# PHYSICAL PROCESSES OF SURFACE-DEEP LAYERS EXCHANGE IN THE BLACK SEA

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**Abstract.** The relatively strong vertical stratification in the Black Sea significantly restricts the exchange between the surface and deep layers. The surface layer, where the anthropogenic flow enters, is separated from the deep layer by a sharp halocline (at depths 120-150m). Questions of changes in the Black Sea environment related to anthropogenic influences require investigation of physical processes which control the intensity of vertical mixing and advection in regions where they may be significant, as well as development of parameteriztion schemes in circulation models. Data from three CoMSBlack expeditions suggest that relatively intense upwelling, downwelling and the related processes of vertical exchange can be observed in some areas over the north-west continental shelf slope of the basin. The existence of these events is connected to nongeostrophic dynamics of waters in the Danube canyon and in the cape Kaliakra area. The buoyancy flux stipulated by vertical exchange processes in these regions is considered as a possible reason for the permanent existence of anticyclonic gyres near cape Kaliakra and Crimea.

## 1. Introduction

The Black Sea is a semi-enclosed sea, connected with the Marmara and Azov seas respectively by the narrow Bosphorus and Kerch Straits. The



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strong salinity stratification, formed due to weak exchanges with the adjacent basins and the large volume of fresh water input, significantly restricts vertical mixing processes. According to [5] the maximum depth of winter convection in the Black Sea is about 50 m. In comparison with other basins, where this depth is of the order of several hundered meters, the Black Sea is a poorly ventilated basin. Some authors(see [13] and [1]) suggest that under the conditions of weak vertical turbulent mixing, the processes of upwelling, downwelling and isopycnical mixing become significant factors which determine the vertical exchange below the seasonal thermocline.

The present article is an attempt to clarify some aspects of the dynamics of these vertical exchange processes as related to the mesoscale variability of the cyclonic Black Sea Main Rim Current (MRC). The results presented are mainly for the north-west shelf. However, they are considered applicable for other parts of the sea where similar dynamic conditions may exist.

Previous studies of the vertical exchange are considered in Section 2. An analysis of CTD and ADCP measurements obtained during CoMSBlack and NATO-TU Black Sea expeditions is presented in Section 3.

## 2. Background

The relatively stable stratification and quasigeostrophic (i.e. quasi-non-divergent) dynamic balance in the deep regions of the Black Sea restrict the processes of vertical advection and mixing here. Under these conditions the upwelling and downwelling (forced by Ekman pumping processes in cyclonic MRC) and isopycnical mixing are considered by different authors (see [4],[1], [13]) as the most significant dynamic processes determining the vertical exchange in the sea.

The cyclonic MRC is a jet-like current, and has maximum intensity over the continental slope. Upwelling and downwelling are observed in the central part and periphery of the deep water area of the sea respectively (see [1], [13] and [2]). [13] showed that winter cooling has maximum intensity in the central part of the basin because of the relatively low depth of mixed layer(ML), which is limited here by the upwelling of the saltier deep waters, and the relatively strong vertical salinity gradient at the bottom of ML. The surface cooled and dense waters during this season sink into CIL following the isopycnical surfaces.

Downwelling is observed along the periphery of the deep water area (see [4])in almost the entire basin. In this connection the region of MRC periphery over the North-West continental shelf slope is of particular significance, because the chemical properties of waters sinking in this area are strongly influenced by the anthropogenic input from rivers (see [1]). Following [1] we will refer to this region as Convergence Zone (CZ). In Figure 3 CZ coincides



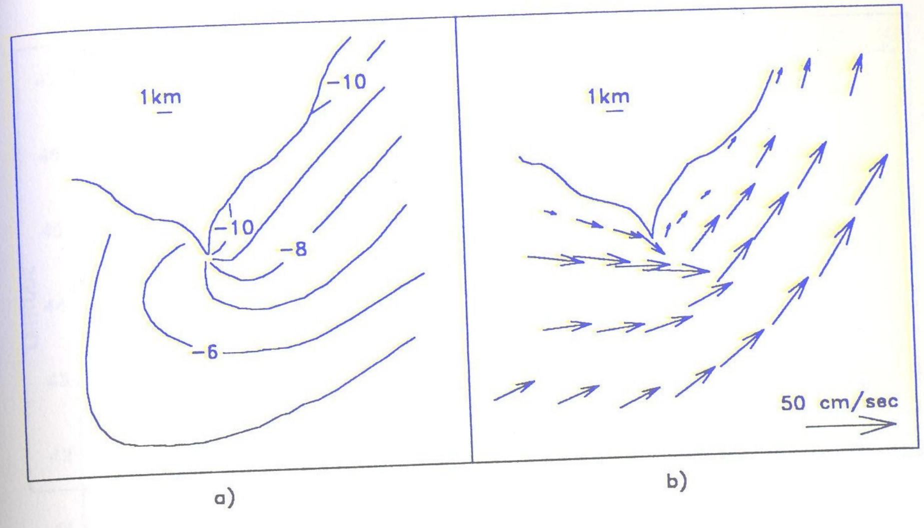


*Figure 1.* Model solution for distribution of a) sea level (cm) and b) vertically mean current velocity near cape Kaliakra under conditions of south(10 m/sec) wind

with the full isolines (downwelling) area over the North-West continental shelf slope.

An important feature of CZ are anticyclonic gyres, which exist in some parts of CZ almost continuosly (see [6]). In the north-west part of the Black Sea anticyclonic gyres are usually observed in CZ near cape Kaliakra and to the south-west of Crimea. Presently the physical reasons for their permanent character are not well known. [10] hypothesized that their stability is due to the vertical buoyancy flux determined by deepening of surface waters in CZ.

[7] used a nonlinear barotropic model on nonregular coordinate system for studying the processes of anticyclonic gyres formation in the region near Cape Kaliakra. The relatively fine grid step near the cape (500 m) allowed to reproduce precisely the vorticity balance in this region. Numerical experiments showed that anticyclonic vorticty here is generated when the model is forced by south and south-west winds. Considerable lowering of sea level is observed in the model solution for this case in a small region, of about 2-3 km extent, around Cape Kaliakra, (Figure 1). This result is in good agreement with field observations which show that under south and south-west winds intensive upwelling occurs in a small region (of scale of several

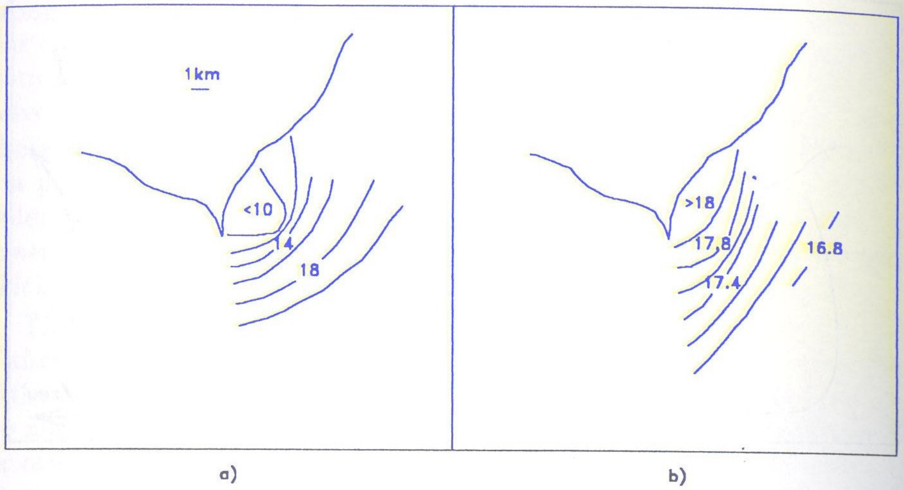


*Figure 2.* Surface a)temperature and b) salinity distributions observed during upwelling near Cape Kaliakra (in July 1987)

kilometers) near Cape Kaliakra (see Figure 2).

According to [7], the dynamic balance in the upwelling region differs significantly from the geostrophical balance, and is characterised by local intensification of horizontal circulation and relatively high divergence of current velocity. Evaluation of vorticity equation terms, presented in Table. 1, shows that vorticity production near Cape Kaliakra is mainly due to the processes of vorticity stretching and turbulent diffusion. Vorticity production in this region has values several orders higher than in the middle shelf and open sea areas.

We should mention that the barotropic model applied by [7] is not able to simulate the complicated baroclinic processes of gyre dynamics in CZ. However, evaluation of the vorticity balance using this model allows us to hypothesize that the nonlinear processes of vorticity production in the small upwelling region near the cape could play an important role in Kaliakra anticyclonic gyre dynamics.



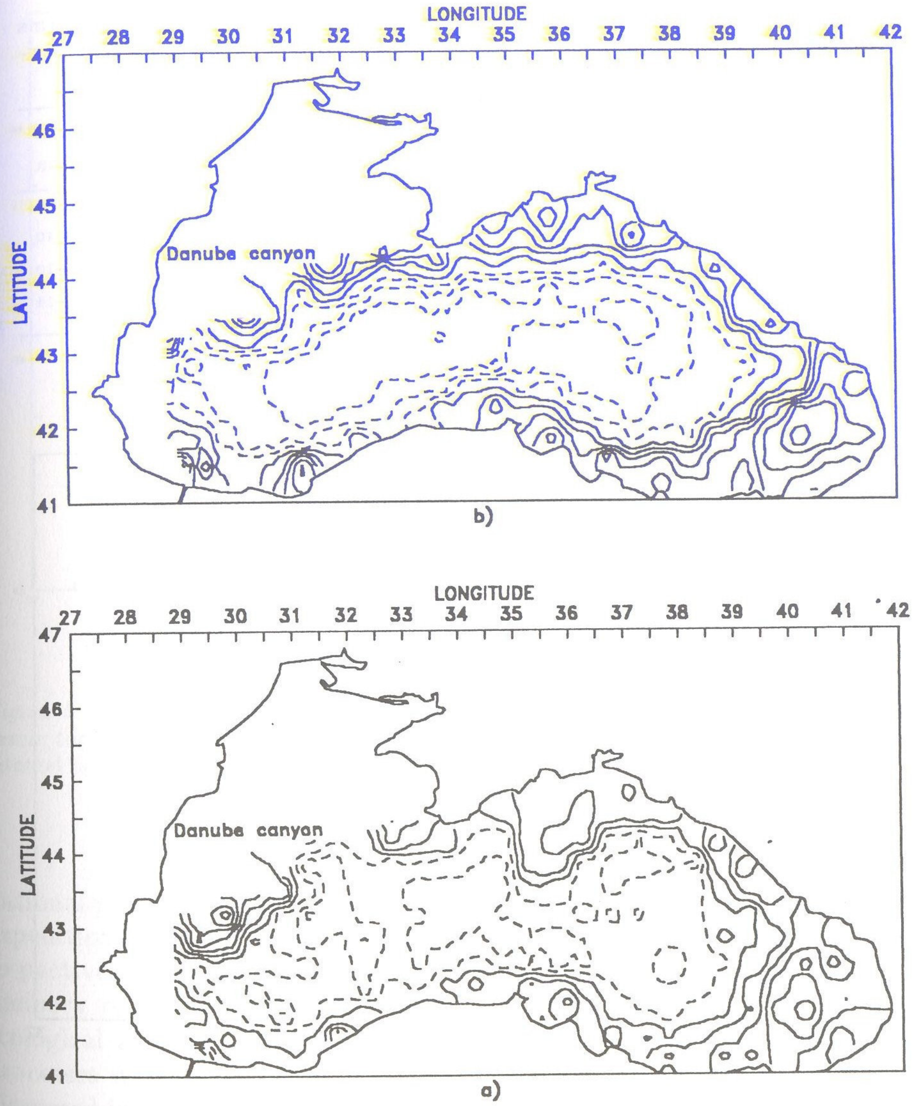


*Figure 3.* Topography of $\sigma_t = 16$ isopycnical surface as measured during a)HydroBlack 91 and b) ComSBlack 92a expeditions. Contour interval is equal to 10 m. Full lines correspond to negative values and broken lines - to positive

TABLE 1. Model estimation of barotropic vorticity balance equation terms ($sec^{-2}$), determining the main mechanisms of vorticity production at four positions in Western part of the Black Sea

| | Vorticity stretching | Bottom friction | Wind forcing | Turbulent diffusion |
|---|---|---|---|---|
| Cape Kalikra | $-1,42.10^{-9}$ | $-5,87.10^{-10}$ | $1,16.10^{-13}$ | $-1,84.10^{-9}$ |
| Cape Emine | $-2,02.10^{-9}$ | $2,39.10^{-10}$ | $-9.65.10^{-10}$ | $7,23.10^{-10}$ |
| middle shelf area | $-2,45.10^{-11}$ | $1,89.10^{-10}$ | $-2,51.10^{-10}$ | $-1,18.10^{-10}$ |
| deep water area | $2,06.10^{-13}$ | $3,18.10^{-15}$ | $5,55.10^{-17}$ | $4,08.10^{-14}$ |

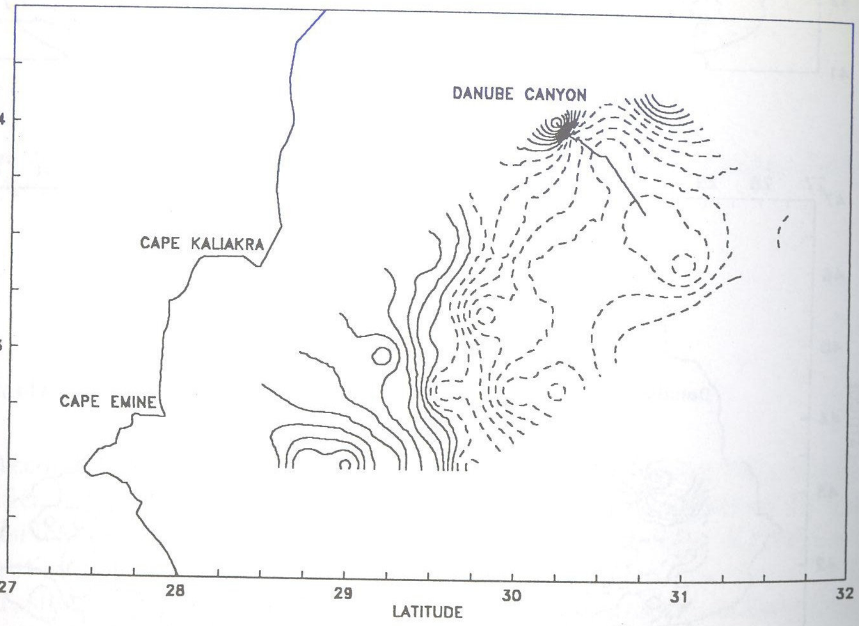


*Figure 4.* Topography of $\sigma_t = 16$ isopycnical surface as measured during CoMSBlack 94a expedition. Contour interval is equal to 5 m. Full lines correspond to negative values and broken lines - to positive

## 3. On Vertical Exchange Processes in the Convergence Zone

The experimental data presented in this section were obtained during three cruises conducted as part of the CoMSBlack and NATO TU Black Sea inter-



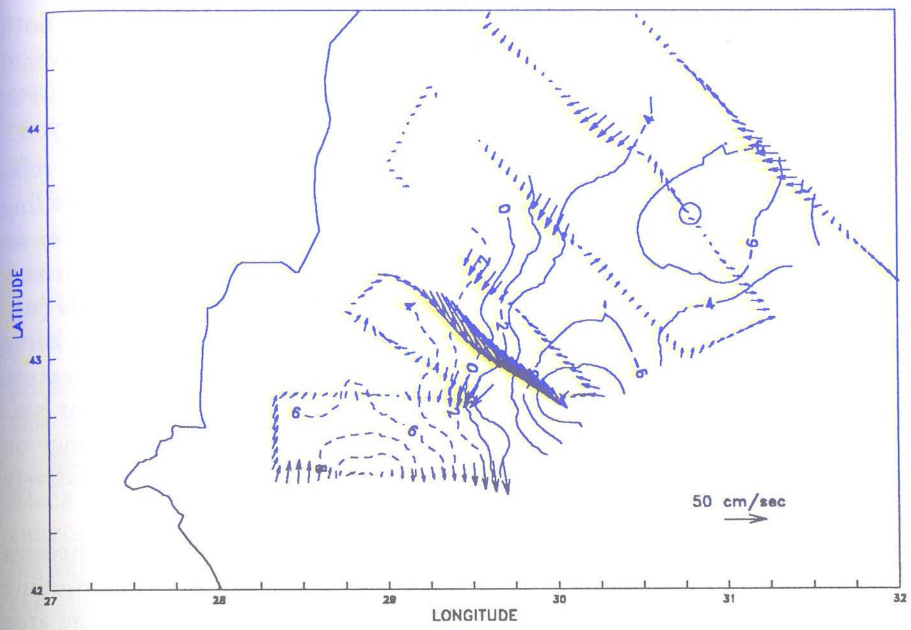


*Figure 5.* Optimally interpolated surface velocity ADCP measurements and 5 db dynamic topography (referenced to 500 db) distributions during CoMSBlack 94a. Contour interval is 2 cm.

national projects. The HydroBlack 91, CoMSBlack 92a and CoMSBlack 94a expeditions were conducted in September 1991, July 1992 and April 1994 respectively. Detailed description of these expeditions as well as some preliminary results of data analysis are presented in [3]; [11]; [12]; [2]. Some ecological aspects of the vertical exchange processes and particularly the processes which take place in CZ as observed during CoMSBlack 92a are discussed in [2].

The topography of the isopycnal surface $\sigma_t = 16$ for the HydroBlack91 and CoMSBlack92a cruises are shown in Figure 3. The positive values of the surface elevations in the central part correspond to the upwelling area whose formation and variability is connected to the MRC dynamics. The CZ in the north-west part of the sea lies in downwelling area over the continental shelf slope.

In both the CoMSBlack 92a and HydroBlack 91 cruises, two anticylonic gyres were observed in the CZ, to the east of cape Kaliakra and to the south-west of Crimea respectively. Downwelling areas in the centres of both anticyclones correspond to the minimum values of depths of the isopycnal surface $\sigma_t = 16$. In both cruises, upwelling was observed in the area between the anticyclons (see Figure 3), which is in the vicinity of Danube canyon.

As mentioned above, the Kaliakra and Crimea anticyclones are relatively stable gyres (see [6]). This gives rise to the question: Is the upwelling above the Danube canyon also a persistent feature? In this connection we should mention that the long term data of [4] show that minima in surface temperature distribution are often observed during spring in this (upwelling) region. The relatively low temperatures are explained [4] as being due to the divergence of the flow here. According to [4], the temperature minimum near the Danube canyon is not well pronounced in other seasons, possibly due to the fact that the upwelling has a greater influence on the surface temperatures during spring, when the mixed layer is relatively shallower, as it starts to develop.

One can expect that the upwelling is related to the dynamic processes which occur in the canyon. On the other hand, the size of the upwelling area is much larger than the width of the canyon, i.e. a relatively large area outside canyon is involved in the upwelling process. During HydroBlack'91 the upwelling area size was comparable to the size of anticyclonic gyres.

The cruise plan of CoMSBlack 94a expedition included a hydrographic section over the canyon in order to obtain data which may help in understanding the upwelling in this area.

It is known that persistent vertical motions are observed in the regions over many canyons of the world ocean (see [8]). According to [9] a dynamicaly significant reason for upwelling or downwelling in canyons can be the specific dynamics here. These are characterized by a relatively small scale (determined by the canyon width) of motion and a dynamic balance which is away from geostrophity. Persistent vertical motion is observed especially in the regions of relatively constant direction of pressure gradient (see [9]). The diagnostic computations of the Black Sea circulation by different authors (see [3]; [6]; [11]; [12]; [15]; [16]) showed that the pressure over the shelf is usually higher than in deep water area, i.e. there exists a relatively constant direction of pressure gradient from the deep water area to the coast. One can expect that in this case downwelling should take place over the Danube canyon.

The topography of the isopycnal surface $\sigma_t = 16$ during the CoMSBlack 94a expedition, Figure 4, supports this conclusion. A sharp area of downwelling is observed over the canyon. Since the downwelling area has a relatively small size it is observed at only one station over the Danube canyon section. The downwelling is supported indepentently by ADCP measurements. Optimaly interpolated data of ADCP measurements of currents



in the surface layer are presented on Figure 5. The optimal interpolation method suggested by [14] was applied for smoothing of the ADCP data over each shelf section. The distribution of the current velocity shows the convergence of the surface flow in a relatively wide area around the canyon and hence supports the presence of downwelling here.

The surface current velocities, Figure 5, are approximately parallel to the isolines of dynamic topography in almost the whole region. A significant crossisosterical (ageostrophical) flow is observed mainly in the region over the Danube canyon.

The downwelling region over the canyon has a relatively small size (comparable with the size of the canyon), however, the surface flow divergence and upwelling occur over a much larger region(see Figures 4 and 5).

We should mention that in the earlier cruises (HydroBlack 91, CoMSBlack 92a) no hydrographical stations were made in the vicinity of the canyon and only the upwellig area was observed near the Danube Canyon, because the douwnwelling area has a size much less the distance between the stations (see Figure 5 and [3]).

## 4. Conclusions

On the basis of the observations and model results discussed above regarding the processes of vertical exchange in CZ over the north-west part of the Black Sea, it can be concluded that relatively intense and permanent regions of upwelling and downwelling exist near Cape Kaliakra and Danube canyon, as a result of dynamic processes occuring in a relatively small area (with space scale of about several kilometers). The high slope of isopycnical surfaces here, which result from the upwelling and downwelling, provides conditions for intensive alongisopycnal mixing between the surface coastal waters (near cape Kaliakra and Danube canyon) and the central downwelling area of anticyclonic gyres. The vertical buoyancy flux, which is due to alongisopycnal flux and topographically induced processes of upwelling and downwelling, can be considered as a possible mechanism for providing potential energy to anticyclonic gyres and as a factor which maintains their persistency.

## 5. Acknowledgments

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### 1. Introduct

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