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SHORT COMMUNICATION

The inflow in the Baltic Proper as recorded in January—February 2015

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Summary Inflowing saline waters of the Major Baltic Inflow (MBI) in 2014 were recorded in the Baltic Proper in January 2015. After 12 years of stagnation, this inflow brought highly saline (about 20) waters into the Bornholm Basin. As in the previous inflow in January 2003, saltwater moved in the near-bottom layer with a current speed of approx. 25 cm s^{-1}. This paper presents data collected in January and February 2015 and compares them to earlier records from 2000 to 2014.

1. Introduction

Since the 1980s stagnation without any inflow has become the usual state in the deep waters of the Baltic Sea (Dahlin et al., 1993; Jakobsen, 1995; Liljebladh and Stigebrandt, 1996; Matthäus and Lass, 1995). However, extreme non-periodic saltwater inflow events, exchanging water between the North Sea and the Baltic, occur at different intervals, ranging from a few years to about a decade (Franck et al., 1987; Matthäus and Franck, 1992). The occurrence of inflows depends mainly on atmospheric forcing, and over 90% of such events take place during late autumn (Matthäus and Franck, 1992). Until the 1980s the longest period without an inflow event was about 3 years; thereafter, however, a decade elapsed between the major inflows observed in 1983, 1993 and 2003 (Franck et al., 1987; Piechura and Beszczyńska-Möller, 2004). Already over 11 years had passed since the last such event in January 2003. Measurements carried out by the Institute of Oceanology, Polish Academy of Sciences (IO PAN) in January 2015 revealed record-high salinities in the deep layers of the Baltic Proper.

Large inflows (100—250 km^3), usually carrying highly saline waters (salinity 17—23 PSU), represent the most important mechanism by which the deep waters of the Baltic Sea are displaced and renewed (Franck et al., 1987; Matthäus and Franck, 1992). The inflows propagate over the bottom but still substantially mix with the overlying surface water (Burchard et al., 2005; Stigebrandt and Gustafsson, 2003).

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Small inflows (10—20 km^3) are insufficient to displace the deep waters and, because of their much lower density, are eventually trapped between the halocline and bottom water on their pathway (Matthäus, 2006; Stigebrandt, 2001). Large and medium-sized inflows are extremely important to the ecosystem, because they oxygenate the deep basins of the Baltic Sea (Matthäus and Lass, 1995).

The main aim of this paper is to describe the recent saltwater inflow from the North Sea into the Baltic Proper as recorded after passing the Danish Straits and the Arkona Basin.

2. Material and methods

2.1. Study area

The high-resolution hydrographic transects used in this paper were obtained using a towed profiling CTD (Conductivity, Temperature, Depth) system. The main transect (Fig. 1) ran along the axis of deep basins, starting from the Arkona Basin (AB), through the Bornholm Deep (BD) and the Słupsk Furrow (SF), and ending in the Gdańsk Deep (GD).

Since 2000 repeated hydrographic measurements, focused on monitoring the origin of waters flowing into the southern Baltic, have been made in different seasons (at least 4 times per year) during regular cruises of r/v 'Oceania' (Fig. 2). This paper focuses on measurements made during two cruises in 2015 (on January 5—9 and February 23—27).

2.2. Field data

The profiling system consisted of a CTD probe (Seabird 49) suspended in a steel frame towed on a cable behind the vessel (Paka et al., 2006). To ensure measurements of high quality, the temperature and conductivity sensors were calibrated annually by the manufacturer. The suspension system maintained the probe in a horizontal position during profiling, the steel frame protected it from mechanical damage, while a chain fixed below the frame reduced the risk of bottom contact. To obtain a profile, the CTD system was lowered and raised between the surface and bottom by releasing or hauling in a towing cable. The horizontal resolution of about 200—500 m was obtained at a constant ship speed of approx. 4 knots for a basin with a typical depth of 60—120 m. With the CTD probe operating at a frequency of 10 Hz, the vertical resolution of the towed measurements was about 30 measurements per metre. Since 2013, high-resolution profiles of dissolved oxygen concentration have been obtained along the hydrographic transects with the Rinko-I sensor mounted on the towed system.

The velocity and direction of sea currents were recorded continuously using the vessel-mounted Acoustic Doppler Current Profiler (RDI ADCP 150 kHz), set up with a cell width of 4 m.

Data provided by the International Council of the Exploration of the Sea (ICES) were used to extend the Bornholm Deep distribution of temperature and salinity. ICES Oceanographic database, Extractions January 1978—December 1995; Hydrological data. ICES, Copenhagen.

3. Results

During the recent inflow, the temperature distribution along the main transect was slightly different from the typical winter situation in the last decade (Rak and Wieczorek, 2012) in that the waters in the Bornholm Deep and Słupsk Furrow in January 2015 were slightly warmer (about 10°C) than the surrounding ones (Fig. 3). This warm layer was about 10 m thick in the Bornholm Deep and almost twice as thick in the Słupsk Furrow. In the Słupsk Furrow the warm layer was formed by the waters previously occupying the deep layer of the Bornholm Deep, which were raised to 50 m depth and in consequence were able to pass over the Słupsk Sill at the

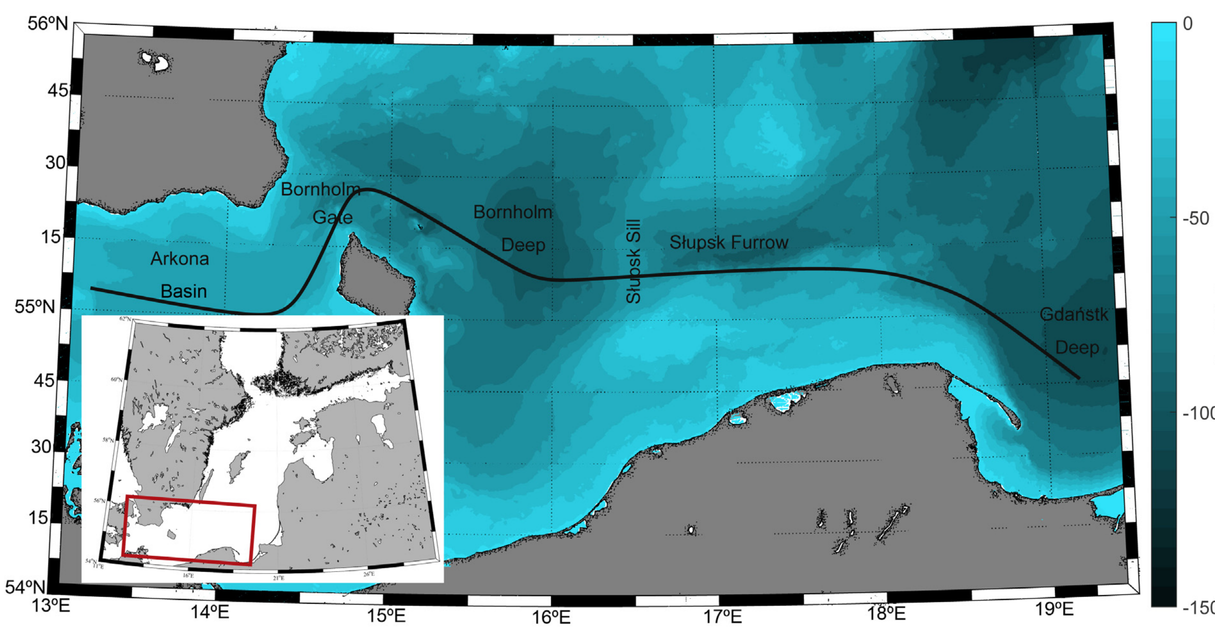

Figure 1 Location of measurements. The main hydrographic transect along the deep basins of the Baltic Proper (2000—2014) is shown as a black line.

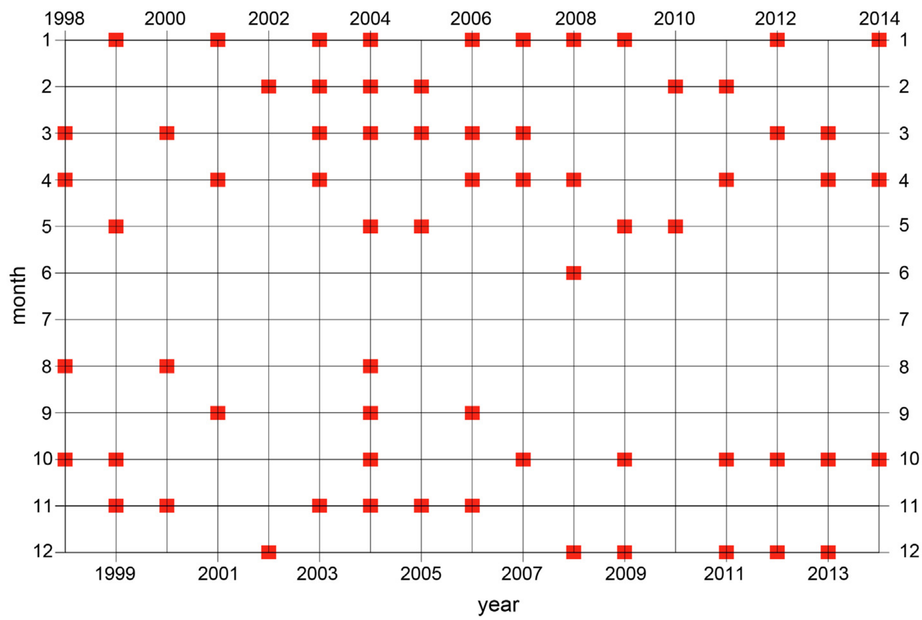

Figure 2 Distribution of r/v Oceania cruises in 1998–2014.

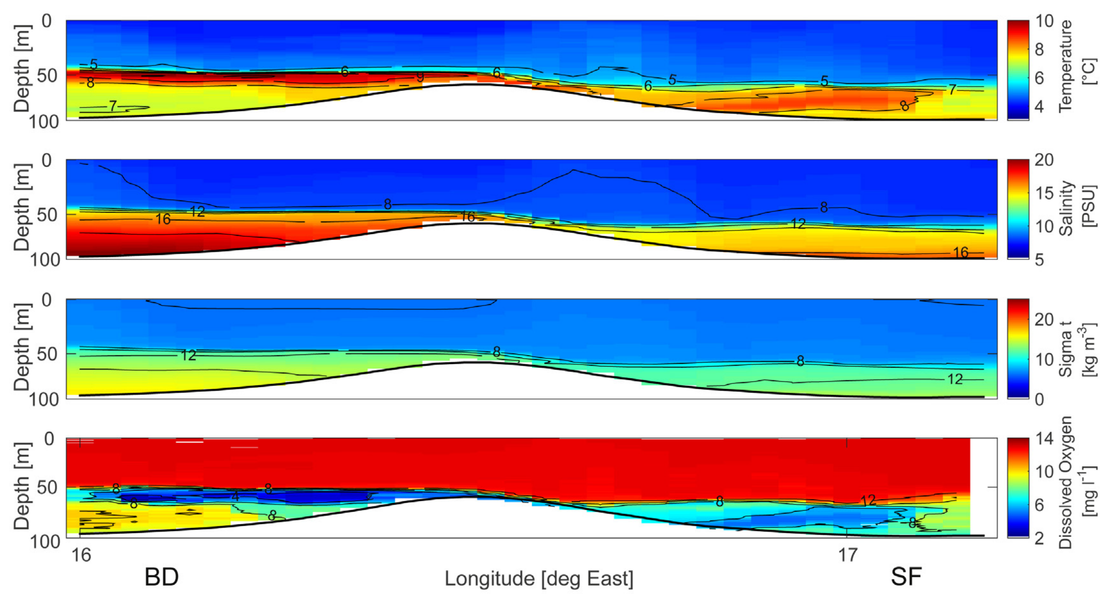

Figure 3 Distribution of temperature, salinity, density and oxygen concentration on the main transect along the axis of the deep basins in the Słupsk Sill area on January 5–9, 2015. BD, the Bornholm Deep; SF, the Słupsk Furrow.

thermocline depth. The thermocline observed along the main section in the Bornholm Basin and Słupsk Furrow was shifted down to a depth of 45–60 m, resulting in an isothermal upper layer with a temperature of about 5°C. Most likely this can be ascribed to the coupled effect of thermal convection due to the positive (upward) heat flux and wind forcing.

The salinity distribution in the upper layers of the Bornholm Deep and Słupsk Furrow was similar to the situation observed in earlier years (Rak and Wieczorek, 2012) with a slightly higher salinity of about 8 PSU measured in relatively small areas (Fig. 3). At the same time, strong rises in salinity to about 20 and 17 PSU in the Bornholm Deep and Słupsk Furrow, respectively, were found in the layer beneath the halocline owing to the recent inflow that had carried extremely saline waters into both basins.

The water originating from the major inflow in 2014 was dense enough to propagate over the bottom layer of the Bornholm Deep, as shown by the density distribution measured in January 2015 (Fig. 3). When the inflow entered the Bornholm Basin, it partially mixed with local waters and pushed them to the halocline depth. After reaching the Słupsk Sill the inflow waters continued over the bottom and crossed the sill into the Słupsk Furrow.

Oxygen concentrations of about 12 mg l^{-1} were recorded in the surface mixed layer (Fig. 3), while in the near-bottom layer of the Bornholm Basin values were lower by

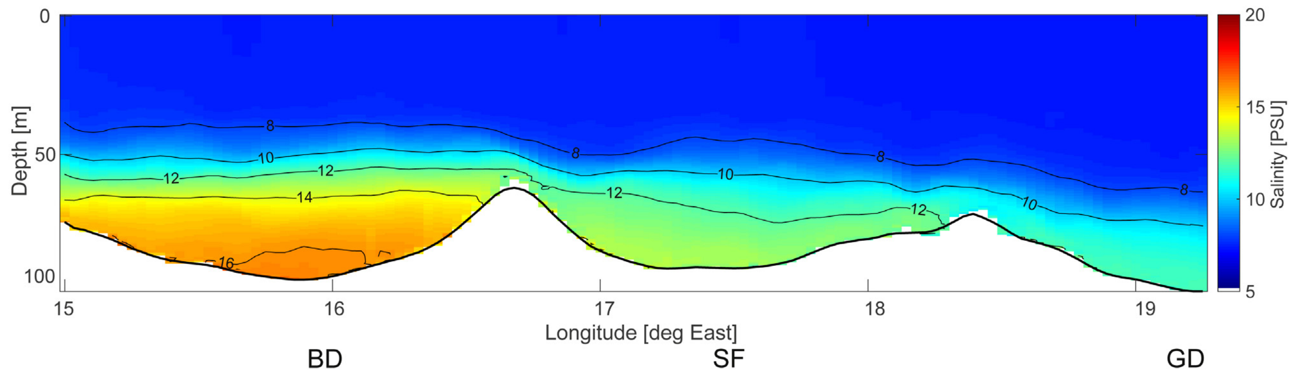

Figure 4 Mean salinity on the main transect, represented by the average of nine cruises in October—November in 2000—2013. BD, the Bornholm Deep; SF, the Słupsk Furrow; GD, the Gdańsk Deep.

4 mg l^{-1}. The Bornholm Deep anoxic waters recorded in January were pushed up towards the halocline and, on crossing the Słupsk Sill, mixed with the inflow waters. There was a difference in near-bottom oxygen concentration of about 6 mg l^{-1} between the areas to the west and east of the Słupsk Furrow.

The salinity distribution in January 2015 was compared to the long-term mean salinity, represented by an average of 9 transects in October—November in 2000—2013 (Fig. 4). The mean salinity distribution in the Baltic Proper was characterized by a slightly deeper halocline in the Bornholm Deep and generally lower salinities than those measured during the 2014 inflow. In the mean situation the halocline is about 5 m deeper than during the recent inflow, which prevents the more saline waters from flowing over the Słupsk Sill. The salinities of the surface layers in the Bornholm Deep and Słupsk Furrow are similar. In the Baltic Proper the largest differences between the mean salinity and the salinity (up to ca 4 PSU) measured during the recent inflow were found in the layer beneath the halocline in the Bornholm Deep and Słupsk Furrow.

The steeper temperature gradient between the surface and bottom layer measured in February 2015 (Fig. 5a) can most probably be attributed to the coupled effect of thermal convection, wind mixing and subsequent cooling of the upper layer. The temperature at the thermocline depth in the Bornholm Deep has remained high since January.

The saline waters that passed through the Słupsk Furrow were recorded in the Gdańsk Deep in February (Fig. 5a). Extremely high salinities of about 20, 16 and 14 PSU were recorded in the Bornholm Basin, Słupsk Furrow and Gdańsk Deep, respectively, after dense and highly saline water originating from the 2014 inflow propagated eastwards along the axis of the main basins. The upward shift of the halocline observed in the Gdańsk Deep was very probably due to the prevailing cyclonic circulation in the basin, or an effect of internal wave.

In February 2015 the near-bottom oxygen concentration was slightly lower in the Bornholm Basin (by approx. 2 mg l^{-1}) than the value measured in January (Fig. 5a). However, the oxygen concentration in the previously anoxic bottom layer increased by 4 mg l^{-1} as a result of mixing processes. Two months later, the water layer beneath the halocline in the Słupsk Furrow had become largely homogeneous. Despite the higher near-bottom oxygen concentration during the inflow, anoxic waters persisted in the Gdańsk Deep until February.

For the measured currents (Fig. 5b), the surface and near-bottom layers were blanked (8 m from the surface and 18% of the total depth from the bottom) owing to the removal of side-lobe effects. In general, moderate current speeds of about 30 cm s^{-1} along the axis of the deep basins prevailed along the most of the transect. Current speeds up to 25 cm s^{-1} with associated velocity error of 0.4 cm s^{-1} were measured in the layer beneath the halocline in the Bornholm Gate. Flows were also faster at the base of the eastern, leeward side of the Słupsk Sill.

Fig. 6 shows the temporal variability of the mean temperature and salinity in the Bornholm Basin, averaged in the layer below 70 m. The mean salinity recorded in the Bornholm Basin in January 2015 had a record-high value in the time series combined from IO PAN data from repeated cruises and the ICES database. Compared to the inflow in February 2003, the maximum salinity observed in the Bornholm Basin in 2014 was 1 PSU higher. The temperature during the recent inflow was similar to that recorded during other early winter cruises (January).

4. Discussion

The inflow of extremely saline waters from the North Sea started to pass through the Bornholm Gate in December 2014 (Mohrholz et al., 2015), bringing more saline waters into the deeper parts of the Baltic Proper. That extreme event created strong vertical and horizontal gradients of salinity and temperature in the studied areas of the southern Baltic Sea. The water from this inflow crossing the Bornholm Basin had a mean salinity of about 20 PSU, a mean temperature of about 8°C, a mean potential density of 17 kg m^{-3} and a mean oxygen concentration of 10 mg l^{-1}. The salinities recorded in January 2015 were the highest in the 16-year long IO PAN record of repeated measurements in the Baltic Proper (Rak and Wieczorek, 2012). In the Bornholm Deep the saltwater influx mixed with and raised the adjacent waters, creating a layer of warm, anoxic waters beneath the halocline. This water body, previously occupying the Bornholm Deep, had originated from a minor inflow in August 2014 (Anderson, 2014). Therefore, the water pushed into the Słupsk Furrow

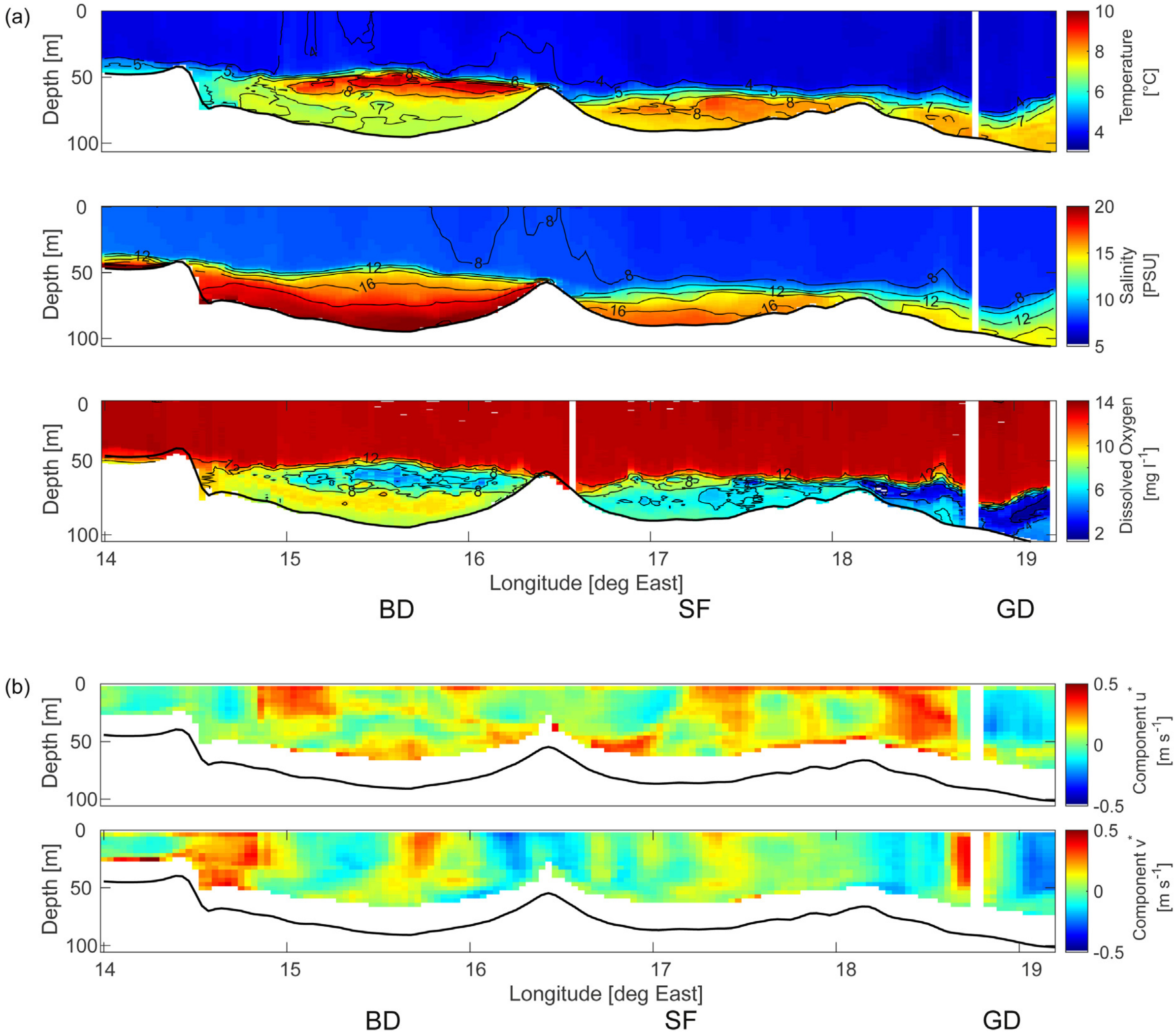

Figure 5 (a) Distribution of temperature, salinity and oxygen concentration on the main transect along the axis of the deep basins in the Baltic Proper on February 23—27, 2015. The vertical white lines represent missing data. (b) The distribution of flow velocity components (u^* parallel and v^* perpendicular to the profile) on the main transect along the axis of the deep basins in the Baltic Proper on February 23—27, 2015. The positive values of u^* indicate direction of flow component along the transect (Fig. 1) from the West to East. The vertical white lines represent missing data. BD, the Bornholm Deep; SF, the Słupsk Furrow; GD, the Gdańsk Deep.

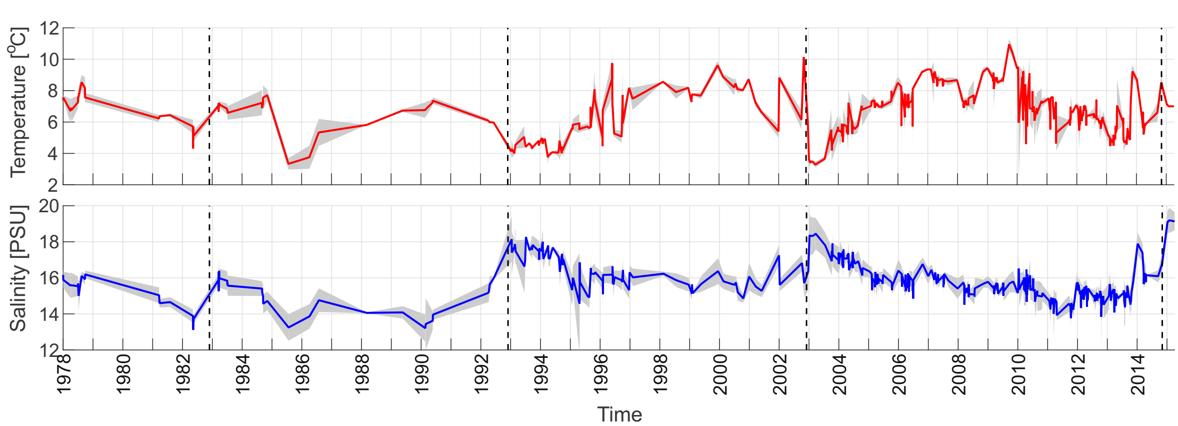

Figure 6 Temperature and salinity averaged between 14.77 and 16.3°E in the layer below 70 m in the Bornholm Basin in 1978—2015. The mean (line) and standard deviation (shaded area) of the temperature and salinity are based on individual cruises. The IO PAN data were extended by data from the ICES database (www.ices.dk/).

was warmer by 4°C and less saline by 3 PSU than the water in the Bornholm Deep originating from the 2015 inflow.

As during the previous inflow, the inflowing water moved over the sea bed with a speed of at least 25 cm s^{-1}. As shown by different authors (Feistel et al., 2003; Fischer and Matthäus, 1996; Franck et al., 1987; Matthäus and Franck, 1992) the barotropic inflows are characterized by:

- forced mainly by sea level differences;
- caused by constant strong westerly winds, preceded by easterly winds;
- the inflowing waters are usually rich in oxygen;
- carry significant amounts of salt up to about 2 Gt (Lass and Mohrholz, 2003; Mohrholz et al., 2006);
- they occur mainly in autumn and winter.

Until the 1980s the average interval between successive inflows was about 3 years, but this period extended to 10 years in 1983—2003. In the last two decades large barotropic inflows have been less frequent, whereas weak and moderate inflows have taken place more often (Meier, 2006). The last two inflows in 1993 and 2003 are well-studied phenomena, both by observation (the 1993 inflow: Jakobsen, 1995; Matthäus and Lass, 1995; the 2003 inflow: Feistel et al., 2003; Piechura and Beszczyńska-Möller, 2004) and by hydrodynamic modelling (the 1993 inflow: Andrejev et al. 2002; Huber et al., 1994; Lehmann, 1995; Meier and Döscher, 2003; the 2003 inflow: Lehmann et al., 2004; Meier et al., 2004). The extensive (ca 200 km^3) inflow in 2003 of extremely low temperature (about 1—2°C) reached all basins in the Baltic Proper (Feistel et al., 2003). Ventilation of the Karlsö Deep (south-west of Gotland) took place 2 years after the inflow event, while the Bornholm and Eastern Gotland Basins were already returning to stagnation (Feistel et al., 2006). According to the latest observations (Mohrholz et al., 2015) the 2014 MBI, the total oxygen transport into the Baltic Sea was estimated at 2.04×10^6 t. Waters with an oxygen concentration of about 10 mg l^{-1} were recorded in the Bornholm Deep in January 2015, but 2 months later the oxygen concentration was 2 mg l^{-1} less. The amount of oxygen pushed into the Gdańsk Deep in February was not yet sufficient to eliminate anoxia from the near bottom layer. The near bottom waters of the Gotland Deep were sufficiently well oxygenated to eliminate hydrogen sulphide in March 2015 (http://www.io-warnemuende.de/suboxic-and-anoxic-regions-in-the-baltic-sea-deep-waters.html).

5. Summary

- In January 2015, after 12 years of stagnation, highly saline and well-oxygenated waters, originating from the major inflow in 2014, were found in the Bornholm Deep, Słupsk Furrow and Gdańsk Deep.
- Record-high salinities in the entire 16-year long period of IO PAN repeated observations were recorded in the Bornholm Basin (about 20 PSU). In 2015 the salinity in the Bornholm Basin was 1 PSU higher compared to the previous inflow in 2003.
- In January 2015 the older waters, previously occupying the deep layer of the Bornholm Deep, were raised to 50 m depth and in consequence were able to pass over the Słupsk Sill at the thermocline depth.
- Instantaneous values of the current component along the inflow axis of about 25 cm s^{-1} were measured in the inflowing waters propagating over the sea bed in the Bornholm Deep.
- The concentration of dissolved oxygen of about 10 mg l^{-1}, measured in January 2015 in the deep layer of the Bornholm Deep, decreased after 1 month by 1 mg l^{-1}.
- The amount of oxygen pushed into in the Gdańsk Deep in February 2015 was not yet sufficient to eliminate the anoxia in the near-bottom layer.

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