Papers

Variability of temperature and salinity over the last decade in selected regions of the southern Baltic Sea

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Abstract

Changes in the basic physical properties of selected areas of the Baltic Proper were analysed on the basis of the results of a 12-year series of high-resolution measurements collected during cruises of r/v 'Oceania'. The high-resolution CTD sections covered three main basins: the Bornholm Basin, Słupsk Furrow and Gdańsk Basin. Positive temperature trends of 0.11 and 0.16°C year^{-1} were observed in the surface and deep layers respectively. The salinity trend was also positive. The rise in the air temperature has probably caused the increase in surface water temperature, while advection has been of greater significance in the deep layer. The increase in salinity coincides with the more frequent occurrence of small and medium-size inflows through the Danish Straits, even though large inflows are evidently less frequent than used to be the case. The seasonal variability of temperature in the water column was analysed. The phase shift in the seasonal evolution with depth is described. The maximum temperature shift in the waters investigated varies from 32 to 38 days.

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

1. Introduction

There are a number of topographical structures in the Baltic which, despite their small dimensions, play an essential role in the circulation and water exchange of this sea. The generally adopted division of the Baltic Sea is therefore based on bottom topography: this highlights the basins with clearly defined hydrographical parameters (Fonselius 1969, Mikulski 1987, HELCOM 1990, Omstedt 1990). i.e. the Gulf of Bothnia, Bothnian Sea, Gulf of Finland, Gulf of Riga, Baltic Proper, Danish Straits and Kattegat. In terms of volume and surface area, the largest basin is the Baltic Proper (more than 50% of the volume and surface area of the Baltic Sea), which in turn consists of three smaller basins – the Bornholm Deep, Słupsk Furrow and Gdańsk Deep. The Gulf of Finland has no distinctive topographic sill; it is separated from adjacent basins by a strong hydrological front.

Owing to the large river discharge and inflows of highly saline oceanic waters (Matthäus & Franck 1992), the Baltic Sea is characterized by very large horizontal and vertical salinity gradients. These contrasting processes, as well as solar radiation and heat exchange with the atmosphere, lead to the formation of a complex and variable thermohaline stratification. The surface and intermediate layers are separated by a thermocline, the intermediate and deep layers by a halocline. Simultaneously, the strong halocline coincides with the pycnocline, which limits the vertical range of wind mixing and convection (Matthäus & Franck 1992, Matthäus & Lass 1995, Lehmann et al. 2004, Feistel et al. 2006, Reissmann et al. 2007). The halocline depth varies from about 50 m in the Bornholm Deep to 60 m in the Gdańsk Deep, becoming shallower after the passage of inflow water bringing saline waters from the North Sea.

The southern Baltic is of particular importance for the whole Baltic Sea, being a transition area for highly saline waters entering from the North Sea (Beszczyńska-Möller 2004). Deep water flow follows the bottom topography. The Słupsk Furrow, with a maximum depth of 92 m and width of 40 km, represents a gateway through which inflowing waters move into the eastern Baltic. The highly saline waters of North Sea origin pass through SF and then split into north-easterly (NE) and south-easterly (SE) branches. The SE branch enters GD, while the NE branch continues through the Hoburg Channel towards the Gotland Basin. Inflows from the Danish Straits cause an increase of salinity and oxygen content in the Baltic Proper, whereas the accompanying change in temperature depends on the season in which the inflow occurs. Major inflows, as defined by Matthäus & Franck (1992), are less common and appear approximately every 10 years. The most recent such inflows occurred in 1993 and 2003 and are the subject of numerous detailed studies (Jakobsen 1995, Matthäus & Lass 1995, Feistel et al. 2003, Piechura & Beszczyńska-Möller 2004). The increased frequency of medium-sized and small baroclinic inflows was reported by Meier et al. (2006), resulting in the higher temperature of intermediate and near-bottom layers (Feistel et al. 2006, Mohrholz et al. 2006).

This study focuses on the seasonal to long-term variability of temperature and salinity in three basins of the southern Baltic: the Bornholm Deep, the Słupsk Furrow and the Gdańsk Deep. According to the latest results, the salinity, stratification and volume of inflows into the Baltic Sea, are expected to change in the present century (Meier 2006). Further changes in water properties and dynamics may be expected in the context of on-going climate change. The paper is structured as follows: data and methods are presented in section 2; the annual cycle of temperature in the upper layers is described in section 3, which also covers the long-term and seasonal changes in salinity and temperature-averaged properties in the basins. The results are discussed in section 4.

2. Data and methodology

The data analysed in this paper were collected during regular cruises of r/v 'Oceania' in the southern Baltic between 1998 and 2010 (Figure 1). The high-resolution hydrographic sections were performed using a profiling

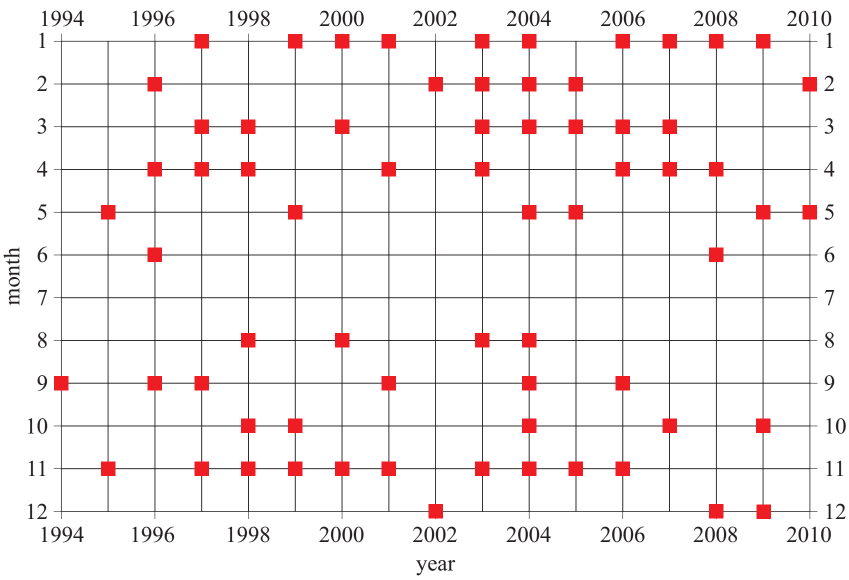

Figure 1. Distribution of r/v 'Oceania' cruises in different months

CTD (Conductivity, Temperature, Depth) probe towed behind the vessel. The main section was located along the axis of deep basins starting from the Arkona Basin, continuing over the Bornholm Deep (BD), Słupsk Furrow (SF) as far as the Gdańsk Deep (GD) (Figure 2).

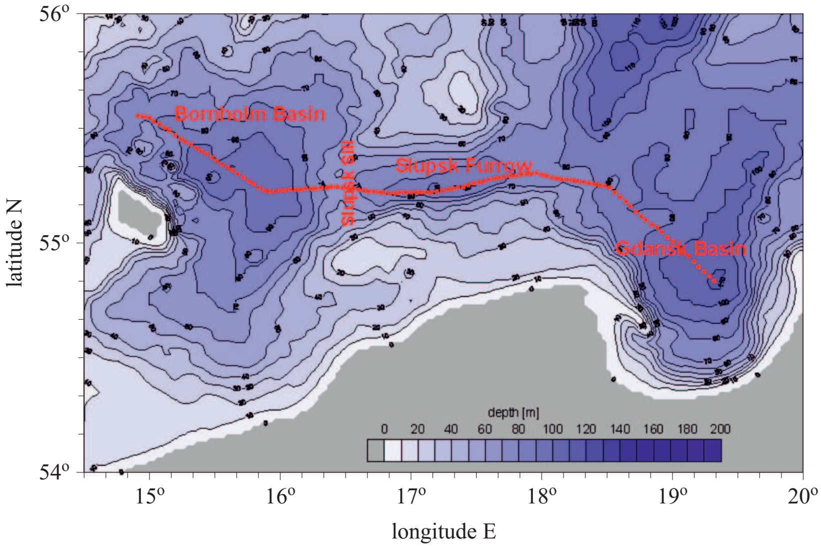

Figure 2. Bottom topography of the southern Baltic with the main section indicated by red dots (each dot represents a single profile)

During almost 20 years of IO PAS measurements with the towed profiling system, two CTD probes were used: Idronaut 316 and Seabird 49. The accuracies of the former were $C = 0.003$ mS cm^{-1}, $T = 0.003$°C, $P = 0.05\%$ of the full scale range, those of the latter were $C = 0.0003$ mS cm^{-1}, $T = 0.002$°C, $P = 0.1\%$ of the full scale range. The temperature and conductivity sensors of each CTD system were calibrated annualy (post-cruise) by the manufacturers. The profiling system consisted of a CTD probe suspended in a steel frame towed on a cable behind the vessel. The suspension system ensured the horizontal position of the probe during profiling, the steel frame protected it from mechanical damage, while a metal chain fixed below the frame reduced the risk of contact with the sea bed. To obtain a profile, the CTD system was lowered or raised between the surface and bottom by releasing or hauling in the towing cable. At a constant ship speed of ca 4 knots, a spatial resolution of ca 200–500 m was obtained for a basin with a typical depth of 60–120 m. With the CTD probe operating at a frequency of 10 Hz, the vertical resolution of the towed measurements was ca 3 cm (30 measurements per metre).

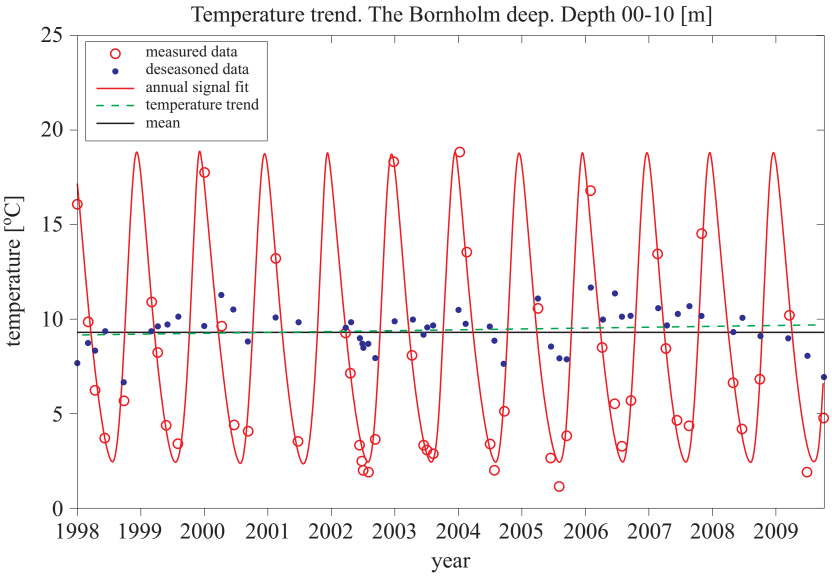

Figure 3. Temperature in the surface layer (red circles), its annual cycle (red line), temperature anomalies from the annual cycle (blue dots) and temperature trend in 1998–2010 (green line)

Along the main axis of the section (Figure 2), three separate regions were reselected with depths exceeding 70 m: the Bornholm Deep, the Słupsk Furrow and the Gdańsk Deep. Temperature and salinity data from 30 982 vertical profiles were collected during the 53 cruises. For a better presentation of the results, the data were vertically averaged into 10 m vertical layers. To study the seasonal variability of temperature and salinity, Fourier analysis was applied to time series of the averaged data (Emery & Thomson 2001). The first three Fourier components were used to represent the annual cycle. To create de-seasoned data, the Fourier fit was subtracted from the temperature time series.

The temperature variability, over time scales different from the seasonal one, was analysed using de-seasoned temperature data (Figure 3). Temperature trends were calculated using de-seasoned time series for layers characterized by a strong seasonal temperature cycle due to atmosphere-ocean interactions. For deeper layers linear regression was employed on the original temperature time series (Emery & Thomson 2001). Fourier analysis was preferred over a number of other available tools, as it faithfully reflects the changes in temperature (Figure 3) while maintaining a high coefficient of determination (>0.9). In addition, this method faithfully reflects the temperature changes during the sesonal cycle.

3. Results

3.1. The structure and average properties of the water column

For the purposes of this analysis, the water column was divided into 3 layers: surface, transition (thermocline, halocline) and bottom. The surface layer, exposed to atmospheric factors, exhibited the greatest variability in temperature (Figure 4). The average long-term temperature in the surface layer is 7.03, 7.21 and 7.58°C for BD, SF and GD respectively. The average salinity of these waters is 7.41, 7.3 and 7.26 PSU respectively (Figure 5). The transition layer is the area between the upper and lower layers.

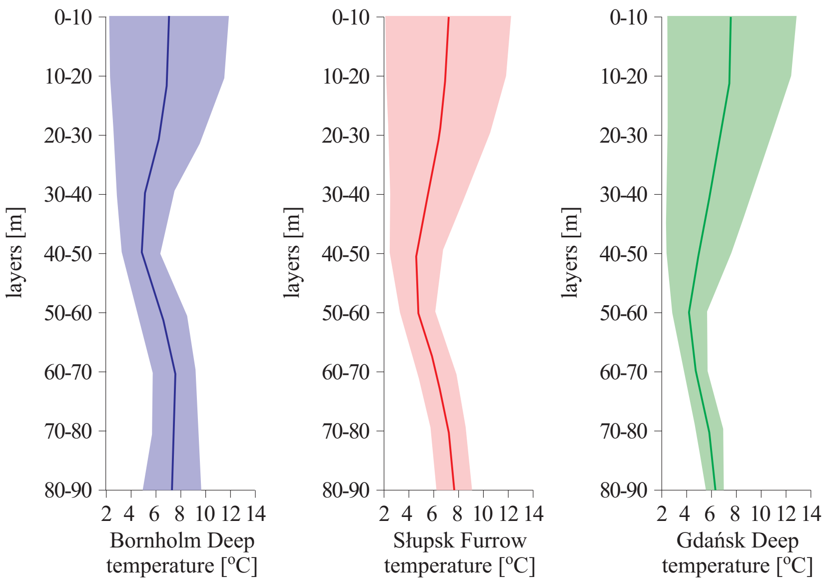

Figure 4. Average long-term temperature and its standard deviation for each layer plotted around the mean value

The depth of the transition layer changes seasonally with the thermocline and depends on the factors that force the mixing of the upper layers. The lower limit of the transition layer reaches to the depth of the halocline, which is the same as the depth of the pycnocline. The depth of the transition layer is therefore locked between 30 and 60 m.

The hydrography of the near-bottom layer (demersal) depends strongly on inflows from the Danish Straits. Mixing between the layers is limited because of the strong stratification. Temperature fluctuations in the near-bottom layer are small and become weaker with distance from the Danish

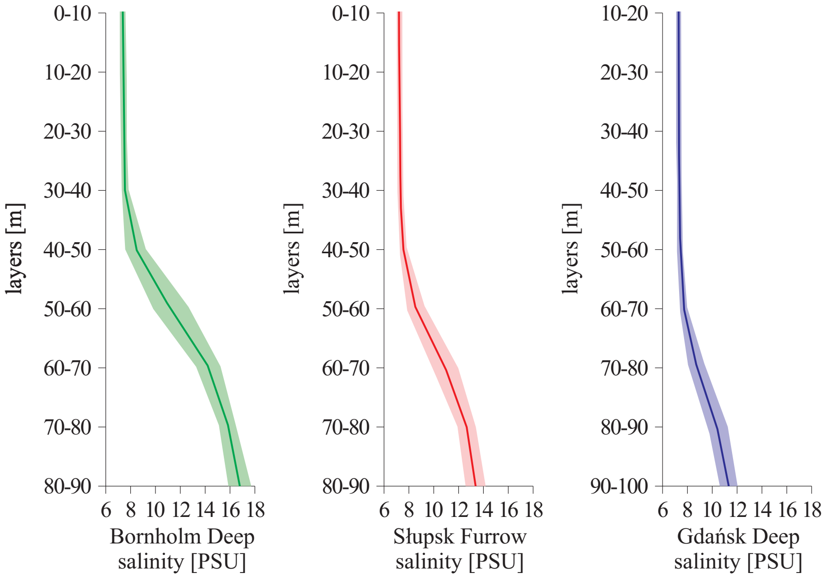

Figure 5. Average long-term salinity and standard deviation for each layer plotted around the mean value

Straits. The average temperature in BD is $7.35 \pm 2.32°C$ and $7.7 \pm 1.44°C$ in SF just after the furrow.

The salinity of Baltic Sea waters does not vary greatly from season to season (Figure 5). In the layer exposed to atmospheric forcing, the average salinity varies within 7.32 ± 0.22 and decreases along the main axis from the Kattegat to the Gulf of Bothnia (Majewski & Lauer (eds.) 1994). The average salinity and standard deviation of the near-bottom layer is 16.78 ± 0.95 in BD and 11.91 ± 0.66 in GD. These changes are caused by inflows of water from the Danish Straits that modify the hydrographical properties of the ambient waters by mixing and cause the pathways to separate.

3.2. Variation in seasonal temperature

The seasonal variability in the surface water temperature is caused mainly by seasonal changes in the supply of solar energy to the sea surface and the changes in the conditions of the exchange of energy between the sea and atmosphere. In BD and SF the maximum temperature of the surface layer occurs on day 249 of the year (7 September) (Appendix – Table 2). In GD the maximum occurs on day 254 (Table 4) of the year (9 September), whereas in BD the temperature maximum at the thermocline depth (20–30 m) occurs with a phase shift of 24 days from the surface layer (Figure 6). In SF the shift is >12 days (Figure 7), in GD it is >7 days (Figure 8).

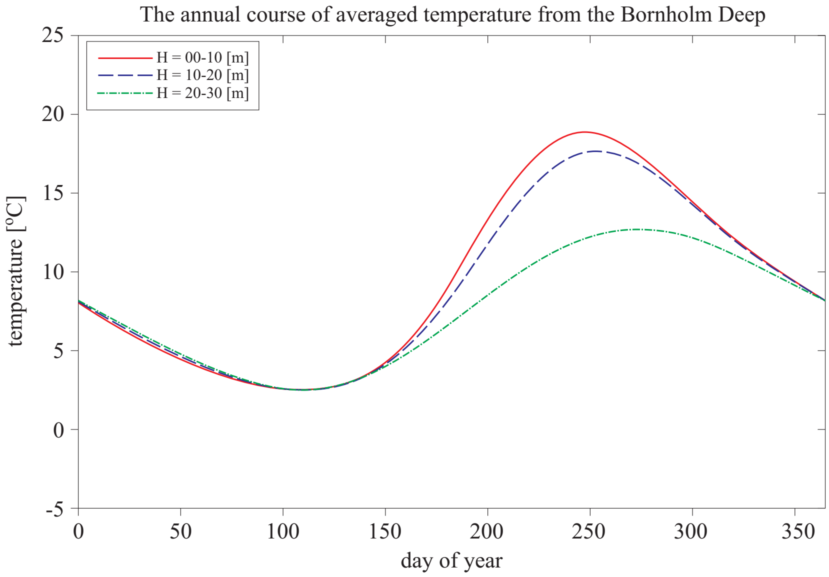

Figure 6. Changes in seasonal temperature of the surface layer: the Bornholm Deep

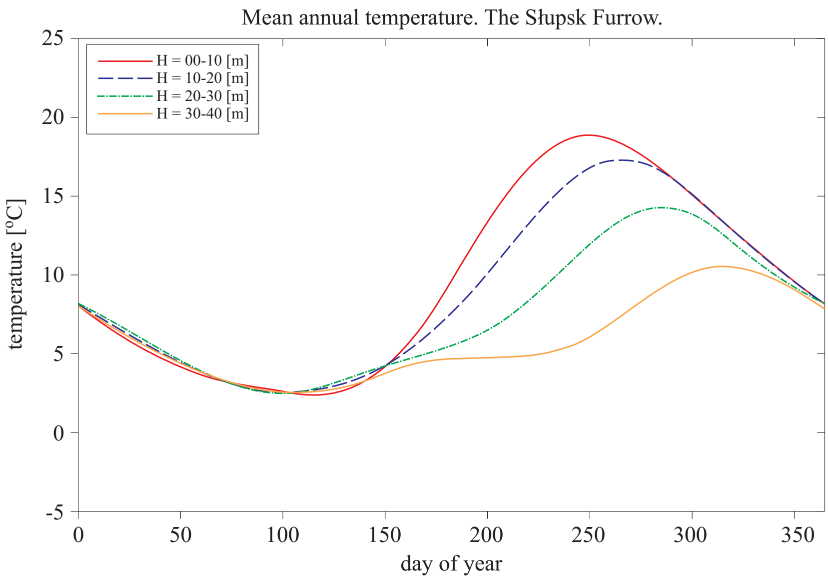

Figure 7. Changes in seasonal temperature of the surface layer: the Słupsk Furrow

The amplitude of the annual temperature cycle in the 20 m surface layer lies between 14.8 and 16.4°C, decreasing with depth, reaching 10°C below

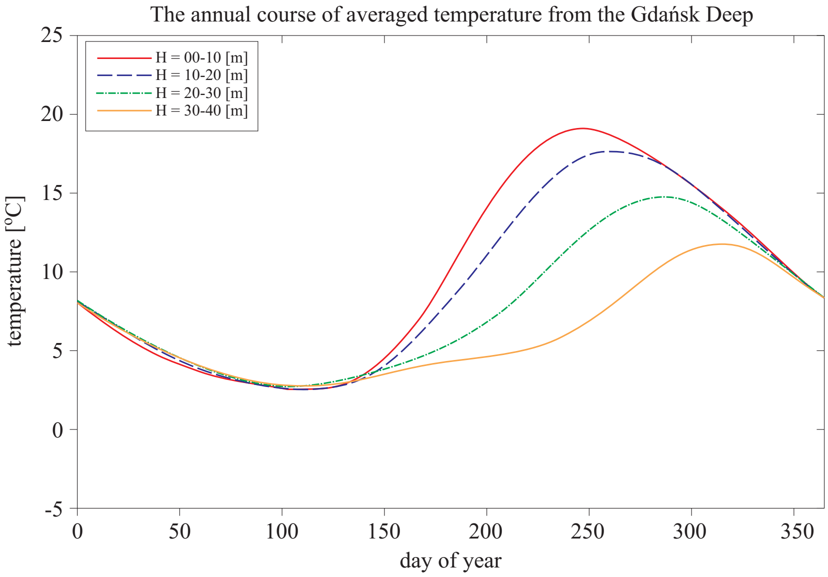

Figure 8. Changes in seasonal temperature of the surface layer: the Gdańsk Deep

20 m in BD and 11.8°C in SF (Table 3) and GD. In the 30–40 m layer of SF and GD the temperature amplitude decreases to 8°C.

Below 30–40 m depth there are no visible seasonal changes in temperature. At these depths advection is the most important forcing factor. In winter, the isothermal layer (Figure 9) with an average temperature of 3–4.5°C extends to a depth of 40–50 m. Despite the warming of the surface layer in April, a 'winter water' layer remains at 50 m depth, where it is likely to remain until the next cold season. A strong thermocline forms in June at a depth of 25 m, after which, as a result of wind mixing it descends to 40–50 m in October. Cooling of the upper layers leads to a nearly constant temperature in the mixed layer, which is typical of the stratification in this season. The near-bottom layer has an average annual temperature of 6–7.5°C, and the fluctuations are associated with inflows of water from the Danish Straits. The properties of such inflowing water depend on the season when the influx occurs.

3.3. Long-term temperature variability

Water temperature during 1998–2010 shows a positive trend in the entire water column (Figure 10). There is a sharp increase in temperature in the surface layer (0–20 m), which is directly exposed to seasonal weather variations and climate change. The temperature rise in this layer is

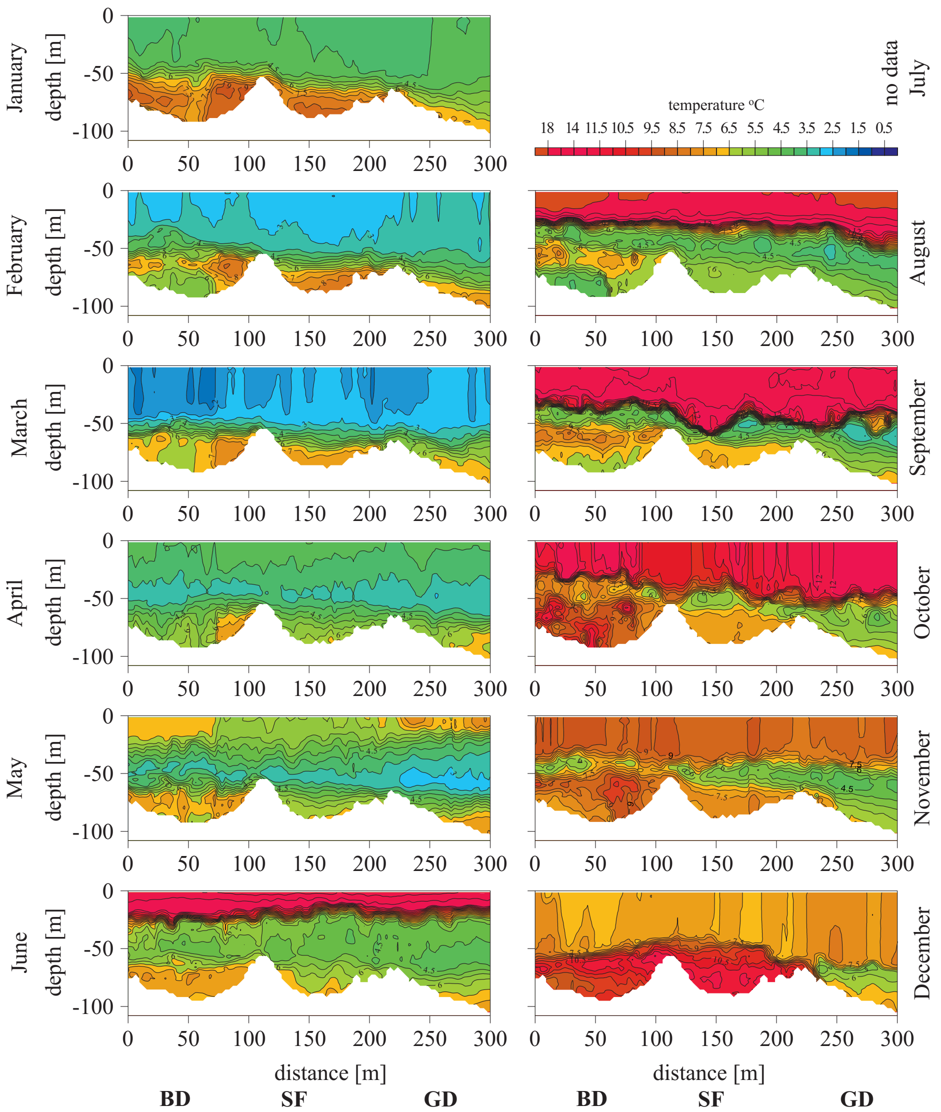

Figure 9. Average monthly temperature sections in 1994–2010. The averages are based on 9 cases in January, 6 in February and March, 5 in April and May, 1 in June, 4 in August, 3 in September, 4 in October, 8 November and 2 in December. BD – Bornholm Deep, SF – Słupsk Furrow, GD – Gdańsk Deep

especially large in SF and GD – more than 0.11°C year^{-1}. The largest increase in the temperature of the transition layer (40–70 m) has taken place in GD ($>$ 0.08°C year^{-1}), and in all areas the trend has been the greatest in the near-bottom layer. The above structure leads to a C-shaped vertical profile of the temperature trend. Therefore, one can conclude that at the surface and close to the bottom, the temperature has increased much more than in the mid-depth layers. These changes could be due to the rise in air temperature and advection from the Danish Straits to the three deep basins. As a result of convection, a slower process compared to advection, the mid-layer temperature has changed less rapidly than the situation illustrated in Figure 10.

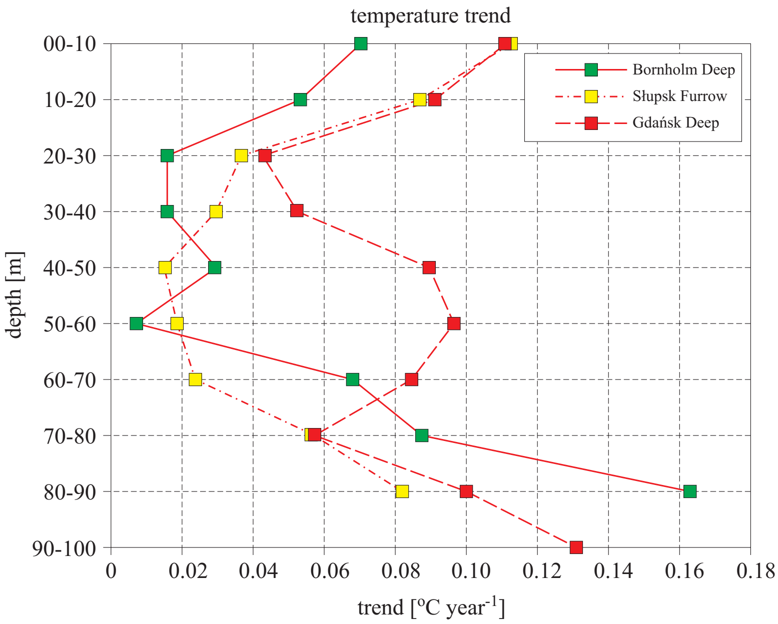

Figure 10. The temperature trend in the areas under investigation

To check the correctness of the calculations, the results were compared to the monthly satelite Sea Surface Temperature (SST) data in the areas under consideration. The SST data used was described in detail by Reynolds et al. (2002). The in situ data were compared to the averaged SST over the period under scrutiny and for the nearest location (Table 1). For example, the in situ surface temperature collected in January was compared to the SST averaged for all the January data from 1998–2010 obtained for the nearest location. The results confirm the correctness of the calculated trends (Figure 10). The difference between the results is approximately 0.02°C.

3.3.1. Long-term variability in salinity

There was a positive trend in salinity in all three areas over the years 1998–2010, (Figure 11). The salinity increase in GD was much faster in the

Table 1. Analysis of SST from satellite imagery

SST	Temperature trend [°C year^{-1}]	Average and standard deviation [°C]
Bornholm Deep	–	–
Słupsk Furrow	0.13	9.36 ± 5.54
Gdańsk Deep	0.14	9.57 ± 5.56

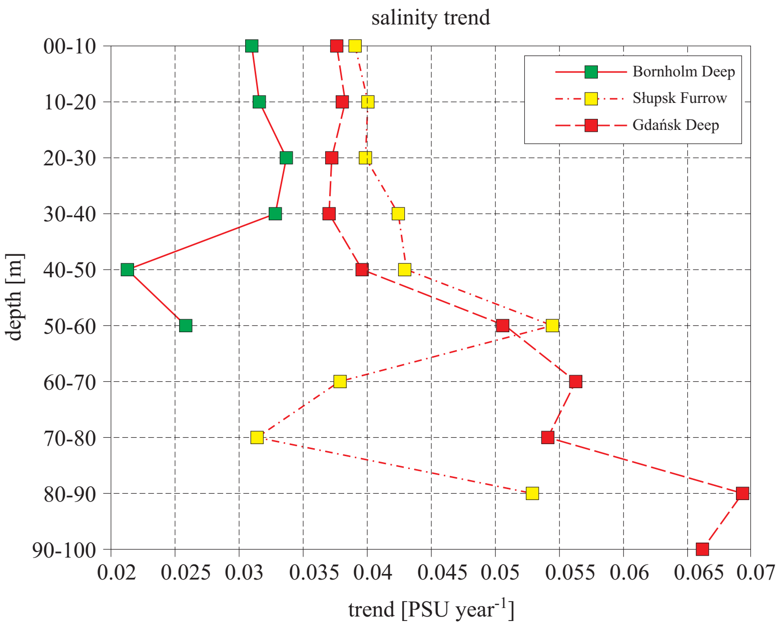

Figure 11. The salinity trend in the waters under investigation

transition and near-bottom layers than at the surface. At the thermocline the salinity trend was 0.5 PSU year^{-1} in SF and GD. In BD the salinity trend was greater at the surface than in the transition layer. In the Gdańsk Basin, on the other hand, the greatest increase of salinity took place in the near-bottom layer, which could have been the effect of a recent strong inflow (Piechura & Beszczyńska-Möller 2004). The results show that regardless of the intensity, inflows increase the salinity trend along the transit axis of inflow waters.

4. Discussion and conclusions

This analysis of three areas in the southern Baltic is complementary to existing knowledge about changes of temperature and salinity in the last 12 years (1998–2010). Technological advances have meant that the data have a very high resolution and are very reliable. Our findings show that temperature is subject to both seasonal and long-term variations. A phase shift of the annual temperature signal was observed in the layer above the halocline, where ocean-atmosphere interaction occurs. This could be due to wind mixing, which modifies the temperature of the upper layer, but only at a depth of about 30–40 m. Convection could also be an important process in the transmission of the signal to the lower layers. The amplitude decreases with depth, which smoothes the seasonal function out.

For the whole period of 1900–1980, the water temperature in all basins has shown a positive trend (Lepperänta & Myrberg 2009). The increase in the surface layer has been of the order of 0.5°C during the last 100 years. The reason is not yet exactly clear, but it is evidently associated with a similar rise in the atmospheric surface layer temperature in the region. Since the 1960s, a reverse trend can be observed (BD is an exception), especially strong in the period 1977–1989 (Cyberska 1994). The present results show that in 1998–2010 there was a positive trend, exceptionally strong at the surface (0.11°C year^{-1}) and in the near-bottom layer (0.16°C year^{-1}). The rise in the water temperature in the near-bottom and transition layers could be due to the increasing impact of small and medium-sized baroclinic inflows (Matthäus & Franck 1992) and to the reduced occurrence of large barotropic inflows, as reported recently by Feistel et al. (2006) and Mohrholz et al. (2006).

The previous decrease in salinity in 1977–1989 (Cyberska 1994) was due to long-term stagnation and occurred after large inflows between 1975–1976 and 1976–1977. This study shows that in 1998–2010, the salinity increased throughout the water column (Figure 8). This could have been caused by an increase in the frequency of small and medium-sized inflows.

This study is important because it extends existing time series of temperature and salinity. The above analysis shows the changes in temperature and salinity that have occurred over the last 12 years in the entire cross-section. The series of measurement is too short to be used to predict future changes. To be able to do this, the time-scale will have to be prolonged. The future work of the authors will be extended by modelling results and available in situ measurements. A combination of these tools should enable temperature and salinity changes to be determined with precision.

References

Beszczyńska-Möller A., 2004, *Dynamika wód wlewowych w Bałtyku Południowym*, Ph.D. thesis, Inst. Oceanology, PAS.

Cyberska B., 1994, *Temperatura wody*, 108–111, [in:] *Atlas Morza Bałtyckiego*, A. Majewski & Z. Lauer (eds.): IMGW, Seria atlasy i monografie, Warszawa, 214 pp.

Elken J., Matthäus W., 2008, *Baltic Sea oceanography*, [in:] *Assessment of climate change for the Baltic Sea basin*, Annex A.1.1, H. von Storch & A. Omstedt (eds.), BALTEX Publ., Springer, Berlin, 474 pp.

Emery W. J., Thomson R. E., 2001, *Data analysis methods in physical ceanography*, Elsevier Sci., Amsterdam, 380–392.

Feistel R., Nausch G., Hagen E., 2006, *Unusual inflow activity in 2002–2003 and varying deep-water properties*, Oceanologia, 48 (S), 21–35.

Feistel R., Nausch G., Mohrholz V., Łysiak-Pastuszak E., Seifert T., Matthäus W., Krüger S., Sehested H. I., 2003, *Warm waters of summer 2002 in the deep Baltic Proper*, Oceanologia, 45 (4), 571–592.

Fonselius S., 1969, *Hydrography of the Baltic Sea deep basin III*, Fishery Board of Sweden, Ser. Hydrogr., 23, 1–97.

HELCOM, 1990, *Second periodic assessment of the state of the marine environment of the Baltic Sea, 1984–88*, Background Doc., Baltic Sea Environ. Proc. No. 35 B, Helsinki Commiss., 432 pp.

Jakobsen F., 1995, *The major inflow to the Baltic Sea during January 1993*, J. Marine Syst., 6 (3), 227–240, http://dx.doi.org/10.1016/0924-7963(94) 00025-7.

Lehmann A., Lorenz P., Jacob D., 2004, *Modelling the exceptional Baltic Sea inflow events in 2002–2003*, Geophys. Res. Lett., 31, L21308, http://dx.doi.org/10.1029/2004GL020830.

Lepperänta M., Myrberg K., 2009, *Physical oceanography of the Baltic Sea*, Springer Praxis, Chichester, 60–125.

Majewski A., Lauer Z. (eds.), 1994, *Atlas Morza Bałtyckiego*, IMGW, Ser. Atlasy Monogr., Warszawa, 214 pp.

Matthäus W., Franck H., 1992, *Characteristics of major Baltic inflows – a statistical analysis*, Cont. Shelf Res., 12 (12), 1375–1400, http://dx.doi.org/10.1016/0278-4343(92)90060-W.

Matthäus W., Lass H. U., 1995, *The recent salt inflow into the Baltic Sea*, J. Phys. Oceanogr., 25, 280–286. http://dx.doi.org/10.1175/1520-0485(1995) 025<0280:TRSIIT>2.0.CO;2.

Mikulski Z., 1982, *River inflow to the Baltic Sea 1921–1975*, PAS, Polish Natl. Committ. IHP, Univ. Warsaw, Fac. Geogr. Reg. Stud., (mimeo).

Mikulski Z., 1987, *Podział regionalny Morza Bałtyckiego*, [in:] *Bałtyk Południowy*, B. Augustowski (ed.), Gdańskie Tow. Nauk., Ossolineum, Wrocław, 41–51.

Meier H. E. M., Feistel R., Piechura J., Arneborg L., Burchard H., Fiekas V., Golenko N., Kuzmina N., Mohrholz V., Nohr C., Paka V. T., Sellschopp J., Stips A., Zhurbas V., 2006, *Ventilation of the Baltic Sea deep water: A brief review of present knowledge from observations and models*, Oceanologia, 48 (S), 133–164.

Mohrholz V., Dutz J., Kraus G., 2006, *The impacts of exceptionally warm summer inflow events on the environmental conditions in the Bornholm Basin*, J. Marine Syst., 60 (3–4), 285–301, http://dx.doi.org/10.1016/j.jmarsys.2005.10.002.

Omstedt A., 1990, *Modelling the Baltic Sea as thirteen sub-basins with vertical resolution*, Tellus A, 42 (2), 286–301, http://dx.doi.org/10.1034/j.1600-0870.1990.00006.x.

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.

Reissmann J., Burchard H., Feistel R., Hagen E., Lass H. U., Mohrholz V., Nausch G., Umlauf L., Wieczorek G., 2009, *Vertical mixing in the Baltic Sea and consequences for eutrophication – A review*, Progr. Oceanogr., 82, 47–80, http://dx.doi.org/10.1016/j.pocean.2007.10.004.

Reynolds R. W., Rayner N. A., Smith T. M., Stokes D. C., Wang A., 2002, *An improved in situ and satellite SST analysis for climate*, J. Climate, 15 (13), 1609–1625, http://dx.doi.org/10.1175/1520-0442(2002)015<1609:AIISAS>2.0.CO;2.

Appendix

Table 2. Seasonal changes of temperature in the surface layer of the Bornholm Deep

Thickness [m]	Mean	Standard deviation	T_{max}	Day of the year	T_{min}	Day of the year	Peak amplitude
0–10	9.38	5.61	18.8	249	2.42	115	16.38
10–20	9.01	5.16	17.57	255	2.46	110	15.1
20–30	7.54	3.53	12.65	273	2.50	107	10.15

Table 3. Seasonal changes of temperature in the surface layer of the Słupsk Furrow

Thickness [m]	Mean	Standard deviation	T_{max}	Day of the year	T_{min}	Day of the year	Peak amplitude
0–10	9.46	5.73	18.75	249	2.32	113	16.42
10–20	8.8	5.07	17.28	268	2.39	101	14.89
20–30	7.46	3.87	14.25	285	2.36	98	11.88
30–40	5.8	2.53	10.52	320	2.5	108	8.01

Table 4. Seasonal changes of temperature in the surface layer of the Gdańsk Deep

Thickness [m]	Mean	Standard deviation	T_{max}	Day of the year	T_{min}	Day of the year	Peak amplitude
0–10	9.77	5.85	18.9	254	2.49	116	16.4
10–20	9.15	5.29	17.63	264	2.63	110	15
20–30	7.7	4.11	14.69	285	2.7	103	11.98
30–40	6.13	2.96	11.74	316	2.75	112	8.98