THE BLACK SEA COLD INTERMEDIATE LAYER

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Abstract. We focus on the volumetric temperature/salinity analysis of the Cold Intermediate Water (CIW) masses, based on data sets obtained in years with normal, severe and mild winter conditions. A comparative analysis of the 1991 and 1992 data is used to study a convection event during the winter of 1991-1992, and April 1993 and March-April 1995 surveys are used to characterise Cold Intermediate Layer (CIL) peculiarities after severe (1993) and mild (1995) winter conditions. A new analysis of the CIW formation is presented, based on the new data sets having high resolution, full basin coverage. Comparative volumetric T,S analyses do not confirm replenishment of CIW in the peripheral 'convergence zone' by water from the cyclonic central region, after being formed there by winter convection, as it had been previously claimed by Ovchinnikov [24]. Subtle evidence supports Kolesnikov's hypothesis [16] of CIW production over the shelf. Yet, the contribution of this mechanism is found to be small. We find that the formation process is a result of advective and convective contributions most actively taking place along the 'convergence zone'.

1. Introduction

An accurate understanding of the sources, formation and spreading mechanisms of the Cold Intermediate Water (CIW) is much needed in the Black Sea. Surface mixing results in formation of CIW, and contributes to the direct ventilation of the upper ocean. The impact of surface mixing on the transport of pollutants and organic matter, and on the new production resulting from the entrainment of nutrients into the surface waters need to be studied for a better understanding.

The CIL is characterised by a minimum in temperature, with T < 8°C, occurring within a typical depth range of about 50 - 180 m overlying the main pycnocline, where vertical stratification is maintained by the salinity gradient.

The low salinity of the surface waters is maintained by fresh water inputs into the Black Sea, and the shallow (~10 -30 m) mixed layer often reflects the effects of seasonal heating and cooling. Although observations are limited, it is often assumed

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that convection driven by wintertime atmospheric cooling should erode the pre-existing thermal structure and establish an isothermal layer reaching from the surface to the core of the CIL. The strong salinity stratification at the pycnocline opposes penetration of turbulent convection into the deeper layers.

We focus on the volumetric temperature/salinity analysis of the CIW, based on recent data sets, covering normal, severe and mild winter conditions. We provide evidence to the claim that the Rim Current prevents direct penetration of the convectively generated waters from the central cyclonic gyres to the periphery of the basin, showing that the CIW in the convergence zone (more than 50 percent of the entire CIL volume) mainly originates from the shelf and the continental slope area.

2. Hypotheses on Winter Convection and CIW Formation

The first attempts to explain the origin of CIL were made by Knipovich [15] and Zoobov [32]. They described the CIL as a remnant of the upper mixed layer formed by winter cooling and convection processes. Continued field studies revealed that, in various parts of the sea, the core of the CIL was often deeper than the lower boundary of the mixed layer observed in winter. In addition, the CIW core properties appeared relatively uniform across the basin, and did not appear to be related to south-north and west-east gradients of air temperature or other meteorological parameters.

These facts served as the ground to formulate hypotheses emphasising the advective nature of CIW formation [7, 8, 16]. In accordance with this theory, the cold waters replenishing the CIL in winter are mostly formed in the northwestern shelf, along the adjoining slope region, as well as in the proximity of the Kerch strait; then advected along the periphery towards south. A number of scientists [4, 30] supported this idea.

The hypothesis on the production of the CIW in the northwest part of the sea dominated until 1984, when Ovchinnikov [24, 25] and MHI scientists [11] strongly argued for the generation of CIW in cyclonic gyres in the central part of the sea. The basic idea of Ovchinnikov was that "there is a slow flow of newly formed cold waters from the centers of cyclonic gyres toward the coasts in the Black Sea but not their advection from the northwest part of the sea as it had been thought previously" [25]. Some other studies added details and provided support to this hypothesis [14].

3. The Surface Circulation in the Basin

The most prominent feature characterising the Black Sea general circulation is a basin-scale cyclonic boundary current referred to as the 'Rim Current' [20].

The existence of forcing by a positive curl of the wind stress [18, 19], thermohaline forcing of nonuniform surface buoyancy fluxes [17, 23, 28] and lateral buoyancy sources from rivers and the Bosphorus inflow [6, 23] have been recognised as driving mechanisms for the cyclonic circulation.

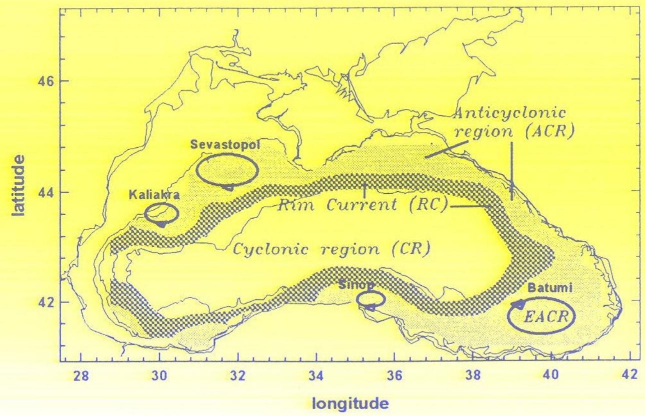

Figure 1. Circulation scheme of the Black Sea based on the 1992 data.

The topography of the pycnocline was used to depict the basic circulation in the basin. The circulation scheme is presented in Fig.1, partially based on the 1992 data: The core of the Rim Current in the scheme corresponds to the zone of maximum pycnocline slope for this survey. The region between the Rim Current and the shelf is typically characterised by a trough formed by the isopycnal surfaces. The anticyclonic cells are often confined to areas of irregular of bottom relief (Sevastopol, Kaliakra, Sinop, Batumi anticyclonic quasi-permanent features) [3, 4, 20, 22]. In analogy with the open ocean cases, this region has been referred to as the 'Convergence Zone' [26], herein referred to as the anticyclonic region (Fig. 1).

4. Data and Analysis Methodology

For the analysis, the data acquired during September 1991 (HydroBlack-91) [1], July 1992 (CoMSBlack-92) [21], April 1993 and March-April 1995 cruises were used. The measurements covered the entire Black Sea in September 1991 and July 1992, and part of it (~50-70 % of total area) in April 1993 and March-April 1995, on a grid allowing to resolve mesoscale features (1/3 degree latitude and 1/2 degree longitude, with increased resolution over slope areas).

The basin-wide data collected during the summer periods of 1991 and 1992 are used to study a convection event that took place in during winter 1991-1992, and the April 1993 and March-April 1995 partial surveys are used to characterise CIL peculiarities after severe (1993) and mild (1995) winter conditions. Although winter 1991-92 data are not available, the comparison of the two summer data sets provide valuable information, because traces of the winter mixing event appear well preserved in the temperature-salinity structure in the following period, particularly due to the peculiarities of the Black Sea pycnocline. It is well known that the density, rather than depth, serves better as a vertical coordinate for studying the vertical structure of various constituents [2, 5] in the pycnocline region. Temperature often acts as a passive tracer, with a smaller contribution to density as compared to the salinity, and therefore the temperature signature of cooling events are demonstrated well by studying temperature structure on density coordinates of the halocline region.

The core of the CIW occurs at σ_θ = 14.2 - 14.8. The coincidence of the lower boundary of the CIL (defined as the crossing point of temperature at T = 8° C) with the main pycnocline at σ_θ = 15.3 - 15.9 indicates that the convection events have limited, short-term effects in modifying the structure of the main pycnocline on a seasonal time scale.

5. Results

5.1 METEOROLOGICAL CONDITIONS

There are numerous indications that the winter of 1991-1992 was one of the coolest winter seasons in the region, relative to climatological averages [10, 29, 31]. For the considered time period, the winter of 1993 was actually the most severe. Temperatures in the core of the CIL as well as meteorological data reveal a decrease in average winter temperatures for the region in 1991-1993 (averaged temperatures for Odessa, Sevastopol, Yalta and Kerch meteorological stations for winters of 1990-91, 1991-92 and 1992-93 were 2.7°C, 2.3°C and 2.0°C, respectively). In contrast, the CIL temperature in 1995 imply a warm anomaly for this winter period, giving us a possibility to compare results of CIW formation during cold and warm winters.

5.2 CIL IN 1991 & 1992: A COMPARATIVE STUDY

The averaged CIL temperatures for the whole range of σ_θ values in July of 1992 appeared to be cooler than in September of 1991 [13]. The most noticeable differences in the CIL and pycnocline T,S structure were confined to the σ_θ = 14.4-15.0 range and the maximum level of downward 'penetration' due to cross-isopycnal mixing for the central part of the sea was estimated to coincide with the σ_θ=15.5 surface, which is close to the lower boundary of CIL.

For the lower part of the CIL, the largest temperature differences between 1991 and 1992 data were in the cyclonic interior region of the basin. In the July 1992 survey, waters underlying the core of the CIL in the central part of the basin were approximately 0.5°C cooler than the waters within the convergence zone (Fig. 2). On the other hand, above the CIL core, the waters in the convergence zone appeared to be much cooler than those in the cyclonic interior [13], which implied appreciable cooling of the intermediate waters during winter, and their warming during summer, to occur over the dome of the cyclonic gyre where the pycnocline is shallower. This fact strongly supports the claim that cooling/ventilation of the upper pycnocline during cold winters basically takes place in the cyclonic interior.

As it can be seen from Table 1, the total volume of the CIL in July 1992 was larger, by about 1527 km^3, compared to that in September 1991. The volume of the

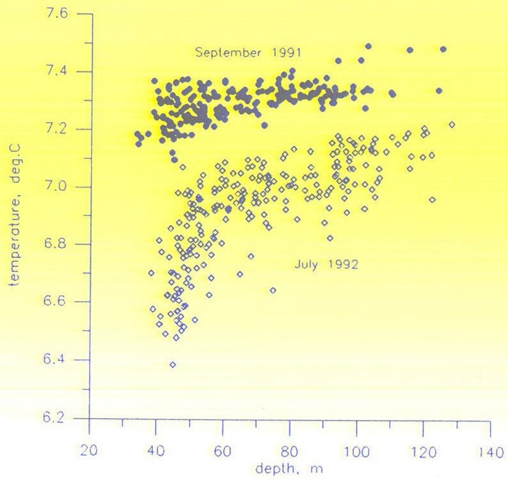

Figure 2. Temperature versus depth on the 14.8 sigma-t.

lower part of the pycnocline was unchanged, to within the accuracy of the estimate. For summer months, Glazkov [9], estimates the average CIL volume to be 16035 km^3. A comparison of this estimate with our calculations implies appreciable interannual variability in CIL thickness. In order to quantify the seasonal cooling effects, we define the CIL negative heat storage per unit area, Q, as follows:

$$Q = \int_{z_2}^{z_1} (T_* - T)\, dz \qquad (1)$$

which excludes the factor ρc_p for simplicity (with $\rho \cong 1 g\ cm^{-3}$ and $c_p \cong 1\ cal\ g^{-1}\ {}^\circ C^{-1}$ accounting for the density and specific heat of sea water). T_* =8 °C is the upper limit temperature used to identify CIW with $T \le T_*$ between intermediate depths z_1 and z_2, corresponding to the crossing points at temperature T_*.

The total negative heat storage, QA (A being the survey area), for the September 1991 survey, was smaller by 7070 °C km^3 compared to July 1992, corresponding to a heat loss of 10.4 10^7 J/m^2 from the CIL from September 1991 to July 1992. The differences in negative heat storage of CIL between the 1991 and 1992 surveys can be attributed to the seasonal course of the thermohaline characteristics (possible changes from July 1991 to September 1991) and the interannual variability in the CIW generation in winters of 1990-91 and 1991-92.

To estimate the contribution seasonal variations to the difference, it is reasonable to expect that T,S changes in summer-fall 1991 would be similar to those in 1992. Based on other measurements, we know that the CIL temperature in the northwestern part of the sea has not changed significantly during summer 1992: only a 0.2°C increase in the temperature of the CIW core has been observed in the summer months [12]. Therefore, one would estimate that seasonal changes would only account for about 30-40% of the calculated 1991-92 difference in total negative heat storage, which would in fact be an underestimate, because it does not include seasonal variations in the total volume of CIW which we do not specifically know. In addition, warming in the upper part of the CIL proceeds faster than in its core, introducing an asymmetry which is difficult to assess here.

TABLE 1. Volumes of water (km^3) for the layers: sea surface - CIL upper boundary, CIL - lower pycnocline (σ_θ =15.6-16.2 surfaces) and the total amount of the CIL negative heat storage Q (°C km^3).

Cruise	Vol.: 0-CIL UB	Vol.: CIL	Vol.: σ_θ=15.6-16.2	Q
September 1991	8398	18361	11787	10430
July 1992	8669	19888	11693	17500

Our rough estimate shows that the interannual variations in CIL total negative heat storage, which are on the same order of magnitude as the seasonal changes, were on the order of 5 10^7 J/m^2 during 1991-1992, with an associated average winter cooling rate of about 7 watt/m^2, if we assume that the cooling period was approximately three months. The heat flux into the cold intermediate layer associated with summer-fall heating (two month period between July and September) can be estimated to be on the order of 10 watt/m^2.

Although the surface area of the cyclonic region (see Fig.1 for definition) is twice as large as the anticyclonic one, the total negative heat storage was calculated to be comparable: 6580 °C km^3 for the convergence zone and 5575 °C km^3 for the cyclonic region. Variations of negative heat storage per unit area in the anticyclonic area (convergence zone), exceed that for the cyclonic domain approximately by a factor of 5. It is evident that the anticyclonic eddies in the Black Sea act as reservoirs where cold waters generated by winter cooling are stored. Whatever changes occur in the Black Sea CIL volume or negative heat storage, these are mostly confined to the areas of the quasi-permanent anticyclonic eddies.

The volumetric T,S diagrams (volumes in km^3 per 0.1°C and 0.1 T,S class) of CIW for the whole Black Sea (excluding the shallow shelf areas) are shown in Figs. 3,a,b respectively for the September 1991 and July 1992 surveys. In general, both figures show that the CIW possesses a prominent core (approximately, between the 14.2 and 14.6 σ_θ interfaces) in the region of the stratified waters of the upper pycnocline, subject to summer warming. On the average, the CIW core in September 1991 is approximately 0.5°C warmer than in July of 1992, as well as being more uniform. In July 1992, the cold core (T<6.2°C) in the cyclonic area was saltier by a difference of about 0.1 as compared to September 1991, linked to deeper convection in 1992.

5.3 CIL VOLUMETRIC STRUCTURE IN 1992

Since features in the temperature - salinity fields are better recognised in 1992, we analyse the July 1992 CIL T,S structure in further detail. For better understanding of the peculiar T,S structure of the whole CIL volume, analogous volumetric T,S diagrams were calculated for the above specified regions (see Fig.1).

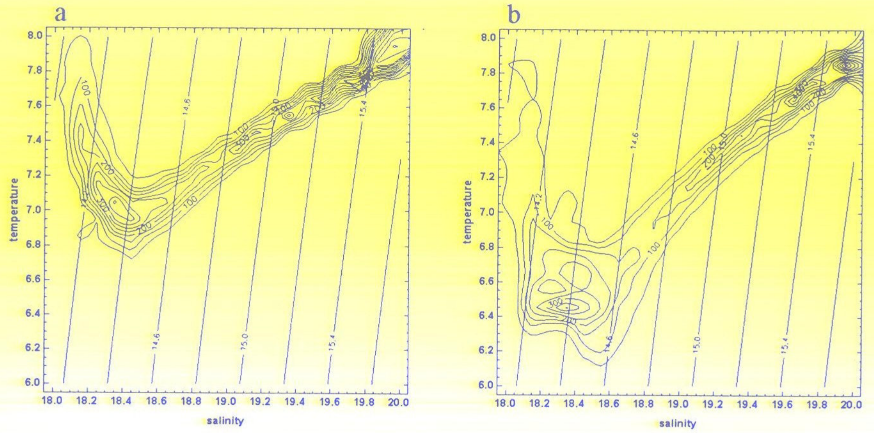

Figure 3 a,b. Volumetric T,S diagrams (km^3 per 0.1°C, 0.1 T,S class) for August-91 (a) & July-92 (b).

These T,S diagrams for different parts of the sea are shown in Figure 4,a-d. For the region of cyclonic circulation (Fig.4,a), maximum volumes were registered in the 6.25° - 6.55°C temperature and 18.55 salinity classes. Comparing Figures 4,a and 3,b, it is possible to verify that, for these T,S classes, waters of the cyclonic interior constitute 50 - 100 % of the volume of the average T,S diagram.

The characteristic feature of the volumetric T,S diagram for this area (see Fig.4,a) is the pattern of isolines within the core of the layer. Waters comprising the core of the layer differ in temperature, but so much in salinity (equal volume contours per T-S class are elongated from low to high temperatures with only a slight slant in salinity), implying that the waters in the cyclonic central domain of the sea were generated locally. The term locally is used here not to identify the *in situ* origin of water but its generation within a specific area of uniform salinity, i.e. of cyclonic circulation. The slant of the elongated contours implies that the salinity CIL core is controlled by winter surface temperature. Cooling implies entrainment and leads to an increase in salinity of the surface waters, as well as the CIL core.

For the anticyclonic region, extremes are observed for the following pairs of (T,S) classes: (6.45° C, 18.15); (6.45° C, 18.35); (6.65° C, 18.35), revealing less saline waters, compared to the central part of the sea (Fig.4,b). The isoline contours within the core of the CIL significantly differ from those for the area of cyclonic circulation. Isoline contours are elongated not 'vertically' but 'horizontally' (broad salinity range), and three water masses can thus be distinguished. For the core of the layer, salinity stratification dominates. In fact, only the upper part of the layer is seen to undergo transformation caused by warming, with most other regions remaining unchanged.

In terms of salinity, both extremes occur for the two salinity classes of 18.1-18.2 and 18.3-18.4 Note that these are waters observed within the deep part of the basin excluding the shallow shelf area. Waters with such low salinities, basically, were not observed in the area of cyclonic circulation. In general, it is reasonable to suppose that less saline waters are of shelf origin. Waters with medium salinities could be generated in the convergence zone.

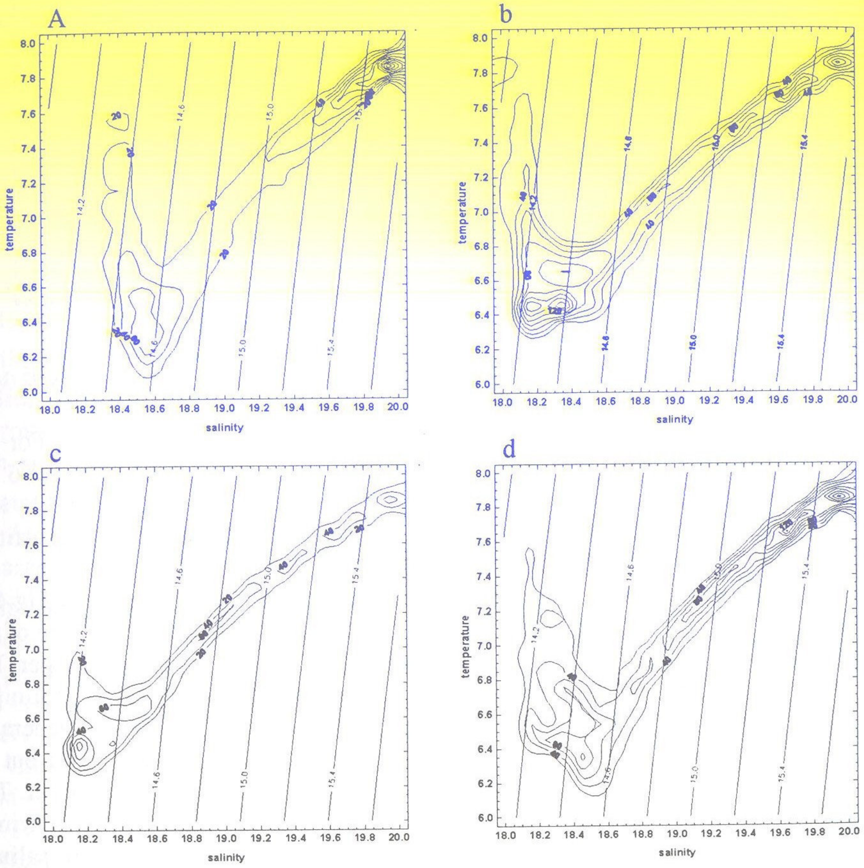

Figure 4 a-d. Volumetric T,S diagrams (as in fig.3) for the CR (a), ACR (b), EACR (c), RC (d).

From a comparison of Figures 4,a and 4,b, it can be easily verified that the CR and ACR T,S diagrams cross each other at only one point. Intersection occurs because of elongation of the upper part of CR T,S diagram induced by summer warming. If we were to focus on the relative position of volume extremes for CR and ACR T,S diagrams, it becomes apparent that they could not be connected in an isopycnal manner. We consider the above facts as strong arguments to show that there is an effective separation of the central and peripheral zones, i.e., from the previous winter formation period until July 1992, CIW from the basin's interior did not replenish the CIL in the convergence zone and *vice a versa.* The Rim Current, being the zone of maximum potential vorticity gradient for the circulation (implicitly, the thickness of the layer characterises the stretching component of potential vorticity), effectively

inhibits the cross stream exchange. Since potential vorticity is a conservative property and major CIW characteristics are preserved during the warm period, significant changes in the entire CR and ACR CIL volumes are unlikely to occur on a seasonal time scale.

The low salinity cold waters, are supposed to be of shelf origin. Their temperatures are close to 6.4-6.5°C and they are concentrated in the region of the eastern anticyclonic eddy (EACR, Fig. 4,c). This fact may have two alternative explanations. These are waters generated in the nearby shelf area or they are from the north shelf of the sea but trapped in the eddy. Such phenomenon can occur if the spring intensification of the eddy coincides in time with the period when low salinity waters reach the region via advection by the Rim Current. In April 1993, low salinity and cold waters have been observed along the Caucasian coast within the convergence zone implying their 'local' origin. More saline waters (18.3-18.4) of the convergence zone were observed in the northern anticyclonic eddies but not in the Batumi eddy.

Climatic data [27] depict southeastern part of the sea as the region with the warmest climate within the Black Sea, and it was never reported as a CIW generation area. Most probably, this low salinity water is formed in the northeastern shelf area.

The CIW present the Rim Current zone (Fig. 4,d) most probably has been formed by waters of the cyclonic gyre and less saline waters of the convergence zone. Thus, the Rim current may be considered as a zone of interaction between waters of the cyclonic region and of the outlying anticyclonic area.

For each volumetric T,S diagram, it is possible to subjectively distinguish a core of newly formed and only slightly transformed cold waters and an 'old' CIW. The 'newly formed, slightly transformed cold waters' are defined, herein, as waters within the layer of relatively weak density stratification (compared to the main pycnocline), with T,S characteristics close to the core values. In the volumetric T,S diagrams, this water volume appears as a 'broad' area with enclosed isoline contours around the CIL core. Since the estimates are subjective, they are used in a qualitative rather than quantitative manner, i.e. for a comparative analysis.

For the anticyclonic area, the volume of the newly formed waters made up about 4000 km^3. This constituted, approximately, 57 per cent of the CIL total volume for this area. For the cyclonic region, the same value was 2700 km^3 (approximately, 50 per cent of the total CIL volume) revealing considerably smaller amount compared to the ACR. The largest portion of newly formed waters characterised the T,S diagram for the Batumi anticyclonic region. For this area, the volume of the CIL 'core' was 1800 km^3 (up to 60 per cent of the total CIL volume). At the same time, the volume of the low salinity waters within this dynamical feature was only 600 km^3, implying relatively insignificant role of the 'shelf source' in contributing to CIW.

5.4 CIL STRUCTURE FOR YEARS WITH ANOMALOUS WINTER CONDITIONS

5.4.1. The case of severe winter meteorological conditions

The April 1993 survey occupied only 70 per cent of the basin, and it was not possible to calculate the exact volume of the CIW. On the other hand, the volumetric T,S diagram of the CIW for the April 1993 survey area revealed major portions of water with different T,S characteristics within the CIL qualitatively similar to the 1992 survey. The largest portion of the newly formed water was rather uniform with temperatures of about 6.0 -6.2° C and with salinities about 18.2-18.3, i.e. with lower salinities than in 1992 for this area. Waters of the northwestern shelf were of anomalously low temperatures (2-5°C) but their total amount was negligible when compared with the CIW volume of anticyclonic and cyclonic areas.

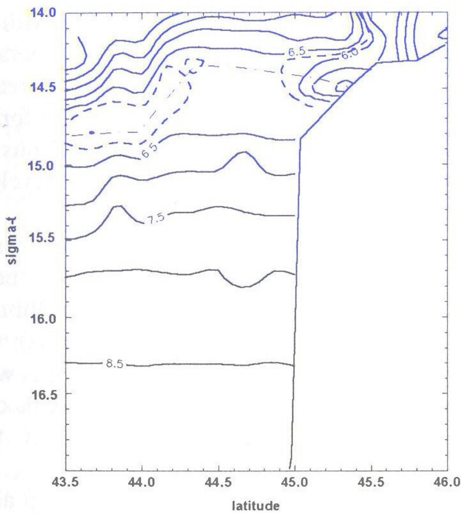

Figure 5. Temperature distribution on a transect along 32° 15' E and across the Rim Current in April 1993.

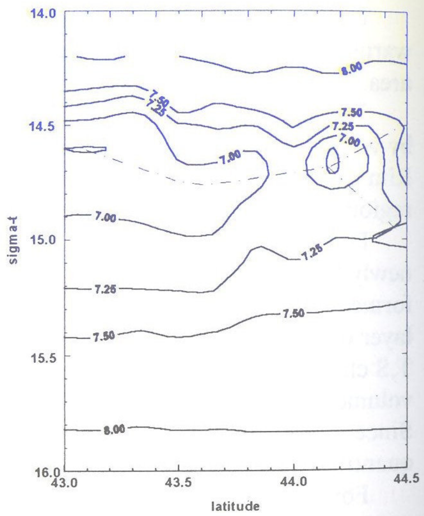

Figure 6. Temperature distribution on a transect along 34° 15' E and across the Rim Current in March 1995.

The above description shows appreciable similarity in CIW T,S structure for the 1992 and 1993 surveys. Note, that some peculiarities were better pronounced in 1993 as a result of severe winter meteorological conditions. For example, CIW salinities (densities) substantially differed across the frontal feature of the 'Rim Current' (Fig.5). The transition zone between denser and less dense waters was less than 20 miles at most of the transects. Salinity differences across the frontal feature were about 0.4 in 1992 and increased up to 0.6 in 1993. Salinities within the anticyclonic eddies were the same, revealing efficient entrainment (erosion of the pycnocline) only in regions with cyclonic circulation.

5.4.2. The case of mild winter meteorological conditions

The temperature distribution in isopycnal coordinates across the 'Rim Current' frontal zone for the 1995 survey is shown in Figure 6, and reveal not only quantitative, but qualitative distinctions between structures for anomalously warm and cold winters. In particular, in contrast with the situation in 1992 and 1993, CIW core densities, in 1995, increased shoreward (up to 14.9). Also, in 1995, the core of the CIL was stratified and its position in the vertical coincided with the largest vertical density gradients, revealing the relict character of the layer.

6. Summary

Since a large portion of new hydrographic data has been analysed, a new perspective on the problem of CIL formation in the Black Sea can be specified in the following section as part of our basic conclusions resulting from the analysis. A schematic illustration of these results is shown in Figure 7. Herein, let us address two basic specific questions: (1) Does the Black Sea CIW have a local or an advective nature? (2) What are the specific CIW source regions?

(1) A basic conclusion derived from the comparative analysis of the Black Sea volumetric T,S diagrams for a number of years and covering different regions is that the water formed by winter convection within the vast central area of cyclonic circulation, does not replenish the CIL in the convergence zone (schematised in the Figure by dashed lines), as it was claimed by Ovchinnikov [24, 25]. The cross frontal exchange within the CIL is strongly inhibited, due to strong cross frontal gradients in potential vorticity. In general, CIW is of 'local' origin if the term 'local' is used to discriminate areas of cyclonic and anticyclonic circulation but not in terms of their *in situ* formation. Within the cyclonic area and the convergence zone, the CIW is advected by currents. Waters of the convergence zone possess strong salinity stratification, which means that the newly formed part of the CIW in this region is of advective nature. Th high occurrence of CIL fine structure anomalies in the periphery of the basin supports this claim [13]. One specific example is the Batumi anticyclonic eddy (shown in Fig.7 by a black spot as a 'sink' region). The CIW found within its area cannot be formed in the southeast but should be advected from the north and the west along the Caucasian and Anatolian coasts within the convergence zone. There are indications of the penetration of a part of shelf generated waters into the ACR but the role of this mechanism is relatively small.

(2) For a cold winter, generation of the CIW within anticyclonic eddies accounts for more than half of the entire Black Sea CIL volume. At the same time, cooling is more 'effective' over the shelf and in the central part of the sea where heat losses per unit volume, apparently exceed the values for the anticyclonic areas. Thus, in terms of efficiency of entrainment, the central part of the sea may be considered as a CIW source region partially in support of Ovchinnikov's hypothesis. For a warm winter,

cross frontal differences in T,S characteristics are small and no quantitative estimates can be provided to support the above claims in this case.

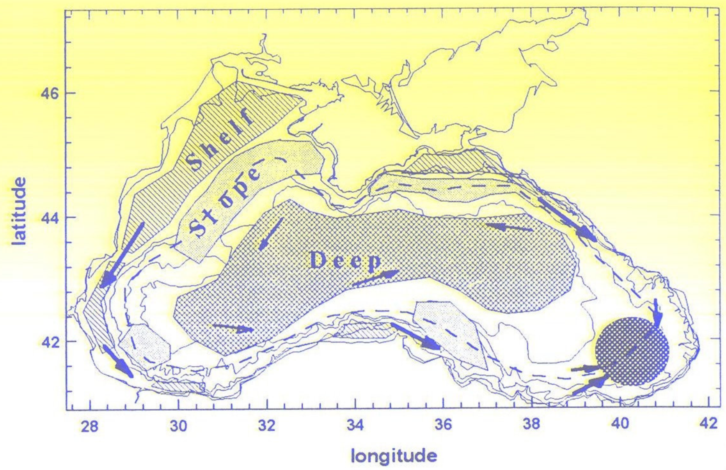

Figure 7. A scheme of CIW formation (source regions) and subsequent spreading. Black spot in the south eastern corner identifies CIW 'storage area' within the Batumi anticyclonic eddy.

7. Acknowledgements

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PHYSICAL OCEANOGRAPHY VARIABILITY IN THE BLACK SEA PYCNOCLINE

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Abstract. Local variability of the Black Sea permanent pycnocline position is caused, basically, by dynamical processes: Ekman pumping, meandering of the Rim current, mesoscale eddies, etc. Recent CTD measurements allow to filter local effects and to study variations of the pycnocline structure in detail with the focus on understanding of the role of different mechanisms which cause these variations. Gradual deepening of the isopycnal interfaces since 1991 as well as cooling (freshening) tendency has been registered. The total range of migration of the sigma-t interfaces within the pycnocline was 9 - 11 meters, with the shallowest position in 1990-91 and the deepest position in 1994. In the particular case, both cooling and freshening during 1991 - 1994 period, to some extent, occurred in response to changing vertical velocity. Cooling in this sense may not coincide with respective variation of annual mean air temperatures. In speculative manner, there should be a balance between combined variations of the basin's water balance, winter meteorological conditions and the thermohaline structure of the pycnocline layer. Weather conditions for the warm part of the year complicate the response in the pycnocline.

1. Introduction

The Black Sea is globally the largest body of anoxic waters facing rapid environmental deterioration under the impact of increasing contaminant inputs [17]. The evolution of the basin density and chemical stratification in the last few millennia results from the invasion of the Black Sea by the Mediterranean waters [6]; yet very little is known of the short term, interannual variability of the halocline or chemocline. Because the chemical changes including the transition from oxic to anoxic waters (i.e. the chemocline and the oxycline) coincide with the permanent halocline, its shoaling would imply adverse changes.

Claims of oxycline shoaling [7,11,18], supposedly in response to decreased freshwater inputs [18], have been contested and proved to be premature by more recent

E. Özsoy and A. Mikaelyan (eds.), Sensitivity to Change: Black Sea, Baltic Sea and North Sea, 265–274.