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Intense ventilation of the Black Sea pycnocline due to vertical turbulent exchange in the Rim Current area

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ABSTRACT

This paper presents new observational data, which indicate that deep ventilation events in the aerobic zone extending across the upper part of the permanent pycnocline may occur sporadically in the Rim Current area, even during relatively warm seasons, when the seasonal thermocline is still notable. The strongest observed event of this type occurred on November 2014 off the continental shelf break near Gelendzhik Bay. Vertical profiles of dissolved oxygen were accurately measured using an SBE 52-MP Conductivity, Temperature, Depth (CTD) probe equipped with a fast-response SBE 43F oxygen sensor mounted on a moored Aqualog automatic mobile profiler. The analysis of the profiling data from October 6 through December 16, 2014, from depths between 35 m and 215 m revealed an anomaly on November 6–7. The dissolved oxygen exceeded the background levels by more than 0.2 ml/l (8.9 μM) at the 14.9–15.7 kg/m^3 isopycnals in the pycnocline and reached approximately 1 ml/l (44.66 μM) for short periods. The peak absolute value of the dissolved oxygen reached an exceptionally high value of approximately 0.3 ml/l (13.4 μM) at the 15.9 kg/m^3 isopycnal. The ventilation event increased the temperature by ~0.2 °C at depths of 120–160 m. The simultaneous observations of both the thermohaline stratification and the ocean currents suggest that the ventilation event was associated with the sinking of pycnocline waters in the near-bottom Ekman layer along the continental slope and intense vertical turbulent exchange in the Rim Current area near the continental slope. The ventilation of the pycnocline when the overlaying upper ocean is stably stratified sharply differs from the convection reaching the Cold Intermediate Layer during extensive cooling of the sea surface. Indications of such ventilation events were also found in the Aqualog mooring data archive from 2012.

1. Introduction

Hydrophysical processes largely govern the vertical distribution of oxygen in the Black Sea; in particular, they affect the deepness of the aerobic zone (e.g., Murray et al., 1991; Konovalov et al., 2006). The supply of oxygen from the upper layers to the permanent pycnocline is vital for the Black Sea ecosystem because it constrains the upper boundary of the hydrogen sulfide zone within the stably stratified area and prevents this boundary from moving upward to the sea surface. The surface layer, which is less saline due to river runoff, is separated by the permanent halocline from the deeper layer, which has a higher salinity due to inflow from the Mediterranean (e.g., Öszoy and Ünlüata, 1997, and references therein).

To understand how the Black Sea ecosystem functions, the common variability patterns of the distribution of low oxygen concentrations should be studied. For example, the oxygen variability in its gradient layer (oxycline) affects diurnal mesozooplankton migrations and the behavior of sea copepods. The finestructure measurements in acoustic sound-scattering layers during the warm season show that daily mesozooplankton migrations extend to depths at which the oxygen content is 2.0–3.7 ml/l (~90-165 μM), a thin layer above the hydrogen sulfide contamination zone at the 15.7 kg/m^3 isopycnal that is occupied by a mesozooplankton diapause that primarily consists of copepods (Ostrovskii and Zatsepin, 2011). The short-period variability is superimposed on the basin-scale environmental changes, which are still poorly understood.

The main source of oxygen for deeper waters is a permanent Cold Intermediate Layer (CIL) at depths of 50–130 m. In 2011–2012, the temperature in the core of the CIL was usually higher than 8 °C (Stanev et al., 2013), which is not consistent with the commonly accepted definition of the CIL as a layer with temperatures lower than 8 °C (e.g., Konovalov et al., 2005). Recently, atmospheric

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warming was shown to reduce the ventilation of the lower oxic layer by lowering CIL formation rates, whereas the basin-averaged oxygen penetration depth has decreased (Capet et al., 2016; see also Pakhomova et al. (2014)). A comprehensive analysis of a composite historical set of oxygen profiles indicated a significant thinning of the oxic layer from 140 m in 1955 to 90 m in 2013, which is the shallowest annual value recorded during that period (Capet et al., 2016).

The oxygen supply into the aerobic zone of the Black Sea is associated with the following processes.

First, oxygen-rich Mediterranean waters steadily enter the SW Black Sea through the Bosporus Strait. These waters, which have high salinities, are mixed with the Black Sea waters to form the so-called Bosporus or Mediterranean Plume (see Buesseler et al. (1991) and references therein, Murray et al. (1991), Gregg and Öszoy (1999) and Stanev et al. (2001)), which descends the continental slope of the Black Sea and causes numerous intrusions that oxygenate the water column up to 500 m deep. Vertical profiles of the redox potential provide evidence of lateral injections, or intrusions, of oxygen at distances of up to 150 km from the Bosporus Strait in 2001 to 95 km in 2003 (Glazer et al., 2006a, 2006b). The oxygen supply of the Mediterranean waters is most remarkable in the area adjacent to the Bosporus Strait. Recently, the impact of lateral intrusions from the Bosporus Plume with emphasis on the spatial and temporal variabilities of the chemical properties of the oxic and suboxic layers in the western Black Sea was studied by Tuğrul et al. (2014).

Winter convection with fairly strong cooling conditions also results in intense ventilation of the aerobic zone in the Black Sea (Ovchinnikov et al., 1993; Ivanov et al., 2001). In the past few decades, this convection has occurred, at most, once every several years. However, the hydrophysical processes of oxygen penetrating the permanent pycnocline layer are still not entirely clear in this non-tidal basin. Oguz (2002) found that even intense turbulent mixing generated by a large loss of buoyancy during an exceptionally cold winter season is unable to generate sufficiently dense water to overturn and temporarily supply oxygen to the suboxic zone. During this convection process, which commonly occurs in the winter, water is renewed in the CIL and reaches its minimum temperature and maximum oxygen saturation by spring. The oxygen content of the CIL after the winter convection determines the initial and boundary conditions for the differential of the dissolved oxygen in the oxycline as well as the rate of the downward oxygen flux. The CIL relaxes until the next winter convective mixing event, its temperature slowly increases, and the oxygen content decreases. The results of microstructural measurements in the center of the Black Sea's Western Gyre (Gregg and Yakushev, 2005) demonstrated a sharp decrease of the vertical oxygen flux in the lower part of the permanent pycnocline. The dissipation of turbulent energy and the turbulent exchange factor both decreased by more than one order of magnitude in the layer between the bottom of the CIL and the top boundary of a barely oxygenated zone. For this reason, the turbulent flux of dissolved oxygen in this layer also decreased rapidly with depth, regardless of its consumption. Later studies of the fine structure and microstructure (Zatsepin et al., 2007) confirmed these conclusions for the NE periphery of the sea (Gregg and Yakushev, 2005).

In addition to convection in the open part of the Black Sea and the Bosporus inflow, the following processes can be considered suppliers of oxygen to the upper layer of the permanent pycnocline (Zatsepin et al., 2007):

- turbulent mixing maintained by vertical shear of the current in the areas of strong horizontal flows;
- vertical mixing due to breaking internal waves;
- sinking of the water in a near-bottom Ekman layer over the continental slope and its convective mixing with the overlying stratified waters.

The redistribution of local mixing effects over the entire sea should be caused by quasi-horizontal isopycnic advection and mesoscale eddy diffusion. The main feature of the upper layer circulation is a strong counterclockwise boundary current over the continental slope known as the Rim Current with speeds up to 0.5–0.7 m/s and cross-frontal scales O(40 km); see (Ivanov et al., 2007) and references therein. The phase of current variability is determined by the seasonal cycle of the wind stress curl. Generally winter circulation consists of gyres in both eastern and western sub-basins but in spring the Rim Current encircles the entire sea along the continental slope. The currents weaken significantly during summer and in the fall the Rim Current usually breaks into mesoscale and submesoscale eddies (Ivanov et al., 2007).

In the Black Sea, the Rim Current often becomes unstable due to atmospheric forcing. This instability results in the generation of large meanders and mesoscale eddies with diameters of approximately 2–7*Rd, where Rd is the local Rossby radius of baroclinic deformation. In the deep part of the sea, the upper limit of $Rd =$ 15–20 km. Hence a mesoscale eddy may exceed 100 km in diameter. Such long-lived (up to 8 months) quasi-geostrophic eddies and eddy dipoles enhance the exchange of water between the deep sea and the coastal shelf area (e.g., Ginzburg et al., 2002; Zatsepin et al., 2003). These eddies also influence the structure and dynamics of the Rim Current. The coastal shelf of the northeastern Black Sea is only 2–10 km wide, which is much narrower than the Rim Current and the horizontal dimensions of the deep mesoscale eddies. Over such a narrow shelf, the ocean's mesoscale dynamic structures dissipate. In addition to damping of the mesoscale dynamics, the shelf currents are characterized by the eigenmodes of the variability and strongly depend on both the wind forcing (e.g., upwelling) and the river runoff. The influence of the bottom topography on the currents and eddies is likely also considerable. Hence, the ocean dynamics that are influenced by external forcing near the shelf exhibit enhanced submesoscale variability (1–10 km, 1–10^2 h) (Zatsepin et al., 2011; Lavrova et al., 2012, 2013). The dynamic processes associated with the mesoscale current meanders and the meso- and submesoscale eddies should contribute substantially to the variability of the dissolved oxygen over the Black Sea continental slope.

Studies of ventilation processes in the stratified bottom part of the aerobic zone of the Black Sea require both Lagrangian and Eulerian measurements. Recently, using data from free-drifting profiling floats with oxygen sensors, Stanev et al. (2014) identified two regimes of ventilation in the pycnocline: a central cyclonic gyre regime during the winter and a continental slope boundary layer regime dominated by anticyclonic eddies during the summer. According to Stanev et al. (2014), these regimes are characterized "by different pathways of oxygen intrusions along the isopycnals and vertical oxygen conveyor belt organized in multiple-layered cells formed in each gyre."

Regular frequent observations at fixed geographic locations, where the conditions are most favorable for the development of vertical turbulent mixing, were initiated in 2011 using a moored Aqualog automatic mobile profiler (http://aqualog.ocean.ru/) at approximately 44°29.4′N, 37°58.3′E (Fig. 1), off Gelendzhik Bay (Ostrovskii et al., 2013). The data analyzed in the present article are vertical profiles of the thermohaline and dynamic parameters as well as the dissolved oxygen content data obtained by the Aqualog profiler in the autumn of 2014.

The technical issues related to the design of the oxygen sensors for seawater are beyond the scope of this work. We only note that such sensors must be sufficiently rapid, accurate and sensitive to be appropriate for vertical profiling in the bottom part of the