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Formation and changes of the Black Sea cold intermediate layer

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ABSTRACT

The local properties of the cold intermediate layer (CIL) in the Black Sea are examined over the period 1960–2015 using a 3D numerical model and realistic forcing. The simulations demonstrate a substantially large multi-annual CIL variability and confirm two major mechanisms: (i) cooling of the surface waters in the basin interior in winter and (ii) transportation of cold water masses, formed in winter on the North Western Shelf (NWS), transported by the main cyclonic current and by mesoscale eddies on the shelf break. Both processes are crucially important for the CIL formation, as was suggested by previous studies. The novel element of the present study is the quantification of the relative importance of these mechanisms during a prolonged time-period. In particular, (i) plays a key role for the CIL formation in the basin interior, while (ii) controls CIL renewal along the main cyclonic current and basin exterior, as well as in the south-eastern region. In order to isolate the effects of basin circulation and the NWS cold water masses contribution, the distribution of passive tracer originating from the NWS is studied. Tracer distribution in the basin interior indicates that a large fraction of the cold NWS water is transported via the main cyclonic current to the eastern convergence and anticyclonic areas. A smaller fraction of the cold NWS water is transported to the central part of the basin. The cooling capacity of the CIL is highly variable and decreases drastically in the last decade of simulation, approaching zero due to changes in regional weather conditions.

1. Introduction

Climate-ocean interaction and its effect on marine internal dynamics has been the focus of a considerable number of studies (e.g., Levitus et al., 2005). The Black Sea is of special interest due to its specific thermohaline structure, whose components respond in different ways to regional, climate induced changes. The Black Sea is connected with the Mediterranean Sea through the Bosphorus Strait and exhibits strong inter-annual variability in its water mass properties. A warming trend in the surface waters of the Black Sea is not clearly identifiable for the last 50–100 years (Polonsky and Lovenkova, 2004; Shapiro et al., 2010; Miladinova et al., 2017), while a positive trend has been described for the last 30 years (Miladinova et al., 2017). It seems likely that the changes in the regional climate affect other thermohaline characteristics first (such as temperature of intermediate layers), followed by an increase in the sea surface temperature. One of the most fundamental features of the Black Sea is the cold intermediate layer (CIL), however its generation and evolution are not yet entirely understood. Characterised by temperatures of less than 8 °C in the subsurface Black Sea's waters, the CIL contains the lowest Black Sea temperatures and most of its pycnocline (Filippov, 1968; Oguz et al., 1993; Oguz and Besiktepe, 1999; Ovchinnikov and Popov, 1987). This layer persists throughout summer, located below warm surface waters that exhibit temperatures greater than 25 °C in some regions, and above the relatively warmer (9 °C) deep waters. In winter, the CIL is mixed with the colder surface waters. It is preserved throughout the year by strong vertical gradients in the permanent pycnocline that prevent the water in the CIL from mixing with adjacent layers. The CIL usually can be found between 25 and 150 m depth. Because of a doming of the isopycnals, as a result of the cyclonic mean circulation, it is shallower at the centre of the basin and deeper at the edges (Murray et al., 1991).

As a distinct feature of the thermohaline structure of the Black Sea, the CIL was a subject of many research analyses and discussions. One of the most important disagreements among the authors is the main source of the CIL water renewal. The earliest attempts to explain the CIL water sources dates from 1938 (Ivanov et al., 1997). The convective mixing during winter season was suggested as a dominant mechanism. Following studies found that the core of the CIL was often deeper than the lower boundary of the winter mixed layer (Filippov, 1968). Moreover, the properties of the cold water masses are somewhat similar in the entire basin and did not appear to be strongly related to the local air temperature and wind. Then, when the coldest surface temperatures were found on the wide Nord Western Shelf (NWS), a hypothesis about advective origin of the CIL was put forward. This hypothesis assumed that the CIL was formed in the north-western part of the sea and subsequently spread around the basin by the large-scale cyclonic current, called Rim Current (Filippov, 1968). Since the wind induced mixing is found to be an important mechanism of water exchange in the central part of the sea, the important role of the central part of the sea is enhanced by the finding that the CIL is mainly formed in the centres of

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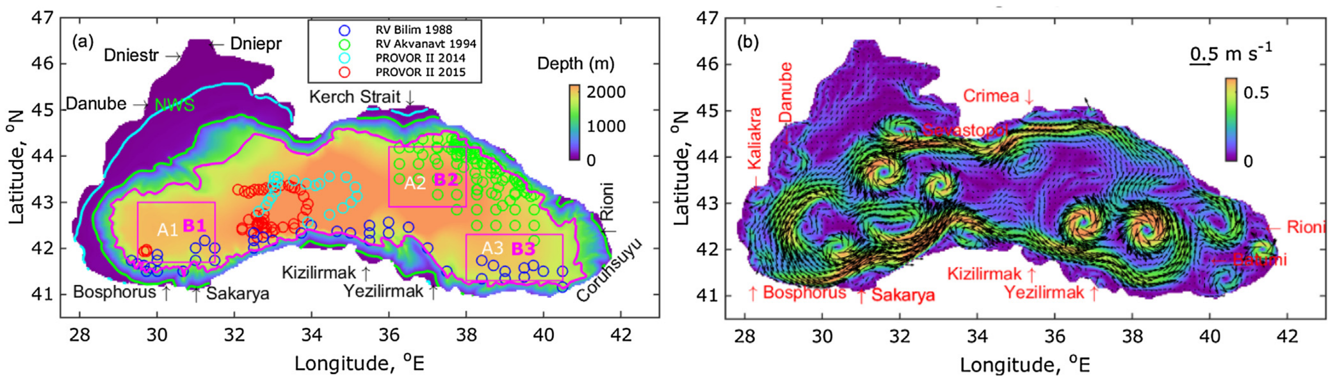

Fig. 1. (a) Bathymetry and location map of the Black Sea and the main rivers. The 1500 m isobath and the boundaries of the three particular compartments B1, B2 and B3 are drawn in magenta. The 200 m isobath is given in green and the 46 m isobath in cyan. A1, A2 and A3 are the locations in the basin interior used for extracting of the vertical tracer profiles. The locations of in-situ observations are denoted with coloured circles: blue – RV Bilim 1988; green –RV Akvanavt 1994; cyan –PROVOR II 2014 and red PROVOR II 2015. (b) Example for the Black Sea surface circulation based on the simulated weekly mean velocity vectors at 5 m depth for the second week of August 2014. The colour bar represents the surface speed, while arrows show both speed and direction. Names and approximate locations of several popular anticyclonic eddies are also shown. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

cyclonic gyres (Ovchinnikov and Popov, 1987). The formation phase is followed by an isopycnal spreading phase of the newly formed cold water masses toward the periphery, where cold water masses are distributed by the Rim Current over the entire basin. On the contrary, several studies (Ivanov et al., 1997; Oguz and Besiktepe, 1999) put forward the argument that the CIL waters of the central part of the sea do not reach the coastal area, where the CIL is thought to be formed from the cold water coming from the zone of anticyclonic eddies on the continental slope of the north-western part of the sea. Horizontal flow of cold water coming from the anticyclonic zones on the continental slope of the north-western part of the basin into the deep sea region is considered as one of the principal mechanisms of CIL formation (Sorokin, 2002; Stanev et al., 2003; Shapiro et al., 2011).

Recently, there is growing consensus that the CIL is formed both in the centres of cyclonic gyres and on the continental slope of the north-western region (Ivanov et al., 1997; Staneva and Stanev, 1997; Stanev et al., 2003). There are only few quantitative estimations in the literature (see the review in the Ivanov and Belokopytov, 2013) of the CIL volume formed in the main cyclonic gyres, in the NWS and in the north-western continental slope. The reported results are inconsistent. For example, the CIL volume formed in particular geographical areas based on temperature and salinity climatological data (Belokopytov, 2004) is estimated as follows: 60% western and 15% eastern gyres and 25% north-western continental slope and NWS. While Stanev et al. (2003) estimated, based on model results, the relative contribution of the areas as: 42% continental slope of the NWS, 20% NWS, 28% both cyclonic gyres, and 10% easternmost part. Interestingly, studies relying on observational data only estimated a higher or equal contribution of the open sea to the CIL formation. Studies based on both data assimilation and numerical modelling emphasise the dominant role of the Black Sea north-western part in CIL formation.

Many studies have focused on the inter-annual variability of the CIL, which is most often associated with climatic and weather conditions: the cooling of the deep sea-surface in winter (Belokopytov, 2011; Ivanov et al., 2000; Dorofeev and Sukhikh, 2017) or the transport of cold water masses from the NWS. Understanding the CIL evolution has been hampered by a lack of continuous long-term winter observations of water mass properties and vertical structure (Ivanov et al., 2000; Belokopytov, 2011). The existing evidence on the CIL properties is either incomplete (for example, there is less data for the eastern part of the sea) or scarce (e.g. low data density during 1995–2010). Many validated models have already been used to simulate the Black Sea hydrodynamics and in this way fill the gaps in observations. Models can be divided in two main groups: data assimilation models and models with strong or weak relaxation. The first type of models failed to reproduce the CIL properties in a realistic way, but are appropriate for operational short term forecasting (CMEMS, http://marine.copernicus.eu/). The second type needs surface salinity time series to be collected for a long period, which are not available, so these models are not appropriate to study the long term CIL variations. The knowledge of the CIL formation and evolution is not only important for the elucidation of water mass dynamics of the Black Sea. It can also help to explain the dynamics of the Black Sea ecosystem (Oguz et al., 2006). Changes in the Black Sea thermohaline structure appear to play a key role in the exchange of nutrients and biological matter and can alter food-web dynamics on several time scales (Daskalov, 2003). There is a clear need for novel in-situ observations and numerical simulations that can assess the effect of the weather conditions on the heat content and temperature of the CIL over short (seasons) and long (decades) time scales.

For this reason we used herein the 3D hydrodynamic model presented in Miladinova et al. (2017), which is capable to simulate the mesoscale circulations and thermohaline structure in the Black Sea for a continuous multi-decadal period without any relaxation towards external fields. The study focuses on the long term CIL evolution in time and space by means of numerical simulations of the Black Sea's hydrodynamics and passive tracers. We study thoroughly the driving forces for the cold water formation and spreading. An additional aim is to quantify specific CIL property changes.

In the present contribution, the CIL formation locations and the mechanisms of cold intermediate water masses circulation in the basin have been established. Two main mechanisms for the CIL formation are examined in detail: (i) cooling of the surface waters in the basin interior (of depth greater than 200 m) in winter and (ii) transportation of the cold water masses, formed in winter on the NWS, by the Rim Current and subsequently by mesoscale anticyclonic eddies on the shelf break.

2. Materials and methods

2.1. Study area

The general circulation of the Black Sea is driven by the wind stress as well as by the large freshwater input from the Danube River and other big rivers (Fig. 1a). The circulation is further constrained by the steep topography around the basin periphery that consists of narrow shelves and a maximum depth of around 2200 m. There exists a major basin wide cyclonic circulation (Rim Current) with well pronounced western and eastern gyres (Oguz et al., 1992, 1994). It is has been recently found that the Black Sea circulation system involves a spatially