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Istrian coastal countercurrent in the year 1997

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Summary. — During the 1966-1997 period the Istrian Coastal Countercurrent (ICCC), *i.e.* the strong southward surface current confined to the coastal belt off Istria, up to 20 Nm wide, appeared and was particularly pronounced in August of those years when mucilage or anoxia events occurred in the northern Adriatic (1977, 1988, 1989, 1991, 1997). In this paper we analyse geostrophic currents and hydrographic characteristics of the northern Adriatic in 1997. We show that the ICCC can appear in months other than August, as well as that its occurrence implies the presence of an anticyclonic gyre in the northeastern Adriatic, in which lower salinity waters, originating in the Po Delta area, are confined. Longer residence times of this nutrient-rich waters can favour eutrophication process and mucilaginous aggregate accumulation. On the basis of the prediction formula derived for the 1966-1992 period we were able to predict the intense episode of the ICCC in August 1997 from air-sea heat flux calculations with −7 months time lag and Po River discharge rate with −1 month time lag.

PACS `92.10.Sx` – Coastal and estuarine oceanography.
PACS `92.10.Mr` – Thermohaline structure and circulation.

1. – Introduction

As an area in which near anoxia or mucilage events are periodically observed, the northern Adriatic is of particular scientific interest. It is widely accepted that surface circulation in the region is cyclonic, with a northward flow along the eastern (Istrian) coast and a southward flow along the western coast. By analysing long-term variations (1966-1997) of the geostrophic current field along a profile extending from Rovinj to 12 Nm off the Po River delta (fig. 1), we have noted that a strong surface countercurrent appeared occasionally in August within the eastern coastal belt, up to 12 Nm wide [1]. The southward current, named the Istrian Coastal Countercurrent (ICCC), was intense (7–15 cm/s) in 1968, 1977, 1983, 1984, 1988, 1989, 1991, 1992, 1996 and 1997, weak (less than 7 cm/s) in 1971, 1972, 1973 and 1986, and completely absent in 1982, 1993,

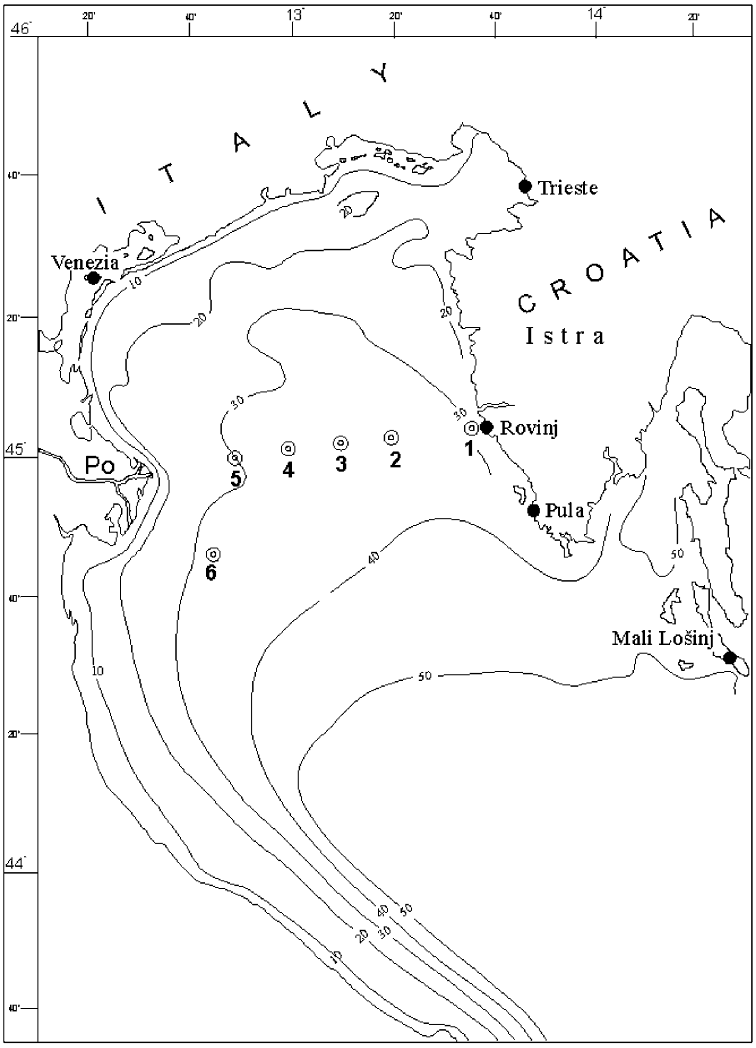

Fig. 1. – Map of the northern Adriatic with position of the meteorological and oceanographic stations.

1994 and 1995. The existence of the ICCC was confirmed by the available direct current measurements, which showed that the descending coastal current was intense in 1977 and 1983, and that it did not develop in 1976, 1978 and 1987.

The appearance of the ICCC in August indicates the presence of a low-salinity, warm and low-density water pool in the northeastern Adriatic open waters that is likely the core of an anticyclonic gyre. Generally, in spring and summer freshened waters spread from the Po Delta area eastwards up to the Istrian coast, but in quantities that significantly vary from year to year. In fact this pool was not observed in years when the ICCC was absent. The understanding of the ICCC phenomenon seems thus to be important for understanding the broader northern Adriatic circulation system along with its year-to-year variability. As the summer mucilage and autumn anoxia events in the northern

TABLE I. – *Latitudes, longitudes and bottom depths of the profile Rovinj-Po Delta stations.*

Station	ϕ	λ	D
1	45°04.8′ N	13°36.6′ E	29 m
2	45°02.9′ N	13°19.0′ E	37 m
3	45°02.0′ N	13°09.3′ E	37 m
4	45°01.0′ N	12°59.6′ E	33 m
5	44°59.9′ N	12°49.8′ E	31 m
6	44°45.4′ N	12° 45.0′ E	31 m

Adriatic in the period 1966-1997 were observed exclusively in years in which the ICCC was more intense (in 1977, 1988, 1989, 1991 and 1997; see [2-4]), the investigations of the ICCC could also lead to better understanding of processes which result in these unusual and undesirable conditions of the ecosystem.

The intensity of the ICCC in August in the period 1966-1992 was found to be highly correlated with the surface heat flux observed in the northern Adriatic with −7 months time lag (previously in January) and with the Po River discharge rate observed with −1 month time lag (in July). On the basis of these correlations we derived a formula to predict the ICCC appearance and intensity in August [1].

In our previous work we focused our attention on the dynamic and hydrographic characteristic of the northern Adriatic in August. Here we aim to show that a strong coastal countercurrent and related specific oceanographic features can appear in months other than August as well. We analyse hydrographic and dynamic conditions in the northern Adriatic in the year 1997, when a massive mucilage event occurred in the area lasting from late June to mid-September. In this analysis we use the available temperature and salinity data set, collected seasonally at the profile Rovinj-Po Delta by the Center for Marine Research (CMR). We also compare the predicted value of the ICCC intensity in August 1997 with its real value.

2. – Data and methods

Our computation of geostrophic currents is based on sea temperature and salinity data collected seasonally in 1997 (*i.e.* in January, March, July, August, September and December of 1997) at six stations of the profile Rovinj-Po Delta (fig. 1, table I) at 0, 5, 10 and 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 here as 1, 2, 3, 4, 5, and 6, respectively. 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.

Using a standard dynamical method we have computed the dynamic depths of the 30 dbar surface (assuming that bottom measurements were taken at 30 m) for each station at the profile and for each cruise in 1997. The values were used to compute the surface geostrophic currents relative to the 30 m level for each pair of neighbouring stations of the profile (st. 1/2, 2/3, 3/4, 4/5, 5/6) for each cruise. A criterion requiring mass conservation through the entire profile was applied next to compute velocity b at the reference level ($b = -Q/P$; Q is the net geostrophic transport when $b = 0$, while P is the total section area of the profile) and the corresponding absolute velocities V_{ij} at

TABLE II. – *Latitudes, longitudes and altitudes of meteorological stations.*

Station	ϕ	λ	h
TRIESTE	45° 39′	13° 45′	45 m
ROVINJ	45° 07′	13° 38′	20 m
PULA	44° 52′	13° 55′	63 m
MALI LOŠINJ	44° 32′	14° 28′	53 m

the j-th level (j = 1,..., 4) of the i-th (i = 1,.., 5) station pair ($V_{ij} = v_{ij} + b$, where v_{ij} is relative geostrophic flow at location ij) [5]. Using the values of absolute currents we determined the net geostrophic transports (*e.g.*, [5]) throughout the eastern (st. 1/2), central (st. 2/5) and western (st. 5/6) part of the profile.

Currents and transports are positive when they mark an inflow into the northern Adriatic and the long-term monthly averages refer to the 1972-1992 period [1].

Surface heat and water fluxes in the northern Adriatic in 1997 have been computed as average value of surface fluxes at Trieste, Rovinj and Mali Lošinj, as in the paper by Supić and Orlić [6]. The fluxes at the three locations (table II) have been computed 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 previously [6]. As the air pressure was not measured in Rovinj, we used the air pressure data collected at the nearby station Pula (table II). Monthly means of meteorological data were computed from hourly values at Trieste and from measurements taken three times a day (7, 14 and 21 h EMT) at Rovinj and Mali Lošinj. The monthly means of SST for Trieste have been derived from daily (10 h EMT) collected data. The monthly means of SST for Rovinj [T_s (RV)] and Mali Lošinj [T_s (ML)] were computed from monthly means of measurements taken three times a day (7, 14 and 21 h EMT) at St. Ivan lighthouse [45° 03′ N, 13° 37′ E; T_s (IV)] and at Veli Rat [44° 09′ N, 14° 50′ E; T_s (VR)] using regression formulae $T_s(\mathrm{RV}) = 1.09 * T_s(\mathrm{IV}) - 0.6$ and $T_s(\mathrm{ML}) = T_s(\mathrm{VR}) - 0.8$. The formulae have been derived on the basis of the monthly means of simultaneous measurements of SST at Rovinj and St. Ivan in the 1984-86 and 1988-92 intervals and at Mali Lošinj and Veli Rat in the 1967-1971 interval, with correlation coefficients 0.99 between each of the two data sets.

3. – Results

3˙1. *Relative geostrophic currents across the profile Rovinj-Po Delta in 1997.* – The geostrophic currents relative to the 30 m level between stations of the profile Rovinj-Po Delta were in 1997 generally more intense than on average (fig. 2). Average monthly values of geostrophic currents are low in autumn and winter (below 5 cm s^{-1} at st. 5/6 and below 2 cm s^{-1} at the other positions) and high in spring and summer (up to 8 cm s^{-1} at st. 5/6 and up to 7 cm s^{-1} elsewhere). The geostrophic flow is on average very weak near the eastern coast (around 1 cm s^{-1}), except in August when it is reinforced (7 cm s^{-1}) due to the appearance of the ICCC. Currents at the profile in January 1997 (around 3–4 cm s^{-1} at st. 1/2 and 5/6 and around 1 cm s^{-1} at other positions) were slightly above the average values (fig. 2), indicating an inflow near the eastern and an outflow near the western coast. From March to September 1997 the currents at the profile (up to 12 cm s^{-1} at st. 5/6, 6–8 cm s^{-1} at st. 1/2 and 4/5 and 1–2 cm s^{-1} at

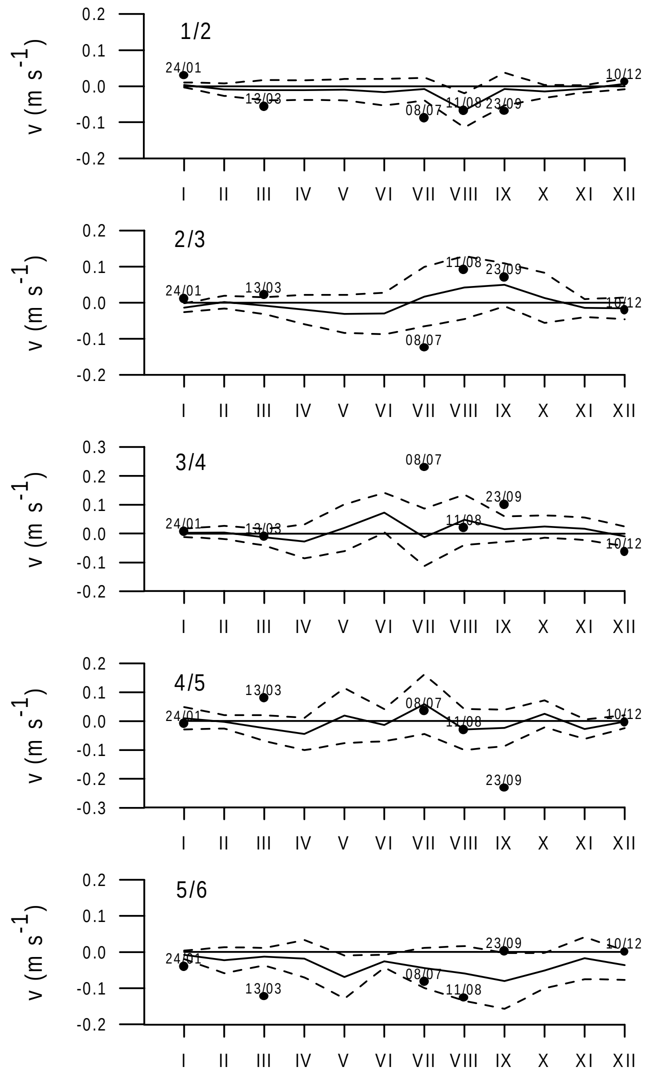

Fig. 2. – Single values (filled circles) and the average annual cycle (for the 1972-1992 interval; solid line) with the corresponding standard deviations (dashed lines) of relative geostrophic currents at st. 1/2, 2/3, 3/4, 4/5 and 5/6 in 1997. Currents are positive when there is an inflow into the northern Adriatic.

other positions in March; up to 23 cm s^{-1} at st. 3/4, 8–13 cm s^{-1} at st. 1/2, 2/3 and 5/6 and 3 cm s^{-1} at st. 4/5 in July; 7–13 cm s^{-1} at st. 1/2, 2/3 and 5/6 and 2–3 cm s^{-1} at st. 3/4 and 4/5 in August; up to 23 cm s^{-1} at st. 4/5, 7–10 cm s^{-1} at st. 1/2, 2/3 and 3/4 and 0 at st. 5/6 in September) were generally much more intense than on average, indicating an outflow both near the eastern and the western coast and an inflow in the central part of the profile. The currents in December 1997 (up to 6 cm s^{-1} at st. 3/4, 1–2 cm s^{-1} at st. 1/2 and 2/3 and 0 at st. 5/6) were close to the averages, indicating a weak inflow near the eastern coast and an intense outflow in the central

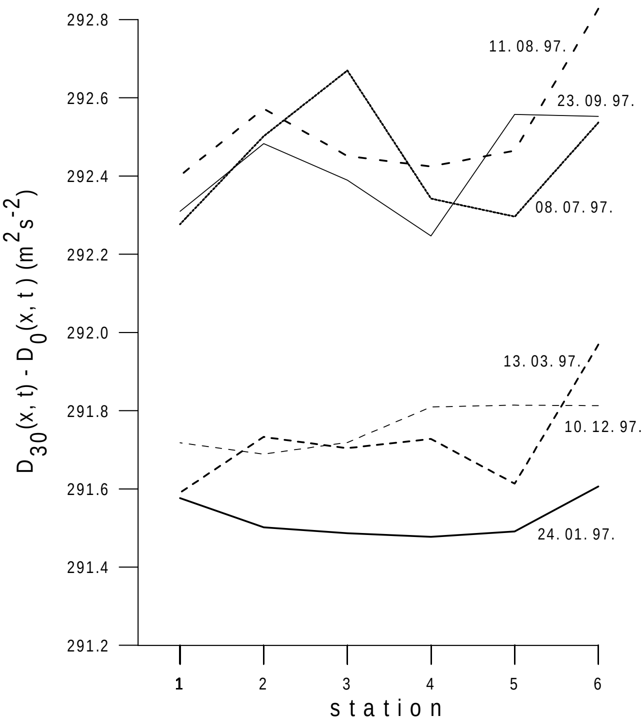

Fig. 3. – Relative dynamic depths of the 30 dbar surface with respect to the sea surface at stations 1-6 in 1997.

part of the profile. The descending current between st. 1 and 2 (*i.e.* the Istrian Coastal Countercurrent, ICCC) was not developed in January and December, but it appeared in March (6 cm s^{-1}), July (9 cm s^{-1}), August (7 cm s^{-1}) and September (7 cm s^{-1}) with almost equal strength.

The dynamic depths of the 30 dbar surface were in 1997 (fig. 3) lower and less variable in space in winter and autumn (291.5–291.6 m^2s^{-2} in January, 291.6–291.9 m^2s^{-2} in March and 291.7–291.8 m^2s^{-2} in December) than in summer (292.3–292.7 m^2s^{-2} in July, 292.4–292.8 m^2s^{-2} in August and 292.2–292.6 m^2s^{-2} in September). In January and December the 30 dbar surface was elevated in the central part of the profile (*e.g.*, at st. 2/5 in January and at st. 2/3 in December) with respect to the coastal area. In the warm part of the year two dynamic depths depression areas were observed: one in the vicinity of the Po River (at st. 6) and another in the eastern/central northern Adriatic (at st. 2/4 in March, at st. 2/3 in July, at st. 2 in August and at st. 2/3 in September).

3˙2. *Net geostrophic transports and absolute currents at the Profile Rovinj-Po Delta in 1997.* – The net geostrophic transport across the profile in 1997 was in general reinforced with respect to the average values (fig. 4). Average transports are much lower during the autumn and winter than in spring and summer, reaching a maximum in August (st. 1/2 and 2/5) or September (st. 5/6). In general, there is a net geostrophic outflow near the western coast (st. 5/6) and net geostrophic inflow in the central (st. 2/5) and eastern (st. 1/2) part of the profile. Note that in August, when the ICCC appears, the average net

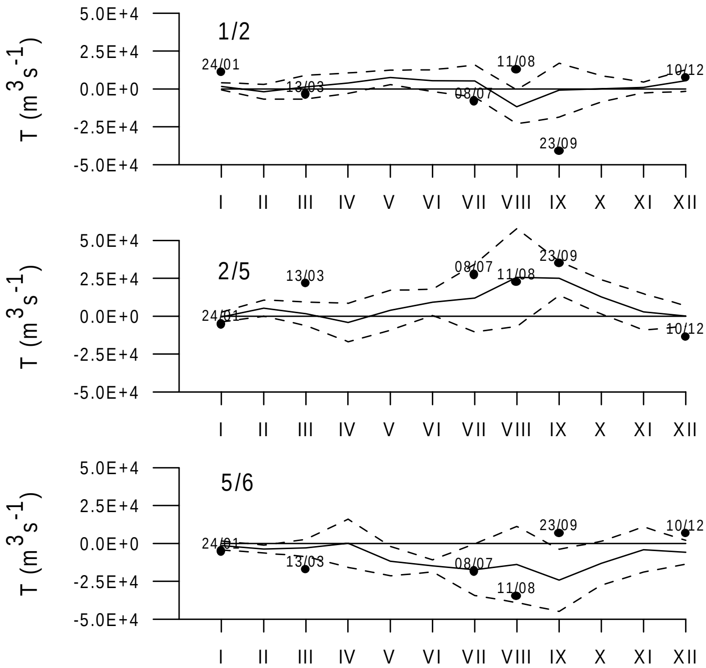

Fig. 4. – Single values (filled circles) and the average annual cycle (for the 1972-1992 interval; solid line) with the corresponding standard deviations (dashed lines) of net geostrophic transports in the eastern (st. 1/2), central (st. 2/5) and western (st. 5/6) part of the profile Rovinj-Po Delta. Transports are positive when there is an inflow into the northern Adriatic.

transport near the eastern coast (st. 1/2) was negative. In January 1997 the transport was positive (the direction denotes an inflow of water in the northern Adriatic) at st. 1/2 and negative at st. 2/5 and 5/6, in March and July it was positive at st. 2/5 and negative at st. 1/2 and 5/6, in August it was positive at st. 1/2 and 2/5 and negative at 5/6, in September it was positive at st. 2/5 and 5/6 and negative at 1/2 while in December it was positive at st. 1/2 and 5/6 and negative at st. 2/5.

The absolute currents at the profile Rovinj-Po Delta were in 1997 much more pronounced and spatially variable in the 0–15 m layer (0–4 cm s^{-1} in January, 0–12 cm s^{-1} in March, 0–22 cm s^{-1} in July, 0–11 cm s^{-1} in August, 0–21 cm s^{-1} in September and 0–6 cm s^{-1}in December) than in the 15–30 m layer of the profile (0–1 cm s^{-1}in January, 0–2 cm s^{-1} in March, 0–6 cm s^{-1} in July, 0–4 cm s^{-1} in August, 0–10 cm s^{-1} in September and 0–2 cm s^{-1}in December; fig. 5). This fact suggests that the surface currents represented the main contribution to the net geostrophic transport across the transect in 1997. According to the distribution of absolute currents the ICCC was, except in July, confined to the upper layers of the water column (0–15 m in March, 0–5 m in August and 0–20 m in September) and to the coastal belt extending between stations 1 and 2 (in March, August and September) or between stations 1 and 3 (in July). Except in August—when it was limited to a very shallow area—the ICCC was associated to a net geostrophic outflow near the Istrian coast (fig. 4).

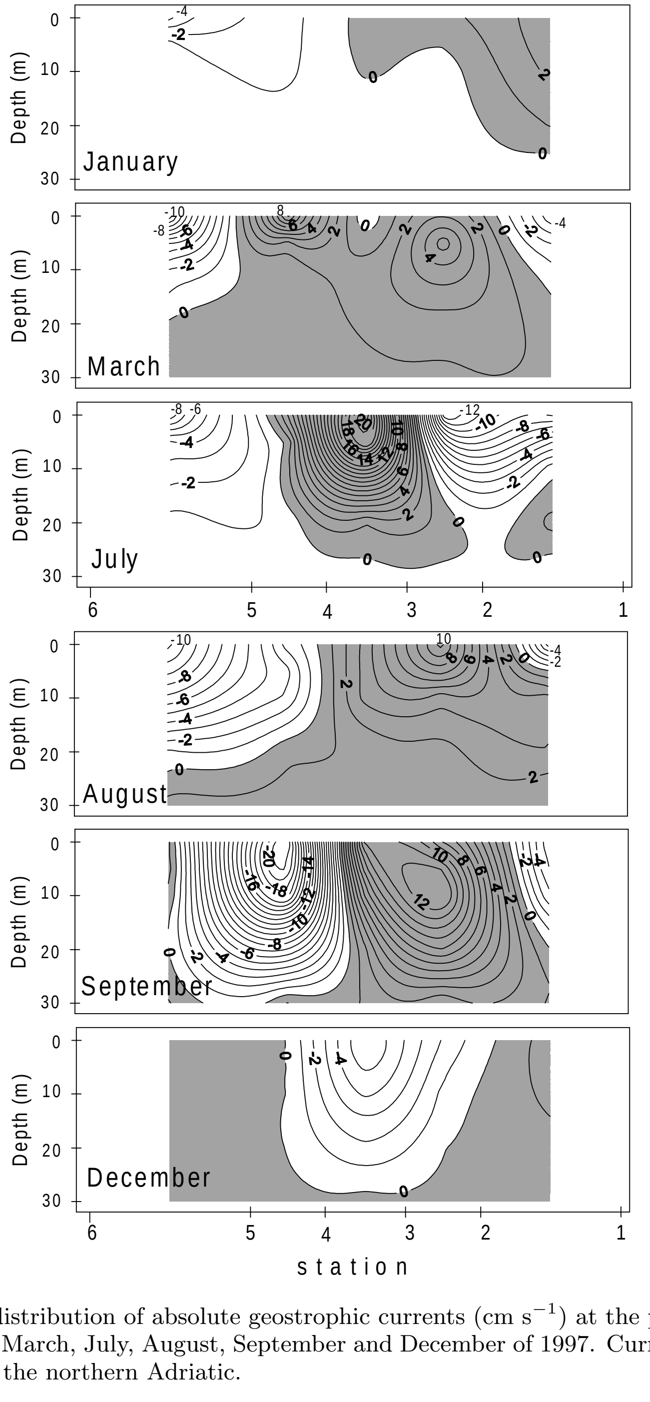

Fig. 5. – Spatial distribution of absolute geostrophic currents (cm s^{-1}) at the profile Rovinj-Po Delta in January, March, July, August, September and December of 1997. Currents are positive for an inflow into the northern Adriatic.

3˙3. *Hydrographic characteristics of the profile Rovinj-Po Delta in 1997.* – The distribution of relative currents and the 30 dbar surface slopes in 1997 reflected the distribution of hydrographic properties along the profile Rovinj-Po Delta (fig. 6). The temperature, salinity and sigma-t values were in January 1997 much lower in the surface (down to 9.8 °C, 31.1 and 24. 7 kg m^{-3} at st. 6) than in the bottom layer (up to 12.1 °C and 38.4 at st. 2 and around 29.2 kg m^{-3} at st. 2/6). The sigma-t values were lower in the water column near both the eastern and western coast than in the central part of the profile. In March 1997 the surface layer was flooded by warm (up to 11.8 °C; st. 3), low-salinity

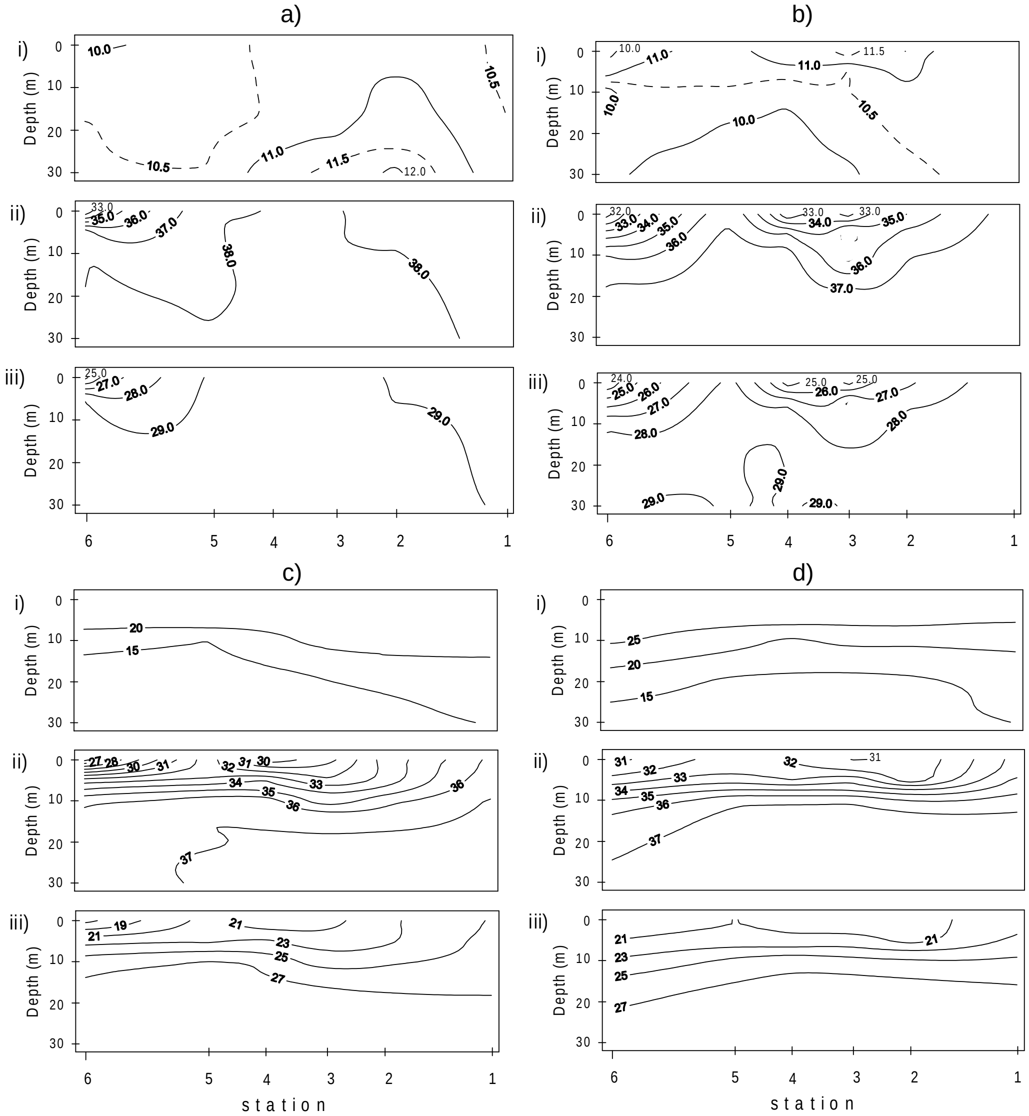

Fig. 6. – Spatial distribution of i) temperature (°C), ii) salinity and iii) sigma-t values at the profile Rovinj-Po Delta in a) January 1997; b) March 1997; c) July 1997; d) August 1997.

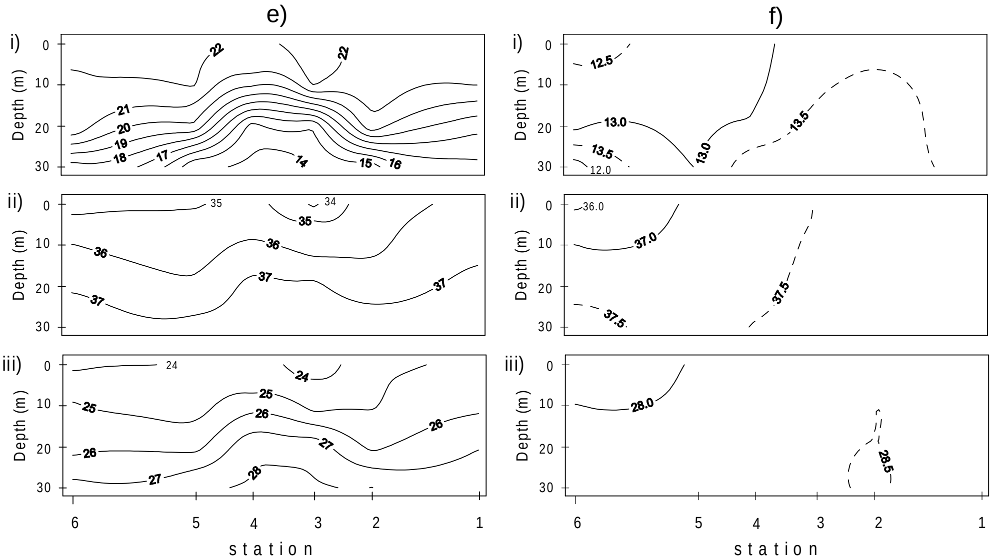

Fig. 6. – *Continued.* e) September 1997; f) December 1997.

(down to 30.5; st. 6) and low-density (down to 23.2 kg m^{-3}; st. 6) water. This water was confined in two surface pools, 10–15 m deep: one off the Po Delta (st. 6) and another in the central part of the northern Adriatic (st. 2-4). In the bottom the temperature was lower (around 10 °C) and salinity and density higher (around 37.5 and 28.9 kg m^{-3}, respectively) than at the surface, and with much smaller variability.

The distributions of the hydrographic parameters during the summer were similar as in March. In fact, the two surface pools of warm, less saline and less dense water (up to 24.8 °C and down to 25.7 and 16.4 kg m^{-3} at st. 6 in July; up to 26.8 °C and down to 30.7 and 19.6 kg m^{-3} at st. 6 in August; up to 22.3 °C at st. 6 and down to 33.8 and 23.3 kg m^{-3} at st. 3 in September) were also observed off the Po delta (at st. 6) and in the central eastern part of the profile (at st. 2-5. in July, at st. 2-4 in August and September). In December the values of temperature, salinity and density were somewhat lower in the 0–20 m layer off the Po delta (down to 12.1 °C, 36.4 and 27.6 kg m^{-3}) than in other parts of the profile (13–14 °C, 37.5–37.9, 28.2–28.5 kg m^{-3}).

3˙4. *Heat and water fluxes and prediction of the ICCC intensity in August 1997.* – The occurrence and intensity of the ICCC in August (Y) can be predicted from the surface heat flux in January (X_1), along with the Po River discharge rate in July (X_2) by applying a statistical relationship developed from the study of long-term changes in the period 1966-1992 [1]:

$$Y = -0.166 - 0.0018X_1 - 0.00006X_2 . \qquad (1)$$

The northern Adriatic in 1997 gained heat from March to September (fig. 7). Surface heat flux was in 1997 out of the standard deviation ranges in January, April, July, November, October and December.

In January, from March to July, and November-December the northern Adriatic gained water at the air-sea interface. The water fluxes in 1997 were out of the standard

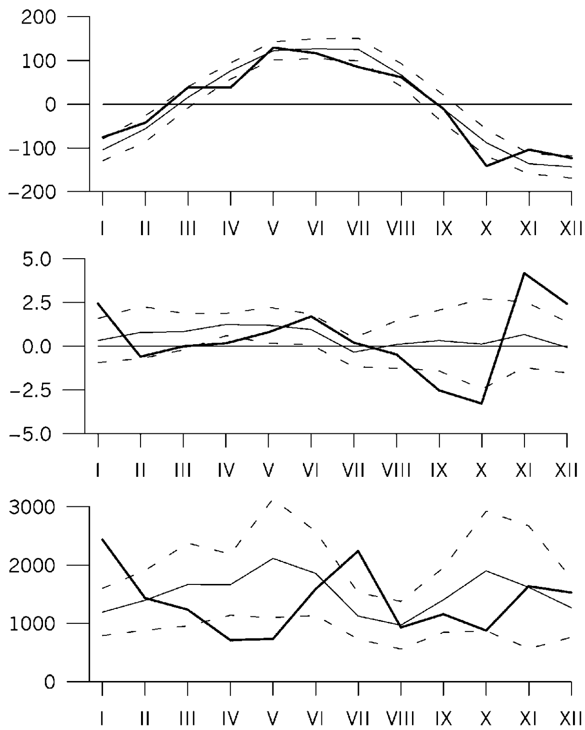

Fig. 7. – Air-sea heat (Q) and water flux (W) along with Po River discharge rate (F) in 1997 (heavy solid lines). Q and W are positive when the sea gains heat or water. The average annual cycles and standard deviations ranges of the three parameters for the 1966-1992 period are denoted by the solid and dashed lines, respectively.

deviation ranges in January and from September to December. The Po River discharge rate was in 1997 in January and July significantly higher and in April and May significantly lower than the long-term averages. Po water discharges were considered much more important than the air-sea water fluxes affecting the geostrophic circulation in the region [1].

The surface heat flux in January 1997 along with the Po River discharge rate in July 1997 have been used to predict the intensity of the ICCC in August 1997 from the above relationship (fig. 8). According to the prediction the ICCC in August 1997 should have been pronounced amounting to 16 ± 3 cm s^{-1}. So, our method turned out to be reliable in prediction of the ICCC intense episode of the August 1997, although the predicted value is higher than the geostrophic approximation of the ICCC for August 1997 (7 cm s^{-1}).

4. – Discussion

The relative currents at the profile Rovinj-Po Delta in 1997 were mostly much more intense than the averages for the period 1966-1992. These currents were weaker in winter and in late autumn (January and December) than in the heating period (*i.e.* in March, July, August and September; unfortunately no data were available for April-June), evidencing very different circulation patterns. During early winter and late autumn an

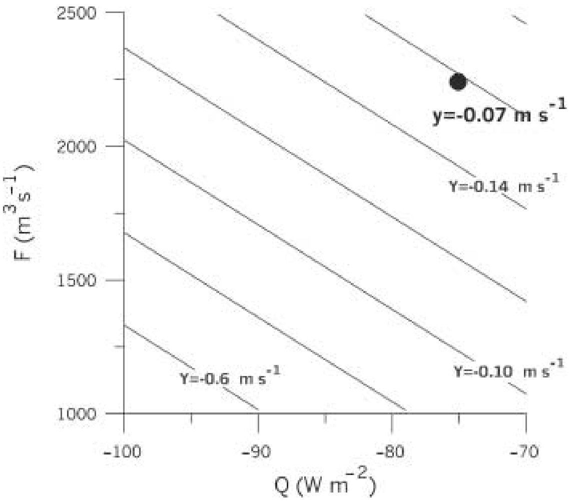

Fig. 8. – The ICCC speed in August (Y) of 1997 with the air-sea flux recorded previously in January (X_1) and the Po River outflow observed in the preceding July (X_2). The isolines (between $Y = -0.06$ and $Y = -0.18$ m s^{-1}) represent the plane defined by the regression formula $Y = -0.166 - 0.0018X_1 - 0.00006X_2$.

inflow near the eastern coast, combined with an outflow from the western/central part of the profile, probably belonged to a single cyclonic gyre across the profile Rovinj-Po Delta. In late winter and summer (and probably also in spring) outflows limited to the coastal areas were associated with an inflow in the central part of the profile, indicating the presence of two gyres, a cyclonic one across the west and an anticyclonic across the eastern part of the profile. In fact, a strong coastal countercurrent (the ICCC) appeared with almost equal intensity in March, July, August and September 1997.

The dynamic depths of the 30 dbar surface were lower in January, March and December 1997 than during the summer. In January and December the 30 dbar surface was slightly elevated in the central part of the profile with respect to the coastal area. From March to September two 30 dbar surface depression areas were observed: one off the Po delta and another in the open waters off Rovinj.

The net geostrophic transport across the profile in 1997 was in general reinforced with respect to the long-term averages. According to the distribution of absolute currents, the ICCC was more often limited to the upper water column and to a coastal belt extending between stations 1 and 2. The ICCC induced a net geostrophic outflow near the Istrian coast, except in August, when it was confined to a very shallow area.

The seasonal differences in the geostrophic currents and isobaric surface slopes could be explained by seasonal changes in the hydrographic conditions at the profile. As previously documented (*e.g.* [7-9]), in 1997 also the temperature seasonal cycle appeared to be influenced mainly by the air-sea heat flux, while the salinity changes were caused in the first place by Po water discharges, rather than by relatively weak air-sea water fluxes. The Po influence was in January and December 1997 limited to the western coastal area, while in March, July, August and September it was extended up to the northeastern Adriatic area. During these months warm and low-salinity Po waters were concentrated in two surface pools, 10–15 m deep: one off the Po Delta and the second in the open central/eastern northern Adriatic.

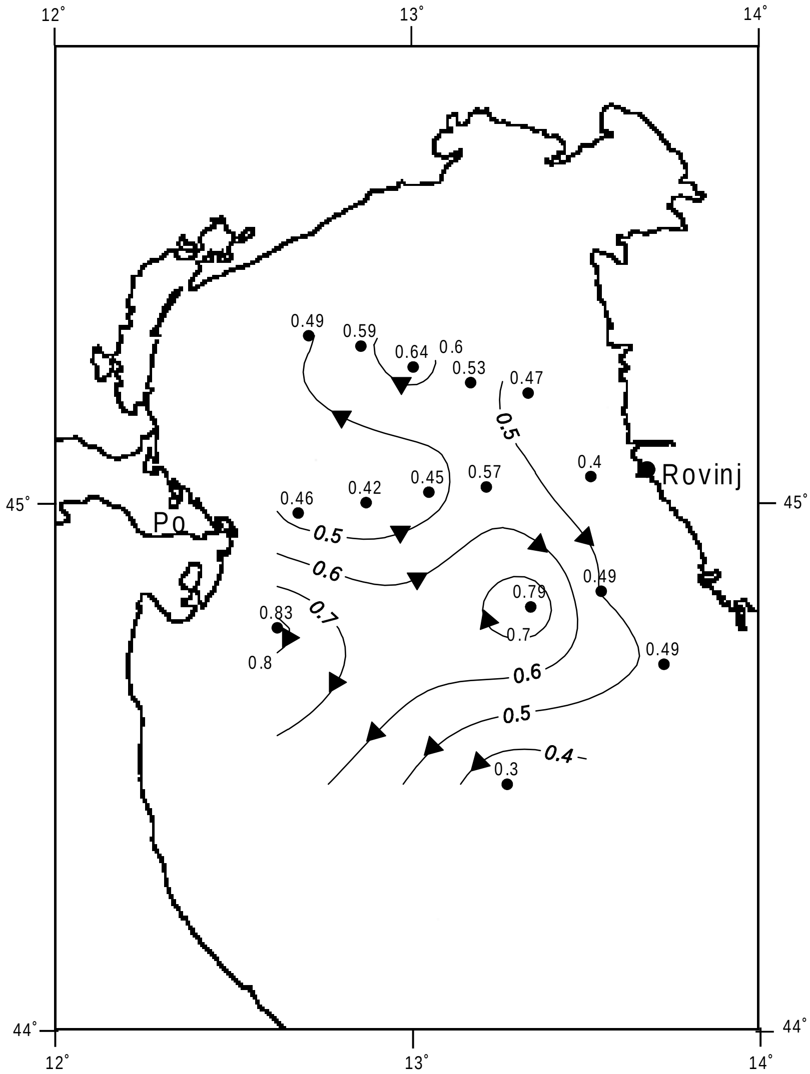

Fig. 9. – Relative dynamic depths of the 30 dbar surface with respect to the sea surface (292 should be added to each value to get the dynamic depths in m^2s^{-2}) in the northern Adriatic between 11 and 13 August 1997 (after [10]). Isolines indicate the geostrophic circulation pattern.

The results suggest that the ICCC marks a strong coastal density gradients induced by the presence of a low-salinity Po water pool in the open northeastern Adriatic. As indicated by the current distribution at the profile Rovinj-Po Delta (outflow near the eastern coast, inflow in the central part of the transect) the pool is likely to be the core of an anticyclonic gyre. Presence of the gyre for August 1997 is confirmed by the distribution of relative dynamic depths of the 30 dbar surface computed over a larger part of the northern Adriatic (fig. 9). Satellite images obtained for 24-26 September 1997 (http://www.me.sai.jrc.it/mewebsite/contents/shared_utilities/frames/archive seawifs.htm) clearly show that in the Istrian coastal boundary layer chlorophyll *a* concentrations were much smaller than in the offshore waters, thus supporting the notion that there is a difference between the dynamics of the coastal and open northern Adriatic.

We were able to predict the ICCC occurrence in August 1997 on the basis of previously recorded air-sea flux and Po River discharge rate. The ICCC was found to be more intense when surface heat loss in January is weak and when Po River discharge in July is high. At present we are not able to give the full explanation of the physical mechanisms of these relationships.

5. – Conclusions

We have shown that the ICCC and the specific oceanographic features related to it could appear not only in August, but also in other months of the heating period. We have also shown that the ICCC appeared as a surface current, confined to the coastal belt of the 20 Nm width. These results are important in future planning of experiments in which the ICCC is to be detected and located more precisely by direct current measurements.

The results presented here enable us in addition to reconstruct the dynamic conditions of the northern Adriatic in 1997. They indicate that the northern Adriatic circulation was at the beginning of 1997 cyclonic and that waters of the Po origin were confined to the western coast. By the end of winter (*i.e.* between 24 January and 13 March) a certain amount of low-salinity waters of Po origin entered the northeastern Adriatic and was kept in the open waters off Rovinj (in the area which during winter was much warmer although equally saline as its surroundings). An anticyclonic gyre around the low-salinity water core was formed. The gyre—filled constantly by the low-salinity Po waters—persisted in the open northeastern Adriatic till the end of summer. In autumn (*i.e.* between 23 September and 10 December) the cyclonic circulation system was re-established while the Po waters left the northeastern Adriatic area.

The presence of the closed anticyclonic circulation cell in the northern Adriatic open waters during spring and summer of 1997 could drastically influence the processes in the ecosystem of the region. Long residence time of Po-influenced waters would favour the eutrophication process and would be responsible for mucilage accumulation as observed in the area by the end of summer.

It is likely that the gyre appeared also in other years in which the ICCC is intense in August. That assumption is supported by the fact that the intense episodes of the ICCC coincide with occurrences of mucilage or anoxia events. The intensity of the ICCC in August was found to be high in years in which surface heat loss in January is low. It may well be that the formation of the anticyclonic gyre depends on winter conditions. However, to confirm or to reject this hypothesis a considerable research effort is to be undertaken.

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