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VOLUMETRIC STRUCTURE OF THE BLACK SEA COLD INTERMEDIATE LAYER

L.I.Ivanov, E.G.Nikolaenko, E.Ozsoy, S.Besiktepe, E.Demirov, and V.Diaconu

MHI NASU, IMS METU, IO BAS, IMR

ABSTRACT. The focus of the paper is the volumetric T,S-analysis of intermediate waters based on the CTD data acquired during HydroBlack'91 and CoMSBlack'92 cruises, in which the whole Black Sea was covered on a grid that allow to resolve mesoscale features. The total CIL volume was estimated to be 18361 km3 in September 1991 and 19888 km^3 in July 1992. Cold water was stored mainly in the anticyclonic eddies in the periphery of the basin, where variations of cold content between the surveys were at least 5–6 times larger than in the cyclonic area. The evidence that the rim current prevents the penetration of waters from the central cyclonic gyres to the periphery of the basin has been provided.

The cold intermediate water (CIW) studies are of great importance for the Black Sea. Because of the presence of a strongly-developed main halocline (pycnocline), the direct ventilation in the Black Sea occurs only in the upper 100–200 m layer, and surface waters penetrate deeper only due to slow diffusive processes. In this manner, all pollutants (suspended and particulate material), organic matter and nutrients that enter the sea penetrate into the pycnocline with the cold intermediate layer (CIL) acting as a conveyer belt between surface and deep layers.

Scientific ideas about the nature of the CIL has transformed in accordance with the existing knowlege about thermohaline structure of the upper layer of the sea. The first rationale of the CIL origin was provided in the 1930's by Knipovich [1] and Zoobov [2]. They described the CIL as a remnant of an upper mixed layer formed due to winter cooling during the previous winter.

Further field studies have shown that in various parts of the sea the core of the CIL lay deeper than the low boundary of the mixed layer in winter. In addition, air temperatures in winter over the sea differ from west to east but, at the same time, CIL temperatures are rather uniform. These facts contradicted the theory implying a local origin of intermediate waters, giving rise to an idea of the advective nature of CIW [3,4].

According to this theory, CIW are generated in the northwest part and, afterwards, are advected to the southern and eastern parts of the sea. Most of the scienticsts [5,6, for example] supported this idea.

It was until 1984, when Ovchinnikov [7,8] and MHI scientists [9] argued for the CIW generation by cyclonic gyres in the central part of the sea. It should be mentioned that in the 1980s, with CTD probes becoming available, field studies of CIW were intensified, because the earlier data had been obtained mainly through the use of Nansen bottles with a very coarse (about 10 m, on average) vertical resolution.

The basic idea of Ovchinnikov was that a slow flow of newly-formed cold waters from the centers of cyclonic gyres shorewards exists in the Black Sea rather than their advection from the northwest part of the sea, as had been thought previously. Some other studies provided support to this idea; in [10], it was shown that in the central part of the sea the CIL is of local origin but on the periphery of the basin it is of advective nature. 1992 field studies [11] led to the conclusion that waters generated in winter in the central part of the sea propagate mainly along streamlines of the geostrophic current and, in summer, they are observed in the cyclonic region. The "light" cold waters of the upper part of the layer occupy mostly the convergence area.

In this paper, we focus on the volumetric T,S analysis of intermediate waters and, on this basis, try to develope theory for CIW generation. We provide more evidence to the fact that the rim current prevents penetration of waters generated in the central cyclonic gyres to the periphery of the basin and CIW of the convergence zone (more then 50% of the entire CIL volume) are generated in the near-coastal zone.

For analysis, the data compiled during September 1991 (HydroBlack) and July 1992 (CoMSBlack) cruises were used. These data are of high accuracy, with one meter vertical resolution [12]. The whole Black Sea was covered on a grid that allows to resolve mesoscale features and that gives a unique opportunity to study CIL and pycnocline volumetric structure.

As can be seen from Table 1, the total volume of the cold intermediate layer in July 1992 was 1527 km^3 larger than in September 1991. The volume of the lower part of the pycnocline (the position of the 15.6 sigma-t interface approximately corresponds to the low boundary of the CIL) was unchanged within the accuracy of the estimate. The total amount of the cold storage is defined as:

$$Q = \int\int\int (8^{\circ} - T(z))\, dx \cdot dy \cdot dz, \text{ deg} \cdot \text{km}^3.$$

Table 1

Volumes of water (cubic km) for the following layers: surface — CIL upper boundary, CIL, low pycnocline (15.6-16.2 sigma-t interfaces) and the total amount of the CIL cold storage (deg·km^3)

The cruise	The layer		
	0 — CIL ub	CIL	15.6–16.2 sigma-t
HydroBlack: vol	8398	18361	11787
Q		10430	
CoMSBlack: vol	8669	19888	11693
Q		17500	

The Q value for September 1991 survey was 7070 deg·km^3 less than that for July 1992. It corresponds to $10.4 \cdot 10^7$ J/m^2 CIL heat loss from: September 1991 through July 1992. The differencies in the amount of cold waters stored in the CIL for 1991 and 1992 surveys may be attributed to both seasonal course of the thermohaline characteristics (possible changes from July 1991 to September 1991) and interannual variations of CIW generation conditions in winters 1990–1991 and 1991–1992.

To estimate the fraction of the differencies that are due to seasonal variations, it is reasonable to suppose that at least summer — fall 1991 T,S changes were similar to those in 1992. Indeed, temperature values in the CIL in 1992 for the northwestern sea did not change significantly during summer. There was only a 0.2°C increase in CIL core temperatures for three month summer period.

Hence, seasonal changes could be responsible for about 30–40% of the described difference in the total amount of cold content in 1991 and 1992. Thus, interannual changes in CIL total cold content were about $7 \cdot 10^7$ J/m^2 and the respective difference in the negative heat flux due to winter cooling in 1991 and 1992 was about 9 watt/m^2 (if we assume three months cooling period). The heat flux into the cold intermediate layer associated with summer-fall heating was about 7 watt/m^2.

Additional negative heat flux during 1991-1992 winter resulted in the generation of extra 640 km^3 of waters with densities corresponding to 14.3–14.4 sigma-t values and about 1500 km^3 of waters with densities 14.5–14.8 sigma-t units (Table 2). Thus, one could distinguish light and more dense fraction in the newly-generated CIW. It means that there are at least two different regions of CIW formation.

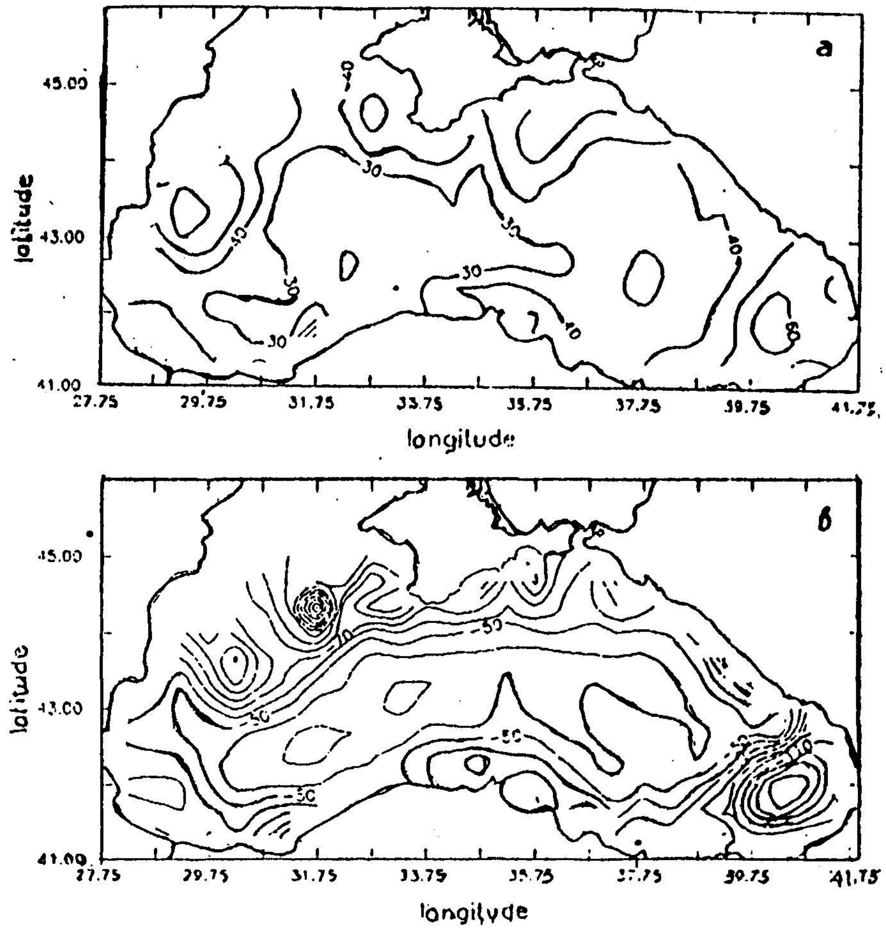
Table 2.

Volumes of water (km^3) between isopycnic interfaces for CoMSBlack and HydroBlack surveys

The layer	CoMSBlack	HydroBlack
sea surface —	10367	10787
– 14.2	1680	2083
14.2 – 14.3	2630	1989
14.3 – 14.4	1481	1586
14.4 – 14.5	2424	1204
14.5 – 14.6	2106	1778
14.6 – 14.8	1684	1550
14.8 – 15.0	1623	1731
15.0 – 15.2	1945	2026
15.2 – 15.4	2321	2361
15.4 – 15.6	11693	11787
15.6 – 16.2		

Cold waters are stored mainly in the convergence zone. Nevertheless the area of the cyclonic region is twice as large as of the anticyclonic one, the total cold content for the 1992 survey was 6580 deg·km^3 for the convergence zone and 5575 deg·km^3 for the cyclonic area.

The spatial distribution of the CIL cold content for September 1991 and July 1992 surveys is shown in Fig.1,*a*,*b*. In general, low values of Q are observed in the central cyclonic part of the basin (about 30–40 deg·m for CoMSBlack and 20–30 deg·m for HydroBlack survey) and the highest correspond to the areas of intense anticyclonic circulation (up to 80 deg·m for September 1991 and 160 deg·m for July 1992).



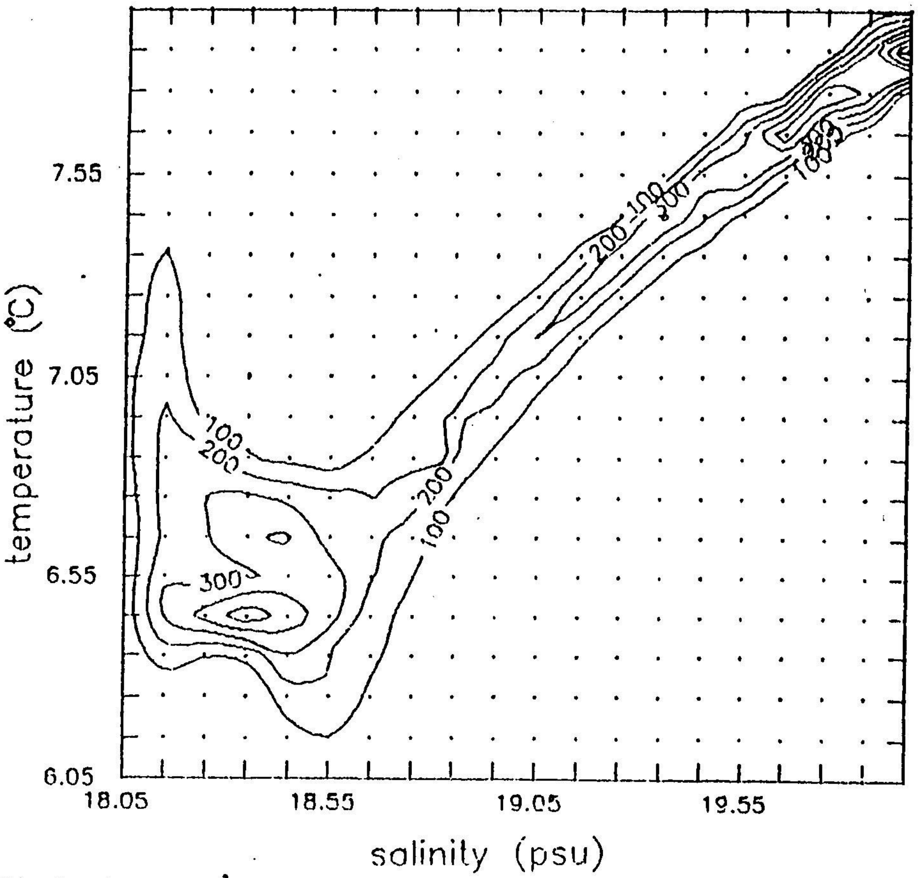
F i g. 1. Distribution of the cold storage values (deg·m) for the September 1991 (*a*) and July 1992 (*b*) surveys

Variations of cold content are at least 5-6 times larger in the convergence zone than in the cyclonic area. Thus it becomes clear that anticyclonic eddies in the Black Sea are reservoires where cold waters generated due to winter cooling are stored. Probably, anticyclonic eddies "lose" intermediate water during the second part of a year after the intensity of circulation weakens.

We shall analise July 1992 CIL *T,S* structure in detail. The volumetric *T,S* diagram of the CIW for the whole Black Sea is shown in Fig.2. There are two extreme points in the *T,S* distribution for the CIL core: 6.45°C, 18.35 psu and 6.65°C, 18.45 psu. The diagram looks like a "foot" with a well-noticeable heel (cold and saline waters of the basin interior).

The *T,S* diagrams for different parts of the sea are shown in Fig.3. From this figure, it becomes clear what waters comprise the above-mentioned extremums on the *T,S* diagram for the whole Black Sea.

One can distinguish the following extremums in the distribution of volumes of waters with different *T,S* characteristics : 6.25°C, 18.55 psu; 6.55°C, 18.55 psu for the region of cyclonic circulation and 6.45°C, 18.15 psu; 6.45°C, 18.35 psu; 6.65°C,

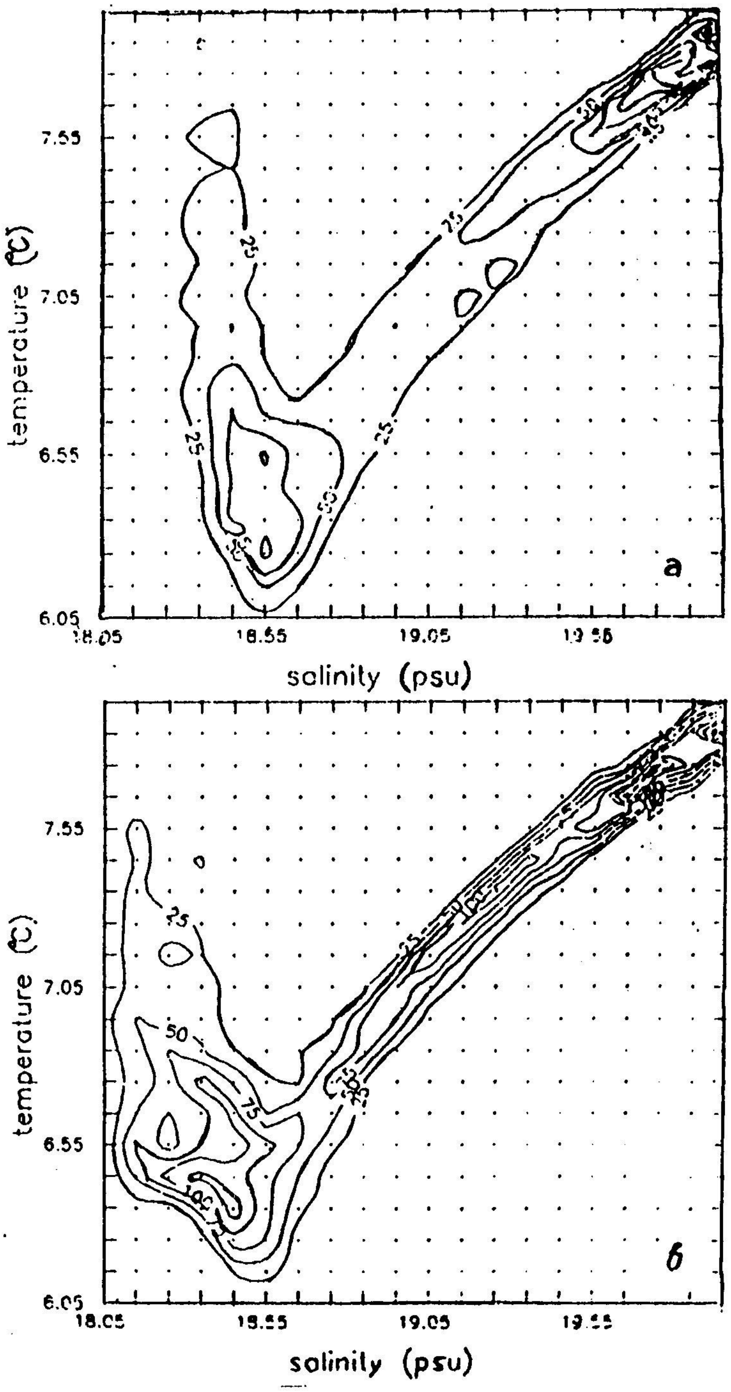


F i g. 2. Volumetric (km^3) *T,S* diagram of the CIW in July 1992 for the whole Black Sea

18.35 psu for the anticyclonic area. The extremums are for three salinity ranges: 18.1–18.2 psu; 18.3–18.4 psu; and 18.5–18.6 psu.

It is reasonable to suppose that low salinities result from the shelf waters with medium salinities could be observed in the convergence zone and high salinity waters are, evidently, from the area of cyclonic circulation. If so, CIL waters from the open sea could be also divided in regard to temperature, probably, as waters from the western (colder) and eastern (warmer) parts of the basin. Freshened cold waters of the shelf area have temperatures 6.4–6.5°C and they are concentrated mostly in the region of the eastern anticyclonic eddy.

It may have two alternative explanations: these waters are generated in the shelf area along the Turkish coast or these are waters from the nortwest shelf of the sea trapped in the eddy (this may occur if spring intensification of the eddy coincides in time with the period when these waters reach the region while advected by the rim current). Here, we choose the last alternative, because it is hardly likely that a large portion of CIW can be generated only along the southern coast of the sea (where are waters from the north shelf in this case?). More saline waters of the



temperature (°C)
7.55
7.05
6.55
6.05
18.05
18.55
19.05
19.55
solinity (psu)
25
50
a
temperature (°C)
7.55
7.05
6.55
6.05
18.05
18.55
19.05
19.55
solinity (psu)
25
50
75
100
б

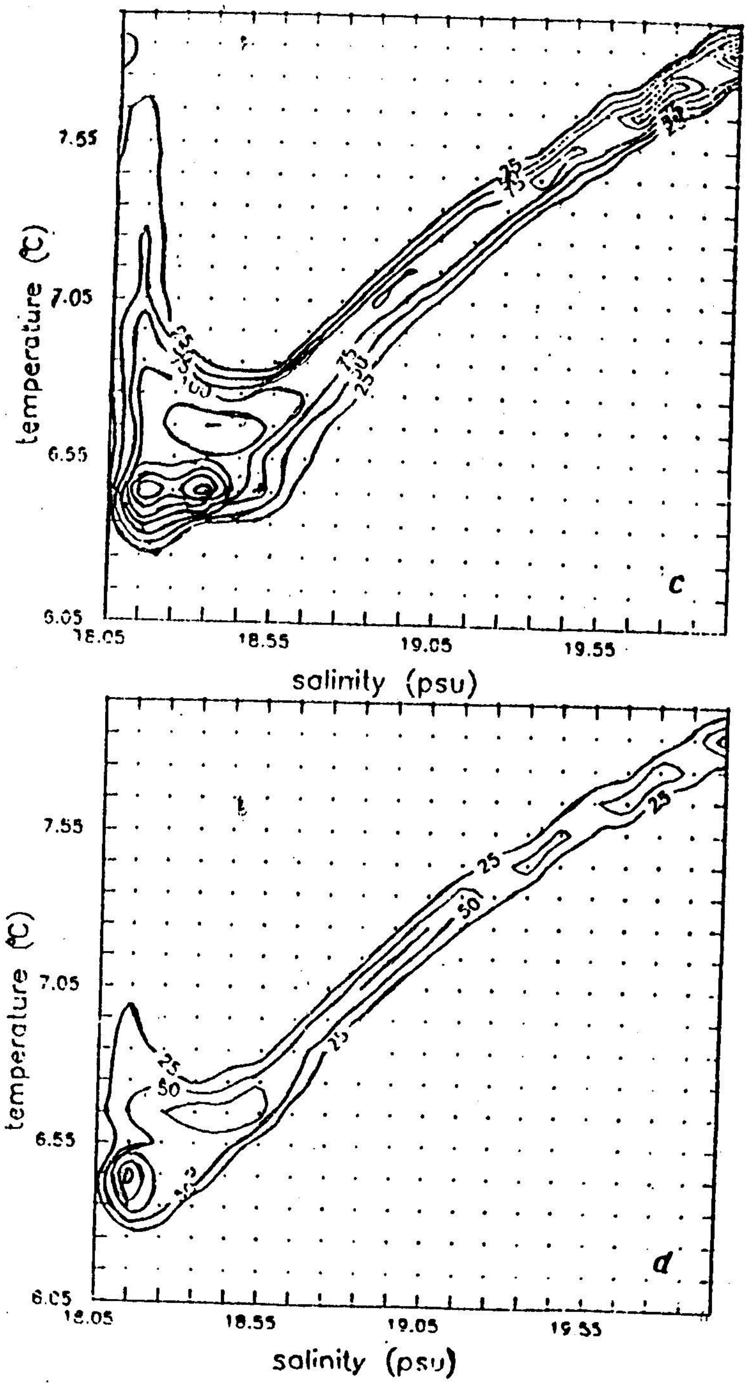


Fig. 3. Volumetric (km^3) T,S diagrams of the CIW in July 1992 for the area of cyclonic circulation (*a*), rim current zone (*b*), anticyclonic region (*c*) and the area of the eastern anticyclonic eddy (*d*)

convergence zone are observed mainly in the northern anticyclonic eddies and are scarcely observed in the eastern eddy.

CIW of the rim current zone are formed by both cyclonic region waters and less saline waters of the convergence zone. Waters of the cyclonic area cannot be seen in 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.

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