Evidence for a warm water inflow into the Baltic Proper in summer 2003

OCEANOLOGIA, 46 (4), 2004.
pp. 581–598.

KEYWORDS
Inflow
Hydrography
Warm water
Temperature
Oxygen conditions
Baltic Sea

Rainer Feistel[1,*]
Günther Nausch[1]
Toralf Heene[1]
Jan Piechura[2]
Eberhard Hagen[1]

[1] Baltic Sea Research Institute,
Seestrasse 15, D–18119 Rostock–Warnemünde, Germany;

e-mail: rainer.feistel@io-warnemuende.de

*corresponding author

[2] Institute of Oceanology,
Polish Academy of Sciences,
Powstańców Warszawy 55, PL–81–712 Sopot, Poland

Manuscript received 29 September 2004, reviewed 15 November 2004, accepted 24 November 2004.

Abstract

The exceptional warm water inflow into the Baltic Sea in summer 2002, which preceded the major Baltic inflow of January 2003, was surprisingly repeated in modified form in summer 2003. Its warm waters even replaced the renewed, cold inflow waters in the eastern Gotland Basin and commenced another warm period in its deep layers, where the previous one had lasted from 1997 to 2003. Details of the temporal and spatial behaviour of this new baroclinic inflow are presented from various measurements carried out from the Kiel Bight up to Gotland, covering the Darss Sill, the Arkona, Bornholm, Gdańsk Basins and the Słupsk Channel, focused mainly on the time period between July 2003 and July 2004. Hypothetically, the repetition of these exceptional warm inflow events could be regarded as a possible regional indicator for global climatic change.

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

1. Introduction

The major Baltic inflow of January 2003 had terminated in a dramatic way the extended 'warm period' of the central Baltic deep water, lasting in the Gotland Deep from December 1997 to May 2003 (Feistel et al. 2003a, Piechura & Beszczyńska-Möller 2004). Quite surprisingly, the new near-bottom minimum temperature there of 3.6°C in November 2003 (SMHI 2003, unpublished) began rising rapidly again and reached as much as 6.8°C already in March 2004 (Feistel 2004). The only plausible explanation for this intense deep-water substitution process is very probably the warm 2003 summer inflow. Its density, magnitude and impact on the Baltic deep water have thus proved unexpectedly strong. It deserves a detailed investigation in view of its possibly long-lasting environmental effects on the physical, chemical and biological conditions in the Baltic Sea. The present paper is intended for this purpose.

The weather in the Belt Sea area in summer 2003 was governed by the calm, warm conditions in June and July 2003 due to a meteorological Ω situation with a stable high-pressure cell over the Baltic leading the passing cyclones around it and over northern Scandinavia. This resulted in the warmest summer in Germany since 1901 due to DWD (2003), perhaps the warmest summer since 1370 in France (Chuine et al. 2004), and since 1500 in Europe (Stott et al. 2004), and the third-warmest since 1890 for the southern Baltic Sea after 1997 and 2002 (Nausch et al. 2004). In the middle of August, the wind changed to westerly directions but without reaching storm force for any length of time. Lasting, calm summer conditions had already enabled an extraordinary inflow process in 2002 which carried extremely warm waters from the Kattegat into the Baltic Proper (Feistel et al. 2003b, Feistel et al. 2004). This process was repeated in modified form in summer 2003, as soon became evident from operational MARNET data and was accordingly announced in August 2003 at the Baltic Sea Science Congress (BSSC) in Helsinki (Feistel et al. 2003b). The warm inflow was apparent as a pronounced signal, especially because it happened against the background of the very cold, deep waters found in the central Baltic after the major inflow of January 2003 (Feistel et al. 2003a, Piechura & Beszczyńska-Möller 2004).

This paper describes the hydrographic situation in the Baltic from the beginning of the warm inflow in early summer 2003 and investigates in detail the temporal and spatial structures related to it in the Darss Sill area. It follows the warm water propagation from the Bornholm Deep through the Słupsk Channel into the Gdańsk Deep in high spatial resolution and time steps of a few weeks. In the eastern Gotland Basin, a long-term time series of temperature is presented, recorded by a moored string of current meters at several levels. The late spring 2004 transect from Fehmarn to Gotland shows the remarkable changes that appeared in the course of one year as a result of the summer inflow 2003.

2. Material and methods

The measurements presented in this paper cover the time period between 1997 and 2004, partly obtained by observations within the framework of the Baltic Monitoring Programme (COMBINE) of the Helsinki Commission (HELCOM) carried out by the Baltic Sea Research Institute (IOW) in Warnemünde, Germany, and high resolution observations of the Institute of Oceanology, Polish Academy of Sciences in Sopot, Poland, using undulated CTD and VM ADCP. Other cruises in August (Jost 2003, Kuß 2003) were carried out by the IOW. The ship-borne investigations were supplemented

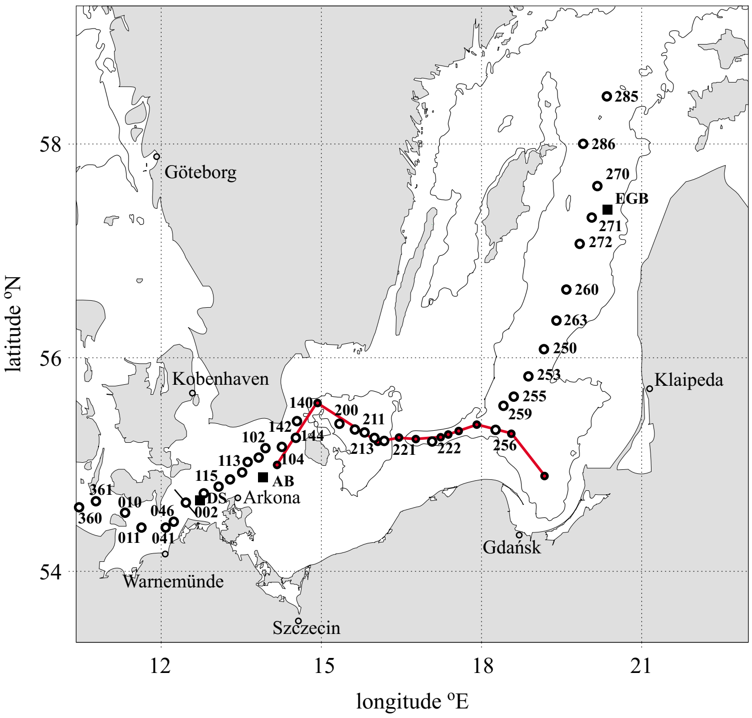

Fig. 1. Station map of the Baltic Sea with 70 m isobath indicated. Stations 360 to 285 mark the regular IOW transect from the Kiel Bight to north of Gotland. Black squares denote the permanent stations DS (Darss Sill mast), AB (Arkona Basin buoy) and EGB (Eastern Gotland Basin mooring). Station 002 belongs to the Darss peninsula–Falster island transect, shown as a short black line. The red track indicates the line of the IOPAS high resolution transects. Digital topography is taken from Seifert et al. (2001), digital shoreline polygons from Feistel (1999)

by continuous records of temperature and salinity at two permanent stations of the German MARine Environment Monitoring NETwork (MARNET) of the Bundesamt für Seeschifffahrt und Hydrographie (BSH), the Darss Sill mast (DS), and the semi-diver buoy Arkona Basin (AB), both operated by IOW. Additionally, current profiles from an Acoustic Doppler Current Profiler (ADCP) were taken between Warnemünde and Gedser during a BASEWECS cruise (Karstensen 2003), and continuously recorded currents and temperatures at six levels (140 m, 155 m, 174 m, 204 m, 219 m) at a mooring in the Eastern Gotland Basin (EGB) were used (Hagen & Feistel 2001, 2004).

All 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.

3. Results

At the end of July 2003, the first warm inflow phase was in progress (Fig. 2). The Arkona Basin near-bottom layer was found to have a temperature of about 10°C and a salinity of 17.4 PSU (Wasmund 2003). The oxygen level of the inflow water was at about 3.4 ml l^{-1}. The tip of the inflow tongue had reached the Bornholm Deep at about 60 m depth, above the still cold (3.7°C) and salty (19.1 PSU) bottom water from the cold January inflow, and below the winter water layer at 4–5°C. Near the bottom of the Gotland Deep the temperature was 4.6°C, and salinity was 12.7 PSU at this time.

At the Darss Sill, the first extended warm inflow period had already occurred between 3 and 16 July (Fig. 3) with salinities between 14 and 18 PSU and temperatures 14–16°C near the bottom. The second period began on 20 July with salinity exceeding 14 PSU at 19 m depth, and ended on 15 August. In this phase the typical temperature near the bottom was 14°C. A third inflow period, although with stronger fluctuations, began on 18 August and lasted until 7 September, carrying water typically at 16°C. A fourth period can be identified between 10 and 23 September, still with the same temperatures as high as c. 16°C.

With respect to salinity, the main inflow period appeared in the first half of August. Temperature, however, revealed a very specific feature along with the summer inflow. A cold intermediate water layer with low salinity was centred at about 12 m depth below the temporary thermocline from mid-July to mid-August, between the very warm, out-flowing, low-salinity Baltic surface water above, and the very warm, inflowing, high-salinity Kattegat surface water below it. Strong winds on 13–15 August destroyed this fragile

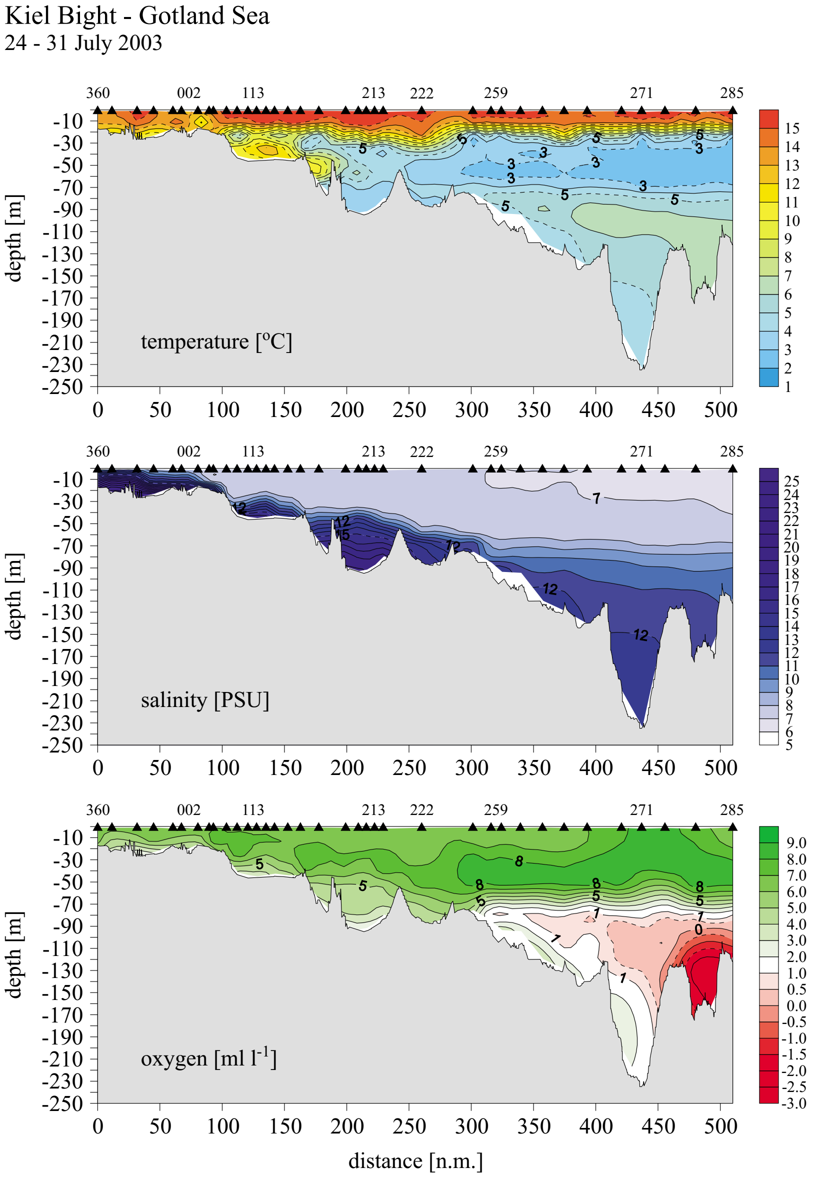

Fig. 2. Transect between IOW stations 360 (Kiel Bight) and 285 (northern Gotland Basin); see station map Fig. 1, for temperature, salinity and oxygen as measured on 24–31 July 2003 (Wasmund 2003). Hydrogen sulphide is shown as negative oxygen equivalent

structure. This cold intermediate layer existed over the entire width of the Darss Sill cross section, as visible on the transects taken there on 6 August (Fig. 4), and contains the highest oxygen concentration (about 7 ml l^{-1}).

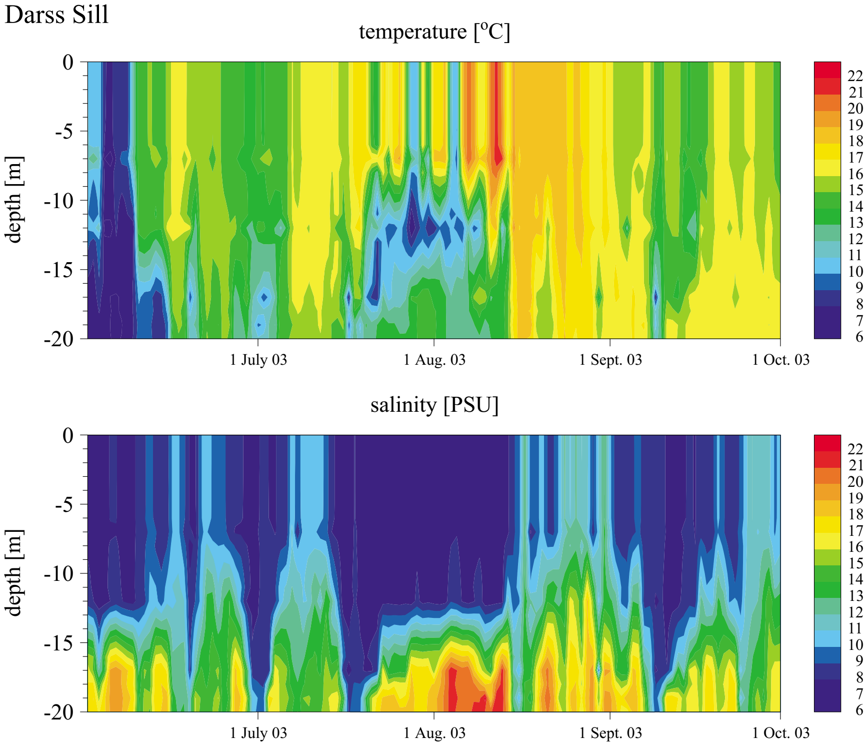

Fig. 3. Time series from June to September 2003 of the vertical temperature (top) and salinity (bottom) profiles at the MARNET Darss Sill mast

Thus, a remnant of winter water could have survived at the shallow Darss Sill until mid-August. The relevant salinity transect is shown in Fig. 5.

Under low-wind conditions, as studied in this paper, the water body flowing over the Darss Sill is laterally non-homogeneous, and strong vertical and horizontal gradients, especially with respect to salinity may be present. This was already demonstrated by an extended field campaign in 1980 (Matthäus et al. 1982), recently reconsidered by Feistel et al. (2004). In order to discover the relevant thermohaline structures for the actual inflow process, dedicated CTD transects were carried out between the Darss peninsula and Falster island on 6, 14, 18 and 21 August as displayed in Fig. 5 (Jost 2003, Kuß 2003). Both the low-salinity and the high-salinity water bodies are clearly distinguished. Inflow and outflow jets are related, but usually not identical to the salinity patterns. While high salinity waters belong mostly to the inflow, the brackish surface layer may be divided horizontally into counter currents (Karstensen 2003, Feistel et al. 2004, see also Fig. 6). These jets are subject to certain meandering processes during the dates shown, which is reflected in the Darss Sill mast time series

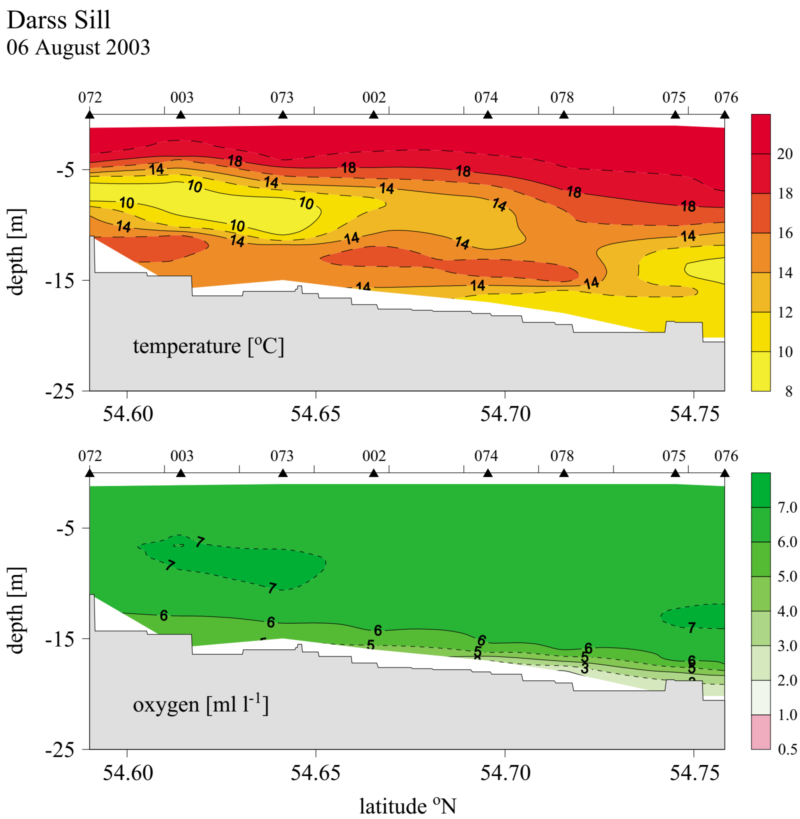

Fig. 4. Temperature and oxygen transects on the Darss Sill cross-section between Darss (left) and Falster (right) on 6 August 2003 (Jost 2003), black line Fig. 1

(Fig. 3) only by the varying salinity of the bottom layer. Extrapolations of these local mast records to the entire cross-section must therefore be treated with great caution, and a computation of total volume and salt transport across the sill from the mast data alone is only possible with significant uncertainties. The meandering transport pattern was probably caused by the variable wind conditions, especially by the change from moderate to strong winds on 13–16 August.

Table 1 shows wind speed maxima at Arkona station for 6–21 August 2003. After the hottest summer day at Arkona with 27.2°C on 13 August, the 2003 annual wind peak velocity of 29.1 m s^{-1} was registered on 14 August (DWD 2003). This storm event destroyed the extremely strong halocline, and reduced the near-bottom salinity significantly (see the panels of 6 and 14 August in Fig. 5). The Landsort sea-level gauge, a measure for the extent of filling of the Baltic Sea, recorded only insignificant fluctuations in the period covered here (SMHI 2003 (unpublished), not shown).

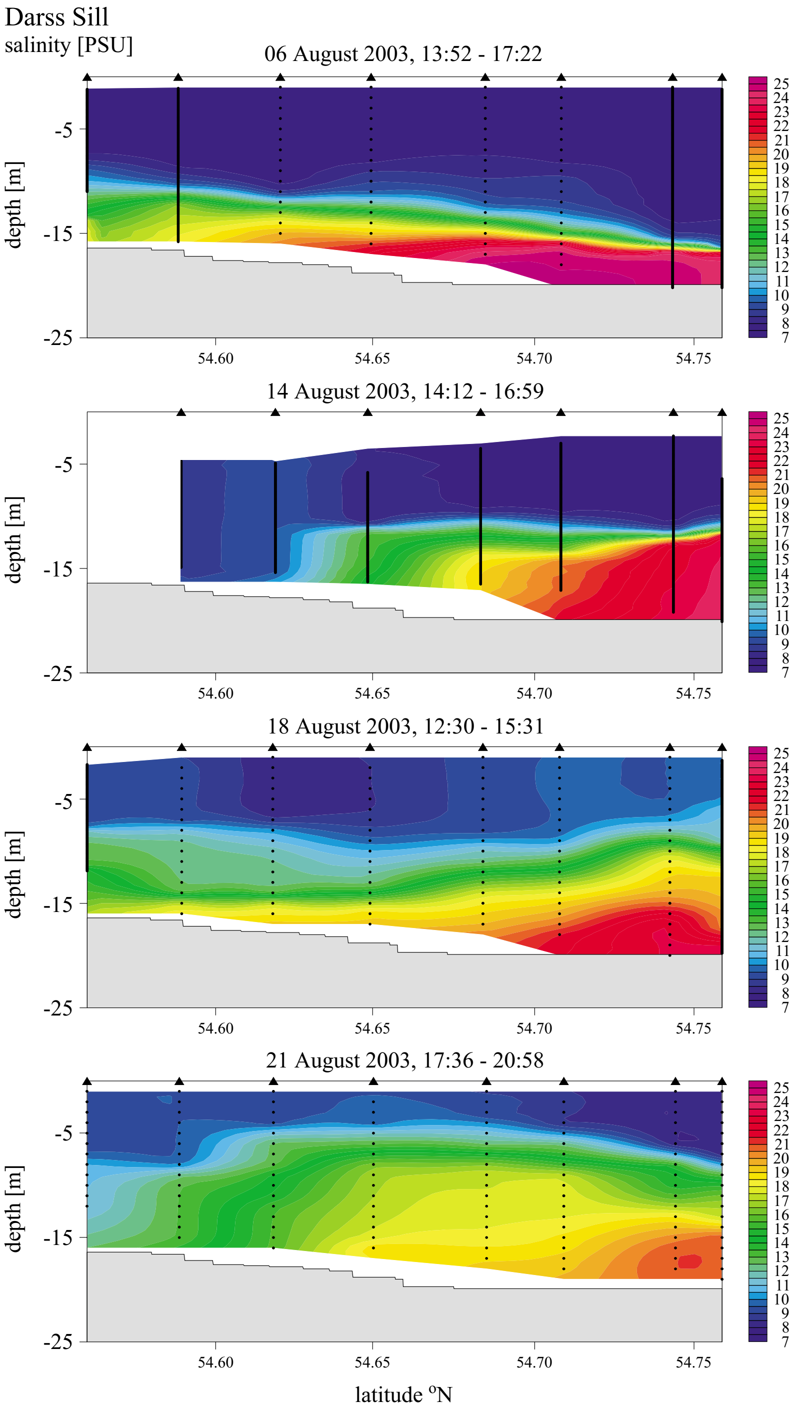

Fig. 5. Meridional CTD transects of salinity covering the Darss Sill cross section between Darss peninsula (left) and Falster island (right) on 6, 14, 18 and 21 August 2003 (Jost 2003, Kuß 2003), black line in Fig. 1. The white areas are due to the lack of data

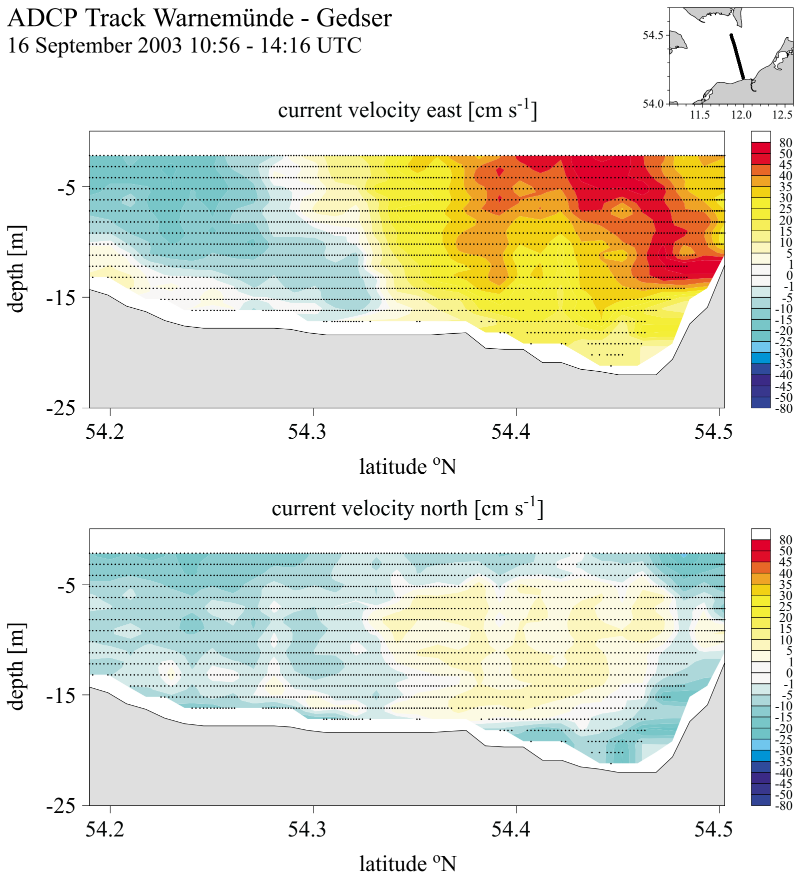

Fig. 6. Meridional transects of zonal (top) and meridional (bottom) current velocities between Warnemünde (left) and Gedser (right) on 16 September 2003. In the upper panel, the eastward current (red) moves along the Kadett Furrow on the northern flank with peak speeds of up to 50 cm s^{-1}. The white areas are due to the lack of data

Table 1. Daily maxima of hourly averaged wind speed at Arkona weather station in August 2003

Date 2003	Time [h]	Speed [m s^{-1}]	Direction [°]	Date 2003	Time [h]	Speed [m s^{-1}]	Direction [°]
Aug. 6	13	4.7	60	Aug. 14	11	15.4	250
Aug. 7	11	4.6	300	Aug. 15	8	16.9	280
Aug. 8	23	5.3	220	Aug. 16	0	14.3	270
Aug. 9	12	10.5	80	Aug. 17	6	6.8	280
Aug. 10	21	6.5	130	Aug. 18	14	6.7	80
Aug. 11	23	6.0	210	Aug. 19	13	9.7	270
Aug. 12	10	9.5	260	Aug. 20	15	12.9	260
Aug. 13	21	13.5	270	Aug. 21	14	10.0	250

The acoustically measured current structure between Warnemünde and Gedser on 16 September showed two horizontally clearly separated jets with peak velocities exceeding 50 cm s^{-1} (inflow) and 15 cm s^{-1} (outflow) in the meridional direction (Fig. 6). Contrary to our initial expectations, these currents did not run with the topographic flank to their right. Thus, the Coriolis force is not the dominant force in this snapshot. From 15 to 19 September, moderate westerly winds prevailed at Arkona. The report by Karstensen (2003) provides additional temperature and salinity transects in the western Baltic from 15 to 18 September 2003, as well as some model results, which indicate that the pattern displayed in Fig. 6 may have been caused by local recirculation processes, but not immediately by the large scale transport through the Danish Straits.

Fig. 7 shows Arkona Basin buoy data of temperature and salinity from January 2003 to May 2004. The cold inflows of January and March 2003 are very distinctive in the near-bottom salinity records. The summer inflow appears as an extended salinity maximum in the deep layer from mid-August to mid-October, but even more striking is the high temperature of the bottom layer with its maximum thickness reached in the first half of October 2003, delayed by two months after the surface temperature peak

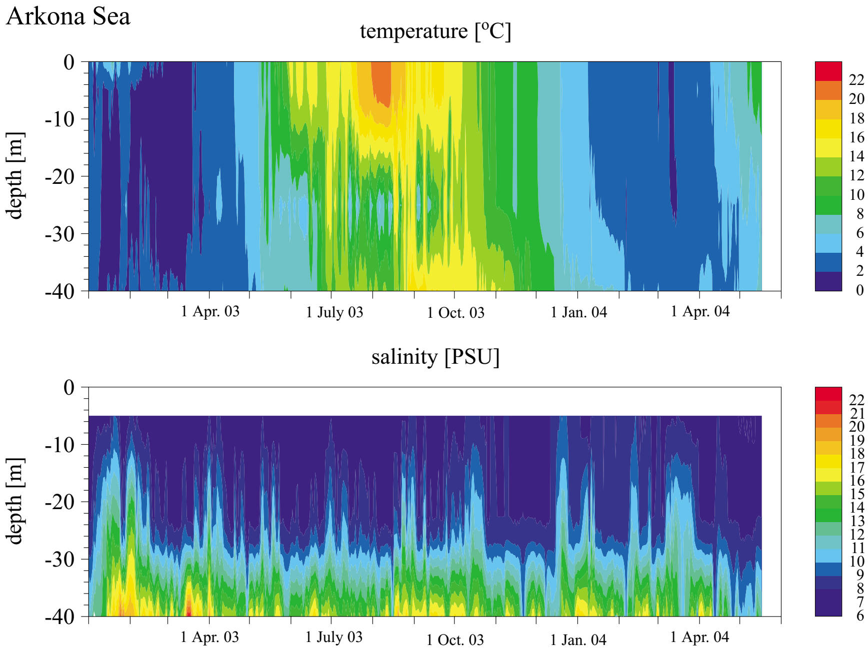

Fig. 7. Time series of vertical temperature and salinity profiles at the MARNET Arkona Basin buoy from January 2003 to May 2004. The warm inflow is especially apparent during the existence of a colder intermediate layer at 25 m depth

in August. The fading of the warm inflow signal continues in the Arkona Basin even until the end of January 2004.

The time evolution in the Bornholm Basin shows a very specific and dynamic history (Fig. 8). The warm inflow of 2002 and the subsequent cold and warm ones in 2003 are transformed here into different spatial and temporal structures as a result of the basin's capacity to buffer and delay

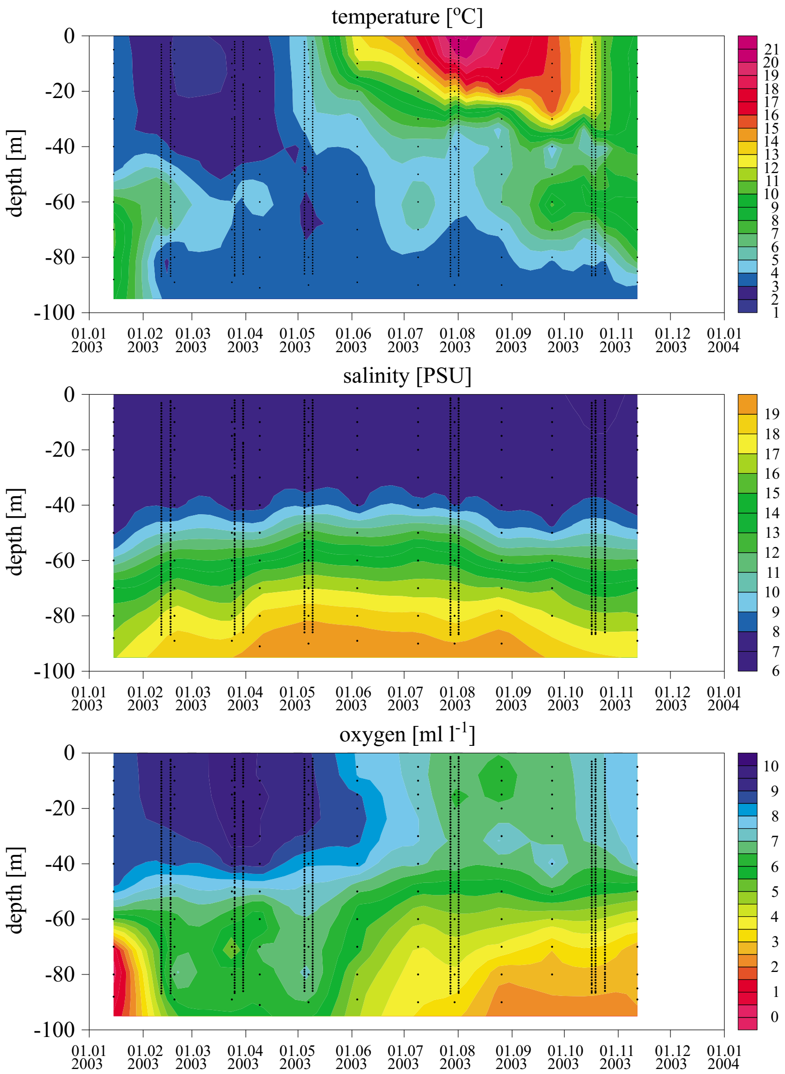

Fig. 8. Bornholm Basin (IOW station 213 = BMP K2, see Fig. 1) time series from 15 January to 12 November 2003 based on IOW and SMHI CTD data of temperature (top), salinity (middle) and oxygen concentration (bottom). Black dots represent single CTD or bottle readings

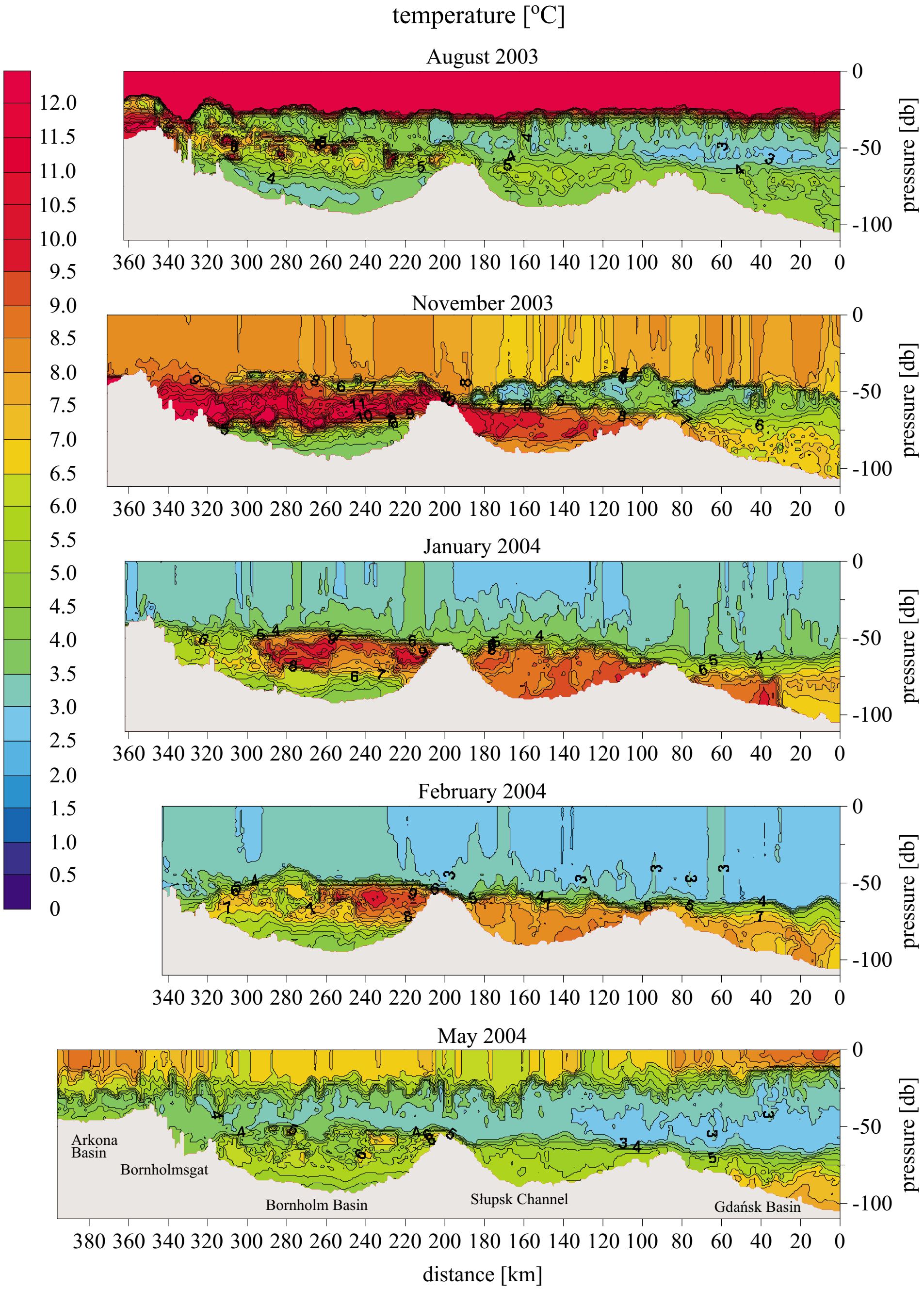

Fig. 9. Bornholm Deep–Słupsk Channel–Gdańsk Deep transects measured by r/v 'Oceania' in November 2003 (top), January 2004, February 2004 and May 2004 (bottom), showing the eastward propagation of warm inflow water over the Słupsk Sill into the south-eastern Gotland Basin

incoming signals (Feistel et al. 2003a b, Piechura & Beszczyńska-Möller 2004). By mid-April 2003, the warm waters residing between 60 m and 90 m depth originating from the 2002 inflow were replaced by cold waters from the January 2003 major inflow. The first batch of the warm 2003 inflow appeared at the end of June at about 60 m depth and was amplified again after mid-August, even extending down to almost bottom depth. Over the same period, the bottom layer oxygen became depleted, and its salinity reduced from 19 to 17 PSU.

Records made by r/v 'Oceania' during the period August 2003–May 2004 show the propagation and transformation of the warm layer in the Bornholm Basin, Słupsk Channel and Gdańsk Basin (Fig. 9). Beginning in August 2003, patches of warm water were found in the intermediate layer of the Bornholm Basin. The intensive inflow of warm water (over 10°C) is seen in the bottom layer of the Bornholmsgat. In November–December 2003 the warm water occupied mainly the layers 40–70 m in the Bornholm Basin and 65 m – bottom in the Słupsk Channel, and their temperatures were 10–11°C and 8–9°C accordingly. Some amounts of warm water were found in the near-bottom layer on the slope towards the Gdańsk Basin; its temperature was lower at c. 6°C. On top of this layer, remains of cold, so-called winter water, were observed, much stronger and colder (4–6°C) in the Słupsk Channel and the Gdańsk Basin than in the Bornholm Basin (6–7°C). In January 2004, the warm layer in general moved to the east;

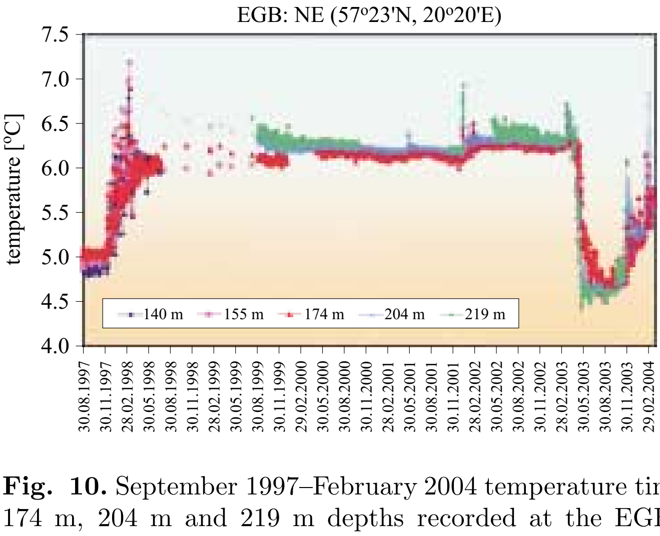

Fig. 10. September 1997–February 2004 temperature time series at 140 m, 155 m, 174 m, 204 m and 219 m depths recorded at the EGB mooring on the north-eastern flank of the Gotland Basin at 224 m bathymetric depth. Single points in the mooring's 1998/99 data gap are CTD readings from the same depths. The cold deep water of the January 2003 major Baltic inflow is already being substituted in autumn 2003 by the new warm summer inflow

later it was recorded in central and eastern parts of the Bornholm Basin (50–75 m layer), in the Słupsk Channel (60 m – bottom), and on the slope towards the Gdańsk Basin (80 m – bottom). Its temperature was lower than 8–10°C in the Bornholm Basin and 6–9°C in the Słupsk Channel, except in the approaches to the Gdańsk Basin where the temperature rose to 6–8°C.

The warm water continued moving eastwards, and in February 2004 it was recorded in the eastern part of the Bornholm Basin, over the Słupsk Sill, in the Słupsk Channel and in the Gdańsk Basin. Compared to January, its temperature was now lower by 1–2°C in the Bornholm Basin, but higher in the Słupsk Channel. In May 2004, remains of this warm inflow were recorded in the Bornholm Basin (patches of water warmer than 6°C) and in the Gdańsk Basin (still over 8°C at the deepest level).

The Eastern Gotland Basin mooring EGB is located at 57°23′N, 20°20′E (see Fig. 1) over the north-eastern flank of the basin at 224 m water depth (Hagen & Feistel 2004). It started recording a warm inflow signal after the temperature drop of May 2003 already in October/November 2003 and continued with steadily rising temperatures until March 2004 (Fig. 10) with embedded spikes, suggesting pulse-like inflow events over the basin rim. This observation is quite remarkable, since it documents the substitution of cold waters from a recent major inflow by the warm ones of a baroclinic inflow in the central basin, although such summer inflows used to be considered as events insignificant for the status of Baltic Proper deep water.

For comparison with the situation in 2003 shown in Fig. 2, the long transect between the Kiel Bight and Gotland is shown again in Fig. 11 for March 2004. The warm inflow water is clearly restricted to depths below 50 m and has completely disappeared from the Arkona Basin and to the west of it. It extends from the Bornholm Basin, centred at about 70 m depth, along the Słupsk Channel and the south-eastern Gotland Basin as a thick near-bottom layer, and has reached the Gotland Deep after lifting up the cold waters residing there. Nevertheless, the inflow did not improve the deep-water oxygen situation, which shows a tendency towards a new stagnation period.

4. Discussion

In comparison to at least half a century of earlier Baltic monitoring the prolonged 'warm period' of the central Gotland Deep water lasting from December 1997 to May 2003, appeared to be an exception, not the rule. The cold inflow of January was thought to have restored the system to 'normality'. However, as revealed by historical retrospect, the recent 2003 warm summer inflow seen in conjunction with the preceding warm inflow of 2002 was only comparable with the processes observed in summer 1959

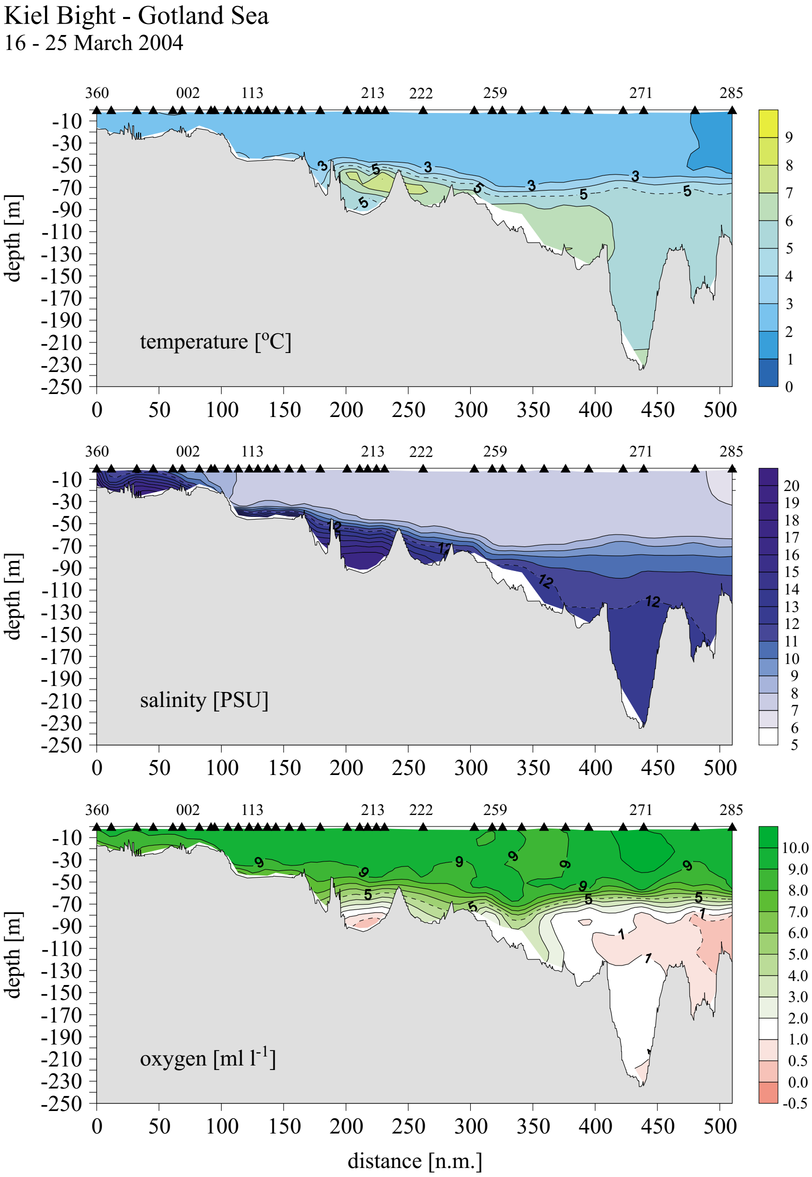

Fig. 11. Transect from the Kiel Bight to the northern Gotland Basin for temperature, salinity and oxygen between 16 and 26 March 2004 (Feistel 2004). Note the extended warming up of water masses below 50 m as compared to Fig. 2

(Feistel et al. 2004), if at all. Warm inflows did occasionally happen in earlier years, but were mostly considered to be of little relevance for the central basins. Processes with an extension, strength and frequency similar to those encountered in 2002 and 2003 have never been described before for the

Baltic Sea. This circumstance raises the question of a possible regime shift in the Baltic Sea, reflecting global climate change in a very specific manner, due to its faint hydrographic coupling to the world ocean by the narrow Danish Straits, and its sensitivity to fluctuations in the meteorological and climatologic conditions over central Europe.

The 2002 summer inflow had very serious biological implications, mainly as a result of the presence of extremely warm deep water in the Bornholm Basin and Słupsk Channel even during winter (Kraus et al. 2003). A similar effect is likely to have been triggered by the inflow of 2003, even though this time, it did not warm up the Bornholm Basin down to the very bottom.

In August 2004, a layer of warm water (6–8°C) again appeared at 60–80 m depth in the Bornholm Basin and 70 m – bottom in the Słupsk Channel (Fig. 12). However, the summer inflow at the Darss Sill ended already after 2 weeks on 23 August 2004 owing to the changing weather conditions, hence the impacts of this process on the central Baltic Sea are expected to be relatively minor.

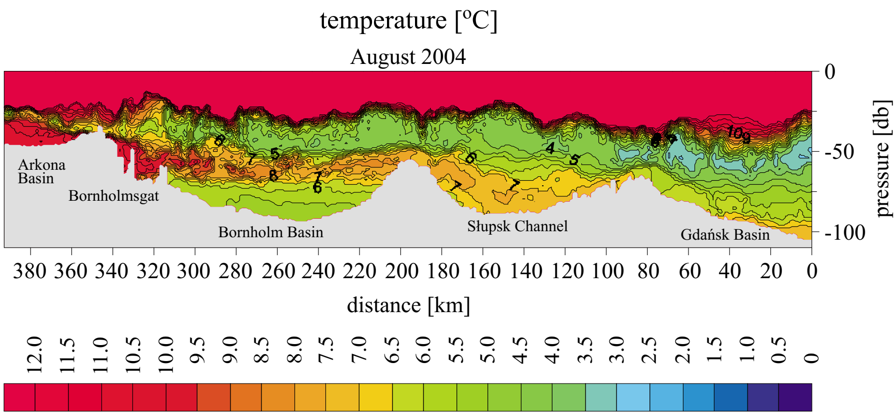

Fig. 12. Transect of temperature from the Arkona to the Gdańsk Basin in August 2004, indicating deep warm water propagation as far as the Słupsk Channel

Acknowledgements

The German part of Baltic Monitoring Programme (COMBINE) and stations of the German Marine Monitoring Network (MARNET) in the Baltic Sea (Darss Sill mast, Arkona Basin buoy) are conducted by IOW on behalf of Bundesamt für Seeschifffahrt and Hydrographie (BSH), financed by the Bundesmisterium für Verkehr (BMV). The authors thank Jan Szaron, Oceanographic Laboratory of the Swedish Meteorological and Hydrological Institute (SMHI), Gothenburg, for providing hydrographic-hydrochemical observations from the Swedish Ocean Archive SHARK, obtained within the framework of the Swedish monitoring programme. The authers are especially indepted to J. Kuß and G. Jost, IOW, who kindly carried out dedicated additional CTD stations in August 2003 to reveal the actual thermohaline structure of the Darss Sill cross section.

References

Chuine I., Yiou P., Viovy N., Seguin B., Daux V., Le Roy Ladurie E., 2004, *Historical phenology: grape ripening as a past climate indicator*, Nature, 432, 289–290.

DWD (Deutscher Wetterdienst), 2003, Witterungsreport Daten, Jg. 5 (Jahresausgabe 2003), 23 pp.

Feistel R., 1999, *New shoreline map-drawing data available*, Eos Trans. Am. Geophys. Union, 80 (22), 249 pp., Electron. Suppl., [http://earth.agu.org/eos_elec/99063e.html].

Feistel R., 2004, IOW Cruise Report 11/04/03, March 2004, [http://www.io-warnemuende.de/projects/monitoring/documents/ cr110403.pdf].

Feistel R., Nausch G., Matthäus W., Hagen E., 2003a, *Temporal and spatial evolution of the Baltic deep water renewal in spring 2003*, Oceanologia, 45 (4), 623–642, [http://www.iopan.gda.pl/oceanologia/454feis2.pdf].

Feistel R., Nausch G., Matthäus W., Łysiak-Pastuszak E., Seifert T., Sehested Hansen I., Mohrholz V., Krüger S., Buch E., Hagen E., 2004, *Background data to the exceptionally warm inflow into the Baltic Sea in late summer of 2002*, Meereswiss. Ber. (Warnemünde), 58, 1–58, [http://www.io-warnemuende.de/research/mebe.html].

Feistel R., Nausch G., Mohrholz V., Łysiak-Pastuszak E., Seifert T., Matthäus W., Krüger S., Sehested Hansen I., 2003b, *Warm waters of summer 2002 in the deep Baltic Proper*, Oceanologia, 45 (4), 571–592, [http://www.iopan.gda.pl/oceanologia/454feis1.pdf].

Hagen E., Feistel R., 2001, *Spreading of Baltic deep water: a case study for the winter 1997–1998*, Meereswiss. Ber. (Warnemünde), 45, 99–133, [http://www.io-warnemuende.de/research/mebe.html].

Hagen E., Feistel R., 2004, *Observations of low-frequency current fluctuations in deep water of the Eastern Gotland Basin/Baltic Sea*, J. Geophys. Res., 109 (C03044), 1–15, [doi: 10.1029/2003JC002017].

HELCOM, 2002, *Manual of marine monitoring in the COMBINE programme of HELCOM*, Baltic Mar. Environ. Prot. Commiss., Helsinki, (updated 2001/2002), [http://www.helcom.fi/mons/combinemanual2/combinehome.htm].

Jost G., 2003, IOW Cruise Report 44/03/08, August 2003, [http://www.io-warnemuende.de/edv-intern/dienst/exberichte/f_cr03029.doc].

Karstensen J., 2003, BASEWECS Cruise Report AL229, IfM Kiel, September 2003, [http://www.ifm.uni-kiel.de/fb/fb1/po2/edu/praktikum/ss03_hf/ss03_hf.html].

Kraus G., Möllmann C., Hinrichsen H.-H., Lehmann A., Schnack D., 2003, *Unusual water mass advection affected Central Baltic key species 1: Sprat and the summer inflow*, GLOBEC Int. Newslett., 9 (2), 27–28, [http://www.pml.ac.uk/globec/Publications/Newsletter/Newsletter.htm].

Kuß J., 2003, IOW Cruise Report 44/03/09, August 2003, [http://www.io--warnemuende.de/edv-intern/dienst/exberichte/f03030.doc].

Matthäus W., Francke E., Lass H. U., Schwabe R., 1982, *Untersuchungen der Wasseraustauschprozesse im Bereich der Darsser Schwelle*, Beitr. Meereskunde., 47, 31–50.

Nausch G., Feistel R., Lass H.-U., Nagel K., Siegel H., 2004, *Hydrographisch-chemische Zustandseinschätzung der Ostsee 2003*, Meereswiss. Ber. (Warnemünde), 59, 1–80, [http://www.io-warnemuende.de/research/ mebe.html].

Piechura J., Beszczyńska-Möller A., 2004, *Inflow waters in the deep regions of the southern Baltic Sea – transport and transformations*, Oceanologia, 46 (1), 113–141, [http://www.iopan.gda.pl/oceanologia/46_1.html].

Seifert T., Tauber F., Kayser B., 2001, *A high resolution spherical grid topography of the Baltic Sea – 2nd edition*, Baltic Sea Sci. Congr., Stockholm 25–29 November 2001, Poster #147, [http://www.io-warnemuende.de/research/de_iowtopo.html].

Stott, P. A., Stone, D. A., Allen, M. R., 2004, *Human contribution to the European heatwave of 2003*, Nature, 432, 610–614.

Wasmund N., 2003, IOW Cruise Report 44/03/07, August 2003, [http://www.io-warnemuende.de/projects/monitoring/documents/cr440307.pdf].