Influence of surface currents on the nutrient fluxes from the shelf to the deep part of the Black Sea

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Abstract. Functioning of marine ecosystems strongly depends on nutrient supply. One of the key sources of nutrients in the Black sea is rivers runoff, concentrated mainly on the northwestern shelf (NWS). Due to surface currents waters from NWS propagate into deep part of the basin and transport nutrients into interior basin. Study of this exchange of water mass and nutrients between the NWS and the deep part of the Black Sea is a goal of this work. It is based on the results of numerical modelling evolution of physical and biogeochemical fields of the Black Sea. The interdisciplinary model of the Black Sea ecosystem consists of a circulation model and a biogeochemical one, describing the interactions between different components of the marine ecosystem. It is shown, that nutrient fluxes between NWS and deep sea are defined by intensity and character of surface currents, which depend on regional wind stress vorticity.

1. Introduction

One of the main sources of nutrients entering the upper layer of the Black sea is rivers runoff. Most of this flow occurs on the northwestern shelf (NWS), which is under increased anthropogenic pressure. The NWS, which occupies 16% of the sea area, receives about 65% of all rivers runoff into the basin. This leads to an increased content of nutrients and, as a consequence, bio-production in the shelf waters. With the help of water exchange, the nutrients penetrate from the NWS into the deep-water part of the Black Sea basin. This can be seen in the images obtained by satellite color scanners. In addition, in winter season cold waters formed on the NWS penetrate into the deep part of the basin. It can be observed on satellite maps of the sea surface temperature. Thus, due to the currents waters from the NWS penetrate into the Black Sea interior. In this paper, we study the dependence of the magnitude of nutrient fluxes between the NWS and the deep part of the Black Sea on the nature of the circulation of the upper layer of the Black sea.

2. Data and methods

The fields of currents and parameters of the marine ecosystem on a regular grid obtained by numerical simulation are used to study the transport processes. The interdisciplinary model of the Black Sea ecosystem consists of two main blocks: a circulation model and a biogeochemical model describing the interactions between different components of the marine ecosystem. The fields of the Black Sea currents used in the study are the result of physical reanalysis for a twenty-year period (from 1993 to 2012) [1]. The basis of reanalysis is a z-level model based on the approximation of a system of primitive equations of ocean dynamics [2]. The used version of the model has a horizontal spatial grid pitch of 4.8 km and 35 vertical calculation levels. This spatial resolution in addition to large-scale allows adequately
describing mesoscale processes in the Black Sea. The boundary conditions on the free surface of the sea for the equations of the circulation model were the parameters of atmospheric forcing obtained by the results of atmospheric reanalysis ERA-Interim (ECMWF): near-surface wind, heat and fresh water flows, and solar radiation.

The Black Sea circulation model includes assimilation of satellite measurements of the sea surface temperature (SST) and anomalies of the sea surface height. The sea surface temperature was taken from the GHRSSST and NODC archives, and for the last period from the OSI TAC archives. To assimilate data on the sea surface height, all available satellite altimetry data for the reanalysis period from NASA, AVISO, and SL TAC archives were used.

The biogeochemical block of the Black Sea ecosystem model includes 15 state variables and describes the processes in the upper 200-meter sea layer. The space step and the calculated levels correspond to the circulation model. The temporal evolution of the ecosystem components is described by the transport–diffusion equations, which in the right hand part include the terms of the source–sink type, describing the interaction between the components of the ecosystem. In places of mouths of the large rivers the fluxes of nutrients proportional to their concentration and intensity of a river runoff were set. An important feature of the biological part of reanalysis is the assimilation of satellite colour scanners data. These data are two-week fields of surface concentration of chlorophyll-a prepared on the basis of SeaWiFS, MODIS and MERIS products according to the algorithm specially developed for the Black Sea [3]. To check the quality of the reanalysis product it was compared with in-situ measurements. The validation has shown that the obtained fields describe the real thermohaline and biogeochemical structure of the Black Sea quite well [1, 4].

3. Results and discussions

The study of the exchange of nutrients between the NWS and the deep part of the Black Sea was carried out using currents and biogeochemical parameters on a regular grid obtained from the reanalysis described in the previous section. The boundary of the NWS consists of three main parts: near Cape Chersonesus, Cape Kaliakra and along the isobath of 200 m between them.

A key role in the nutrients fluxes is played by water exchange between the NWS and interior basin, the main part of which occurs through the zonal cross section near Cape Kaliakra and through the lateral boundary. Average monthly values of water mass fluxes through these surfaces in the upper 50 m layer are presented in figure 1 (upper panel). The water flux through the zonal section in Cape Kaliakra is...
almost always directed from the NWS, while the flux through the surface formed by the isobath of 200 m is directed mainly to the shelf. There is a fairly good correlation between the high values of the first flux and the low values of the second one. The lower panel of the figure 1 demonstrates the graph of changes in the kinetic energy density of the currents in the Black Sea upper layer, derived from reanalysis. Maximum values of the kinetic energy correspond to the maximums of the mass fluxes from the shelf at Cape Kaliakra and minimums of the mass fluxes through the lateral surface, respectively.

The main element of circulation in the upper layer of the Black Sea is intense Rim Current, localized in the area of the continental slope. It forms a large-scale cyclonic gyre, which can weaken and break into separate eddies. Usually intense jet flows are observed in the winter season. In summer time the surface circulation attains its most disorganized form, identified by a series of cyclonic eddies within the interior basin and accompanying larger coastal anticyclonic eddies around the periphery. High values of the kinetic energy density correspond to the cases when intense Rim Current is observed. Figure 2 shows examples of monthly averaged currents in the upper layer of the western part of the Black Sea for cases of high kinetic energy (figure 1).

Figure 2. Season-mean surface currents for autumn 2000, winter 2003, autumn 2005 and winter 2010.

These maps demonstrate a well pronounced Rim Current jet, which comes partially on the shelf in the area of the Eastern edge of the NWS. As a result, the mass flux of water through the surface, bounded by isobaths of 200 m, is directed from the deep sea to the shelf and has maximum absolute values. The mass flow through the zonal cross-section in Cape Kaliakra, on the contrary, is directed from the shelf and also has maximum values (figure 1).

Figure 3. Season-mean surface currents for spring 2004, spring 2005, summer 2008 and summer 2011.
Figure 3 shows examples of the surface currents in western part of the Black Sea for cases of low values of the kinetic energy in figure 1. There the Rim Current can be observed only fragmentarily. Most obviously it is shown in the map for spring 2005, but the center of the flow in this case is shifted to the south of the NWS and its impact on the water exchange with the shelf is small. In general, the upper layer currents on this examples have disorganized form with a large influence of vortex structures on the mass transport. As a result, water fluxes across the NWS boundaries have minimal absolute values and can be directed in the opposite direction with respect to the cases shown in figure 2.

Fluxes of nutrients and bio-production from the NWS to the deep sea depend mainly on the flow of fluid that carries impurities. However, in contrast to mass fluxes, the fluxes of impurities also depend on difference of concentrations. The concentration of nutrients in the surface layer of the Black Sea on the NWS is much higher than in the deep part, which is caused by rivers discharging. Accordingly, the increased concentration of bio-production is also observed on the NWS, which is clearly seen on the satellite maps of chlorophyll distribution. A higher concentration of nutrients in the NWS leads to a generally positive flux into the deep sea. Figure 4 shows the fluxes of inorganic nitrogen (nitrate, nitrite and ammonium) from the shelf to the deep sea through the surface along 200 m isobath (upper panel) and zonal cross sections near Cape Kaliakra (lower panel).

![Figure 4](image)

**Figure 4.** Monthly-mean inorganic nitrogen fluxes from NWS (grey line – running averaged).

Fluxes of inorganic nitrogen near Cape Kaliakra are almost always positive, and their maximum values coincide with the maximums of the mass fluxes through this section. However, these maximums in the graph for nitrogen concentration are more pronounced, due to its higher concentration on the NWS. Nitrogen fluxes through the surface along the 200 m isobath have both positive and negative values, in contrast to mass fluxes through this surface, which were mostly negative. At the same time, the minimum values of inorganic nitrogen fluxes correlate with the maximums of fluxes through the zonal section.

Variations in nutrient fluxes from the NWS to the deep part of the Black Sea form different patterns of nutrients spatial distribution. Figure 5 presents monthly averaged maps of inorganic nitrogen concentration in the surface layer of the Black Sea corresponding to circulation shown in figure 2.
Figure 5. Surface nutrient distributions for November 2000, March 2003, November 2005, March 2010.

The maps show distribution of nutrients in narrow strip along the western coast and extending quite far along the southern coast. Moreover, the maximum concentration of inorganic nitrogen on the NWS is pressed down to the western coast. Such a pattern can be explained by currents in the surface layer. All these cases are characterized by surface circulation with a pronounced intensive Rim Current along the depth drop, which is pressed down to the shelf. A powerful jet of Rim Current along the slope prevents from impurity transfer across isobaths. Moreover, on these currents maps, we can see that on the shelf surface currents are directed mainly to the western direction. To compensate this flow, a narrow, intense southwards jet is formed near the western coast. It transports waters with the most concentrated part of the nutrients to the place where they are picked up by the Rim Current flow, which transports them up to the Anatolian coast.

Figure 6. Surface nutrient distributions for May 2004, May 2005, July 2008, August 2011.
However, the above-described surface distributions of nutrients on the NWS are not always observed. Figure 6 presents examples of surface distribution of inorganic nitrogen which are qualitatively different from that presented in figure 5. These surface nutrient concentrations correspond to the circulations shown in figure 3. A characteristic feature of the circulation in the examples given in this figure is the absence of a clearly defined jet of the Rim Current, with the exception of the spring circulation of 2005. However, in this case, its rod in the northwestern part passes far enough from the edge of the shelf. In addition, in all cases illustrated in figure 3 currents on the NWS are directed to the north and do not transport the impurity to the deep-water part of the basin. As a result, the greatest values of nutrients on maps in figure 6 are concentrated in a small area near river estuaries.

Thus, the presented examples of the surface concentration of inorganic nitrogen distributions show, that surface currents make a decisive contribution to transport of nutrients and exchange between the shelf and the interior part of the basin. At the same time, currents are important not only in the deep part of the sea, but also on the shelf. Cases when nutrients spread far along the coast, correspond to the surface circulation with a pronounced Rim Current jet, which is pressed to the edge of the shelf and the western shore of the Black Sea. At the NWS, surface currents are directed to the west, as a result along-shore current is formed, which transports the impurity to the south, where it is picked up by the Rim Current.

![Figure 7](image)

**Figure 7.** Monthly-mean wind stress vorticity in western part of the Black Sea.

The circulation in the Black Sea is of a cyclonic nature, which is mainly due to the cyclonic nature of the atmospheric circulation in the region. It is shown [1] that the pattern of the surface circulation (the presence of a pronounced jet of Rim Current or not) depends on vorticity of the wind stress field over the Black Sea: the higher is value of the vorticity, the more intensive the Rim Current is. Figure 7 shows variability of the wind stress vorticity, averaged over the area of the western deep part of the Black Sea. For this estimation parameters from the atmospheric reanalysis ERA-Interim were used. These atmospheric fields were also used as boundary conditions on the free surface for the circulation model equations. High positive values of the wind stress in figure 7 correlate well with the high values of the kinetic energy density of the surface currents in figure 1. Thus, we can conclude that the vorticity of the wind stress field plays a significant role in the nature of the distribution of nutrients and their penetration from the NWS into the deep part of the Black Sea.

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References
[1] Dorofeyev V L, Sukhikh L I 2017 *Izv. Atm. and Oceanic Physics* **53** (2) 224–32
[2] Korotaev G K, Oguz T, Dorofeyev V L, Demyshev S G, Kubriakov A I, Rutner Yu B 2011 *Ocean Sci.* **7** (5) 629–49
[3] Suslin V, Churilova T 2016 *Int. J. Remote Sensing* **37** (18) 4380–400
[4] Dorofeyev V, Sukhikh L 2018 *Int. J. Remote Sensing* **39** (24) 9339–55