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Long-term variability of water temperature and salinity at the Polish coast

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Abstract. The variability of surface water temperature and water salinity at the south coast of the Baltic in the years 1950–2015 was studied in the article. To that aim, monthly surface water temperature values in Świnoujście, Międzyzdroje, Kołobrzeg (from 1957), Władysławowo, Hel and Gdynia were used, as well as monthly water salinity values in Międzyzdroje, Władysławowo, Hel and Gdynia, all obtained from IMGW-PIB (Institute of Meteorology and Water Management – National Research Institute). Linear regression and Pearson's simple correlation coefficient of individual monthly, seasonal and annual series of temperature and salinity values over time (in subsequent years) were used to analyse the temporal changes of the examined parameters. In the analysed period a rise in the annual water temperature was recorded in Międzyzdroje, Władysławowo, Hel and Gdynia, while the extent of the changes increased towards the east. There were also positive trends in temperature values in individual months. At the same time, there was a decrease in water salinity, which was also found to be most distinct in the eastern part of the coast. In Władysławowo, Hel and Gdynia, statistically significant drops occurred in nearly all months. During the months featuring statistically insignificant trends, the observed change trends were also negative. Concurrent water temperature increases and water salinity decreases consequently caused a decline in sea water surface density at the Polish Baltic coast.

Key words:
water temperature,
salinity,
Pomeranian Bay,
Gdańsk Bay,
trends

Introduction

The objective of the paper involved examining the variability of sea water temperature and sea water salinity at the Polish coast of the Baltic in individual months, seasons of the year and their annual values from the mid-20th century until 2015.

Changes in both sea water temperature and salinity have a strong impact on the development of life. A rise in temperature results in a series of bio-chemical changes occurring in the depths of the sea, *inter alia*, a reduction in the amount of dissolved oxygen with a simultaneous spike in biological demand for oxygen, which contributes to an oxygen deficit in the water. When changes occur too rapidly, they became a serious problem for living organisms, since by forcing the organisms to adapt to new conditions they frequently cause population size reduction or even a complete disappearance of a certain species. A rise in temperature results in a series of other processes that are unfavourable to the marine environment, such as phytoplankton growth, causing excessive eutrophication of water reservoirs (Siegel et al. 2008), as well as the multiplication of toxic blue-green algae (Strömer 2011). Furthermore, water salinity plays an exceptionally significant role in the marine ecosystem. Some species need a strictly specific salinity level during certain life stages (the BACC Author Team

2008). Currently, the majority of species living in the Baltic are experiencing physiological stress, because the water is too fresh for typically marine species, while at the same time it is too salty for fresh water species (Meier et al. 2006). Moreover, as a result of diminished salinity and a simultaneous water temperature increase, foreign (non-native; Strömer 2011) species are being introduced. The most drastic changes in the environment of deep Baltic waters were observed in the 1980s, when inflows of heavily salinised and oxygenated oceanic waters were not recorded (Matthäus 1995).

Water temperature and its salinity, and consequently its density, additionally determine vertical and horizontal circulatory movements of sea water. Moreover, a rise in surface water temperature causes an upsurge of precipitation in the summer in the entire Baltic Sea through the intensification of the processes related to water circulation in the natural environment, particularly in the summer, as shown in research conducted by Kjellström et al. (2005). The variability of water temperature, and to a lesser degree of salinity, further changes the surface, thickness and form of sea icing, which in turn affects navigation and fishing conditions (Girjatowicz 1983; Zakrzewski 1983).

On account of the natural and economic importance of salinity and temperature variability of the Baltic waters, *inter alia*, in order to identify and understand the processes that determine them, a huge international BALTEX research project, i.e. the Baltic Sea Experiment, was conducted (Omstedt et al. 2004; the BACC Author Team 2008; the BACC II Author Team 2015), concerning, among other things, the variability of the physical properties of sea water and the related water circulation, but it also involved forecasts of future changes (Meier 2015). At present, the programme operates under the modified name "Baltic Earth" (https://www.baltic-earth.eu). The monographs edited by Wulff, Rahn and Larsson (2001) and by Leppärant and Myrberg (2009) contributed substantially to learning about the salinity and temperatures of the Baltic waters.

The rise in Baltic water temperature relates to an air temperature increase in the Baltic Sea Basin. The greatest changes concern the Bothnian Sea and the northern section of the Baltic Proper, although water temperature rises are also observed in the more southern part of the Baltic – in the Arkona Sea and the Gotland Sea, particularly in August and in September (an increase of 1.5°C per decade in the period of 1990–2004; Siegel et al. 2006). What is more, it was observed that water temperature in the halocline in the Bornholm Sea during the years 1989–2004 was 1°C higher than in 1950–2004 (Elken et al. 2015).

In the past the salinity of the Baltic waters was strongly affected by inflows of salty oceanic waters from the North Sea (major Baltic inflows). In the Gotland Sea it was high from the early 1950s on account of a stronger oceanic inflow in 1951. Following that, salinity remained at a fairly stable level, reaching a local minimum in 1978. In 1993 the drop in salinity was halted by a very powerful salty water inflow (Leppäranta and Myrberg 2009). Generally, a rise in rainfall in the Baltic Sea basin and less frequent oceanic inflows have resulted in a year-to-year decrease in the salinity of the central Baltic waters (Matthaäus et al. 2008; Leppäranta and Myrberg 2009; Elken et al. 2015).

Not only were studies carried out on the previous variability of the physical properties of the sea waters in the Baltic, but attempts were also made to modernise and forecast future changes (Meier 2015). Changes in temperatures and salinity were modelled, among other things, in the Baltic Proper and the Kattegat waters as a transition zone between the Baltic and the North Sea (Omstedt and Axell 1998) as well as in the Gulf of Bothnia, the Gulf of Finland and the Gulf of Riga (Omstedt and Axell 2003).

The information on the variability of water temperature and salinity on the southern shores of the Baltic can be found, *inter alia*, in monographs dedicated to hydrological and meteorological conditions of the Pomeranian Bay (Majewski 1974), the Bay of Gdansk (Młodzińska 1974; Cyberska 1990) and the remaining waters of the southern Baltic (Schernewski et al. 2011). The variability of water temperature on the Polish coast during the years 1947–1993 was researched by Girjatowicz and Chabior (1995). It was also studied at selected stations of the Polish coast within the scope of IMGW KBN 5 Research Project as task 5.4b (Miętus et al. 2003). The variability of water salinity and temperature in the southern portion of the Baltic was studied by, *inter alia*, Rak and Wieczorek (2012) demonstrating a growth in surface water temperature, as well as a drop in salinity in that region. They justified the growth in surface water temperature by a spike in air temperature and a decrease in salinity due to waning oceanic water inflows into the Baltic. Variations in sea water temperatures at selected seaside locations were described in a paper by Świątek (2016), where slight increases in annual average surface water temperature were determined at certain locations on the Polish Baltic coast, particularly in Gdynia. The year-to-year variability of salinity on the southern shores of the Baltic is mentioned in the works of Piechura (1974), Cyberska (1994) and Girjatowicz (2008a), who demonstrated slight salinity increases in that region. A distinct decline in salinity on the Polish coast was determined, particularly within the region of Hel, in the period 1950–2012, where a negative salinity trend was found to be significant even at the level of α=0.001 (Girjatowicz 2017).

Materials and methods

Monthly water surface temperatures in the years 1950–2015 at the stations located along the Polish part of the Baltic coast – in Świnoujście, Międzyzdroje, Kołobrzeg (from 1957 onwards, due to lack of data), Władysławowo, Hel and Gdynia were used in the paper along with monthly water salinity values in Międzyzdroje, Władysławowo, Hel and Gdynia. The locations of the measurement stations are presented in Figure 1. The data were obtained from hydrographic yearbooks, while some were provided directly by IMGW-PIB (Institute of Meteorology and Water Management – National Research Institute). Temperature and salinity measurements were taken at the same sites every day at 06:00 UTC at a depth of 0.5m. At those sites the depth of the bottom reached several metres. In Świnoujście the measurement apparatus is situated in the harbour canal, and in Międzyzdroje and Kołobrzeg at the pier, while in Władysławowo, Hel and Gdynia it is at the breakwater sheltering the harbour basin, on the seaward side.

The long-term variability of water temperature and salinity was described with the use of standard deviation. Linear regression and the correlation of individual series of water temperature and salinity over time (subsequent years) were employed to analyse the changes in the examined parameters, in line with the formulae: (t) water temperature = A* time + B; and (s) water salinity = A* time + B. Statistical significance was determined

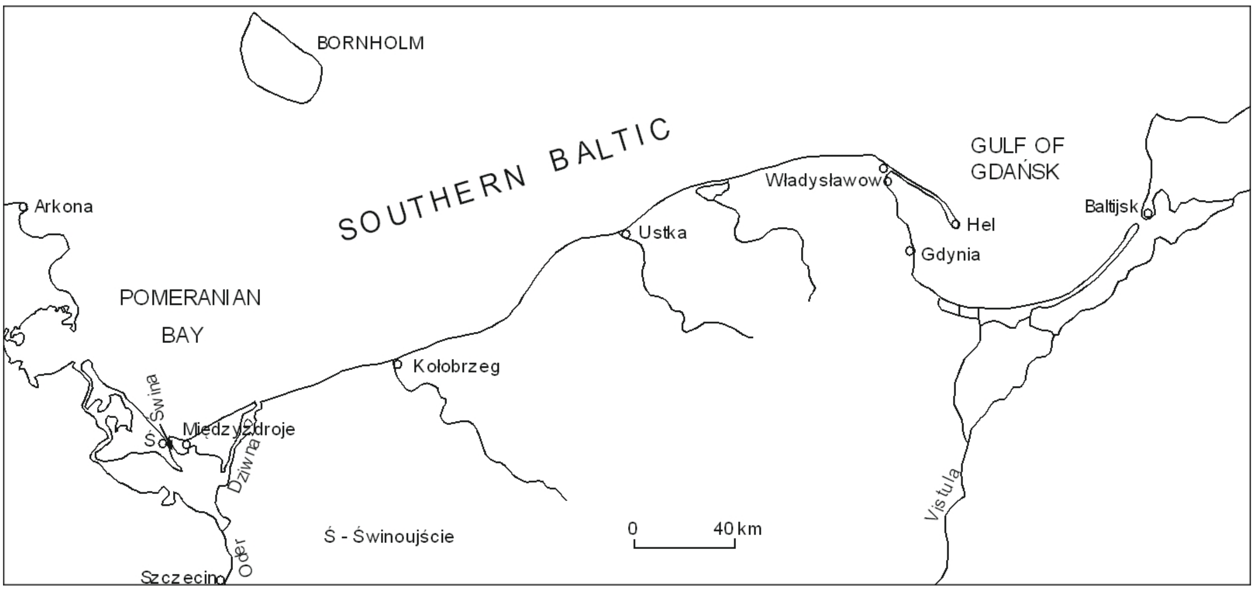

Fig. 1. Location of the stations providing the data used in the article

with the use of Fisher–Snedecor test (Time series analysis…, 2010).

Results

The highest temperatures of surface water in all seasons of the year except for winter were recorded in Świnoujście, while the lowest were in Władysławowo, i.e. in the open sea (Table 1). Międzyzdroje features the greatest variability of long-term values of both water temperature and water salinity. The variability of water temperature at all stations and in all months is similar – the values of standard deviations range around 1°C. The greatest variability of surface water temperature occurs at the central and eastern coast in the summer, which involves year-to-year oscillations in the frequency of upwellings cooling down the coastal waters, whereas in Świnoujście and in Międzyzdroje it occurs in March, which may result from high sensitivity of those relatively shallow water bodies to air temperature oscillations, while in spring thermal contrasts are particularly significant on the Polish coast. At the remaining stations a second (local) maximum is observed in March.

The long-term variability of salinity is lower and more spatially and temporally varied. Although the greatest variability of water temperature occurs in different seasons, the greatest variability of salinity at each station occurs in winter – in Międzyzdroje in February, in Władysławowo and Gdynia in De-

Table. 1. Standard deviations (SD) and average values (A) of surface water temperature (t) and salinity (s) at selected stations of the Polish coast of the Baltic, years 1950-2015

Period		Świnoujście	Międzyzdroje		Kołobrzeg (1957-2015)	Władysławowo		Hel		Gdynia	
		t [°C]	t [°C]	s [PSU]	t [°C]	t [°C]	s [PSU]	t [°C]	s [PSU]	t [°C]	s [PSU]
Jan	SD	0.94	1.17	0.60	1.28	1.14	0.25	1.15	0.71	1.13	0.49
Feb	SD	0.96	1.11	0.80	1.18	1.12	0.27	1.10	0.38	1.15	0.36
Mar	SD	1.51	1.54	0.73	1.35	1.33	0.27	1.31	0.36	1.31	0.31
Apr	SD	1.39	1.33	0.68	1.05	1.05	0.26	1.17	0.41	1.38	0.38
May	SD	1.13	1.41	0.64	1.07	1,00	0.21	1.38	0.39	1.54	0.44
Jun	SD	1.10	1.06	0.63	1.04	1.16	0.20	1.35	0.33	1.44	0.38
Jul	SD	1.32	1.32	0.51	0.96	1.09	0.22	1.22	0.31	1.69	0.35
Aug	SD	1.11	1.15	0.50	1.42	1.34	0.20	1.11	0.25	1.31	0.32
Sep	SD	1.12	1.12	0.57	0.93	0.99	0.24	0.93	0.25	0.96	0.20
Oct	SD	1.07	1.01	0.57	1.04	1.13	0.23	0.91	0.30	0.96	0.21
Nov	SD	1.07	0.99	0.49	0.97	1,00	0.23	0.90	0.30	1.12	0.22
Dec	SD	1.12	1.14	0.54	1.18	1.09	0.35	1.02	0.60	1.06	0.55
Dec-	SD	0.76	0.89	0.55	1.01	0.90	0.24	0.90	0.45	0.88	0.36
-Feb	*A*	*1.70*	*1.71*	*6.74*	*2.16*	*1.95*	*7.48*	*2.54*	*7.27*	*2.14*	*7.31*
Mar-	SD	1.05	1.26	0.56	1.02	1,00	0.22	1.14	0.30	1.20	0.29
-May	*A*	*7.78*	*7.01*	*6.34*	*6.52*	*5.98*	*7.49*	*5.98*	*7.18*	*6.27*	*7.17*
Jun-	SD	0.82	0.90	0.44	0.81	0.94	0.19	0.90	0.26	1.04	0.28
-Aug	*A*	*18.56*	*17.87*	*6.37*	*16.58*	*16.09*	*7.40*	*16.69*	*7.16*	*17.41*	*7.09*
Sep-	SD	0.79	0.82	0.42	0.64	1.71	0.20	0.72	0.23	0.74	0.19
-Nov	*A*	*11.26*	*11.17*	*6.61*	*11.02*	*10.64*	*7.33*	*11.85*	*7.25*	*11.41*	*7.23*
Year	SD	0.55	0.68	0.36	0.62	0.64	0.18	0.66	0.23	0.65	0.22
Year	*A*	*9.83*	*9.45*	*6.52*	*9.07*	*8.68*	*7.43*	*9.18*	*7.23*	*9.32*	*7.21*

Grey background marks the largest standard deviation at a given station cember, and in Hel in January (Table 1), which are affected by major Baltic flows occurring from time to time, chiefly in winter. In turn, the smallest salinity oscillations occur in summer, when the number of storms that may cause major Baltic inflows is the lowest.

In the analysed period a rise in annual water temperature values was observed simultaneously with a decline in salinity, which consequently caused a decrease in the density of surface sea water, since warmer water has a lower density than cooler water does, while fresher water has lower density than saltier water. Growing temporal trends of temperature and salinity (decreasing), which were statistically significant, occurred in the eastern part of the Polish coast – in Władysławowo (Fig. 2), in Hel (Fig. 3) and in Gdynia (Fig. 4). The greatest change in water temperature was demonstrated in Gdynia, and in salinity in Hel. In Międzyzdroje there was a statistically significant upsurge in water temperature (Table 2), whereas salinity did not change significantly (Table 3).

The statistically significant growth in annual water temperatures at individual stations ranged between 0.11 and 0.18°C per ten years (Table 2). The intensity of changes grew towards the east – the greatest being recorded in Gdynia, where the trend of changes described with a regression coefficient was the strongest. The statistically significant decreasing trend of annual salinity of surface water ranged between 0.04 and 0.08 PSU per ten years, and was found to be strongest in Hel (Table 3).

The greatest simultaneous increases in monthly and seasonal water temperature values and drops in salinity were found for Hel and Gdynia in spring and summer (Table 2 and Table 3). An exceptionally strong decreasing trend of water salinity related to the January values in Hel (Fig. 5), at -0.17 PSU per decade. Such a strong decreasing trend resulted from very low salinity over the course of several years at the end of the research period, namely in 1996, 1999, 2004, 2006, 2010 and 2012, when salinity dropped below 6 PSU (with an average for Hel during the examined period in January equal to 7.22 PSU), which resulted from the lack of intensive oceanic water inflows, which previously, prior to 1990, had occurred relatively frequently in January. In the years of 2004 and 2010 salinity dropped even below 5 PSU, respectively to 4.57 and 4.89 PSU

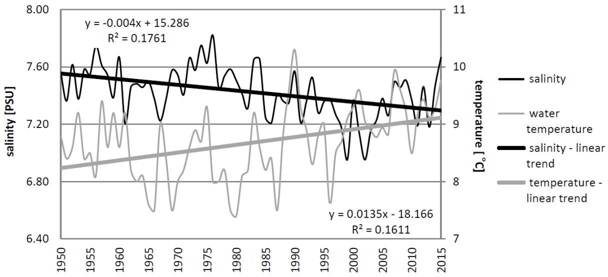

Fig. 2. Annual values of salinity and surface water temperature in Władysławowo (1950–2015) along with a linear regression line – temporal trend, equation of the regression line (y) along with determination coefficient (R^2)

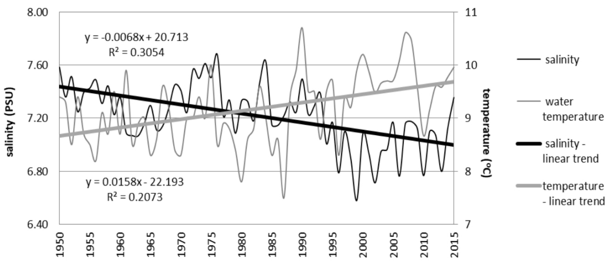

Fig. 3. Annual values of salinity and surface water temperature in Hel (1950–2015) along with a linear regression line – temporal trend, equation of the regression line (y) along with determination coefficient (R^2)

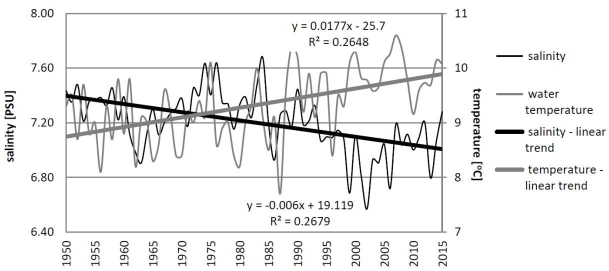

Fig. 4. Annual values of salinity and surface water temperature in Gdynia (1950–2015) along with a linear regression line – temporal trend, equation of the regression line (y) along with determination coefficient (R^2)

(Fig. 5). An exceptionally low salinity level was recorded in Hel in December 1996 (4.70 PSU). In the remaining months and at other analysed stations, deviations from the average values were not as substantial. An increase in water temperate at the time was not significant, while the level of temporal trend significance in December amounted to α=0.076 in Hel (Table 2).

The greatest water temperature growth occurred in April and May, as well as on average in the spring in Hel and Gdynia. In those months and in the spring the pace of changes at these stations was approximately 0.03°C *per annum*, which translates into a temperature rise of as much as 3°C per century. The greatest declines in monthly salinity values also concerned Hel and Gdynia, in winter months in particular, and especially in January (Table 3). They were, similarly to annual values, statistically significant even at the level of $\alpha<0.001$. During the months featuring statistically insignificant trends, the observed change patterns were also negative. Decreases in salinity concerning monthly, seasonal and annual values were within the range of a thousandth of a PSU. Only the salinity drops recorded in wintertime (Dec–Feb) and in January and in December amount to more than 0.1 PSU per decade.

When analysing Table 3, it is worth noting the fact that variations in salinity levels in Władysławowo in May and October were significant at the level of $\alpha=0.052$, thus nearly at the level of 0.05, which, as a norm, is assumed to be the level of statistical significance in scientific papers.

In order to verify the similarity of the variability of long-term surface water temperature and salinity at individual stations, respective annual values of temperature (Table 4) and salinity (Table 5) at the examined stations were compared to one another. Correlation coefficients between annual values of both temperature and salinity at all stations were significant at the level of $\alpha<0.05$, which demonstrates very close change trends between the two parameters. Of course, the data from the nearest-lying stations showed the greatest similarities. The most intensive differences in changes were found on the western coast. In terms of temperature, Świnoujście diverged most significantly from the remaining stations, and in terms of salinity it was Międzyzydroje (no data were available for Świnoujście). The lowest correlation coefficient existed between salinity in Międzyzdroje and salinity in Gdynia, equalling 0.59 (Table 5).

Discussion

The water temperature increases in a majority of the stations on the Polish coast examined in this paper relate to the changes observed in other parts of the Baltic, *inter alia*, in its central portion (Matthaäus et al. 2008; Leppäranta and Myrberg 2009; Elken et al. 2015) as well as in the Arkona Sea (Siegel et al. 2006) and in the southern part of the Baltic (Rak and Wieczorek 2012).

The main reason for the water temperature rise on the Polish shores of the Baltic was a rise in air temperature over the Baltic and its catchment area (Filipiak 2004; Omstedt et al. 2004; Biernacik et al. 2010), compounded by the effects of global changes. The analyses of changes in the global surface temperature, taking into account both surface water temperature of seas and oceans, and that of the land up to a land depth of 1.5m (Jones and Moberg 2003), demonstrated a particularly distinct temperature rise from the 1970s onwards, while in the northern hemisphere this rise was 0.7°C higher than in the southern hemisphere. Even more evident positive water temperature trends have been observed since 1990 (Siegel et al. 2008). Not everywhere is the relation between air and water temperature equally strong. In the Baltic regions that feature the greatest dynamics in terms of circulation, i.e. in the areas where currents or exceptionally strong water circulation appear, those relations are relatively small (Bradtke et al. 2010).

A spike in water temperature at the majority of analysed stations is linked to an increase in air temperature in individual seasons of the year. Positive trends of annual and certain monthly temperature values were observed on the Polish Baltic coast at individual stations (the years 1951–2010). Statistically significant increases were recorded in February, in spring months, and in July and August. The most significant spikes in monthly air temperature values were observed in spring months – in April (Szczecin, Świnoujście and Elbląg) and in May (Hel and Gdynia). In Ustka (central coast) the strongest air temperature growth took place in August, but it exceeded the April temperature rise only very slightly (Świątek 2013). Those changes translate into analogous water temperature rises. Only in Świnoujście were no water temperature variations observed, despite a change in air temperature. Overall, the course of changes in water temperature in Świnoujście was decidedly different from the remaining stations. This results from the fact that the measurement point is located in the estuarial section of the Świna River. Temperature values were largely impacted by wind direction and water levels determining the inflow of waters from the open sea or from the Szczecin Lagoon. These reservoirs

Table 2. Regression coefficient (b) and significance level (α) of water temperature (°C) over time (temporal trends) at the selected stations of the Polish Baltic coast, the years 1950-2015

Period		Świnoujście	Międzyzdroje	Kołobrzeg (1957-2015)	Władysławowo	Hel	Gdynia
Jan	b	0.0081	0.0137	0.0242	0.0201	0.013	0.0124
	α	*0.199*	*0.0759*	*0.0135*	*0.00522*	*0.0759*	*0.0906*
Feb	b	0.0027	0.014	0.0101	0.0129	0.0144	0.011
	α	*0.69*	*0.0523*	*0.257*	*0.0759*	*0.0429*	*0.1481*
Mar	b	0.01	0.0249	0.0151	0.216	0.0236	0.0248
	α	*0.298*	*0.0113*	*0.1495*	*0.01131*	*0.00522*	*0.002988*
Apr	b	0.0168	0.0245	0.0041	0.0187	0.0271	0.0315
	α	*0.0632*	*0.00397*	*0.5983*	*0.00522*	*0.000218*	*0.00015*
May	b	0.0061	0.0262	0.0049	0.0145	0.0322	0.0378
	α	*0.424*	*0.00397*	*0.547*	*0.02279*	*0.000218*	*0.00015*
Jun	b	-0.0115	0.0078	0.0139	0.025	0.0143	0.0131
	α	*0.107*	*0.2622*	*0.0797*	*0.000629*	*0.107381*	*0.17236*
Jul	b	-0.0025	0.0092	-0.009	0.0076	0.0209	0.0295
	α	*0.749*	*0.298*	*0.2261*	*0.2982*	*0.008811*	*0.00681*
Aug	b	0.0078	0.0126	0.0031	0.0118	0.0164	0.024
	α	*0.2982*	*0.0906*	*0.7636*	*0.17236*	*0.02279*	*0.00397*
Sep	b	-0.0023	-0.0022	-0.00107	0.0012	0.0128	0.0144
	α	*0.75*	*0.7498*	*0.1288*	*0.87336*	*0.035*	*0.018179*
Oct	b	-0.0008	-0.0025	-0.0093	-0.0009	0.0039	0.0026
	α	*0.936*	*0.6901*	*0.2568*	*0.87336*	*0.5231*	*0.6901*
Nov	b	0.0086	0.0016	0.0171	0.013	0.0068	0.0038
	α	*0.229*	*0.811*	*0.021*	*0.0429*	*0.2622*	*0.6517*
Dec	b	0.0031	0.0061	0.0186	0.014	0.0083	0.0058
	α	*0.69*	*0.4244*	*0.0386*	*0.0429*	*0.2261*	*0.4244*
Dec-Feb	b	0.0037	0.0107	0.0167	0.0152	0.0115	0.0093
	α	*0.472*	*0.0759*	*0.0317*	*0.008811*	*0.05226*	*0.107*
Mar-May	b	0.011	0.0252	0.0078	0.0185	0.0274	0.0314
	α	*0.107*	*0.00165*	*0.3264*	*0.0003967*	*0.000102*	*0.000019*
Jun-Aug	b	-0.0021	0.0099	0.0026	0.0152	0.0172	0.0221
	α	*0.69*	*0.0906*	*0.6517*	*0.01131*	*0.02988*	*0.000629*
Sep-Nov	b	0.0019	-0.001	-0.0008	0.0045	0.0078	0.0068
	α	*0.75*	*0.8734*	*0.8805*	*0.33719*	*0.0906*	*0.148113*
Year	b	0.0035	0.0113	0.0068	0.0135	0.0158	0.0177
	α	*0.33719*	*0.000314*	*0.149483*	*0.000876*	*0.000102*	*0.000012*

Grey background marks statistically significant coefficients at the level of α<0.05

Table 3. Regression coefficient (b) and significance level (α) of salinity (PSU) over time (temporal trends) at the selected stations of the Polish Baltic coast, the years 1950-2015

Period		Międzyzdroje	Władysławowo	Hel	Gdynia
Jan	b	-0.0054	-0.0056	-0.017	-0.0108
	α	*0.17236*	*0.000314*	*0.000068*	*0.000447*
Feb	b	-0.0074	-0.0041	-0.0089	-0.0057
	α	*0.148113*	*0.018179*	*0.00015*	*0.01439*
Mar	b	-0.0041	-0.005	-0.0026	-0.0042
	α	*0.3793*	*0.0003967*	*0.0759*	*0.0429*
Apr	b	-0.0014	-0.0044	-0.0069	-0.0033
	α	*0.75*	*0.0008811*	*0.018179*	*0.2261*
May	b	-0.0019	-0.0026	-0.0062	-0.0066
	α	*0.6517*	*0.0523*	*0.018179*	*0.02279*
Jun	b	-0.0024	-0.0027	-0.0049	-0.0042
	α	*0.5983*	*0.035*	*0.0759*	*0.0906*
Jul	b	0.0011	-0.0023	-0.0067	-0.0062
	α	*0.749*	*0.0906*	*0.00223*	*0.00522*
Aug	b	-0.0019	-0.0025	-0.0058	-0.0045
	α	*0.5983*	*0.0797*	*0.001208*	*0.0386*
Sep	b	-0.0019	-0.0026	-0.0048	-0.0054
	α	*0.6517*	*0.107*	*0.01439*	*0.000019*
Oct	b	-0.0041	-0.0028	-0.0058	-0.0047
	α	*0.2622*	*0.0523*	*0.008811*	*0.000447*
Nov	b	-0.0003	-0.0043	-0.0053	-0.0043
	α	*0.9365*	*0.029888*	*0.01439*	*0.000223*
Dec	b	0.0038	-0.0086	-0.0127	-0.0123
	α	*0.2982*	*0.000102*	*0.006811*	*0.000314*
Dec-Feb	b	-0.0057	-0.0074	-0.014	-0.0099
	α	*0.107*	*0.00003*	*0.000008*	*0.000012*
Mar-May	b	-0.0025	-0.004	-0.0052	-0.0047
	α	*0.547*	*0.003967*	*0.003967*	*0.01439*
Jun-Aug	b	-0.0011	-0.0025	-0.0058	-0.005
	α	*0.69*	*0.0429*	*0.02988*	*0.00922*
Sep-Nov	b	-0.0021	-0.0032	-0.0053	-0.0048
	α	*0.424*	*0.01439*	*0.00165*	*0.000068*
Year	b	-0.0028	-0.004	-0.0075	-0.006
	α	*0.229*	*0.000447*	*0.00002*	*0.000008*

Grey background marks statistically significant coefficients at the level of α<0.05

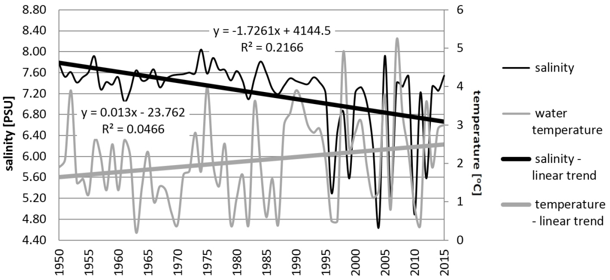

Fig. 5. Monthly values of salinity and surface water temperature in Hel (1950–2015) in January along with a linear regression line – temporal trend, equation of the regression line (y) along with determination coefficient (R2)

feature different thermal characteristics in individual seasons.

The occurrence of an upwelling phenomenon in the region affected the specificity of the long-term variability in surface water temperature in Kołobrzeg (cf. Kowalewski and Ostrowski 2005; Krężel at al. 2005). The specific bathymetry of the sea floor and the relatively great depth of the reservoir not far offshore favour the appearance of that phenomenon – upwelling occurs at the edge of the shallows (threshold). This type of phenomenon can be observed in the region of Władysławowo and Hel as well. Most likely, it was precisely this more active upwelling that showed up in the values of temperature standard deviation, particularly in August at both stations. The most active upwellings also occur on the Polish shores along the Hel Spit on the seaward side (in this paper the analyses involved water temperature from the side of the Bay of Puck). The frequency of occurrence of upwellings featuring speeds exceeding $10^{-4}ms^{-1}$ is greatest in March and September in that location, when the probability of upwelling occurrence is more than 30%. In Kołobrzeg the frequency of upwelling appearance shows little differentiation and is slightly more differentiated in spring and early autumn. In those seasons, the likelihood of an intensive upwelling (higher than $10^{-4}ms^{-1}$) occurs there on approximately 20% of days, while a weak upwelling (lower than $10^{-4}ms^{-1}$) is likely in slightly fewer than 50% of cases (Kowalewski and Ostrowski 2005). Irrespective of the speed of water shifting, the greatest impact on the change of coastal water temperature is exerted by the occurrence of such types of phenomena in the summer, when the difference between surface water and deep-sea water is greatest.

Table 4. Correlation coefficients of yearly water temperature (°C) between selected stations of the Polish Baltic coast, the years 1950-2015

	Świnoujście	**Międzyzdroje**	**Kołobrzeg ***	**Władysławowo**	**Hel**	**Gdynia**
Świnoujście	1	0.8362	0.7716	0.6561	0.7677	0.7585
Międzyzdroje	0.8362	1	0.8536	0.8517	0.9081	0.8949
Kołobrzeg *	0.7716	0.8536	1	0.829	0.8781	0.8074
Władysławowo	0.6561	0.8517	0.829	1	0.8955	0.8725
Hel	0.7677	0.9081	0.8781	0.8955	1	0.9509
Gdynia	0.7585	0.8949	0.8074	0.8725	0.9509	1

all coefficients are significant at the level α<0.01, * 1957-2015

Table 5. Correlation coefficients of yearly water salinity (PSU) between selected stations of the Polish Baltic coast, the years 1950-2015

	Międzyzdroje	**Władysławowo**	**Hel**	**Gdynia**
Międzyzdroje	1	0.6613	0.6651	0.5901
Władysławowo	0.6614	1	0.8136	0.8117
Hel	0.6651	0.8136	1	0.9234
Gdynia	0.5900	0.8117	0.9234	1

all coefficients are significant at the level α<0.01

A rise in the frequency of anticyclonic circulation and of a positive North Atlantic Oscillation (NAO) phase, which occurred particularly frequently within the last fifteen years of the 20th century, affected the increase in water temperature values to a certain degree (Omstedt et al. 2004). The NAO exerts the greatest impact on hydrological conditions in the Baltic Sea basin, *inter alia* on surface water temperature at the Polish Baltic coast, in winter when differences in the oscillation values are the most significant (Girjatowicz 2008b). At the same time, in winter the relatively low variability in water temperature is caused by the limit on it dropping below the sea-water freezing point, which at the Polish coast ranges between -0.3 and -0.4°C with an average salinity of about 7 PSU.

According to Neumann and Friedland (2011), the main reason for the thermal changes observed within the region of the Baltic Sea basin is anthropogenic factors, chiefly a rise in greenhouse gas emissions and their concentration in the atmosphere. This has a particularly significant impact in the case of the strongly industrialised area of the Baltic Sea basin (Heino et al. 2008; Neumann and Friedland 2011). The scenarios of climate change developed by the IPCC (Intergovernmental Panel on Climate Change) and describing the economic development affecting greenhouse gas emissions predict a rise in average annual temperature in Poland of nearly 3°C in 2050 in comparison to the base period of 1961–1990, while in the north of Poland it will be slightly lower (Kundzewicz 2010).

A gradual decline in the Baltic Sea salinity that started in the mid-1970s has been observed by many researchers (Matthäus 1995; Samuelsson 1996; Zorita and Laine 2000). It was especially noticeable in the 1980s (Meier and Kauker 2003). Freshening of the surface waters at the southern shores of the Baltic ought to be linked chiefly to inflows of oceanic waters into the Baltic waning (in both frequency and intensity) (Cyberski 2002; Rak and Wieczorek 2012; Elken et al. 2015). The decrease in sea water salinity at the Polish coast started in the early 1950s and lasted until the end of the 20th century, particularly after 1982 (Matthäus 2006). Declining salinity trends were significantly affected by, *inter alia*, a very strong inflow of salty waters through the Danish Straits in 1951, contributing to a relatively high salinity level in the Baltic at the beginning of the measurement period (Winsor et al. 2001; Matthäus 2006). On account of the fact that the influxes of salty waters from the North Sea normally occur in winter, accompanying the storms that are strongest at the time, changes in salinity are chiefly observed in the winter months, and the largest ones are recorded in January. The significance of oceanic inflows in shaping the salinity at the Polish Baltic coast is evidenced by the fact that in the 1950s and 1970s, when major Baltic inflows were occurring relatively frequently (Matthäus and Schinke 1994), water salinity at the Polish coast was fairly high. In the period from February 1983 until the beginning of 1993, when there were no inflows (apart from very weak, sporadic ones; Matthäus and Schinke 1994; Schinke and Matthäus 1998), water salinity in the examined body of water was systematically falling. It is noteworthy that regular inflows have a greater impact than singular, very strong ones do. Even the very powerful inflows of January 1993 (Jakobsen 1995) or January 2003 (Meier et al. 2004) are not reflected in particularly high salinity rises at individual stations on the Polish Baltic coast.

The salinity of sea waters at the coast is further determined by the inflow of fresh river waters (and underground waters) from the land. A rising river outflow makes sea waters fresher, while a decreasing outflow contributes to the growth in their salinity. The trend of the Vistula river outflow in the period 1951–2010 was statistically insignificant, although the value showed a growing trend. The trend of the Oder river outflow was also insignificant (with an increasing trend; Girjatowicz and Świątek 2016). River outflow had a substantial impact on the changes in water salinity in other regions of the Baltic. At the beginning of the 1970s, a growth in the volume of river outflow from the Baltic was already being noted (Matthäus and Schinke 1999; Pawlak and Leppänen (ed.) 2007), particularly from the Gulf of Finland (Bergström et al. 2001) and the northern part of the Baltic (Graham 2004). It could be supposed that, freshened by river waters, the surface waters moved to the southern part of the sea. Wind direction, influencing the spread of freshened waters in the sea, plays a considerable role, since a land-bound wind significantly hampers the outflow of fresh waters from land.

Surface water salinity along the Baltic coast is additionally affected by the frequency of the upwelling phenomenon, which enables the inflow of more salty benthic waters towards the surface. Along the Polish coast that phenomenon accompanies chiefly eastern winds (Kowalewski and Ostrowski 2005; Lehmann and Myrberg 2008), the frequency of which decreased in the examined body of water (Girjatowicz 2017). Consequently, it caused a drop in the frequency of upwelling phenomenon (Omstedt at al. 2014). At the same time, it needs to be remembered that the impact of a decreased upwelling frequency, which results from rarer eastern winds, on the variations of water salinity is rather limited, since in the majority of the southern Baltic coast a permanent halocline generally does not occur, owing to the small depth of the reservoirs.

Moreover, precipitation affects the salinity of sea waters as well. In the second half of the 20th century, at the southern shores of the Baltic, the changeability of atmospheric precipitation was statistically insignificant, at the same time displaying a mostly growing trend (Świątek 2011). Substantial increases in the amount of precipitation were observed within the area of the Bornholm Deep and in the Gulf of Bothnia (Zorita and Laine 2000; Bergström et al. 2001; Busuioc et al. 2001). A rise in precipitation in parts of the Baltic Sea basin other than the examined reservoir also affects the surface water salinity at the Polish coast due to water mixing. In the period when western circulation wanes on the Polish Baltic coast (the years 1971–1986), when the frequency of days with precipitation (and to a limited degree also total precipitation) was relatively low in that region (Świątek, 2011), salinity was higher than in the subsequent period (1987–1998), when the number of days with precipitation was high, which involved an intensified dominance of western circulation bringing masses of humid air from the Atlantic.

The substantial year-to-year variability of salinity (similarly as in the case of temperature) in Międzyzdroje is determined by the station's location between the mouths of two straits (of the Świna and the Dziwna rivers), which, depending on wind direction, bring sea waters into the Szczecin Lagoon or do not (when the phenomenon of backwater from the sea takes place). When wind blowing from land directions occurs, there is an intensive water outflow from the Szczecin Lagoon to the sea, whereas with strong winds blowing towards the shores, an inflow of sea water to the Lagoon is observed (cf. Majewski 1972; Robakiewicz 1993). River waters have a particularly strong influence on sea water salinity in the shallow Pomeranian Bay, since its average depth reaches a mere 13 m. The impact of the Szczecin Lagoon waters on the salinity of surface sea waters in the region of Międzyzdroje becomes evident through its salinity being lower than at other stations, despite it being located most closely to the North Sea. The average salinity (1950–2015) at the station amounted to 6.52 PSU, whereas in Władysławowo it was 7.43 PSU, in Hel 7.23 PSU and in Gdynia 7.21 PSU. The above-specified factors further contribute to the lack of significant salinity trends in Międzyzdroje.

Relatively substantial salinity variability at individual stations in winter is caused by the occurrence of powerful storms at the time, which enable salt water inflows from the North Sea into the Baltic. Such powerful storms do not happen too often (Matthäus 2006; Elken et al. 2015) – Baltic salinity is determined by the fact of a strong inflow taking place in a given year and its force.

The impact of the NAO on water salinity in the Baltic Sea is not clear. A high (positive) value of the NAO instead tends to cause a drop in salinity, as it contributes to a rise in total precipitation, particularly in Sweden, which causes a greater fresh water inflow (López-Moreno and Vincente-Serrano 2006).

Substantial variability of salinity in winter (in relation to other seasons of the year) is caused by the more intensive activity of atmospheric circulation and frequently changing directions of the wind, which is stronger in winter than in other seasons. Depending on wind direction, surface fresh waters of river origin (land origin) occurring on the coast will remain or flow out of the examined body of water. When the wind blows from the land and from the east, coastal waters will be pushed deep into the sea, thereby uncovering more salty sea waters (cf. Girjatowicz 2017).

The variability of salinity in winter is also affected to a certain degree by phenomena occurring on land, and particularly those taking place at the beginning of winter – in December and in January, when the first ice typically forms. In the studied regions significant variability of ice phenomena occurs year-to-year, and these usually do not take place during mild winters and are common in severe winter seasons. For instance, west of the town of Hel (Hel W station) and to the north of it (N Hel station) in the period of 1946/1947–1999/2000 there were 31 and 44 winters without ice, respectively (Girjatowicz 2011). On average, the frequency of ice phenomena on the Polish coast is about 30% (Jevrejeva et al. 2004). Most typically, ice phenomena on the Polish coast appear in Świnoujście (Girjatowicz 1990; Schmelzer and Holfart 2012).

It needs to be remembered that water salinity rises during ice formation as a result of ice crystal creation and the trickling of condensed salt solution to the sea (Palosuo 1961; Zakrzewski 1983; Leppäranta and Myrberg 2009). A similar variability of salinity appears at the end of winter in February or in March, when ice melts and disappears at the Polish Baltic coast (Jevrejeva et al. 2004; Girjatowicz 2011). During the melt, brine flows from ice canals, increasing sea water salinity.

Summary and conclusions

Variability and long-term temperature and water salinity trends at the Polish Baltic coast were analysed with statistical methods. To that end, monthly, seasonal and annual values of surface temperature and water salinity from the period of 1950 to 2015 were used. The results shed new light on the variability of the above-mentioned parameters of those water bodies. In summary, the following conclusions can be presented.

- On the southern coast of the Baltic the greatest year-to-year water temperature variability occurs in spring (Świnoujście, Międzyzdroje and Hel) or summer (Kołobrzeg, Władysławowo and Gdynia), whereas the greatest changes in salinity are observed in winter.
- Long-term variability of temperature is less seasonally varied than salinity is. The lower variability of water temperature in winter was affected, *inter alia*, by its not being able to drop below freezing point.
- The variability of water temperature is chiefly affected by the influx of river waters, particularly in spring, and by the upwelling phenomena, which interfere most powerfully in its summer variability.
- The variability of salinity is chiefly impacted by irregular inflows of salty waters from the North Sea and such factors as: the variability of river water inflows, variability of wind directions determining the retention or outflow of fresh surface waters of land origin and a high degree of year-to-year variability of ice phenomenon occurrence and the related processes of ice crystal formation and melting, which increase water salinity. The occurrence of upwelling has only a slight impact, on account of the low depth of the examined reservoirs, hence the lack of permanent halocline.
- Alongside the Polish coast of the Baltic, water temperature rise and a decrease in water salinity were determined in the years 1950–2015. The greatest changes, regarding both salinity (decreases) and temperature (increases) were observed on the eastern coast – in Hel and in Gdynia. The trends of monthly salinity values (with individual exceptions) and seasonal salinity values are statistically significant in those locations at least at the level of $\alpha=0.05$, as are winter trends (being strong on account of the decreased frequency and force of winter inflows of salty waters from the North Sea) and annual values – even at the level of $\alpha=0.001$. In turn, apart from annual values, the most marked increases in surface water temperature concern the spring months. In Świnoujście no significant trends of temperature changes were observed in any of the months and in Międzyzdroje no significant trend was observed in terms of changes in salinity.
- A decline in surface salinity of water with a simultaneous rise in its temperature results in a decrease in sea water density, causing circulation changes in the sea, particularly in the vertical plane, as well as the conditions for the development of life. Warmer and more salty water (thus lighter water) of lower density cannot drop to the bottom, transferring, for example, oxygen there from water surface, which contributes to an increase in oxygen shortage in the benthonic layers of sea depths. The research results presented in the paper demonstrate a decreasing trend of water density at the southern shores of the Baltic.

Disclosure statement

No potential conflict of interest was reported by the author.

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