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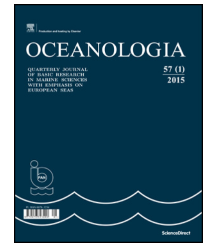

ORIGINAL RESEARCH ARTICLE

Processes and factors influencing the through-flow of new deepwater in the Bornholm Basin

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Summary This paper is based on the idea that the hydrographical conditions in the Bornholm Basin, and any other basin, can be understood from knowledge of general hydromechanical principles and basin-specific factors. Published results on the variability of the vertical stratification are shown and discussed. Such analyses demonstrate the residence time of water at different depth levels. Different modes of currents forced by winds and by stratification gradients at open vertical boundaries are presented. Vertical mixing is discussed and published results for the Bornholm Basin are shown. An experiment demonstrates that the diffusive properties of the enclosed basin, i.e. below the sill depth of the Słupsk Furrow, can be computed quite well from the horizontal mean vertical diffusivity obtained from historical hydrographical observations. A published two decades long simulation of the vertical stratification shows that the through flow and modification of new deepwater in the Bornholm Basin can be well described based on existing knowledge regarding crucial hydromechanical processes. It also suggests, indirectly, that there should be a weak anticyclonic circulation above the sill depth, which is supported by current measurements.

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1. Introduction

When the sea level is higher in Kattegat than in the Arkona Basin, salty water flows across the shallow sills in Fehmarn Belt and the Öresund into the Arkona Basin. Because this water has higher salinity and density than the surface water of the Arkona Basin, it descends along the seabed whereby the potential energy of the dense water is transferred to kinetic energy. Due to friction against the seabed and the overlying water, kinetic energy is transformed to turbulent energy that causes entrainment of the overlying water whereby the volume flow of the inflowing water increases and its salinity decreases. The inflowing saline water is the source of new deepwater in the Baltic proper. In the present paper it is called the new deepwater. Finally, the new deepwater is added to the dense bottom pool in the Arkona Basin. The water from this pool is evacuated through the Bornholm Channel. When this occurs it will undergo further dilution with less dense ambient water in the Bornholm Basin. If the new deepwater has sufficiently high density, it will penetrate into the enclosed part of the Bornholm Basin, below the level of the deepest connection with the Gdańsk Basin (the so-called sill depth) through the Stolpe Channel (Słupsk Furrow). Otherwise it will be interleaved in the halocline above the sill depth from where it may escape the Bornholm Basin through the Stolpe Channel.

The oxygen conditions in the basin water, below the sill level, depend on the rates of supply and consumption of oxygen. Oxygen supply is essentially due to inflowing new deepwater while oxygen consumption primarily depends on decomposition of organic matter sinking down from the surface layer where it is produced. Since the salinity of the new deepwater during an inflow event increases as the inflow progresses (Stigebrandt, 1987a; Stigebrandt et al., 2015), only the later-coming part of very large inflows has high enough salinity to replace the residing deepwater. This means that with the actual rate of vertical mixing, it may take a couple of years before an initially very salty deepwater becomes exchanged. If the long-term oxygen consumption is larger than the oxygen supply, the basin may become exhausted in oxygen and hydrogen sulfide may be added to the water column before the next event of deepwater renewal brings in new oxygen as demonstrated by observations and model simulations in Stigebrandt et al. (2015).

The oxygen conditions are very important for the ecology and the water quality in a basin. Higher forms of life may have difficulties in getting enough of oxygen in hypoxic conditions ($O_2 < 2$ mg L^{-1}). In the Bornholm Basin the bottoms in the deepest part are episodically anoxic (no O_2) and azoic, i.e. they lack animals. This is a large disadvantage for e.g. cod that largely feed on benthic animals. For successful recruitment, cod is depending on the existence of oxic ($O_2 > 2$ mg L^{-1}) water with salinity >11 PSU (e.g. Stigebrandt et al., 2015; and references therein). When oxygen disappears (anoxic), red-ox reactions are reversed and, for instance, the bottom sediment starts to leak phosphorus (e.g. Stigebrandt and Kalén, 2013). This is eventually mixed into the surface layers which increase the biological production which leads to increased oxygen consumption in the deepwater implying expanding bottom areas with anoxic conditions which further increase the phosphorus leakage.

This paper describes and discusses the mixing and through-flow of new deepwater in the Bornholm Basin. The applied approach is to first describe the topography and the hydrographical properties. Thereafter the oceanographic processes influencing the mixing and the through-flow are described. The idea is that the conditions in the Bornholm Basin can be understood from knowledge of general principles and basin-specific factors. Finally some results from a vertical advection-diffusion circulation model are described.

2. Topography, sediment conditions and other external facts

In the central parts, the Bornholm Basin reaches about 100 m depth (Fig. 1). The deepest connection between the Bornholm Basin and the basins east and north of it is 59 m and it goes through the Stolpe Channel. East of the isle of Öland there is an about 46 m deep connection to the West Gotland Basin. Consequently the Bornholm Basin is closed beneath 59 m depth. The horizontal area at this depth equals about 14 150 km^2 and the volume of the closed part beneath this depth equals about 200 km^3 (e.g. Stigebrandt and Kalén, 2013). The vertical circulation of the Bornholm Basin can be thought of as taking place in a so-called diffusive filling-box where new deepwater enters essentially through the Bornholm Strait in the northwest and leaves through the Stolpe Channel in the southeast. During strong inflow events with highly elevated halocline in the Arkona Basin some deepwater may likely enter the Bornholm Basin also across the ~29 m deep sill southwest of Bornholm Island (Lass et al., 2001; Stigebrandt, 1987a).

A map of surficial sediment types shows that bottoms in the deeper parts of the Bornholm Basin usually are muddy and covered by soft material. However, in an area stretching southeastwards from the Bornholm Channel, east of Bornholm Island, bottoms are made up of sand and hard clay (Fig. 2). As further discussed in Section 4.3, it is obvious that the hard bottoms are swept clear of soft matter during occasional events with high-speed dense bottom currents, carrying new deepwater to the Bornholm Basin. Svikov and Sviridov (1994) constructed a map of occasional high bottom speeds based on the properties of the surface sediment.

The Bornholm Basin is the area with the lowest frequency of ice cover in the whole Baltic Sea. The hundred-year wind wave height has been estimated to be 15 m, see Ödalen and Stigebrandt (2013b) for additional information.

The studies referred to in the present paper have largely used hydrographical data from stations BY4 and BY5 in the Bornholm Basin (Fig. 1) but also from stations in neighboring basins. All data can be obtained from official databases. Additional data are available from HELCOM. Furthermore, Nord Stream collected data on salinity, temperature and currents with high vertical resolution in two locations using moored instruments. These and other data are available from Nord Stream (see https://www.nord-stream.com/environment/data-and-information-fund/dif/).

3. Hydrography

Salinity and oxygen concentrations of the water column in the Bornholm Basin are shown in Fig. 3 for the period