Warm waters of summer 2002 in the deep Baltic Proper*

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Abstract

From October 2002 until March 2003 surprisingly warm, oxygenated waters were frequently encountered in the Baltic Sea in the area between the Bornholm and

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Fårö Deeps from the halocline down to the bottom. Owing to their ventilation effect in the stagnating deep waters, their occasional observations have partly been incorrectly attributed to the inflow events of October 2002 or January 2003. The emergence of some of these waters can be traced back to the exceptional summer weather conditions in August and September 2002 in central Europe. The warm waters played a remarkable renewal pacemaker role for the subsequent important winter inflow of January 2003. The evolution of this summer inflow is described and possible causes are discussed.

1. Introduction

In August and September 2002, Germany and the surrounding regions suffered from a lingering humid 'Mediterranean' heat period with very light southerly or south-easterly winds. With unusual frequency, so-called Vb- or Adriatic Lows crossed the Alps in a northward direction, bringing torrential rains which locally reached amounts not experienced for a century or longer, and causing substantial flooding, human tragedies and economic damage. The affected areas belonged mainly to the drainage basin of the North Sea, so no immediate effect was noted in Baltic Sea waters.

Between the end of June and the middle of September 2002, moderate winds with an easterly component prevailed over the western Baltic Sea. For a period of about eight weeks, the Baltic Sea Research Institute (IOW) mast at the Darss Sill recorded bottom salinities of up to 20 PSU and temperatures up to 20°C (cf. Nausch et al. 2003), while the 14 PSU isohaline almost permanently enclosed a dense near-bottom layer with a mean thickness of about 5 m. The Baltic Sea filling factor as indicated by the Landsort sea level gauge was constantly below average from the end of July to the end of October, and showed only insignificant fluctuations, but no sudden rise in level as is otherwise typical of inflow events.

Despite the almost continuous surface outflow, substantial amounts of Kattegat waters were persistently flowing over a period of eight weeks along the sea floor in the opposite direction and accumulating in the adjacent deeper basins. As opposed to other warm, late-summer or autumnal inflows poor in oxygen, like those observed in September 1997 (Matthäus et al. 1999, Hagen & Feistel 2001) or in October 2001 (Feistel et al. 2003a), this particular current was characterised by strong stratification, the absence of wind mixing, and the separation of the dense water from the atmosphere already in the Belt Sea. For the hydrographic and hydrochemical assessment of the Baltic Sea in 2002 cf. Nausch et al. (2003).

At the end of July 2002, the monitoring cruise of the IOW reported near-bottom temperatures of less than 12°C in the Arkona Basin, and below 9°C in the Bornholm Basin (Wasmund 2002). During the IOW's autumnal monitoring cruise, water bodies warmer than 14°C were found at the bottom of the Arkona Basin, 13°C in the Bornholm Basin, 11°C in the Słupsk Channel, and 7°C beyond the Słupsk Channel (Schmidt 2002), carrying oxygenated waters towards the Gotland Basin, one week before the small inflow of Kattegat water was recorded on 28th October 2002. This evidence confirms that those warm waters, which replaced the previously anoxic waters of the Gdańsk Basin with oxygenated and exceedingly warm waters by November 2002, had arrived to the relevant basins much earlier, though not before August 2002. For later reference, the Arkona Basin (50 m deep) has only a shallow sill – the Bornholm Sill (45 m) – with two submarine canyons crossing it. The Bornholm Basin (100 m) is limited by the Słupsk Sill (60 m) and covers 225 km^3 below that. The Gotland Deep (250 m) contains 38 km^3 of water below the enclosing 190 m isobath.

The strong inflow in January 2003 (Feistel et al. 2003b in this volume) triggered a dedicated ad-hoc research cruise to study its propagation and fate in the Arkona and Bornholm Basins (Nausch 2003a). The measurements detected the cold water front located within the Bornholm Basin with temperatures below 3°C and an oxygen content of about 7 ml l^{-1}, even though on its eastern side temperatures were still in excess of 10°C and oxygen was as low as 4 ml l^{-1}. During the subsequent monitoring cruise in February 2003, warm deep waters were observed between the Słupsk Channel and the Gotland Deep, in part warmer than 7°C (Nagel 2003) and still surprisingly warm (9.1°C) in the Gdańsk Deep (IMGW 2003).

In March 2003, the formerly strongly anoxic waters in the Gotland Deep proved to be partly ventilated, especially at about 200 m depth, and contained traces of oxygen even at the very bottom (Feistel 2003). The high temperatures found there disproved the hypothetical origin of these renewal waters as being from the cold January inflow. The warm waters exceeding 7°C had travelled even farther north towards the Fårö Deep, and were observed there as a faint temperature signal in the layers between 100 and 120 m depth.

2. Material and methods

The measurements presented in this paper cover the period between July 2002 and May 2003, and were obtained in part by observations within the framework of the Baltic Monitoring Programme (COMBINE) of the Helsinki Commission (HELCOM) carried out by the IOW in Warnemünde, Germany, and the Institute of Meteorology and Water Management (IMGW) in Gdynia, Poland. The regular monitoring cruises covered the months of August (Wasmund 2002), October (Łysiak-Pastuszak & Drgas 2002, IMGW 2002, Schmidt 2002) and November 2002 (Łysiak-Pastuszak & Drgas 2002, IMGW 2002), and February (Nagel 2003, IMGW 2003), March (Feistel

2003) and May 2003 (Nausch 2003b). Moreover, research cruises with in the framework of GLOBEC Germany, were undertaken in October (Dutz 2002) and November 2002 (Herrmann 2002). An inflow tracking cruise in January 2003 (Nausch 2003a) and several other cruises in August (Siegel 2002, Roeder 2002a), September (Voss 2002) and December 2002 (Roeder 2002b) were carried out by the Baltic Sea Research Institute.

The ship-borne investigations were supplemented by continuous records of temperature, salinity and partly oxygen at two permanent stations of the German *MAR*ine Environment Monitoring *NET*work (MARNET) of the Bundesamt für Seeschifffahrt und Hydrographie (BSH): the Darss Sill mast (DS) (Krüger et al. 2003), and the semi-diver buoy Arkona Basin (AB) (Krüger 2001), both operated by IOW. Additionally, current profiles

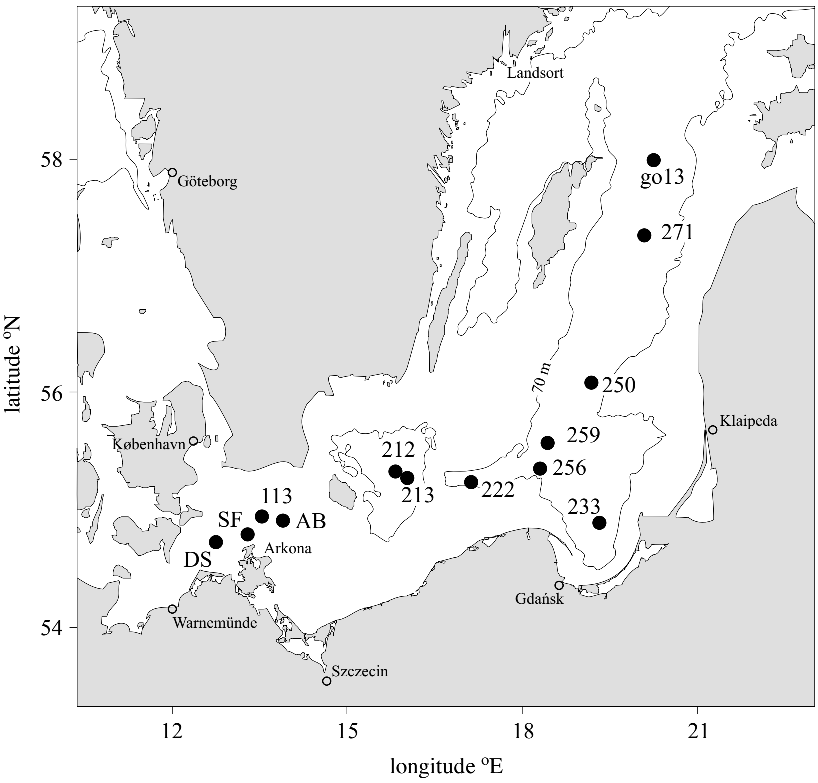

Fig. 1. Warm water observation positions in IOW notation: AB = Arkona Basin buoy, DS = Darss Sill mast, SF = a scanfish reading. The deep stations of the main basins are: Arkona Basin (AB) = 113, Bornholm Basin (BB) = 213 = BMP K2 and 212 = GLOBEC 023, Słupsk Channel (SC) = 222, Gdańsk Basin (DB) = 233 = P1, South-Eastern Gotland Basin (SEGB) = 259 = P140, Gotland Basin (GB) = 271, Fårö Deep (FD) = go13 = GOBEX 13

are available from an Acoustic Doppler Current Profiler (ADCP) moored at Darss Sill.

All the hydrographic and chemical variables studied and the methods used were based on the standard guidelines for the COMBINE programme of HELCOM (HELCOM 2002). The positions of the stations of all cruises and the MARNET stations are shown in Fig. 1.

Two numerical models were used for interpretation of the summer inflow event. The simulation by the IOW model of the Baltic Sea relies on an adaptation of the MOM-3 code (Pacanowski & Griffies 2000) to the Baltic Sea with a free sea surface and a tracer conserving fresh water input (Griffies et al. 2001). The operational model of the Belt Sea by Danish Hydraulic Institute (DHI) is the 3D professional free-surface model MIKE 3 (DHI 2003a, b).

3. Results

The Darss Sill temperature, salinity and current profiles (Fig. 2) of the late summer 2002 show a salty bottom layer of about 5 m thickness, with bottom salinities exceeding 17 PSU, almost continuously present over the entire period between 5th August and 11th October. The temperature of this layer was about 13°C on 5th August, rose to 15°C after a gradual increase on 12th August, reached a maximum of 18°C on 19th September and, together with the salinity, dropped below 15°C again on 11th October 2002. The oxygen concentration in the near-bottom water fell to 2 ml l^{-1} on 5th August and continued to oscillate between 1 and 4 ml l^{-1} for the entire period. These values correspond well to the pronounced oxygen deficiency observed simultaneously over wide areas of the Belt Sea (HELCOM 2003). Although most of the time the water column was strongly stratified, the alternating inflow/outflow phases recorded by the current profiler revealed an almost barotropic motion. Thus, during inflow phases, the whole water column including the low-salinity top layer had moved in a north-easterly direction. During the outflow intervals (hatched), the halocline appeared at greater depths. Only short periods at the turning points from outflow to inflow can be called baroclinic, with the surface layer flowing outwards over the bottom layer flowing into the Baltic Sea.

The unusual, strongly stratified inflow in the summer was followed by a 'normal', small one in early November 2002, forced hydraulically by westerly gales. The Darss Sill near-bottom salinity exceeded 17 PSU only on 1st and 2nd November, with water temperatures still above 10°C (cf. Fig. 2). This time, the water column was significantly less stratified than during the summer inflow described before.

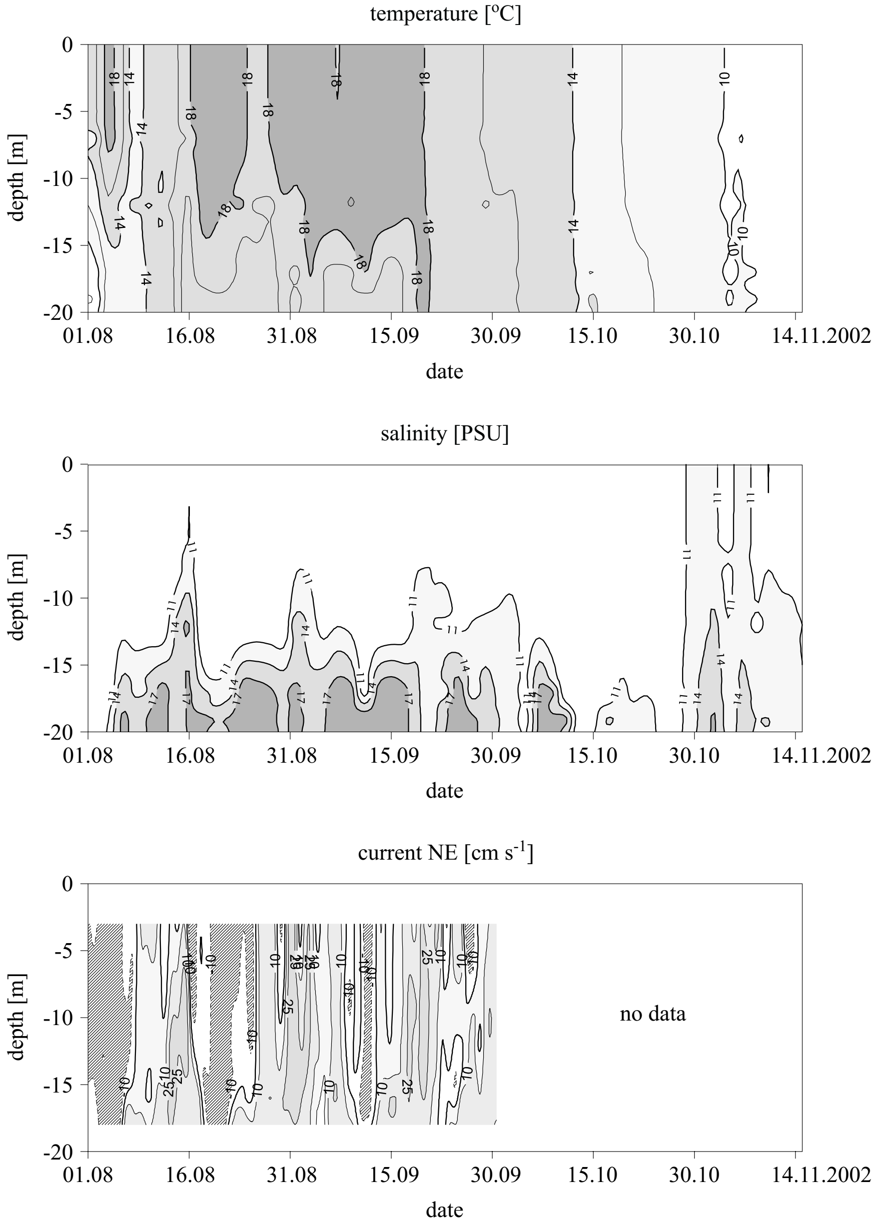

Fig. 2. Vertical profiles of temperature, salinity and north-easterly current component at the Darss Sill measuring mast between 1st August 2002 and 14th November 2002. Note especially the strong salinity stratification as opposed to the almost homogeneous vertical current profiles

The Arkona Basin buoy started operating at the end of September 2002. In Fig. 3, the time series from this buoy is combined with several CTD

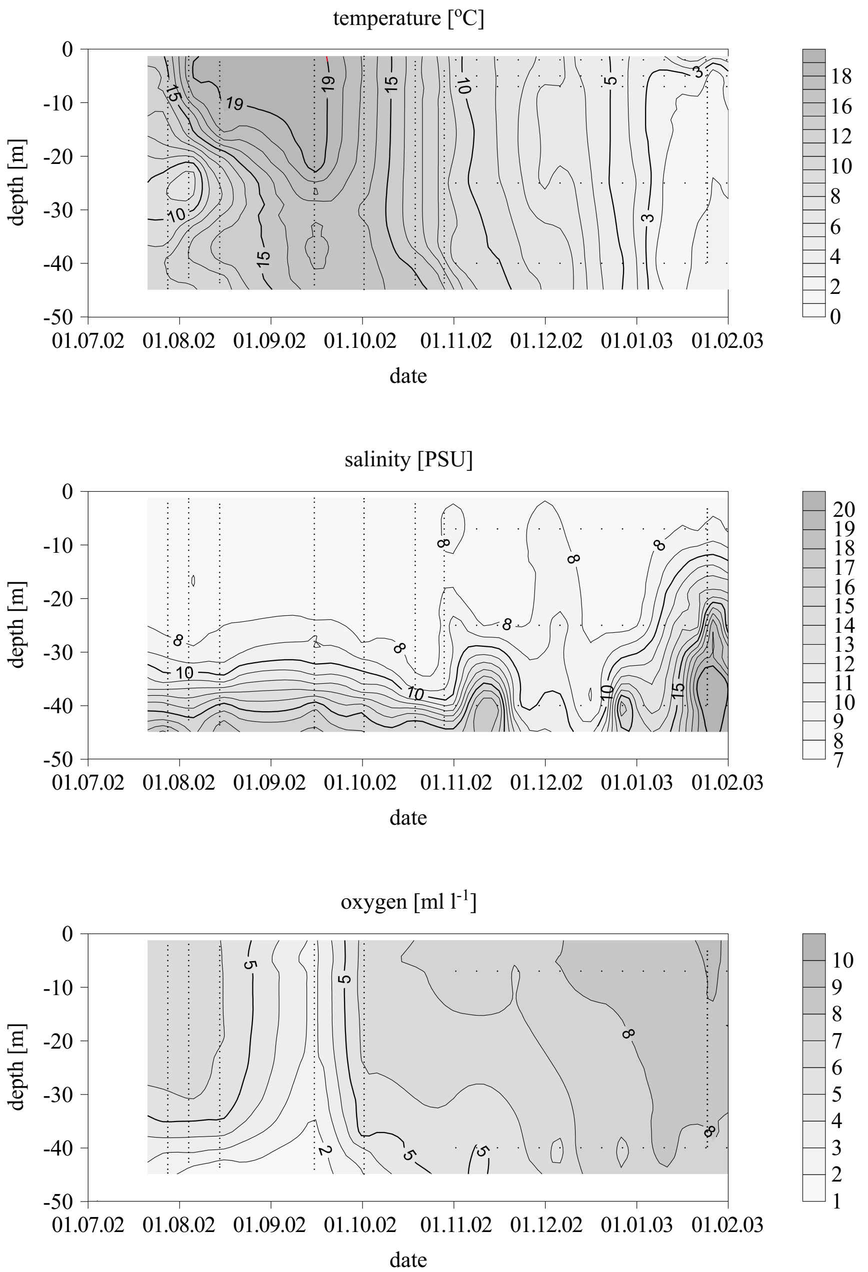

Fig. 3. Vertical profiles of temperature, salinity and oxygen concentration recorded by the Arkona Basin buoy (after September 2002) combined with ship-borne CTD measurements for the period 27th July 2002 – 1st February 2003. The dots indicate measured samples. The warm inflow period peaked in mid-September 2002 and coincided with a significant oxygen deficiency throughout the water column

casts at neighbouring positions. The typical summer stratification became significantly weakened in August and disappeared completely in October. In September, near-bottom waters were warmer than 16°C. Salinities above the sea floor exceeded 17 PSU in August and September, accompanied by oxygen levels below 2 ml l^{-1}, marking the very warm summer inflow. The subsequent small inflow in November was clearly visible by its steeply rising isohalines, oxygen content higher than 5 ml l^{-1} and temperatures about 10°C. In January 2003, the strong, cold inflow was approaching with significant salinity increase.

The summer waters appeared in the Bornholm Basin mainly in September 2002, at a depth centred at about 60 m (Fig. 4). We shall denote these water masses as BB60 waters. Located within the halocline, they had apparently exchanged properties with the colder intermediate waters above, thus temperatures were now about 13°C and oxygen concentrations about 4 ml l^{-1}. The next inflow of November 2002 was characterised by higher densities and was well-pronounced in the oxygen pattern at 90 m depth (Fig. 4); these waters we shall denote by BB90. They lifted up the entire old water column and in this way brought the deeper fraction of BB60 above the Słupsk threshold of 64 m, causing this BB60 fraction to disappear gradually during December 2002. In February 2003, the BB90 waters were subject to a similar process: they were uplifted by the January inflow and released to propagate further eastward into the central Baltic basins.

The temporal evolution in parameter values (temperature, salinity and oxygen) in the Gdańsk Basin is depicted in Fig. 5. A quite unusual environmental situation was observed in the near-bottom waters of the Gdańsk Deep (station P1, Fig. 1) and in the south-eastern Gotland Basin (station P140, Fig. 1) in autumn 2002. The relatively cold and extremely anoxic water present near the bottom of the Gdańsk Deep at the end of September 2002 was replaced by very warm water, referred to as summer BB60 water, some time before November. The warm water contained enough oxygen to neutralise all the hydrogen sulphide present and raise the oxygen level to nearly 2 ml l^{-1}. The layer of warm water was quite thick and extended from 80 m to the bottom (107 m). Between 70–60 m there was a layer of colder water (6.6 and 5.5°C respectively) and the upper water column was still warm after summer or from the sinking thermocline (c. 7.5°C). The exceptionally warm water was still present at the base of the water column in the Gdańsk Deep in February 2003, until it was finally removed by the conspicuous inflow of January 2003, arriving in April 2003. It is interesting that the observed changes in temperature and oxygen values were much more striking than in the salinity (see Fig. 5), which did not undergo such extensive variations.

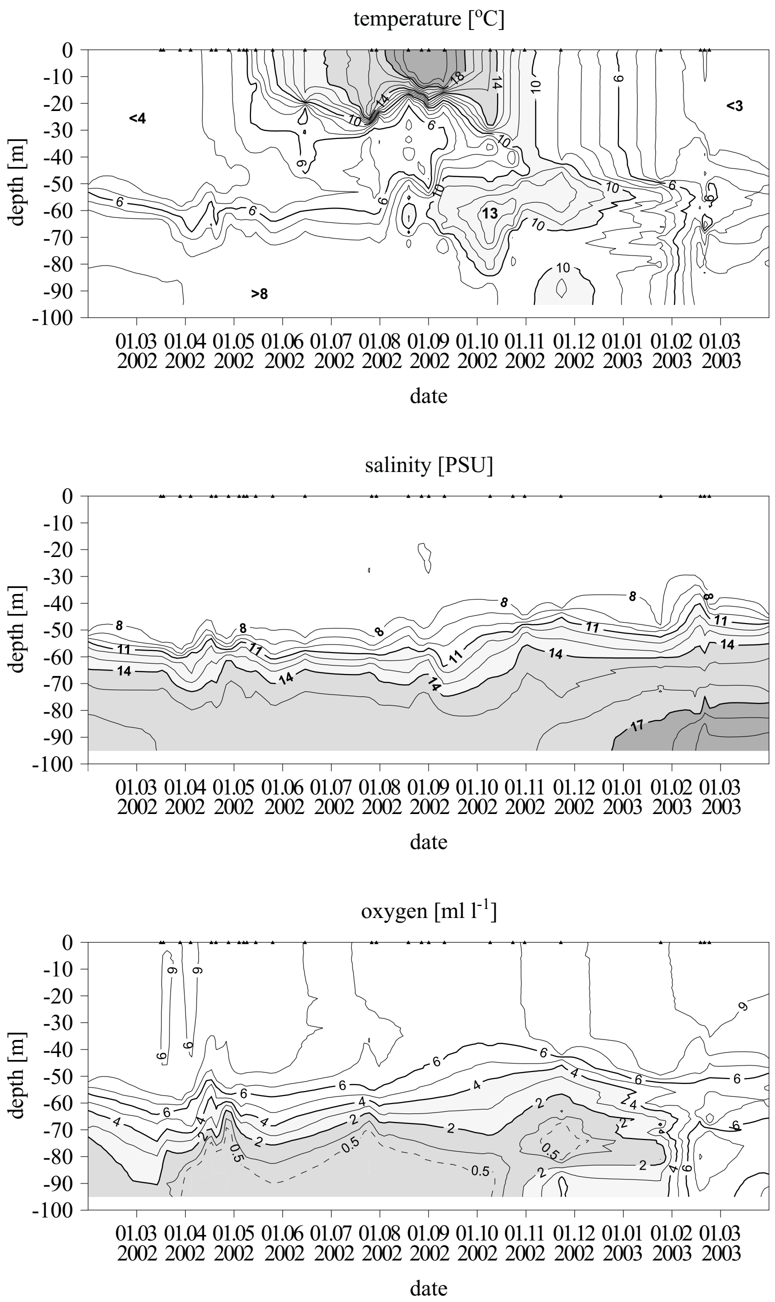

Fig. 4. Vertical profiles of temperature, salinity and oxygen concentration at IOW station 212 in the central Bornholm Basin, as obtained from CTD casts between February 2002 and March 2003. The two temperature maxima in early October 2002, at 60 m depth, and in mid-November 2002, at 90 m depth, mark the so-called BB60 and BB90 waters of the summer inflow

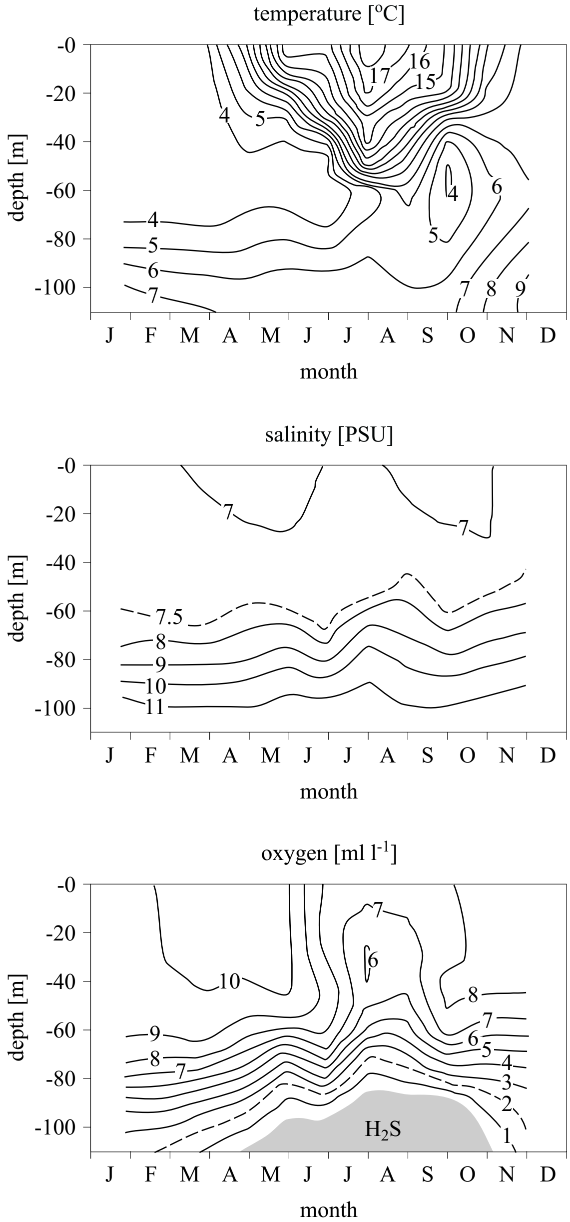

Fig. 5. Vertical profiles of temperature, salinity and oxygen concentration in the Gdańsk Deep (southern Baltic Sea, IMGW station P1 = BMP L1 = IOW 233) between January and December 2002. Note the disappearance of H_2S in October, together with the rise in water temperature in the deeper water layers

In the central Gotland Deep, too, the clearest indicators of inflow waters are the graphs of oxygen (or hydrogen sulphide) concentrations and temperatures (Fig. 6). The first splash of the inflow appeared in the bottom

Fig. 6. Vertical profiles of temperature, salinity and oxygen concentration at IOW station 271 in the central Gotland Basin, as obtained from CTD casts between July 2002 and May 2003. (*continued* on page 581)

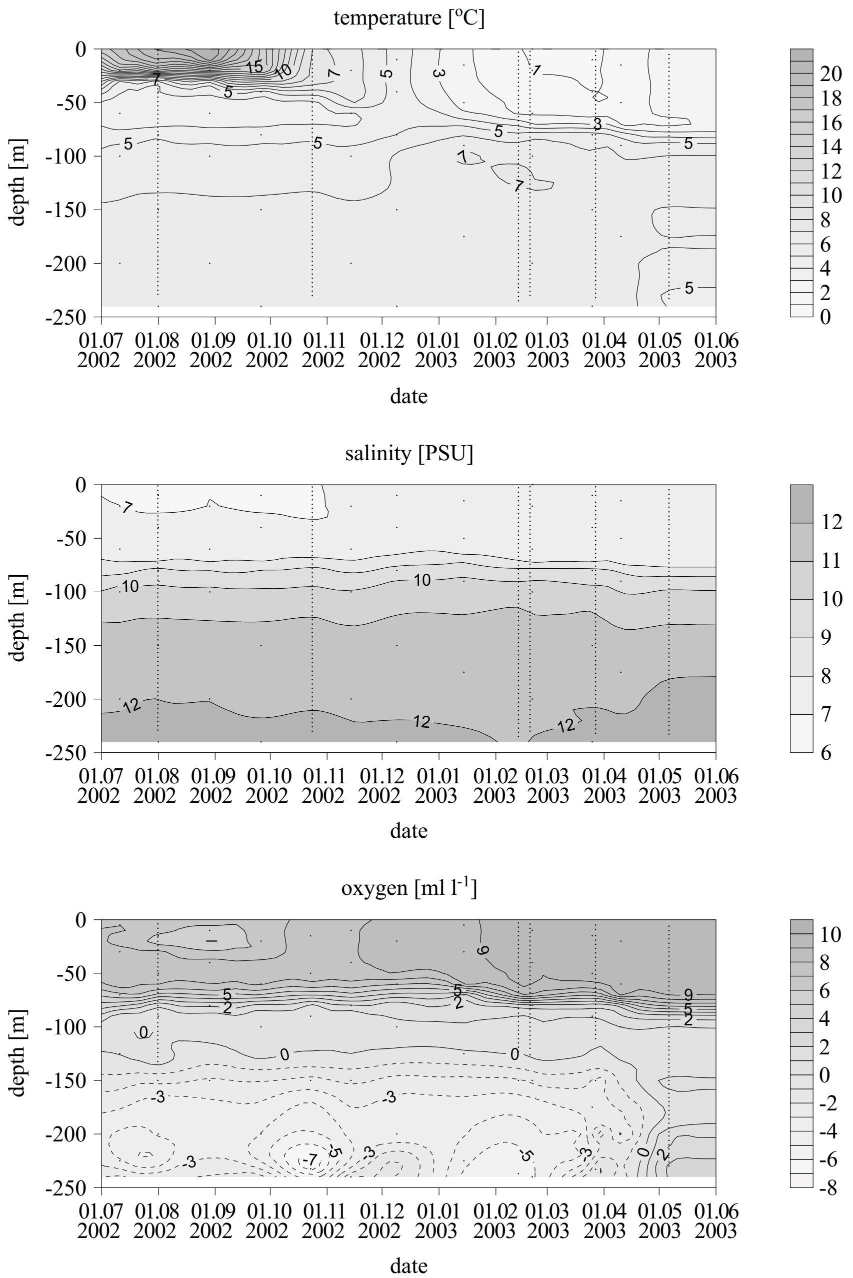

Fig. 6. ... Note the disappearing 4°C isotherm at 60 m depth in mid-November 2002, while the water surface still was warm at 6°C. Another warm signal (> 7°C) arrived in January 2003 at 100 m depth and in February 2003 at 120 m depth. At the bottom, hydrogen sulphide was already oxidised by the end of March 2003, before the cold January inflow arrived there at the end of April 2003. Bottle data kindly provided by SMHI are included in the diagram

layer at the beginning of December 2002, reducing the hydrogen sulphide concentration there. With its salinity of about 12 PSU and temperature of about 6°C, it lifted the water column, apparently even destroyed the cold (< 4°C) intermediate layer above the halocline, and raised the surface salinity to over 7 PSU. In the middle of January 2003, the very warm BB60 waters occurred in the Gotland Basin at depths between 100 and 120 m, still with temperatures above 7°C. The two temperature maxima at different densities and with a delay of 1 month suggest that the second batch of BB60 waters arrived only after its uplift and release in the Bornholm Basin by BB90 waters in November 2002. The latter arrived in the bottom layers of the Gotland Basin after yet another month, in March 2003. They are clearly discernible in all three plots of Fig. 6. The BB90 waters were capable of ventilating most of the water below 200 m before the arrival of the much more intense January inflow at the end of April 2003.

4. Discussion

The late-summer inflow of 2002 into the Baltic Sea was an extraordinary process in various respects:

- according to the criteria of Franck et al. (1987), it is not even considered as a relevant major inflow for its low surface salinity at the Darss Sill; none the less, it left traces in various deep Baltic basins for several months;
- it was apparently not driven by westerly gales and the related sea level differences between the Kattegat and the south-western Baltic;
- its net salt inflow occurred in conjunction with a net volume outflow from the Baltic Sea;
- it displayed a strong salinity stratification while passing the Darss Sill mast;
- it was almost exclusively fed in by the Great Belt with extremely small contributions from the Sound;
- its dynamic details have not yet been properly reflected by numerical models;
- it coincided with the appearance of a very pronounced, permanent thermocline in the Belt Sea and widespread, severe oxygen deficiency conditions in its surface layer;
- although it carried mainly oxygen-poor water over the Darss Sill, it did ventilate the previously anoxic Gdańsk Basin soon afterwards;

- it brought exceptionally warm water into deep basins, for example, the warmest water on record at 100 m depth in the Gdańsk and Gotland Basins;
- its warm signals contrast in a remarkable way to the subsequent cold inflow of January 2003;
- it had an unexpected impact on the ecosystem, which is currently still being investigated;
- a comparable process has never before been described for the Baltic Sea.

Unfortunately, for the exceptional inflow period between 5th August and 11th October 2002, no extended hydrographic measurements are available from the Belt Sea west of the Darss Sill. It is assumed here that the almost continuous calm weather until 14th September played a key role in the driving mechanism of this inflow, which is still unknown in its details. The absence of strong barotropic pressure gradients (mainly sea level differences) over a longer period may have allowed the weaker and otherwise often less important baroclinic pressure gradients (mainly horizontal salinity differences) to gain the upper hand over the dynamic processes between Kattegat, the Great Belt and the Darss Sill.

Between 1st August and 1st October 2002 the north-eastward mass and salt transport at the Darss Sill mast position was integrated vertically and temporally. Unfortunately, this computation could not be prolonged until 11th October because current meter data were lacking. The results are a 2D-volume inflow of about 5 km^2 and a salt inflow of about 80 PSU $\times$ km^2. Only tentatively can these values be extended to the entire Darss Sill cross-section of about 50 km width. This calculation of the raw estimate yields figures of 250 km^3 of water and 4 Gt (4×10^{12} kg) of salt. This result corresponds to the magnitude of water and salt transport observed during 'ordinary' strong inflows (Matthäus & Franck 1990, Fischer & Matthäus 1996). Even if these estimated figures are encumbered with considerable error, they do give some idea of the magnitude and sign of the event, which can explain the strength of its effects observed in the deeper basins.

For the total water balance, a useful indicator is the Landsort sea level, which was 184 cm on 1st August and 177 cm on 1st October (cf. Nausch et al. 2003). Thus, in the period considered, the Baltic had lost about 30 km^3 of its water volume, despite the continuous river input and the inflow over the Darss Sill. The corresponding volume transport through the Sound was measured by SMHI as an outflow of about 40 km^3 (SMHI 2002); the inflow of salt was irrelevant. Therefore, the net volume transport passing the Darss Sill and Great Belt must have been an outflow of the order of a climatological river input of 70 km^3 (Mikulski 1982), along with a significant, related volume outflow compensating for the total salt inflow. To work out the equilibria, we used DHI model transport data for the Great Belt, which yielded about 100 km^3 of volume outflow and 0.09 Gt of salt export from the Baltic. The Darss Sill and Great Belt data are supposed to describe the same total exchange, but they are obviously contradictory even in their signs of water and salt transports.

The obtained Great Belt volume export is very probably compatible with the observed negative total Baltic water balance, but the net flow of salt as computed by the model is outbound. On the other hand, the Darss Sill data provide the observed salt inflow, but not the simultaneous outflow of the same volume plus the river discharge, as is required for an almost constant Landsort gauge reading. Thus, the vertical profile at the mast cannot be representative of the entire cross section, and strong horizontal gradients, like those reported by Matthäus et al. (1982, 1983), must be assumed. To discover the responsible current patterns in the Belt Sea, we studied specific runs of the IOW numerical model. Passing the Darss Sill in August and September, it calculated a 38 km^3 volume outflow together with a salt inflow of 0.23 Gt, which meets the expectations for this area at least qualitatively. It reproduced the observed vertical structures of temperature and salinity fairly well, but the current patterns measured at the Darss Sill mast only much worse. Therefore, these model results as well as those of the DHI model were only of limited help in the elucidation of the detailed, very specific hydrographic conditions of this summer inflow.

As a working hypothesis, we may imagine a windless Baltic Sea, relaxed into a stationary regime after about 10 days with constant boundary conditions. The sea level in the south-western Baltic is only slightly above the average Kattegat level, to ensure the continuous outflow of excess river water, especially through the Sound. Baroclinic pressure gradients force highly saline waters to enter the Baltic Sea from the Kattegat through the Great Belt against this net outflow. In the absence of wind stress, Coriolis forces balancing the buoyancy keep the dense, salty current along the southern flank on its way from the Great Belt to the Darss Sill. On the northern side, off the island of Møn, less dense brackish waters are flowing in the opposite direction when crossing the Darss Sill. This kind of transport pattern was frequently measured in the Darss Sill area (cf. e.g. Matthäus et al. 1982) and is also found in IOW model runs. The measuring mast is placed somewhere in between the two jets, and may record meandering current fluctuations as local flow reversals. In the narrow Great Belt, conditions could be more complicated. The tidal range in the Kattegat has a larger amplitude than the mean level slope along the Belt, causing the water to oscillate between opposite current directions. This may act as a 'tidal pump', on average carrying salt water into the Baltic and brackish water out of it, without a surface current flowing in the opposite direction to the layer below actually being observed inside the Belt. As a rough estimate in this picture, the balance figures of the DHI model given above are approximately met by, for instance, a 190 km^3 outflow of average salinity 8 PSU and a simultaneous 90 km^3 inflow of 16 PSU, yielding a salt import of 1.4 Gt by the latter. Unfortunately, at present these gross fluxes are not available from the DHI model.

Such a scenario is supported by the fact that the Darss Sill inflow phases in August and September 2002 coincide well with periods of alternating tidal flow through the Great Belt as computed by the DHI model, and simultaneous calm wind conditions. This could perhaps be one of the very rare cases in which tides prove relevant to the Baltic Sea. The slightly lowered Landsort level observed during the summer inflow period does not directly support the general outflow tendency, but may be explained by the prevailing moderate south-easterly winds, establishing the required higher level at the entrance to the Danish Straits. Over the first half of July 1936, current measurements at six depth levels at the southern entrance to the Great Belt carried out under calm wind conditions showed that the residual transport (after tide removal) was always directed southwards between 15 and 25 m depth, but was changing due to wind conditions in the layers above, although predominantly pointing northwards (Thiel 1938). This observation was confirmed by Wyrtki (1953, 1954) for the Fehmarn Belt with measurements from August 1951 in a calm outflow situation. Baroclinic back currents in a constriction can significantly be enhanced by tidal oscillations (Stigebrandt 1976).

The warm water masses arrived in the Bornholm Basin in two separate batches with distinct T–S–O_2 properties, here called BB60 and BB90 waters after the depths where they emerged, and left the basin in the form of three successive pulses. We identified the water properties encountered at various times and locations as shown in Tables 1 a and b. The BB60 waters were carried along the pycnocline between the Bornholm Basin and the Słupsk Channel and apparently exchanged properties with the cold, oxygen-rich intermediate water layer above. This hypothesis may explain the fact that BB60 waters cooled down but gained oxygen on their way to the Gdańsk Basin, even though they were mostly oxygen-poor when they crossed the Darss Sill and entered the Arkona Basin. The first, less dense batch of these BB60 waters, which rapidly passed the Słupsk Sill and ventilated the Gdańsk Basin, probably in October 2002, obviously originated from

Table 1. T–S–O_2 characteristics of BB60 waters (a) and BB90 waters (b), selected by temperature maxima. Darss Sill (DS), Arkona Basin (AB), Bornholm Basin (BB), Słupsk Channel (SC), Gdańsk Basin (DB), South-Eastern Gotland Basin (SEGB), Gotland Basin (GB), Fårö Deep (FD). Station positions are shown in Fig. 1. PAP is r/v 'Prof. Albrecht Penck', AvH is r/v 'A.v.Humboldt'.
[1)]values taken at bottom salinity maxima, [2)]scanfish measurement at 54.760°N, 13.254°E, not beyond 35 m depth, [3)]bottle taken at 40 m depth, [4)]r/v 'Argos' data were kindly provided by SMHI

(a) BB60 waters

Location	Year	Month	Day	p [dbar]	T [°C]	S [PSU]	O_2 [ml l^{-1}]	Station	r/v
DS[1)]	2002	8	12	19.00	14.52	18.27	2.84	DS	DS
DS[1)]	2002	8	18	19.00	15.09	18.22	3.01	DS	DS
DS[1)]	2002	8	23	19.00	14.82	19.00	1.69	DS	DS
DS[1)]	2002	9	6	19.00	15.17	19.20	1.50	DS	DS
DS[1)]	2002	9	13	19.00	14.73	20.12	0.47	DS	DS
DS[1)]	2002	9	24	19.00	16.49	18.92	1.24	DS	DS
DS[1)]	2002	10	7	19.00	15.08	19.42	0.97	DS	DS
DS[1)]	2002	10	8	19.00	15.11	19.42	0.91	DS	DS
AB	2002	8	14	37.25	15.66	12.38	4.47	113	PAP
AB	2002	8	20	33.60	16.48	13.23		SF[2)]	PAP
AB	2002	9	14	37.25	17.78	12.90	1.70	113	PAP
AB	2002	9	14	40.50	17.33	16.18	1.59	113	PAP
AB	2002	10	18	43.00	15.34	15.71	2.66	113	Gauss
AB	2002	10	28	44.00	14.39	15.17	2.17	113	Gauss
AB	2002	11	2	40.00	13.74	14.77	1.60	AB	AB
BB	2002	10	5	62.15	13.79	13.27	3.01	212	AvH
BB	2002	10	19	60.00	13.63	13.66	2.57	212	Gauss
BB	2002	10	19	57.00	13.76	13.31	3.08	213	Gauss
BB[4)]	2002	11	13	60.00	12.72	13.79	1.72	K2	Argos
SC	2002	10	22	68.00	11.34	10.79	3.61	222	Gauss
SC	2002	10	22	75.00	10.42	11.53	2.94	256	Gauss
DB	2002	11	20	100.00	9.45	11.59	1.60	P1	Baltica
SEGB	2002	10	11	87.00	7.58	12.12	1.69	P140	Baltica
SEGB	2002	11	21	86.00	8.12	11.22	1.24	P140	Baltica
GB	2003	2	12	96.00	7.44	10.79	1.33	250	Gauss
GB	2003	3	26	98.00	6.89	10.63	0.68	250	Gauss

Table 1. (*continued*)

Location	Year	Month	Day	p [dbar]	T [°C]	S [PSU]	O_2 [ml l^{-1}]	Station	r/v
GB	2003	2	13	121.0	7.41	11.13	0.82	271	Gauss
FD	2003	3	28	100.0	7.29	10.84	0.60	go13	Gauss

(b) BB90 waters

Location	Year	Month	Day	p [dbar]	T [°C]	S [PSU]	O_2 [ml l^{-1}]	Station	r/v
DS[1)]	2002	11	2	19.00	10.58	17.20	6.04	DS	DS
AB	2002	12	6	40.00	9.50	11.89	5.62	AB	AB
AB	2002	12	13	42.25	8.55	10.21	7.61[3)]	AB	PAP
BB	2002	11	18	89.00	11.16	16.34	4.38	023	Heincke
BB[4)]	2002	12	10	88.00	10.11	15.84	1.23	K2	Argos
BB	2003	1	25	64.25	10.96	13.96	4.21	213	PAP
BB	2003	2	11	51.00	9.49	13.06	5.76	213	Gauss
BB	2003	2	16	67.00	7.77	15.30	2.84	213	Gauss
SC	2003	2	11	87.00	6.99	14.06	5.55	222	Gauss
SC	2003	2	16	88.00	5.99	13.55	5.93	222	Gauss
SC	2003	2	12	74.00	7.97	12.68	4.52	256	Gauss
SC	2003	2	16	75.00	6.71	12.76	6.31	256	Gauss
GB	2003	3	27	233.0	6.69	12.16	0.04	271	Gauss

the August/September inflow. The effects of this BB60 summer water were most probably enhanced by the subsequent inflow of BB90 water, i.e. the inflow of salt water from the Kattegat in early November. Note that it takes about 3 months for an inflow to travel from the Kattegat to the Gdańsk Deep and SE Gotland Basin.

In historical retrospect, deep water temperatures as high as those described in this paper have only rarely been encountered. The annual maximum temperatures of 62531 samples measured in the Arkona Basin at depths of 35 m or greater are shown in Fig. 7. Only three times between 1952 and 2002 values exceeding 18°C have been recorded: on 19th August 1959 (18.41°C), 8th September 1997 (18.39°C) and 25th July 2001 (18.37°C). This time, on 14th September 2002, the highest recorded value was 17.78°C, so that the 1959 'record' remains intact.

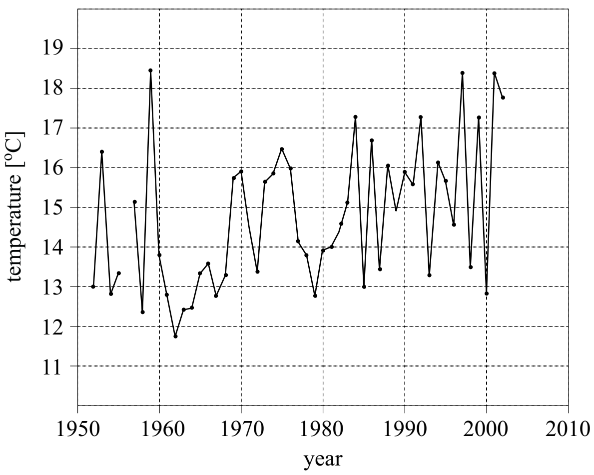

Fig. 7. Annual maximum temperatures in the Arkona Basin below 35 m depth selected from the IOW data base between 1952 and 2003. Only three times did temperatures exceed 18°C: in 1959, 1997 and 2001. The actual summer inflow of 2002 ranks 4th in this plot

The Bornholm and Gdańsk Basin deep waters show characteristic annual temperature cycles (Matthäus 1977). These variations are caused by the different inflow activities during the year and from year to year. Within or immediately below the pycnocline, inflows frequently passed the Bornholm Basin relatively quickly, crossing the 60 m deep Słupsk Sill in an easterly direction. In contrast to the upstream basins, the eastern Gotland Basin deep water displays no significant annual variations.

The evaluation of long-term temperature data in the near-bottom layer of the Gdańsk Deep showed an increasing number of elevated temperature values in the 1950s, 1970s and since 1990. About 20 cases of temperature $T > 7.0$°C in the period 1959–2002 and less than 10 in the SE Gotland Basin (1986–2002) have been recorded. The values measured at the end of 1959 and in November 2002 are the highest in the recorded data series (Fig. 8).

The temperature data in the near-bottom layer of the Gdańsk Deep and the 100 m level of the Gotland Deep showed mean positive trends from the mid-1950s to the late 1970s. From then to the end of the 1980s a mean negative trend was dominant. Starting in the late 1980s, the temperature increased again significantly.

Since 1989, the correlation coefficient in the near-bottom layer of the Gdańsk Deep is $R = 0.48$ for the computed trend of 0.12°C year^{-1}. It shows that most of the inflows (splashes) into the Gdańsk Basin taking place in the last decade of the 20th century were of warm autumnal water. That seems to indicate a shift in inflow intensity from winter to autumn in this

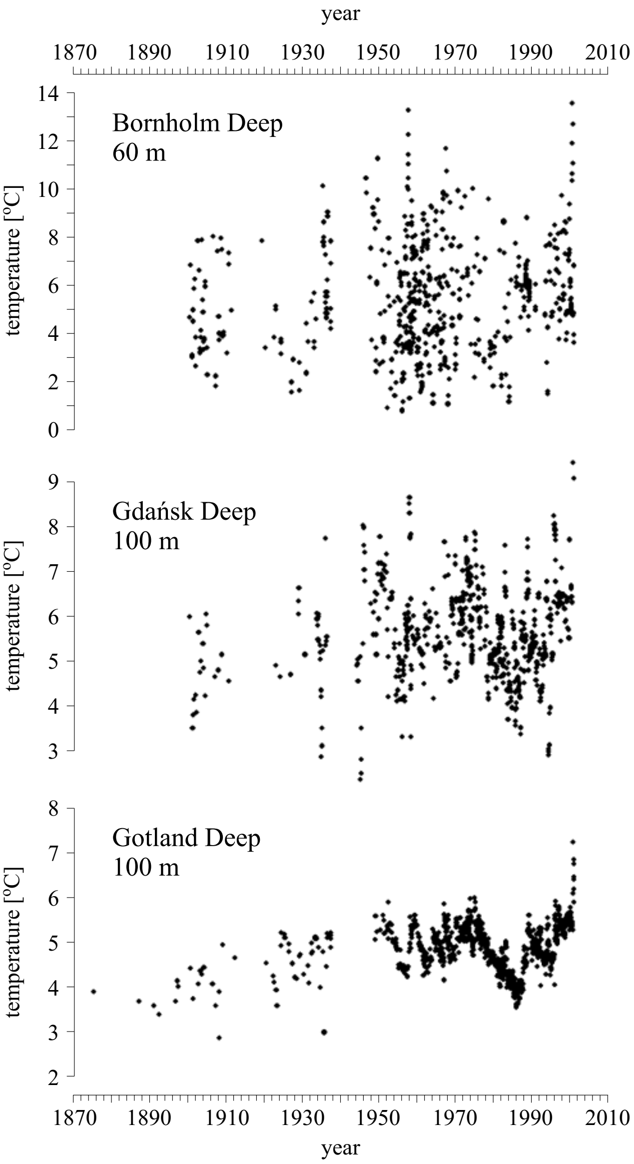

Fig. 8. Long-term variation of temperature in the Bornholm (60 m), Gdańsk (100 m) and Gotland Deeps (100 m)

period in comparison to the period before. The linear regression analysis of temperature in the near-bottom water of the south-eastern Gotland Basin also showed a positive trend between 1986 and 2002.

The unusually warm water penetrating into the Baltic Sea in August/September 2002 caused, in autumn 2002, the highest temperatures on record at the 60 m level of the Bornholm Basin and at the bottom of the Gdańsk Basin. In these basins, similarly warm water has only been recorded in October/November 1959. In spring 2003, the inflowing warm waters also brought about the highest temperatures ever measured at the 100 m level of the Gotland Deep (Fig. 8).

Preliminary observations during the calm weeks in July and August 2003 indicate that a repetition of a similar inflow event this summer may be in the offing. The Darss Sill mast recorded a bottom layer with significant salinity lasting for much of July, and in the Bornholm Basin a warm water tongue exceeding 10°C is forming at about 50 m depth (Wasmund 2003).

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