Temporal and spatial evolution of the Baltic deep water renewal in spring 2003*

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Abstract

In January 2003, a deep-water renewal process in the Baltic Sea commenced with an inflow of about 200 km^3 of cold and well oxygenated water from the Kattegat, half of which was of salinity > 17 PSU; it is considered to be the most important inflow since 1993. Related front propagation and the ventilation of anoxic waters between the western and the central Baltic were recorded by the Darss Sill measuring mast, the Arkona Basin buoy, a subsurface mooring in the Eastern Gotland Basin, and hydrographic research cruises conducted in January, February, March, May and August 2003. Already in May, the central Gotland Basin was reached by water with near-bottom oxygen concentrations among the highest ever recorded there. A comprehensive review of the observed spatial and temporal structures together with additional background data is presented. Estimates of the intensity of the present inflow are discussed.

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1. Introduction

Since the strong inflows of North Sea water into the Baltic Sea in 1975/76 and 1993, only weak and moderate events of this kind have been observed, and with a much reduced frequency as compared to previous decades (Matthäus & Franck 1992, Matthäus & Nausch 2003). The latest of these now rare events happened in 1983 and 1993. Quite recently, they were followed by one of comparable importance in January 2003. After the classification scheme of Franck et al. (1987), henceforth referred to as FMS 87, the current inflow with intensity $Q = 12$ ranks among the weaker ones ($Q = 0 \dots 15$), but it has been accorded attention principally because of the extreme anoxic situation observed in Baltic deep waters in recent years (Nausch et al. 2002), and some related, accompanying events between August 2002 and March 2003 (Feistel et al. 2003b in this volume).

The initial inflow from the Kattegat into the western Baltic in January 2003 was first noticed by the Swedish r/v 'Argos', which was carrying out monitoring observations in the Belt Sea at that time. That an inflow was occurring was confirmed by data from the Darss Sill mast a few days later, when highly saline waters were recorded there on several consecutive days. Motivated by this, the Baltic Sea Research Institute in Warnemünde (IOW) prepared a short ad-hoc expedition on the r/v 'Prof. A. Penck' (Nausch 2003a). The successive penetration of the cold and salty water masses into deeper basins could be tracked by regular monitoring cruises in February, March, May and August 2003, and by records of a long-term subsurface mooring above the north-eastern topographic flank of the Gotland Deep. The details are reported in the Results section (this paper). In the Discussion, we assess the strength of the present inflow, especially in comparison to the 1993 event.

2. Material and Methods

The measurements presented in this paper cover the period between August 2002 and August 2003. The observations were part of the Baltic Monitoring Programme (COMBINE) of the Helsinki Commission (HELCOM) carried out by the Baltic Sea Research Institute in Warnemünde, Germany. They comprise both the ad-hoc research cruise in January (Nausch 2003a) and regular monitoring cruises in February (Nagel 2003), March (Feistel 2003), May (Nausch 2003b) and August 2003 (Wasmund 2003). The ship-borne investigations were supplemented by continuous records of temperature, salinity and 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, continuously recorded currents and temperatures at three levels (174 m, 204 m, 219 m) at a mooring in the Eastern Gotland Basin (EGB) were used (Hagen & Feistel 2001).

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 monitoring stations, MARNET stations (DS, AB) and the Eastern Gotland Basin mooring (EGB) are shown in Fig. 1. Salinities are expressed as PSU on the Practical Salinity Scale 1978.

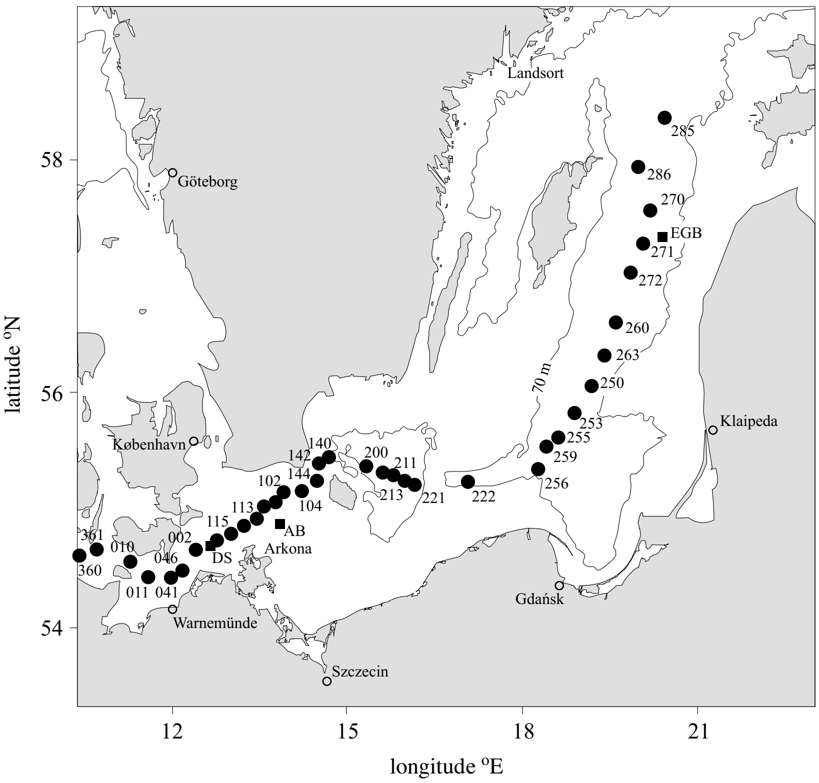

Fig. 1. Positions of the permanent observation platforms (squares): Darss Sill mast (DS), Arkona Basin buoy (AB), Gotland Basin subsurface mooring (EGB), and of regularly surveyed transect stations (circles) from the Kiel Bight (no. 360, depth 20 m) via the Fehmarn Belt (010, 28 m), Arkona Basin (113, 47 m), Bornholm Basin (213, 91 m), Słupsk Channel (222, 93 m) and Gotland Deep (271, 249 m) to the Fårö Deep (286, 203 m)

3. Results

The Darss Sill vertical profiles of temperature, salinity and oxygen between 1st July 2002 and 1st June 2003 are shown in Fig. 2. The salinity patterns clearly indicate alternating inflow and outflow periods. In this series, the most important results from the inflow of highly saline waters were those obtained between 16th and 25th January 2003, when salinities of up to 21 PSU at the bottom and 18 PSU at the surface can be spotted in the data record. These waters were cold (typically 1°C) and oxygen-rich (about 7 ml l^{-1}).

This inflow event was followed by weaker ones in March and in May. While the March event had almost the same temperature and oxygen signature, but showed a strong stratification, the small inflow in May was significantly warmer (5–10°C) and was accompanied by surface salinities above 10 PSU. Both these post-inflows enhanced the January event because the Arkona and Bornholm Basins were already filled with heavy waters and favoured the rapid eastward propagation into the central Baltic region.

Two other weak inflows preceded the main event in January, both supporting the effect on the deeper basins by the latter one. The August/September 2002 inflow possessed a strong halocline; it was linked to unusual weather conditions in late summer and brought extremely warm (17°C) and oxygen-poor (2 ml l^{-1}) water into the deeper layers. In particular, it caused the Gdańsk Basin to be ventilated by November 2002, and a partial improvement even in the anoxic conditions at the 100 m levels of the Gotland Basin in spring 2003 (Feistel et al. 2003b in this volume). The following shorter overflow of the Darss Sill in the first half of November 2002 was driven by westerly gales and carried well-oxygenated waters (about 6 ml l^{-1}) with still rather high temperatures of about 10°C into the Bornholm Basin, replacing the bottom waters resting there during November.

In the Arkona Basin, a permanent buoy was deployed by the Baltic Sea Research Institute in late summer 2002. Its data records were combined with CTD casts taken at station 113 as shown in Fig. 3. The water column was strongly stratified with respect to salinity through the 10-month record from July 2002 to May 2003, but was thermally almost homogeneous from October 2002 onwards. In August 2002, we observed a well-developed thermocline at about 20 m depth, followed by the salty, warm and oxygen-poor inflow waters in September (Feistel et al. 2003b in this volume). After that, the temperature decreased monotonically until the end of 2002, but the bottom salinity showed a clear maximum at the beginning of November, just after the small warm October inflow. The January event is the dominating

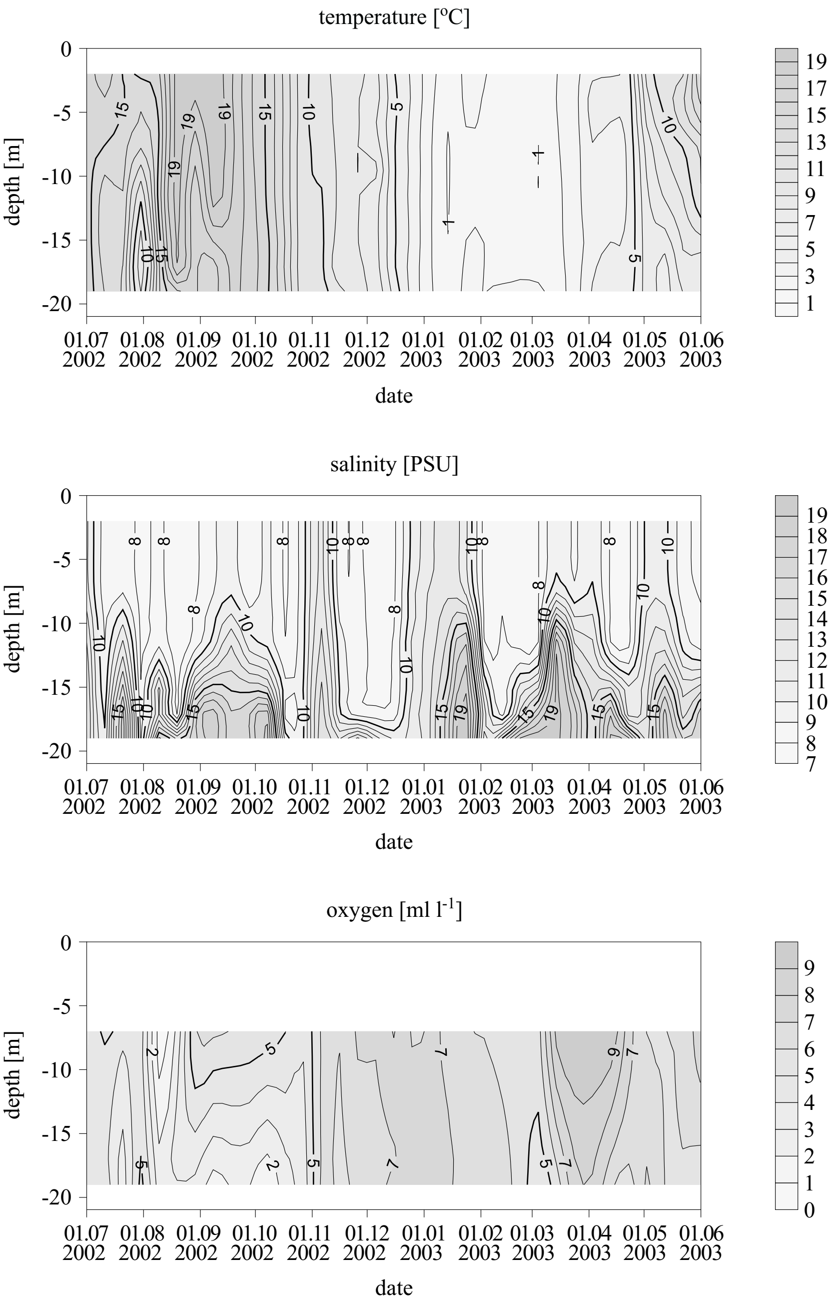

Fig. 2. Vertical profiles of temperature, salinity and oxygen recorded at the Darss Sill measuring mast between 1st July 2002 and 1st June 2003. The January inflow is marked especially by its lasting high surface salinity. Note the accompanying weaker inflow signals in September and November 2002 and in March and May 2003

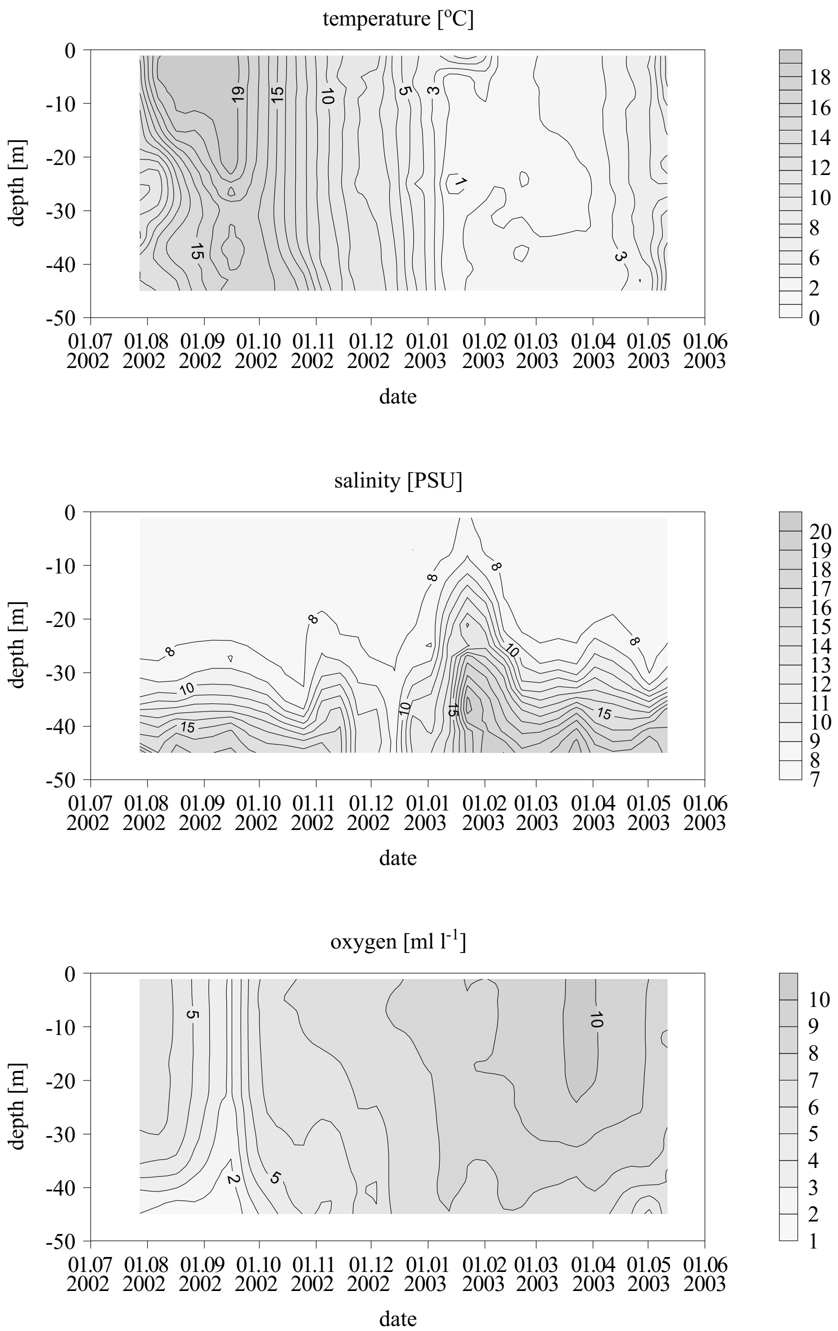

Fig. 3. Vertical profiles of temperature, salinity and oxygen recorded at the Arkona Basin buoy and by nearby ship-borne CTD casts between 27th July 2002 and 11th May 2003. The January inflow is the dominating salinity signal, followed by a smaller one in March

signal in salinity, followed by a smaller one at the end of March, both with cold and oxygen-rich waters.

The January cruise with r/v 'Prof. A. Penck' was dedicated in particular to the inflow already signalled by the Darss Sill data received online. Its observations depicted the situation when the front of the renewal process had reached the Bornholm Basin, strikingly indicated by the vertical shape of temperature and oxygen isolines in that area (Fig. 4). In the Arkona Basin, the inflowing water formed a 10 m thick saline layer at the bottom. This water was well enriched with oxygen (around 8 ml l^{-1}). In the Bornholmsgat, highly saline water of up to 24.5 PSU near to the bottom was observed, indicating the contribution of inflowing water via the Sound. In the western part of the Bornholm Basin, the whole water column was well oxygenated with 6.7 ml l^{-1} near to the bottom. The salinity measured there was 18.7 PSU. Also at the central station 213 in the Bornholm Basin (BMP K5) the first signs of the inflow could be seen. An oxygen-poor layer was raised by new, inflowing water with 16.2 PSU and 3 ml l^{-1} oxygen at 87 m depth.

The February cruise provided ample documentation of the further progress of the renewal process (Fig. 5). In the central Arkona Basin station (113, BMP K2), bottom salinities were still very high with 20.8 PSU at 2.7°C and 7.6 ml l^{-1} oxygen, forming layers of 10–20 m thickness. In the Bornholm Basin, the older warm water had been raised to about 60 m depth, above a 10-m-thick bottom layer with $S = 18.5$ PSU, $T = 3.1$°C and $O_2 = 7.5$ ml l^{-1}. These cold waters had filled up the basin area but had not yet flowed over the Słupsk Sill (60 m saddle depth), since temperatures as high as 7.5°C were still being measured in the Słupsk Channel, although the salinity was 14 PSU and oxygen levels were as high as 3.4 ml l^{-1}. While faint traces of oxygen could be detected at the floor of the south-eastern Gotland Basin, high concentrations of hydrogen sulphide (–5.9 ml l^{-1} oxygen equivalent) still covered the Gotland Deep. These data suggest that the warm inflow of October 2002 was trapped in the Bornholm Basin at depths greater than 60 m until February 2003, was then released, after which it continued to propagate into the deeper basins of the Baltic Proper, thus heralding the subsequent, more significant inflow.

For the March cruise, the arrival of cold waters in the central Gotland Deep was expected and additional CTD stations were planned in that area accordingly. A longitudinal transect of the Baltic is given in Fig. 6. In the west, this shows the March inflow as a salty bottom layer from the Darss Sill as far as the entrance to the Słupsk Channel. The slightly warmer (4°C)

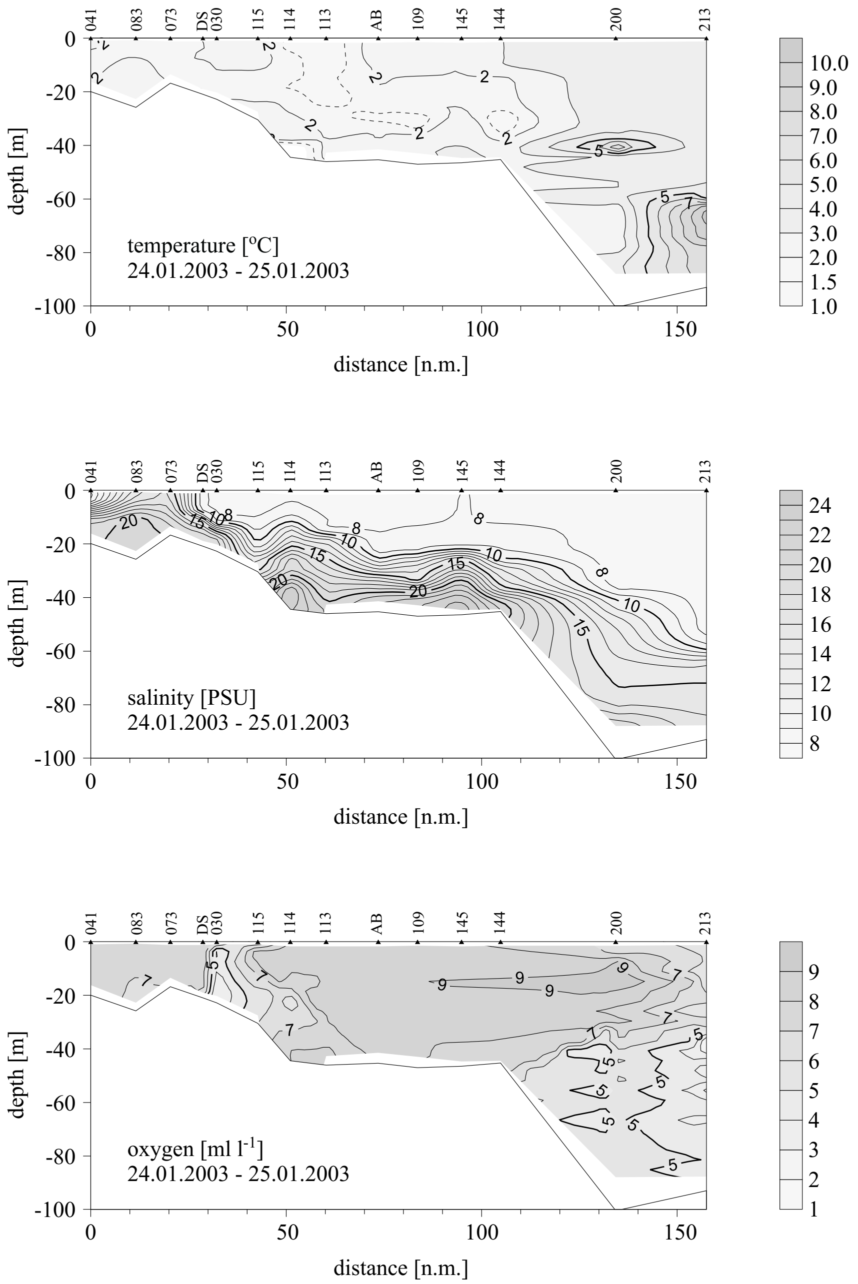

Fig. 4. Transects of temperature, salinity and oxygen from the Darss Sill via the Arkona Basin to the Bornholm Deep, recorded immediately at the inflow ending phase, 24–25th January 2003. Note the almost vertical temperature and oxygen front shape in the Bornholm Basin, indicating intensely progressing dynamic processes

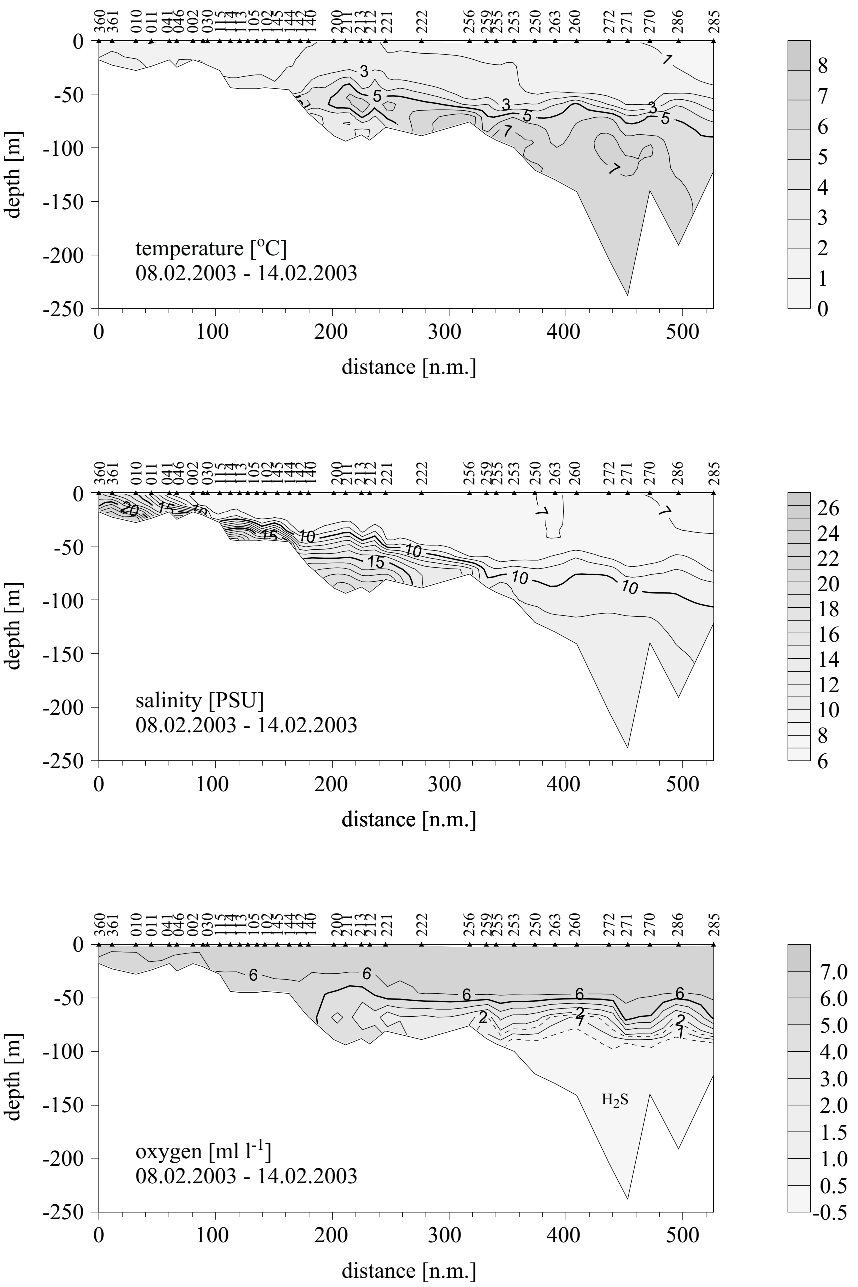

Fig. 5. Transects of temperature, salinity and oxygen from the Fehmarn Belt via the Bornholm Basin to the Gotland and Fårö Deeps, investigated by the February monitoring cruise. Cold and oxygenated bottom waters have reached the entrance to the Słupsk Channel, while warm and anoxic waters dominate the Gotland Basin Area

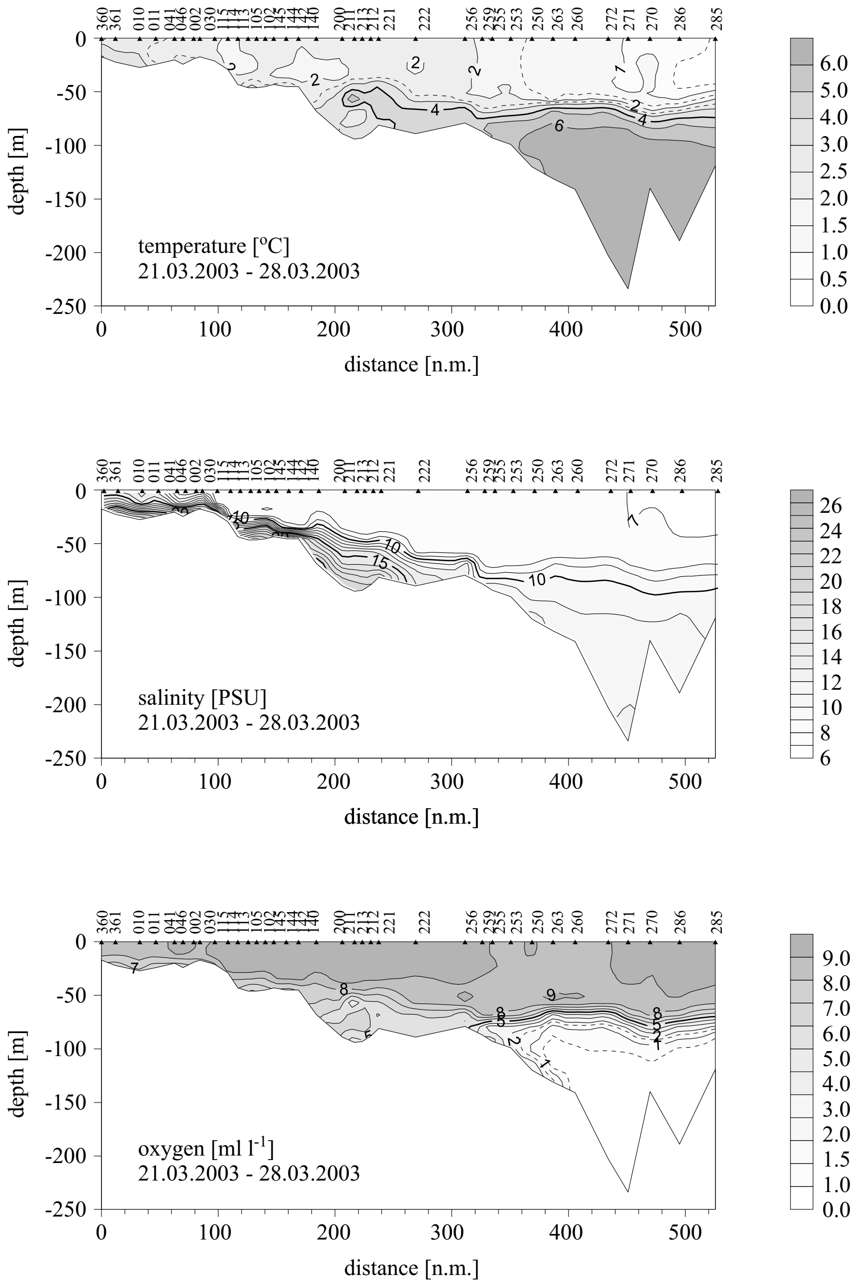

Fig. 6. Transects of temperature, salinity and oxygen from the Fehmarn Belt via the Bornholm Basin to the Gotland and Fårö Deeps, investigated by the March monitoring cruise. Cold and oxygenated bottom waters have progressed into the south-eastern Gotland Basin. Salty water masses are flowing over the Darss Sill, Bornholmsgat and Słupsk Sill

water uplifted to 60 m depth in the Bornholm Basin was passing through the Słupsk Channel and sliding down the slope of the south-eastern Gotland Basin. The central basin was still filled with warm anoxic water (> 6°C), while at the bottom and the 100 m level this was interspersed with oxygen-poor water originating from the warm 2002 autumn inflows.

At station 260, in front of the apparent tip of the inflowing tongue, all waters below 110 m were anoxic. Only weak signs, like the increasing salinity gradient and decreasing temperatures from 128 m downwards, were signalling the adjacent inflow. Further north, a zonal cross-section at 56°45′N (at station 260, cf. Fig. 1) revealed that the inflowing waters had formed a jet current 10–20 n.m. in width and 10–20 m thick at the eastern flank of the valley leading into the Gotland Basin (not shown). This jet ran only 10 n.m. east of the regular monitoring path at station 260, where almost no effect of the inflow was detectable. Its centre had an oxygen level of 0.2 ml l^{-1} and a temperature of 6°C, whereas the surrounding waters were slightly warmer at 6.3°C, but anoxic. Further north in the Basin, at the latitude of the Gotland Deep (station 271), there was no longer any sign of this jet on the eastern flank.

The region with the progressing inflow front was again investigated some days later in order to estimate the time scales involved. The results are given in Table 1.

Table 1. Temporal water property changes in the near-bottom layer after two visits separated by 3–5 days from the Bornholm Deep (213) via the Słupsk Channel (222) to the southern edge of the Gotland Deep (260). The first visit is shown in the left-hand columns, the second visit in the right-hand columns; between them – the delay time in hours

Station	S [PSU]	T [°C]	O_2 [ml l^{-1}]	Δt [h]	S [PSU]	T [°C]	O_2 [ml l^{-1}]
260	11.6	6.28	–3.5	71	12.0	6.00	1.8
263	12.1	5.84	2.2	80	12.7	5.73	2.6
250	12.3	5.66	2.8	85	11.9	5.40	3.9
253	11.5	5.56	2.6	89	11.8	5.17	3.8
255	12.0	4.93	4.8	92	11.9	5.26	3.3
259	10.8	5.03	3.1	96	12.2	5.26	3.0
256	12.2	4.79	5.4	100	12.2	4.69	5.3
222	13.8	4.52	5.4	109	14.3	4.70	5.1
213	17.1	3.03	6.5	118	17.1	3.19	6.4

Within only 3 days, the front had reached the formerly anoxic station 260, and all the oxygen levels along the slope had increased noticeably.

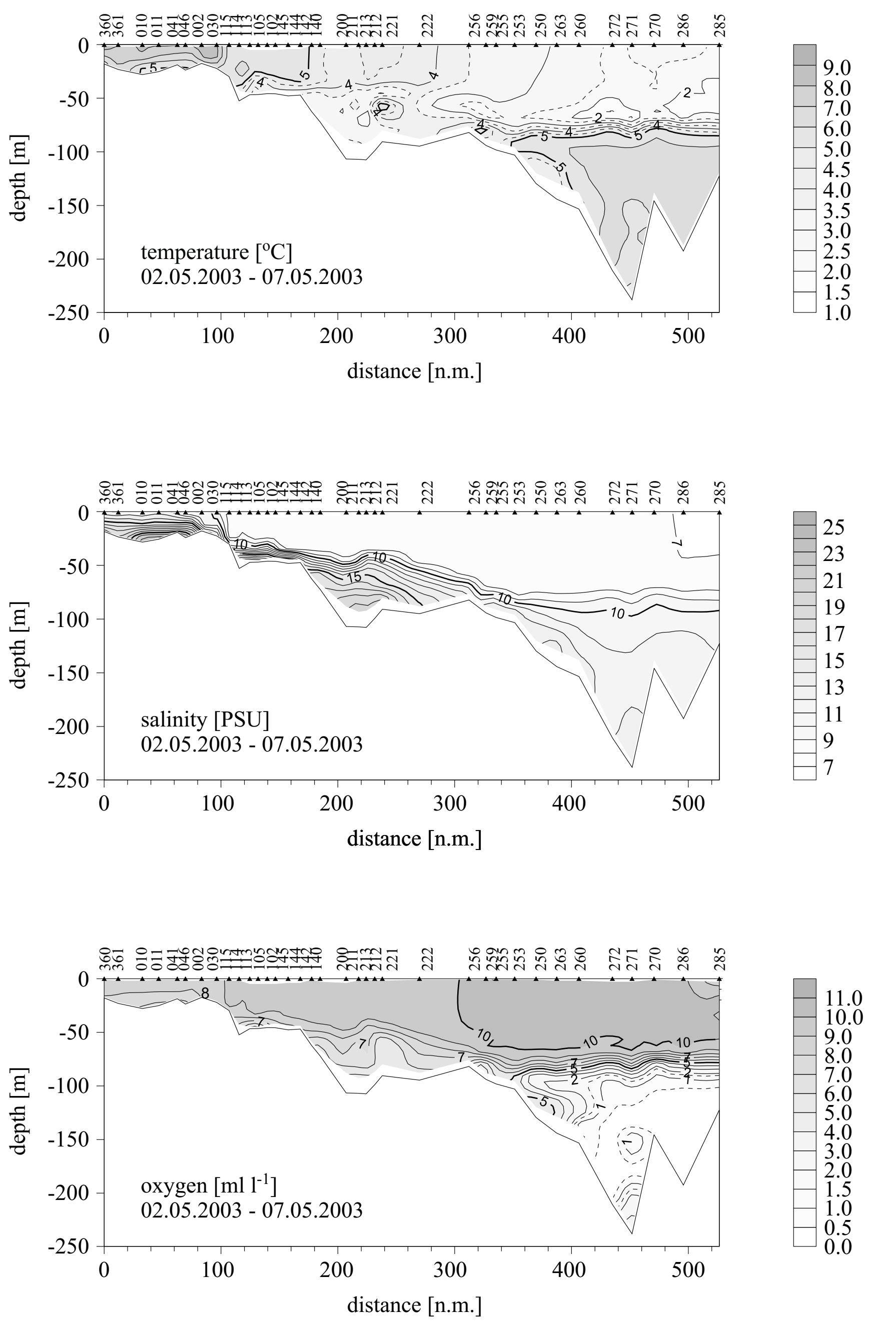

Fig. 7. Transects of temperature, salinity and oxygen from the Fehmarn Belt via the Bornholm Basin to the Gotland and Fårö Deeps, investigated by the May monitoring cruise. Cold and oxygenated bottom waters have reached the Gotland Deep but not yet ventilated the entire basin

On the other hand, oxygen and temperature values changed in the opposite direction in the Słupsk Channel. This observation supports the impression that the driving forces in the Bornholm Basin area were already weakening, and that possibly this inflow batch found in the SE Gotland Basin area had largely been triggered by the post-inflow in March in the Belt Sea.

During the May cruise, the March CTD station network was revisited with extended investigations in the Eastern Gotland Basin area. The inflow had penetrated further north (Fig. 7). The jet current was observed on the eastern side of the southern and middle zonal cross-section, whereas the stations in the north were still anoxic. At the central station 271 (BMP J1) between 200 m and the bottom considerable amounts of oxygen were found – as much as 4 ml l^{-1} at 232 m depth. Similar amounts of oxygen were measured only on two previous occasions, in the 1930s and in May 1994 (Nehring et al. 1995). Above the oxygenated layer uplifted older waters were found, but only at 175 m was oxygen near to zero, and there was no measurable hydrogen sulphide.

Above the north-eastern slope of the Eastern Gotland Basin, a long-term mooring was recovered in May 2003. It had recorded the arrival of cold waters on 24th April 2003 (see Fig. 8). This date marks the end of the

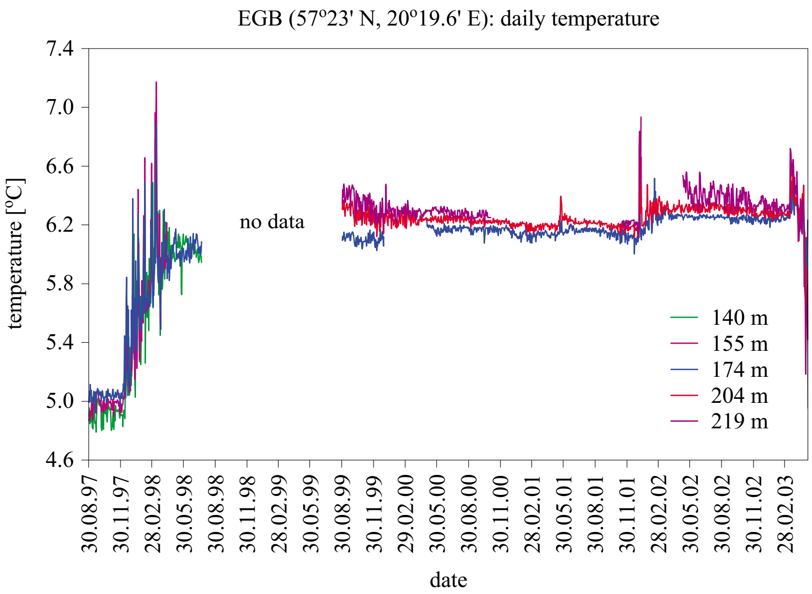

Fig. 8. Temperature time series from August 1997 to May 2003 recorded at five depth levels of a subsurface Gotland Basin mooring (labelled EGB in Fig. 1), deployed at the north-eastern topographic flank. The pronounced 'warm period' began with the inflow of September 1997 and was terminated after more than 5 years by the present one

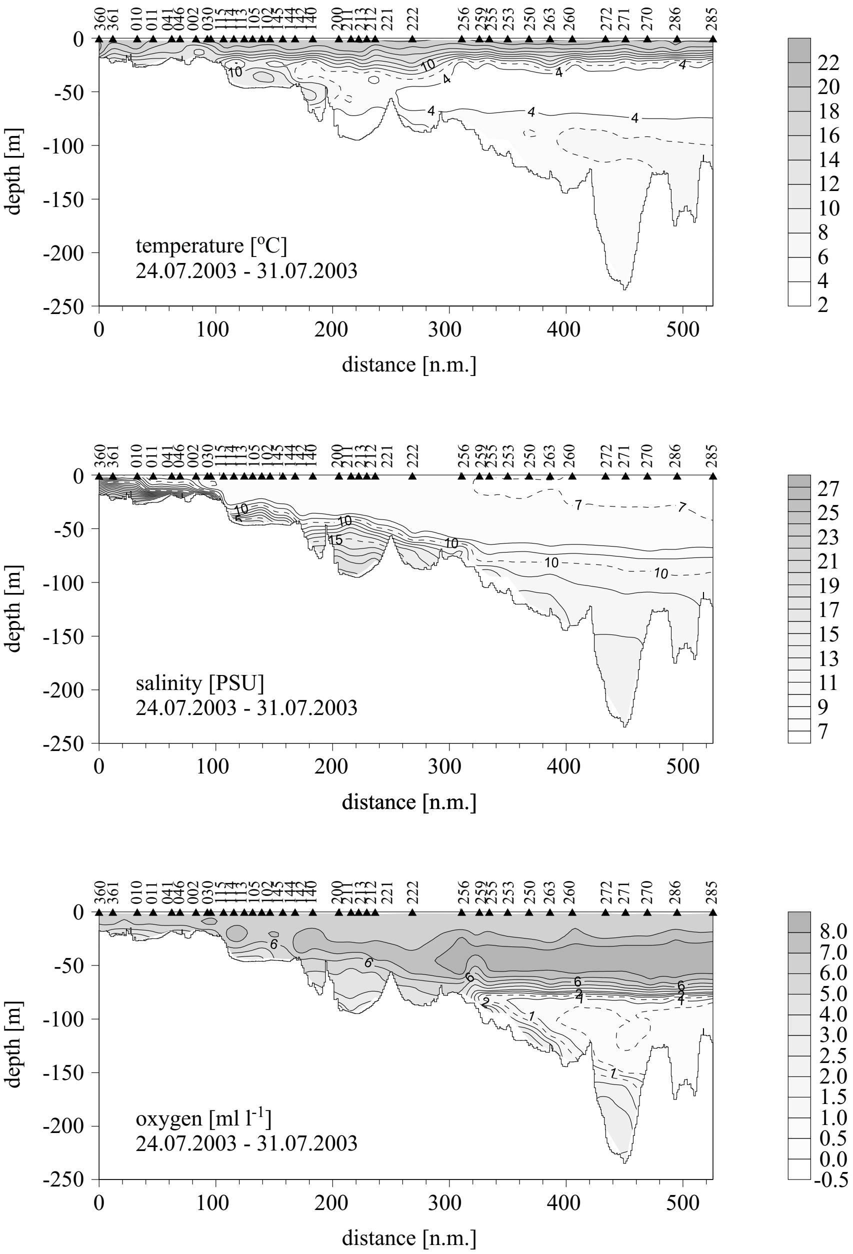

Fig. 9. Transects of temperature, salinity and oxygen from the Fehmarn Belt via the Bornholm Basin to the Gotland and Fårö Deeps, investigated by the August monitoring cruise. Cold and oxygenated bottom waters have ventilated the Gotland Basin already to a large extent, but have not yet reached the Fårö Deep. On the south-western slope of the Gotland Basin, the substitution process is still progressing by additional renewal water moving towards the central deep

longer, mostly anoxic 'warm period' of the Gotland Deep, which had begun in December 1997 after the extremely warm inflow in September (Hagen & Feistel 2001). The unusually high deep-water temperatures above 6°C were maintained by several smaller warm inflow events like that of autumn 2001 (Feistel et al. 2003a), which are clearly pronounced in Fig. 8. The last of these 'hot' spikes appeared in March 2003, probably belonging to the warm inflow waters of October 2002 (see Fig. 2), and had ventilated the Gotland Deep bottom layers already before the main substitution process by cold waters began (Feistel et al. 2003b in this volume).

The August cruise (Wasmund 2003) showed that the process of cold and oxygen-rich waters propagating deeper into the central Gotland Basin was continuing (Fig. 9). The ventilation of the water body below the halocline is still in dynamic progress. At the central station 271, the whole water column is now oxygenated, with the lowest concentration (0.5 ml l^{-1}) at 100 m depth, even though temperatures there are still higher than 6°C. Near the bottom, oxygen depletion processes have by now reduced the concentration from almost 4 ml l^{-1} in May to 2.3 ml l^{-1}. The deep water in the Fårö Deep is still completely anoxic, though with reduced hydrogen sulphide levels.

4. Discussion

After the strong inflow event of January 1993 and the subsequent small inflows in December 1993 and March 1994, oxygen conditions in the deep basins improved considerably in summer 1994. Oxygen concentrations measured in the Gotland Deep below 170 m were the highest since the 1930s (Nehring et al. 1995). Already in 1996 the system had returned to extended anoxic stagnation conditions (Matthäus et al. 1996). In September 1997, a small inflow of intensity $Q = 11.8$ on the FMS 87 scale occurred, which carried unusually warm but oxygen-poor waters into the basins (Hagen & Feistel 2001). It lasted for 8 days from 15th to 23rd September, with an average Darss Sill salinity of 17.8 PSU. Another very small event (below the FMS 87 scale) in autumn 2001 brought some relief for a short period (Feistel et al. 2003a), but in summer 2002 practically the entire water body below 70 m depth in the central Baltic suffered from oxygen deficiency and in part displayed high concentrations of hydrogen sulphide.

Exceptional weather conditions in late summer 2002 caused the transport of extremely warm waters into layers at and below the permanent pycnocline. Although carrying only small amounts of oxygen, they were capable of completely ventilating the Gdańsk Basin by November 2002, and reducing hydrogen sulphide concentrations even as far as the Gotland Basin (Feistel et al. 2003b in this volume).

As a result of a stable high pressure cell over Scandinavia associated with north-easterly winds at the beginning of 2003, the mean Baltic water level was 20–30 cm below normal (Stockholm gauge). After the wind over the western Baltic had turned to 15 m s^{-1} gale force from westerly directions on 11th January, the western Baltic sea level suddenly fell to –80 cm and a strong inflow commenced. The intrusion continued with heavy fluctuations until the wind began fading on the 18th, leaving the Stockholm level at 25 cm above normal. North Sea water started to propagate over the sills into the deeper basins with a delay of a few days. This slower process was further supported by observed southerly winds continuously blowing until the 24th, thus allowing the heavy waters piled up in the shallow western Baltic to further flow eastwards and preventing them from being flushed straight back into the Kattegat.

In the Sound, very high salinities were reported on 15th January – 26.6 PSU and 2.5°C, and on 18th January – 26.4 PSU and 2.2°C (SMHI 2003). Extrapolating these values to the whole inflow volume of about 32 km^3 (SMHI 2003), we can estimate a salt transport of $M_S = 0.85$ Gt (0.85×10^{12} kg) through the Sound. This is only about one half of the values assumed for the 1993 inflow, which range between 1.6 and 2.0 Gt (Fischer & Matthäus 1996).

The autonomous measuring platforms located at the Darss Sill, the main entrance to the deeper Baltic Sea basins, and in the Arkona Basin, recorded an inflow of highly saline, cold and extremely oxygen-rich water from the North Sea between 16th and 25th January. At the Darss Sill, salinities up to 21 PSU at the bottom and 18 PSU at the surface were measured (Fig. 2).

Following the criteria proposed by FMS 87, an inflow intensity index of

$$Q = 2 \times k\,[\mathrm{d}] + 7.143 \times S\,[\mathrm{PSU}] - 131.429 = 12.1,$$

can be derived from these data, which ranks among the weak inflows ($Q < 15$). Here, $k = 6.4$ is the duration in days and $S = 18.3$ PSU the average salinity for the time period between 16th January, 12:00 hrs and 22nd January, 21:00 hrs. It must be noted here that the FMS 87 formula was designed for data from the Gedser Rev light vessel, which was anchored west of the Darss Sill, while the actual measurements are taken from the Darss Sill mast, located east of this topographic barrier. Further, the relatively sparse data available from l/v Gedser Rev cause severe uncertainties in the evaluation of inflows. For example, the 1993 inflow was a strong event with $Q = 34$ after Jakobsen (1995), or a medium one with $Q = 20.1$, recomputed after Fischer & Matthäus (1996).

The salt transport of January 2003 over the Darss Sill can be estimated roughly by the parametric relation $M_B \approx Q \times 0.05$ Gt (Fischer & Matthäus

1996), which yields an approximate Belt transport of $M_B = 0.6$ Gt of salt for the inflow and is, by this quite formal method, less than the corresponding transport figure through the Sound. More physically, the salt transport estimated using the Baltic volume variation according to the average sea level rise of 20 cm at Stockholm after 17th January, split into about 10 km^3 passing the Sound and a 65 km^3 inflow of mean salinity 18.3 PSU across the Darss Sill, results in a Great Belt salt transport of $M_B = 1.18$ Gt. Summing this figure with the above Sound estimate $M_S = 0.85$ Gt, we find the new intensity measure FM 96 (Fischer & Matthäus 1996) for 2003 to be

$$Q_T = \frac{M_S + M_B}{0.1\,\mathrm{Gt}} = 20.3,$$

which is just at the lower limit of the strong interval $20 < Q_T \leq 30$ on the new scale. In comparison, for the 1993 inflow, Håkansson et al. (1993) had obtained $M_S = 2.1$ Gt and $M_B = 1.9$ Gt, which leads to a very strong FM 96 index $Q_T = 40$, even exceeding the corresponding estimate of $Q_T = 34$ of Fischer & Matthäus (1996).

While the actual Q is computed quite accurately for the Darss Sill mast, it certainly possesses an unknown systematic offset with respect to water properties at the former l/v Gedser Rev position, and all the other measures given above suffer from significant additional uncertainties.

In order to integrate the recent event into the series of 97 major Baltic inflows (MBI) identified since 1897, Table 2 shows the ranking of the five strongest inflows according to FM 96 index compared to the 1975/1976, 1993 and 2003 events.

Table 2. Characteristic properties of the five strongest major Baltic inflows (MBI) since 1897 (after Fischer & Matthäus 1996) compared to the 1975/1976 and 2003 events. Index Q_T is the gross salt import (in units of 0.1 Gt), the mean salinities S [PSU] are given separately for the Sound (S_S) and Belt (S_B) fractions, and the related inflow volumes V of waters with $S \geq 17$ PSU [km^3]

Rank	MBI	Q_T	S_B	S_S	V_B	V_S	V_{tot}
1	November/December 1951	51.7	22.5	24.7	172	53	225
2	December 1921/January 1922	51.2	19.2	22.2	202	56	258
3	November/December 1913	38.0	21.0	23.6	123	51	174
4	January 1993	34.0	18.7	25.2	93	66	159
5	November/December 1897	33.5	18.5	21.3	147	30	177
14	December 1975/January 1976	25.6	20.1	23.1	108	17	125
25	**January 2003**	**20.3**	**18.3**	**26.0**	**65**	**32**	**97**

The effect of the January 2003 inflow was enhanced by the smaller events in autumn 2002 (Feistel et al. 2003b in this volume), and especially by the oxygen-rich and cold waters passing the sill during almost the whole of March 2003 (Fig. 2). They seem to have caused the overflow from the Bornholm Basin through the Słupsk Channel observed at the end of March (Feistel 2003a) causing the observed near-bottom, narrow jet-like current down the slope into the Gotland Basin, centred on the eastern flank of the valley and showing rapid temporal changes on a scale of days. The Gotland Deep mooring, which was recovered in May 2003, showed the arrival of this jet at the end of April, accompanied by a substantial decrease in temperature, and enhanced basin deep circulation current (cf. Fig. 8). For the future persistence of the Gotland Deep ventilation status, the oxygen depletion rate between March and August proved a useful indicator, as could be observed after the 1993 inflow (see Table 3).

Table 3. Near-bottom oxygen concentrations [ml l^{-1}] in the Gotland Deep determined during IOW monitoring cruises after the 1993 inflow, in comparison with the recent development in 2003. The strongest depletion usually occurs between May and August

Year\Months	February	April	May	August	November
1994	–1.00	2.55	**3.50**	**1.59**	1.41
1995	1.48	1.20	**1.17**	**0.55**	0.48
1996	0.00	–0.34	**0.05**	**–1.24**	–1.60
2003	–5.93	0.04	**3.96**	**2.31**	1.58

The corresponding observations in 2003 suggest that the current inflow may have lasting effects on the deep-water ventilation status comparable to those following the 1993 inflow.

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