Distinctive features of water exchange across the Słupsk Sill (a full-scale experiment)*

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Thermohaline structure
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Abstract

The flows of brackish waters in the upper layer and saline waters in the lower layer meet above the Słupsk Sill, which makes this one of the most significant features of the Baltic Sea, controlling as it does the ventilation of the deep basins in its central region. Earlier high-resolution measurements using towed scanning probes conducted here for more than ten years had revealed the complexity and variability of the water dynamics in this area.

Mapping surveys repeated in quick succession are needed to study the water exchange in such an area. A survey of this kind was attempted in October 2003 during the 57th cruise of the r/v 'Professor Shtokman'. Three surveys were carried out in the areas of the Słupsk Sill, the eastern Bornholm Basin, and the western Słupsk Furrow by means of a scanning probe towed along closely-spaced transects. The water structure around the sill was different each time, despite the rather short time gaps between the surveys. As follows from the data analysis, during the first survey, the saline Bornholm waters flowed over the sill as an axially symmetrical jet and entrained the adjacent freshened cold waters of the intermediate layer. In ten days, this joint flow displaced to the southern flank of the sill and propagated

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in the Słupsk Furrow along its southern border, with the dense core of saline waters gradually moving over the bottom to the northern border. Concurrently, the contrary flow of the main volume of cold freshened waters, originating from northern areas and leaving the Baltic Sea, was pushed away from the southern wall of the furrow and blocked at a significant distance from the sill. In three days, the blocked waters forced their way through towards its northern flank. Just below these waters, waters of elevated salinity were found above the eastern slope of the sill at the depth of its ridge, while waters of a similar salinity occurred below the depth of the ridge above the western slope of the sill. There were no indications of intensive overflow in the central and southern areas of the sill. Accordingly, the return flow of Bornholm waters across the sill became possible.

1. Introduction

The ecosystem of the semi-enclosed Baltic Sea is distinguished by the fact that the saline waters, being much denser than the brackish waters of the upper layer, are supplied with oxygen from inflows of water of higher salinity from the Skagerrak (Matthäus & Franck 1992). The water exchange occurs through the Kattegat, the Sound, the Great Belt and the Little Belt. Characteristic of these straits is a strong stratification of salinity and density, which hampers vertical exchange. Oxygen consumption is therefore not made good when such highly saline waters are present in the shallow and polluted straits during the warm seasons. Such inflows occur at irregular intervals, once in several years. As a result, the aeration of the deep waters in the Baltic Sea below the halocline (about 60–70 m) is always low and occasionally drops to zero. Basins where stagnation takes place are typical of the entire Baltic Sea all the way up to the Bothnian Sea. Accordingly, the inflow waters have to follow a long and complicated path for stagnation to be eliminated. Straddling this path, elevations of the seabed rising to the level of the halocline prevent the free movement of the inflow waters. The most important of these is the Słupsk Sill, which separates the deep waters of the Bornholm Basin from those in the Słupsk Furrow (Fig. 1). The depth of water at the deepest spot of the sill's saddle is about 60 m (Fig. 1), so that saline waters are able to cross the sill only when, as a result of one event or another, they are flowing at depths shallower than 60 m. The amount of oxygen transported beyond the sill depends on the volume of water crossing it, and consequently, on the features of water exchange across the sill. The bottom topography shown in Fig. 1 is based on data given in Seifert & Kayser (1995).

The aim of the present work was to study the mechanisms of water exchange across the Słupsk Sill under conditions that can be related to different stages of the life cycle of large inflows. Earlier studies with similar objectives were the most fruitful when high-resolution transects of the

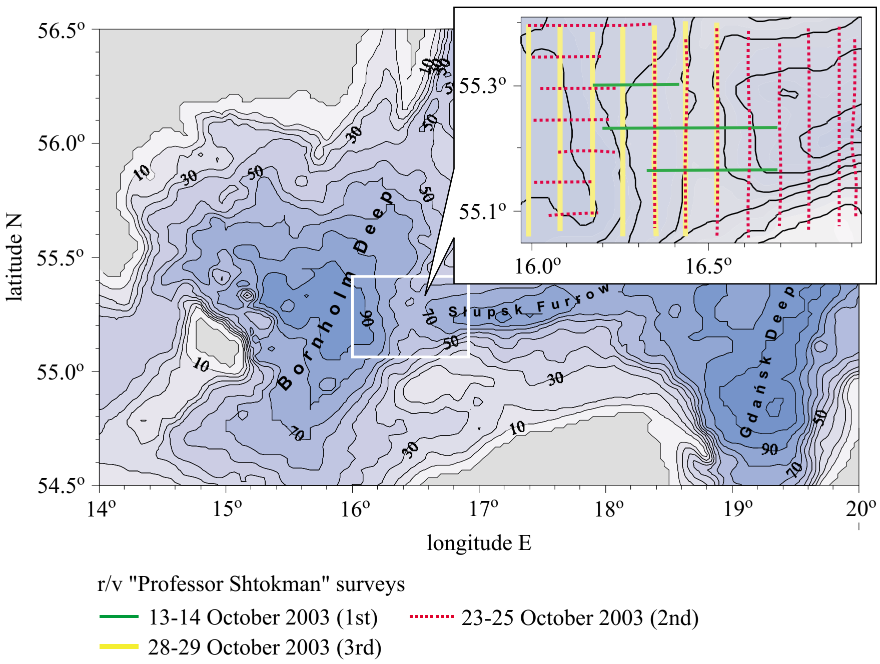

Fig. 1. The map of the study area and maneuvering of the r/v 'Professor Shtokman' during transects from the Arkona to the Bornholm Basin, 11–12 October (magenta lines), and surveys: on 13–14 October 2003, 23–25 October 2003, 28–29 October 2003

thermohaline structure could be obtained in these waters using towed scanning probes (Paka 1996, Piechura & Beszczyńska-Möller 2004). As a rule, they were single west- or eastward transects across the sill but in some cases they ran longitudinally along the ridge. As follows from all this evidence, the flows of Bornholm waters across the sill are very irregular, and their cores tend to be displaced to the southern slope of the sill's saddle. Such asymmetry is also characteristic of the water structure of the Słupsk Furrow (Paka 1996). In order to obtain a more detailed pattern, a comprehensive repeated area survey was undertaken.

2. Measurements

The survey was organized as a set of closely-spaced parallel transects covering the area from the eastern Bornholm Basin to the westerly Słupsk Furrow with the sill in the middle. The thermohaline structure of waters was recorded with a towed CTD-probe mounted on a winch-operated vehicle undulating underway between the water surface and the sea floor. The towing speed was c. 6 knots (3 m s^{-1}), and the vertical speed was

c. 0.5 m s^{-1}. To eliminate effects of depth sensor hysteresis, the transects were plotted exclusively from submersion data.

Measurements were performed with *Idronaut 316, Katran 3* and *YSI* CTD probes. The specifications of the *Idronaut 316* probe ensured an accuracy better than 0.05°N and 0.05 PSU. The *Katran 3* probe, developed at the Marine Hydrophysical Institute (Sevastopol), was less accurate than the *Idronaut* and *YSI.* The more accurate but slower *YSI* probe (0.5 Hz operating rate) was combined with the *Katran 3* in order to improve the reliability of the system.

Initially, we had planned two area surveys of twelve 20-mile-long meridional transects separated by 3 mile gaps in longitude. One such survey takes 50 hours to complete. Unfortunately, we failed to complete the first survey. After the eighth transect, the *Idronaut 316* probe was lost, and we were forced to return to Kaliningrad to take the other probes (*Katran 3* and *YSI*) on board. After this, the survey was resumed.

3. Preconditions

The experiment was conducted in October 2003, ten months after the major inflow of January 2003. Since this has been studied intensively, we now have a good understanding of the environmental conditions preceding the experiment described here. A special volume of *Oceanologia, 45 (4)/2003* was dedicated to the results of the study of this inflow; in addition, some relevant results from the AB IO RAS (the Atlantic Branch of the Institute of Oceanology, Russian Academy of Sciences) are presented in Paka & Golenko (2004).

If we take a close look at how the inflowing and forced out waters spread following a major inflow, we shall see that this process takes place in a number of stages.

The first stage involves the inflow of new waters and their accumulation in the Bornholm Basin. As this takes place, a corresponding volume of 'old' Bornholm water, which has been stagnating for some considerable time, is forced to rise into higher layers. Here it mixes with ambient waters, and then spills over the sill into the Słupsk Furrow, whose waters, in their turn, are displaced in the direction of the Gdańsk and the Eastern Gotland Basins. Were it not for the Słupsk Sill, the dense waters of the major inflow could freely propagate eastwards. The existence of the sill thus retards the progress of the saline inflow waters.

The second stage begins when the radically renewed Bornholm water arrives at the level of the Słupsk Sill and starts to spread eastwards. By the end of March, the inflow waters were present along the full length of the Słupsk Furrow. Partial renewal of waters also occurred in the Gotland

Basin. To the south–east of the latter, both salinity and oxygen increased, while hydrogen sulphide disappeared at maximum depths (Feistel et al. 2003). On the assumption that the second stage comes to an end when the inflow volume stops increasing in the Bornholm basins and to the east of it, then this stage lasted at least until early May. Observations in May 2003 substantiate this inference (Feistel et al. 2003).

In June, the inflow ceased to feed the bottom Bornholm layer, as is evident from our transects done aboard the sailing catamaran 'Centaurus 2' (Fig. 2). At that time, warmer and less saline water, unable to sink to

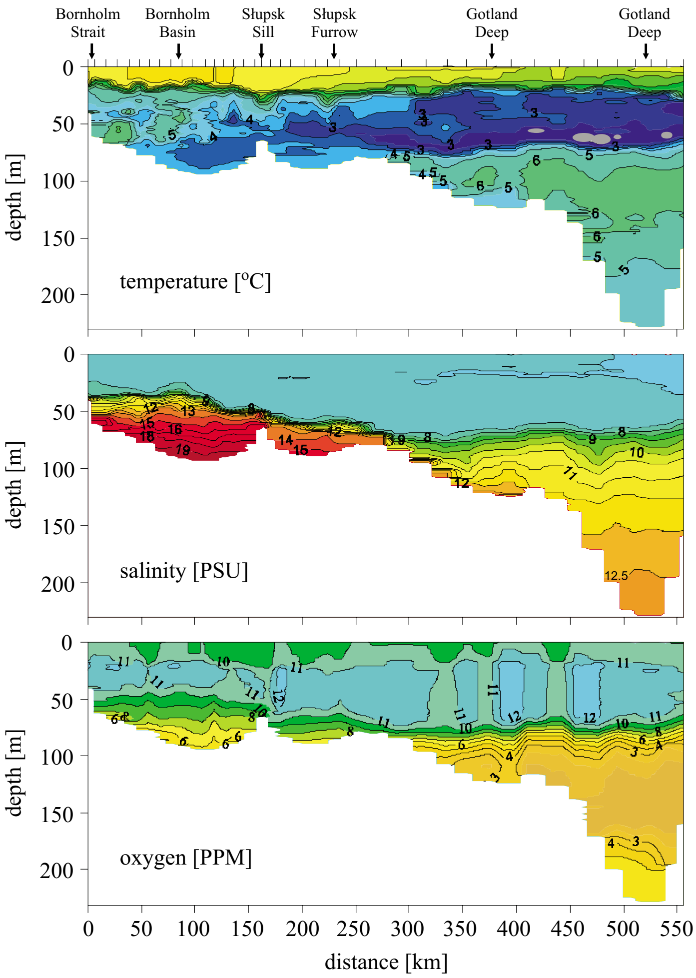

Fig. 2. Distributions of the temperature, salinity, and oxygen when the catamaran 'Centaurus 2' sailing through the Bornholm Strait, the Bornholm Basin, the Słupsk Sill, the Słupsk Furrow, and the Gotland Deep, 17–19.06.03

the floor of the basin, penetrated into the Bornholm Basin through the Bornholm Channel. We can thus reasonably infer that by this time the process of inflow assimilation had reached its third stage. During this period, the variations in the hydrological and ecological features of deep basins are determined mainly by the redistribution of the newly-arrived waters between the basins. This process is expected to last as long as there is a backwater – that is, as long as the halocline in the Bornholm Basin lies at a shallower depth than the Słupsk Sill. Persisting weak inflows from the Arkona Basin contribute to the flow crossing the Słupsk Sill, thereby renewing the bottom waters in the central Baltic Sea. As this replenishment dwindles, the Bornholm halocline sinks to the level of the Słupsk Sill and weaker inflows may become locked inside the Bornholm Basin. From this point on, active ventilation of the central Baltic basins weakens, which means the beginning of the fourth and last assimilation stage of the major inflow: in the absence of a new, major inflow, it starts to stagnate.

In October, on the eve of the present experiment, we surveyed a section from the Arkona Basin across the Bornholm Channel into the western Bornholm Basin (Fig. 3). We found that warm waters ($> 14°$C) were penetrating into the Bornholm Basin and spreading further at the depth of the 15 PSU isohaline (60 m), that is, at the level of the Słupsk Sill. According to our data from autumn 2001, during inflow-free periods the maximum salinity in the Bornholm Basin was < 16 PSU, whereas the 15 PSU isohaline lay at 70 m. In this case, the intrusion, characterized by the features observed in October 2003, would sink below sill level when trapped in the Bornholm Basin. Nevertheless, such an intrusion is still able to overcome the sill under post-inflow conditions.

In summary, these studies of the water exchange mechanisms were timed to coincide with the last active stage of the major inflow's assimilation, during which a geopotential gradient was formed. This enables waters of salinity higher than that of the stagnating water (up to 15 PSU) to cross the Słupsk Sill. The waters flowing over the sill contain a certain portion of recent intrusions from the Arkona Basin, which helps to maintain propitious ecological conditions in the central areas of the sea and slows down the rate of stagnation.

4. Weather conditions

On the eve of and during the first area survey, the weather was determined by the south–westerly periphery of a south–eastwards moving depression centred near St. Petersburg.

There were moderate to strong north–westerly winds of speeds 7–12 m s^{-1}, sometimes 15 m s^{-1}.

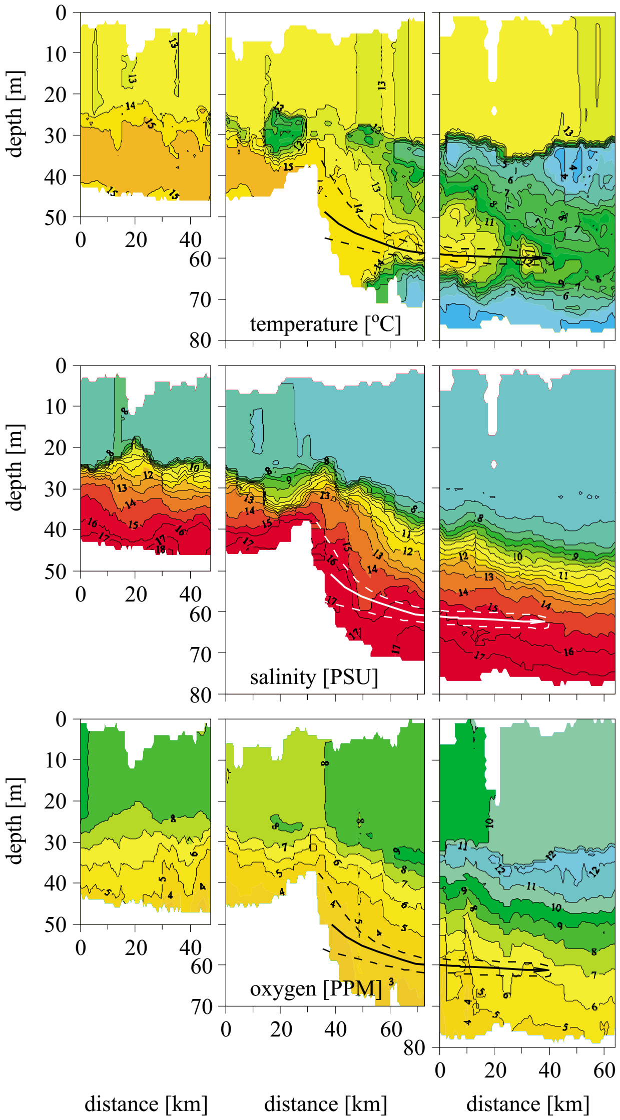

Fig. 3. Distributions of the temperature, salinity, and oxygen in a section occupied by r/v 'Professor Shtokman' when sailing from the Arkona Basin to the Bornholm Basin on 11–12 October 2003. The arrow designates a warm water intrusion

During the second survey, the weather was determined by the south–eastern and southern periphery of a low-pressure area over central Scandinavia. This depression moved in a south–easterly direction towards the Gulf of Finland. The measurements were started in calm weather, but the westerly wind strengthened to a speed that forced us to abandon the meridional transects along the storm-wave crests and instead to use longitudinal transects to sail at right-angles to the waves.

– 22 October: north–easterly wind 7–12 m s^{-1}, gusting up to 14 m s^{-1}; in the evening 5–10 m s^{-1}, with gusts up to 12 m s^{-1};

- 23 October: easterly or north–easterly winds 4–9 m s^{-1};
- 24 October: variable winds 4–9 m s^{-1}; in the daytime, westerlies 6–11 m s^{-1}, gusting up to 13 m s^{-1}; in the evening 7–12 m s^{-1}, gusting up to 15 m s^{-1};
- 25 October: south–westerlies or westerlies 10–15 m s^{-1} with gusts up to 18 m s^{-1} in the morning, 15–20 m s^{-1} with gusts up to 23 m s^{-1} during the day; westerlies or north–westerlies 7–12 m s^{-1} with gusts up to 15 m s^{-1} in the evening.

A high-altitude, south–westerly frontal zone lay over the Baltic Sea and Scandinavia during the third area survey.

- 27 October: the weather was determined by a ridge of high pressure centred over the southern UK;
- 28 October: the weather was shaped by the southern periphery of a low centred over the Barents Sea and displacing eastwards;
- 29 October: the weather was determined by the north–westerly periphery of an anticyclone over Ukraine.

Winds:

- 27 October: westerly, north–westerly in the daytime, south–westerly 5–10 m s^{-1} in the evening;
- 28 October: south–westerly 7–12 m s^{-1} with gusts up to 15 m s^{-1} in the morning, 12–17 m s^{-1} with gusts up to 20 m s^{-1} in the evening;
- 29 October: south–westerly, southerly in the daytime, south–easterly 5–10 m s^{-1}.

5. Results

Fig. 1 shows the course of the r/v 'Professor Shtokman' during the three surveys, which were carried out on 13–14.10.2003, 23–25.10.2003, and 28–29.10.2003.

The first survey started in the Bornholm Basin 15 miles from the ridge of the Słupsk Sill and was interrupted just after passing the latter.

The route, shown as an inset in Fig. 4, was traversed without interruption in 34 hours at 5 knots. Every section took about 3.5 hours, plus 1.5 hours for manoeuvring between transects. The results of this survey are presented in Fig. 4 as a series of transects (Nos. 1–7 from left to right) demonstrating temperature and salinity distributions in meridional transects over the area that borders with the Słupsk Sill in the west (here, south is on the left and north is on the right).

The following features are characteristic of this area's structure.

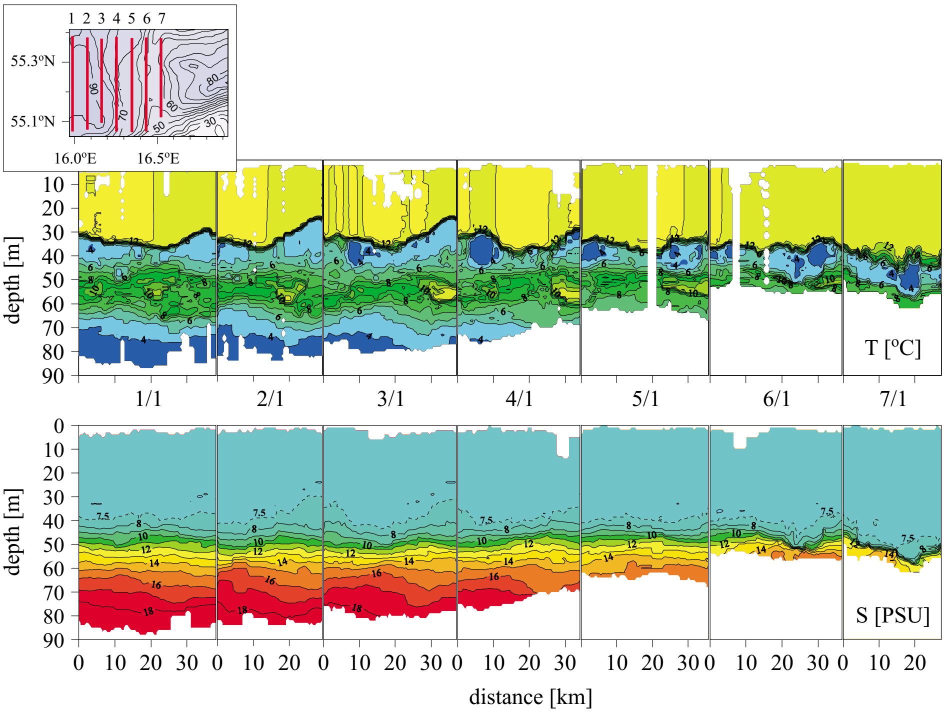

Fig. 4. Temperature (upper panel) and salinity (lower panel) transects in this survey. Symbols 1/1, 2/1, . . . ,7/1 – numbers of transects in this survey. The inset in the top left corner presents the scheme of the transects

There is a universally sharply-defined seasonal thermocline interfacing the warm upper homogeneous layer (UHL) with a mean temperature of 13°C and the intermediate cold layer (ICL) with temperatures of 5–4°C . Beneath the latter the temperature first rises, but then falls below 4°C at maximum depths approaching the bottom. The second layer with a steep gradient is associated with the permanent halocline. Both UHL and ICL have no remarkable differences in salinity (av. 7 PSU), which is characteristic of the brackish waters of the southern Baltic. The salinity increases monotonically *vs* depth from the halocline down to maximum depths, where it reaches a maximum of 18.61 PSU. The upper boundary of the halocline was detected at 45 m depth, while the depth of the Słupsk Sill was about 60 m. At the level of the sill (60 m) the salinity is 15 PSU (transects 2/1, 3/1, 4/1, 5/1 on Fig. 4). The considerable elevation of the halocline above the level of the sill as well as the low temperature and high salinity of the deep waters were caused by the recent major inflow.

In addition to the features of the thermohaline structure, which are to be expected from general concepts, it is worth noting some of its particular features deserving special interpretation and which may provide a basis for inferences concerning flows over the Słupsk Sill.

A patchy structure is inherent to the temperature within the ICL and halocline core. This property can be explained by the intermittent entry of anomalously cold brackish waters and anomalously warm saline waters that respectively build up in the surface layers of the northern Baltic Sea and Danish Straits. However, based on the topography of the thermo- and halocline, the flow within the ICL during the first survey advanced eastwards rather than westwards, as one would have expected from the climatic data. The following consideration corroborates this inference. The eastward flow of the saline water is evident: there is a strong backwater as well as a sag in the halocline boundary, where one may assume the build-up of a strong jet of saline Bornholm water sweeping down the eastern slope of the sill (see transects 6 and 7, which are symmetrical with reference to the axis of the sill valley). However, there is a layer of cold, freshened water above the valley. The upper boundary topography of this layer lacks the sag noted in the saline water layer. Nevertheless, the ICL clearly appears in the last section (beyond the sill), since the topography of the ICL is similar to that of the halocline surface. This gives grounds for inferring that, near the sill, dense saline waters have built up a fast jet, where the flow has been compressed in the horizontal and the vertical. The current in the adjacent, cold freshened layer was not strong enough to influence the topography of the thermocline. The entrainment effect was enhanced beyond the sill, where the flow of dense, near-bottom water turned out to be descending and accelerating. Under these conditions, both adjacent layers made up a joint flow that was symmetrical with reference to the longitudinal axis of the sill and directed towards the Słupsk Furrow.

There is no possibility of determining flow direction within the amorphous UHL.

It is a remarkable event, one deserving of an explanation, that the sinking of the upper halocline boundary over the western slope of the sill is accompanied by the ascent of underlying, more saline waters, which have to overcome the forces of buoyancy. This is evident from transects 5 and 6. This is obviously a hydrodynamic phenomenon. If one acknowledges that a strong jet entrains a current within the halocline, it is reasonable to assume that the underlying layer of denser water above the western slope of the sill is subjected to the same effect. This occurred only in the close vicinity of the sill. If we discount local deformation, there were no meaningfully sloping isohalines far from the sill (transects 1–5).

The extremely warm patches in the halocline at the level of the sill were remarkable for the reproducibility of their structure. Such patches up to

10 km wide occurred in all the transects west of the sill. Though relatively weak in the first section, their properties intensify to reach a maximum in transects 3 and 4, after which they again weaken. The inference regarding the continuity of this intrusive body seems quite natural. Apparently, a warm intrusion of Arkona water, similar to that visible in the transect in the west of the basin (Fig. 4), took on a sickle-like shape, and its eastern part was entrained in the run-off jet near the sill. There is no intrusion in the last section beyond the sill. This fact is consistent with the idea of entrainment, as a result of which the entrained water jet has to be elongated and constricted to such a degree that detecting the narrow jet becomes hardly possible when scanning with a horizontal step of 350 m. These features of the thermohaline structure can be consistently explained if one supposes that the water exchange of 13–14 October took place in line with the following scenario: the outflow of saline Bornholm waters occurred as a relatively narrow jet developed in the middle of the Słupsk Sill. The waters bordering on the main jet from above, from below, and from either side were entrained in the main jet and formed a joint flow, which remained strongly stratified after crossing the sill. The seasonal thermocline and the permanent halocline became very sharply defined as a result of vertical compression.

The second survey was started in the Słupsk Furrow at a distance of 15 miles from the ridge of the Słupsk Sill. At first, the weather was favourable for manoeuvring according to the scheduled layout of meridional transects, but we were forced to change their orientation by 90° after traversing eight of the twelve transects because the vessel had started to roll quite strongly. In the end, however, the second survey did cover the whole predefined area. The results are shown in Fig. 5 (the Bornholm area) and Fig. 6 (the western slope of the sill, the sill, and the western part of the Słupsk Furrow). Conditions in the Bornholm area changed substantially during the ten days elapsing between the first and the second surveys (Figs 4 and 5). The UHL temperature dropped on average to 9.5°C , in accordance with autumnal cooling, while the maximum temperature of warm intrusions increased from 12.8°C to 14°C . The halocline boundary associated with the 8 PSU isohaline remained at a depth of 45 m, but away from the sill the salinity gradient dropped and the more saline waters sank. According to that, the 15 PSU isohaline, which was found at the sill depth during the 1st survey, now was found 8–10 m deeper than previously (compare salinity transects 7/2a, 6/2a with transects 3/2a, 2/2a, 1/2a, Fig. 5). Warm intrusions of isopycnal spreading also sank. Despite the lowering of the isohalines

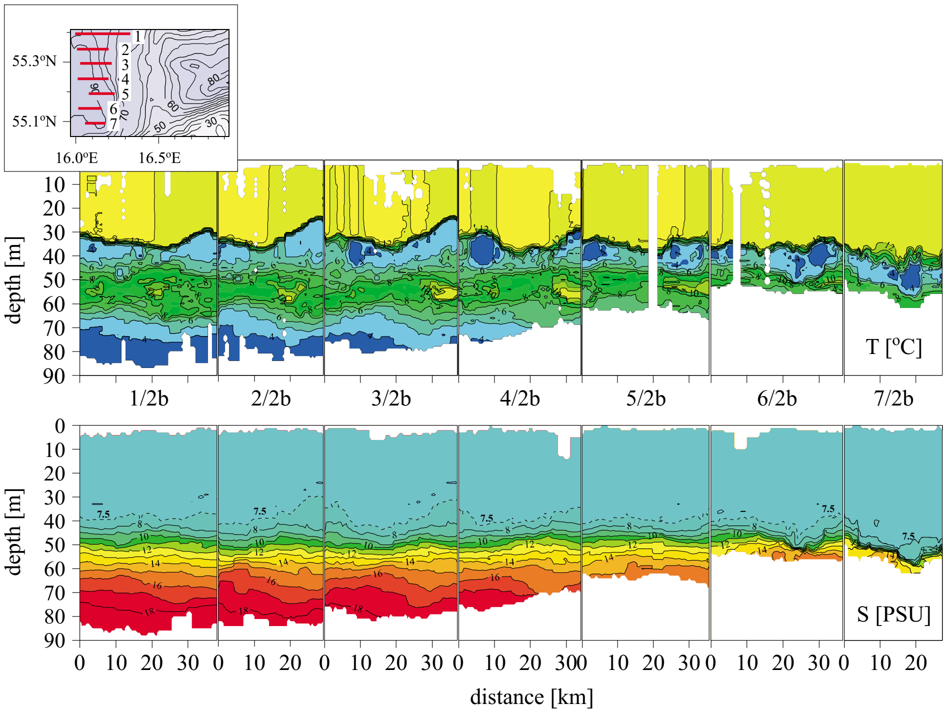

Fig. 5. Results of the 2nd survey in the area of the Słupsk Sill on the Bornholm Basin side, temperature (upper panel) and salinity (lower panel) distributions. Symbols 1/2b, 2/2b, …,7/2b – numbers of transects in this survey. The inset in the top left corner presents the scheme of the transects

water of 15 PSU salinity reached the sill. Over the eastern slope of the sill, both surveys revealed the absence of increased salinity with respect to the waters above the halocline.

Evidently, in ten days the Bornholm waters continued to overflow the sill in spite of the weaker geopotential gradient driving the supply of saline waters to the sill. As follows from transects 8/2a and 7/2a, closest to the ridge of the sill on the Bornholm side (Fig. 6), T and S distributions became asymmetrically distributed in contrast to the first survey: the tilting of the thermocline and halocline tended to increase southwards with unchanging depth of the seasonal thermocline and decreasing depth of the halocline. This means that the outflow from the Bornholm Basin must deviate from the longitudinal axis of the sill valley and ascend the southern slope of the valley. After passing the ridge, the Bornholm water flows within the bed of the Słupsk Furrow. The borders of the Słupsk Furrow are higher than the sill ridge level; because of that, the Bornholm saline waters occupy only the lower part of the furrow's cross-section. The remaining volume between the

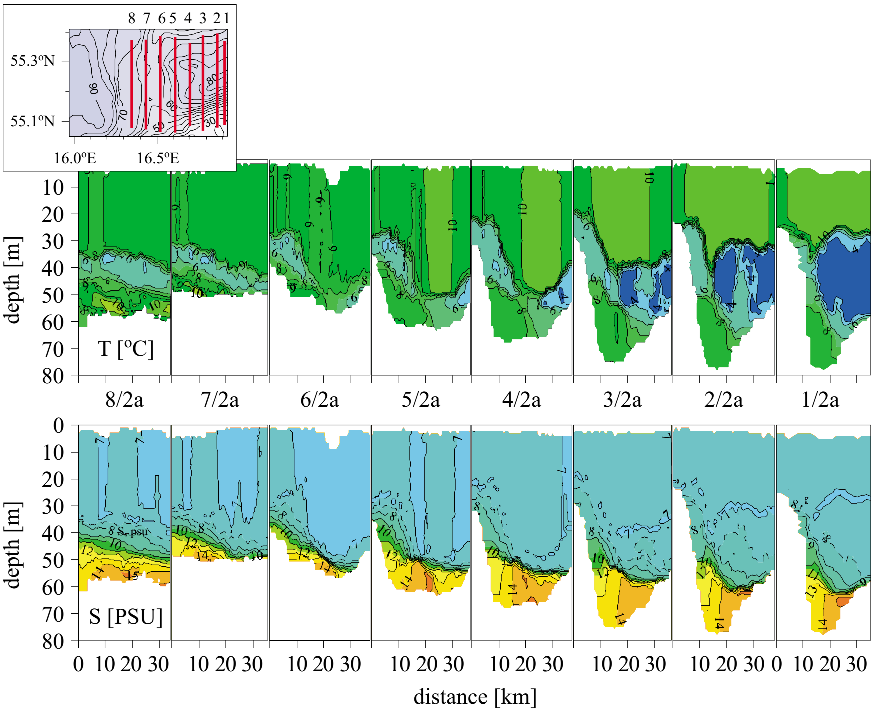

Fig. 6. Results of the 2nd survey in the area of the Słupsk Sill on the furrow side, temperature (upper panel) and salinity (lower panel) distributions. Symbols 1/2a, 2/2a, . . . ,8/2a – numbers of transects in this survey. The inset in the top left corner presents the scheme of the transects

borders is occupied by brackish waters, so the interaction between the adjacent layers in the furrow should have properties different from those in the wide basin. The boundary of the halocline is subjected to strong distortion; in temperature transects 6/2a, 5/2a and so on until 1/2a (Fig. 6) this deformation looks like a growing wave splash near the southern border of the furrow. The temperature structure near the axis of the furrow is characteristically quasi-horizontal, but more complicated on its northern border. This is clearly visible in the successive transects 6/2a, 5/2a etc.

The salinity distribution has similar deformations on the surface of halocline, but of most interest is the formation of a unique fan-like structure, characterized by the a wide divergence of the isohalines on the southern slope and their convergence on the northern slope of the furrow, building up in the halocline in transects 5/2a, 4/2a . . . 1/2a. Along this variation of the salinity field structure, the maximum salinity core is gradually displaced from the southern side of the sill valley (7/2a) via the central region (5/2a, 5/2a) to the northern border (4/2a . . . 1/2a).

We have already observed some specific features of the thermohaline structure in the Słupsk Furrow (Paka 1996). The fan-like structure was simulated on the basis of the POM model (Paka et al. 1998) and was attributed to the effect of the Ekman layer being trapped near the bottom of the furrow ('the arrested Ekman layer' – Garrett et al. 1993). This feature results from the double-cell transverse circulation in the furrow induced by near-bottom Ekman transport, provided that saline waters flow eastwards while the overlying freshened ones flow westwards.

According to our earlier observations, the fan-like structure of the halocline exists in the eastern Słupsk Furrow under gentle, moderate, or fresh breezes from any direction, but disappears in high south–westerly winds. This specific feature of the halocline may be less pronounced in the central Słupsk Furrow and does not occur over the sill itself. NE, E and W winds dominated on the eve of and during the second survey. The only exception was on the last day, when winds blew from the SW for a time, but they quickly veered to W and NW again. Our earlier explanation of the fan-like structure of the halocline (Paka et al., 1998) seems to be the most plausible in the context of the results presented here.

It is worth noting some additional features. First, the separation of waters within the ICL. These waters make up a uniform body before the sill (transects 8/2a and 7/2a, Fig. 6), but this body splits into two unequal parts just after the sill (section 6/2a). Most of the cold brackish water is displaced together with saline water towards the southern border (section 6/2a). Next, the transects bear evidence of the same structural coupling. Hence, the waters of the ICL flow eastwards along with saline Bornholm waters over the southern border of the Słupsk Furrow. Obviously, the ICL waters were forced to return to the Słupsk Furrow as a result of being entrained into the more powerful saline jet. When moving over the southern border of the furrow, the upper boundary of the ICL flow ascends from section to section as the bottom rises, reaching its highest level of 20 m in section 3/2a.

On the opposite (north) side of the furrow, there was an insignificant body of cold brackish water near the sill (transect 6/2a); but this enlarges with distance from the sill to prevail in the three last transects, where the temperature contrast attains a maximum. Evidently, the westward ICL flow decelerated in section 4/2a, probably because of the strong eastward outflow of Bornholm waters.

The following inferences summarize the events and processes observed in the course of the second survey. The flow of Bornholm water over the Słupsk Sill appeared to be an asymmetrical eastward stream involving saline waters as well as freshened ones from the ICL backed up against the southern side of the sill valley. When moving eastwards in the furrow, the brackish waters accumulate over its southern border and weakly interact with surrounding waters down to section 4/2a, where they decelerate. The saline waters flow freely but their core, that is, the most saline and warm waters, are gradually displaced from the southern border to the northern one.

Over the northern border, the ICL waters prevail far away from the sill (transects 1/2a, 2/2a). Originating in the Northern Baltic, the cold brackish water in the Southern Baltic should propagate westward overflowing the Słupsk Sill. We possess numerous transects for previous years showing the continuous distribution of ICL along the whole extension of the Słupsk Furrow from east to west and then penetrating into the Bornholm Basin. But in this particular case, the usual westward propagation of ICL seems to be blocked at the position of transects 3/2a–4/2a. To the east of that site, there is a very thick ICL containing the coldest water ($< 4°$C); to west of that site, this coldest water despaired. Hence, eastward water transport dominated over the Słupsk Sill during the second survey. This water flowed as a strongly asymmetrical and distinctly stratified stream. At first, this was entirely backed up against the southern border of the furrow, but as the stream moved to the east, its upper, freshened part decelerated and spread at its depth, while the main body of saline water continued to move towards the outlet of the Słupsk Furrow. During this process, the denser core of the stream passed along the northern border of the furrow.

Taking into account the fact that ICL waters originate in the central/northern Baltic Sea and are an inherent attribute of the Bornholm Basin, we can infer that deceleration of the westward transport of ICL waters is only transient. Apparently, the outflow of a large body of ICL waters from the Bornholm Basin over the southern border into the Słupsk Furrow is also of a transient nature.

The third survey involved three longitudinal transects; their layout and navigation are shown in Fig. 7. The survey started in the middle transect and terminated in the northern one. The measurements were occasionally interrupted for technical reasons, which caused some gaps in them. Nevertheless, the main features of hydrological structure were revealed.

In spite of the fact that the third survey took place only three days after the second one, the thermohaline structure was much changed. The ICL waters came up to the sill, even though they were stopped on 23 October 2003, 10 miles away from the sill when moving westwards along the Słupsk Furrow. In the northern section, the ICL waters of temperature 4°C, did cross the sill, but were flowing too slowly to leave the near-slope area. A wave-shaped structure about 20 m high developed in the ICL (Fig. 7,

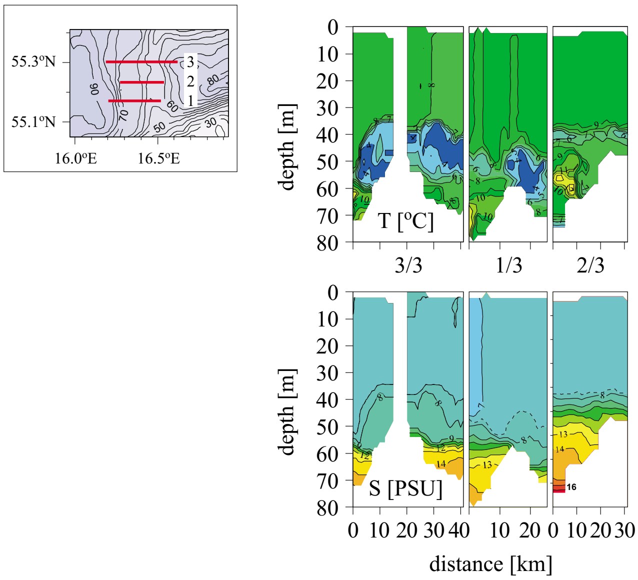

Fig. 7. Results of the 3rd survey in the area of the Słupsk Sill, temperature (upper panel) and salinity (lower panel) distributions. Symbols 1/3, 2/3, 3/3 – numbers of transects in this survey. The inset in the top left corner presents the scheme of the transects

transect 3/3). This wave was propagated westwards and featured a steep leading edge.

In the medium section above the sill, there was a water body with a temperature as low as that in the northern section. Most waters of this type occurred over the eastern slope of the sill. The upper ICL boundary exhibits a complicated configuration with a narrower depth range and shorter horizontal scales than those on the northern side. Weak temperature contrasts and a smoothed structure were characteristic of the northern flank. Evidently, this is a manifestation of the peripheral part of a large body of extremely cold brackish water, whose core was displaced northwards.

The salinity distribution appeared to be very unusual. For the first time in our experience, we observed that the halocline over the eastern sill slope was located in shallower waters than over the western sill slope (Fig. 7, 3/3). This is easily seen in the northern salinity cross-section. There were no indications that the isohaline was sinking on moving eastwards away from the sill. Hence, the saline waters within this near-sill area were flowing westwards, that is, against the climatic trend. Such indications were also lacking on the western side of the sill, though; this suggests that the dynamic anomaly around the sill is a local phenomenon. In the middle section, the ratio of halocline elevation exhibits no anomalies and corresponds to the conditions when the sill interrupts the eastward motion of Bornholm waters.

As compared to the earlier situation near the sill (see the salinity in transect 7/2a, Fig. 6), the halocline descended by about 10 m on the Bornholm side, and the salinity of the water at the ridge level was about 11 PSU, not 14 PSU as it had been earlier.

Summarizing the results of the third survey and comparing them to the results of the preceding ones, it is reasonable to infer that the intensive stream of saline Bornholm waters and the entrained flow of brackish Słupsk waters eastwards across the sill ceased to exist. The blocking of cold waters at the sill end of the Słupsk Furrow also ceased, after which these waters streamed up to the sill and crossed it. At the same time, a large body of saline waters moved to the north–eastern part of the sill valley, and the isohaline 13 PSU occurred at the level of the sill ridge; this does not exclude the possible backward outflow of saline waters into the Bornholm Basin. Simulations of flows in the Słupsk Furrow (Paka et al. 1998) indicate that the observed changes in the water structure over the Słupsk Sill can be attributed to variability in the direction of the flow of saline waters in the furrow caused by the south–westerly wind.

6. Conclusions

The structure of flows determining water exchange across the Słupsk Sill varies, depending on a number of factors. One of the most important is the volume of dense saline waters in the Bornholm Basin, which determines the elevation of the halocline above the ridge of the Słupsk Sill. However, the nature of water exchange across the sill varied during a few days, even at the high levels of the Bornholm halocline in October 2003. Three surveys revealed three different patterns above the Słupsk Sill. With moderate to strong NW winds, a structure occurred above the Słupsk Sill that can be explained by the eastward flow of saline Bornholm waters. This flow was symmetrical with respect to the longitudinal axis of the sill. Waters of the ICL were entrained by this flow in the same direction. During the second survey moderate north–easterly winds prevailed. These became stronger, backing westerly at the end of the survey, by which time the sill area had already been passed. Under these conditions, the thermohaline structure exhibited the presence of a saline water flow with a strong southward current component. This flow approached the Słupsk Sill, driving further eastward water transport. In addition, it entrained the overlying waters of the ICL. Under such conditions, a unique fan-like structure developed in the pycnocline of the Słupsk Furrow away from the sill. This corresponds to the propagation of the main current jet along the southern slope, with the dense core gradually moving towards the northern slope. We had observed such a structure earlier; we later demonstrated by means of simulation that it develops under all wind directions except south–westerly. The latter occurred during the third survey, which corroborated our earlier inference: the transport of Bornholm waters across the sill ceased and turned westwards to the north of the sill saddle.

To all appearances, the diversity of mechanisms of the water exchange across the Słupsk Sill has not yet been fully revealed by these surveys. It is advisable, therefore, to repeat such surveys, to conduct them as multi-ship expeditions, and to combine the use of scanning CTD probes with the deployment of ADCP current profilers in order to eliminate the vagueness of inferences on the strength and direction of currents. It is not improbable that a thorough understanding of the peculiar properties of the water exchange across the Słupsk Sill, which impedes the continuous ventilation of Baltic waters below the halocline, may force us to recognize the necessity to artificially lower the depth of the Sill and create a scientific basis for the relevant hydroengineering project.

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