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Sea-surface currents measured by coastal HF radar off-shore Ancona

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Abstract - The CODAR (Coastal Ocean Dynamics Application Radar) system, was installed for the first time in the Adriatic Sea off the Ancona coast (Italy). The system operated continuously, from September 1997 through February 2000. Some results of the data analysis on a monthly time-scale for one whole year (September 1997-August 1998) are shown. They corroborate a presence of a 10-15 km wide coastal flow, known as WAC (Western Adriatic Current), prevalently flowing towards the south-east. Its variability on a seasonal time scale is clearly evident. A possible influence on the WAC of the freshwater discharge from the Po River (acting through a horizontal pressure gradient) and its spreading in the Northern Adriatic basin is documented. A freshwater discharge confined to the western coast is associated to a stronger horizontal pressure gradient which then reinforces the WAC. On the contrary, fresh water dissipated in the surface layer towards the eastern coast and trapped in the northernmost sub-basin of the Adriatic, as may occur during summer, is associated to the much weaker WAC. Some hints of a synoptic time scale variability in the current field are reported, putting into evidence a reversal of the prevalent south-eastward current observed in some meteorological situations characterized by a SE (sirocco) wind.

1. Introduction

Surface currents have an important role in the dynamics of erosion and in the deposit of sediment along the coasts, as well as in the control of the environmental parameters of coastal waters. Currents in the first meter below the sea surface are extremely variable, being influenced both by geostrophic motions and tides as well as by local winds and wave fields. Time evolution

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of environmental coastal parameters is complex as the winds and currents interact on often very small space and time scales, leading to widely varying phenomena.

The data collected by a coastal HF (High-Frequency) radar in the zone off Ancona (northern Adriatic Sea, Fig. 1) during about two and half years offer a wide range of information. Some preliminary results presented by Budillon et al. (2000) were obtained from the analysis during the validation period, and then during the first three months of operations (September – November 1997). Their aim was to report the results considering the propagation of the errors contained in the measurements, and to validate the currents measured by HF radar both by Eulerian and Lagrangian methods. Even though the three types of measurement, i.e., HF radar, moored current meters and drifters are not completely comparable, a good correspondence especially for the low-pass data from a moored current meter was found. Also, Lagrangian trajectories of surface drifters were coherent with the flow structure from the radar. The surface current spectrum showed the diurnal and semidiurnal tidal signal which propagated from the NW toward SE, and whose energy diminished from the coast off-shore. Additionally, an episode of the NE bora wind was associated to the increased mean kinetic energy. These preliminary results have shown that the HF radar is a powerful and quite reliable tool for determining the spatial and temporal features of the surface current field structure. Successively, Budillon et al. (2001c) constructed weekly maps of the low-frequency currents over a determined grid off

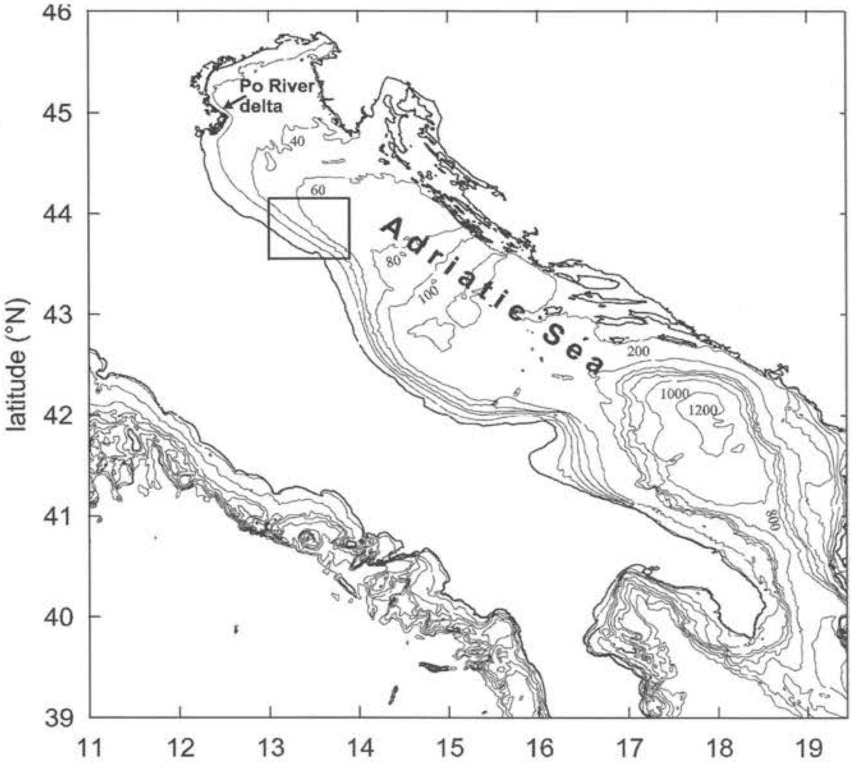

Fig. 1 - Bathymetric map of the Adriatic Sea. Depths are given in metres. Area investigated by CODAR measurements in the northern Adriatic Sea is denoted by a rectangle.

Ancona for the period August-October 1997. These maps delineate a high variability of a current field at synoptic time scales (of the order of several days), and variable spatial scales, including mesoscale eddies and coastal jets. In Budillon et al. (2001b) another kind of information, derived from the radar currents, is reported. It was shown that the energy of near-inertial current increases exponentially away from the coast.

Our aim is to present at first, a mean monthly current field, with the scope of detecting the seasonal variability of the flow, in particular, the WAC (Western Adriatic Current, see, for instance, Hopkins et al., 1999a), and to try to relate it to possible driving mechanisms. In addition, some hints on the synoptic time-scale variability will be given, primarily associated to the wind forcing.

The paper is organized as follows: in section 2 we present some details on the measurement technique and on its application in our study area; in section 3 the data processing, analysis and results are reported, while in section 4 we summarize our findings and draw some conclusions.

2. Some considerations on the measurement technique

The shore-based oceanographic HF radar is capable of monitoring sea-surface currents in ample coastal regions. It operates in the HF band between frequencies $f \approx 10\text{-}50$ MHz, with wavelengths $\lambda \approx 30\text{-}6$ m (Paduan and Graber, 1997). The working frequency band implies a spatial resolution that can vary from some hundreds of meters to a few kilometres, while the spatial coverage offshore the coast can go from tens to hundreds of kilometres. Surface currents are measured by analysing the reflection and dispersion of electromagnetic radiation by the sea waves, which are generally of varying length. The spectrum of echoes received contains two dominant peaks, symmetrically located around the transmission frequency. They are the HF signals produced by the train of marine waves which have a wavelength exactly half of the transmitted one (Bragg effect), and that move radially to and from the radar. The Doppler shift due to both the gravity surface waves and the superimposed horizontal currents is detected, and from which current velocity is determined.

The working range of the HF radar depends, substantially, on the attenuation the electromagnetic waves undergo along the trajectory between the transmitter, the target and back. It also depends on the diffusion of energy generated by the roughness of the sea surface, and on the noise of radio interference (Gurgel et al., 1999). Moreover, the maximum range, for each frequency, depends on the radar parameters, such as power, wave band, antenna model, etc.

The thickness of the surface layer d, producing the "Doppler shift" in the presence of a surface current, is approximately $d = \lambda / (8\pi)$ (Stewart and Joy, 1974). Thus, for electromagnetic waves having a length of 12 m ($f = 25$ MHz), only surface currents in the 50 cm top layer can be measured using the Bragg effect.

Since each radar station can only measure the radial component of the current vector, at least two coastal transmitting-receiving stations, operating simultaneously, are required. The maximum precision is obtained when the two radial vectors form a 90° angle. Generally speaking, the angular separation between the two radial currents should be between 30° and

150° (Paduan and Graber, 1997), for a correct determination of the current vector.

The resolution in space is affected by the disturbance coming from the nearby radio stations. This factor is minimized by using transmission signals from a narrow band.

A more detailed description of the HF functioning is reported in Barrick et al. (1977), for instance, and can also be found in the series of papers by Budillon et al. (2000, 2001a, 2001b).

The HF radar system implemented in Ancona is a CODAR (Coastal Ocean Dynamics Application Radar; Lipa and Barrick, 1983), that operates at a frequency of around 24.7 MHz. The range is about 40 km, while the resolution is of 1.5 km. The two antenna sites chosen were a small building on the shoreline of Senigallia and the North Pier ("Molo Nord") in the port of Ancona. The air-distance between Senigallia and Ancona is about 20 km, and the total area covered was about 1000 -1200 km^2. Each hour, a polar map, representing the radial components of the surface currents is created for every site. The whole area covered by the two remote sites is virtually subdivided into cells. Each cell can be associated to a vector that is the resultant average of all the radial vectors determined within the cell area.

An example of the radial maps, the current vectors resultant from them, and corresponding errors can be found in Budillon et al. (2001b).

With an increasing distance of the observation point from the antennas, the measurement reliability decreases due to distortion errors; additional errors can be due to a narrow view angle. The error is made apparent, mainly, by remarkable structures, which are not physically acceptable, such as a strong convergence or divergence in the current field, incoherency with the surrounding currents, and/or singular high velocity currents, not justifiable, and not comparable to the neighbouring values.

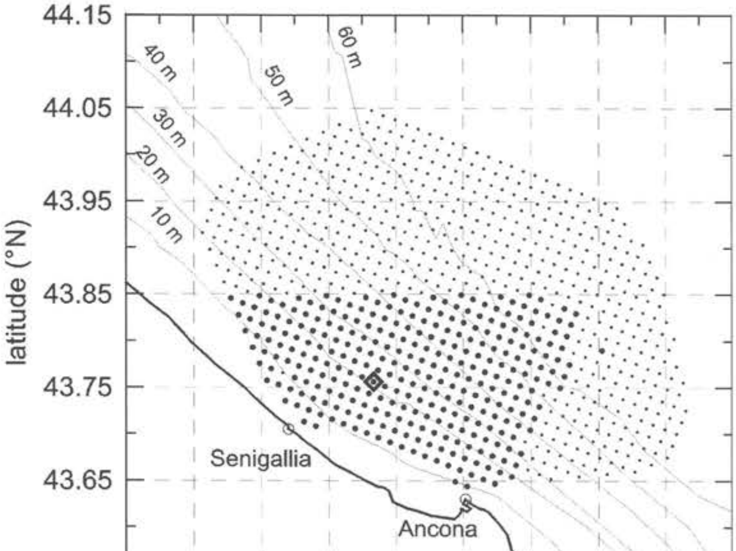

Fig. 2 - Bathymetry of the study zone offshore Ancona with a nominal grid and a sub-grid indicated by thin and thick circles respectively. A square symbol indicates a position of the location used for a statistical analysis in Table 1.

The above-mentioned errors are larger, especially in presence of weak winds and currents, hence, the need to edit the maps by eliminating false vectors and non-realistic structures, becomes the prerequisite for verifying the reliability of the radar system. This editing technique is sensitive to local disturbances and meteo-oceanographic conditions, which may create gaps both in time and space, leading to a non-uniform temporal and spatial coverage.

The CODAR-inferred currents were verified at the beginning of the measurements by pinpointing the position of a drifter (a CODE type, such as used by Poulain, 2001), off the coast between Senigallia and Ancona. This was done in August 1997 (Mazzoldi et al., 1999), giving a good agreement, considering the difference between the two methods of measurement (Paduan et al., 1996), despite the existence of major differences mostly at very high or very low speeds.

Comparing the current field measured by HF radar with drifters that were crossing the area during the measurement interval, Mihanović et al. (2001) suggested that a strong convergence or divergence in the current field, observed on a daily time scale, were unrealistic and physically unacceptable features, and their presence must be a result of growing errors in the north-western corner of the grid.

Taking into account all these considerations and the data density distribution, we have performed the analysis on a sub-grid which sufficiently covers the investigated area, but does not extend north of 43.85° N. Fig. 2 shows both the nominal grid, with a total of 841 points, and a sub-grid with 306 points, used in our analysis.

3. Data analysis and results

3.1. Maps of the monthly mean flow

The hourly measurements of the surface current, carried out offshore Ancona from 1 September 1997 to 31 August 1998, offer the possibility of studying a wide range of both temporal variations and spatial variations of the current field. In our preliminary approach we discuss mean monthly flow structures for one entire year, from which some features of the long-term variability at seasonal time-scales can be obtained. We will also anticipate a very important part of the current variability, the one at synoptic time scales (of the order of few days) which is very energetic, and can to a certain extent, influence the characteristics of the monthly mean current field. The average monthly values in each point of the sub-grid were calculated from the available hourly data.

Further analyses showed that the gaps in the time series (due to various disturbances, see section 2), can affect the statistical representativeness of the average monthly value. Consequently, only the points where the number of missing data did not exceed 20% of the total data for the month, were considered. As a consequence, the number of valid grid points varies from month to month.

Twelve monthly maps are presented in Figs. 3a-d. In September 1997 (Fig. 3a) the mean monthly values depict a south-eastward flow in the 15 km wide coastal strip. A weak current

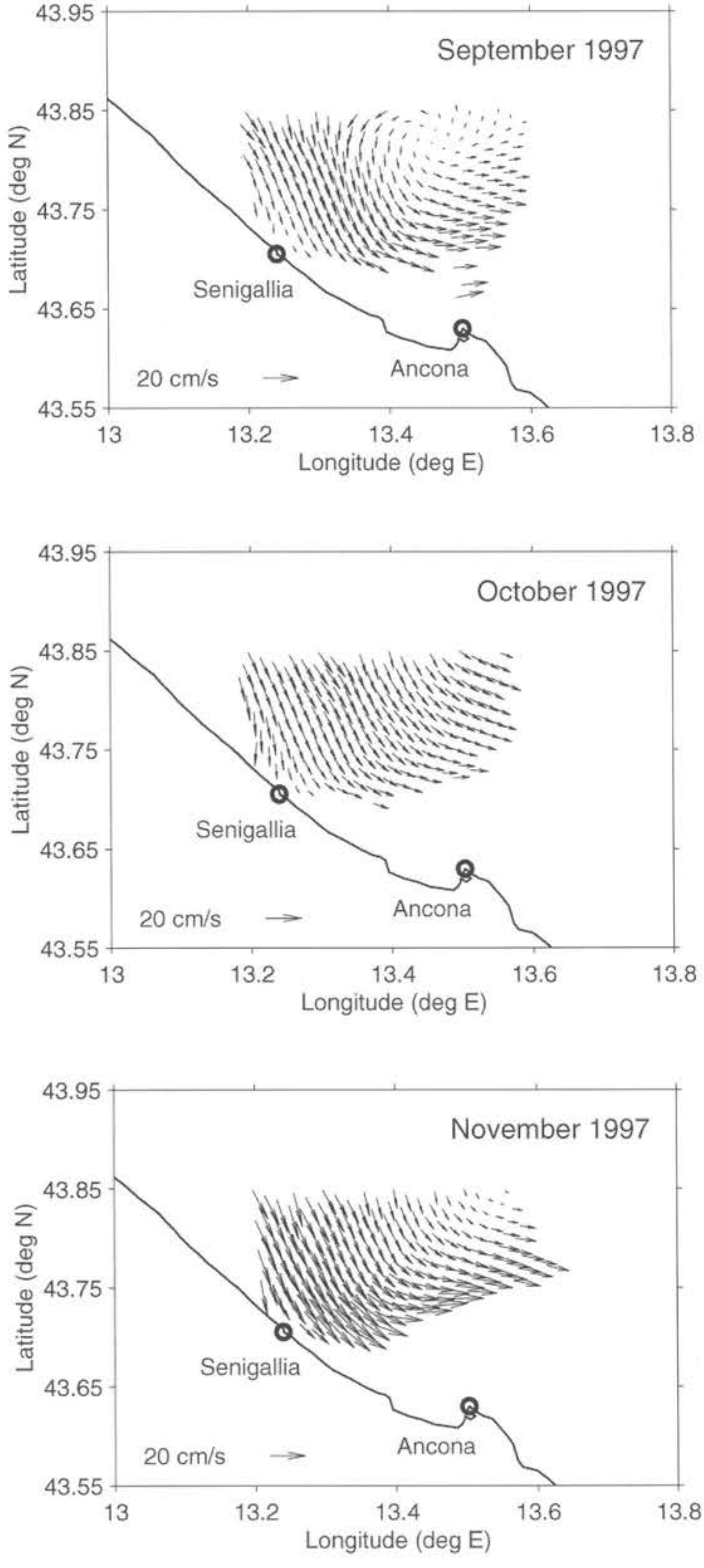

Fig. 3a - Maps of the mean monthly current field for a three-month period from September 1997 to November 1997.

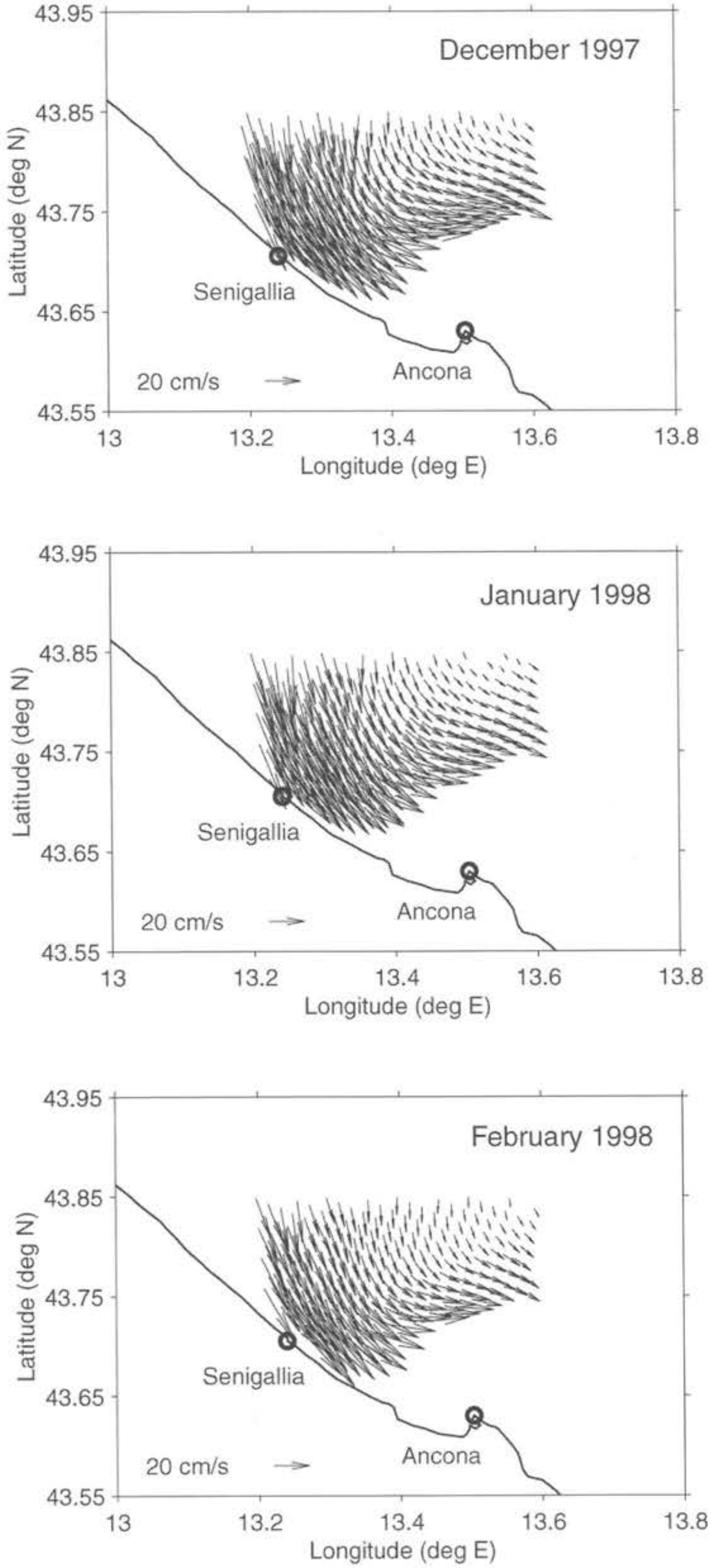

Fig. 3b - Same as Fig. 3a except for the period from December 1997 to February 1998.

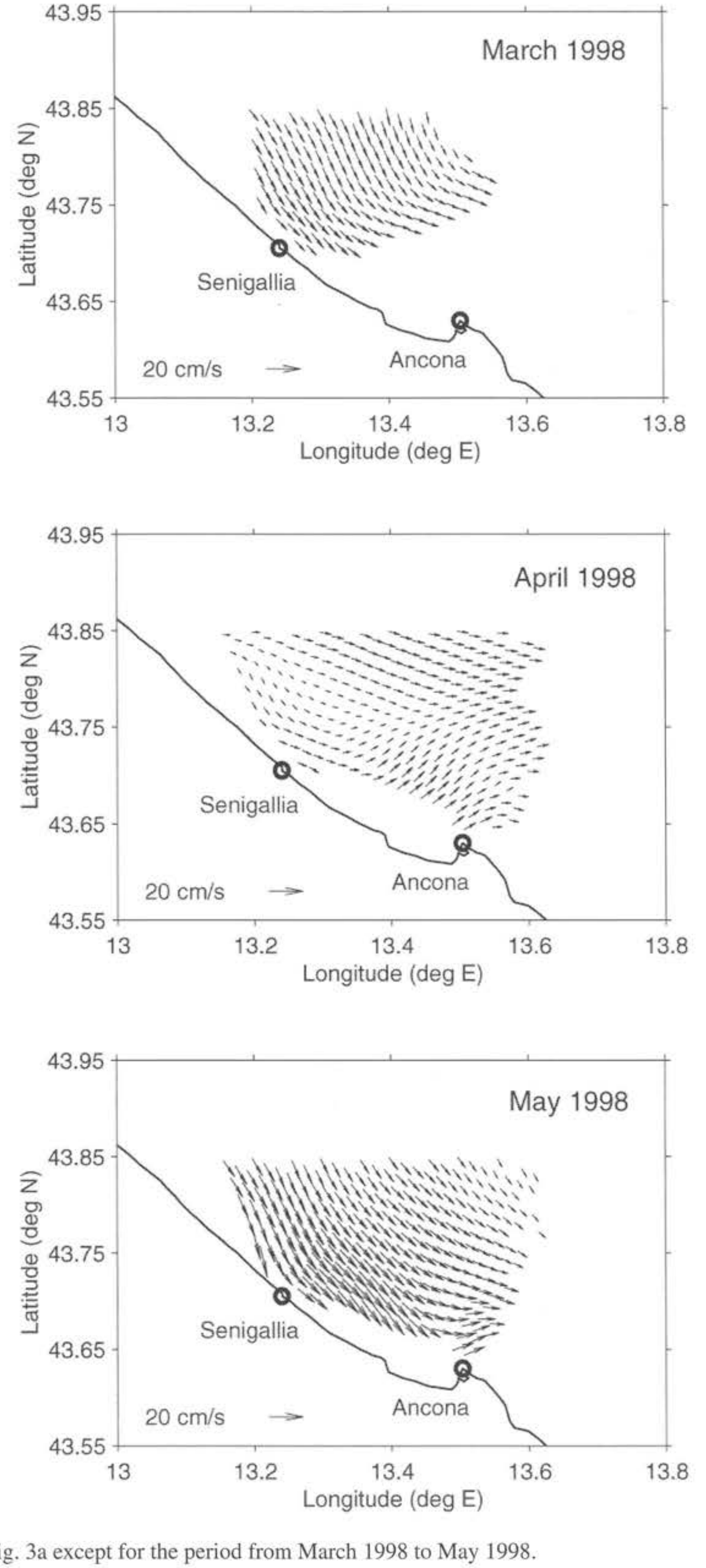

Fig. 3c - Same as Fig. 3a except for the period from March 1998 to May 1998.

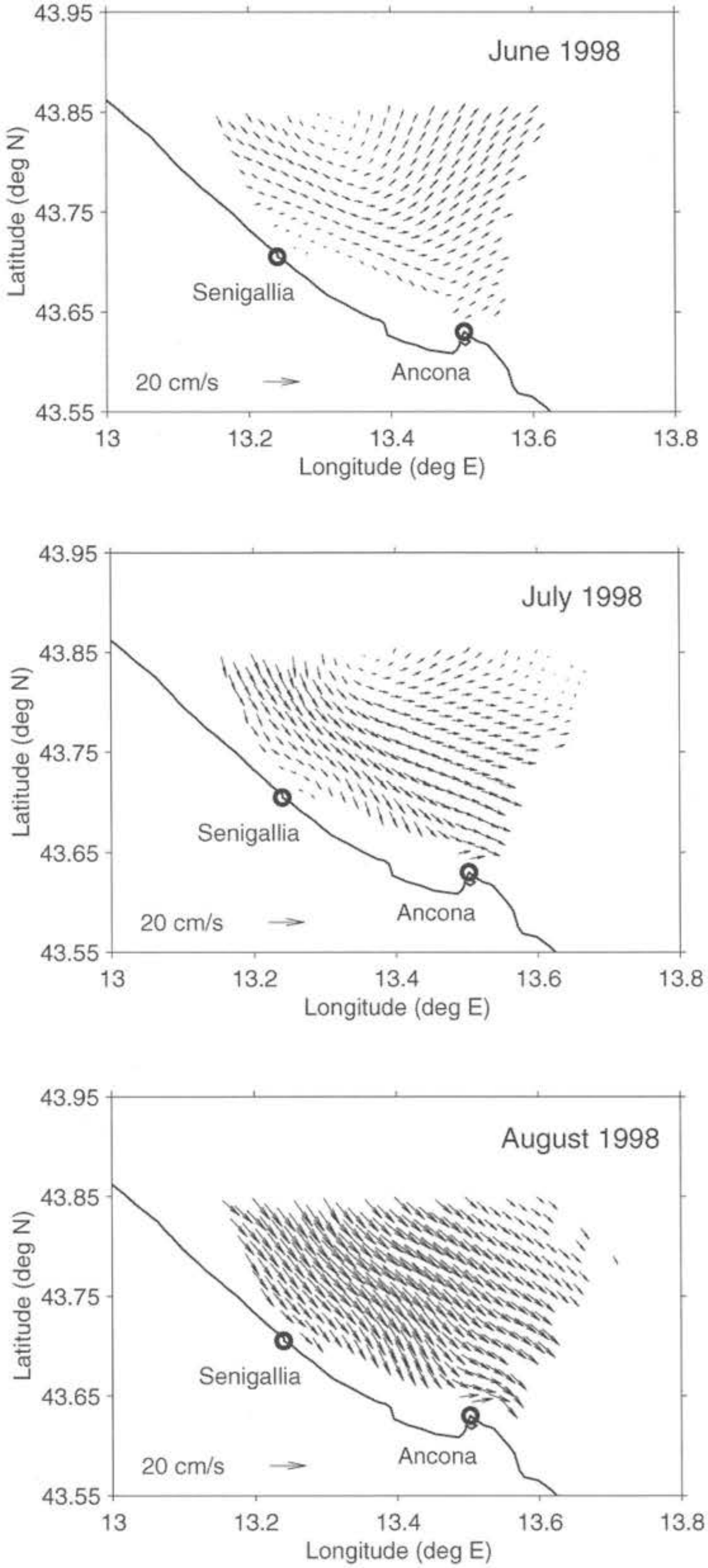

Fig. 3d - Same as Fig. 3a except for the period from June 1998 to August 1998.

shear is evident. The flow is maximum (about 15 cm/s) in a vein 10 km distant from the shore. Close to the coast, and further offshore, the flow is weaker. The mean flow for October 1997 (Fig. 3a) remains south-eastward, but the current shear is weaker than in September. In November 1997 (Fig. 3a) the flow in the coastal zone increases to about 20 cm/s, while the offshore flow decreases (5 cm/s), creating thus a strong current shear. In December 1997 (Fig. 3b) further strengthening of the strong south-eastern coastal current is evident. Maximum values reach about 35 cm/s. Such a strong flow remains confined to a relatively narrow (10 km wide) coastal zone. A similar pattern persists in January and February 1998 (Fig. 3b). In March 1998 (Fig. 3c), the current intensity significantly decreases with respect to the previous period: speed is reduced to about 10 cm/s, while direction remains the same. There is no evidence of the current shear zone which separates a narrow coastal stream from the open sea flow. This is also valid for April 1998 (Fig. 3c), except that the flow pattern is characterized by a prevalent eastward direction and is less organized than in March. In May 1998 (Fig. 3c), the usual flow pattern is established again, with a well developed south-eastward coastal current (up to 15 cm/s) and a weaker flow offshore. In June 1998 (Fig. 3d), the flow is again weak, hardly exceeding 5 cm/s, and it becomes north-eastward offshore Ancona. In July 1998 (Fig. 3d), the flow is still weak and with variable direction offshore, while in a coastal zone a somewhat stronger south-eastward flow is established again. In August 1998 (Fig. 3d), the core of the maximum flow, of about 15 cm/s, is detached from the coast by about 10 km.

On the basis of these monthly maps, it can be deduced that a south-eastward current, with a variable speed of 15-35 cm/s, occupies the 10-15 km wide coastal band, clearly evidencing the permanent presence of the WAC. Beyond this coastal band, the current is less organized, with lower speeds (below 10-15 cm/s) and variable directions. The WAC is stronger during most of autumn and winter (November-February) and weaker during spring and summer (March-August). The current shear is more evident in the November-February period when the WAC is well developed.

The winter and spring period of our time interval are marked by a considerable discharge of fresh water from the Po River (Fig. 4), whose mouth is located approximately 200 km north of the study area (Fig. 1). With the scope of relating the possible influence of the horizontal pressure gradient, induced by the fresh water input, on the observed current field structures, we examined maps of the horizontal salinity distribution in the surface layer, and in particular those obtained from oceanographic campaigns undertaken in the framework of the PRISMA 2 project (on 11-14 May and on 15-20 June 1998). The choice of the salinity field lies in the fact that a presence of fresh water almost entirely determines the density field, and hence the horizontal pressure gradient. Figure 5a shows the salinity of the top four meters of the surface layer in the Northern Adriatic Sea, in May 1998. Its horizontal distribution shows that the inflow of fresh water induces such a pressure gradient due to the salinity, which favours the formation of a current along the western coast. The fresh water confined along the coast causes a strong horizontal pressure gradient also in the Ancona area (Fig. 5b), in good agreement with the existence of an intense coastal current determined by the radar in May (Fig. 3c). During the month of June 1998 the structure of the current field is considerably different (Fig. 3d): a well organized coastal current is not evident, there is no current shear, and the maximum flow does

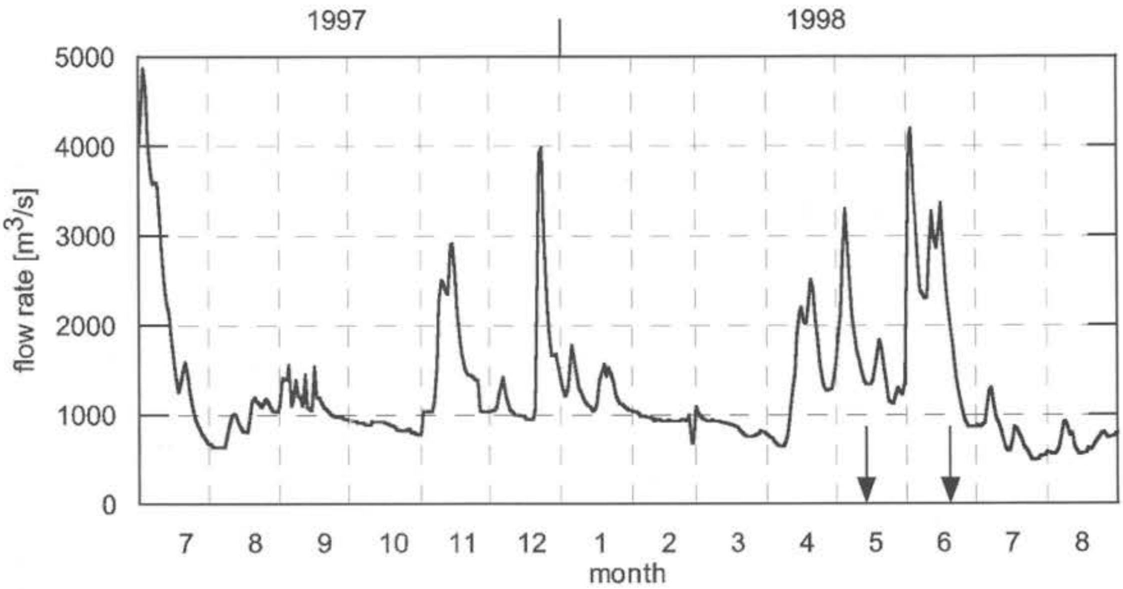

Fig. 4 - Daily fresh water discharge of the Po River in the period July 1997 - August 1998. Arrows indicate the period relevant to horizontal distribution of salinity in Figs. 5 and 6.

not exceed 10 cm/s, in spite of the fresh water discharge from the Po River being stronger than in May (Fig. 4), especially in the first few days of June. The hydrographic conditions, to the north, show that the fresh water is spread over the surface layer of the whole northern basin (Fig. 6a) and is trapped in a vast area of cyclonic circulation, instead of flowing southward along the western coast. Consequently, the haline gradient observed offshore Ancona (Fig. 6b) is much weaker with respect to the May one, resulting in the weaker density gradients and weaker currents.

3.2. Main statistical characteristics at a single location in the coastal zone

The basic results of the analysis of the hourly time series for a year-long period, are now discussed to give an idea about the long-term annual mean current within a coastal flow and its variability. These are shown for the location indicated in Fig. 2, where the quantity of missing data is relatively low. The time-series of hourly data was interpolated to fill the gaps with missing data, and then treated by the 49-element filter (Thompson, 1983), in order to extract the low-frequency signal. Table 1 shows the statistical elements for the three bands: for the original hourly data, and for the low (< 1 cpd) and high frequency (> 1 cpd) bands. The oscillating, high-frequency currents, have an average value equal to zero, and an amplitude of about 40 cm/s, while the low frequency ones constitute the net flow in the south-eastward direction. The values of a standard deviation of the low-frequency currents, having the same order of magnitude as the average values, indicate a remarkable variability, corroborating quantitatively, what has been already shown by the series of the monthly maps.

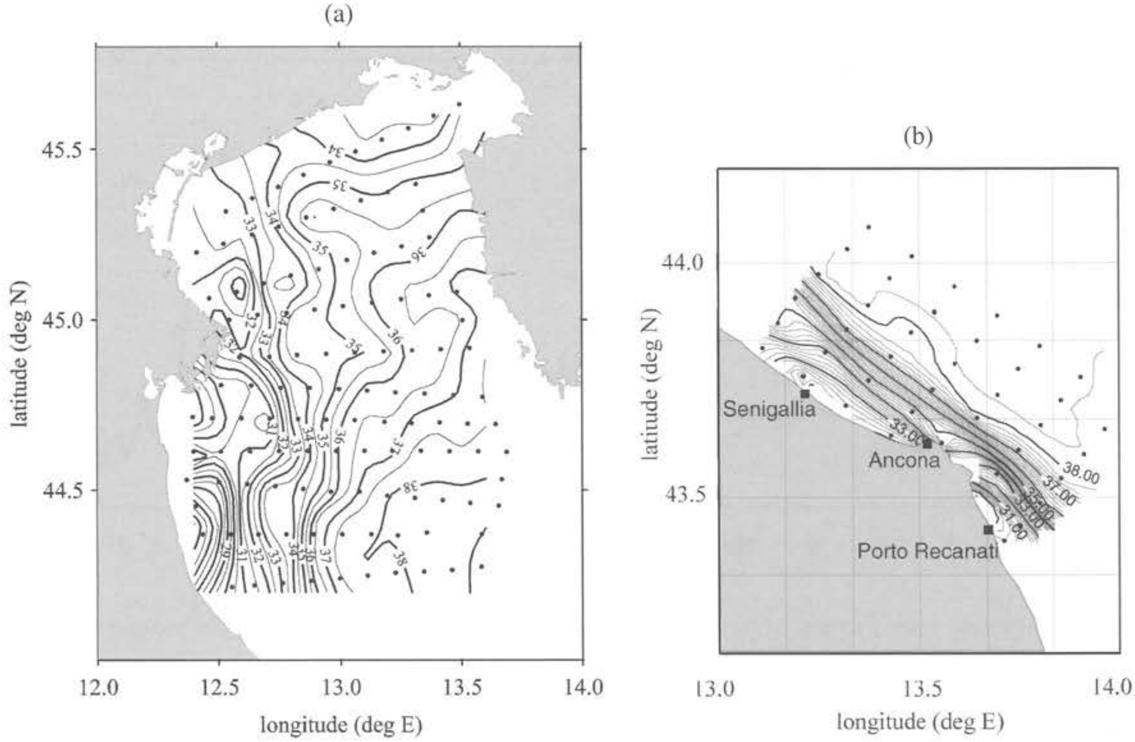

Fig. 5 - Horizontal distribution of salinity in the surface layer in May 1998: (a) in the northernmost basin of the Northern Adriatic, and (b) in the area offshore Ancona.

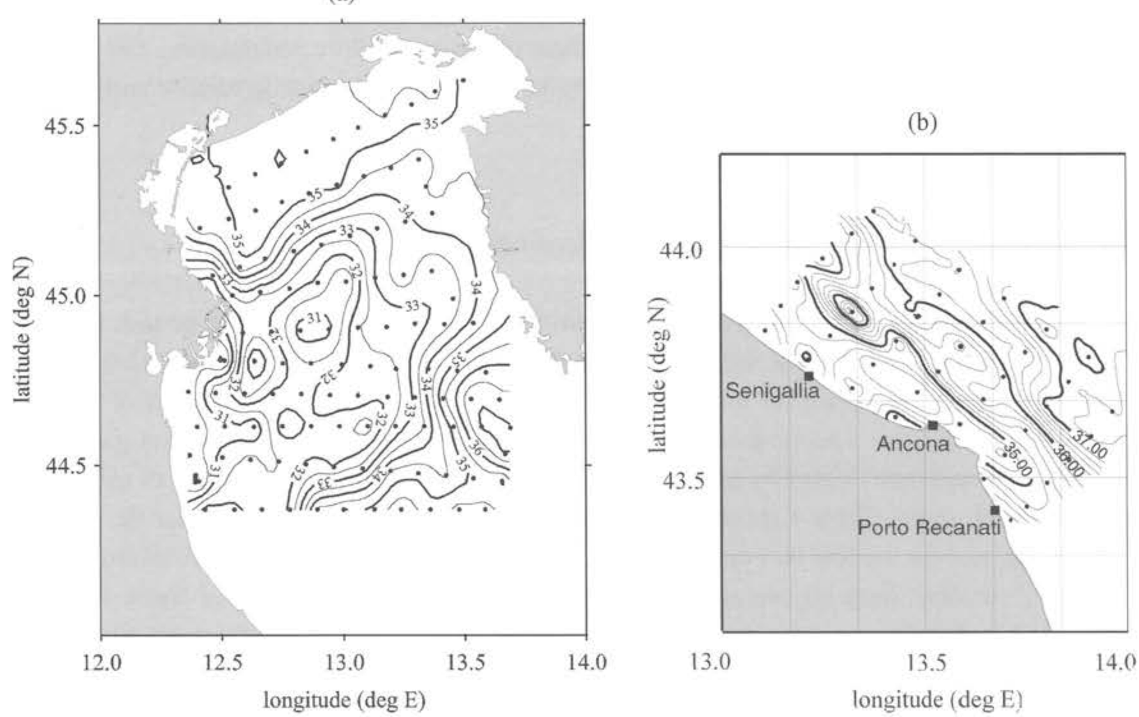

Fig. 6 - Same as Fig. 5 except for June 1998.

Table 1 - Main statistical values of the current (in cm/s) evaluated at 43° 45.36' N, 13° 21.98' E grid node (see Fig. 2 for its location) in the period from 1 September, 1997 to 31 August, 1998, for the northward (N) and eastward (E) components. LF – low-frequency currents, HF – high-frequency currents.

Data	comp	min	max	average	std	Avg. velocity and direction
Hourly	E	-37	74	10	13	12 125° (SE)
	N	-65	49	-7	14	
LH	E	-20	38	10	9	12 125° (SE)
	N	-31	18	-7	9	
HF	E	-39	40	0	9	0 -
	N	-45	41	0	10	

3.2. Some hints on the synoptic time-scale variability of currents

Although the aim of the present analysis is mainly focused on the presentation of monthly mean circulation patterns, we find it useful to show some specific situations, which depict the variability of the current field influenced by the winds at synoptic time-scales of the order of a week. We selected two situations in 1998; the first, for February 26, is characterized by a NE bora wind blowing over the Adriatic (Fig. 7a). The low-frequency current field at noon of the same day is depicted in Fig. 8a. A well coherent current is confined to the coastal strip, while in the open-sea area the flow is less intense, more variable, but prevalently of an on-shore

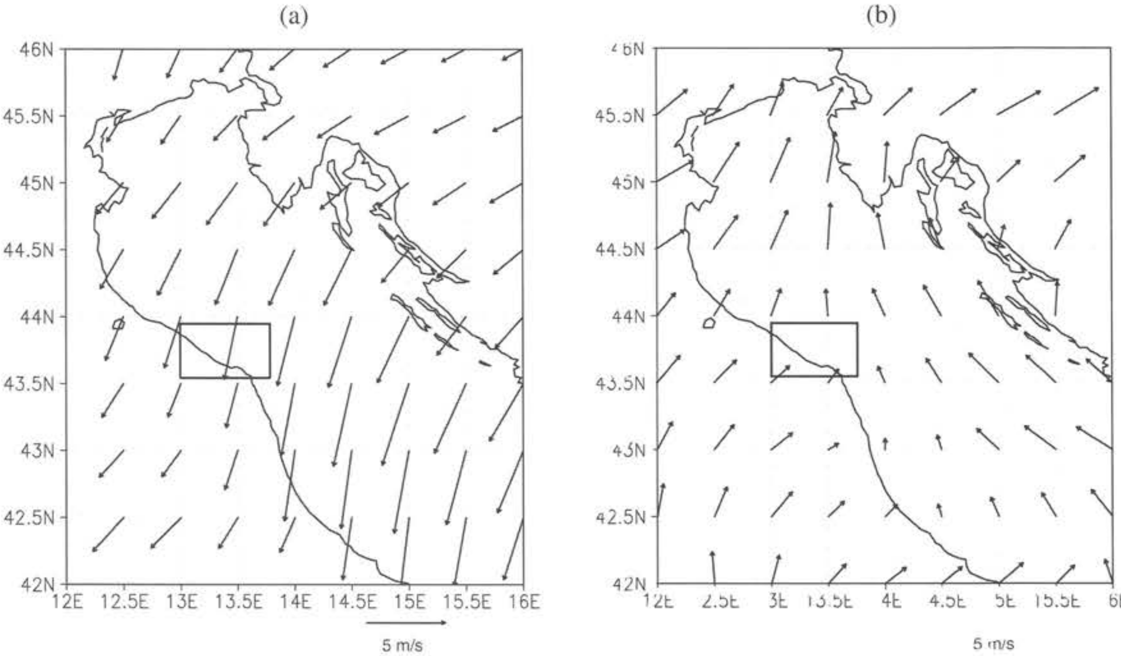

Fig. 7 - Mean daily surface wind over the northern and central Adriatic on a) 26 February, 1998, characterized by a NE bora wind, and b) 1 June, 1998, characterized by a SE sirocco wind. A rectangle delimits the study area in Fig. 8.

direction. The second situation is characterized by a SE sirocco wind episode on June 1 (Fig. 7b). The low-frequency current field at noon of the following day shows an inversion of the coastal current, and a current shear which demonstrates a reduction in speed from 15 cm/s near coast down to 10 cm/s beyond it (Fig. 8b). The frequency of such inversions may influence the mean current flow on a monthly scale as well. One might ask why we associate the current reversal with a 1-day lag with respect to the wind. We also examined the current maps on the same day, but the reversal was much more evident the day after. It seems that the response of the current field, i.e. the adjustment under the coupled influence of the buoyancy and wind forcing, might lag in the case of sirocco, while the response to the bora wind is more immediate.

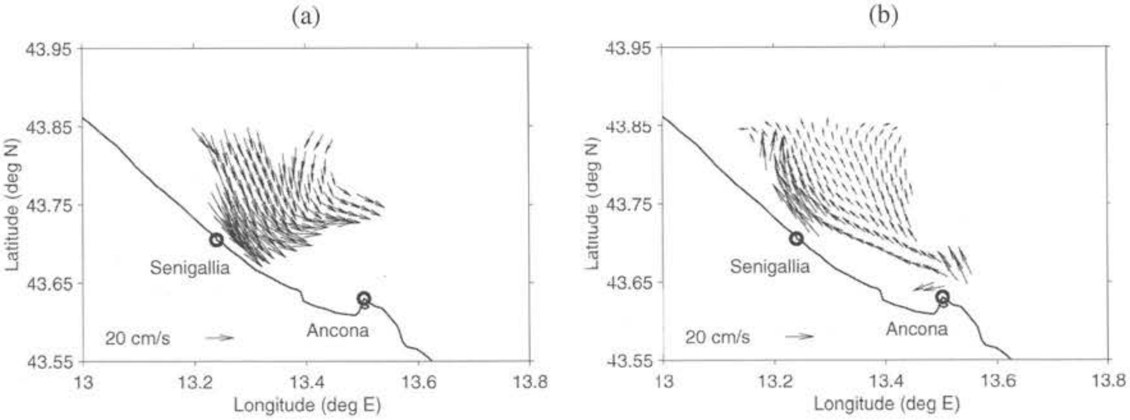

Fig. 8 - Low-frequency current flow sub-sampled at noon on a) 26 February, 1998, and b) 2 June, 1998.

4. Discussion and conclusions

The preliminary results obtained by analysing the measurements of the surface current near Ancona, reveal the presence of south-eastward currents (WAC) within a 10-15 km wide coastal band, with annual average speed of approximately 10 cm/s. Conversely, the currents beyond the coastal band have a lower intensity and variable directions. The inspection of the average monthly current field over the entire year, shows a remarkable seasonal variability. During the autumn and winter months (November, December, January and February) the current in the coastal strip is more intense and well defined with respect to the currents further away from the coast, and the average speeds reach 20-30 cm/s. In the same period, a current shear is evident as well. A similar conclusion is reached by Budillon et al. (2001a) considering the mean seasonal current field for the period December 1997 - February 1998, while for March-May 1998 and June-August 1998 they find the current much weaker. From our monthly maps, the weakest current is observed in April and June 1998.

Comparisons with the horizontal maps of surface salinity in the Northern Adriatic basin, close to the Po River delta, indicate a possible connection between the intensity of the monthly current field near Ancona and the spreading pattern of the fresh water from the Po River. When the fresh water is confined along the western coast of the Adriatic Sea, as it is during winter and spring, a strong horizontal density and pressure gradient arises, leading to an intense south-eastward current (WAC). In contrast, when the fresh water spreads radially from the Po River delta towards the eastern Adriatic coast, like in summer, which is also known from past observations (e.g., Franco and Michelato, 1992), the density gradient downstream, i.e. in the vicinity of Ancona, is diminished, and therefore the coastal current is weak and less organized. The observed dynamical features of the surface currents are in good agreement with the results reported by Artegiani et al. (1999). On the basis of a long-term monitoring of hydrographic properties along a transect perpendicular to the coast off-shore Senigallia, these authors demonstrated the seasonal variability influenced by the Po River discharge. They also showed that the width of the WAC is reduced in winter with respect to summer due to the rotation of the thermal gradient.

A significant portion of the time variability in the current field, is present at the synoptic scale. At this time-scale, the local wind may remarkably influence the coastal circulation in the Adriatic Sea, as shown, for example, by the studies of Franco and Michelato (1992), Orlić et al. (1994), Bergamasco and Gačić (1996), Artegiani et al. (1999), and Hopkins et al. (1999b). The long-term current measurements provided by the radars off Ancona offer additional examples. We presented just two different events in 1998. One event corresponds to a current reversal after a SE sirocco wind blew over the major portion of the Adriatic Sea. Such reversals were also observed in the past by Artegiani et al. (1983). Since the current response to the SE wind forcing along the western Adriatic coast is down-wind, i. e., north-westward, (Orlić et al., 1994), opposed to the prevalent south-eastward flow driven by the horizontal density gradient, the current reversal has some delay with respect to the SE wind. The other event corresponds to an episode of the NE bora wind, which coincides with the intensification of the WAC, responding promptly and directly to the wind (Orlić et al., 1994). Another analogue example was depicted by Budillon et al. (2001b) for an episode of bora wind in September 1997, which resulted in increased kinetic energy of the coastal flow. Artegiani et al. (1999) also reported the influence of the wind forcing on the WAC. The frequency and intensity of the wind forcing may influence the thermohaline structure and, consequently, affect average monthly currents.

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