Progress in Oceanography 167 (2018) 44–63

Contents lists available at ScienceDirect

Progress in Oceanography

journal homepage: www.elsevier.com/locate/pocean

Thermohaline structure, transport and evolution of the Black Sea eddies from hydrological and satellite data

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ARTICLE INFO

Keywords:
Mesoscale eddies
Stratification
Eddy transport
Thermohaline structure
Vertical velocity
Geostrophic velocity
Eddy evolution
The Black Sea
The Rim current

ABSTRACT

Combination of altimetry-based method of eddy identification and historical hydrological measurements for 1992–2015 is used to analyze the thermohaline and dynamic structure of the Black Sea eddies and its relation with eddy intensity, eddy age and season of a year. Anticyclonic eddies (AEs) are characterized by negative salinity anomalies, which can reach −1.7 psu at the depth of the main halocline. The temperature anomalies are positive in their upper layers, and negative in the deeper layers, because of the vertical displacement of the waters of the Cold Intermediate Layer (CIL). Cyclonic eddies (CEs) have the opposite structure with increased salinity, colder upper layers and warmer deeper layers. Thermohaline anomalies in the eddies of both signs are maximal in summer, while in winter they are shallowest and minimal. The displacement of pycnocline in eddies causes the decrease/increase of stratification in the upper layer of AEs/CEs and opposite increase/decrease in their deeper layers. It also causes the deepening/uplift of the layer of maximum geostrophic vertical shear in AEs/CEs. The latter is the probable reason of the observed higher intensity and deeper penetration of orbital velocities in AEs than in CEs. The changes of isopycnals positions during the eddies' lifetime are used to quantify the evolution of vertical velocity in AEs and CEs. In the beginning of AEs life during intensification phase, vertical velocity is directed downward, while during the decaying phase it change its sign and is directed upward. The opposite is observed in CEs. Vertical velocity is maximal at the pycnocline depth of 100–110 m with values changing from $(-8 \text{ to } 8)*10^{-6}$ m/s in AEs, and from $(+5 \text{ to } -25)*10^{-6}$ m/s in CEs. Eddies thermohaline structure and altimetry-derived orbital velocity is tightly related. This relation obtained in the study and altimetry-derived data on the distribution of eddy frequency, translational speed and orbital velocity is used to quantify eddies salt, heat content and transport in the basin. The transport velocity of water in the eddies core (2–4 cm/s) is significantly smaller than the average velocity of the large-scale currents (~10–40 cm/s). Such slowing causes the "relative" transport of eddies against the mean flow direction. This effect leads to the accumulation of brackish and cold water in the deep layers of east Black Sea and maintain the observed east-west asymmetry of the basin thermohaline fields.

1. Introduction

The Black Sea (BS) is a semi-enclosed basin of the Mediterranean Sea. Sharp halocline at the depths 50–100 m, induced by the large riverine inflow at the surface layers and the inflow of salty Mediterranean waters in the deeper layers, separates the upper and the deeper layers of the basin (Blatov et al., 1984; Özsoy and Ünlüata, 1997; Ivanov and Belokopytov, 2013). During winter convection cold waters do not penetrate through the halo-pycnocline and form Cold Intermediate Layer (CIL) at 50–150 m deep with a lowest temperature (T < 8 °C) and high amount of oxygen. Strong stratification is one of the reasons of the anoxic and almost lifeless conditions in the Black Sea deep layers below 100–200 m depth (Konovalov and Murray, 2001).

Black Sea dynamics largely affect the thermohaline and chemical structure of the basin. The main feature of the basin large-scale dynamics is the cyclonic Rim current rounding the basin over the continental slope (see scheme in Fig. 1). Overall cyclonic circulation pushes the halocline upward in the center of the sea and downward over the continental slope. The abundance of intense baroclinic eddies observed in the basin is another important element of the Black Sea dynamics. Eddies play a significant role in the horizontal exchange of salt, heat, and nutrients in the basin (Sur et al., 1994; Sur and Ilyin (1997); Ginzburg et al., 2000,2002a,b; Staneva et al., 2001; Oguz, 2002; Zatsepin et al., 2002, 2003; Shapiro et al., 2010; Kubryakov et al., 2016,

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https://doi.org/10.1016/j.pocean.2018.07.007
Received 8 December 2017; Received in revised form 4 June 2018; Accepted 24 July 2018
Available online 25 July 2018

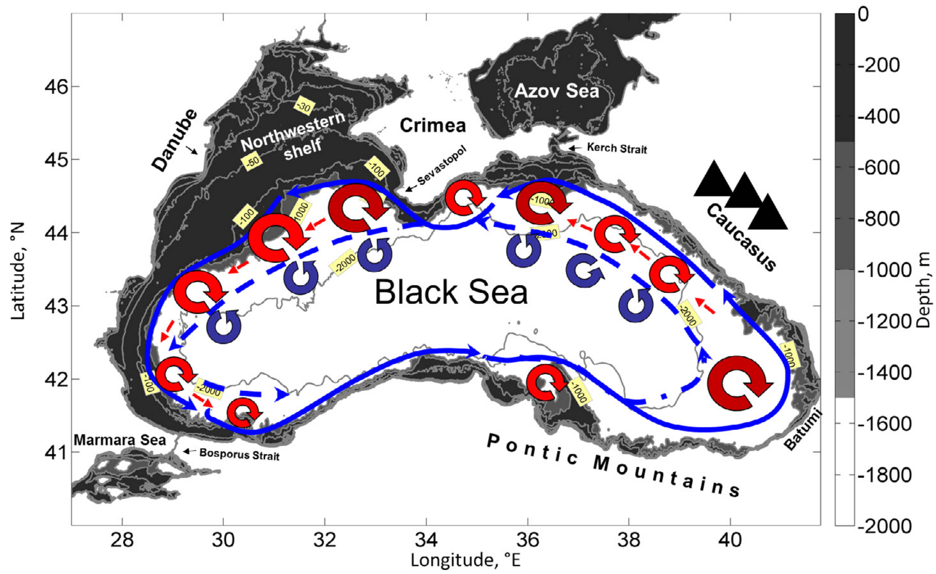

Fig. 1. Schematic presentation of the Black Sea dynamics. Solid blue arrows – the Rim current position in winter season, blue dashed arrows – the Rim current position in summer season, red circles – mesoscale anticyclones; blue circles – mesoscale cyclones.

2018a). Convergent/divergent motions in the eddies influence the thermohaline and oxic structure of the basin, vertical mixing and entrainment of nutrients into the upper layers (e.g. Latun, 1990a; Oguz et al., 1993; Krivosheya et al., 2000; Zatsepin et al., 2003). Usually anticyclones are observed on the coastal right side of the Rim current, while cyclones are formed to the left from the jet (Krivosheya et al., 1997, 1998) In summer season the Rim current weakens and large anticyclones are formed over the continental slope as a result of current instability (Kubryakov and Stanichny (2015b)). Hydrological measurements (e.g. Latun, 1990a; Korotaev et al., 2006) show that large anticyclones in the Black Sea can penetrate down to 500–1000 depths, therefore affecting the turbulence generation and ventilation in the deepest layers of the basin.

Thermohaline structure of the Black Sea eddies has previously been investigated in a number of studies basing on hydrological data (Latun, 1990a,b, 1995; Golubev and Tuzhilkin, 1990, 1992; Ovchinnikov and Titov, 1990; Oguz et al., 1992, 1993, 1994;Oguz and Besiktepe, 1999; Oguz, 2002; Krivosheya et al., 1997, 1998, 2000; Titov, 1992, 2002; Ginzburg et al., 2002a, 2008; Zatsepin et al., 2003) and numerical modeling (Staneva et al., 2001; Enriquez et al., 2005; Demyshev and Dymova (2013); Zalesnyi et al., 2013, 2016; Zhou et al.,2014; Korotenko, 2015). Vertical movements in the eddies displace the isopycnals surfaces that leads to the ascend/descend of all thermohaline and chemical layers (see review in Ginzburg et al., 2008; Ivanov and Belokopytov, 2013). Particularly, the depth of the minimum temperature of the CIL can decrease down to 110–220 m in anticyclonic eddies (AEs), depending on their intensity, and rise up to 30 m in cyclonic eddies (CEs) (Oguz et al., 1992; Krivosheya et al., 1998; Titov, 2002; Zatsepin et al., 2003; Akpinar et al., 2017) from its average values of 60–90 m for the continental slope. Convergent motions in an intensifying AEs lead to the accumulation of the surface and CIL waters in their core. As a result, the width of the CIL can increase considerably in the AEs (Blatov et al., 1984; Latun, 1990a; Oguz et al., 1993; Krivosheya et al., 2000; Ivanov et al., 2001; Staneva et al., 2001; Zatsepin et al., 2003; Akpinar et al., 2017). The CIL waters are rich in oxygen, and AEs can be regarded as an effective storages and transporters of oxygen in the basin (Latun, 1990a; Stanev et al., 2014). The upper boundary of the anoxic zone, extremely important for the Black Sea ecosystem, is related to the isopycnal $\rho = 1016.2\ kg/m^3$, which can decrease in AEs down to 150 m (Zatsepin et al., 2003) or even to 190–210 m (Latun, 1990a; Krivosheya et al., 2000) from its average values of ~130 m over the continental slope. In CEs the anoxic waters come closer to the surface to the depths of 100–110 m (Zatsepin et al., 2003). The depth of the pycnocline varies from 50 m in AEs to 100 m in CEs by the estimates of (Ivanov and Belokopytov, 2013), that can significantly impact the vertical mixing in the basin.

Satellite optical and infrared measurements provide a lot of information about eddies distribution in the BS, their characteristics, pathways, and evolution (Sur et al., 1994; Sur and Ilyin, 1997; Ginzburg et al., 2000,2002a,b; Oguz, 2002; Zatsepin et al., 2003; Mityagina et al., 2010; Shapiro et al., 2010; Karimova, 2011). Satellite altimetry gives a possibility to reconstruct the Black Sea geostrophic circulation from space with unprecedented time resolution (Stanev et al., 2000; Korotaev et al., 2003). These data provide new insights into the eddies dynamics and their geographical distribution (Sokolova et al., 2001; Korotaev et al., 2003; Zatsepin et al., 2003). Altimetry-based methods of the eddy automated identification allow to obtain large amounts of statistical data about the Black Sea eddies Kubryakov and Stanichny (2015a,b), Kubryakov et al., 2016). These methods were used to study the different properties of these eddies, such as radius, lifetime, vorticity, their spatial distribution, seasonal and interannual variability (Kubryakov and Stanichny, 2015a,b; Kubryakov et al., 2016).

A combination of the altimetry-based information about the eddies position with hydrological data can be used to pick out all the measurements inside the mesoscale eddies, providing a possibility to obtain new information about the eddies' vertical structure (Chaigneau et al., 2011). Such methods have successfully been used to study the eddies thermohaline and dynamic structure, their impact on the heat and salt transport in different regions of the World Ocean (Chaigneau et al., 2011; Kang and Curchitser, 2013; Castelao and He, 2013; Frenger et al., 2015; Yang et al., in press; Amores et al., 2017; Sun et al., 2017) and globally (Dong et al., 2014).

Since the beginning of the high-resolution satellite altimetry era in 1992, many hydrological measurements in the Black Sea (more than 70 000 profiles) have been obtained and collected in the Marine Hydrophysical Institute (MHI) database. The emergence of several Argo buoys in the Black Sea since 2002 gives additional contribution to our knowledge about the Black Sea thermohaline structure. Particularly, the Argo data were used for the study of dynamics in the deep layers (Korotaev et al., 2006; Markova and Bagaev, 2016), vertical mixing (Stanev et al., 2014), the thermohaline, and oxic structure of the basin (Belokopytov, 2011; Belokopytov and Bagaev, 2012; Ivanov and Belokopytov, 2013; Stanev et al., 2014; Korotaev et al., 2016; Capet et al., 2016; Falina et al., 2017; Akpinar et al., 2017).