernog Jadrana u okviru ASCOP eksperimenta. Vremenske nizove struja podijelili smo u tri podjednaka podintervala u kojima su strujni vektori imali gotovo konstantan smjer. Za svaki od njih izračunate su rezidualne struje. Kao najinteresantnije obilježje tih struja pokazala se varijabilnost na vremenskoj skali od otprilike 10 dana. Sličnu pojavu uočili su i talijanski istraživači u sjeverozapadnom dijelu Jadrana tijekom nekoliko ljeta.

Strujomjerni i hidrografski podaci uspoređeni su s meteorološkim podacima. U analiziranom razdoblju zabilježene su samo dvije pojave vjetra koje su uzrokovale značajne promjene temperature i saliniteta, ali nisu neposredno izazvale opažene promjene u strujnom polju. Promjene protoka rijeke Po bile su zanemarive, pa smo i njih isključili iz daljnjeg razmatranja.

Temperaturni podaci iz analiziranog područja uputili su na stratifikaciju kao mogući faktor koji kontrolira opažene promjene struja. Sama stratifikacija pod utjecajem je vjetra i termohalinih procesa. No, potpunije razumijevanje dinamike opaženog problema zahtijeva daljnja teorijska i empirijska istraživanja.

1. Introduction

The North Adriatic circulation has been studied quite intensively during the past fifteen or so years, yielding a number of mathematical modelling and empirical results on the subject. However, the majority of the papers have dealt with the winter situation. Strong convection and mixing processes that occur in winter homogenize the water column, making the basin more amenable to either mathematical or descriptive analysis. Hendershott and Rizzoli (1976), for example, investigated the residual currents: they developed a numerical model of the winter circulation, inspired by a hydrographic data set. Cavallini (1985) investigated tidal currents using a numerical model of the North Adriatic and comparing its results with field measurements. Kuzmić and Orlić (1987) analysed the wind-induced currents using both empirical data and a three-dimensional numerical model.

In summer, the Adriatic is stratified along the vertical. The majority of summer studies are of an empirical, descriptive nature. Accerboni et al. (1981) presented some characteristics of summer circulation in the North Adriatic and their influence on the pollution. Franco et al. (1982) collected and classified all the data they had at their disposal and made a descriptive analysis for both the winter and summer situations. Michelato (1983) made an analysis of the coastal waters of the Emilia-Romagna region. Zore-Armanda and Vučak (1984) analysed some properties of the residual currents in the North Adriatic for the whole year. Accerboni et al. (1989) considered both dynamic and hydrographic properties of the North and Middle Adriatic in the spring and summer period. Orlić (1989) analysed salinity data from the North Adriatic and constructed residual current fields for the winter and summer period. Typical of all the mentioned studies is the consideration of processes on monthly or seasonal scales.

The only model that recognizes stratification was developed by Malanotte-Rizzoli and Bergamasco (1983). The model was used to investigate the influence of the Po River waters on the nearcostal shelf circulation.

The purpose of the present paper is to analyse data collected within the framework of the Adriatic Scientific COoperation Programme (ASCOP), near the north-eastern Adriatic coast, during August and September 1989 in order to get a better insight into the summer current field of the North Adriatic and its variability on short time scales. We have been particularly interested in the wind-driven currents and residual circulation characterized by a several-day time variability. The inertia-period motions, although very important in summer (Orlić, 1987), as well as the tidal currents, have been disregarded here.

The paper is organized as follows. In the next, second section, a discussion of data is given. Meteorological conditions prevailing during the experiment are described in the third section. Characteristics of the wind-induced currents and mixing are described in the fourth section. In the same section the residual dynamics is analysed as well. The final, fifth section, presents the conclusions of the paper.

2. Data presentation

The data analysed in this paper were collected at the measurement stations shown in Fig. 1.

Within the framework of the ASCOP experiment currents and temperatures were measured at stations 1, 2 and 3, using Aanderaa RCM 4 current meters equipped with temperature sensors. The measurements were carried out at two levels. The sampling interval was 10 minutes. The measured values were low-pass filtered in order to remove inertial and tidal oscillations. The half-power point of the filter was placed at 0.03 cph, and the length of the weight function equaled 49; the filter weights were computed according to Davis (1971).

From the overall observation period satisfactory current records were obtained from 11 August to 10 September. However, the records from the lower current meter of station 1 could not be used even for this subinterval. The upper current meter also malfunctioned between 1 and 3 September. The strong overgrowth caused problems to the bottom current meter of station 2 from 3 September onwards, and the surface current meter record seems doubtful on 9 and 10 September. The records from station 3 seem to be satisfactory for the whole analysed period.

Due to sensor calibration problems, the temperature records have been analysed only relatively. Moreover, the 'bottom' record from station 2 could not be used after 7 September, and the lower-level record from station 3 could not be used at all.

To complement these sets of measurements we also had at our disposal some additional hydrographic data. These additional data were collected at the surface and bottom levels of stations 1 and 2a, usually once or twice a month during 1988 and 1989. Temperature measurements were made using reversing thermometers. Salinity was determined with a Beckman RS7c salinometer.

Finally, in order to interpret oceanographic data, we have used simultaneous meteorological and hydrologic information. We have gathered wind observations from Pula, Poreč and Rovinj (Fig. 1), and daily Po River outflows registered at Pontelagoscuro (Regione Emilia-Romagna, 1990).

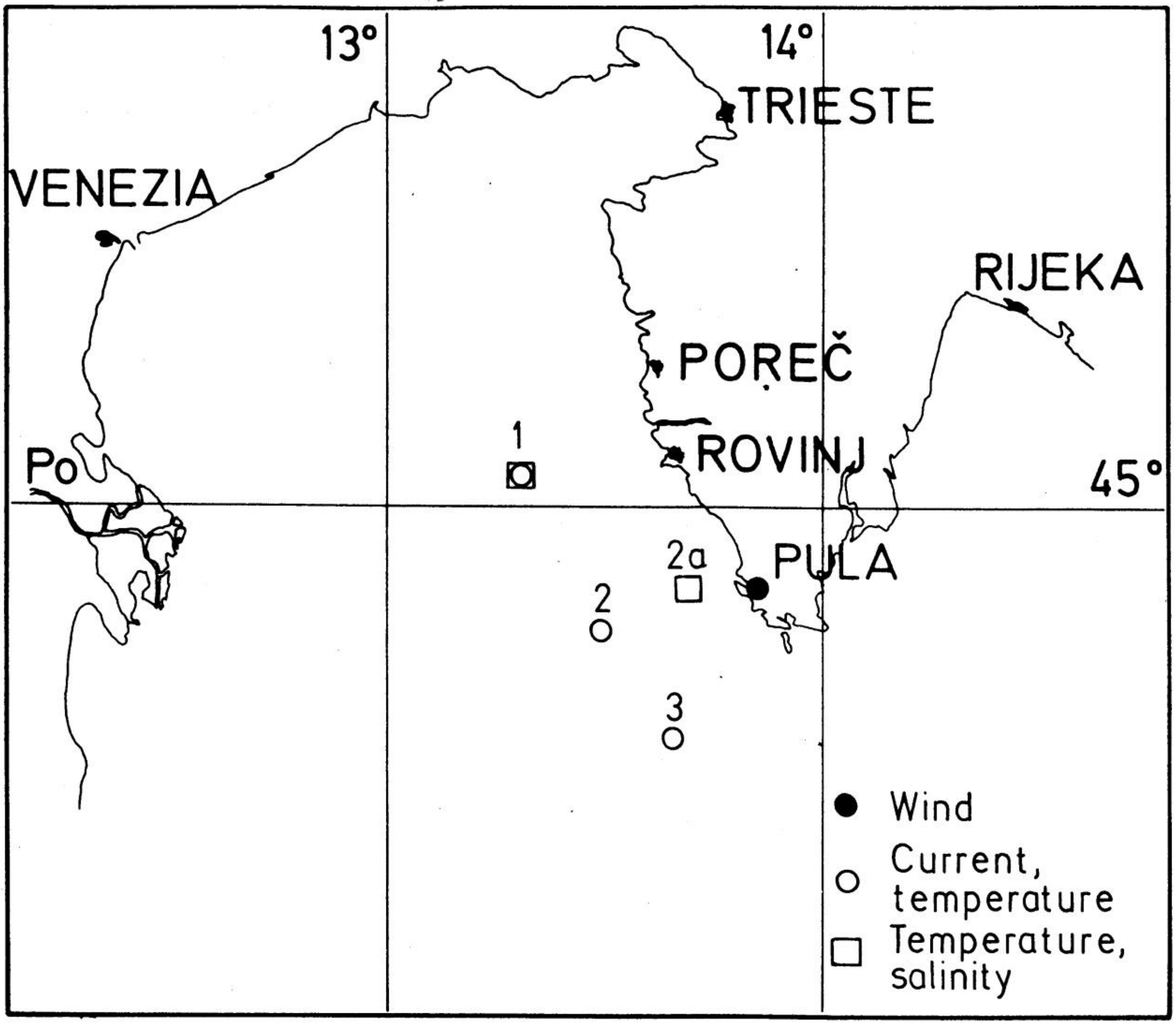

Figure 1. The North Adriatic with position of sampling stations.

3. Meteorological conditions

In order to be able to distinguish wind-driven currents from residual ones, we first analysed the meteorological synoptic situations registered between 11 August and 10 September 1989 (Deutscher Wetterdienst, 1989).

After a quiescent interval, two cyclonic disturbances traversed the North Adriatic. At first, a cyclone appeared above Northern Europe and between 27 and 28 August a secondary cyclone was formed on its cold front (Fig. 2). During the next day this cyclone passed above the North Adriatic and went eastward, while another disturbance came from the west. On the surface chart for 29 August (00 h GMT) one can see this disturbance above the Adriatic region. During the day it proceeded eastward. A stable situation lasted until 1 September when in the Western Mediterranean a new cyclone was formed (Fig. 3). During the night between 2 and 3 September it covered the Adriatic, but it traveled very fast and left the Adriatic region before midday on 3 September, as

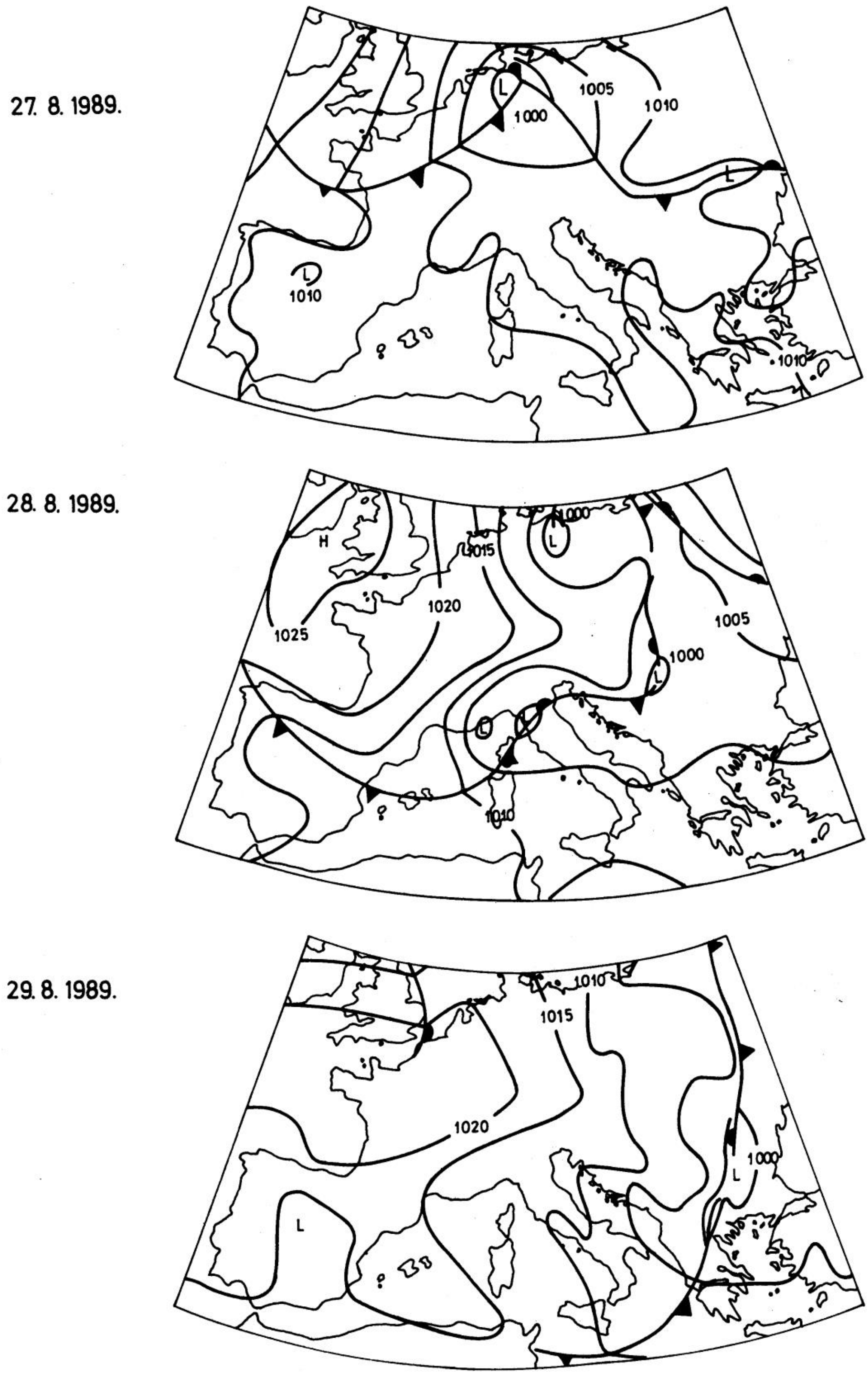

Figure 2. Successive synoptic charts for 27, 28 and 29 August 1989 (12 h GMT).

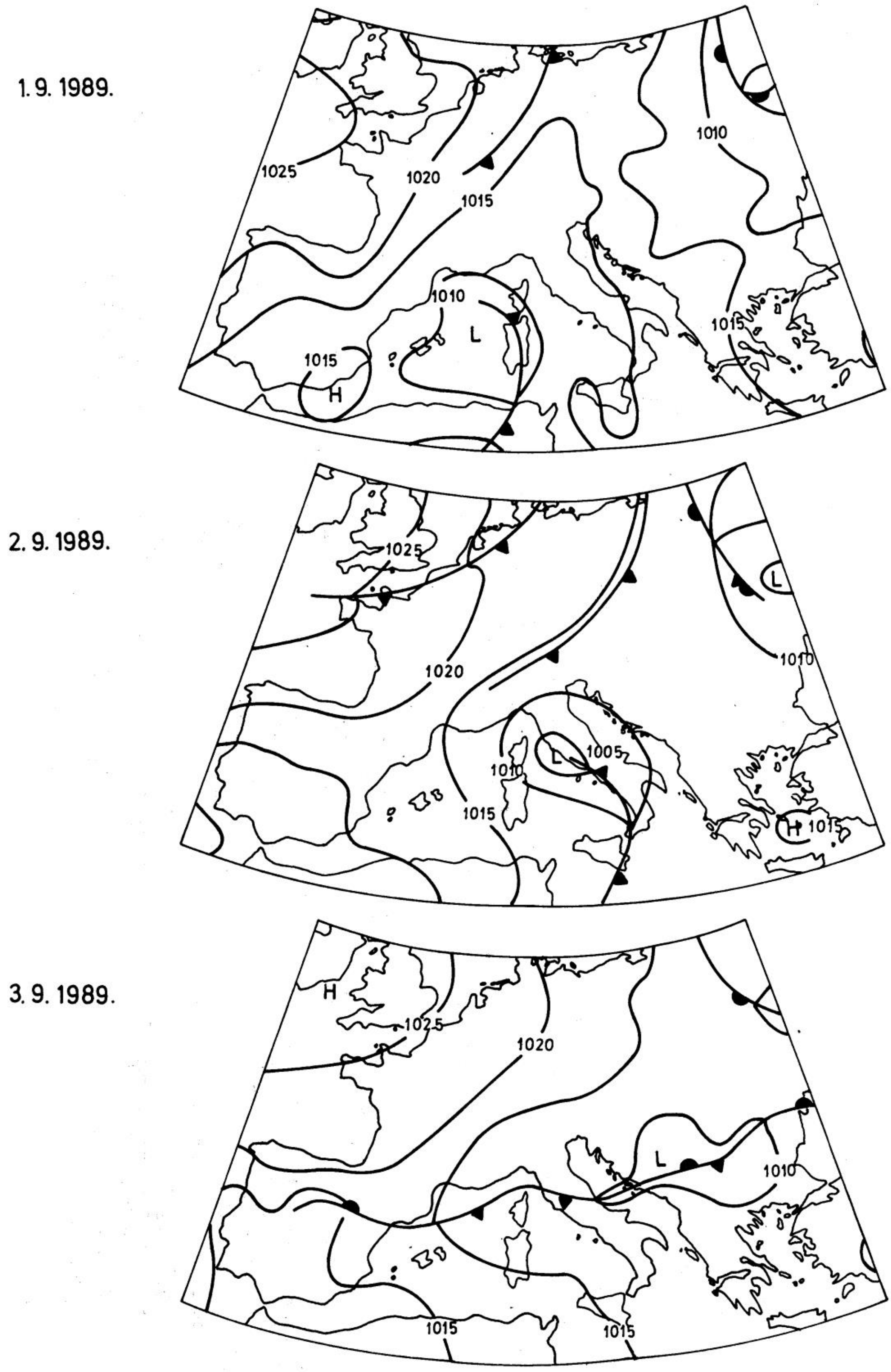

Figure 3. Successive synoptic charts for 1, 2 and 3 September 1989 (12 h GMT).

one can see on the last chart in Fig. 3. Until the end of the analysed period a typical summer situation was established: an anticyclone above the Azores and consequently undisturbed weather above the Adriatic.

As we have been particularly interested in the wind influence on the sea, we have analysed wind records from Pula (Fig. 4), and have also looked at wind data

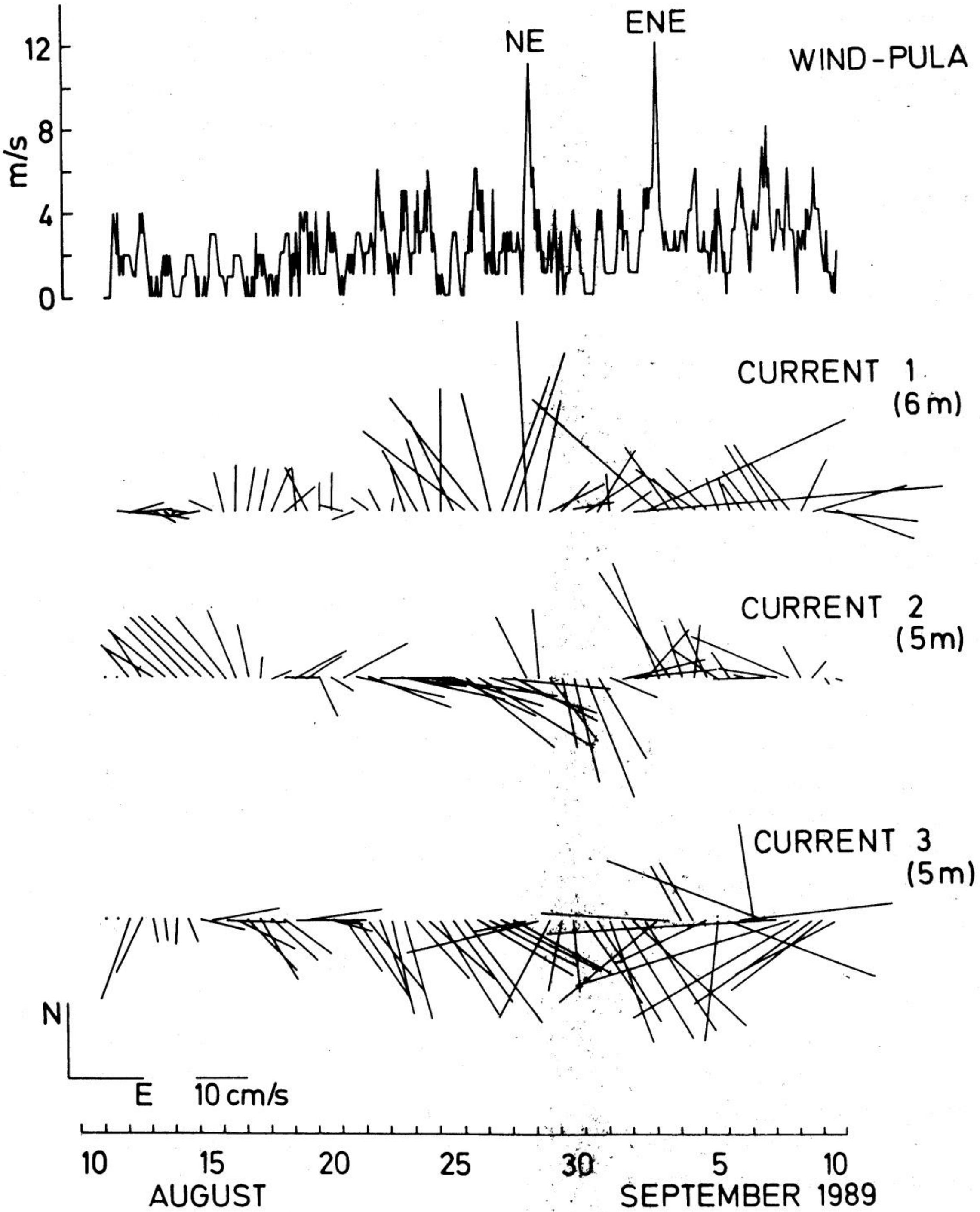

Figure 4. Low-pass filtered currents, measured at the surface level of stations 1, 2 and 3 and decimated to 12-hourly values, and related wind data, observed in Pula. The wind direction for the two wind-speed maxima is indicated.

observed at Poreč and Rovinj. The analysis revealed several disturbances of local importance, but there were only two wind episodes recorded at all of the stations. Both were dominated by the bura wind, blowing from the north-east. The first bura episode, recorded on 28 August 1989, coincided with a cyclone formed over the North Adriatic region. The second bura event was on 2/3 September and it was also related to a cyclonic disturbance over the North Adriatic region traveling eastward. The two bura episodes were of short duration (less than 12 hours) and the recorded wind speeds were close to 10 m/s. Comparing wind data from Pula, Rovinj and Poreč one can see that in both situations wind speeds recorded in Rovinj were lower than those in Pula and Poreč, pointing to the existence of a wind curl. During the other days a regular alternation of land and sea breezes was observed.

4. Processes in the sea

4.1. Wind-induced dynamics

Our first concern was a possible response of the sea to the wind forcing. It has already been pointed out that only two bura episodes occurred in the studied period. Both episodes were of short duration, which agrees with climatological findings for the warmer part of the year (Lukšić, 1975). The measured wind speeds were close to 10 m/s.

During the days with bura episodes (28 August, 2 and 3 September) the current field was different from the pattern of the previous and following days: currents were stronger and changed direction (Fig. 4). Response to the wind forcing was obvious but short-lived. These perceptions are in accordance with the results of the numerical modelling of the wind influence on the Adriatic during the summer period (Malanotte-Rizzoli and Bergamasco, 1983). It is difficult to carry out further comparisons because the cited paper concentrates on the circulation in the vicinity of the Italian coast. Simulations of wind-driven circulation near the Yugoslav coast can be found in the literature, but they cover winter situations only. These results cannot be used in analysing the summer situations because of the differences in both the density field and meteorological conditions.

The wind influence on the sea is also visible from the temperature records (Fig. 5). The temperature of the surface layer increased at all stations at the beginning of the analysed period, when the meteorological conditions were quiescent. The first bura episode of 28 August caused a rapid and intensive cooling of the surface layer at all stations. Another decrease of surface temperature was related to the second bura episode, but it was less pronounced. The decrease of surface temperature continued for the next two days. After that stable conditions were established again and the surface heating lasted until the end of September. The variability of bottom temperature was less pronounced.

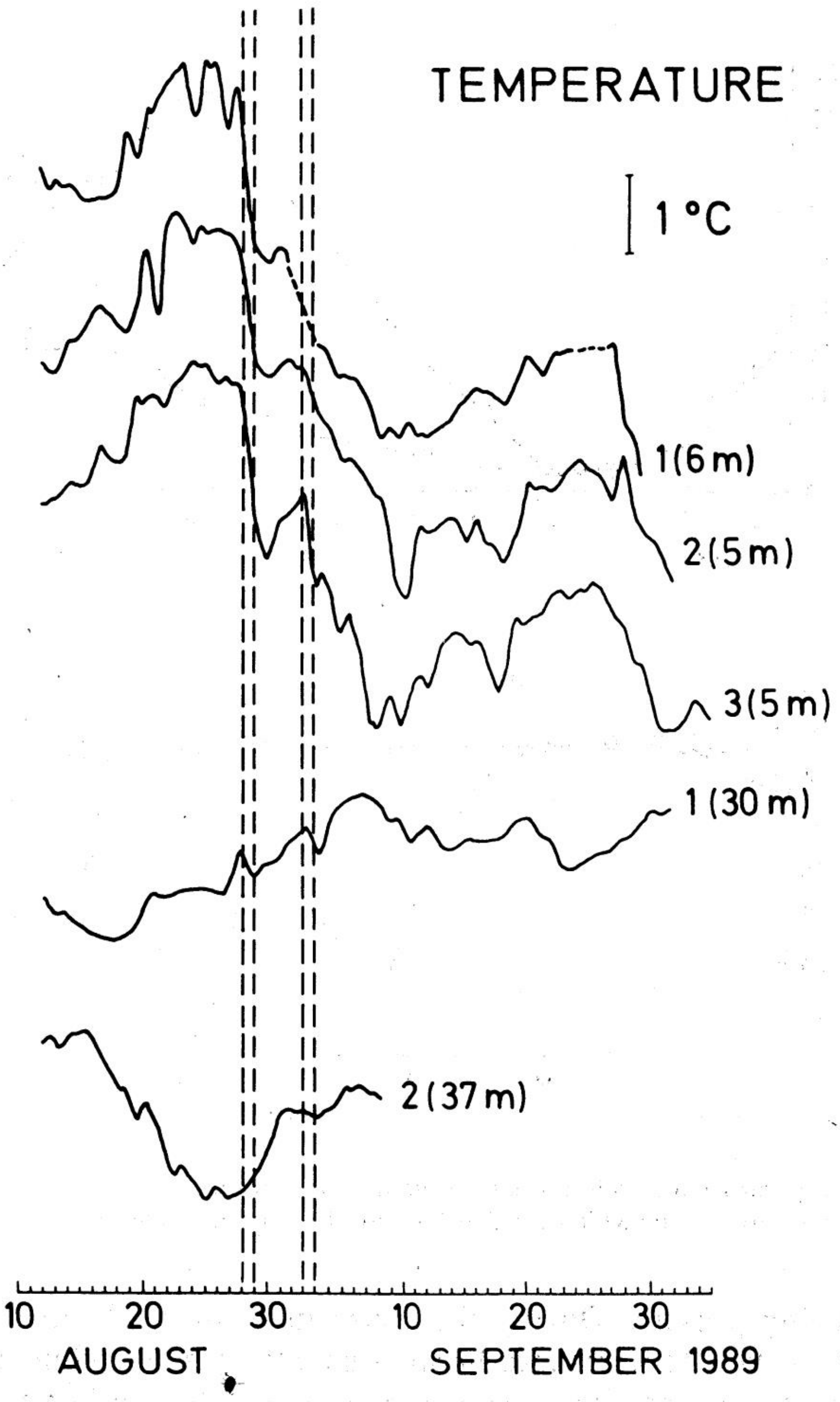

Figure 5. Low-pass filtered temperature records from stations 1, 2 and 3. Dashed lines indicate the wind episodes.

Similar conclusions can be drawn from Figs. 6 and 7. From the middle of August until the beginning of September a remarkable decrease of surface temperature accompanied by a slight increase of bottom temperature is visible. During the same period surface salinity increased, while bottom salinity slightly decreased. All those changes indicate again the occurrence of vertical mixing and convection, but the great increase of surface salinity also points to advection

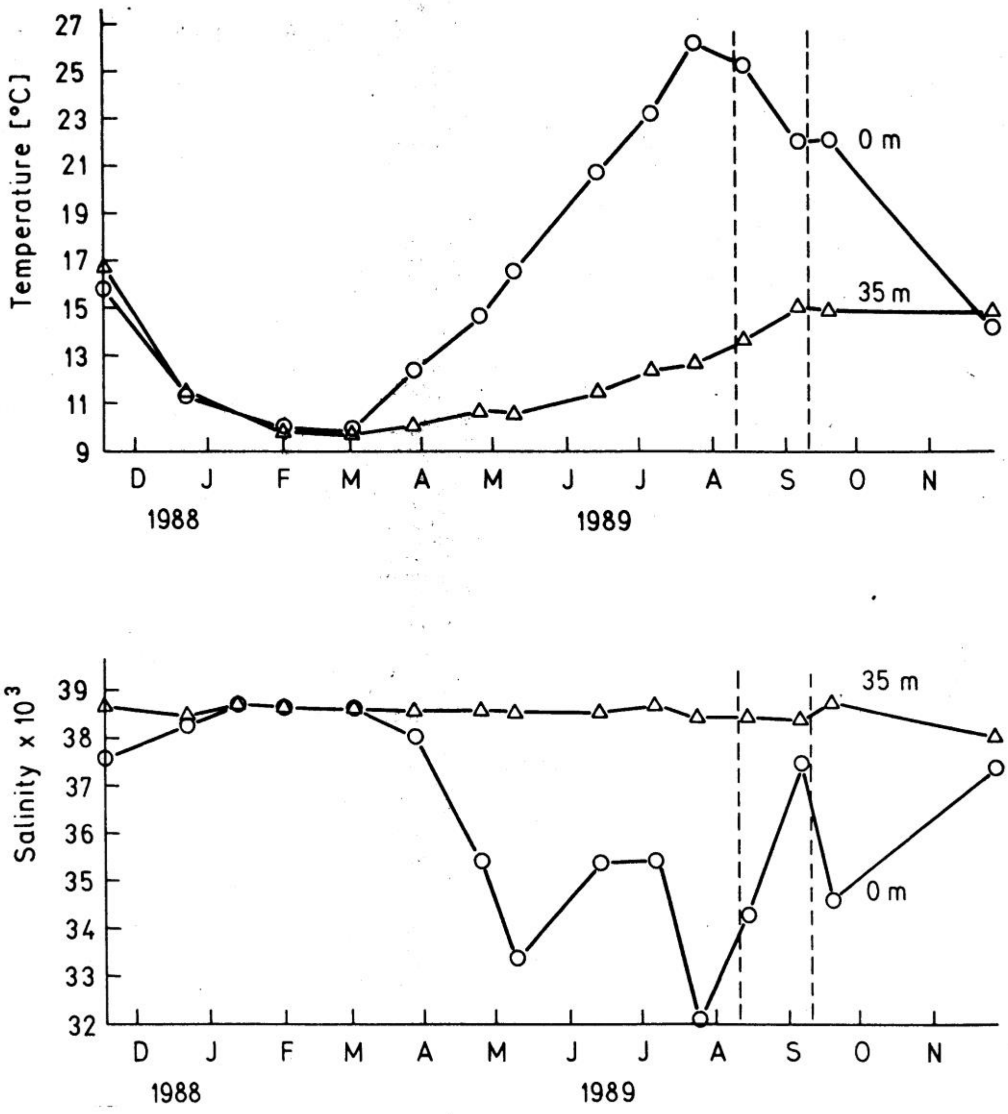

Figure 6. Temperature and salinity data measured at station 1 in 1988 and 1989. Dashed lines indicate the time interval for which the ASCOP data have been analysed.

processes being present. During the consecutive interval, until the middle of September, surface temperature became slightly higher, while surface salinity values decreased, suggesting a reappearance of stable weather conditions.

4.2. Residual dynamics

Another subject of our concern was residual dynamics. If one looks carefully at Fig. 4, one can observe that the main feature of the current time series is variability at a time scale of about ten days. This is especially well pronounced in current data from station 2, which are shown by means of a progressive vector diagram in Fig. 8. Such a variability has also been observed by Italian researchers near the western Adriatic coast. Some evidence for summer current variability in 1979 and 1980 was presented by Accerboni et al. (1981) and

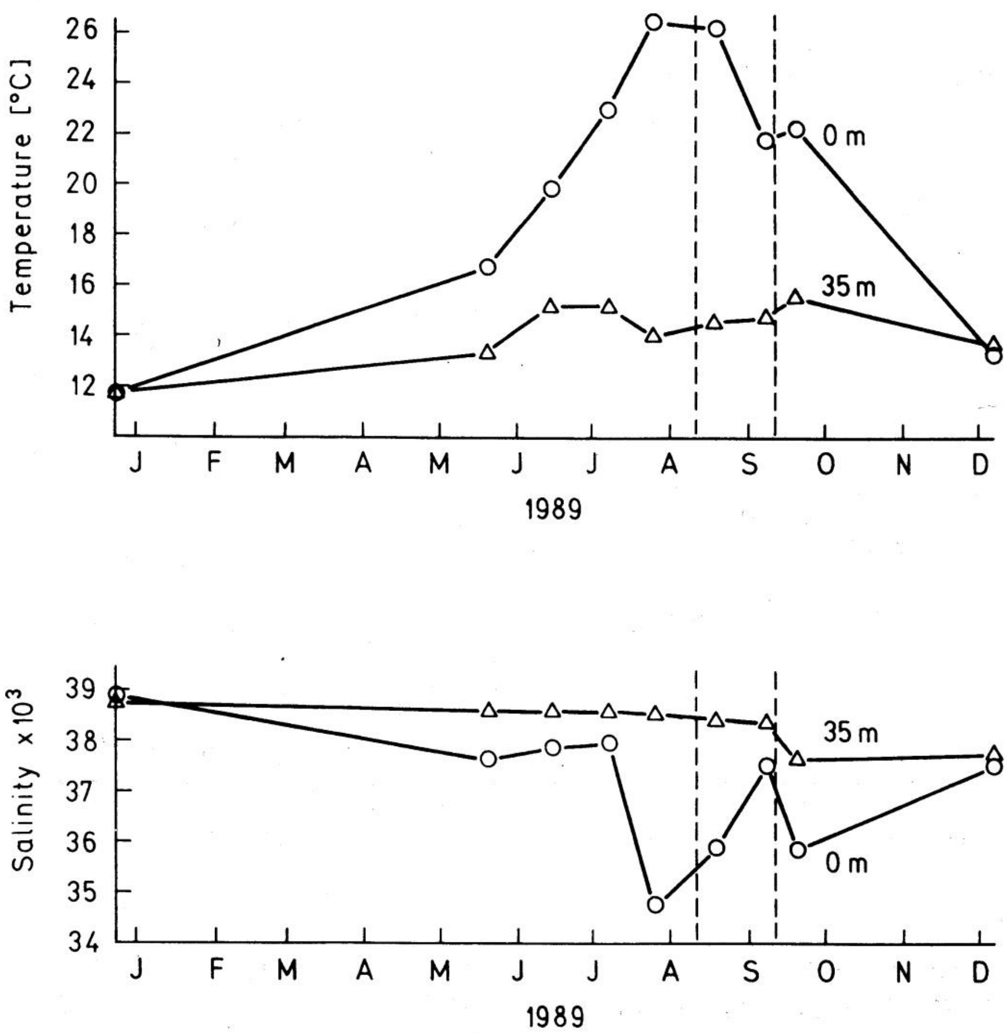

Figure 7. Temperature and salinity data measured at station 2a in 1989. Dashed lines indicate the time interval for which the ASCOP data have been analysed.

Michelato (1983), while Malanotte-Rizzoli and Bergamasco (1983) analysed it in the modelling framework. The current data measured in summer 1983 and 1984 near the Italian coast also showed a similar feature (Accerboni el al., 1989).

In accordance with the observed current variability, the measurement interval was divided into three nearly equal subintervals characterized by an almost constant direction of current vectors. We estimated the residual currents for each subinterval: an average vector was calculated from low-passed time series sampled at 12-hour intervals for each location and depth. Residual currents obtained in this way may contain, as main components, geostrophic and wind-drift contributions. In principle, geostrophic contribution could be driven by wind or buoyancy fluxes, or it could be due to a baroclinic wave disturbance in the current field, while wind-drift contribution is due to momentum exchange at the air/sea interface. Residual currents are presented in Fig. 9. One can see how well they fit into the system of residual circulation in the North Adriatic,

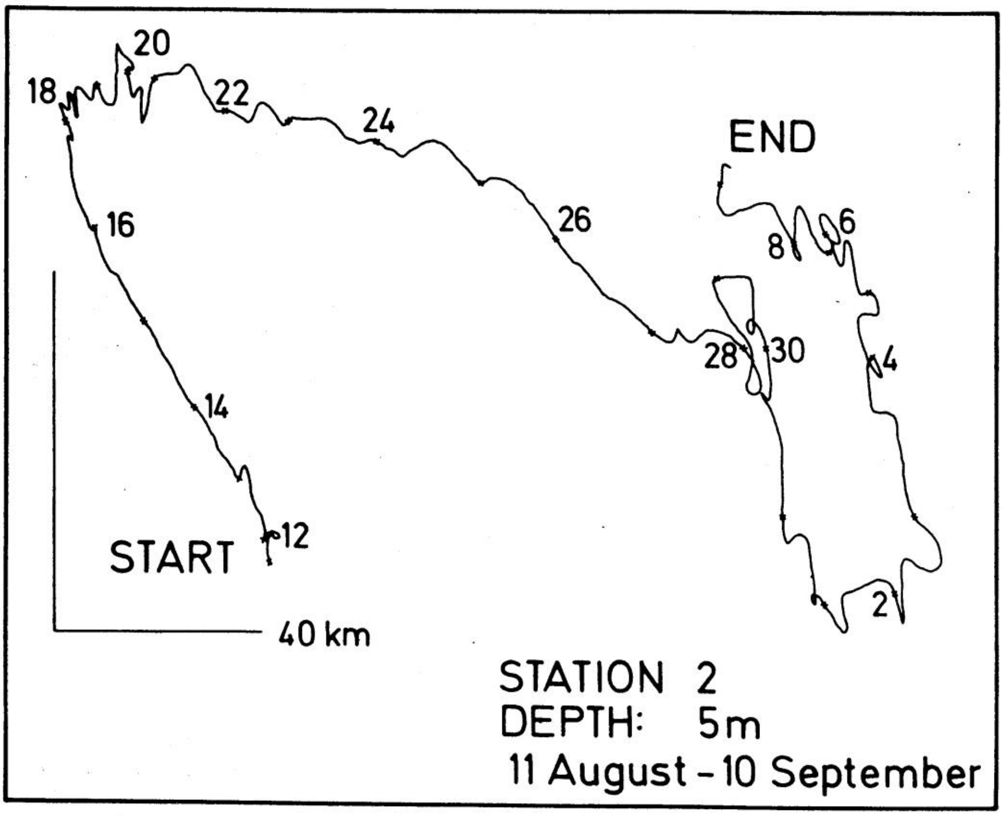

Figure 8. Progressive vector diagram for the surface level of station 2 (11 August – 10 September 1989).

which was established recently (Franco et al. 1982; Malanotte-Rizzoli and Bergamasco, 1983; Zore-Armanda and Vučak, 1984).

During the first subinterval (12–20 August) stations 1 and 2 were located in a cyclonic gyre dominating the north-west part of the Adriatic Sea. At the same time the southernmost station was embedded in an anticyclonic gyre.

The next subinterval (21–31 August) shows a similar pattern: the residual current at station 1 was directed north-eastward, which means it was still a part of a cyclonic gyre, whereas stations 2 and 3 were in an anticyclonic current system. It seems that the cyclonic gyre moved northward, occupying a smaller region. Moreover, the currents intensified in respect to the first subinterval.

During the last subinterval (1–10 September) a different pattern appeared: in the south-east part of the analysed area one can see a cyclonic gyre which characterizes the Middle and South Adriatic circulation during the whole year. This is the typical summer pattern (Orlić, 1989). The current reversal that occurred at the beginning of September is confirmed by salinity data measured at stations 1 and 2a (Figs. 6, 7). During the first subinterval (14 August) salinity measured at station 1 was much lower than salinity at station 2a, which can be interpreted in terms of the influence of the Po River outflow and the Mediterranean water advected from the south, respectively. After the current reorientation, salinity measured at station 1 was much higher, now being almost equal to

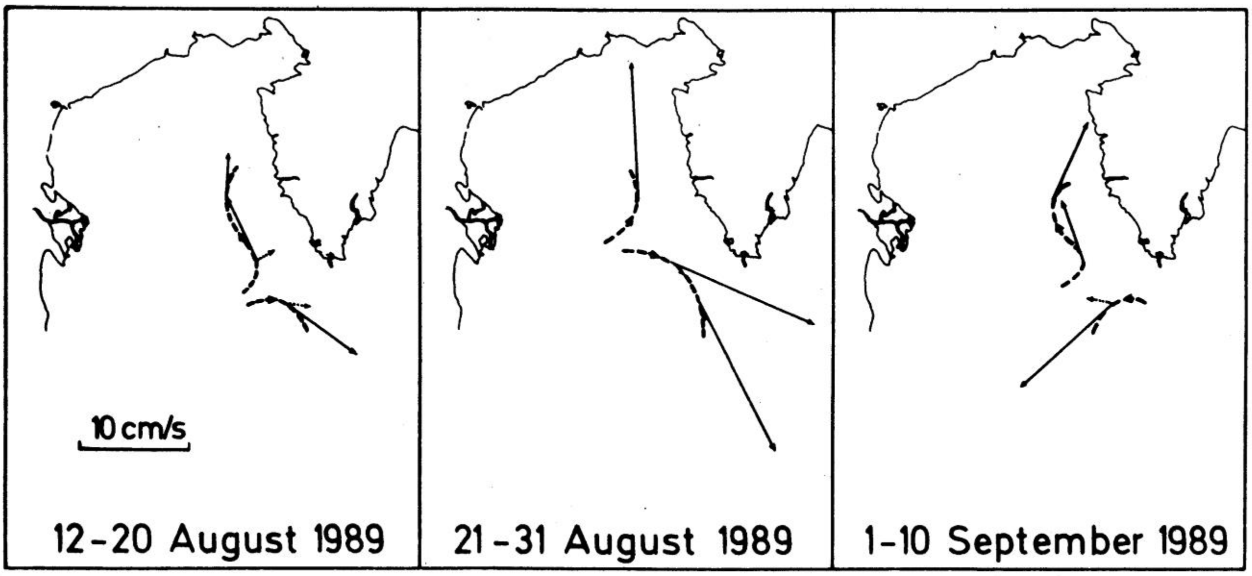

Figure 9. Ten-day current vector averages for the surface (——) and bottom (· · · ·) levels; streamlines (– – –) indicate parts of a double gyre structure that changed during the measurement interval.

the value measured at station 2a. The northward shift of the cyclonic gyre, characterizing the Middle and South Adriatic, would explain such an observation.

The question here is: what caused the observed changes in the current field?

It is well known that the Po River outflow is the most important source of fresh water in the Adriatic, so we first looked at the Po outflow data for the analysed period. The flow rates were nearly equal in all three subintervals, with average values of 912, 889 and 1159 m^3/s respectively. These values are similar to the climatological ones for this part of the year, and it seemed safe to assume that the observed current reorientation was not caused by changes in the Po River outflow.

Direct wind influence could also be ruled out. Looking at the wind data we saw that only two weak bura episodes of short duration were recorded. They could not have directly caused the observed variability.

At the beginning of the analysed period the temperature measured at station 1 (Fig. 6) was higher than the average value for the nearby Rovinj station (Supić, 1988), enabling the fresh water of the Po River to penetrate far offshore. The surface-to-bottom temperature difference increased during the second subinterval (Fig. 5), favoring intensification of the double-cell circulation. After the wind episodes had caused vertical mixing and convection, stability conditions changed (Figs. 5–7), making the offshore penetration of the Po water more difficult. Consequently, the typical summer circulation was established. Orlić (1989) invoked the same mechanism in order to explain the differences in salinity minima observed at Rovinj in 1956 and 1958, when the Po outflows were of a similar amount.

5. Conclusions

Current, temperature and salinity data gathered in August and September 1989 at four locations near the north-eastern Adriatic coast have been considered in this paper.

An analysis of related meteorological synoptic data revealed only two weak bura episodes (each lasting less than a day). The wind pulses generated response which produced a remarkable but short-lived change in the velocity field. Temperature and salinity data from the analysed stations showed that both wind episodes induced vertical mixing and convection, manifested by a remarkable decrease of the sea surface temperature.

Current time series showed variability at a time scale of about ten days. Therefore, the analysed period was divided into three nearly equal subintervals with an almost constant direction of current vectors. For each subinterval residual currents were calculated. They suggested the presence of a cyclonic gyre in the northernmost part of the Adriatic Sea. In the southern part of the measurement polygon an anticyclonic gyre was observed at the beginning of the analysed period, whereas a cyclonic gyre was found there at the end of the experiment. The latter circulation pattern, consisting of two cyclonic gyres, is typical of the summer period (Orlić, 1989). Present current records suggest shifting of the gyres at a time scale of about ten days. A similar phenomenon was also observed by Italian researches in the north-western part of the Adriatic Sea in the course of several summers (1979, 1980, 1983, 1984). All the data gathered during the ASCOP experiment point to stratification as the factor controlling the observed current variations. The stratification itself is influenced by buoyancy fluxes and wind forcing.

Acknowledgements – The temperature and salinity data in Figures 6 and 7 were furnished by the Centre for Marine Research of the Rudjer Bošković Institute in Rovinj. Current and temperature time series were collected within the ASCOP. The Hydrometeorological Office of the Republic of Croatia kindly supplied the wind data. The work reported here was supported by the Croatian Ministry of Science, Technology and Informatics, Grant 1-06-125.

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