Inflow waters in the deep regions of the southern Baltic Sea – transport and transformations*

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Abstract

A medium-sized inflow (about 200 km^3 according to IOW data, – personal communication) of saline water into the southern Baltic Sea occurred during January 2003. Unlike any previously observed inflow, this one brought very cold water, of temperatures around 1–2°C and less. Since the temperature of the deep water in the southern Baltic before the inflow was exceptionally high (11–12°C), the inflowing waters produced dramatic changes and a steep temperature gradient. The movement of the inflowing waters through the deep basins and channels of the Baltic Sea from the Arkona Basin to the Gdańsk Deep during next 4–8 months is described. Frequent mesoscale structures and intensive mixing followed the eastward transport of the inflow water, particularly in the Bornholm Deep and

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The complete text of the paper is available at http://www.iopan.gda.pl/oceanologia/

Słupsk Furrow. The present paper is based on data collected during 6 cruises r/v 'Oceania' between December 2002 and August 2003. The last cruise in August took place in order to assess the long-term consequences of the inflow.

1. Introduction

Water exchange through the Danish Straits is a process crucial to the Baltic Sea's hydrography, environment and ecosystem. A special role is ascribed to rapid inflows bringing hundreds of cubic kilometers of well oxygenated, saline waters into the Baltic Sea within a few days. The temperature of these waters depends on the time of year when the inflow occurs, but usually it is a few degrees higher than that of deep waters in the southern Baltic (Piechura 1993). The occurrence of inflows depends mainly on the atmospheric circulation and requires an appropriate sequence of wind forcing and sea level changes. Though these are irregular phenomena, over 90% of such events occur during late autumn and winter, until the 1980s on average every 4–5 years (Matthäus & Franck 1992). Since that time, however, large inflows have taken place much less frequently (1983, 1993, 2003), about once every 10 years. The latest inflow and its consequences within the Baltic Sea led to the first comprehensive investigation of the phenomenon, 15 cruises of research vessels from Sweden, Germany, Poland, Russia and Finland taking place from December 2002 until August 2003. This provided a good opportunity to learn more about the inflow phenomenon itself and its consequences within the Baltic Sea. The first results were presented at the Baltic Sea Science Congress in Helsinki on 24–28 August 2003. A special 'Salt Water Inflow' workshop at this Congress was devoted to this topic as well. At present we can talk about the changes in the physical and chemical environment; the changes in the ecosystem require time and will become apparent later.

2. Data

The data obtained during 7 cruises by r/v 'Oceania' in the Gdańsk Deep – Słupsk Furrow – Bornholm Deep – Bornholm Gate – Arkona Basin area are applied in this paper. The dates of the cruises were as follows: 3–4 December, 21–26 January, 4–6 February, 17–18 February, 16–16 March, 26–27 April and 16–17 August 2003. Temperature and salinity were measured with a towed CTD (Sea Bird SB49). Depending on the bottom depth, CTD casts were done 100–300 m apart and as close as 1–2 m above the bottom. Currents were recorded continuously using a ship-mounted ADCP (RDI 150 kHz). Standard oceanographic processing techniques were applied. The location of the transects is shown in Fig. 1.

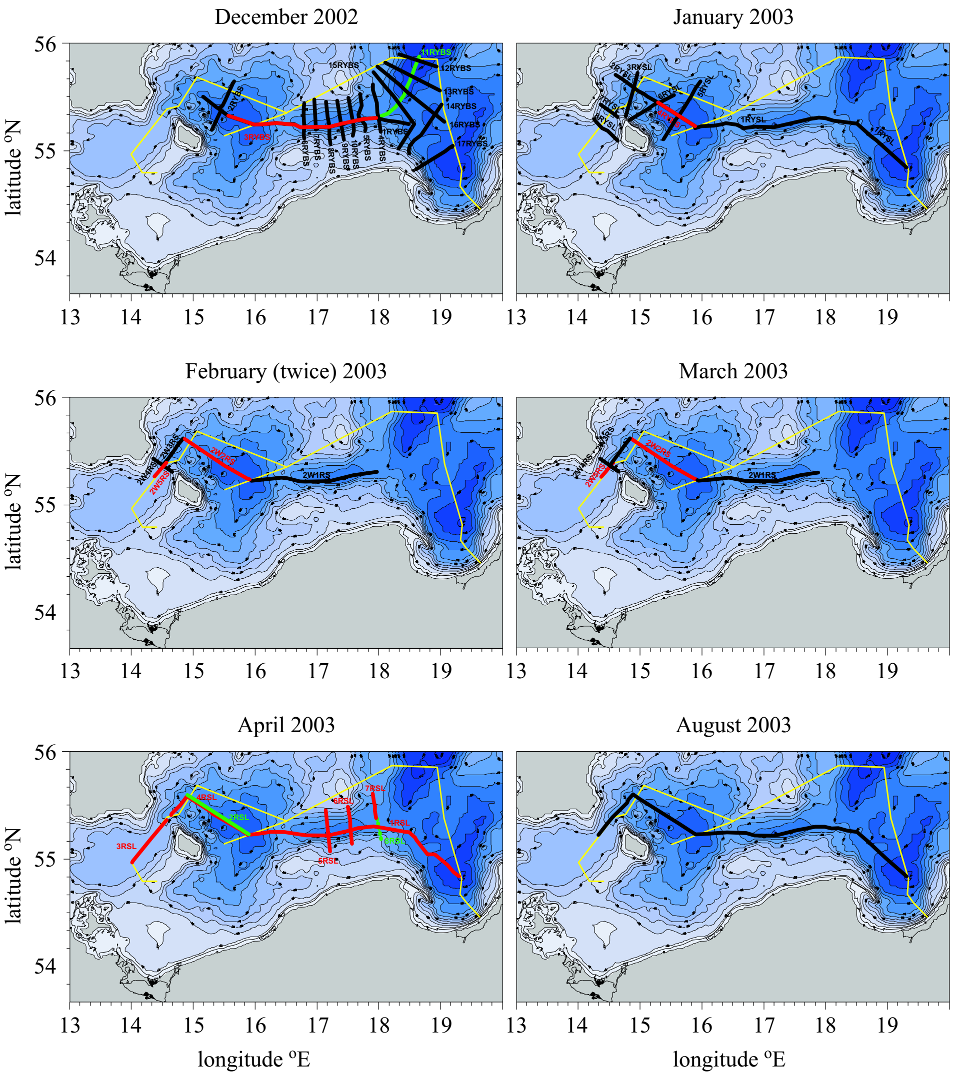

Fig. 1. Location of CTD/ADCP transects during inflow event

3. History of the inflow

The inflow over the Drogden Sill took place from 11 to 18 January (SMHI data) and over the Darss Sill from 16 to 25 January (IOW data). Before we start to describe the inflow and its consequences in the Baltic Sea, let us have a look at the situation before it started. Fortunately we have data collected by r/v 'Oceania' at the beginning of December 2002.

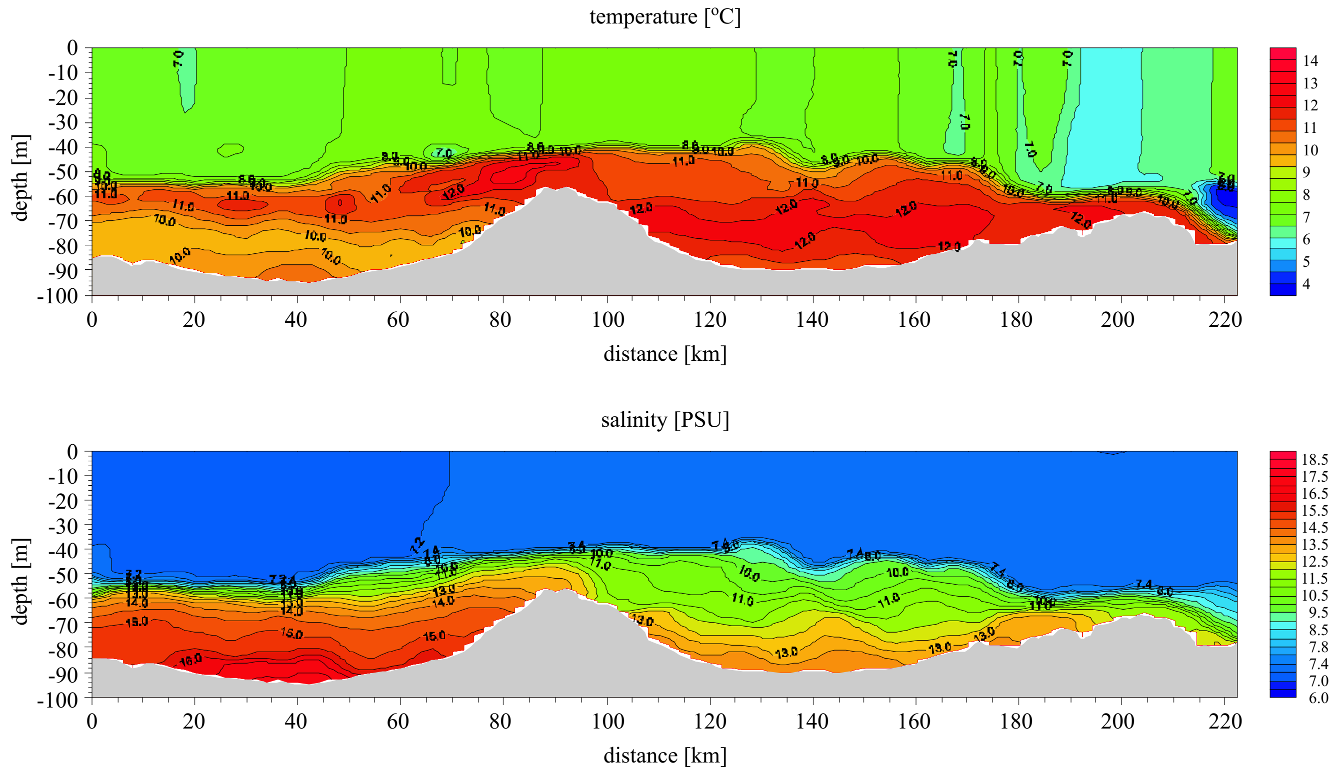

Fig. 2. Temperature and salinity along the main transect. 3–4 December 2002

3–4 December 2002

Some striking features of the December 2002 conditions in the deep regions of the southern Baltic Sea include the extremely high water temperature (Fig. 2): about 7°C in the upper layer and up to 11–12°C in the deep layer. Probably this is the highest value ever to have been recorded in this month. The high water temperature was the consequence of the inflow recorded in August 2002. A detailed description and explanation of these phenomena is given in the paper by Feistel et al. (2003a, b, this volume). At the same time the salinity distribution was quite normal: about 7.5 PSU in the mixed upper layer, the halocline below 40–60 m, and the salinity increasing to 17 PSU near the bottom of the Bornholm Deep and to 13.5 PSU near the bottom of the Słupsk Furrow.

21–26 January 2003

In January (23.01.03) inflow waters were noted already in the Arkona Basin, the Bornholm Gate and the northern part of the Bornholm Deep.

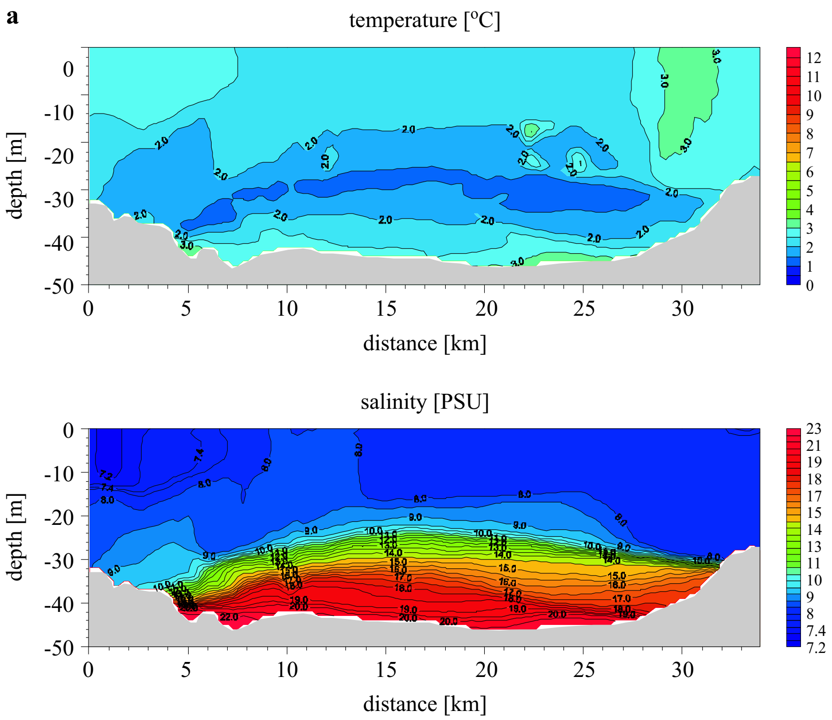

Fig. 3. Temperature, salinity and currents. 25–26 January 2003. Arkona Basin (a) and Bornholm Gate (b)

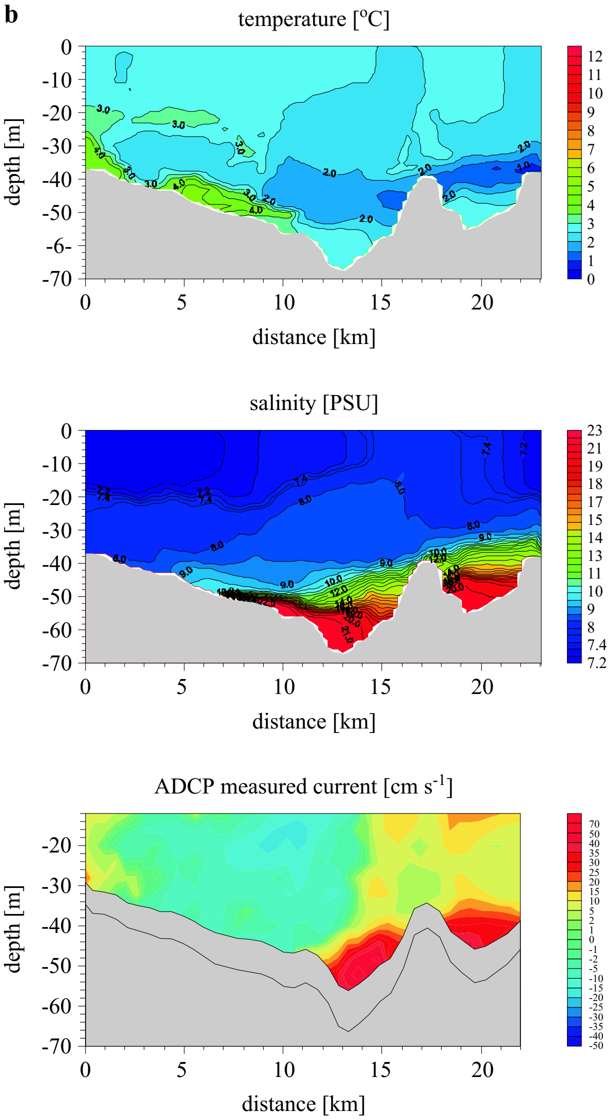

Fig. 3. (*continued*)

In the Arkona Basin (Fig. 3) the temperature dropped to below 2°C (in a thin layer at about 30 m depth even to below 1.5°C) and the salinity rose to over 20 PSU near the bottom. In the deepest part of the Basin – a narrow trench at the northern end – a value of over 22.5 PSU was measured. The shape of the density surfaces suggests the existence of a cyclonic eddy below 20 m in the Arkona Basin, roughly equal in dimensions to those of the Basin. In the Bornholm Gate there

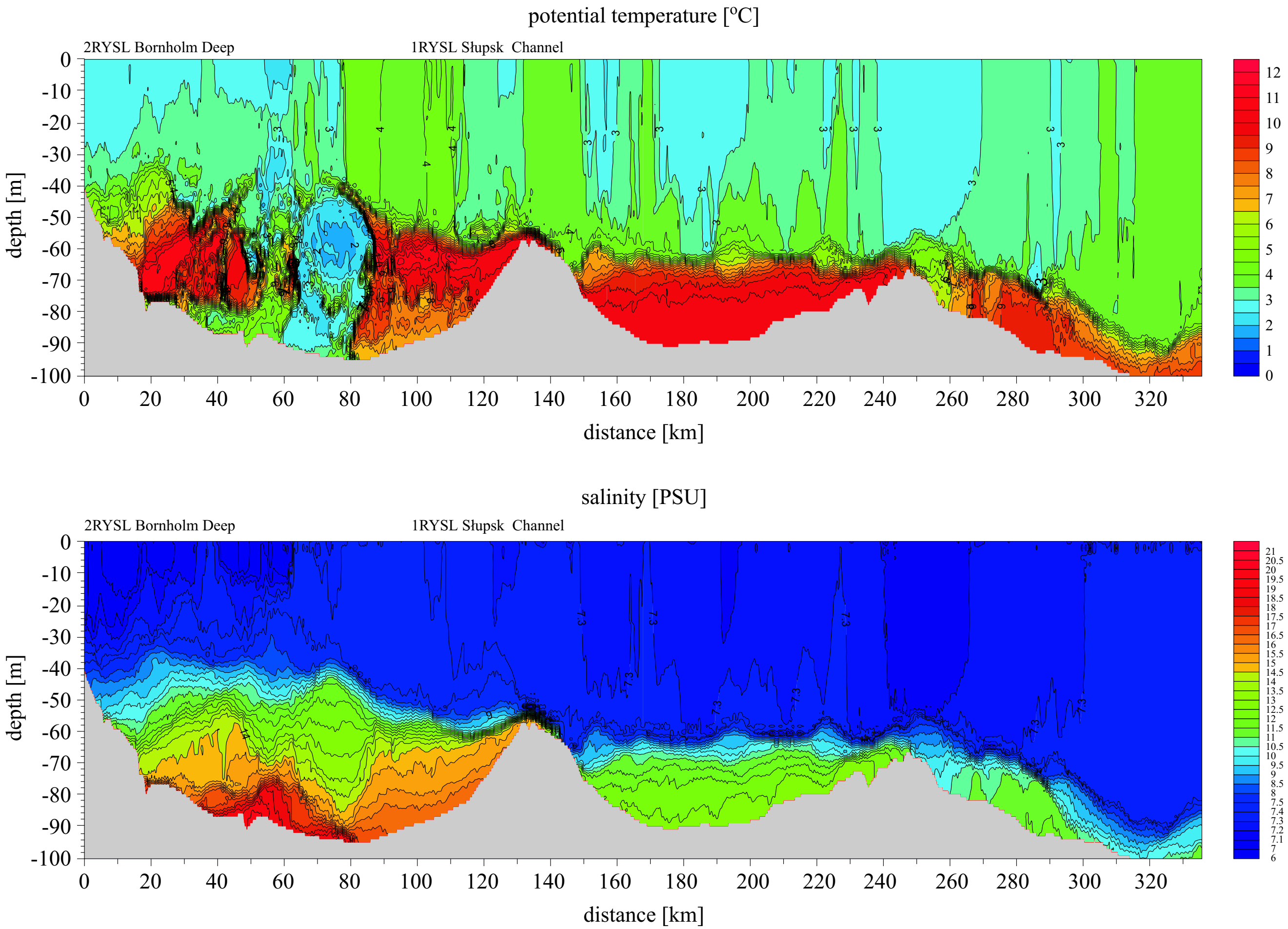

Fig. 4. Temperature and salinity along the main transect. 25–26 January 2003

was inflowing water in the near-bottom layer of the deep channels on the southern slope. The upper layers of the inflow climbed the southern slope, pushing the bottom layer so that it rose up the northern slope. The lowest temperature, below 2°C, with a minimum below 1°C was recorded at 30–40 m depth. This means that inflowing water was less well mixed here than in the Arkona Basin. The highest salinity – over 23 PSU – was recorded at the bottom of the northern slope. Here we observed the effect of bottom Ekman flow. In the central and western parts of the Bornholm Deep (Fig. 4) the usual layering of temperature became totally disrupted. Instead, we saw the chaotic distribution of patches of old-warm (> 10°C) and new-cold (< 2°C) water. This could have meant that the inflow water arrived there only a short time before, that most probably the process was running its course, and there had been no time for mixing to occur. We observed very steep temperature gradients, especially in the horizontal plane. The inflow water had not arrived there directly from the Bornholm Gate but was flowing along the western slope and into the central part of the Bornholm Deep in the cyclonic eddy. Confirmation of this assumption will be found in the ADCP data (Fig. 5) at depths of 50 m and 60 m. The salinity/density distributions indicated the presence of numerous mesoscale eddies, both with cyclonic and anticyclonic circulation, like that with the center close to the 80 km line. There we had a cyclonic circulation in the upper part of the deep layer and an anticyclonic one below. Such a combination had been

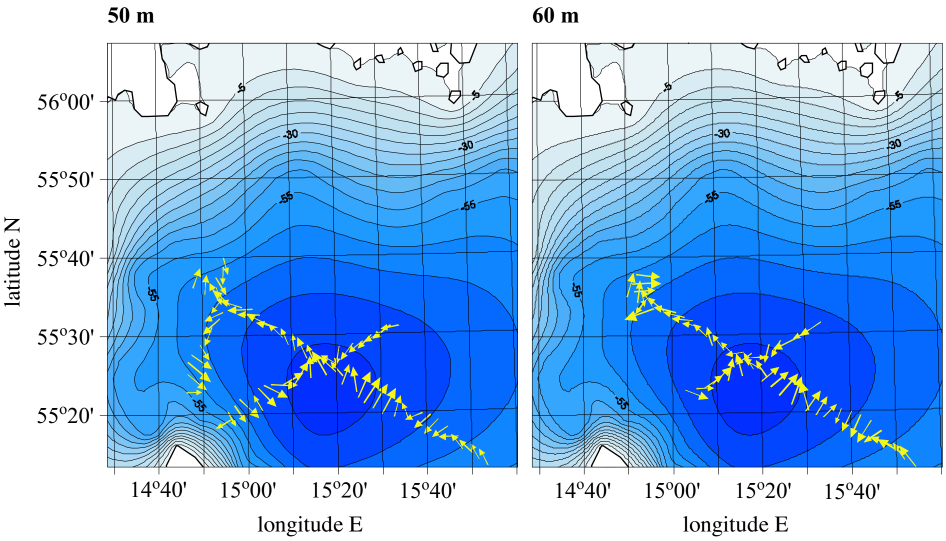

Fig. 5. Currents at the 50 and 60 m levels in the Bornholm Deep – ADCP data. January 2003

observed a few times before, e.g. in the Gotland Deep (DIAMIX IOPAS data) and in the Słupsk Channel. In another place, close to 56 km, we saw the opposite configuration: an anticyclonic rotation on top of a cyclonic one. Their dimensions varied between 20 and 40 km in the horizontal plane and 20–30 m in the vertical. The inflow water raised the halocline in the Bornholm Deep by 10–20 m, pushing the old-warm and mixed water upwards on to the eastern slope. In the Słupsk Channel there was no sign yet of the inflow water; the temperature of the deep layer was still very high and above 10°C. But the deep layer itself was now thinner by about 20 m, the negative thermocline and the halocline were now at about 60 m, whereas in December they had been at about 40 m. Moreover, the salinity of the deep layer had decreased by about 1 PSU. Such changes could not have been due to vertical mixing; advection had to be regarded as the principal cause.

4–7 February 2003

In the Arkona Basin surface cooling and the low temperature of the inflow rendered the whole layer thermally homogeneous with a temperature of about 2°C. The salinity in the bottom layer had decreased by 2–4 PSU during the previous 10–12 days (Fig. 6). In the Bornholm Gate cold (≈ 2°C) and fresh (≈ 10 PSU) water was found, so we can assume that there was no salt water flow at that particular moment. But we did find cold and saline water cascading down the slope into the Bornholm Deep, pushing the remaining warmer water away. The distributions of temperature, salinity and density suggest that the water was moving in pulses and that the bottom topography was affecting the movement. Very intensive mixing was going on in the Bornholm Deep (Fig. 7). The body of old warm water had broken down into small patches concentrated in the 60–70 m layer (temperature 6–7°C) and the 45–55 m layer (temperature 4–5°C). Further details can be seen in the next figure (Fig. 8). Cold water below 4°C occupied the bottom layer below 70 m and the thin layer separating the above-mentioned warmer layers. The idea sprang to mind that these two cold-inflow water layers could have come from different sources; the upper, less saline one from the Øresund and the lower, more saline one from the Belts, or was it perhaps the other way around? The deep layer extended further upwards but only by 5–10 m. The large body of old-warm saline water was still climbing the eastern slope of the Bornholm Deep; at the top of the Słupsk Sill we now had water at 7–8°C and 16 PSU. On the other side of the sill we could see a break in the saline water flow, which happened some time before the start of the flow of a new pulse of such water. In the Słupsk Furrow the effects of the inflow could already be seen, but they were mainly due to the

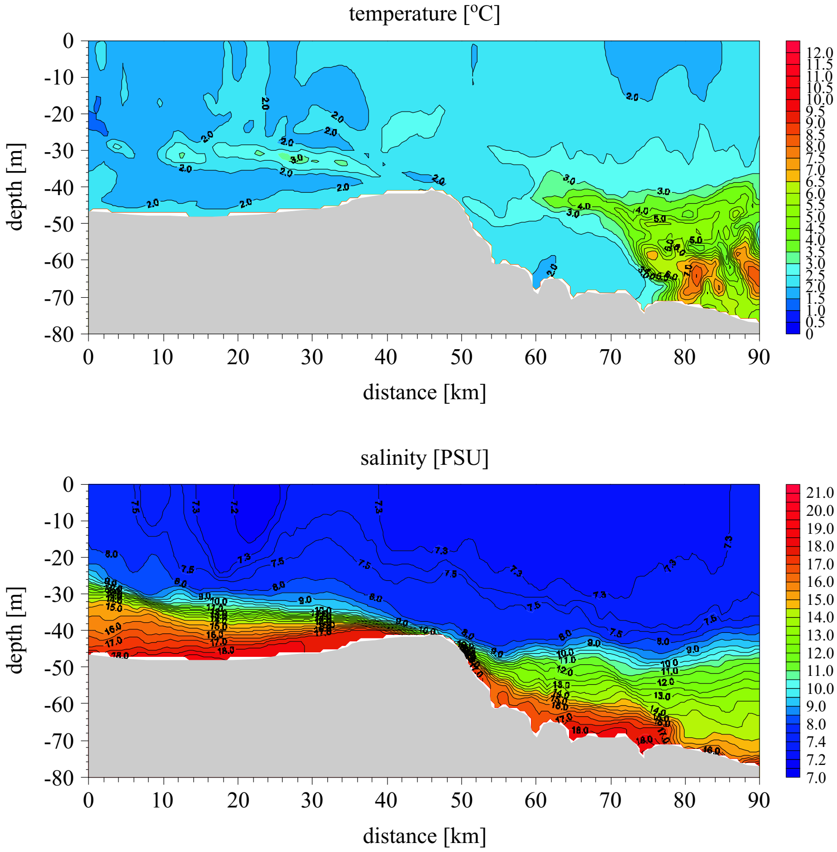

Fig. 6. Temperature and salinity in the Bornholm Gate. 7 February 2003

inflow of old waters from the intermediate layers of the Bornholm Deep. As a consequence the warm waters in the Furrow were being pushed eastwards and upwards (the deep layer had extended upwards by about 10 m) and the salinity had increased by about 1 PSU. Some of the warm waters were cascading downslope into the Gdańsk Deep.

16–18 February 2003

No dramatic changes were observed in the Arkona Basin and the Bornholm Gate (Fig. 9). Somewhat warmer water appeared on the slope of the Bornholm Gate and the salinity in the deepest trench again increased to over 20 PSU. In the Bornholm Deep (Fig. 10) mixing was going on all the time, and the lenses of warmer and cold water were becoming more numerous but smaller. There was now a general decrease in temperature, and only small patches of warm water with a temperature of 5–6°C were

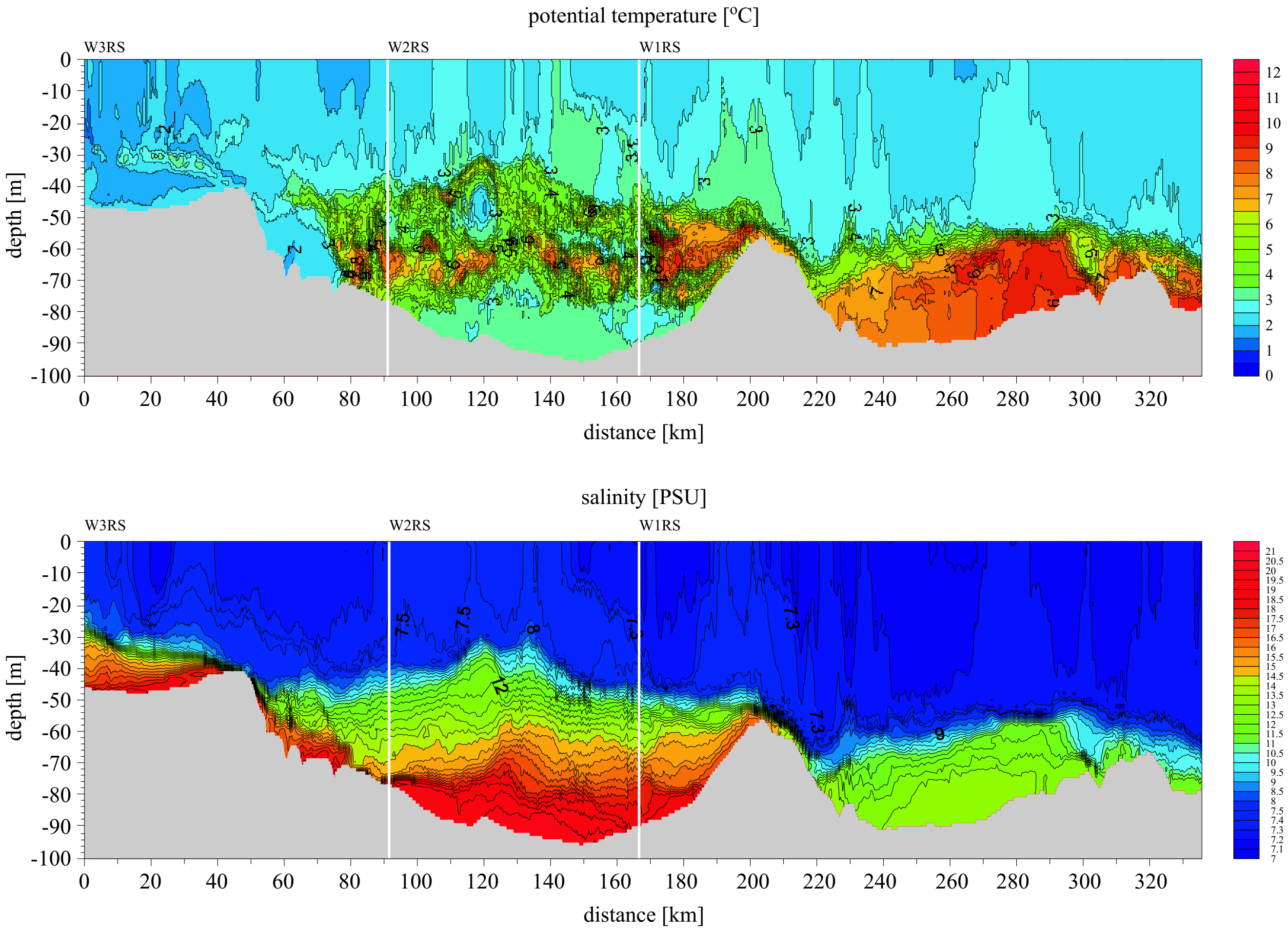

Fig. 7. Temperature and salinity along the main transect. 4–7 February 2003

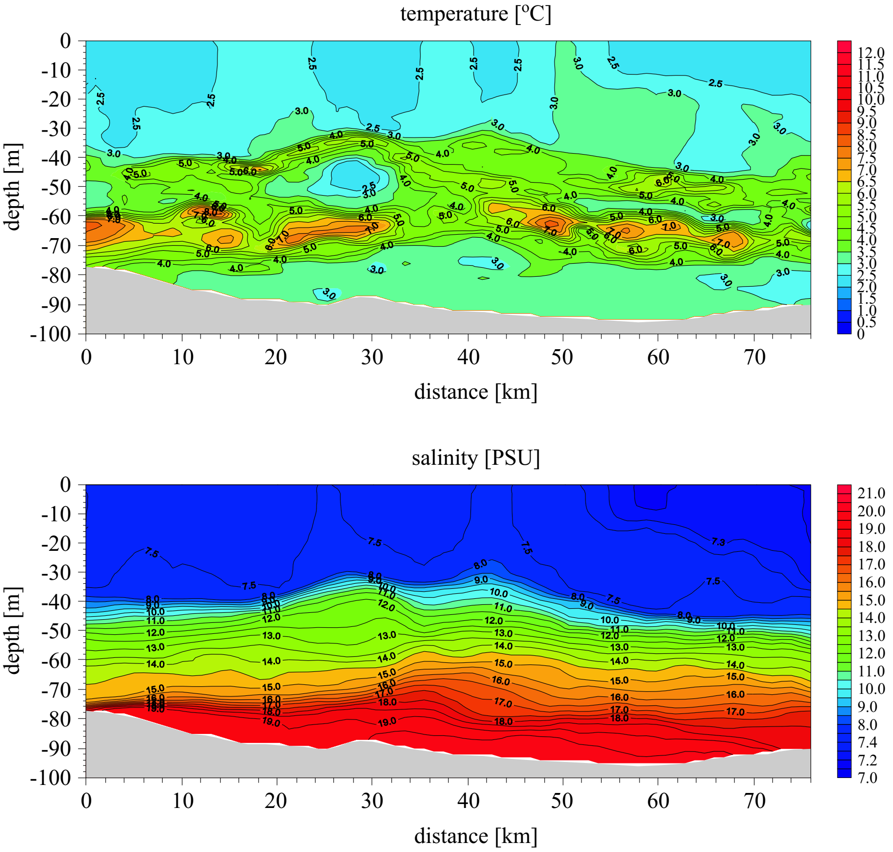

Fig. 8. Temperature and salinity in the Bornholm Deep. 6–7 February 2003

left. A large body of warm water remained over the eastern slope, but was now smaller and its fragmentation had already begun. The salinity of the deep layer further increased slightly and the layer itself extended further upwards to the shallowest depth of 26–28 m but in the center of the Bornholm Deep only. The salinity/density distribution suggested one huge cyclonic eddy about 80–90 km in diameter. The movement of old-mixed and inflowing waters continued eastwards along the Słupsk Channel, but seemed to have slowed down. The highest temperature (over 6°C) was measured at the eastern end of the Channel. The remnants of the old waters from the intermediate layers of the Bornholm Deep Water continued moving along the eastern slope of the Słupsk Sill into the Słupsk Furrow. The upper boundary of the deep layer there stayed at a depth of 50–60 m, its temperature decreased to 5–6°C and salinity increased to a maximum of over 14 PSU near the bottom.

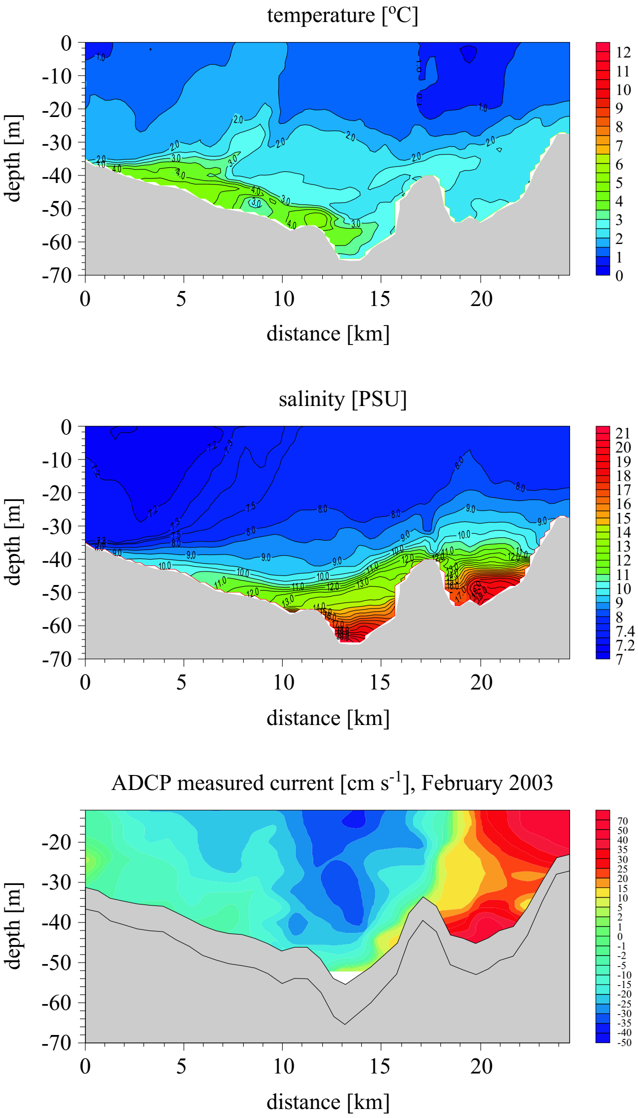

Fig. 9. Temperature and salinity across the Bornholm Gate. 16–18 February 2003

15–17 March 2003

In the Arkona Basin-Bornholm Gate area (Fig. 11) the temperature of the near-bottom layer increased slightly (2–3°C) and the salinity decreased to 15–16 PSU. It is safe to say that there were now no further signs of the January inflow in this area and that the situation had returned to 'normal'. The body of warmer, saline water could be seen on the slope towards the

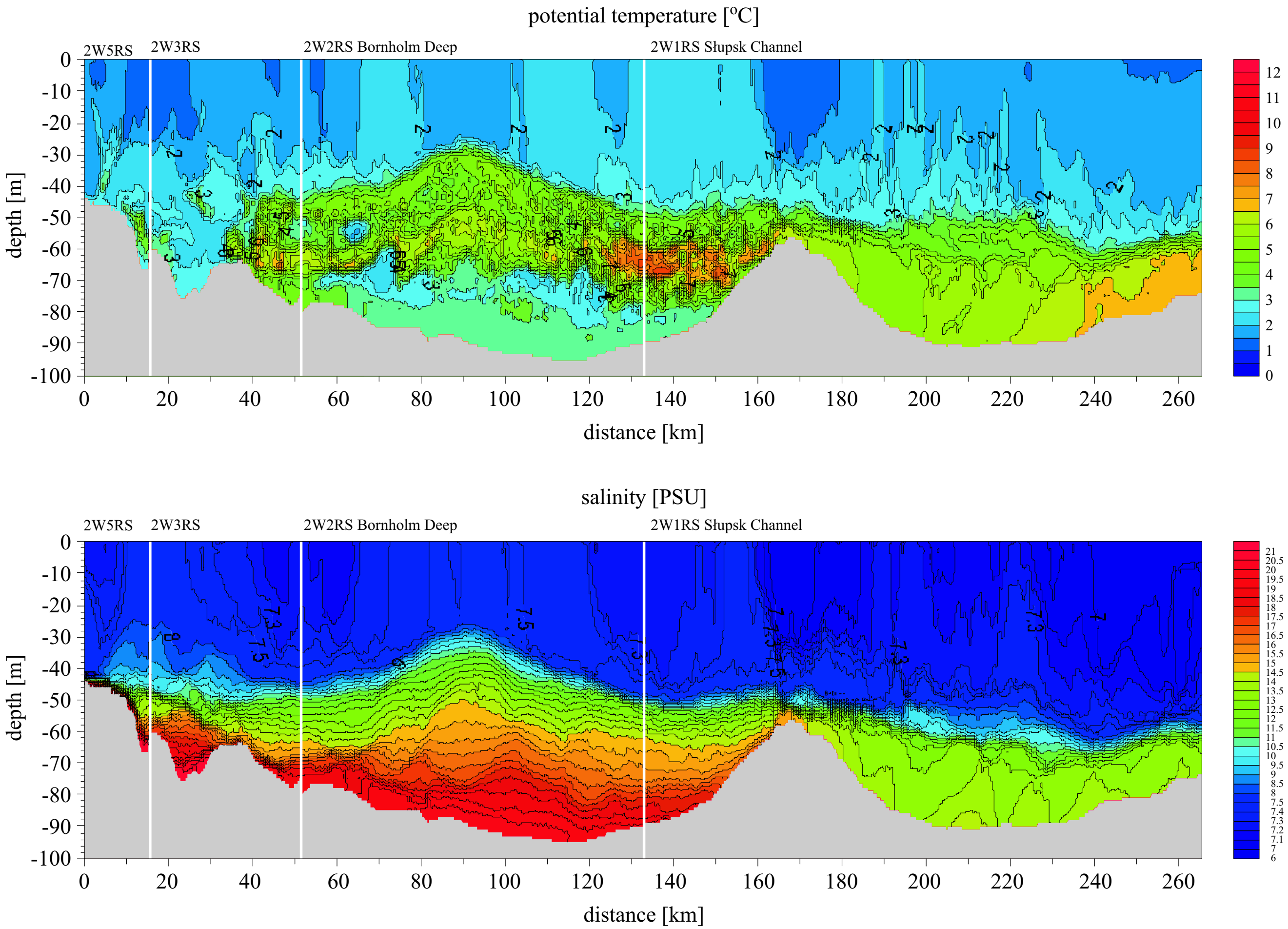

Fig. 10. Temperature and salinity along the main transect. 16–18 February 2003

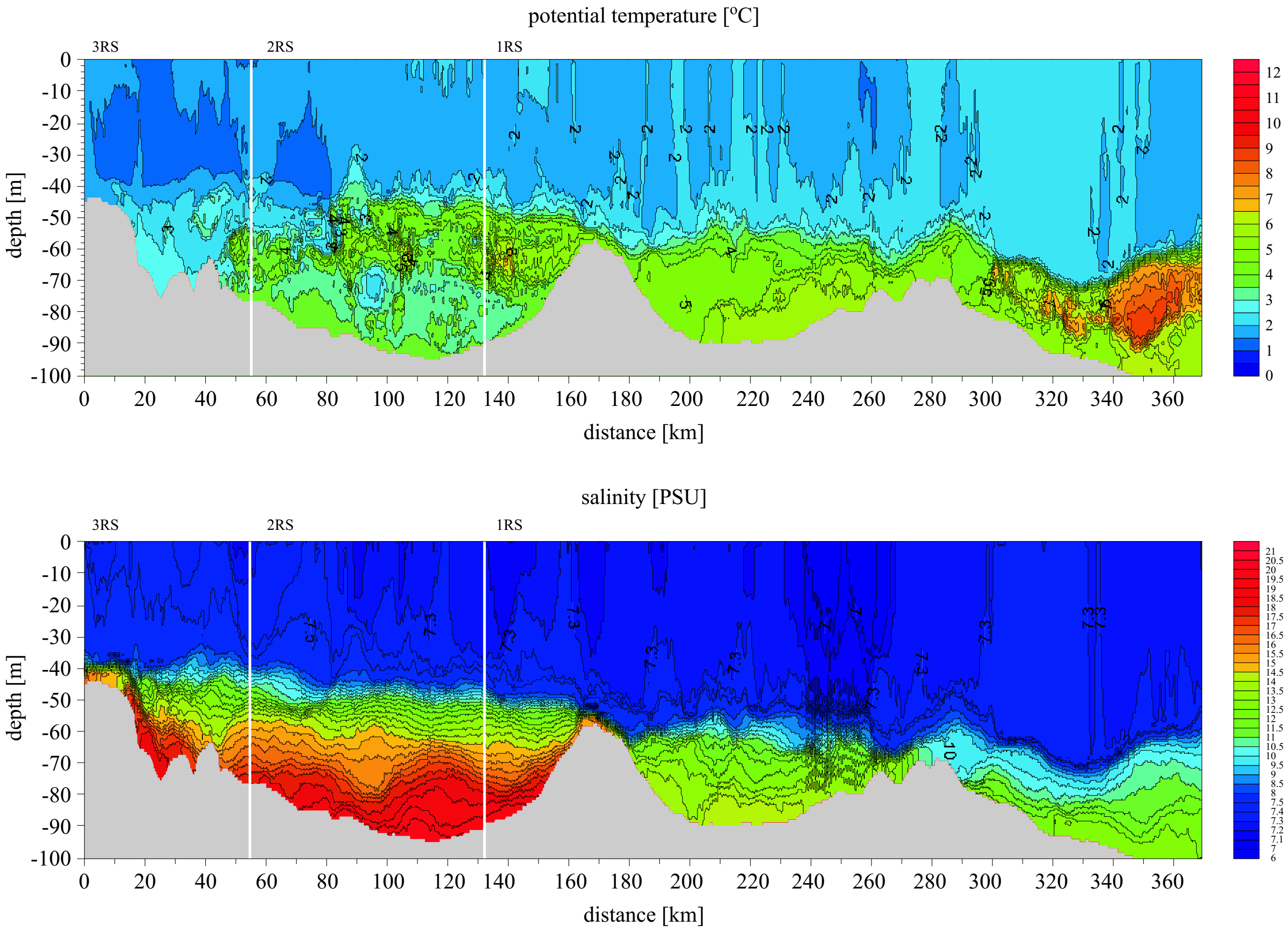

Fig. 11. Temperature and salinity along the main transect. 15–17 March 2003

Bornholm Deep. In the Bornholm Deep mixing was going on all the time and now all of the deep layer contained mixed water; the largest influence of the old water could be detected in the upper part of this layer, where lenses of warmer water (up to 5°C) were recorded at about 60 m, as well as a layer of temperature > 4°C at 40–50 m. The salinity of the deep layer decreased slightly here and there were signs of a cyclonic circulation in the lower part. The upper boundary of the deep layer dropped to an average depth of about 40–45 m, which could can be regarded as the end of the inflow's influence here. The thickness of the deep layer decreased in the Słupsk Furrow as well, its upper boundary was now located at 50–60 m, except in the eastern part over the sill, where this boundary was pushed upwards again (to 45–50 m). The deep layer in the Słupsk Furrow became more saline (a maximum of > 14 PSU in a larger volume near the bottom) and cooler (4–5.5°C). Mixed water from intermediate layers of the Bornholm Deep continued to flow over the Słupsk Sill.

22–24 April 2003

There was no further indication of the inflow in the Arkona Basin and Bornholm Gate. The temperature of the deep layer started to rise (3–4°C) and the salinity at the bottom increased to 14 PSU (Fig. 12). In the deep layer of the Bornholm Basin the temperature eventually became almost homogeneous at around 3°C. The vertical salinity and density gradients remained steep all the time; thermal conductivity may have played some part in this. A body of slightly warmer water (> 4°C) was noted at 50–60 m above the Słupsk Sill and in the Słupsk Furrow, where the deep layer had further cooled to 3–4°C. What was left of the warm water was present on the slope of the Gdańsk Deep only. The salinity of the deep layer had decreased slightly in the Bornholm Deep but had increased considerably in the Słupsk Channel to over 15 PSU. Since the March cruise the deep layer had extended slightly upwards here. The salinity distribution in the Słupsk Furrow suggests that a quite large body of saline water had flowed from intermediate layers of the Bornholm Deep over the Słupsk Sill into the Channel.

16–17 August 2003

Signs of the January inflow were detected in the bottom layer of the Bornholm Basin, Słupsk Furrow and Gdańsk Deep as a low 4–5°C temperature layer (Fig. 13). Additionally, in the Słupsk Channel and Gdańsk Deep the salinity also remained high (> 14.5 PSU). Another intrusion of warmer water 10–12°C was seen in the Arkona Basin near the bottom and in the Bornholm Gate and Basin at intermediate depths of

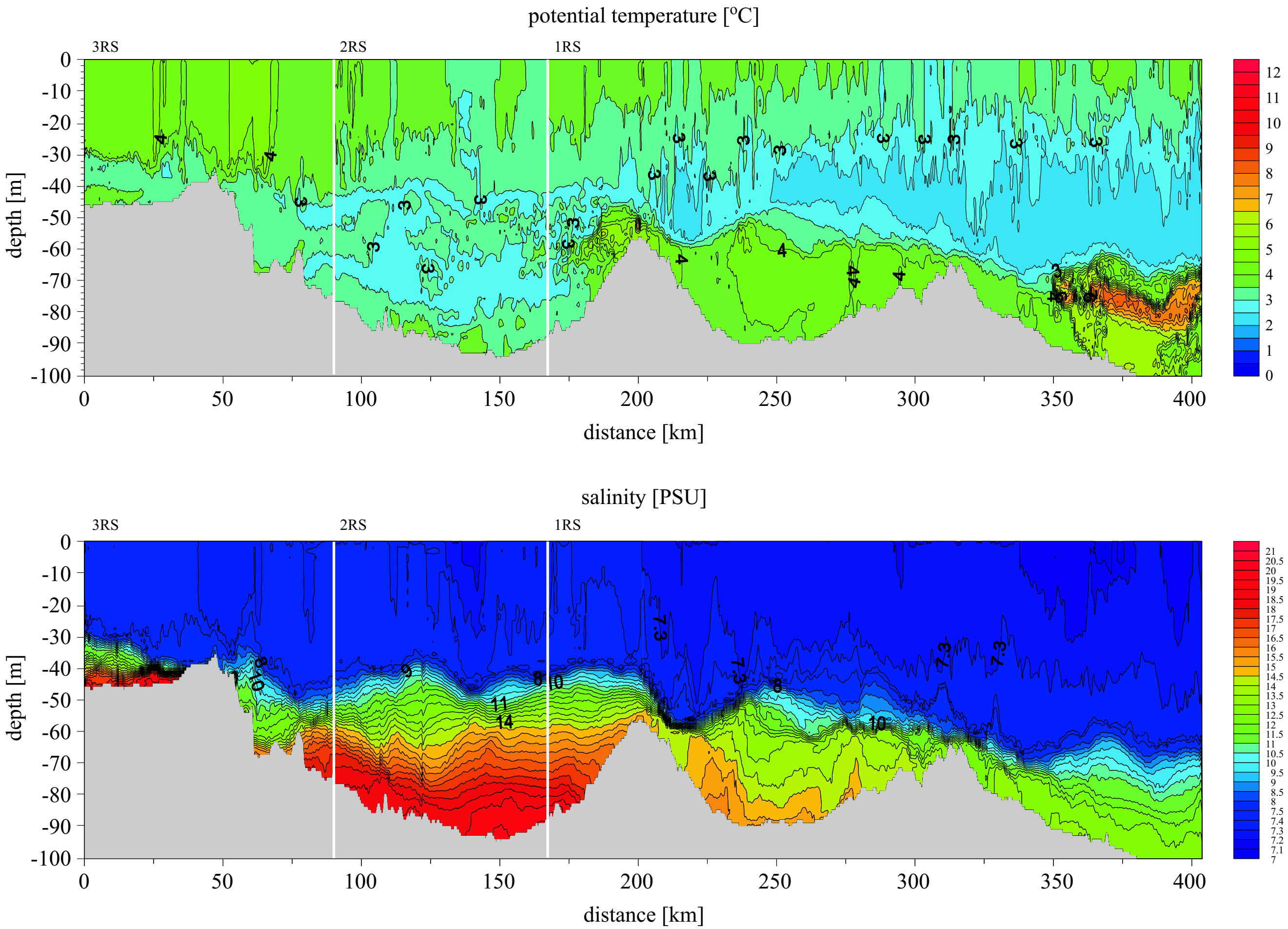

Fig. 12. Temperature and salinity along the main transect. 22–26 April 2003

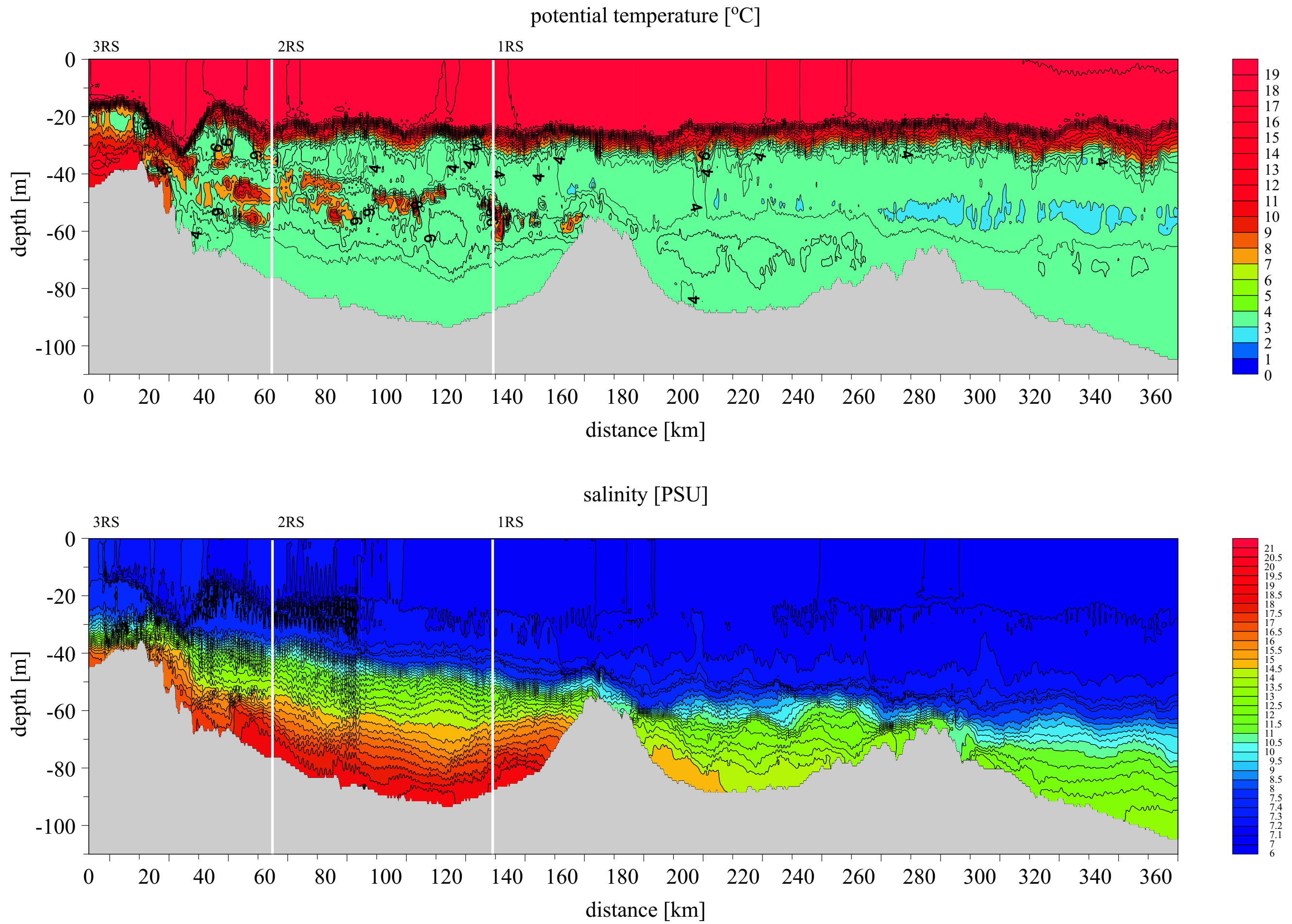

Fig. 13. Temperature and salinity along the main transect. 15–17 August 2003

30–60 m in the form of discrete lenses of different dimensions. Their salinity varied around 10–12 PSU. Above this layer patches of cold water (5–6°C) remained.

4. Discussion

A medium-sized inflow started to cross the sills in the western Baltic Sea in the second ten days of January, bringing more saline and colder waters. The low temperature of these inflow waters (close to 1°C) was a very exceptional feature: previously observed inflows carried waters distinctly warmer than the local Baltic Sea waters. This coincided with another exceptional feature: the very high temperature of the deep waters within the Baltic (11–12°C), caused by another inflow which had taken place in August 2002 (IOW data). This created a large difference in temperature at least between the inflowing and ambient waters. This gave us a unique opportunity to follow the movement of the inflowing water within the Baltic and to learn more about the mixing processes. A further exceptional feature of this particular inflow was that the water moved very rapidly in the first stage of the process, covering a distance of about 140–150 nautical miles from the Drogden and Darss sills to the middle of the Bornholm Basin in less than 12 days, at a speed of at least 30 cm s^{-1}. The usual speed of inflowing water is about 3–5 cm s^{-1}.

The first disturbance of the smooth flow was noticed already in the Arkona Basin, where a cyclonic eddy with the same diameter as the entire Basin was detected. The downstream inflow on the southern edge reached a maximum speed of 45 cm s^{-1}, while the downstream transport measured 129×10^3 m^3 s^{-1} (Fig. 14). In the Bornholm Gate inflowing waters were pushed up on to the southern slope (Fig. 15).

However, the most interesting processes were going on in the Bornholm Deep itself. Because of the complicated circulation, the transport of more or less pure inflow waters come to an end there, and intensive mixing with ambient waters transforms it; only this mixed water enters the Słupsk Channel further to the east.

The longitudinal section across the northern edge of the Bornholm Basin in January 2003 (Fig. 16) shows a near-bottom gravity-driven current of inflow water with a maximum salinity of 21 PSU, extremely low temperature (down to 1.5°C) and a measured velocity up to 75 cm s^{-1} entering the Bornholm Basin along its southern rim, suggesting a cyclonic circulation. Another cyclonic structure in the northern part of the basin with a radius of about 10 km and a maximum rotational speed of 20 cm s^{-1} was probably due to a local circulation in old, stagnating, deep waters.

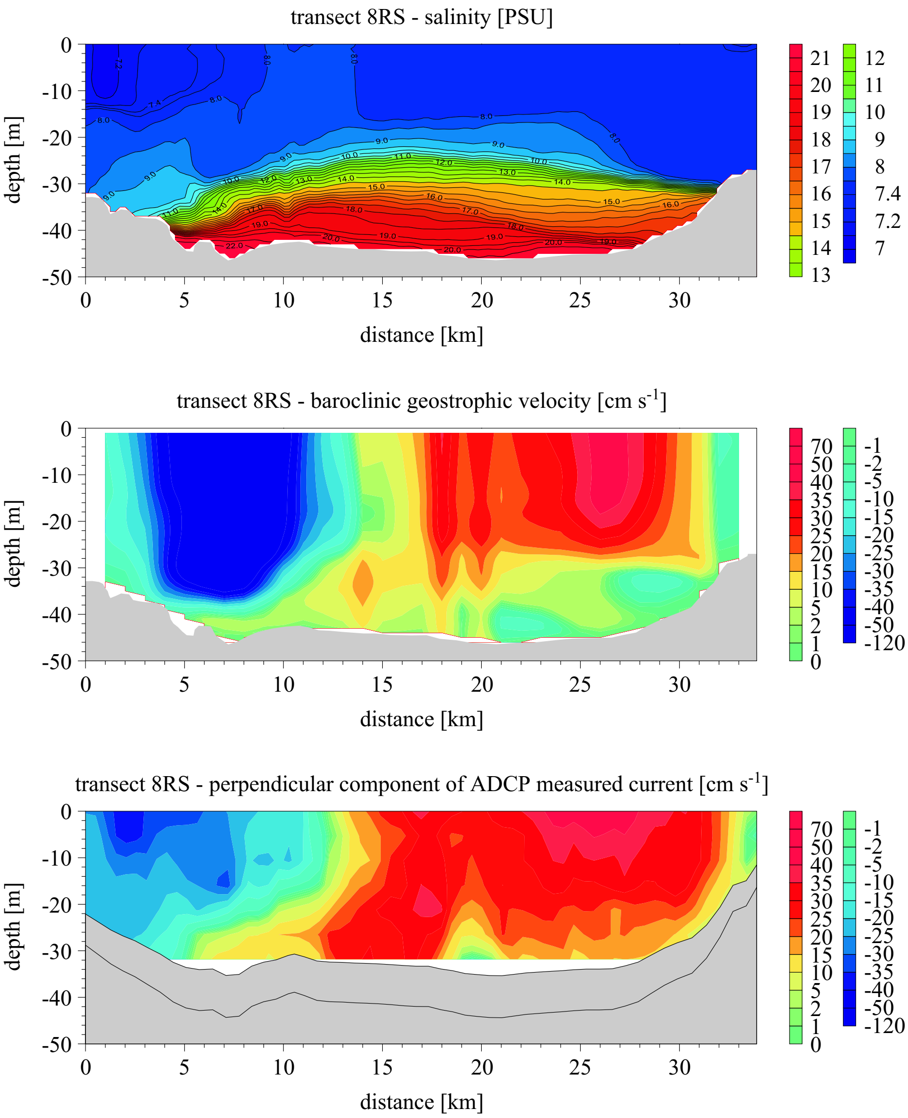

Fig. 14. Pool of the inflow waters in the Arkona Basin. 26 January 2003

The net volume transport across the whole section is about 81×10^3 m^3 s^{-1} in an easterly direction, while the volume transport of waters (S > 8.5 PSU) reaches 107.3×10^3 m^3 s^{-1}.

The section across the central part of the Bornholm Basin measured twice in January 2003 (Fig. 17) showed a strong anticyclonic lens-like eddy 35 km in diameter with a rotational speed of up to 50 cm s^{-1}. It is filled with cold waters originating from the inflow (minimum temperature 1.8°C).

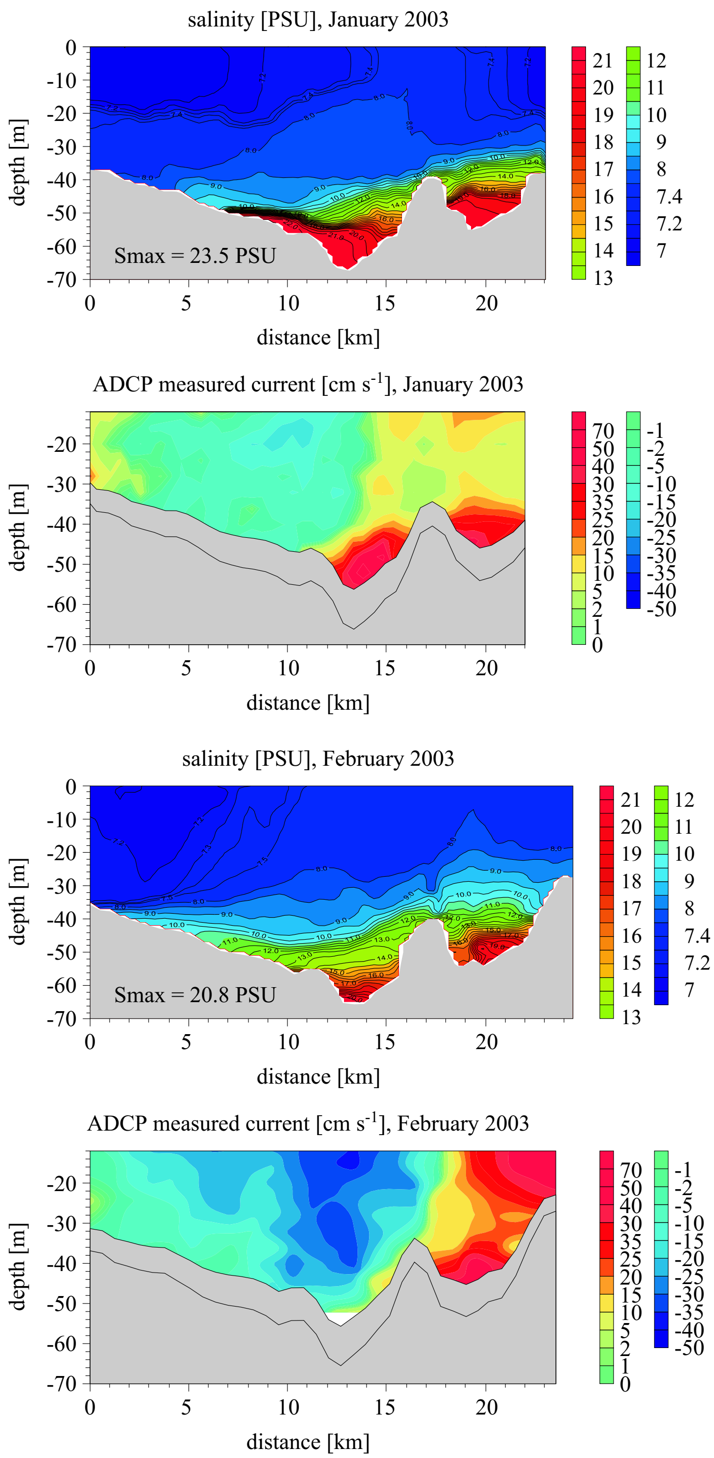

Fig. 15. Transportation of the inflow waters through the Bornholm Channel

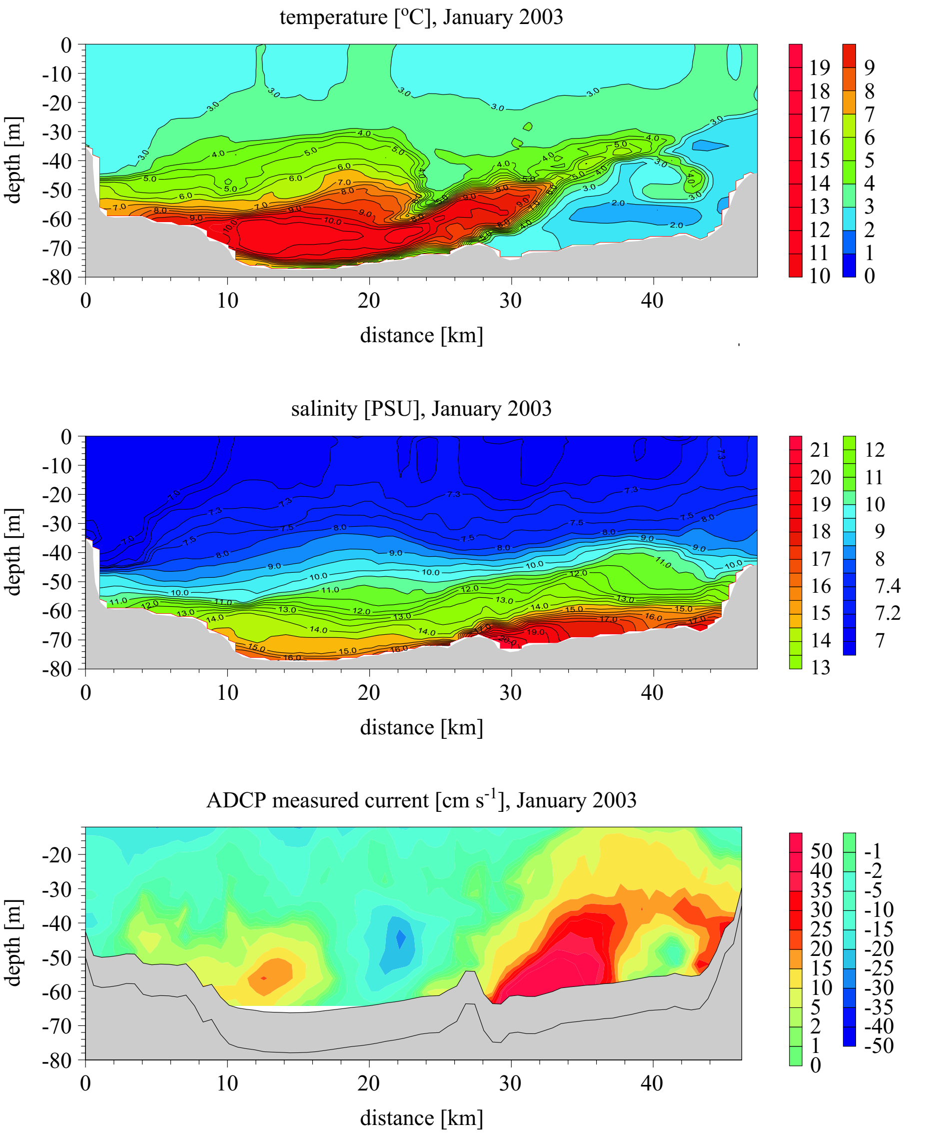

Fig. 16. Dense bottom current entering into the Bornholm Basin. January 2003

The development of a baroclinic eddy is the result of a dense bottom current meandering along the southern slope of the Bornholm Basin. The presence of lens-like eddies can reduce the speed of the most saline waters in the near-bottom layer in the downstream direction. Cold water included in the core of a lens-like eddy in January 2003 was mixing with ambient waters at the edges of the eddy.

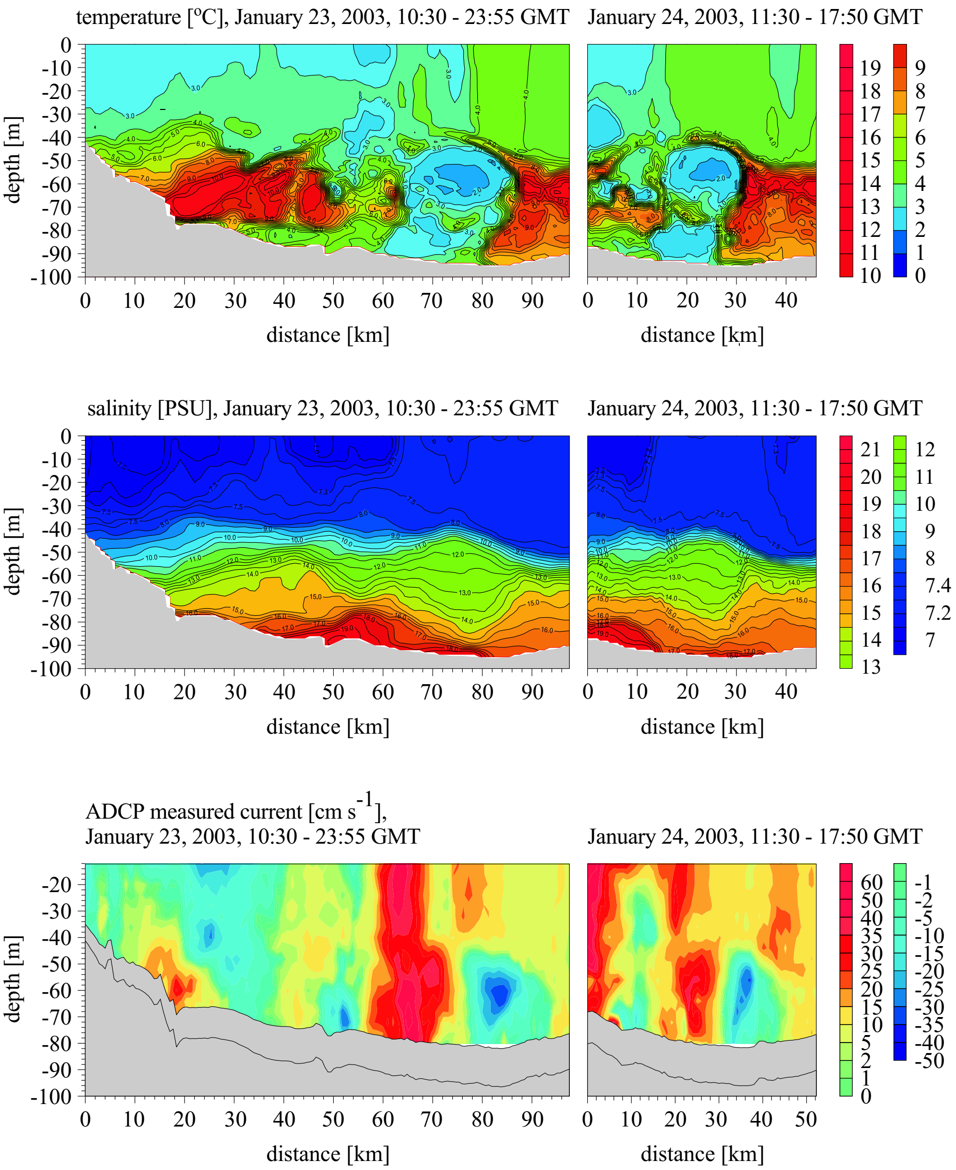

Fig. 17. Eddies and meandering of slope current in the Bornholm Basin. January 2003

The overflow across the Słupsk Sill contains mostly mixed water from the intermediate layer of the Bornholm Deep, but because of additional forcing, these overflowing waters usually come from a much greater depth than that of the sill layers. The process whereby deep waters rise from below sill level up to the sill and spill over it is frequently observed.

Some of the inflow water arrived in the Słupsk Channel already in February and March, but the largest volume appeared in March and April. The evolution of the waters above the Słupsk Sill is shown in Fig. 18.

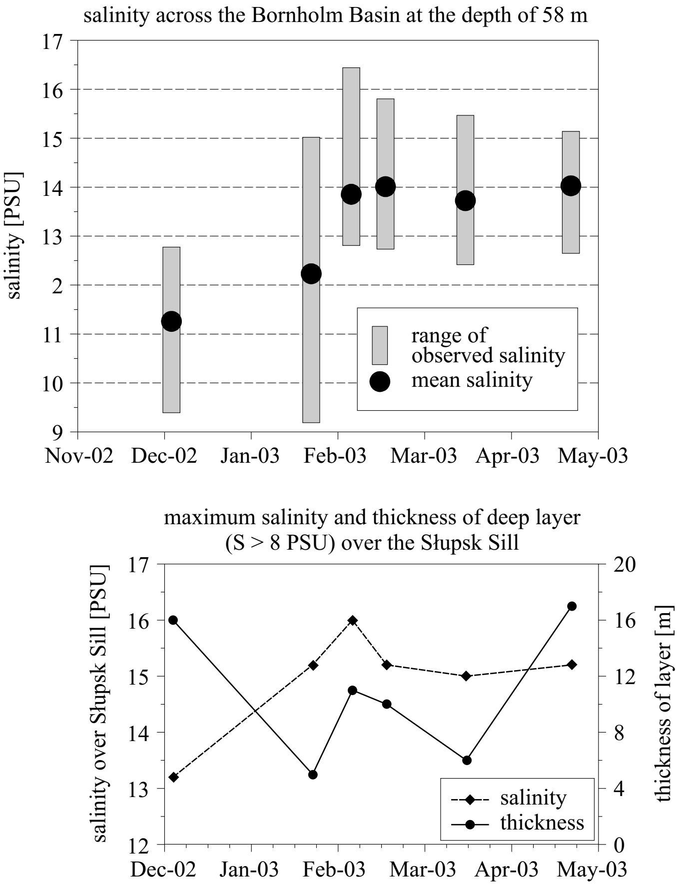

Fig. 18. Transport of the inflow waters over the Słupsk Sill

The section across the central part of the Słupsk Channel in April 2003 (Fig. 19) shows inflowing waters with a salinity of > 15 PSU carried by a near-bottom, density driven current. A westward flow is dominant in the whole water column; only in the deep layer core is an eastward current detectable. The similar structure of the calculated baroclinic flow field and ADCP measured current suggest that the flow in the Słupsk Channel is mainly baroclinic with a weak barotropic component directed to the west.

The section across the eastern part of the Słupsk Channel in April 2003 (Fig. 20) indicates a downstream transport of inflowing waters (with maximum $S = 14.5$ PSU) shifted towards the northern slope of the channel

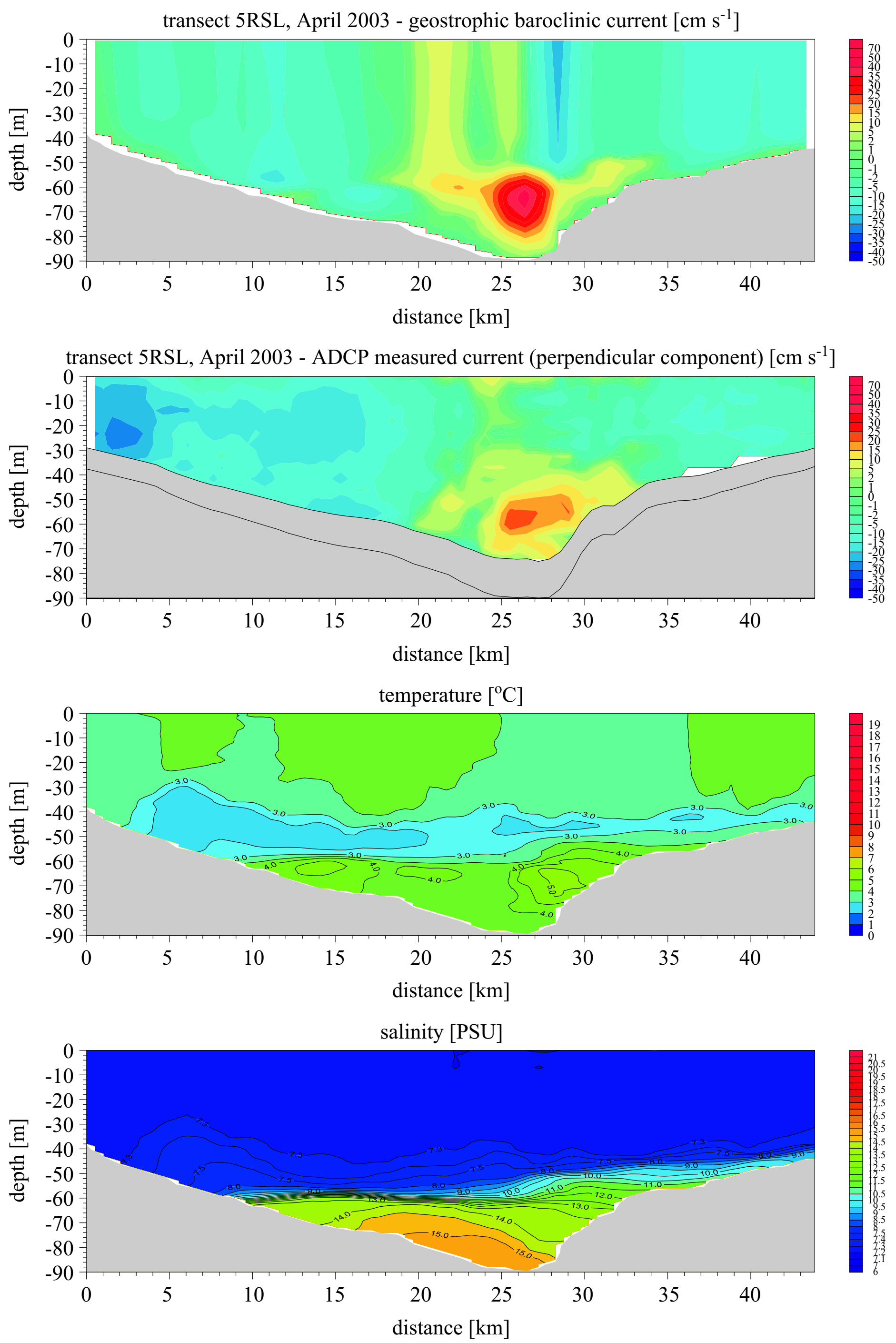

Fig. 19. Transport of the inflow waters in the Słupsk Channel at transect 5RSL. April 2003

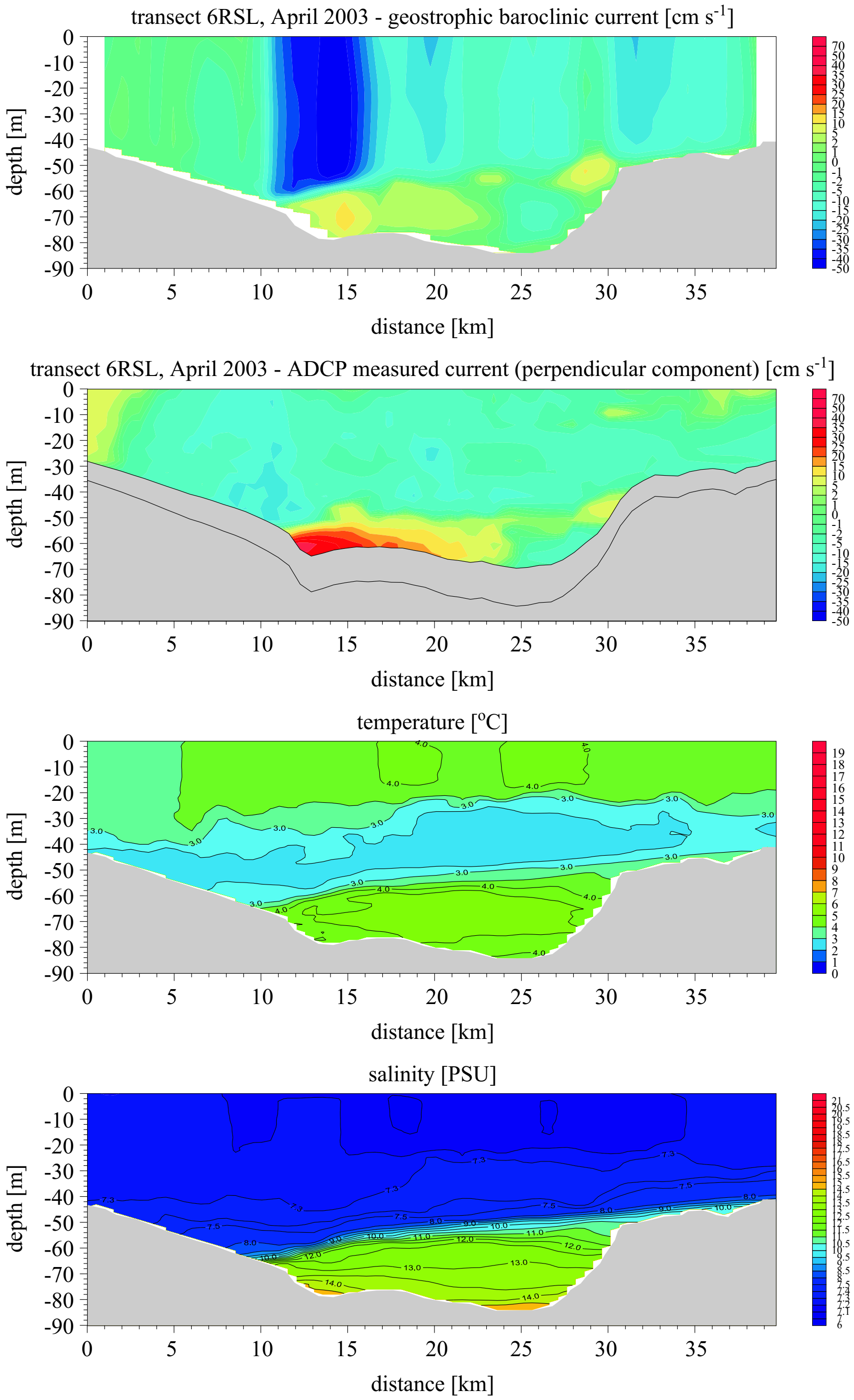

Fig. 20. Transport of the inflow waters in the Słupsk Channel at transect 6RSL. April 2003

and confined only to the deep layer. A westward flow prevails in the channel, resulting in significant upstream transport.

The transformation of deep waters in the Bornholm Basin and Słupsk Furrow is shown in Figs 21 and 22. Dramatic changes in the TS structure are taking place in the Bornholm Deep.

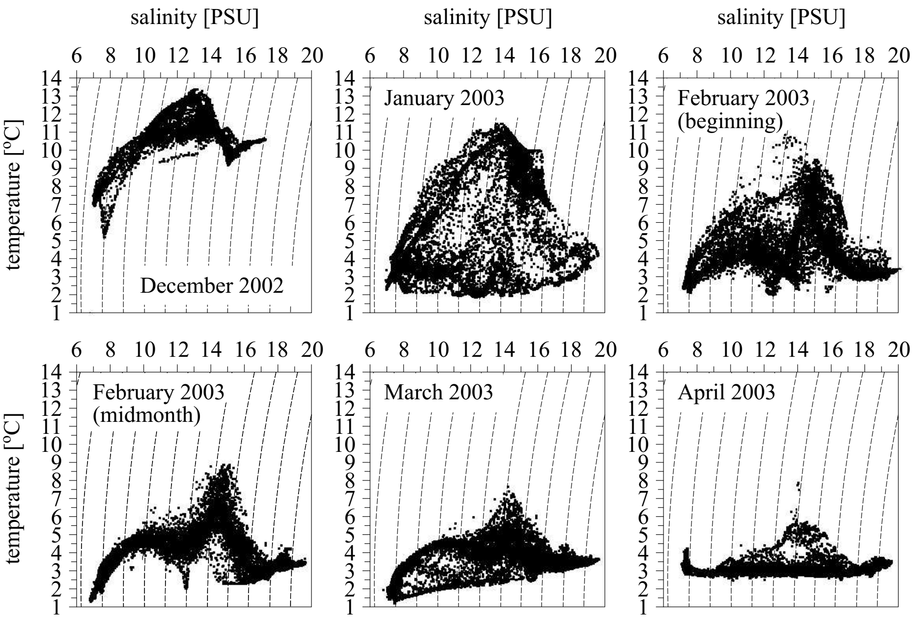

Fig. 21. Transformation of water masses during the successive stages of inflow in 2003 – Bornholm Basin

December: Most of the water is at a very high temperature (8–13°C) and has a salinity range of 8–15 PSU. The body of bottom water is defined by 9–11°C and 14–18.0 PSU.

January: There is a very broad range of temperature and salinity within the deep layer, 2–11°C and 9–21 PSU respectively. Generally, strong cooling and increasing salinity are the rule.

February, March, April: Further cooling is in progress, the temperature range is becoming narrower (2–10°C at the beginning of February, and 2–8°C in mid-February, 2–7°C in March and 3–5°C in April); the salinity range remains nearly the same.

The cumulative TS for Słupsk Furrow shows similar but less dramatic changes caused by the inflow: cooling is much slower, and there is an increase in salinity.

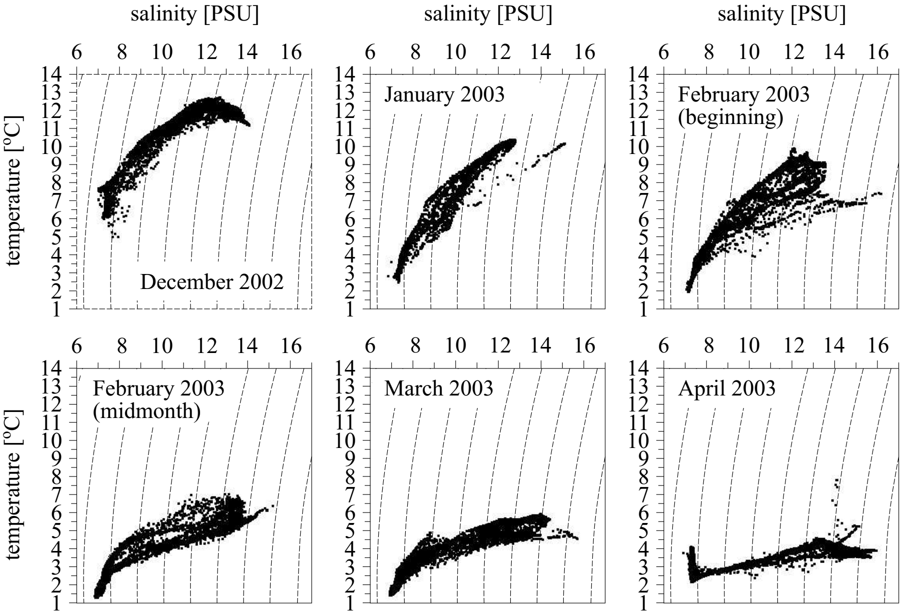

Fig. 22. Transformation of water masses during the successive stages of inflow in 2003 – Słupsk Channel

5. Conclusions

- In January 2003 we witnessed **very** interesting features: an inflow of medium size carrying about 200 km^3 of highly saline and exceptionally cold water into a deep layer of exceptionally warm waters.
- The inflowing waters moved exceptionally fast into the Arkona Basin and through the Bornholm Gate into the Bornholm Basin: the estimated speed was about 30 cm s^{-1}.
- The dynamics of inflowing waters was disturbed by frequent baroclinic eddies, particularly numerous in the Bornholm Deep.
- The Bornholm Basin was the main area where mixing of cold inflow waters with local warm waters was taking place.
- To the east of the Bornholm Basin no 'pure' inflow waters were detected; only mixed waters were present.
- The inflow pushed ambient waters upwards by 20–30 m; thus, the volume of the inflow grew considerably by entrainment and mixing.
- As a consequence of the inflow, colder and more saline, mixed waters from the intermediate layers of the Bornholm Deep flowed into the Słupsk Furrow over the Słupsk Sill and farther to the Gdańsk Deep.

- Despite the strong density stratification, heat exchange was intensive throughout the process.

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