



Vertical structure and seasonal evolution of the cold intermediate layer in the Baltic Proper

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ABSTRACT

Vertical T,S structure of waters of the cold intermediate layer (CIL) is examined on the base of high-resolution CTD profiles obtained in the Baltic Sea Proper in spring and early-summer periods. Basic elements of the structure of the CIL are identified and possible mechanisms responsible for their formation are suggested. Seasonal evolution of the CIL structure is considered. Its four stages are discussed: formation in early spring; late-spring adjustment; slow summer-time modification; and fall/winter-time washing-out/preconditioning to the next cycle. The mechanisms of mixing and stirring which could be responsible for the observed features of the CIL structure are discussed. It is proposed to consider the Baltic CIL not as a phenomenon which appears during the warm season only, but as a manifestation of a permanently current process of basin-scale water exchange. Further targeted investigations are urged disclosing the role of this exchange in general thermo-haline circulation of the Baltic Sea.

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1. Introduction

In many seas and oceans of the Earth, intermediate waters, or waters of intermediate layers, are characteristically different, in some way or another, from the upper or the lower water layers. As a consequence, many publications are devoted to investigations of mechanisms of generation, of the formation regions, volumes and characteristics of these intermediate waters, as well as of the ways of their propagation within the sea water body. For example, intermediate layers of inland seas are discussed in detail, such as the Mediterranean (Lascaratos et al., 1999; Menna and Poulain, 2010) and the Black Sea (Oguz and Besiktepe, 1999; Staneva and Stanev, 1997; Stanev and Staneva, 2001; Stanev et al., 2003). Recently, Izhitskiy et al. (2014) investigated the thermo-haline structure of the Western Large Aral Sea and found that it had an obvious intermediate layer as well. Mechanisms of formation and evolution of the cold intermediate layer of the Gulf of St. Lawrence are studied in (Cyr et al., 2011).

In the Baltic Sea, the cold intermediate layer (CIL) is an

important characteristic feature of the thermohaline structure (Hydrometeorology and hydrochemistry ..., 1992). The CIL is usually considered to be characteristic of the deep part of the Baltic Sea Proper, and it is also observed in the Sea of Bothnia (Leppäranta and Myrberg, 2009). Previous investigations using monthly averaged temperature profiles showed high correlation between February–March surface temperatures and temperatures of the CIL during the summer period (Hinrichsen et al., 2007). In this and other publications (e.g., the book (Leppäranta and Myrberg, 2009)), the CIL of the Baltic Sea is often called the «winter water»; however, as measurement data show, it should better be termed as «spring water» (see, e.g., Stepanova et al., 2015). This is because it is in early spring when exceptionally cold waters appear in intermediate layers all over the Baltic Sea, and they begin to form what will be called “the CIL” throughout the warm period of a year. Spring-time mixing processes in the Baltic Sea are very complicated and have attracted attention in a number of studies (e.g., Zhurbas and Paka, 1999; Stipa and Vepsäläinen, 2002; Chubarenko and Demchenko, 2010; Chubarenko et al., 2017). All of them highlight obvious contribution of lateral advection to the formation of the summer vertical thermohaline structure, which has a 30–40-m thick cold layer in-between the warmer surface and the bottom waters over the entire sea area. Later in a year, thermohaline fields in the Baltic

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no longer experience such cardinal changes in their vertical structure (see, e.g., Lepäntä and Myrberg, 2009).

This article aims at detailed examination, general physical description and understanding of the Baltic CIL features and their seasonal variations on the base of real-measurement data. As a straightforward continuation of analysis provided in (Stepanova et al., 2015), this study presents, on a broader experimental basis, the general description of structural elements of the Baltic CIL, which could be extracted from a detailed study of the thermohaline characteristics of waters in the Baltic Proper. Analysis of characteristic time variations in the CIL vertical structure permits to suggest the most probable driving mechanisms that contribute to the formation of the observed variations.

Since the goal of this study is to enhance of our physical insight into an evolution of a natural basin, as complicated as is the Baltic Sea, it was of our initial intention to limit this analysis to the data obtained by the direct high-resolution *in-situ* field measurements. Neither data interpolated to standard horizons, nor time or space averages were considered. For the same reason, we did not use numerical modelling data: even though modern numerical models are able to reproduce the CIL *per se* (e.g., Lehmann, 1995), its finer structure (i.e., temperature jumps, quasi-homogeneous or high-gradient sublayers, etc.) cannot be reproduced with existing vertical grid discretizations, and thus no considerations on the formation mechanisms are possible. At the same time, general insight into ongoing processes, obtained directly from the field data analysis, should further be compared with the results of numerical modelling. Such a comparison is on the way, but lies beyond the scope of this paper.

2. Data and methods

The following data obtained by different organizations in the coastal and the deep parts of the Baltic Proper were used for the analysis of the CIL structure and evolution (see the map on Fig. 1).

- The data of CTD-measurements performed in 11 expeditions on the research vessel “Professor Shtokman” of the P.P. Shirshov Institute of Oceanology (AB IO RAS, Kaliningrad), cruises NN 59, 60, 61, 62, 68, 75, 76, 78, 87, 93, 95 – in the south-eastern and northern parts of the Baltic Sea Proper in all the seasons (March, May, July, October) from 2004 to 2008. They were used for the analysis of seasonal variations of general vertical thermohaline structure and the structure of the CIL, as well as for the comparative analysis of T,S characteristics of coastal and CIL waters. This data set (except for one expedition – cruise No 76 to the northern Gotland Basin and the Gulf of Finland) was examined in detail in (Stepanova et al., 2015; complete material presented in Stepanova, 2015a) and served as a background to develop the methodology of the analysis: definition of the CIL boundaries, selection of its permanently existing and temporarily emerging structural elements.

- Data of 2006–2013 of a hydrophysical monitoring program carried out by the AB IO RAS (Kaliningrad) in coastal and open waters of the Gdansk bay and the Russian part of the south Gotland basin. A subset of this data for 2010–2013, including 11 expeditions, was obtained in frames of a specially designed measurement program aimed at investigation of thermohaline structure of coastal and open-sea waters during the period of formation of the CIL (from the beginning of March to mid-May). CTD-profilings were used on a standardized 18-km long cross-section from the coast to the isobaths of 65–70 m (every 500 m along the transect) with a time step of 1–2 weeks. They embraced periods from winter-time vertical mixing regime to summer-time thermal stratification, including transfer of the water temperature across the temperature of maximum density (*T_{md}*). For more details on this data see (Chubarenko et al., 2017).

- CTD data gathered under the HELCOM environmental monitoring program in 2005–2006 along the standard cross-section in the Baltic Sea Proper. These data were kindly provided by the Leibniz Institute for Baltic Sea Research in Warnemünde (IOW) and are available for research purposes by request (<http://www.iowarnemuende.de>). The structure of the CIL at vertical CTD-profiles obtained in 6 expeditions (2005–2006) at the station TF0271 (in the central Gotland basin) was examined. A combination of data from cruise No 76 of r/v “Professor Shtokman” (AB SIO; 23 April – 4 May 2006; the Gulf of Finland – the Gotland basin) and cruise No 11/06/05 of r/v “Gauss” (IOW; 4–12 May 2006; Kiel Bight – northern Gotland basin) allowed us to analyse spatial variations in vertical thermohaline structure in spring along the main long axis of the Baltic Sea.

- CTD profiles from open data bases of the Baltic Sea NEST (Baltic Environmental Database <http://www.balticnest.org>) and ICES (<http://www.ices.dk>) were used from time to time for particular years/situations only, in order to compliment the available (listed above) expeditionary data and verify the analysis of the CIL vertical structure for other Baltic basins.

Vertical CTD-profiles of the expeditions of r/v “Professor Stockman” and archive data from the laboratory of Coastal Systems Study of AB IO RAS were obtained with the vertical resolution of 0.1–0.2–0.3 m. The data of r/v “Gauss” had vertical resolution of about 1 m. The data from the ICES and NEST databases had vertical resolution of 1 m. During pre-processing, biases and reverse motions were manually eliminated from the raw data. Neither data interpolation to standard horizons, nor time or space averages were performed. The density was calculated from the measured *T*, *S*, *p*-data using (Chen and Millero, 1980).

Raw data with various vertical resolutions were used in the analysis. Therefore, it doesn't make sense to compare the values of the vertical temperature gradients at the CIL boundaries. For the analysis, only the depth of the maximum gradient was used.

A detailed analysis of T,S structure of the CIL requires its most possibly exact (mathematical) definition. Following (Stepanova, 2015a; Stepanova et al., 2015), for the purpose of this study the CIL is formally defined as a layer between the depths where the temperature has its maximum negative and maximum positive gradient in vertical (Fig. 2). This definition differs from the one used in other seas with the CIL present in their vertical structure; e.g., in the Black Sea, the 8-C isotherm delineates both upper and lower CIL boundaries (Kolesnikov, 1953). We take advantage to offer the very first formal criterion for the Baltic CIL boundaries, and its obvious merit is taking into account the specific conditions of the Baltic Sea, where both water temperature and salinity significantly change from south to north along the main sea axis, reflecting variations of climatic conditions due to its large geographical extent.

In order to grasp structural features, all the used profiles were first of all analysed by visual inspection of graphical representation. Within the (formally obtained) boundaries of the CIL, the permanently existing and temporarily observed elements of vertical structure (sublayers) were defined. The boundary between the quasi-homogeneous and the gradient salinity sublayers was associated with the horizon where the salinity increase with depth becomes larger than the scale of characteristic variations of the salinity in the upper mixed layer on the given profile. The core of the CIL was defined as the minimum of water temperature (following (Hydrometeorology and hydrochemistry ..., 1992)). Homogeneous in all the physical parameters (water temperature, salinity, density) sublayers were determined as sublayers where variations of all values had the same order of magnitude as in the upper mixed layer on the given profile.

An initial analysis, performed in (Stepanova et al., 2015) on the basis of the data of 8 expeditions by the r/v “Professor Shtokman”

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