# Vertical structure of the current field in the Northern Black Sea

Black Sea circulation
Cyclonic current
Anticyclonic counter-current

Circulation de la Mer Noire
Courant cyclonique
Contre-courant anticyclonique

**Sergey N. BULGAKOV and Vladimir M. KUSHNIR**

Marine Hydrophysical Institute, National Academy of Sciences of Ukraine, 2, Kapitanskaya St., Sevastopol, 335000 Crimea.

Received 17/03/95, in revised form 11/05/95, accepted 23/05/95.

ABSTRACT

A possible three-layer vertical structure of the horizontal circulation in the Black Sea was inferred on the basis of theoretical analysis and laboratory tests (Bulgakov *et al.*, 1993 *a*, *b*). The existence of an unknown anticyclonic counter-current at the main pycnocline depths (100-400 m) under the surface cyclonic Main Black Sea Rim current was predicted. It may have a horizontal scale of the order of the Rossby deformation radius (10-20 miles), with maximum velocity of about 0.20-0.25 m/s.

To investigate the vertical structure of the current field, special field observations using an OLT acoustic profiler and mooring stations were carried out in autumn 1993 in the Northern Black Sea. The anticyclonic flow with the predicted characteristics was observed from direct current-meter measurements.

RÉSUMÉ

Structure verticale du champ de courant dans le nord de la Mer Noire.

Un modèle à trois couches de la circulation en Mer Noire a été élaboré à partir d'une analyse théorique et d'une expérimentation en laboratoire (Bulgakov *et al.*, 1993 *a*, *b*). Il révèle la présence d'un contre-courant anticyclonique dans la pycnocline principale (100-400 m) au-dessous du courant cyclonique de surface. Sa dimension horizontale est de l'ordre du rayon de déformation de Rossby (10 à 20 milles) avec des vitesses maximales voisines de 0,20 à 0,25 m/s.

Une campagne de mesures a été effectuée à l'automne 1993 dans le nord de la Mer Noire avec un courantomètre acoustique OLT et des courantomètres ancrés. Les résultats sont en bon accord avec les caractéristiques déterminées par le modèle.

*Oceanologica Acta*, 1996, **19**, 5, 513-522.

## INTRODUCTION

At present there is a common point of view concerning the patterns of the large-scale dynamics at the surface of the Black Sea, based on the results of experimental and theoretical studies: Blatov *et al.* (1984), Stanev (1988), Bulgakov and Korotaev (1989), Eremeev *et al.* (1992), Oguz *et al.* (1992) and others. Among the main elements of the surface circulation, the generally cyclonic system of water movement, the jet-stream character of the Main Black Sea Rim current (in the bottom slope regions at depths of 500-2000 m) and two macro-cyclonic gyres in the eastern and western parts of the basin – the so-called "Knipovich spectacles" – have been detailed. However, the question about the features of the vertical structure of the current field in the Black Sea remains open.

Originally, an idea on this topic arose in the early 1940s out of geostrophic velocity calculations based on the dynamic method (Neumann, 1942, 1943). The results of these calculations permitted the generalization of a two-layer system of water movement: of a cyclonic type in the upper layer; and with an opposite sign of rotation below 300 metres. Maximum velocities of anticyclonic flows were revealed at about 1000 m depth. Similar conclusions regarding the two-layer structure of the current field in the Black Sea were made somewhat later by Novitsky (1964) and Tolmazin and Rozengurt (1965).

In opposition to those conclusions, proof of uniform cyclonic circulation through all the depths of the Black Sea was presented in other studies (Vladimirtsev, 1964; Filippov, 1968).

Bogatko *et al.* (1979) carried out a generalization of the available current-meter observations from 175 mooring stations. The authors confirmed the generally cyclonic character of the surface circulation, but drew no conclusions about dynamic patterns in the lower layers of the basin because of the lack of sufficient data for the deep zone.

The numerous diagnostic velocity calculations carried out for the Black sea (see review Bulgakov *et al.*, 1992) have demonstrated mainly one-layer cyclonic water movement at all depths. But calculations of this kind were based on rare hydrological data with not less than 20-miles horizontal spacing and relating to the upper 300-metre layer.

Recent geostrophic velocity calculations based on more detailed hydrological data (20 × 20 miles grid) in relation to 1500 dbar surface (Oguz *et al.*, 1993) and current-meter measurements using an ADCP acoustic profilometer (Oguz *et al.*, 1994) have confirmed the conclusion about the generally cyclonic character of the Black Sea water circulation at the surface and in the intermediate layers.

At the same time, however, mooring current-meter measurements (Latun, 1989; Bulgakov and Golubev, 1990) and diagnostic velocity calculations (Truhchev *et al.*, 1993) provided new arguments to back the hypothesis of a two-layer system of currents in the Black Sea: a cyclonic movement in the upper 300 m layer and an anticyclonic movement in the lower layer.

Thus the problem of the vertical structure of the current field in the Black Sea remains debatable. Until quite recently, two different points of view have existed on this question, favouring a one- and two-layered system, respectively.

A third hypothesis, involving a three-layer vertical structure of the horizontal circulation in the Black Sea, was proposed by Bulgakov *et al.* (1993 *a*, *b*). Results of theoretical and laboratory modelling (Bulgakov *et al.*, 1996 *a*, *b*) indicated that more complicated dynamics may exist in the Black Sea, and more specifically, the existence of an anticyclonic counter-current under the Main Black Sea Rim current at the main pycnocline depths was predicted. The expected horizontal scale of this counter-current is of the order of the Rossby deformation radius (10-20 miles for the Black Sea), and its maximum velocity values are about 0.20-0.25 m/s.

The main purpose of this study is to clarify the isssue of the real vertical structure of the current field in the Black Sea.

## THEORETICAL BACKGROUND

Up to now, there have been several different points of view concerning the mechanisms of large-scale circulation in the Black Sea (wind forcing, buoyancy fluxes, etc.) One opinion is based on the haline hypothesis (Bulgakov and Korotaev, 1984) which attributes an important role to river runoff and salinity exchange through the Bosphorus Strait. To testify to this idea, a set of theoretical models of varying complexity (0, 1- and 2-dimensional) was constructed by Bulgakov and Korotaev (1989). The results of mutual-parameter models have demonstrated the possibility of reproducing any of the major elements of the Black Sea dynamics and water structure, such as the generally cyclonic nature of the surface circulation, the jet-stream character of the coastal current, the sharp pycnocline at the mid-depths, and others. Unfortunately, analysis of the vertical structure of the horizontal circulation was limited in these studies, because of some poorly understood model parameters.

Later, the problem of buoyancy-flux induced circulation and water structure patterns in the Black Sea was investigated by Stanev (1990) and Ozsoy *et al.* (1995). It appears that their numerical experiments were carried out for a relatively short period of time, insufficient to achieve the steady state of the sea basin. According to estimations by Boguslavsky and Kotovschikov (1984) and Maderich and Efroimson (1986), the process of formation of the modern state of the Black Sea from the initially rested and homogeneous water by lateral buoyancy fluxes takes some considerable time, of the order of a few thousand years. A decisive answer to this question probably requires further investigation and alternative methods of study.

The general mathematical statement of the problem of circulation and stratification formation by lateral buoyancy fluxes is based on a system involving equations of motion, continuity and density diffusion equations and hydrostatic and Boussinesq approximations, *viz.*

$$\frac{du}{dt} - fv = -\frac{1}{\rho}\frac{\partial p}{\partial x} + \nu_l \Delta_l u + \nu_z \frac{\partial^2 u}{\partial z^2} \tag{1}$$

$$\frac{dv}{dt} + fu = -\frac{1}{\rho}\frac{\partial p}{\partial y} + \nu_l \Delta_l v + \nu_z \frac{\partial^2 v}{\partial z^2} \tag{2}$$

$$\frac{\partial p}{\partial z} = \rho g \tag{3}$$

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \tag{4}$$

$$\frac{d\rho}{dt} = \kappa_l \Delta_l \rho + \kappa_z \frac{\partial^2 \rho}{\partial z^2} \tag{5}$$

with the following boundary and initial conditions

$$z = 0: \quad \frac{\partial u}{\partial z} = \frac{\partial v}{\partial z} = w = \frac{\partial \rho}{\partial z} = 0 \qquad (6)$$

$$z = H: \quad u = v = w = \frac{\partial \rho}{\partial z} = 0 \qquad (7)$$

$$x, y \leq l_1: \quad u = u_\iota, \quad v = v_\iota, \quad \kappa_\iota \frac{\partial \rho}{\partial n} = \Gamma \qquad (8)$$

$$x, y \leq l_2: \quad u = \frac{\partial \rho}{\partial n} = 0 \qquad (9)$$

$$t = 0: \quad u = v = 0, \quad \rho = \text{const} \qquad (10)$$

where $l_1$ and $l_2$ are open and closed parts of the coastline, $\vec{n}$ is a normal to the basin boundary, $\Gamma = u_n \delta\rho$ is a density flux, $u_n$ (z) is a normal component of the horizontal velocity (which is related to the Bosphorus Strait or river inflow), $\delta\rho$ is a horizontal density difference between the Marmara (or river) and Black Sea waters and the other symbols are conventional.

If, to introduce the characteristic scales of horizontal, vertical movements and pressure

$$U = \frac{g\delta\rho H}{\rho L f}, \quad W = \frac{g\delta\rho H^2}{\rho L^2 f}, \quad P = \frac{g\delta\rho H}{\rho}, \qquad (11)$$

to assume $(\nu_\iota/L^2) = (\nu_z/H^2)$ and $(\kappa_\iota/L^2) = (\kappa_z/H^2)$, then it is possible to rewrite the governing steady equations in dimensionless form

$$\mathrm{Ro}\left(u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z}\right) - v = -\frac{\partial \rho}{\partial x} + \mathrm{Ek}\,\Delta u \qquad (12)$$

$$\mathrm{Ro}\left(u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + w\frac{\partial v}{\partial z}\right) + u = -\frac{\partial \rho}{\partial y} + \mathrm{Ek}\,\Delta v \qquad (13)$$

$$\frac{\partial p}{\partial z} = \rho \qquad (14)$$

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \qquad (15)$$

$$\mathrm{Pr}\,\mathrm{Ro}\left(u\frac{\partial \rho}{\partial x} + v\frac{\partial \rho}{\partial y} + w\frac{\partial \rho}{\partial z}\right) = \mathrm{Ek}\,\Delta\rho \qquad (16)$$

with the three dimensionless parameters

$$\left.\begin{aligned} \mathrm{Ro} = \frac{U}{fL} = \frac{g\delta\rho H}{\rho f^2 L^2}, \quad \mathrm{Ek} = \frac{\nu_\iota}{fL^2} = \frac{\nu_z}{fH^2}, \\ \mathrm{Pr} = \frac{\nu_\iota}{\kappa_\iota} = \frac{\nu_z}{\kappa_z} \end{aligned}\right\} \qquad (17)$$

known as the Rossby, Ekman and Prandtl numbers.

The analysis of three parameter models for the linear (Ro >> Ek), quasi-linear (Ro ≅ Ek) and non-linear (Ro << Ek) cases in the two-dimensional channel will be presented by Bulgakov *et al.* (1996*a*). The main findings of this study are common to all the cases mentioned, namely: an intrusion of fresh water at the surface and salt water in the lower layer leads to the formation of the three-layer system of the horizontal circulation, with cyclonic flows at the surface and in the deep layers and an anticyclonic flow at the main pycnocline depths (Fig. 1 *a*). The anticipated horizontal scale of the anticyclonic counter-current under Black Sea conditions coincides with the Rossby deformation radius (≅ 25-30 km). The assumed intensity of this flow is about 0.20-0.25 m/s.

The corresponding cross-basin movement derived from the analysis of vertical stream function (Fig. 1 *b*) is weaker and consists of two cells of vertical circulation with opposite rotation in the boundary layer region between the upper and lower layers.

The density field has the particular widening structure of the pycnocline. The opposite slopes of the isopycnals (Fig. 1*c*) demonstrate the reversal of the sign of the horizontal circulation in the vertical plane. The position of the counter-current core corresponds closely to the location of the maximum vertical density differences.

To confirm these theoretical results, a series of laboratory experiments based on the similarity of dynamic processes with the Black Sea was carried out in the Geophysical Fluid Dynamics Laboratory at Woods Hole Oceanographic Institution (Bulgakov *et al.*, 1996*b*).

These experiments were carried out in a rotating basin with heat and salt fluxes as the driving forces. This study has demonstrated the formation of elements of the current and density fields which are analogous to the large-scale ones in the sea basin (Main Black Sea Rim current, "Knipovich spectacles", sharp pycnocline and others). Moreover, the finding as a result of the theoretical analysis, of the possible existence of an anticyclonic counter-current under the Main Black Sea Rim current at 100-400 metre depths, unknown from the previous observations, was confirmed.

Direct experimental testing of the theoretical and laboratory evidence, and a search for the predicted anticyclonic flow, were carried out by means of special current-meter observations from the research vessel "Trepang" in the northern Black Sea in autumn 1993. The instruments and methods of measurement are described below.

## INSTRUMENTS AND METHODS OF MEASUREMENT

A hydrophysical OLT probe-profiler (Kushnir, 1988, 1994; Drozdov *et al.*, 1991) was used to measure the current vectors and the vertical distribution of hydrological parameters. Characteristics of the OLT measuring channels are presented in the Table.

The total error of current measurements by OLT profiler has three components: the error of the acoustic current sensor (0.015-0.020 m/s when the average current velocity changes from 0.1 to 0.4 m/s); the error of probe estimation velocity movement with respect to the vessel (0.010-0.015 m/s); and the error of vessel drift velocity definition (0.03-0.04 m/s), or the "residual" current at depths greater than 500 metres, which has approximately the same value. As these errors are independent, with a probability of 0.95 the total measuring error does not exceed 0.035-0.050 m/s.

The technique of measuring by OLT profiler is similar to the traditional technique of observations with a conventional CTD probe, except for the necessity of determining the parameters of vessel drift during profiling. This is of no importance when measuring current profiles with respect to any layer where the flows are insignificant (it is an analog of "zero velocity" dynamical surface). In the Black Sea, this layer is situated at depths of not less 400-500 metres.

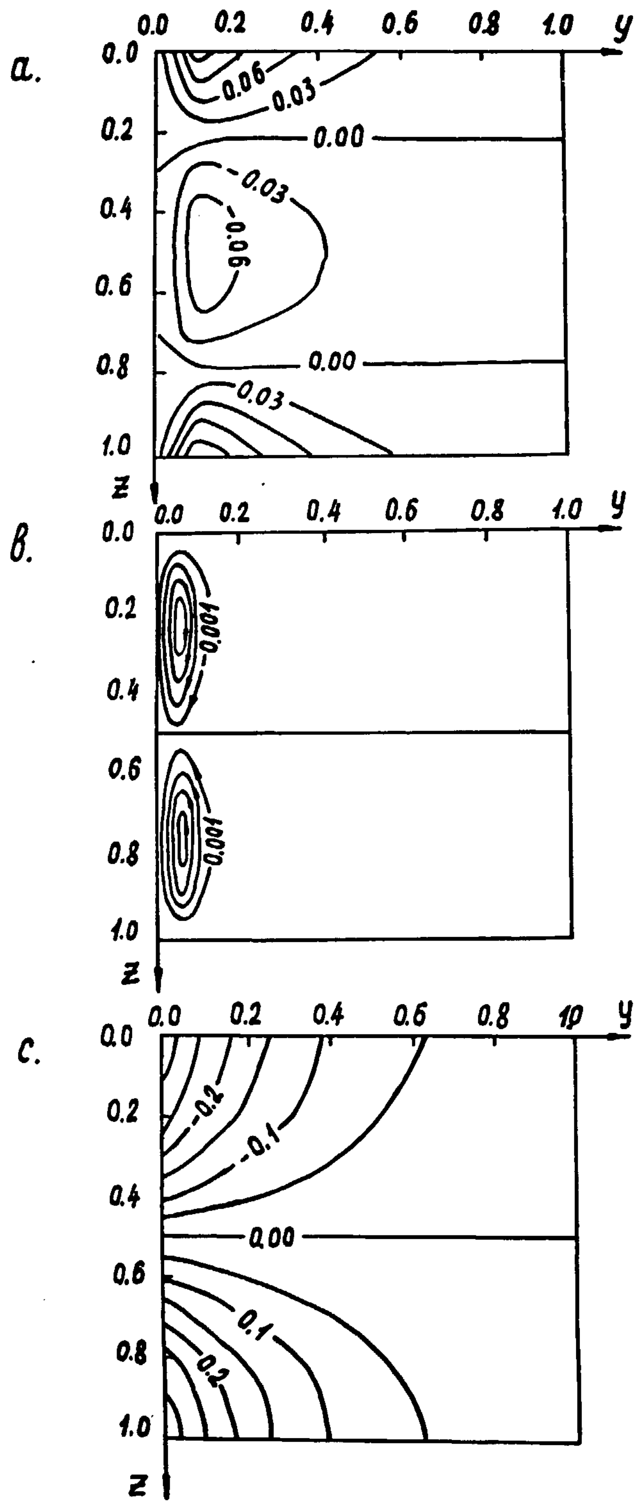


Figure 1

*Cross-sections of dimensionless functions:*
*a - along the channel velocity component u (y, z)*
*b - vertical stream function Ψ(y, z)*
*c - density ρ (y, z)*
*in two-dimensional channel for linear case (Ek = $10^{-3}$) (from Bulgakov* et al., *1996*a).

In the course of profiling, data from the OLT profiler are fed into a computer of the PC/AT type, where they are accumulated and partially processed, this being necessary for rapid control of the main measuring channels and velocity management of the probe submergence. For this purpose, the main measuring parameters, including zenithal angle (or angle of longitudinal probe axis from vertical direction), are displayed on the screen. If the zenithal angle is increased by more than 20-25 degrees, the speed of probe movement is slowed down. Usually the zenithal angle does not exceed 6-10 degrees. The effective suppression of noise factors is done by the median and more efficient regressive filtering of data from the measuring channels (Kushnir, 1988). The frequency and intensity of the probe fluctuations were evalued by a mutual statistical processing of information from the acoustic probe and the pendulum sensor of angular deviation. On the basis of this information, the filtering mechanism was set up. Averaging of the data at a particular depth layer with interpolation onto the regular grid and Batherworth recursive filter of the fifth order were used. Usually, during calm weather conditions or with a little vessel roll, the vertical allowance on depth was about one metre. With a stronger vessel roll, the allowance was about five metres (instrument permission on depth is 0.25 m).

In accordance with the CoMBlack-93 international programme observations in the northern and northwestern parts of the Black Sea, using the OLT profiler, were made from onboard the RV "*Trepang*" between 21 October and 7 November 1993. Station locations are presented in Figure 2. Measurements at each station were carried out up to 500-metre depth. To obtain a detailed spatial structure of the current field, the station grid was chosen as 5 × 11 miles.

Processing of current-meter observations at the first polygon (stations 1-57) made it possible to establish the position of the Main Black Sea Rim current. Two under-surface mooring stations with DISK current meters (Fomin *et al.*, 1989) were then installed on 27 and 28 October near OLT stations 16 and 18. The location of the mooring stations in Figure 2 is marked by the small flags.

DISK current meters at the northern buoy were set at 120, 220 and 320-metres depths. The horizons of observations at the southern buoy were 120, 155, 190, 290 and 340 metres. The time interval of the current vectors and temperature measurements was ten minutes. The total duration of observations at the two mooring stations was 96 days.

## RESULTS

General patterns of the current field from hydrological observations at the surface of the experimental area as a function of the dynamical heights in relation to 500 dbar are shown in Figure 3. The Main Black Sea Rim current of the cyclonic rotation is a principal element of the water circulation, with prevailing westward and southward flow direc-

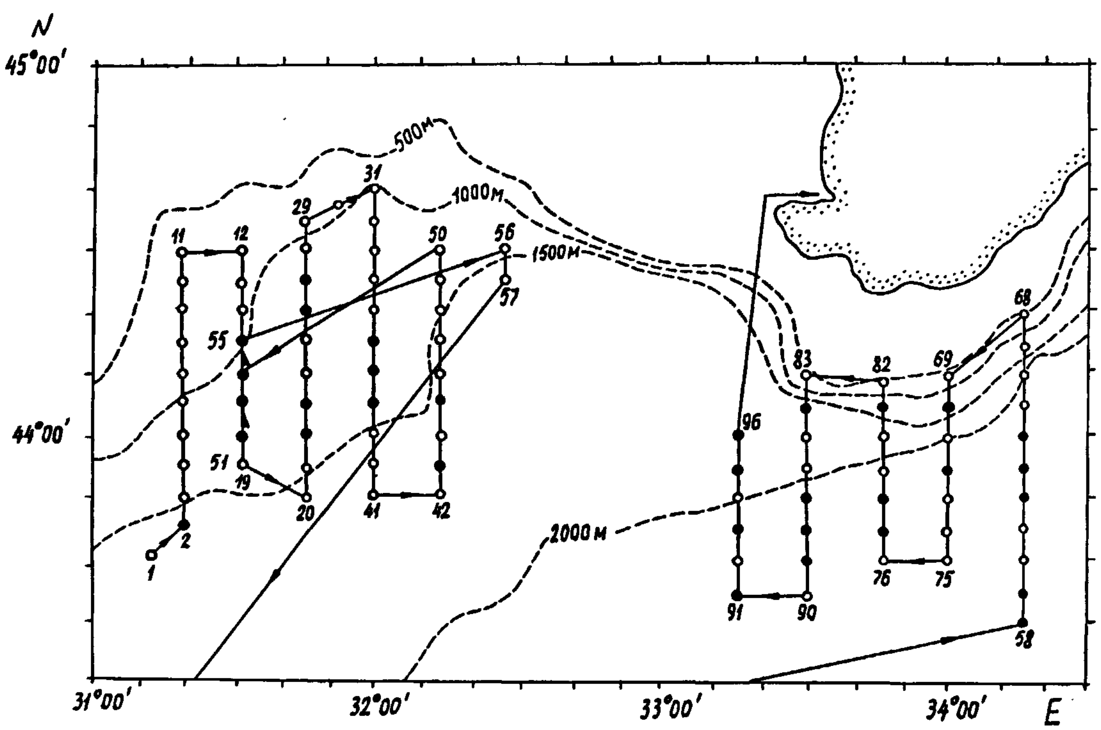

Figure 2

*Ship's track, locations of acoustic (O, ●) and mooring stations ( ).*

tions in different regions of the two polygons. The cyclonic and anticyclonic eddies also visible in Figure 3 are illustrative of the unstable regime of the general circulation and the intensive meandering of the Main Black Sea Rim current jet.

Current-meter measurements using the OLT profiler demonstrate the layered structure of the current field in the vertical plane. More particularly, under the Main Black Sea Rim current or in its immediate vicinity at the horizons of the main pycnocline layer (100-400 m), a flow counter to the generally eastward direction of the water movement was observed. This peculiarity of the vertical structure of the current field can be seen in Figure 4, where the vertical profiles of the longitudinal and latidudinal components of the current vectors at the stations 12-19 are presented.

The distribution of the zonal component of the velocity vectors from OLT observations at the section along the meridian 31° 30' E is shown in Figure 5. It can be seen that the eastward flow, with maximum velocity values of about 0.25 m/s, is located in the 100-400 m layer. The horizontal scale of the counter-current is of the order of 20 miles.

From the analysis of all the observations it was established that the counter-current may have a single as well as multiple core structures with a characteristic width of 10-20 miles. The example of the three-core structure of the counter-current on the 34° 15' E meridian is shown in Figure 6. The position of the counter-current at various stations of the two polygons is marked by black circles in Figure 2.

The density distribution of the sea waters in the vicinity of the anticyclonic counter-current is in accordance with the theoretical notions (Fig. 1 *c*). So, the meridian sections of the $\sigma_t$ field along 31° 30' E (Fig. 7) and 34° 15' E (Fig. 8) display the widening structure of the pycnocline and correlate with the current field peculiarities discussed above. They are reflected in the changing of the sign of the horizontal circulation on the vertical plane, as well as in the single and multiple core structure of the counter-current.

The current measurements at the two under-surface mooring stations as a whole correspond well to the data of vertical current profiling. The vertical distribution of current vectors, measured by the OLT profiler at stations 16 and 18 near the two mentioned under-surface mooring stations, is shown on Figure 9 for comparison with these independent measurements. It may be seen that under the surface southwestward current, a southeastward undercurrent exists at depths of 100-400 m, with maximum velocity values 0.20-0.25 m/s at the dephts of 150-250 m. A slowing of the current velocities to values of less than 0.1 m/s occurs at a depth of 300 m. At a depth of 400 m, velocity values do not exceed 0.03-0.04 m/s.

Southeastward currents of the same (0.20-0.25 m/s) intensity were registered in the main pycnocline layer at depths

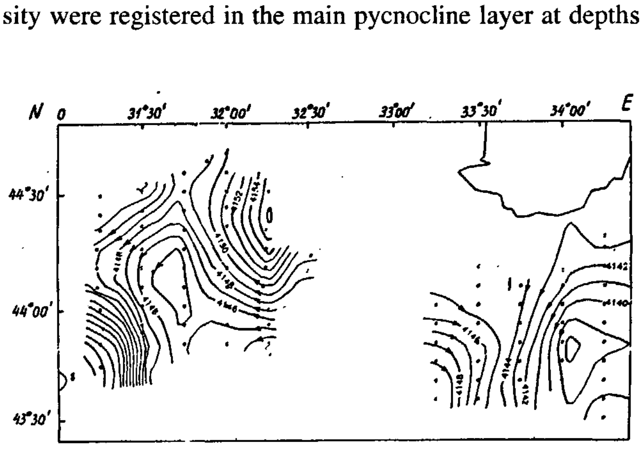

Figure 3

*Dynamic topography at the surface of the experimental areas in relation to 500 dbar.*

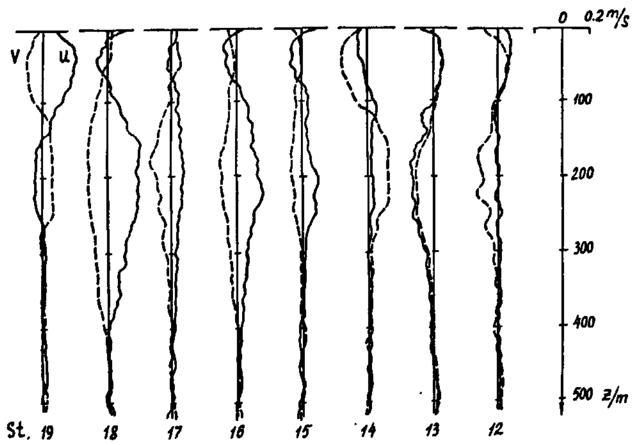


Figure 4

*Vertical structure of the horizontal components of velocity vectors u (z) and v (z) at acoustic stations along 31° 30' E.*

of 120-290 m at two under-surface mooring stations. A fragment of temporal variability of the currents, calculated with two-hour averaging from the southern buoy data during first ten days of observations, is shown in Figure 10. The above-mentioned undercurrent is also visible at depths of 120-290 m, and its value decreases sharply to values of 0.05-0.07 m/s at a depth of 290 m. At 340 m depth, the average value of the current velocity was equal to 0.02 m/s, with variations not exceeding 0.02-0.03 m/s.

The insignificant values of the current velocities at depths greater than 350 m from the mooring station data, and the absence of sufficient horizontal density gradients at a depth of 500 m from the CTD data have permitted use of this depth as a "zero" dynamical surface for the OLT current profile calculations.

The results of the OLT measurements have shown that the vertical current profiling data (Fig. 9) are in satisfactory agreement with the mooring station data (Fig. 10). Some relatively small deviations of the velocity values may be explained by the spatial variability of the current field (because the OLT stations were carried out at 0.5 mile distance from the buoys), the use of two-hour averaging of the DISK data (the OLT profiler gives an "instantaneous" picture) and also by instrumental errors.

Twelve days after the beginning of observations at the southern mooring station, we observed rapid and significant flow vector transformation from the southeastward to the prevailing northwestward direction. Probably the anticyclonic flow was shifted from the place of observations due to meandering of the current systems.

A similar situation was observed at the northern buoy. From the current-meter observations at this mooring station, the above-mentioned counter-current in a southeastward direction was observed during the first three days of observations. Thereafter, a similar flow transformation takes a place here as well as at the southern buoy.

## DISCUSSION AND CONCLUSION

The most important feature to result from the current-meter observations carried out in autumn 1993 was the discovery of the anticipated anticyclonic counter-current under the Main Black Sea Rim current in the northern and northwestern parts of the sea basin. This counter-current was registered both by the acoustic OLT profiler measurements from onboard the vessel and by the independent mooring observations.

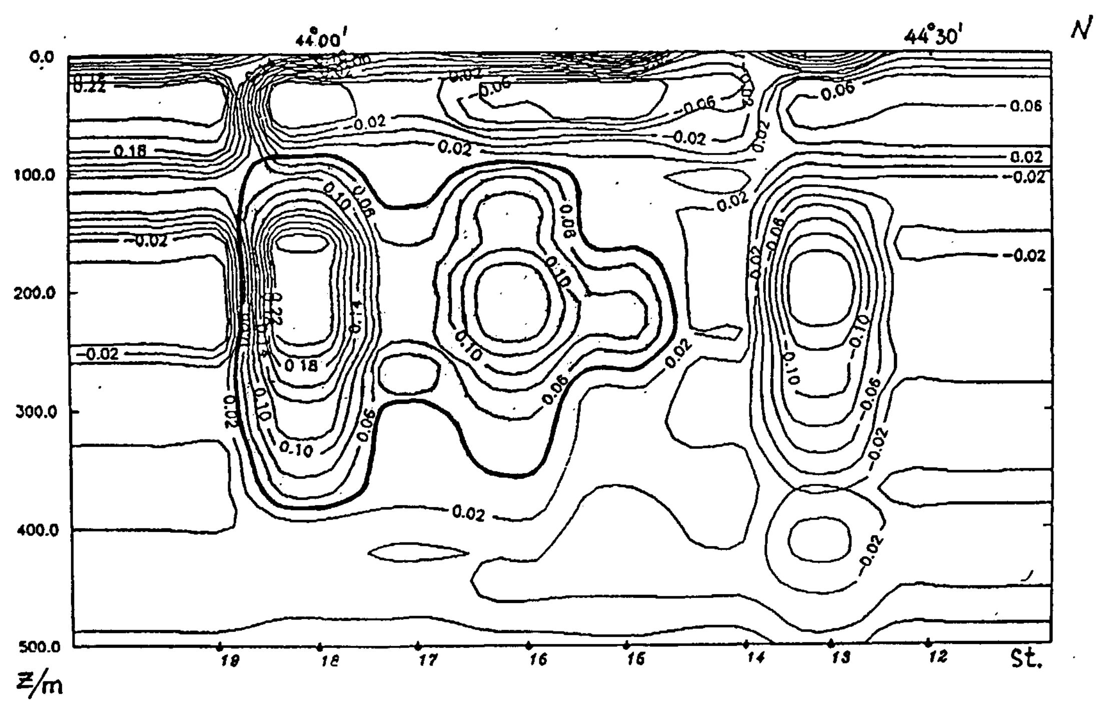


Figure 5

*Zonal component of velocity vector u(y, z) at the meridional section along 31° 30' E from acoustic measurements (in m/s).*

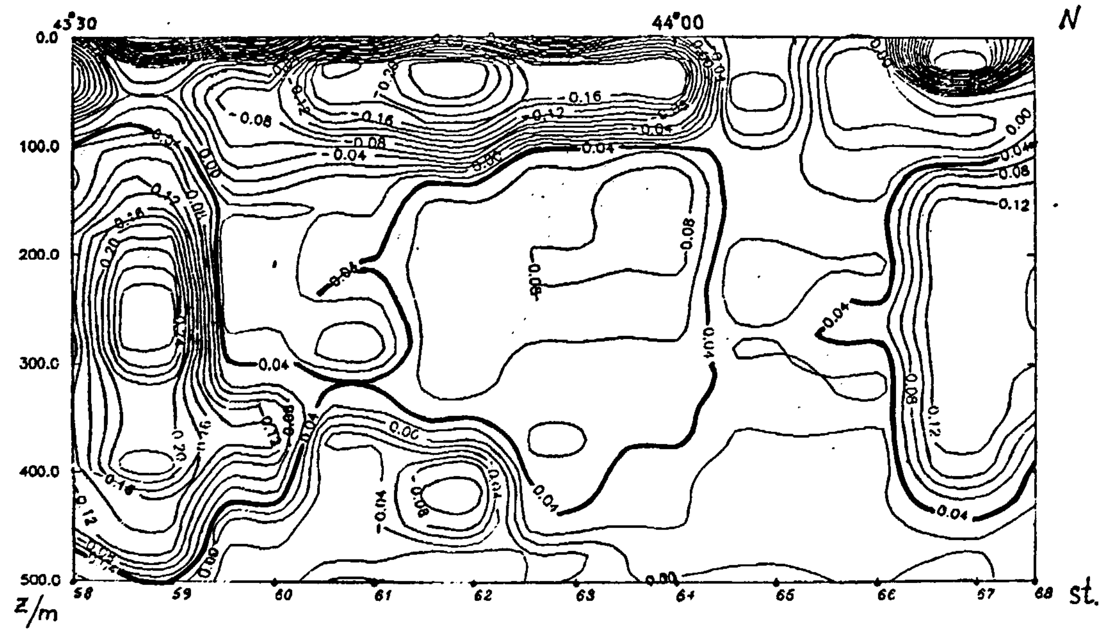


Figure 6

*Zonal component of velocity vector u(y, z) at the meridional section along 34° 15' E from acoustic measurements (in m/s).*

The density field distribution confirms the existence of a counter-current due to the widening structure of the pycnocline, with the different inclinations of isopycnal surfaces.

Detection of the above-mentioned counter-current at a few adjacent stations of the meridional sections made it possible to estimate the characteristics horizontal scales of the anticyclonic flow (10-20 miles).

The position of the counter-current on the vertical plane (100-400 m), and the maximum velocity values (0.20-0.25 m/s) from current-meter observations are in full agreement with the theoretical and laboratory predictions (Bulgakov *et al.*, 1996 *a, b*).

The results of the analysis of the previous current-meter observations carried out in August 1992 in the northwestern part of the Black Sea using a OLT profiler with 10-mile spacing confirm very closely the results of the present study.

All the above enables us to draw a conclusion with regard to the more complicated (than was mentioned earlier) three-layered vertical structure of the current field in the Black Sea, with an anticyclonic counter-current under the Main Black Sea Rim current.

At the same time the following question arises: are the observed eastward flows the traces of cyclonic and anticy-

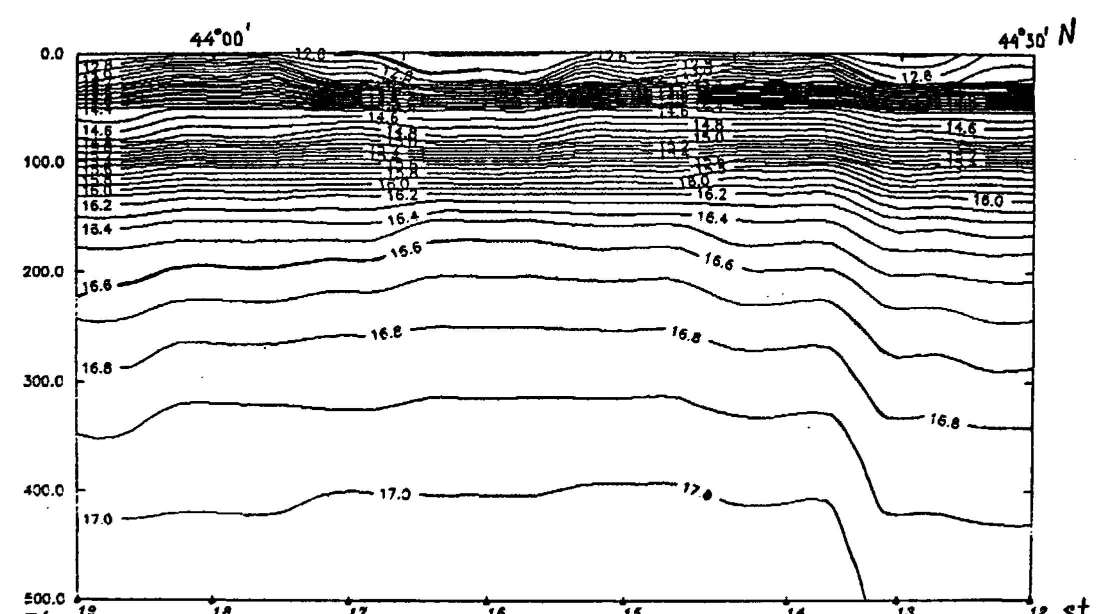


Figure 7

*Density distribution $\sigma_t$ (y, z) at 31° 30' E.*

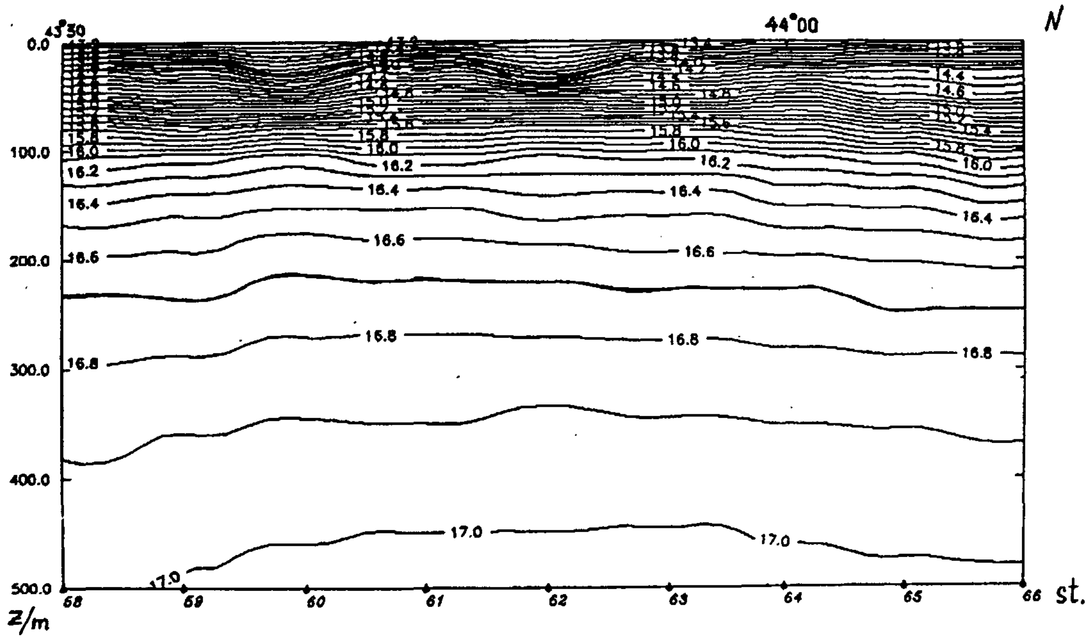


Figure 8

*Density distribution $\sigma_t(y, z)$ at 34° 15' E.*

clonic eddies, located for example on each side of the Rim current periphery, or are they the result of long-wave movements in the Black Sea basin ?

It appears to us to be rather difficult to explain this phenomenon the eddies hypothesis alone, because the counter-current could have a three-core structure as presented in Figure 6. Moreover, these eddies must have an extremely sloped vertical axis for the opposite-directed flow to be situated under the surface Rim current.

Probably, the anticyclonic flow under discussion cannot be generated also by the long waves. According to Yoon and Philander (1982), barotropic and baroclinic Kelvin waves forced by eastward winds at the northern boundary of the stratified sea could really form two-layer current system with anticyclonic flow at the surface and cyclonic flow at the middle depths. At the same time, the converse situation (with cyclonic current and anticyclonic counter-current) is impossible there. In case of the westward wind which does not form an upwelling zone, the structure of currrents is of the cyclonic and one-layer type.

Moreover, according to the classification presented by Ivanov and Yankovsky (1992), virtually the entire spectrum of the Black Sea long-wave movements in characterized by a common feature: shelf, topographic and Kelvin-trapped waves are propagated cyclonically. Rossby waves are moved to the west, *i.e.* cyclonically, in the northern Black Sea. Thus at present the long-wave mechanism of anticyclonic counter-current formation in the Black Sea is unknow for us.

The other question is why the anticyclonic counter-current under discussion was not discovered earlier. We can provide the following explanation. As was established from the

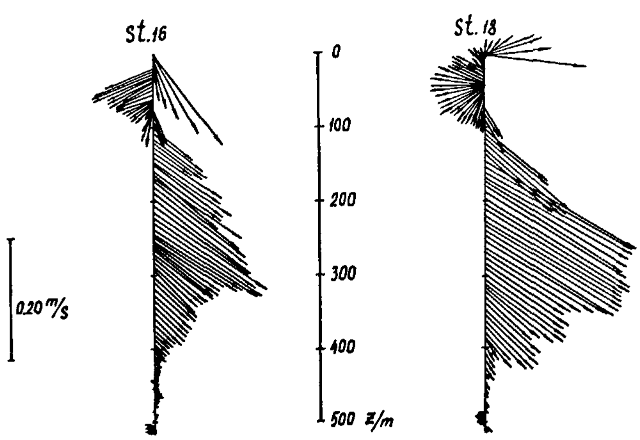


Figure 9

*Vertical structure of currents at stations 16 and 18 from the acoustic measurements.*

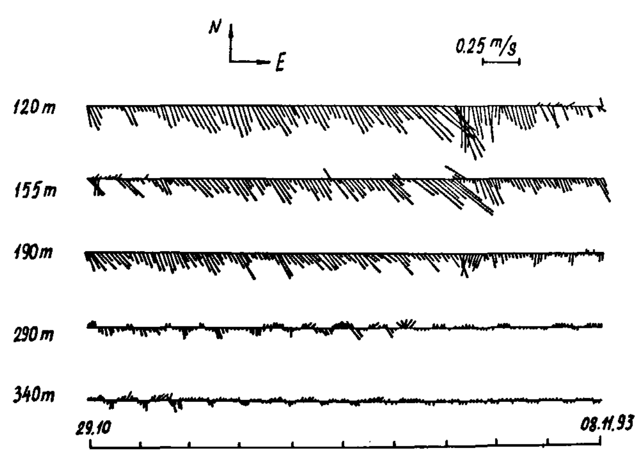


Figure 10

*Two-hour averaged mooring observations of velocity vectors at five levels near station 18.*

Table 1.

*Characteristics of the measuring channels of the OLT acoustic profiler.*

| Measuring parameter | Range | Sensitivity | Max error |
|---|---|---|---|
| Current velocity, m/s | (-2.5; 2.5) | 0.002 | (1+4V) × 0.01 |
| Temperature, °C | (-2.0; 35.0) | 0.0004 | 0.01 |
| Relative elect. conductivity | (0.35; 1.7) | 0.00002 | 0.0004 |
| Sound velocity, m/s | (1400; 1600) | 0.0075 | 0.3 |
| Hydr. pressure, MPa | (0.0; 20.0) | 0.0025 | 0.05 |
| Heel and different angle, degree | (-45;45) | 0.2 | 1 |
| Course angle, degree | (0;360) | 0.5 | 3 |
| Cable length, m | (0;3200) | 0.1 | (2+0.12L) × 0.01 |
| Vert. deviation of cable,degree | (-10;80) | 0.5 | 1 |
| Horizontal cable declination, degree | (-90;90) | 0.5 | 1 |
| Vessel course, degree | (0;360) | 0.5 | 0.5 |

V is the current velocity; L is the cable length.

theoretical analysis and field observations, the horizontal scale of the counter-current is of the order of the Rossby deformation radius (15 miles), whereas most of the hydrological surveys in the Black Sea were conducted with the more coarse (20-30 miles) spacing.

Moreover, current-meter observations using ADCP in the western Black Sea (Oguz *et al.*, 1996) were not obtained on a station grid detailed enough and below the 200-metre layer. This would appear to exclude the possibility of detecting the flow in question from these data. It is also probable that the small horizontal scale and the spatial variability of the counter-current, due to the meandering of the current system, did not allow it to be systematically observed from the mooring stations. Finally, it should be noted that the basic difference between the present field observations and the preceding ones consists in the fact that, firstly, the distance (5 mile) between the OLT stations was chosen from the preliminary theoretical estimations; and secondly, the locations of two mooring stations were not random: they were defined after operative processing of OLT data. All the above made it possible to reveal the anticyclonic counter-current, and to investigate some of its general patterns.

As in the case of any other study, the results of the present investigation have posed a lot of new questions. The basic ones, to our mind, may be formulated as follows :

– Does the observed anticyclonic counter-current exist around the entire basin boundary or is it an element of the Northern Black Sea circulation only ?

– Could the discussed counter-current be formed by other mechanisms ?

– What are the peculiarities of the temporal and spatial variability of the counter-current, and what is its correlation with the meandering of the Main Black Sea Rim current ?

– Do similar counter-currents occur in other marginal seas (in the Mediterranean, in the Sea of Marmara, in the Red Sea or in the Baltic, for example), where buoyancy fluxes can play an important role in dynamics formation ?

The answers to these questions will, it is hoped, be provided in further studies.

## Acknowlegments

The dynamics experiment in autumn 1993 in the Northern Black Sea was organized and carried out by the Marine Hydrophysical Institute of the National Academy of Sciences of Ukraine, with the financial support from the Ukrainian State Committee for Science and Technology.

The authors are very grateful to all the colleagues who participated in this expedition, as well as to Dr. L.I. Ivanov for the opportunity of consulting unpublished papers (Oguz *et al.*, 1995; 1996).

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