GEOFIZIKA VOL. 18-19 2001-2002

Original scientific paper
UDC 551.465

Occurrence of the Istrian Coastal Countercurrent in 2000, a year with a mucilage event

Nastjenjka Supić[a], Mirko Orlić[b], Danilo Degobbis[a], Tamara Đakovac[a], Valter Krajcar[a] and Robert Precali[a]

[a]Center for Marine Research, Rudjer Bošković Institute, Rovinj, Croatia

[b]Andrija Mohorovičić Geophysical Institute, Faculty of Science, University of Zagreb, Zagreb, Croatia

Received 9 December 2002, in final form 23 January 2003

The Istrian Coastal Countercurrent (ICCC) appeared in March (7 cm/s), August and September (4 cm/s) 2000, and a mucilage event occurred during late June–early July. Remarkably, previous investigations indicated that recurrent occurrences of intense ICCC coincided with mucilage and/or anoxia events in the region. In fact, already during late winter, when a sea heat gain was relatively intense, a significant transversal transport of freshened waters of Po origin occurred. Lower salinity and warmer water pool, which might be the core of an anticyclonic gyre in the northeastern Adriatic, was present also during spring and summer. This indicates the establishment of a pronounced closed circulation system in the area.

Keywords: northern Adriatic Sea, heat and water surface fluxes, Po river runoff, geostrophic currents, mucilaginous aggregates

1. Introduction

Changes in the circulation pattern have been assumed to play an essential role in the development of undesirable phenomena (mucilage and bottom anoxia events) that were recurrently observed in the northern Adriatic basin during summer and autumn (*e.g.* Degobbis et al., 1995, 1999, 2000).

Originally, it was held that surface circulation in the region is cyclonic, with a northward flow along the eastern (Istrian) coast, both in winter and summer conditions (*e.g.,* Franco and Michelato, 1992). However, an analysis of relative geostrophic currents for the 1966–1997 period has indicated that a countercurrent can be established within the eastern (Istrian) coastal belt, up to 12 Nm wide (Supić et al., 2000). This southward current, named the Istrian Coastal Countercurrent (ICCC), was usually well developed in August (up to 15 cm/s), particularly in years when summer mucilage events and/or autumn anoxia occurred in the northern Adriatic basin (*e.g.* 1977, 1988, 1989, 1991 and 1997). The August ICCC occurrences were found to be related to the formation of less saline and warmer water pools in the northeastern Adriatic, compared to years when ICCC did not appear. According to the geostrophic circulation patterns, the pool of lower salinity water acted as a core of an anticyclonic gyre. A strong ICCC in August may therefore indicate the establishment of a semienclosed circulation cell, in which freshened waters, mainly originating in the Po delta area, are recirculated, favouring the accumulation of mucilaginous material (Supić, 2000; Supić et al., 2000).

In summer of 2000 a mucilage event occurred in the northern Adriatic in the period mid June–mid July (CMR, data base). To verify the hypothesis of a possible link between this event and ICCC occurrences, geostrophic current and surface flux calculations were performed, based on meteorological data and thermohaline properties of a profile between Rovinj and the Po River delta.

2. Materials and methods

The analyses of oceanographic and dynamic features of the northern Adriatic in 2000 were based on sea temperature and salinity data collected at six stations (1–6) of the Rovinj–Po River delta profile (Figure 1) at 0, 5, 10, 20 m, and at 2 m above the bottom. The stations are specified as RV001, SJ107, SJ105, SJ103, SJ101 and SJ108 in the CMR oceanographic data base, but are renamed in this paper as 1, 2, 3, 4, 5, and 6, respectively. The data set covers almost the entire annual cycle (almost all months, except May; 15 cruises all together). However, only the 12 cruises when data were collected on the whole Rovinj–Po River delta profile were used for computations of geostrophic currents.

Temperature was measured by protected reversing thermometers (Richter and Wiese, Berlin, precision ± 0.01°C) and salinity was determined to at least ± 0.01 by using a high precision laboratory salinometer YEO-KAL Mark II.

Dynamic depths of the 30-dbar surface were computed using a standard dynamical method for each station, and were then used to estimate the surface geostrophic currents relative to the 30 m level for each pair of neighboring stations for each cruise (see Supić et al., 2000 for details and references). The velocity at the reference level b and the corresponding absolute velocities V_{ij} at the jth level ($j = 1,..., 4$) of the ith ($i = 1,..,5$) station pair were computed applying a criterion requiring mass conservation through the entire profile (*e.g.* Marinone and Ripa, 1988). While b is taken to be $-Q/P$ (Q is the net geostrophic transport when $b = 0$, while P is the total area of the profile), V_{ij} is equal to $v_{ij} + b$, where v_{ij} is relative geostrophic flow at location ij. Using the absolute current values the net geostrophic transport was determined (*e.g.* according to Marinone and Ripa, 1988) throughout the eastern (between stations 1 and 2), central (between stations 2 and 5) and western (between stations 5 and 6) part of the investigated profile.

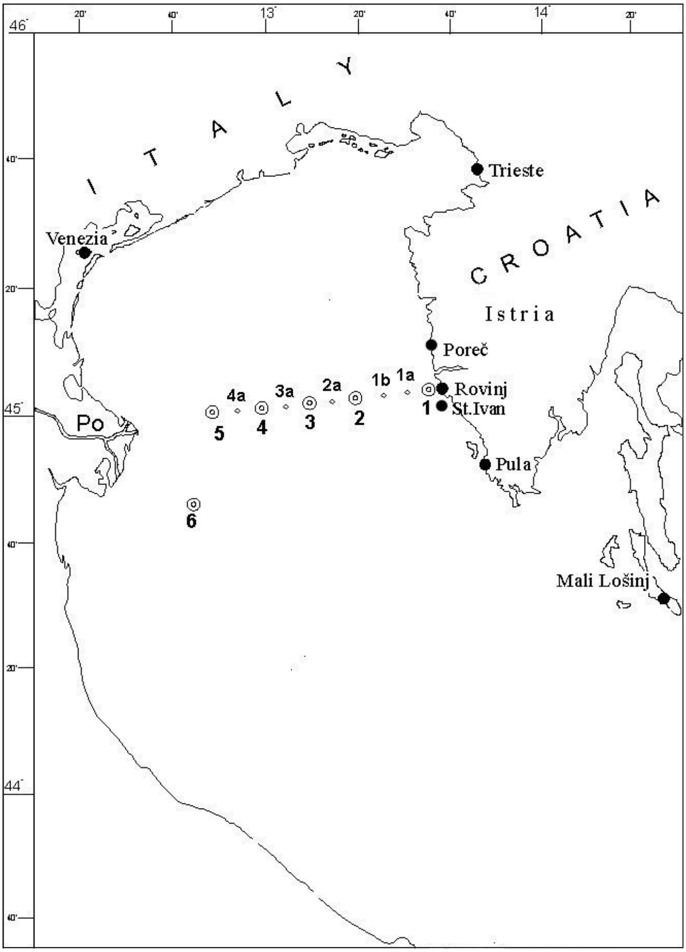

Figure 1. Map of the northern Adriatic with position of the meteorological and oceanographic stations.

Current and transport values are positive when they mark an inflow into the northern Adriatic and their average monthly values are related to the 1972–1992 period (Supić et al., 2000).

CTD (Sea Bird SBE 25) data were collected during the 2000 cruises at a larger number of stations along the Rovinj–Po River delta profile (Figure 1). The data were sampled every 10 cm, but average values were calculated for 0.5 m depth intervals. These values were used to compute geostrophic currents relative to the 30 m level between each of the two neighboring stations (*i.e.* between stations 1 and 1a, 1a and 1b, 1b and 2, 2 and 2a, 2a and 3, 2 and 3a, 3a and 4, 4 and 4a, 4a and 5) by the standard dynamical method. Occasional missed values for salinity or temperature in the surface and bottom layers were assumed to be equal to the closest existing values.

Surface heat and water fluxes for the year 2000 have been computed using data from the meteorological stations of Trieste, Rovinj and Mali Lošinj (Figure 1), and then averaged. The fluxes at the three locations have been calculated from monthly means of standard meteorological data (air pressure, air temperature, scalar wind speed, cloud cover, specific humidity and precipitation) and SST data following the same procedure as described by Supić and Orlić (1999). The data were provided by the Trieste University, Hydrometeorological Institute, Zagreb, and Maritime Meteorological Center, Split. As the air pressure was not measured at Rovinj, data collected at the nearby station Poreč (45° 13' N, 13° 36' E) were used in the analysis. Monthly means of meteorological data (except precipitation which had been estimated daily) were computed from hourly values at Trieste and from measurements taken three times a day (7, 14 and 21 h CET) at Rovinj and Mali Lošinj. The monthly means of SST for Trieste have been derived from daily (10 h CET) collected data. Monthly means of SST for St. Ivan lighthouse [45° 03' N, 13° 37' E; Ts(IV)] near Rovinj and for Mali Lošinj were computed from monthly means of measurements taken three times a day (7, 14 and 21 h CET). Monthly means of SST for Rovinj [Ts(RV)] were computed using regression formula:

$$Ts(\mathrm{RV}) = 1.09\ Ts(\mathrm{IV}) - 0.6.$$

The formula was derived from monthly means of simultaneous measurements of SST at Rovinj and St. Ivan Island in 1984–86 and 1988–92 periods, with correlation coefficients of 0.99 between the both data sets.

3. Results and discussion

a) Thermohaline conditions

In January 2000 the temperature, salinity and density excess values were significantly lower and highly variable in the upper water column of the station 6, located about 15 Nm SE of the Po delta main arm (Po della Pila), compared to the much larger part of the investigated profile (Figure 2, left). Generally, in this month the central and eastern areas of the northern Adriatic are occupied by saline waters (>38) originating in the central Adriatic with minimal horizontal and negligible vertical density gradients. In January 2000 the salinity of this water was even higher, up to 0.4 higher than the long-term averages for the same stations (1966–1997; CMR, data base). Similar distributions were observed also in February, but the value ranges were smaller than in January, indicating a reduced influence of freshwater in the western area of the profile. In fact, the Po River flow in these months was lower than the 1966–1992 averages (see section 3. b).

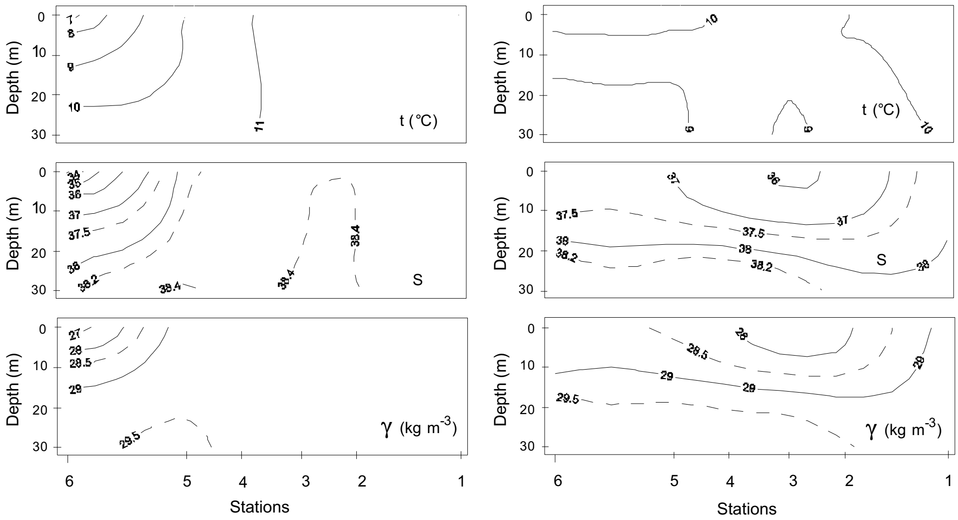

Figure 2. Spatial distribution of temperature, salinity and density excess at the Po–Rovinj profile on 5 January 2000 (left) and on 17 March 2000 (right).

Oceanographic situation changed markedly in March (Figure 2, right). The temperature was higher than in February, both in the surface and in the bottom layer, and larger than the long-term averages, indicating that the sea warming started earlier than usual. The distributions of salinity and density anomaly were also unexpected. Exceptionally high values of the two parameters were measured off the Po delta, while a large pool of lower salinity and less dense water (down to 35.8 and 27.6 kg m^{-3}) was observed in the upper water column of the eastern part of the profile (stations 2–4). Highly likely, this water was formed in the Po Delta area and then transported eastwards rather than to be exported southwards, like in the preceding months. In contrast, the bottom salinity and density remained high (up to 38.3 and 29.8 kg m^{-3}), resulting in a significant stratification of the water column. Remarkably, in March the Po River flow was exceptionally low (see section 3.b). Eastward advection of lower salinity waters, formed off the Po Delta, after strong bora events, has been described by mathematical models and verified with satellite imagery (Sturm et al., 1992; Beg Paklar et al., 2001). In contrast, in March of 2000 the wind was generally weak (see section 3.b), indicating that other mechanisms, rather than wind forcing, induced freshwater spreading over the northern Adriatic region in conditions of very low Po discharge rates. The bottom salinity and density remained however rather high (up to 38.3 and 29.8 kg m^{-3}), resulting in a significant stratification of the water column.

The thermal vertical stratification gradually increased through the spring, raising towards the maximum in August (examples in Figure 3). The values of temperature in the upper and/or middle water column from June to August were significantly higher than the long-term means. During spring and summer a fresh water layer extended to the Istrian coast (Figure 3), but its salinity and density excess values (greater than 33.5 and 24.9 kg m^{-3} in April, 33.8 and 22.3 kg m^{-3} in June, 35.9 and 24.6 kg m^{-3} in July) were higher than the long-term averages. The exception is station 5 in August (29.6 and 18.0 kg m^{-3}), as a consequence of Po River runoff which was lower than usual (see section 3. b). Moreover, the salinity was unusually high also in the rest of the water column. In the western part of the profile the water column stratification remained marked also in September, but on the eastern side it was considerably reduced, mainly because of saline water intrusions from the central Adriatic (Figure 4, left). In addition, a pool of warmer and lower salinity water was observed at station 2. In October the water column was highly stratified off the Po delta, due to exceptional river discharge rates (see section 3. b), but it was much more uniform in the central and eastern part of the profile, where the parameter values mostly lay within the long-term ranges. The water column was more mixed in December than in preceding months, but still vertical temperature and salinity gradients were more marked than usual for this month (Figure 4, right), due to freshwater discharge rates higher than the average (see section 3. b). The temperature values were much higher than the averages, except in the low-salinity layer in the western and central area. The salinity values were lower than the averages for the surface layer, but significantly higher in the rest of the water column.

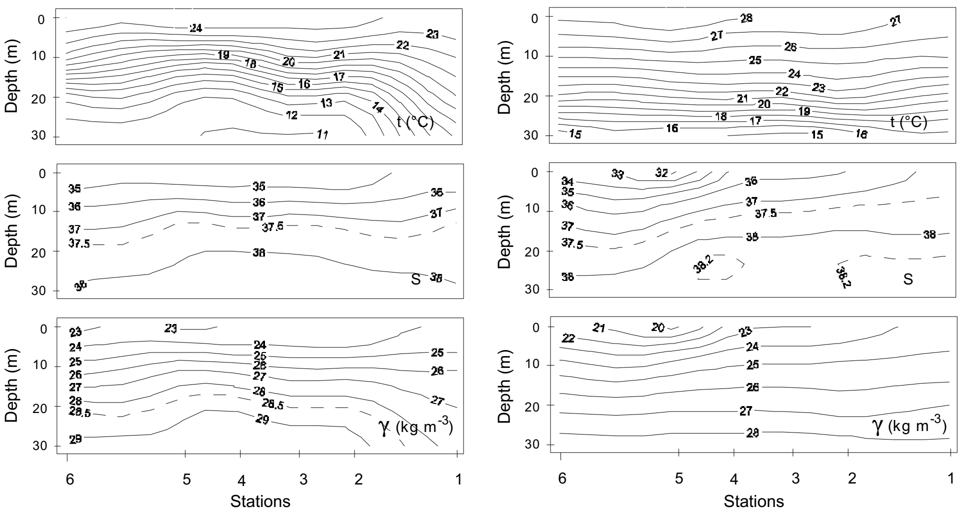

Figure 3. Spatial distribution of temperature, salinity and density excess at the Po–Rovinj profile on 29 June 2000 (left) and on 25 August 2000 (right).

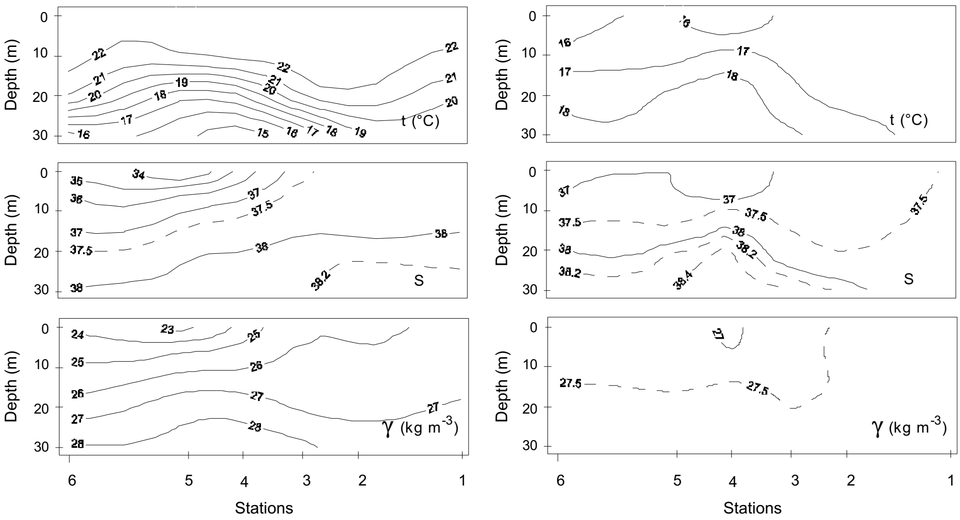

Figure 4. Spatial distribution of temperature, salinity and density excess at the Po–Rovinj profile on 26 September 2000 (left) and on 4 December 2000 (right).

b) Surface fluxes and Po River influence

Changes of oceanographic conditions in the northern Adriatic are mainly driven by surface fluxes and Po River water discharge (*e.g.* Franco and Michelato, 1992; Orlić et al., 1992; Supić et al., 1997). Generally, the freshened waters are confined near the western coast in winter, whereas during late spring and summer, when the river discharge rates often increase considerably, they can spread over larger areas of the northern Adriatic. However, their influence on the northeastern Adriatic can significantly vary from year to year.

Surface heat and water fluxes in the year 2000 were significantly different from the long-term averages (1966–1992) in July, when the heat input was very low, in September and October, when the evaporation rate significantly prevailed over precipitation, and in November and December, when precipitation was dominant (Figure 5). The Po discharge rate was very low in March and extremely high in October, November and December (Figure 5). Remarkably, southerly winds prevailed during the major part of the year (Figure 6), whereas northerly winds blowed mainly in January, February, and mid summer (late July–first half of August).

Seasonal changes in temperature at the profile in 2000 could be explained by heating and cooling processes induced by seasonal changes in surface heat flux. The temperature at the profile started to rise in March, when sea surface heat flux became positive (Figures 2 and 5). During the heating

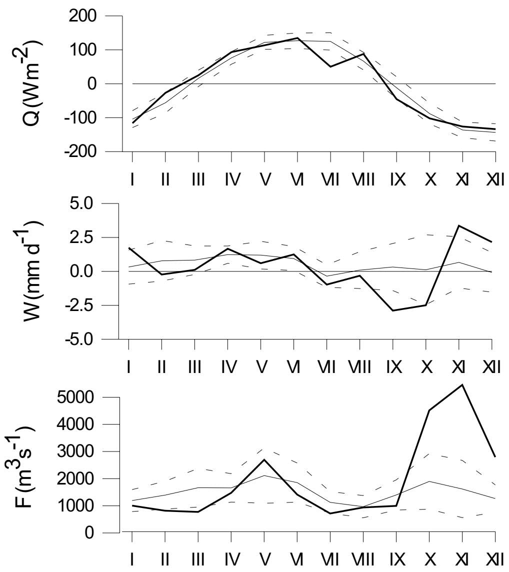

Figure 5. Air-sea heat flux (Q), air-sea water flux (W) and Po River flow (F) in 2000 (heavy solid lines). Solid and dashed lines represent averages and standard deviations for the 1972–1992 period.

period (from March to August) the heat was accumulated mostly in the surface layer, causing a significant thermal stratification in the water column. Cooling process started in September, inducing vertical mixing in the water column with decreases in surface and increases in bottom temperatures. By the end of 2000 the water column was still lightly stratified, presumably because of relatively low air-sea heat exchange rate.

Seasonal changes in salinity at the profile in 2000 are related both to Po River influence, to surface water flux changes (Figures 2–4 and 5) and to advection of saline waters from the southeast. Significant decrease of surface salinity along almost entire profile in March, when the water flux was close to zero, seems to be induced by inflow of low salinity water of Po origin, despite the flow rates being significantly lower than the long-term average for this month. Eastward intrusions of freshened water continued up to August. Rise of salinity in the central and eastern parts of the profile started already in September, probably

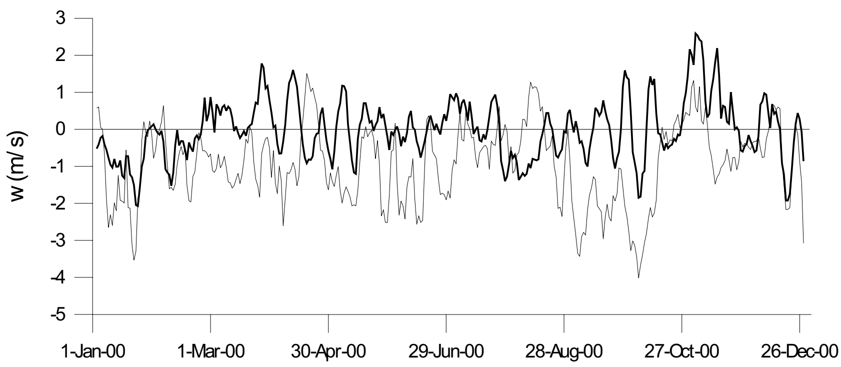

Figure 6. E (solid line) and N (heavy solid line) components of daily averaged wind speed at Pula airport in 2000 filtered with 5 day running means. The components are defined following oceanographic convention.

due to a reestablishment of the »winter« cyclonic circulation in the Adriatic, when the largest part of the freshened water is exported along the western coast. Even higher salinities, with exceptional surface values at the eastern stations (up to 38.3), were measured in October, and were probably also related to extensive evaporation, in addition to inflow of high salinity water from central Adriatic. The surface salinity in the western part of the profile was very low in October, due to reinforced but localised influence of Po waters, in conditions of very high discharge rates. In December the freshwater influence was greatly reduced in western part, while some residual low-salinity water remained in the eastern part.

c) Geostrophic currents and the ICCC

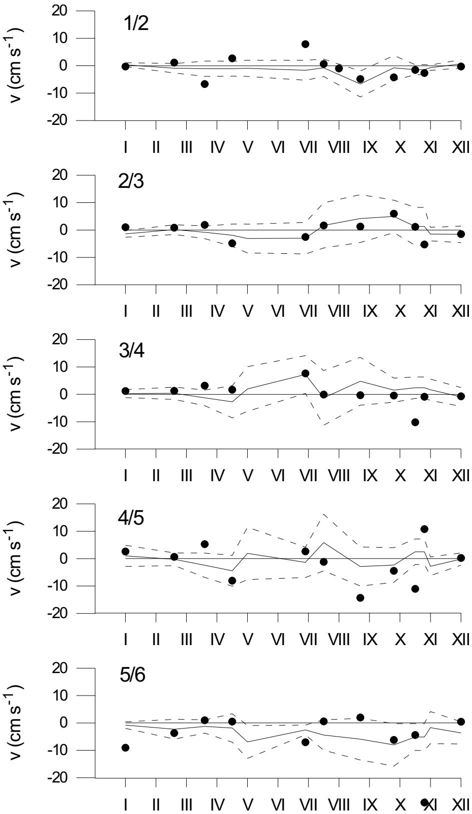

Figure 7. Geostrophic currents relative to 30 m between station pairs during 2000 (filled circles). Solid and dashed lines represent averages and standard deviations for the 1972–1992 period.

Geostrophic currents between the stations along the Rovinj–Po delta profile were in 2000 generally close to the average values for the 1966–1992 period (Figure 7). The currents were more pronounced from late winter to early autumn than over the rest of the year. At the beginning of 2000 (January and February) there was an inflow of water into the northern Adriatic in the eastern and central parts of the profile (positive values) and an outflow of water near the western coast (negative values). In contrast, the circulation in spring and summer was more complex, indicating the occurrence of several cyclonic and anticyclonic gyres across the profile.The ICCC was stronger in March (7 cm/s), and in late August and September (4 cm/s). According to the absolute current distributions (Figure 8) the ICCC was confined to coastal belt between stations 1 and 2, and to a layer down to approximately 20 m depth. The ICCC induced unusually high net outflow of water near the Istrian coast in March (about 0.015 Sv), whereas the net transports in August and September in the area (0.007–0.008 Sv) were close to the 1966–1992 averages (Supić et al., 2000).

Distributions of relative geostrophic currents across the profile based on CTD data (Figure 9) showed that in March and late August the ICCC was situated more offshore (between stations 1a and 2a) than in September, when it was confined to the coast (between stations 1 and 2). While in March and late August the ICCC had the highest speed in surface layer, in September it was very strong in the entire 0–20 m layer.

The ICCC episodes in March, late August and September of 2000 were related to coastal gradients induced by low salinity and low density pools in the open northern Adriatic (between stations 2–4 in March and August and at station 2 in September, Figures 2–4). The distribution of geostrophic currents across the profile (inflow between stations 2 and 4 and outflow between stations 1 and 2 in March and August, inflow between stations 2 and 3 and outflow between stations 1 and 2 in September; Figure 7) suggests that these pools were a part of an anticyclonic gyre. The analysis of the oceanographic and dynamic conditions at the Rovinj–Po delta profile indicated that the circulation pattern in the northern Adriatic changed drastically between 21 February and 17 March. The salinity in the region was high in January and February when the circulation across the profile appeared to be cyclonic,

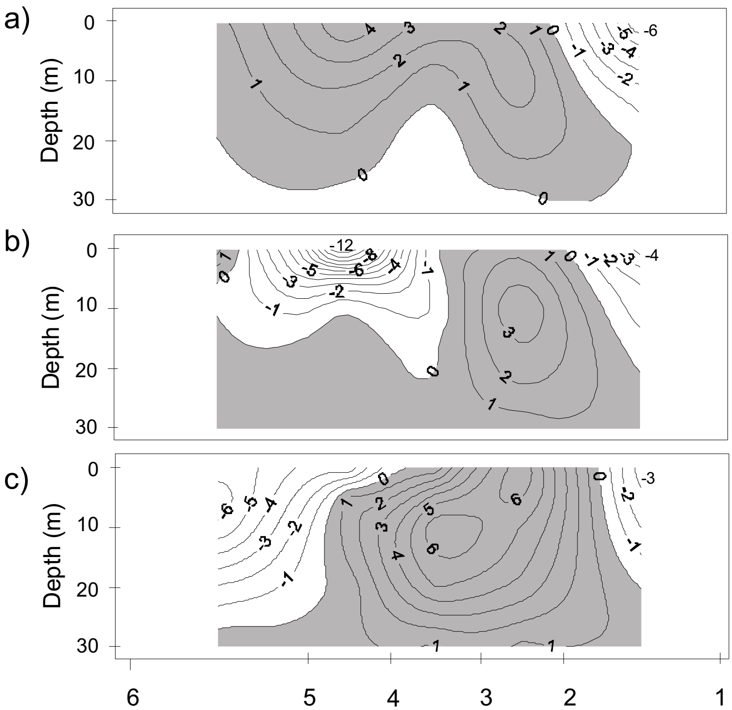

Figure 8. Distribution of absolute geostrophic currents (cm s^{-1}) at the Rovinj–Po delta profile on (a) 17 March, (b) 25 August and (c) 26 September 2000.

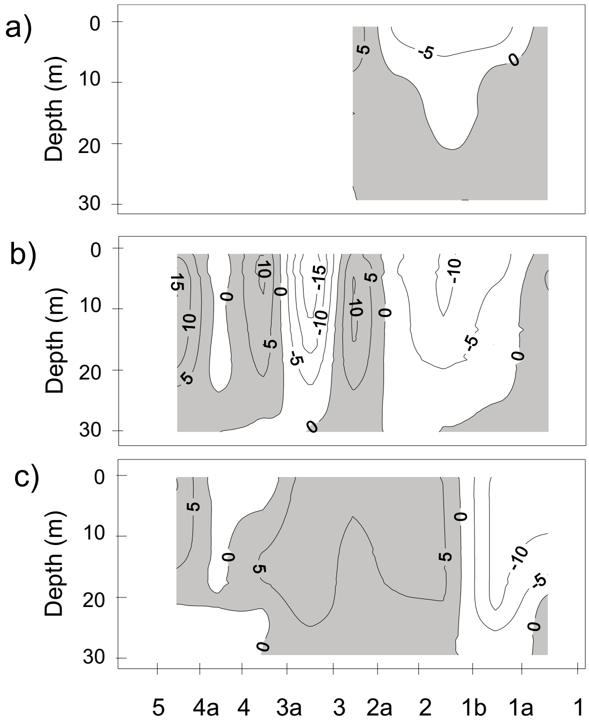

Figure 9. Spatial distribution of relative geostrophic currents (cm s^{-1}) at the Po–Rovinj profile as derived from CTD data on (a) 17 March, (b) 25 August and (c) 26 September 2000.

with inflow in the eastern part of the profile and outflow near the Po delta transporting the freshened water southwards. In contrast, a significant eastward transport of freshened water was observed in March, probably because of a considerable warming of the surface, indicated by heat flux values above the averages coupled with rather weak winds (Figures 5 and 6). This suggests that other mechanisms can generate transversal currents, rather than large freshwater discharges, as generally observed in the region in the spring season (*e.g.* Franco and Michelato, 1992; Degobbis et al., 2000).

4. Summary and conclusion

During the year 2000 the Istrian Coastal Countercurrent (ICCC) occurred in March, August, and September in the upper water column (down to 20 m depth) of the northeastern Adriatic, within 20 Nm from the Istrian coast. The ICCC intensity in August was lower than in some other years in the 1966–1997 period, when mucilage events were also observed in the region (e.g. in 1977, 1988, 1989, 1991 and 1997). However, during those years the events lasted longer than in 2000, generally up to August (*e.g.* Degobbis et al., 1995), or even to September (in 1997; CMR, unpub. data).

In all the situations in 2000 when the ICCC was pronounced, pools of lower salinity water were observed in the northeastern Adriatic Sea. These pools appeared by the end of winter, when freshened water was spread over almost the entire profile, in spite of exceptionally low Po River flow rates. This process occurred in conditions of more intense sea surface warming than usual, probably also favoured by the absence of strong winds. The spreading of freshened waters coincided with changes in the circulation pattern across the Rovinj–Po delta profile. While in January and February a single cyclonic structure was present, the geostrophic circulation was more complex during spring and summer, including both cyclonic and anticyclonic patterns.

It was hypothesized that the ICCC occurred in August in years in which a significant amount of freshened waters entered the northeastern Adriatic and was kept in the area within an anticyclonic gyre (Supić et al., 2000). The formation of the gyre may depend on winter conditions. For example, the gyre is more likely to be formed in warmer winter, as in 2000. The increased residence time of the freshened waters, richer in nutrients and organic matter, would enhance the consequences of eutrophication (marked hypoxia) and favour mucilage accumulation in the area, particularly in the central part of the gyre.

Acknowledgements – This research was supported by the Ministry of Science and Technology of the Republic of Croatia (projects 0098111, 0098121, 119299 and »Jadran«) and Italian Ministry for the Environment (Project MAT).

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SAŽETAK

Pojava Istarske obalne protustruje u 2000. godini, u kojoj su opažene i sluzave nakupine

Nastjenjka Supić, Mirko Orlić, Danilo Degobbis, Tamara Đakovac, Valter Krajcar i Robert Precali

Istarska obalna protustruja (IOPS) pojavila se u ožujku (7 cm/s), kolovozu i rujnu (4 cm/s) 2000. godine, a pojava sluzavih nakupina opažena je tijekom kasnog lipnja i početkom srpnja. Prema ranijim istraživanjima, povremene pojave IOPS podudarale su se s pojavom sluzavih nakupina i/ili anoksije u ovom području. Već tijekom kasne zime, kada je more iz atmosfere primalo razmjerno veliku količinu topline, opažen je značajan transverzalan prijenos zaslađenih voda porijeklom iz Poa. Bazen zaslađene i toplije vode, koji bi mogao biti središte anticiklonalnog vrtloga u istočnom dijelu sjevernog Jadrana, bio je prisutan i tijekom proljeća i ljeta. To ukazuje na postojanje zatvorenog sustava cirkulacije u promatranom području.

Ključne riječi: sjeverni Jadran, površinski protoci topline i vlage, protok rijeke Po, geostrofičke struje, sluzave nakupine

Corresponding author's address: Nastjenjka Supić, Center for Marine Research, Rudjer Bošković Institute, G. Paliaga 5, 52210 Rovinj, Croatia. e-mail: supic@cim.irb.hr