ON THE ADCP-DERIVED RIM CURRENT STRUCTURE, CIW FORMATION AND THE ROLE OF MESOSCALE EDDIES ON THE CIW TRANSPORT IN THE BLACK SEA: RESULTS FROM APRIL 1993 OBSERVATIONS

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Abstract: The shipboard CTD and ADCP current measurements, performed during 2-15 April 1993, yield new information on the current and hydrographic structures of the continental shelf and slope of the western Black Sea. The region is shown to be populated by pronounced current meandering and eddy activity. The narrow Rim Current frontal zone of the width $\sim$ 50 km has a uniform upper layer speed in excess of 50 cm/s, with maximum measured currents of $\sim$ 100 cm/s over the steepest topographic slope. Following a relatively sharp decrease across the pycnocline, uniform currents of $\sim$ 20 cm/s are observed up to the depth of $\sim$ 300 dbar, being the approximate limit of the ADCP measurements. The cross-stream velocity structure exhibit a narrow core region ($\sim$ 10-20 km) confined over the topographic slope, flanked by a narrow zone of anticyclonic shear and a broader region of cyclonic shear on its coastal and offshore sides, respectively. The anticyclonic shear is stronger, comparable with the Coriolis parameter, and extends to greater depths. Except in the localized regions of the onshelf meanders of the Rim Current, the northwestern shelf circulation is decoupled from the influence of the basin-wide circulation,

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and characterized by much weaker currents of ~ 10 cm/s. The southward coastal flow associated with Danube and Dinepr Rivers is considerably weak at this time of the year and is confined to a narrow zone of ~ 20-30 km along the coast. The CTD data suggest temperature-induced overturning prior to the measurements, and subsequent formation of the Cold Intermediate Water (CIW) within the Northwestern Shelf (NWS) and center of the cyclonic gyre occupying the interior of the western basin. The newly formed shelf CIW is transported in part by the coastal current system, and in part, it flows downslope along the shelf in response to mesoscale structure of the local circulation system and intrude subsequently into the residual cold intermediate layer preserved in the frontal zone from the early winter season. The data indicate that the CIW mass, injected into the Rim Current zone quasi-horizontally from the shelf and periphery of the cyclonic gyre of the interior region, is carried by the Rim Current system around the basin.

1. Introduction

The western Black Sea (Fig. 1), covering the region to the west of ~ 35°E longitude, possesses a SW-NE elongated rectangular basin with depths exceeding 2000 m, and a fairly wide (equivalent to about 15% of the surface area of the sea), and shallow (average depth ~ 25 m) northwestern shelf region (henceforth, it is referred to as NWS). The shelf extends in the form of a gradually narrowing coastal strip towards south along the Romanian, Bulgarian and Turkish coast. The continental slope, defined by the region between 100 and 2000 m topography contours, runs almost parallel to the coast and attains approximately the same width as the shelf. Along the Turkish coast, the shelf terminates abruptly near the Sakarya Canyon region (~ 32 °E), east of which has very narrow shelf and very steep continental slope up to the Cape Sinop (~ 35 °E).

Coastal strip of the entire Black Sea is characterized by strong thermohaline gradients between fresher (less dense) shelf water and saltier (denser) interior water, forming a frontal boundary over the continental slope (see Fig. 5 in Oguz et al. 1994). This frontal boundary is associated with a band of permanent strong current system, known as the Rim Current, encircling the basin cyclonically. It involves meanders, filaments, eddies, and thereby gives rise to a complex pattern of interaction of shelf water with the cyclonic gyral circulation of the basin (Oguz et al., 1992, 1994, 1998). Different studies (e.g. Blatov et al., 1984; Eremeev et al., 1993; Oguz et al. 1994; Sur et al. 1994) have documented the extreme mesoscale variability of the circulation, including the seasonal and interannual fluctuations of the interior cyclonic gyre and the marginal anticyclonic features. Our present understanding of the horizontal and vertical structures of the Rim Current is based on the geostrophic calculations from the hydrographic data and qualitative interpretation of satellite imagery.

The NWS and the near-surface water on top of thermohaline domes of cyclonic gyres within the basin's interior are known as the sites of dense water formation in winter (Filippov, 1968; Tolmazin, 1985; Ovchinnikov and Popov, 1987). These regions are reported to exhibit vertically homogeneous conditions in response to strong atmospheric cooling, evaporation, and intensified wind mixing associated with a succession of strong, cold and dry continental wind events in the winter season. As the vernal warming stratifies the surface water, the convectively generated cold water is traced below the seasonal thermocline, and constitutes the so-called the Cold Intermediate Layer (CIL) of the upper layer thermohaline structure. During the same period, abundance of fresh water input strengthens the southward baroclinic flow along the western coast, spreads the stratified brakish water towards the outer shelf, and thus reinforces the frontal boundary between the interior and coastal waters by increasing the cross-shelf salinity contrast.

As a part of an international multi-disciplinary study organized in the western Black Sea, the Turkish ship R.V. Bilim acquired high resolution CTD data at a series of cross-shelf sections and monitored currents with the Acoustic Doppler Current Profiler (ADCP) measurements in the Turkish waters well as within the Ukranian and Romanian EEZ's of the NWS during 2-15 April 1993 (Fig. 1). In this paper, we provide a three dimensional quasi-synoptic view of the regional flow field representative of the late winter-early spring season. Our two primary objectives are (i) to explore, for the first time, the detailed horizontal and vertical structures of the topographically-controlled, strong jet-like Rim Current structure by means of the directly measured currents, and to relate them to the water property distributions and to estimates of the geostrophic flow, (ii) to document the late winter-early spring time evolution of the CIL with particular emphasis given to its formation and subsequent transformation characteristics as the cold water mass intrudes to the frontal zone from its source regions.

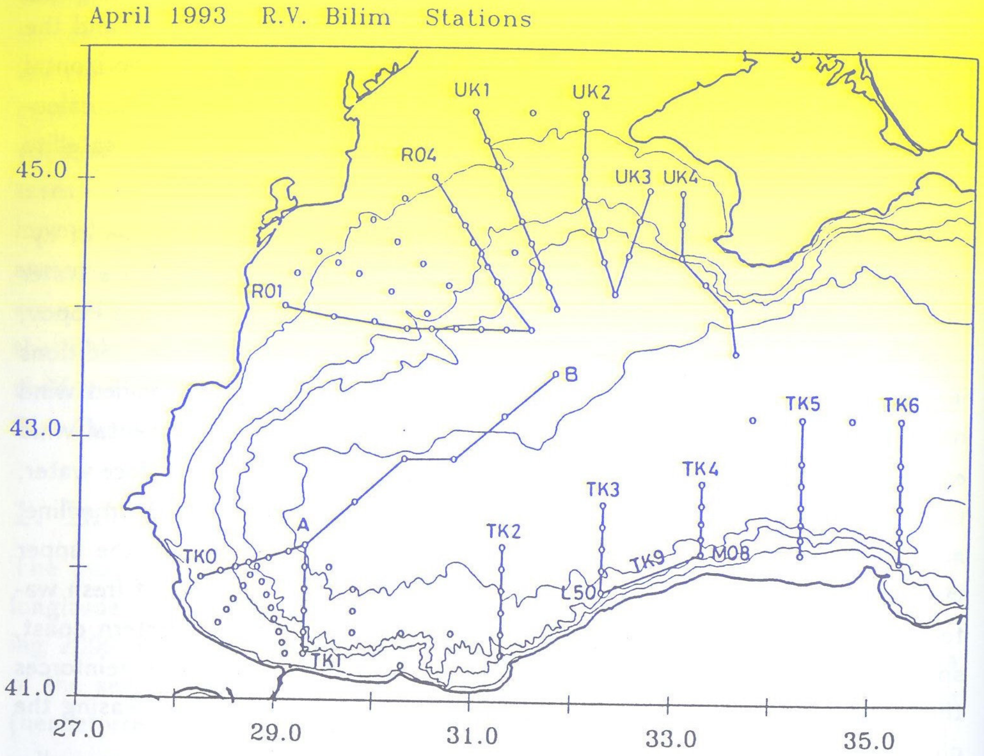

Figure 1. Station network and bathymetry of the Black Sea with the sections referred to in the text. The bathymetry includes only 50, 200, 1000 and 2000m contours

2. Data Collection

The measurements are performed on a sampling grid (see Fig. 1) consisting of a series of sections covering a major part of the northwestern continental shelf and slope with some limited extent to the basin's interior in most of the sections. Along the southern coast, sampling is taken along several meridional sections extending approximately 100 km offshore from the coast. The sampling period was virtually calm, characterized by light easterly winds. The low-pass filtered winds measured on board ship was not more than 5 m/sec during the period of observations.

The hydrographic observations were made with a SeaBird SBE-9 CTD system lowered at an approximate rate of 30-45 m/min to a maximum depth of 500 m or to a few meters above the bottom over the continental shelf and upper slope. The CTD data were then processed to calculate the potential temperature, salinity and density at 1 dbar bins. Vertical profiles of E-W and N-S current components were obtained continuously along the ship track using a vessel mounted 150 kHz Acoustic Doppler Current Profiler manufactured by RD Instruments. In deeper parts of the analysis region, currents were measured for a depth range varying generally between 150 and 250 m, and even for greater depths up to 400 m at some selected stations. The measurements were made using ensemble averaging period of 10 min, pulse length of 4 m, and vertical bin length of 4 m. Within the shelf where bottom tracking of the beam was possible, the ensemble averaging period and bin length were reduced to 5 min and 2 m, respectively. The current profiles are generally reliable from ~ 8 m below the surface to within 15-25 m above the bottom, depending on the depth of the water column. The relative velocities are converted to the absolute velocities using the Global Positioning System (GPS) navigation. Errors in the absolute current velocities are expected to be on the order of 5 cm/s.

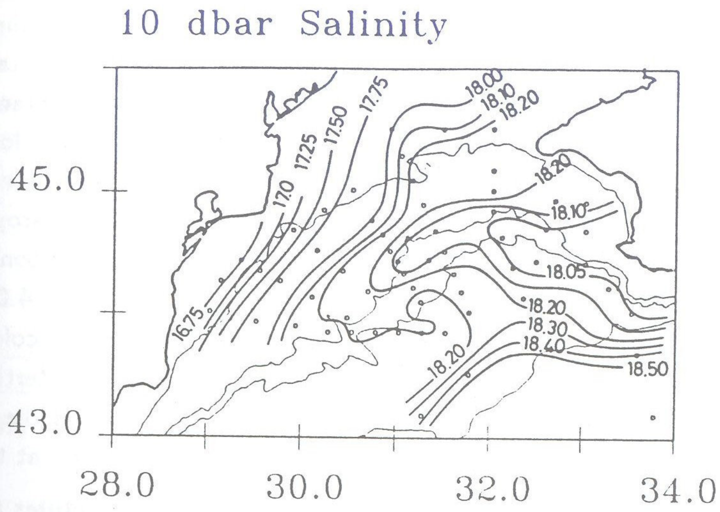

Figure 2a. 10 dbar horizontal salinity distribution.

3. NWS Circulation inferred from horizontal salinity fields

The 10 dbar salinity field for the NWS (Fig. 2a) reveals a band of low salinity (~ 17.0) coastal water derived from river discharges along the western coast. Its influence on the surface water of the inner shelf is evidently marked by horizontal salinity gradients of 1.0 psu/50 km. This salinity gradient is however much lower than those observed during the late spring and summer months corresponding with the times of increased run-off (Oguz et al. 1998). The outer shelf and upper continental slope regions are characterized by fairly uniform salinities of ~ 18.0-18.2. A distinct frontal boundary of ~ 20 km having a maximum salinity variation of 0.3 sepatates them from the basin's interior with S~ 18.5. The Rim Current associated with the frontal zone advects the lower salinity (~ 18.0-18.1) upstream water westward along the Crimean coast (see Fig. 3a). This water mass intrudes partially into the shelf and contributes to the well-known quasi-persistent anticyclonic Sevastopol Eddy situated adjacent to the west coast of the Crimean Peninsula (Oguz et al., 1993a).

At 40 dbar level, the surface intensified coastal fresh water front is no longer present, and the entire shelf is occupied by a NE-SW elongated cell with a uniform salinity of ~ 18.25 (Fig. 2b). As in the 10 dbar level, the salinity exhibits its highest variability, between 18.2 and 18.7, across the frontal zone of ~ 50 km over the topographic slope. The frontal zone undergoes intense cross-isobath meandering across the relatively wide topographic slope along ~ 32 °E. This causes intrusion of more saline water of the interior origin towards the shelf break region, and defines the outer boundary of the Sevastopol Eddy. The inner shelf region characterized by uniform salinities possesses considerable cross-shelf temperature gradient; the temperature varies between 4.0 and 6.0 °C over a distance of about 50 km. This zone constitutes the coldest part of the sea and, as we shall see below, is responsible for the wintertime local water mass formation process. The Sevastopol Eddy constitutes the warmest (T~ 6.5 °C) and least saline (S~ 18.1) water mass of the region at this level.

The temperature and salinity fields present more organized structures at deeper levels. Towards the base of the permanent pycnocline at ~ 150 dbar, the frontal intensities increase with depth, while the frontal shapes tend to be retained (see Fig. 2c for the fields at 120 dbar level). In addition to the Sevastopol Eddy and the intense inshore meandering of the temperature and salinity fronts over the

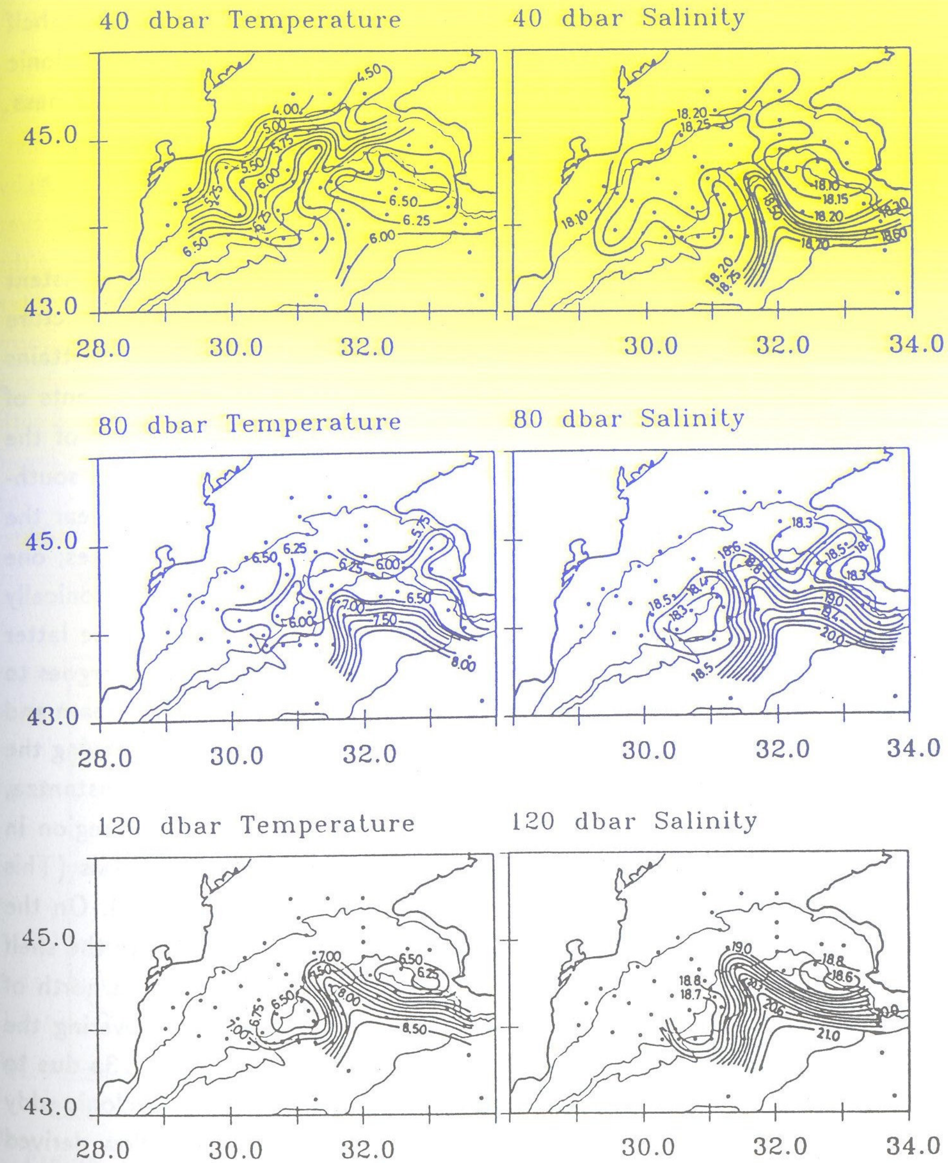

Figure 2. Horizontal distributions of temperature and salinity at (b) 40 dbar, (c) 80 dbar, (d) 120 dbar.

slope, a subsurface mesoscale eddy constitutes a major feature of the outer shelf and upper slope regions downstream of the meander. The eddy is anticyclonic and identified by colder (T~ 6.5 °C) and less saline (S~ 18.7 psu) water mass.

4. Horizontal current fields from ADCP measurements

The velocity distributions obtained from ADCP measurements are consistent with the horizontal temperature and salinity variations. Dominant structure of the upper layer velocity field is the strength of the Rim Current. It attains average speed of 50 cm/s in or near its core, contrary to weaker currents of ≤10 cm/s within the shelf (Fig. 3a). Near the northeastern corner of the analysis region, the Rim Current flowing over the topographic slope southwest of Crimea veers towards the NWS near 32 °E. Upon reaching near the shelf break during its onshelf excursion, it is separated into two branches; one branch forms the Sevastopol Anticyclonic Eddy, the other turns cyclonically in the offshore direction and forms the meander shown in Fig. 2. The latter branch is then steered topographically south-southwestwards and undergoes to a series of successive bifurcations. A part of it splits from the main stream and veers anticyclonically into the shelf to support the cyclonic eddy occupying the Romanian shelf. Another part undergoes anticyclonic rotation off Constantza, and forms apparently the second anticyclonic eddy of the analysis region in the NWS, named as the Constantza Eddy in the subsequent analysis (This is the same eddy observed in Fig. 2c, centered at 44°N and 31°E). On the other hand, a small part of the flow which penetrated northward into the shelf along the western Crimean coast appears to turn cyclonically to the north of the Sevastopol Eddy and supports eventually the cyclonic eddy covering the Romanian shelf waters. Although it is not particularly clear in Fig. 3a due to the measurement limitations in the Romanian coastal waters, the cyclonic eddy is expected to be supported at near-surface levels by the coastal flow derived from river discharges. An indication of this coastal current system is given earlier in Fig. 2a.

Distribution of horizontal current vectors along the southern coast between 28°E and 35°E reveal much stronger flow structure with considerable cross-stream variability (Fig. 3b). The typical surface current speed is ~ 80 cm/s within the core of the jet, exceeding at times 100 cm/s. In the region to the

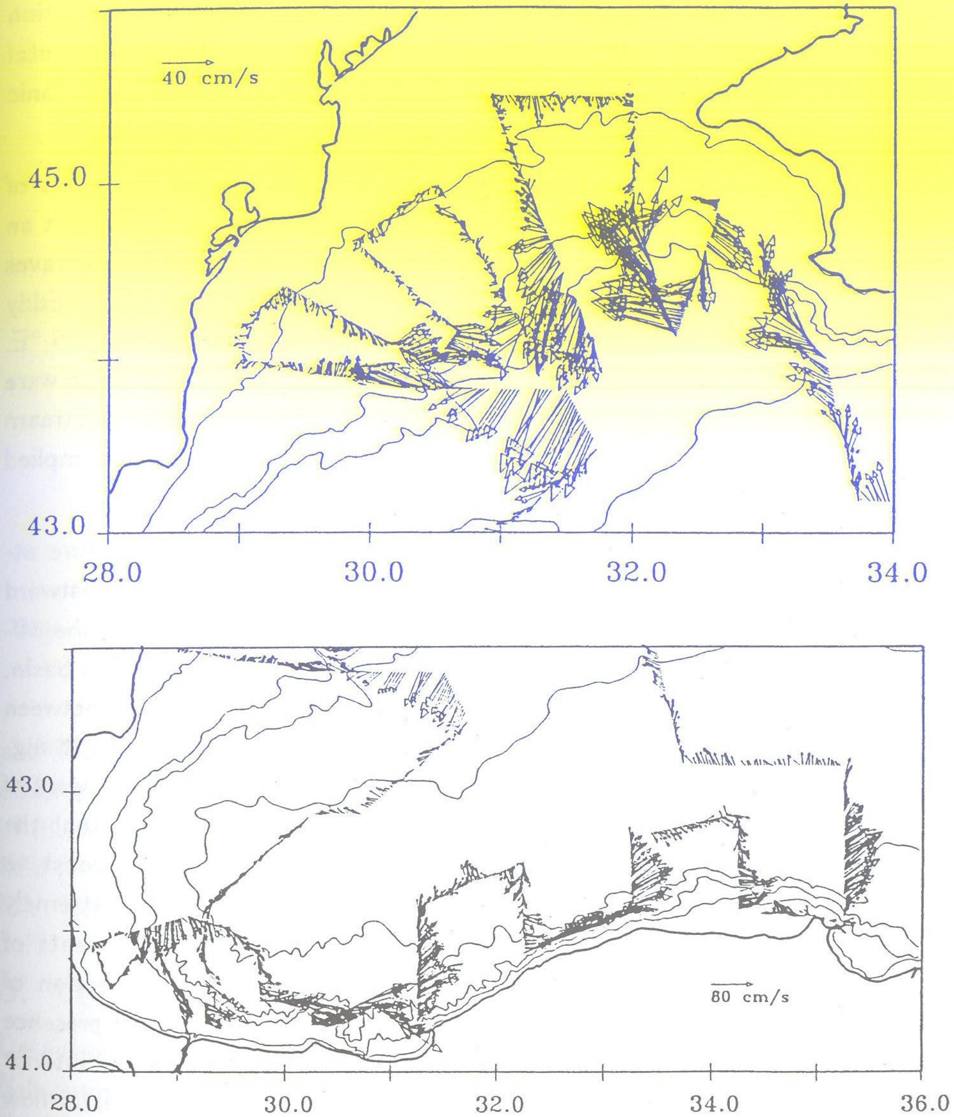

Figure 3. Horizontal distributions of ADCP vectors at 20 dbar level (a) for the northwestern shelf and slope region, (b) along the Turkish coast.

west of the Bosphorus exit, the main current proceeds in the southeast direction by following generally local isobaths within a narrow belt of the continental margin topography. Within the narrow shelf zone, an elongated anticyclonic eddy (named as the Bosphorus Eddy in Oguz et al., 1993) is present.

To the east of the Bosphorus at ~ 29 °E, the flow is subject to a series of meanders along the coast. It attains an almost sinusoidal wave form with an amplitude of ~ 25 km and a wavelength of ~ 150 km, comprising 4 waves within a distance of ~ 600 km. The well-known quasi-persistent Sakarya Eddy (Oguz et al., 1993) seems to be also observed in this survey near ~ 31.5 °E. Our interpretation of the regional ADCP current distribution is that we were able to capture only the offshore periphery of the eddy. The main jet stream seems to proceed eastward along the offshore periphery of the eddy as implied by the position of the jet core at the adjecent meridional section TK2.

Along the meridional section TK2, the onshore-offshore current structure attains an approximately parabolic form. The flow is directed east-northeastward parallel to the local isobaths near the coast, and veers cyclonically in the offshore direction, suggesting a flow bifurcation towards the interior of the basin. When the direction of currents along section AB and along the coast between the Bosphorus exit and the Sakarya Eddy are taken into consideration, it suggests presence of a cyclonic gyre occupying interior of the basin to the west of ~ 32 °E. The form of currents along sections TK2 and TK3 implies that the main part of the flow appears to meander and thus deflect towards the coast, to the east of section TK2. The Rim Current is then confined within the extremely narrow margin topography close to the coast. The most intense currents of ~ 100 cm/s are measured along the coastal section TK9. The direction of currents observed at two meridional sections on its both sides implies presence of a cyclonic eddy adjacent to this coastal jet. This eddy transports interior flow up to the coast, and therefore leads to intensification of the coastal flow between 32.5 and 33.5 °E longitudes.

Along sections TK4 and TK6, to the east of 33.5 °E, the boundary current system attains similar parabolic form as in section TK2. The directions of currents between these two sections indicate a sinusoidal meandering along the coast as well as presence of either a mesoscale cyclonic eddy or a cyclonic veering of the interior flow, being a part of a large scale circulation in the basin. The westerly currents observed along the coast between sections TK5

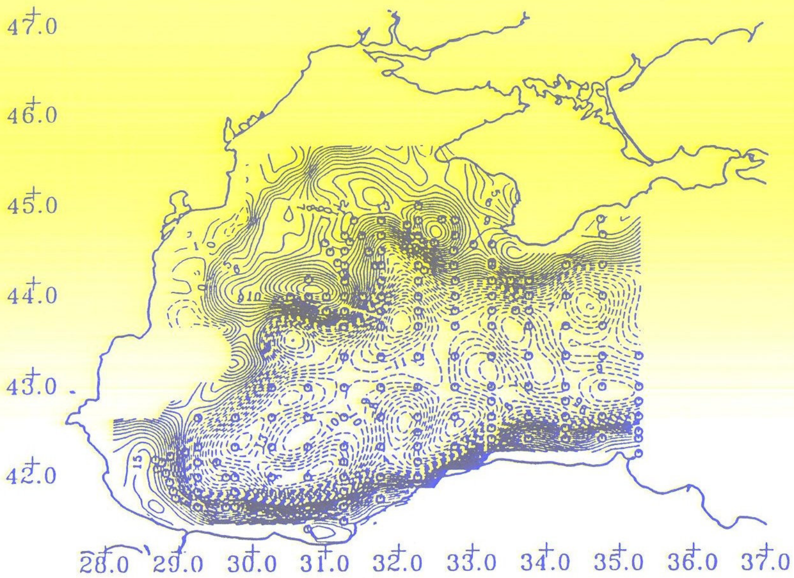

Figure 3c. 10 dbar dynamic height (cm) field for the western Black Sea.

and TK6 appear to be associated with the Sinop anticyclonic Eddy, frequently observed at this location (Oguz et al., 1992, 1993a). Most of these features of the western basin circulation are also presented in the 10 m dynamic height field (relative to 500 m) obtained from the pooled data sets of R.V Bilim and R.V. Kolesnikov (Fig. 3c).

5. Vertical structure of the Rim Current

Details of the vertical flow structure are given by cross-sections for the E-W and N-S current components. Fig. 4 shows clearly the northwestward deflection of the Rim Current, and its subsequent bifurcation along section UK2. The branch forming the periphery of the Sevastopol Anticyclonic Eddy is well marked at station U10, whereas the cyclonic southward turn takes place near station U9. The core of the Rim Current is located at stations U11 and U12, lying along the topographic slope. The currents in excess of 60 cm/s within the jet core extend nearly to the permanent pycnocline (~ 125 dbar) below which the currents, decreasing towards deeper levels, have a magnitude of about 25 cm/s at the

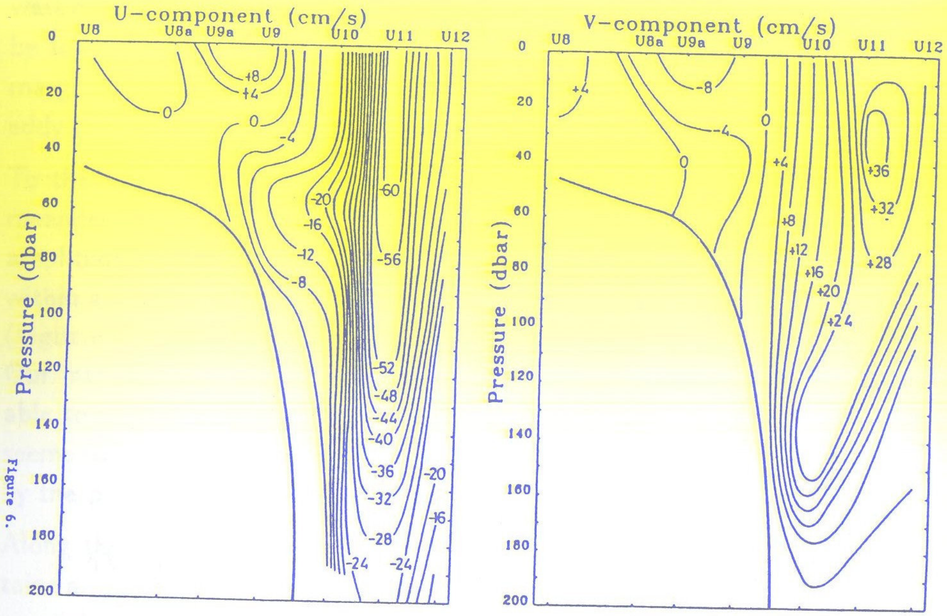

Figure 4. Vertical sections of the U (eastward) and V (northward) components of the ADCP currents (cm/s) for section UK2.

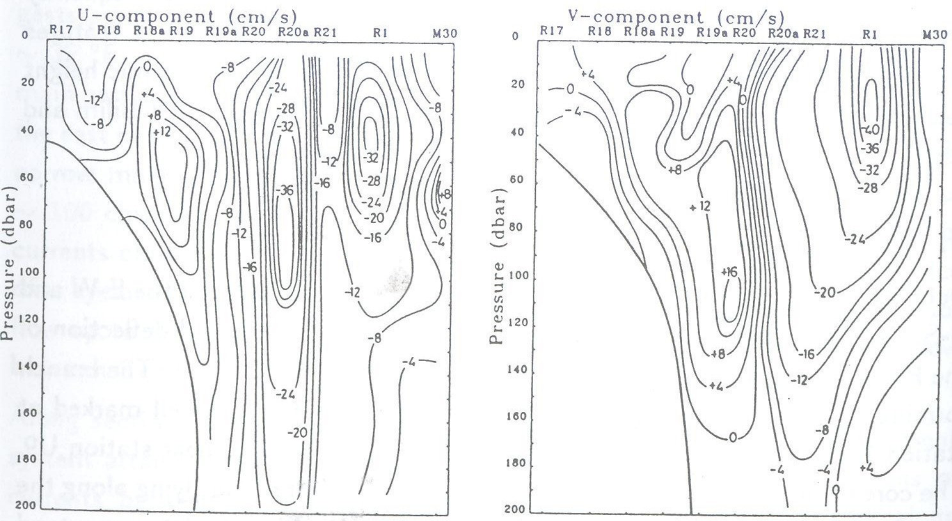

Figure 5. Vertical sections of the U (eastward) and V (northward) components of the ADCP currents (cm/s) for section RO4.

depth of 200 dbar. The current intensity changes significantly across the shelf break. The shelf is characterized by weak currents of the order of 5 cm/s in the upper levels, decreasing slightly towards the bottom.

Three distinct jet cores are identified on section RO4 extending off the Danube estuary (Fig. 5). The jet centered at station R1 represent the outer part of the Rim current, which follows the isobaths greater than $\sim$ 1000 dbar. The other core is centered further inward at station R20a. It represents the part of the Rim Current after it is deflected cyclonically towards south in the offshore direction. The third core is associated with onshelf bifurcation of the flow in the northwestward direction with a maximum speed of $\sim$ 15 cm/s at the subsurface levels. As it was mentioned earlier, this branch supports the cyclonic eddy residing within the middle shelf to the south of 45 °N (see Fig. 3a). The cyclonic eddy seems to be also supported by the southerly flowing coastal current due to the river discharge. Close to the bottom, the shelf currents are seen to be reversed to the offshelf direction.

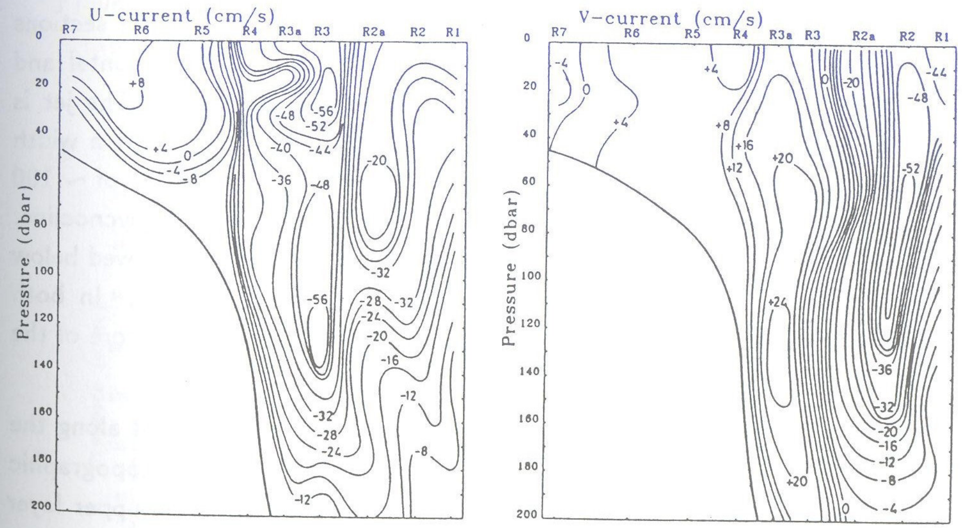

Figure 6. Vertical sections of the U (eastward) and V (northward) components of the ADCP currents (cm/s) for section RO1.

The vertical flow structure across the Constantza Eddy is shown in Fig. 6

for section RO1. A part of the Rim Current lying over the continental slope (i.e. between stations R4 and R1) are characterized by strong currents (~ 70 cm/s maximum) and considerable horizontal shear in accord with anticyclonic turning of the flow. The shelf has comparatively weaker northeasterly (i.e. offshelf) currents at the near-surface levels, representing the coastal extention of the anticyclonic circulation whose coastal periphery is clearly indicated in the temperature transect by the strong temperature contrast near station R6. The southerly flowing coastal current of ~ 5 cm/s is discernable within the upper 20 m of station R7. The current as well as temperature and salinity sections imply that the core of this coastal current system is, in fact, closer to the coast where no measurement is available. Furthermore, except this coastal water mass, the shelf water is almost vertically uniform in salinity (S~ 18.2), and temperature which varies laterally about 1.0 °C over a distance of 30 km near the coast. The near-bottom currents of ~ 10 cm/s are directed offshore, and as we shall se in the next section, lead to offshelf transport of cold intermediate waters to the Rim Current frontal zone.

Vertical sections of the E-W and N-S current components taken on sections TK1 and TK5 (Figs. 7 and 8) provide two examples for the horizontal and vertical extents of the strong jet flow along the southern coast. The jet is confined to upper continental slope close to the shelf-break and has a width of ~ 50 km. It has nearly uniform speed of ~ 70 cm/s to the depth of ~ 100 dbar, possessing no appreciable vertical shear above the permanent pycnocline. Sharp decrease in the intensity of flow across the pycnocline is followed below by approximately uniform current structure towards deeper levels. In both sections, the lower layer currents attains about 20 cm/s within the core of the jet.

Much stronger currents, both above and below the pycnocline exist along the coast-parallel section TK9 taken approximately along the steep topographic slope (Fig. 9). The speed of 70 to 100 cm/s is typical within the upper layer along the section. Below the pycnocline, the vertically uniform currents in the range of 20 to 40 cm/s are measured to the depth of ~ 300 dbar.

A notable feature of the current structure on section TK1 is presence of the northwesterly currents (i.e. normal to the jet stream) with a maximum speed of ~ 20 cm/s between the depths of 150 and 200 dbar at station L30L15 (see Figs. 7 and 10). As compared with that observed at the adjacent station situated

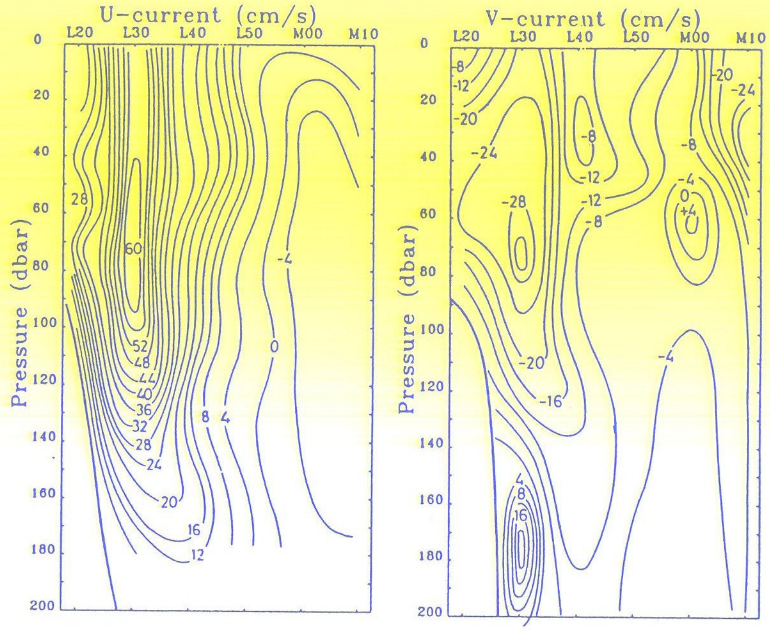

Figure 7. Vertical sections of the U (eastward) and V (northward) components of the ADCP currents (cm/s) for section TK1.

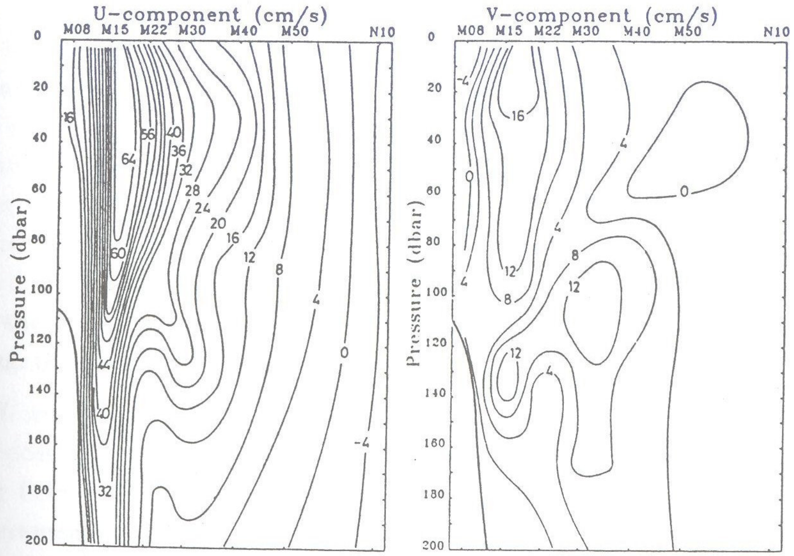

Figure 8. Vertical sections of the U (eastward) and V (northward) components of the ADCP currents (cm/s) for section TK5.

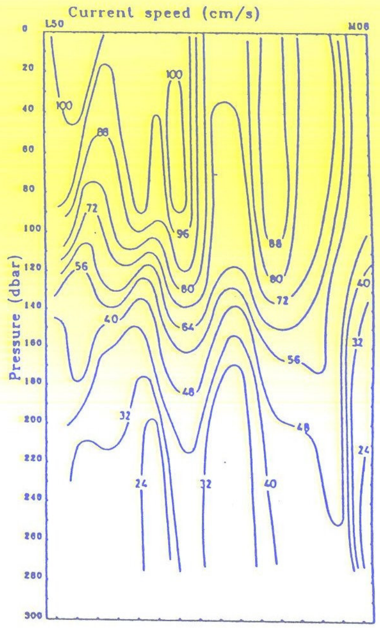

Figure 9. Vertical sections of the U (eastward) and V (northward) components of the ADCP currents (cm/s) for section TK9.

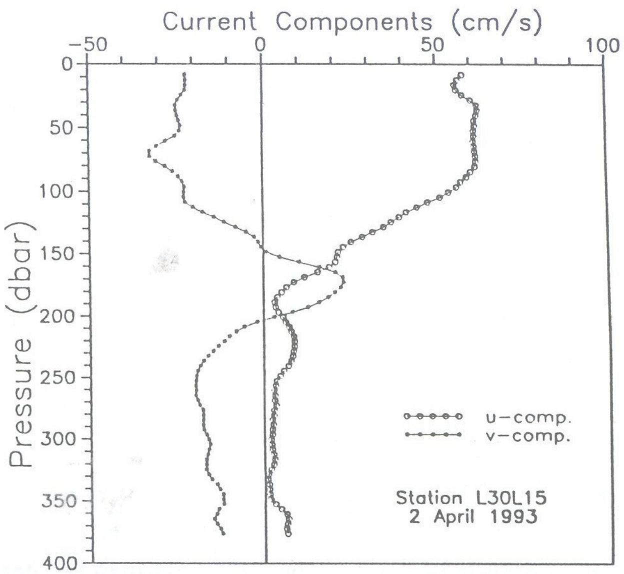

Figure 10. Vertical profiles of the U and V components of the ADCP current (cm/sec) at station L30L15 located along the slope section outside the Bosphorus exit section.

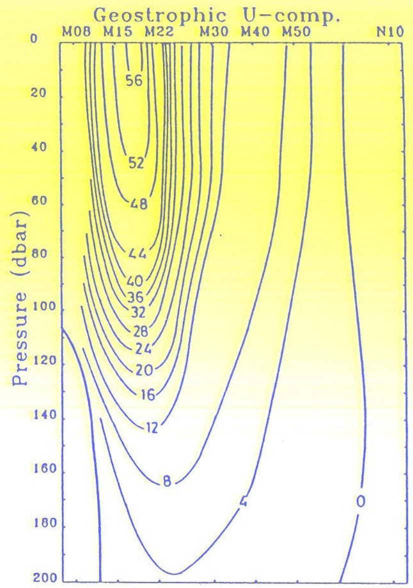

Figure 11. Zonal component of the geostrophic current (cm/sec) for section TK5.

~ 20 km north of it, this offshore flow is characterized by cooler (about 0.7 °C), less saline (about 1) and thus less dense (about 0.6 kg/m^3) anomalous water mass having a thickness of approximately 100 m. Both direction of the flow and T, S characteristics of this water mass observed at this station as well as the adjacent one (st. L30L45) situated 40 km eastward suggest that a parcel of shelf water moves isopycnally in the west-northwestward direction along the periphery of the cyclonic gyre. The strong subsurface density front along the periphery of the cyclone (see Fig. 13) seems to prevent its spreading towards the interior of the gyre.

Data from several hydrographic sections along the Turkish coast revealed some differences between the geostrophic currents (calculated using the dynamic height field relative to 300 dbar) and those obtained directly by the ADCP measurements. As illustrated for section TK5 in Fig. 11, the major difference occurs at the magnitudes of horizontal and vertical shears (compare Fig. 11 with Fig. 8). While the ADCP upper layer currents reveal more or less uniform structure, the geostrophic currents exhibit monotonic decrease from surface to the deeper levels. The horizontal jet structure obtained by the ADCP measurements turns out to be much sharper on both sides of the jet core.

6. CIW formation and transport

As shown in Fig. 12 for section UK1, vertically uniform salinity and temperature structures with S~ 18.1-18.2 and T~5 °C observed throughout the shelf provides an indication for the CIL formation within the NWS on account of surface cooling and subsequent overturning of the upper part of the water column prior to the measurements. The survey period coincides with initiation of the temperature stratification in the surface water as a response to vernal warming, and subsequently isolation of the convectively generated cold water patch within the near-bottom levels of the shelf.

The data also provide evidence of the CIL formation event within the cyclonic gyre of the western basin's interior. For example, the temperature transect for section TK1 (Fig. 13) reveals a cold water lens with a thickness of ~ 20m, and minimum temperature of ~5.5 °C on top of the thermocline dome. The uniformity of salinity and density of the water column (S~18.6, σ_t ~14.6 kg/m^3) at the same place suggests that the lens is a remnant of the 40m thick mixed layer formed earlier during the winter. We note that the salinity and density of the mixed layer are higher by about 0.4 and 0.4 kg/m^3 as compared to those in the NWS shelf. Similar CIL structure is consistently observed at other meridional sections along the Turkish coast.

The data further provide the role of mesoscale eddies on the basinwide transport of the CIL water by the Rim Current. The temperature transect acroos section UK4 (Fig. 14) exhibits the standard case of isopycnal sinking of cold water from the source regions. In this particular example, the relatively warmer water mass confined in the frontal zone is cooled throughly by intrusions from both sides up to the depth of ~120 dbar. The interior cold water mass is transported to the Rim Current frontal zone (shown in Fig. 14 by stations U18 and U19) by the northwesterly currents of the cyclonic circulation of the western gyre (see Fig. 3a). The cold water mass from the shelf is supplied by the southeasterly currents along the periphery of the Sevastopol Eddy located further westward. As a result of the continuous supply of cold water, a new temperature stratification is developed within the Rim Current zone, in which a cooler and deeper CIL is extended approximately to the 150 m depth.

An example of more limited supply of cold waters to the Rim Current zone is shown in Fig. 15 for section UK2. The data suggest southward advection of the cold and dense near-bottom water towards the shelf break region. The

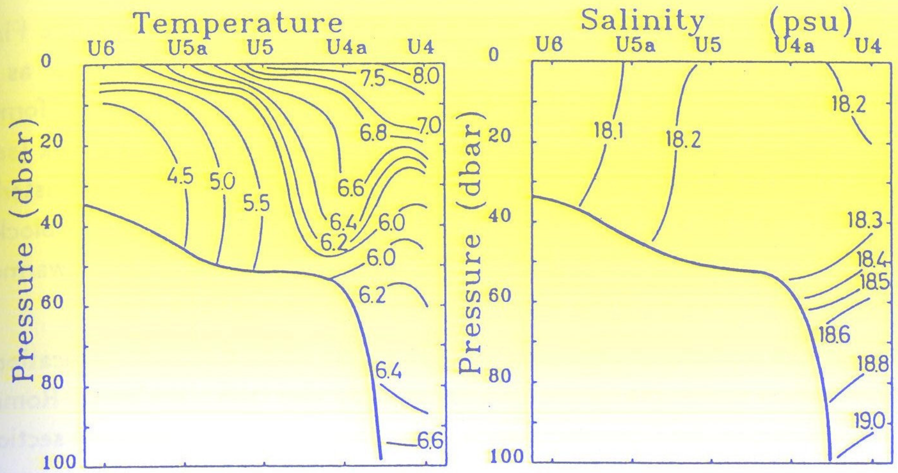

Figure 12. Temperature °C and salinity transects along the section UK1.

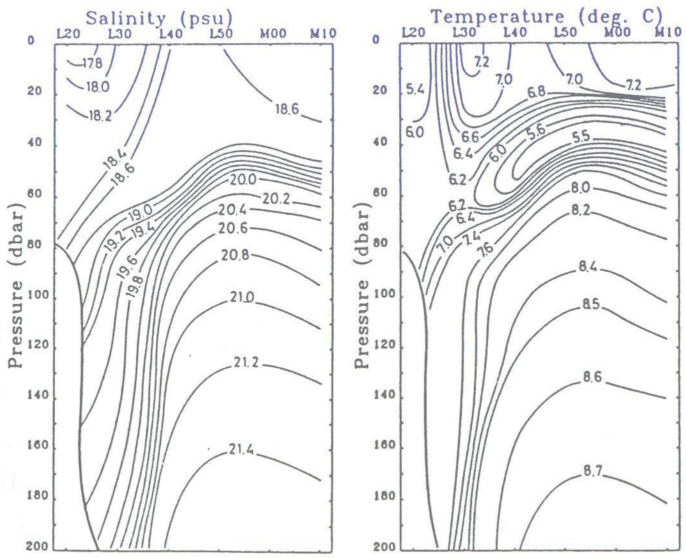

Figure 13. Temperature °C and salinity transects along the section TK1

offshelf transport is maintained by the weak southeasterly currents (see Fig. 4). A similar transport is also indicated in the figure from the interior as a result of northwestward deflection of the Rim Current to the shelf, which forms the peripheral flow of the Sevastopol eddy on its west-northwestern flank (see Fig. 3a). The offshelf transport is maintained by the weak southeasterly currents (see Fig. 4). On the other hand, this strong peripheral flow blocks the southeastward advection of shelf CIW and maintains the relatively warmer temperature structure of the eddy, as noted at station U11 in Fig. 15.

The features associated with spring-time evolution of the CIL and modifications on shelf-slope exchanges by the Sevastopol Eddy also take place on the Romanian shelf due to the Constantza eddy. Fig. 16 shows the temperature section RO4. The southeasterly offshelf directed currents (see Fig. 5) support quasi-horizontal transport of subsurface cold shelf waters with T~6.0 °C towards the northern flank of the Constantza anticyclonic Eddy. This cold water seems to penetrate partially interior of the eddy (characterized by stations R20, R20a in this figure) at 60-70 dbar levels. Similar quasi-horizontal transport mechanism from upstream due to southwesterly currents contributes cooling of the eddy at slightly deeper levels. A patch of relatively warmer subsurface water mass with T~6.4-6.6°C is however still preserved within the center of eddy centered at the depth of 110 dbar during the time of measurements.

As note from Fig. 6 that the Constantza anticyclonic Eddy is located along the wide topographic slope region of the northwestern Black Sea and is isolated from the shelf by strong northeasterly currents along its periphery. This stong shelf break flow blocks the offshelf transport of the cold shelf water as inferred by the temperature front to the left of station R5 in Fig. 17. On the other hand, the southwesterly currents along the offshore periphery of the eddy, supported by the Rim Current flow, leads to injection of relatively colder offshore waters into the eddy and provide cooling of the upper levels of the eddy (at 50-80 m depths), while the deeper levels of the eddy still maintains relatively warmer, downwelling structure.

7. Summary and Conclusions

The combined use of ship mounted Acoustic Doppler Current Profiler and high resolution CTD measurements carried out during 2-15 April 1993 provided several important features of the structure and motion of the shelf and slope

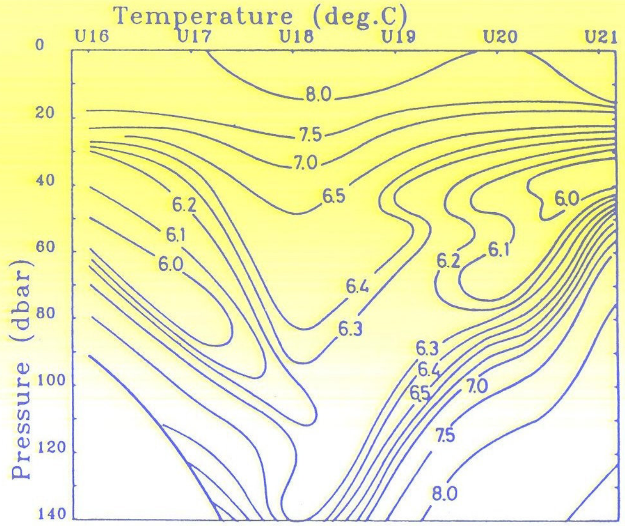

Figure 14. Temperature °C transect along section UK4.

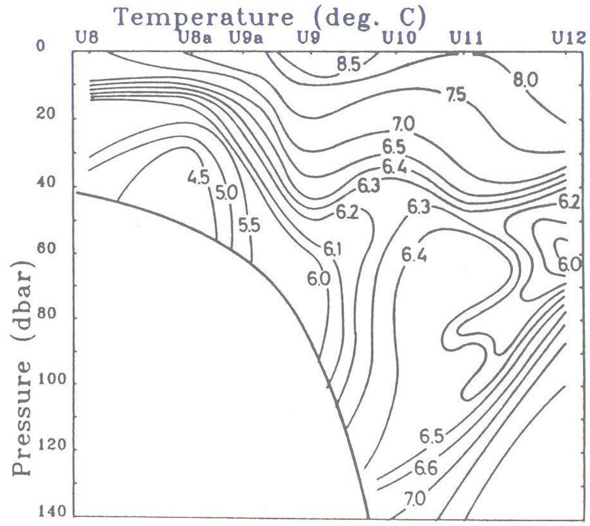

Figure 15. Temperature °C transect along section UK2.

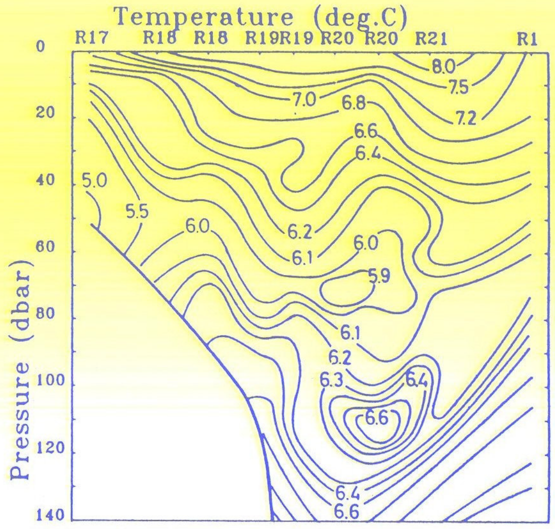

Figure 16. Temperature °C transect along section RO4.

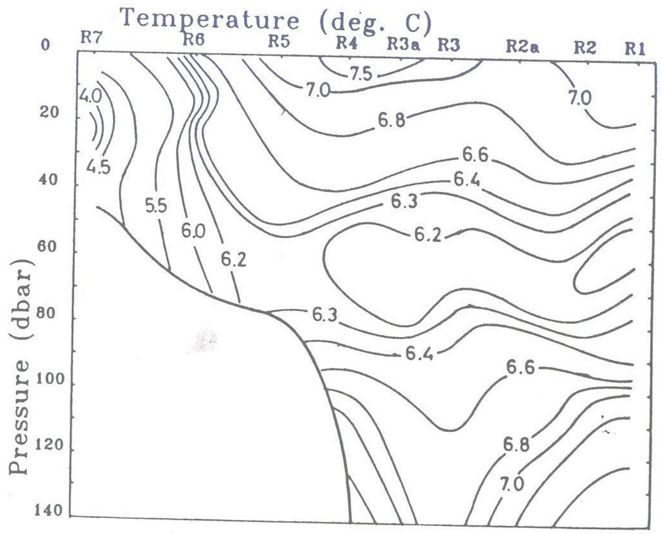

Figure 17. Temperature °C transect along section RO1.

regions of the western Black Sea, which have not been reported before and have greatly improved the regional flow description. The principal results are concerned with (i) the strength, and three dimensional structure of the Rim Current flowing cyclonically along the periphery of the basin, (ii) documentation of the cold water formation event took place within the shelf and on top of the thermohaline dome of the interior cyclonic circulation in winter, prior to the measurements, (iii) shelf-slope exchanges and transport of the newly formed CIL water by the Rim Current within the basin.

The Rim Current, a jet-like boundary flow system with a typical width of 50 km, possesses appreciable horizontal shear on the cross stream direction with peak currents generally confined within the upper continental slope. The coastal side of the jet is a region of strong anticyclonic shear, typically 30-50 cm/s per 10 km. On the offshore (cyclonic) side, the isotachs more spread out, and the lateral shear is not as large, but it can still attain a value of about 10-20 cm/s per 10 km. The most notable feature of the vertical structure is its strength and uniformity of currents within the upper layer. The core speed reaches 100 cm/s, but are normally in excess of about 50 cm/s up to the depth of 100 dbar. Following a strongly sheared zone across the permanent pycnocline, uniform currents are found to extend to $\sim$ 300 dbar. The lower layer currents, measured up to $\sim$ 40 cm/s at the 300 dbar level, are evidently much stronger than those reported by the existing data (e.g. Titov, 1980). The currents are almost unidirectional within the range of ADCP measurements.

Contrary to the jet-like flow structure over the upper continental slope, the currents in the northwestern shelf (NWS) are generally less than 10 cm/s. Relative weakness of the shelf currents is, however, consistent with the fact that the continental slope acts as an insulator on the shelf circulation from the influence of the deep ocean (e.g. Wang, 1982; Chapman and Brink, 1987). The data indicate that the NWS is not affected much by the onshore meanders of the Rim Current which only extends up to nearly the shelf break. Accordingly, apart from the contribution from river runoff, the NWS circulation is essentially wind-driven.

When they are compared with the baroclinic currents predicted from the hydrographic observations by assuming geostrophic dynamics, the ADCP currents are much stronger within the jet of the peripheral current system. The ADCP measurements provide much more detail in the velocity field, in terms of the sharpness, vertical extent and uniformity of the jet. It appears that the baroclinic currents underestimates the vertical jet structure considerably suggesting importance of the ageostrophic effects as well as the barotropic component of the current structure. Furthermore, the upper layer geostrophic currents computed from the present data are almost twice of those obtained from the summer surveys of September 1990, September 1991 and July 1992. This confirms presence of considerable seasonal variability in the strength of the circulation of the sea.

The mesoscale eddies and onshore-offshore meandering of the Rim Current provide a great deal of spatial variability in the basin. The most conspicious mesoscale features are the Sevastopol, Bosphorus, Sakarya and Sinop anticyclonic Eddies which are known to be the quasi-permanent elements of the mesoscale circulation of the sea (see Oguz et al., 1993a,b for further discussion on their persistency). The cyclonic eddy covering the Romanian shelf is, on the other hand, a new feature which, to our knowledge, was not reported before. The Constantza Eddy may, on the other hand, not be a separate entity, but possibly constitutes the northern part of the Kaliakra Eddy, being a recurrent feature centered along ~ 43.0-43.5 °N near the Bulgarian coast (Oguz et al., 1993b).

The present data suggest the CIL formation event took place within the NWS and over the dome of the cyclonic gyre of the western basin prior to the measurements. The cold pool in the shelf is found to be relatively colder and fresher (less dense) than that formed within the near-surface levels of the cyclonic gyre. The shelf CIW has typical salinities of 18.2 whereas the interior CIW is identified by an approximately 0.4 higher salinity structure. Both of these cold water sources, on the other hand, have similar temperatures of 5-6 °C. This implies that the CIL formed at different regions of the sea are distinguishable by their different T, S characteristics.

The part of the CIW formed on the northwestern shelf is shown to advect along the western coast of the basin by coastal/inner shelf current system. It is partly modified by the mesoscale variability associated with the Rim Current frontal zone, and may then be subject to cross-shelf transports. This is shown in the data as elongated parcels of the relatively colder water from near-bottom levels of the shelf to the shelf break-slope region. Similar intrusions also take place from the periphery of the cyclonic gyre towards the shelf break. Similar

processes were also suggested to contribute shelf break frontal exchanges in the Middle Atlantic Bight (Churchill et al.,1986,1989; Houghton et al.,1986).

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WESTERN BLACK SEA
SATELLITE IMAGERY

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Abstract. Observations b
were carried out in the
CoMSBlack and NATO T
Black Sea circulation. In t
measured currents and ge
describing the meso-scale
were also analyzed to com

1. Introduction

General structure of the
compilation of early and
meandering Rim Current
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regions and the deep-wa
Sevastopol eddy) are q
The other meso-scale fea
variable forcing (upwel
instabilities) [4].

The objective of this
pattern observed in the A

L.I. Ivanov and T. Oguz (eds.),