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ORIGINAL RESEARCH ARTICLE

Effects of atmospheric circulation on water temperature along the southern Baltic Sea coast

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Summary The relationships between atmospheric circulation patterns and water surface temperature along the coast of the southern Baltic Sea were studied. Seasonal water temperature values for Świnoujście, Międzyzdroje, Kołobrzeg, Władysławowo, Hel and Gdynia stations measured during the period of 1951—2010 were used. The methods of correlation and regression were applied to determine the relationships between water temperature and the number of days of atmospheric circulation patterns.

It was demonstrated that the strongest relationships occur in winter, chiefly on account of intense atmospheric circulation activity and weaker effects of solar radiation. The relationships with western circulation are slightly stronger than that associated with the eastern circulation. During the remaining seasons, those dependencies are clearly weaker. Asynchronous relationships between water temperature and atmospheric circulation are less pronounced than the synchronous ones. Despite being weaker, the asynchronous relations are still statistically significant, mainly in the spring season and as such, they may have a prognostic significance.

1. Introduction

The surface water temperature along the southern coast of the Baltic Sea depends mostly on the solar radiation and thermal properties of air masses as well as on the water circulation. In general, the SST depends on the heat transfer between air mass and water surface — the exchange that includes the processes of convection and turbulence movements, phase transitions, thermal conductivity and radiation. However, it is the atmospheric circulation that is the

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principal climate-shaping factor affecting water thermal conditions in the cold season (Leppäranta and Myrberg, 2009; Omstedt et al., 2014). In turn, during the warm season (spring, summer) solar radiation has a dominant influence on the water thermal conditions (Miętus, 1999). In addition, Stramska and Białogrodzka (2015) showed significant correlations between the NAO index value and the Baltic Sea SST in winter, with a simultaneous lack of significant relations between the average annual values.

The relations between the Baltic Sea SST and atmospheric circulation were also studied by, i.a. Siegel et al. (2008). Strong relationships have been demonstrated between the atmospheric circulation during January—March period and the water temperature in March. In case of the Arkona Basin, the SST in March correlated with monthly North Atlantic Oscillation (NAO) index for three cold months (January—March) and the determination coefficient amounted to 0.84, while for the analogous correlations with Arctic Oscillation (AO) index, the coefficient amounted to 0.6. Additionally, the correlation with the Baltic Winter Index (WIBIX) introduced by Hagen and Feinstel (2005) was calculated as 0.86.

As for the southern coasts of the Baltic Sea, the relationships between the NAO index and SST in winter months (December—February) were weaker (Girjatowicz, 2008). The determination coefficients fluctuated in the range of 0.41—0.56.

The NAO and AO are the phenomena related to the hemispherical atmospheric circulation, whereas WIBIX is related to the regional circulation. The relations of SST in the Bornholm Basin showed respective determination coefficients of 0.8, 0.61 and 0.77. Atmospheric circulation (defined by NAO, AO and WIBIX) has the strongest impact on the minimum temperature and ice range in March. On that account, the index values during January—March period (JFM) demonstrate the strongest correlations with March surface water temperature (Hagen and Feinstel, 2005). According to the study of Siegel et al. (2006), the WIBIX index is correlated with the minimum water temperature during winter in the Arkona Basin, i.e. a site located relatively close to the area analysed in the study.

In literature, the influence of atmospheric circulation on the air temperature was analysed far more frequently than its influence on the water temperature. The variability and values of both variables for the southern Baltic Sea demonstrate substantial convergence (Siegel et al., 1999; Stramska and Białogrodzka, 2015), e.g. water temperature in both the Arkona Basin as well as the Danish Straits shows, more or less, a monthly delay in relation to air temperature value in Warnemünde (Siegel et al., 1999). The highest average SST value can be observed in August and the lowest in February—March (Bradtke et al., 2010), due to a slower reaction of the water temperature to the solar radiation inflow compared to the air temperature reaction. The research conducted by Stramska and Białogrodzka (2015) showed significant correlations between the NAO index value and SST for the Baltic Sea in winter with a simultaneous lack of significant relations between average annual values.

The influence of directions of air masses advection on surface water temperature distribution in the Baltic Sea was also analysed on the basis of satellite data by Kozlov et al. (2012) and Siegel et al. (1996, 1999). Satellite data analyses were used to determine the time and place of the water temperature decrease alongside the coast in the summer months caused by upwelling (Gurova et al., 2013; Lehmann et al., 2012; Uiboupin and Laanemets, 2009).

Currently, at the SatBałtyk system site (satbaltyk.iopan.gda.pl), ongoing hydrometeorological characteristics of the Baltic Sea are posted four times daily. The SST satellite observations are one of the fundamental SatBałtyk products complemented by model data of the cloud-covered regions. The principles of functioning and the characteristics of the products obtained within the framework of the SatBałtyk project were described in the publications of Paszkuta and his team (Paszkuta et al., 2012) as well as in the publications of Woźniak and his team (Woźniak et al., 2008, 2011a, 2011b).

A difference of surface water temperature between the littoral zone and open waters of the southern Baltic Sea is noticeable. The average annual water temperature is slightly higher in the littoral zone. Greater differences are evident in individual seasons. In spring, the water temperature in the littoral zone is higher by 4°C on average, than that at the open sea. Similar differences, although lower in value, are observed in summer. In winter and autumn, the waters of the open southern Baltic Sea are warmer than the waters in the littoral zone by approximately 2°C (Cyberska, 1994). This difference is most visible in the region of Pomeranian Bay, chiefly due to the local conditions, such as bathymetry and the inflow of river waters.

In this work, atmospheric circulation was described with the use of the circulations types defined in accordance with Lityński's method. The first analytic surveys regarding the impact of atmospheric circulation types on water temperature (based on Lityński's method (1969)), were undertaken in 1999 (Girjatowicz, 1999). It was found that during the six cold months (October, November, December, January, February and March) those relationships become statistically significant; even at the level of α = 0.01, when individual circulation types are combined into sectors, and individual months into periods of several months. However, the research referred only to Międzyzdroje and Władysławowo during the colder seasons (October—March) between the years 1951 and 1990. The problem that still needs to be examined concerns Lityński's individual atmospheric circulation types occurrence and their influence on the water temperature of the southern Baltic Sea coast. The following questions remain: What are the strength and statistical significance of such relationships? Does the strength of those relationships vary in terms of space and season? Which of the non-circulation factors can affect such variations?

The purpose of the paper is to determine and examine the correlations between the atmospheric circulation patterns (specified in accordance with Lityński's classification) and surface water temperature along the southern coast of the Baltic Sea, using the data from possibly the longest timespan (1951—2010), encompassing all seasons of the year (December—February, March—May, June—August, September—November). In addition, the spatial and seasonal variability of the strength of the relationships, as well as the contribution of non-atmospheric factors, were investigated.

2. Material and methods

In this study, average seasonal values of surface water temperature on the southern coast of the Baltic Sea were used for individual seasons: winter (December—February), spring

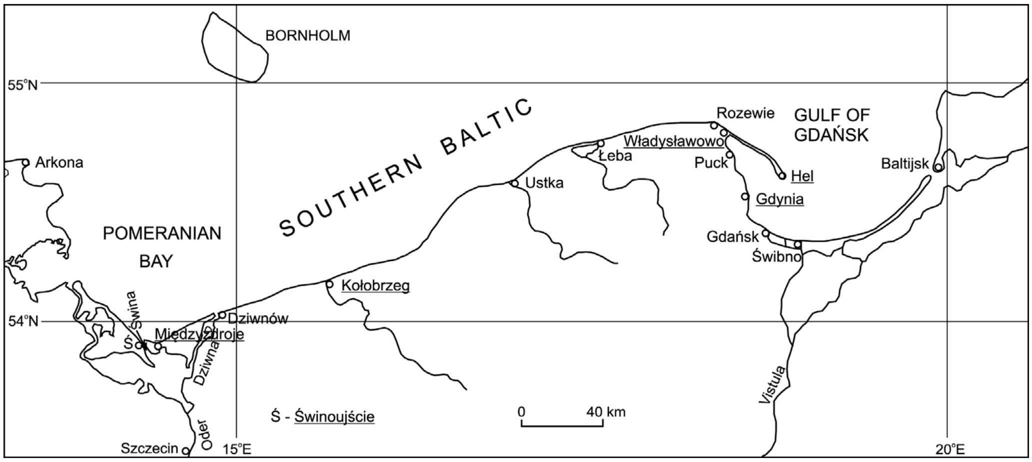

Figure 1 Location of hydrometeorological stations on the south coast of the Baltic Sea.

(March—May), summer (June—August) and autumn (September—November), mainly from the period of 1951—2010. Data were gathered by the Institute of Meteorology and Water Management — National Research Institute (IMGW-PIB) at Świnoujście, Międzyzdroje, Kołobrzeg, Władysławowo, Hel and Gdynia stations (Figure 1). As far as Kołobrzeg is concerned, the data refer to the years 1957—2010. The longest-running study of water temperature has been conducted for these 6 aforementioned stations. Average monthly water temperatures, calculated on the basis of daily values, were published in IMGW's materials (Cyberska et al., 1986—1998; *Hydrographic*..., 1950—1970; *Hydrological*..., 1961—1990; Krzymiński et al., 1999—2001; Miętus et al. 2002—2010). Using the monthly values, seasonal means from individual years were calculated. Means, extreme means and their amplitudes as well as standard deviations of seasonal surface water temperature for those regions are presented in Table 1. The mean amplitude was calculated as a difference between the mean maximum, i.e. maximum seasonal mean temperature averaged over all stations, and mean minimum seasonal water temperature values.

Water temperature measurements were taken outside the harbour breakwater in Władysławowo, Hel and Gdynia, from the pier — in Kołobrzeg and Międzyzdroje, and in the harbour canal in Świnoujście. The measurements were taken with mercurial thermometers, with the accuracy of 0.1°C, in the surface water layer at the depth of 0.5 m at 06:00 UTC. The location of water temperature measurement did not change in the course of the analysed period. The measurement points analysed in the paper are representative of the littoral zone of the southern Baltic Sea. Further away from the coast, in the open waters of the southern Baltic Sea, water temperature is different, particularly during the transitional seasons (Cyberska, 1994).

It was decided not to use the data obtained from satellite measurements, taking into consideration their imprecision and that they are available for much shorter periods than measurements collected at coastal stations. The statistical

Table 1 Mean, extreme, amplitude (A) and standard deviations (B) of water temperature (°C) in individual seasons (1951—2010).

Season		Świnoujście	Międzyzdroje	Kołobrzeg	Władysławowo	Hel	Gdynia	Mean	Mean amplitude
A									
Dec.—Feb.	min	0.4	0.0	0.1	0.4	1.0	0.4	0.4	
	mean	1.7	1.7	2.2	1.9	2.5	2.1	2.0	4.3
	max	4.0	4.5	5.3	4.5	5.0	4.6	4.7	
Mar.—May	min	5.5	4.6	4.8	4.2	3.3	3.7	4.4	
	mean	7.7	6.9	6.5	5.9	5.5	6.2	6.5	4.8
	max	9.9	10.4	9.1	8.3	8.2	9.0	9.2	
Jun.—Aug.	min	16.3	15.9	15.1	13.8	14.4	14.9	15.1	
	mean	18.5	17.8	16.6	16.0	16.7	17.4	17.2	4.0
	max	20.0	20.0	18.3	17.9	18.7	19.2	19.0	
Sep.—Nov.	min	9.8	8.4	9.7	8.6	9.4	8.6	9.1	
	mean	11.2	11.1	11.0	10.6	11.8	11.3	11.2	3.9
	max	13.1	13.2	12.3	12.5	13.5	13.5	13.0	
B									
Dec.—Feb.		0.76	0.89	1.02	0.89	0.90	0.88	0.9	
Mar.—May		1.07	1.28	1.04	0.99	1.17	1.23	1.1	
Jun.—Aug.		0.82	0.93	0.83	0.95	0.94	1.08	0.9	
Sep.—Nov.		0.77	0.80	0.65	0.71	0.73	0.73	0.7	

error of 1.2°C (expressed as a standard deviation of the differences between the temperature determined with the use of a retrieval algorithm and the temperature measured *in situ*) was demonstrated through a comparison of the satellite data (even after the application of so-called data assimilation process) with water temperature obtained from the coastal stations. An additional shortcoming of the data obtained from the satellite model is the fact, that it works by assimilating inflowing satellite data concerning SST only for cloudless areas (Kowalewski, 2016).

Atmospheric circulation data come from "Calendar of atmospheric circulation patterns" (Pianko-Kluczyńska, 2006) devised in line with Lityński's method (Lityński, 1969). More recent data (2006—2010) were obtained directly from IMGW-PIB. Lityński (1969) used an equiprobable, three-class, numerical classification to define atmospheric circulation while determining frequency distribution curves. He defined an atmospheric circulation pattern with three numerical parameters: zonal circulation index (Ws), meridional circulation index (Wp) as well as pressure index at the point coinciding with the location of Warsaw (Cp). Zonal and meridional circulation indices, defining the advection direction of air masses, were determined for the area limited by 40°N and 65°N parallels as well as 0°E and 35°E meridians. The atmospheric pressure was read from the same weather charts from which atmospheric circulation indices were calculated.

Lityński (1969) calculated the zonal circulation index, in accordance with Rossby's definition (after Lityński, 1969), from a formula that contains averaging latitudinal component of the geostrophic wind:

$$Ws = \frac{4.8\overline{\Delta p}}{\sin\overline{\varphi}\Delta n},$$

where Ws — zonal index in m/s,

$\frac{\overline{\Delta p}}{\Delta n}$ — average pressure gradient in hPa per 1° longitude,

$\overline{\varphi}$ — average latitude.

Once the figures resulting from the determined zone of index calculation are entered, the formula assumes the following form (Lityński, 1969):

$$Ws = 6.1\,\frac{P_{40}-P_{65}}{25},$$

where P_{40} — average pressure at the section of 40°N latitude in 0—35°E zone,

P_{65} — average pressure at the section of 65°N latitude in 0—35°E zone.

In order to compute the meridional circulation index, Lityński (1969) adopted an analogous formula, taking into account the fact that 1° at a parallel is of smaller length than 1° at a meridian:

$$Wp = 10.0\,\frac{P_{35}-P_{0}}{35},$$

where Wp — meridional index in m/s,

P_{35} — average pressure at the section of 35°E longitude in 40—65°N zone,

P_0 — average pressure at the section of 0° longitude in 40—65°N zone.

Lityński (1969) defined *Ws* index with the following classes: E (eastern), 0 (zero), W (western), and Wp index — N (northern), 0 (zero), S (southern). In turn, Cp atmospheric pressure was defined by him with the following classes: c (cyclonic), 0 (zero — close to normal) and a (anticyclonic). He thus arrived at a total of 27 circulation patterns: Nc, N_0, Na, NEc, NE_0, NEa, Ec, E_0, Ea, SEc, SE_0, SEa, Sc, S_0, Sa, SWc, SW_0, SWa, Wc, W_0, Wa, NWc, NW_0, NWa, 0c, 0_0, 0a.

Dominant circulation types of each day in the period from 1951 to 2010 used in this work originate from "Calendar of atmospheric circulation patterns" (Pianko-Kluczyńska, 2006) as well as from the materials obtained directly from IMGW-PIB. The authors summed up the numbers of days with particular circulation types.

In order to obtain stronger relationships, the authors combined individual circulation patterns into sectors. Generally, sectors were adopted from zonal directions that exert the greatest impact on water temperature. These are chiefly sectors of eastern directions, such as: NE + E (23°—112°), NE + E + SE (23°—157°), E + SE + S (68°—202°) and western directions, such as: SW + W (203°—292°), SW + W + NW (203°—337°), W + NW + N (248°—22°). Except for summer, seasonal atmospheric circulation patterns were not differentiated in terms of pressure indexes (c, 0, a).

Subsequently, the number of days for given atmospheric circulation patterns were calculated in previously mentioned sectors (NE + E, NE + E + SE, E + SE + S, SW + W, SW + W + NW and W + NW + N) yearly for each individual season, from 1951 to 2010. As opposed to monthly relationships, seasonal relationships provide greater averaging of variable values, the reduction of their extremes and smaller deviations of empirical points in the Cartesian coordinate system from the regression line, which strengthens the correlation. However, in transition periods between two different regimes, the averaging may reduce correlations.

The analysis methods of correlation and regression were applied in order to determine and examine statistical dependency between seasonal water temperatures (dependent variable) and the number of days with a given atmospheric circulation type in the studied sectors (independent variable; Łomnicki, 1999; *Time*..., 2010). Statistical significance of these relationships was analysed with Fisher—Snedecor test (F) at significance levels of α = 0.05, α = 0.01 and α = 0.001 (risk of error amounted to 5%, 1% and 0.1% respectively). The null hypothesis of the test was formulated under an assumption that the regression coefficient value is equal to zero, i.e. in the considered population (in the study period) one of the variables does not exert influence on the other variable. Statistical significance less than, or equal to, the adopted levels (0.05, 0.01 and 0.001) showed grounds for rejection of the null hypothesis claiming lack of influence of the number of days in the given circulation type on the SST near the Baltic Sea coast, i.e. accepting a hypothetical existence of a correlation between the analysed variables.

The strength of relationships between the examined variables was defined with a correlation coefficient (r), while the degree of their dependency — with a determination coefficient ($r^2 \times 100\%$). The determination coefficient is the proportion of the variance in the dependent variable that is predictable from the independent one. Moreover, mean values and standard deviation values were computed for seasonal water temperatures, constituting a measure of dispersion (the information on the dispersion of the values of the variables around their mean value).

Table 2 Correlation coefficients between the number of days with selected atmospheric circulation patterns and water temperature in individual seasons (1951—2010).

Circulation	Świnoujście	Międzyzdroje	Kołobrzeg	Władysławowo	Hel	Gdynia
Winter						
NE + E	−0.57[c]	−0.55[c]	−0.58[c]	−0.61[c]	−0.57[c]	−0.60[c]
NE + E + SE	−0.64[c]	−0.58[c]	−0.65[c]	−0.69[c]	−0.63[c]	−0.70[c]
E + SE + S	−0.54[c]	−0.44[c]	−0.53[c]	−0.56[c]	−0.50[c]	−0.58[c]
SW + W	0.62[c]	0.57[c]	0.62[c]	0.66[c]	0.62[c]	0.64[c]
SW + W + NW	0.68[c]	0.62[c]	0.67[c]	0.72[c]	0.64[c]	0.70[c]
W + NW + N	0.49[c]	0.40[b]	0.46[c]	0.49[c]	0.42[c]	0.52[c]
Spring						
NE + E	−0.32[a]	−0.35[b]	−0.37[b]	−0.34[b]	−0.38[b]	−0.39[b]
NE + E + SE	−0.34[b]	−0.40[b]	−0.41[c]	−0.37[b]	−0.42[c]	−0.41[c]
E + SE + S	−0.11	−0.28[a]	−0.27[a]	−0.23	−0.14	−0.10
SW + W	0.09	0.19	0.24	0.13	0.25	0.20
SW + W + NW	0.22	0.31[a]	0.44[c]	0.30[a]	0.32[a]	0.23
W + NW + N	0.35[b]	0.44[c]	0.47[c]	0.39[b]	0.36[b]	0.28[a]
Summer						
NE + E	0.48[c]	0.29[a]	−0.03	−0.03	0.12	0.27[a]
NE + E + SE	0.54[c]	0.34[b]	−0.13	−0.09	0.19	0.33[b]
E + SE + S	0.49[c]	0.35[b]	−0.11	−0.12	0.32[a]	0.37[b]
SW + W	−0.27[a]	−0.10	0.14	0.16	−0.06	−0.26[a]
SW + W + NW	−0.50[c]	−0.25	0.07	0.04	−0.22	−0.42[c]
W + NW + N	−0.51[c]	−0.41[c]	0.00	−0.02	−0.27[a]	−0.46[c]
Autumn						
NE + E	−0.21	−0.28[a]	−0.09	−0.13	−0.19	−0.24
NE + E + SE	−0.09	−0.20	−0.24	−0.31[a]	−0.29[a]	−0.35[b]
E + SE + S	0.19	0.04	−0.26[a]	−0.40[b]	−0.13	−0.23
SW + W	0.08	0.08	0.19	0.24	0.24	0.28[a]
SW + W + NW	−0.12	0.03	0.21	0.27[a]	0.15	0.20
W + NW + N	−0.27[a]	−0.04	0.11	0.25	−0.02	0.09

[a] Values significant at the level α = 0.05.
[b] Values significant at the level α = 0.01.
[c] Values significant at the level α = 0.001.

3. Results

3.1. Synchronous relationships between water temperature and atmospheric circulation patterns

When examining the relationship between the number of days with given type of atmospheric circulation (combined into sectors from zonal directions) and water surface temperatures in the individual seasons, it was found that stronger relationships occur during the winter season. For nearly all of the studied regions, those relationships are statistically significant even at a level of α = 0.001 (Table 2). The relationships between water temperature and the number of days with a circulation from the western sector (SW + W, SW + W + NW) are slightly stronger than that related to the eastern sector (NE + E, NE + E + SE). For SW + W + NW circulation correlation coefficients range from 0.62 in Międzyzdroje to 0.72 in Władysławowo. The strongest seasonal relationship with the correlation coefficient of 0.72 occurs in winter in Władysławowo. As demonstrated by the determination coefficient of average winter (from three winter months), water temperature variability can be explained by the variability of the number of days with SW + W + NW circulation in 51% of the cases. The increase in the number of days by 1 with SW + W + NW circulation will result in an increase by an average of 0.036°C in the winter water temperature in Władysławowo. The same circulation pattern explains winter water temperature in Gdynia in 50%, and in Międzyzdroje, in 39% of the cases. In summer, the diversification of determination coefficients is greater along the southern Baltic Sea coast. Values for the SST association with the number of days featuring SW + W + NW circulation amount to 0—25% and with NE + E + SE circulation to 1—30%. In the Pomeranian Bay (Świnoujście, Międzyzdroje) and in the Gdańsk Bay (Gdynia) the relations of water temperature in summer, both with the number of days featuring NE + E + SE as well as SW + W + NW circulation, are statistically significant even at levels α = 0.01 and α = 0.001. However, these relations are not statistically significant alongside open (unshielded) shores.

The differentiation in the strength of correlation coefficients during individual seasons, in the region that is exposed the most to the sea influences, is presented for Władysławowo (Figure 2). In winter, correlation coefficients are the strongest and these relationships are statistically significant even at a level of α = 0.001. During transitory seasons, i.e. in spring and autumn, the relationships are evidently weaker, but still statistically significant, typically at a level of α = 0.05. The correlations of water temperatures and the number of days with atmospheric circulation during summer

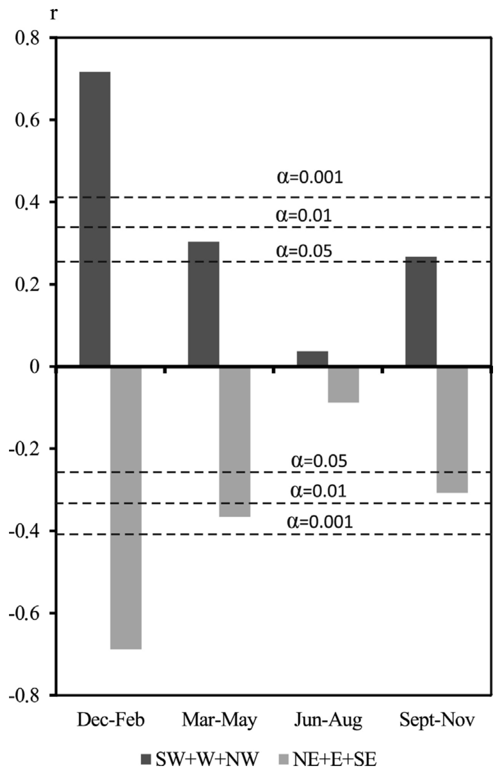

Figure 2 Correlation coefficients (*r*) of the water temperatures at Władysławowo and number of days with atmospheric circulation (SW + W + NW, NE + E + SE) in individual seasons (1951—2010).

seasons are statistically insignificant (Figure 2). In this season, anticyclonic types of circulation have an impact on water temperature. However, the correlation coefficients between water temperature and the number of days featuring an eastern anticyclonic (NEa + Ea + SEa), cyclonic (NEc + Ec + SEc) and zero (NE0 + E0 + SE0) circulation patterns for Władysławowo amount to 0.06, −0.12 and −0.19 and are statistically insignificant, respectively. In turn, certain relations concerning bays, particularly the Pomeranian Bay, appeared to be statistically significant. The relations that are significant (at the level of at least α = 0.05) were found in Świnoujście — with the number of days featuring NEa + Ea + SEa (r = 0.49) and NEc + Ec + SEc (r = 0.30) circulation, and in Międzyzdroje — with the number of days featuring NEa + Ea + SEa (r = 0.37) circulation, in Kołobrzeg — with the number of days featuring NE0 + E0 + SE0 (−0.30) circulation, and in Gdynia — with the number of days featuring NEa + Ea + SEa circulation (r = 0.31).

It can further be observed, that the studied correlations considering SW + W + NW as well as the NE + E + SE circulation pattern give similar absolute values and they differ only with a direction (indicated a positive linear relationship or the negative one) (Figure 2). It was found that the fraction of a total number of days with (SW + W + NW) + (NE + E + SE) circulation patterns in an individual season is not too high and it varies from 65% in summer to 67% in winter. The yearly variability of the number of days with the circulation from the western and eastern sectors (defined by the variation coefficient) is the same in spring, summer and autumn, and amounts to 0.14. In winter, it is significantly greater — the variation coefficient is equal to 0.17.

More detailed analyses demonstrated that in the examined multiyear period in Władysławowo (at the level of α = 0.001) the water temperature in February and May is significantly correlated with spring (March—May) and summer (June—August) water temperature, respectively, with the spring relations being stronger (r = 0.83) than the ones observed in summer (r = 0.52). The relations between water temperature in November and August and respectively winter (December—February) as well as autumn (September—November) water temperatures appeared to be statistically insignificant. The study also comprised the relations between average water temperature values in Władysławowo in individual seasons of the year and the respective average seasonal air temperatures in Gdynia. It was found that these dependencies are stronger than the relation between the water temperature and the number of days with a given atmospheric circulation type. The strongest relations occurred in winter (r = 0.91) and in spring (r = 0.84), while the weakest ones were observed in summer (r = 0.43) and in autumn (r = 0.65). In summer, correlation coefficients between the average water temperature and the number of days with western or eastern atmospheric circulations are statistically insignificant at stations exposed to sea (unsheltered) shores (Kołobrzeg, Władysławowo).

Figure 3 demonstrates some empirical points clearly outlying from the regression line. This figure shows the relationship between the average water temperature in Władysławowo and the number of days with the atmospheric circulation types — western (A) and eastern (B) in winter (December—February). The regression coefficients are 0.036 (A) and 0.045 (B), while the determination coefficients are 0.51 and 0.47, respectively. Such point distribution from the regression line refers to atypical cases, chiefly very mild winters. The points that are most distant from the regression line are the ones with coordinates referring to the winter of 2006/2007. In the winter of 2006/2007 very high water temperature was observed in Władysławowo (4.5°C) in comparison to the average value (2.0°C). The number of days with the circulation bringing warmer weather (SW + W + NW) amounted to 54 (Figure 3A). Both December 2006 and January 2007 featured particularly high water temperatures. The deviations from an average SST for the multiyear period of 1950—2010 during these two months were equal to 3.4°C and 3.5°C, respectively. Thermal water inertia affected a relatively high water temperature in February (as well as additional deviation from the average value amounting to 1°C) despite distinct dominance of the number of days featuring NE + E + SE circulation (9 days, 32% days in month) over the number of days featuring SE + W + NW circulation (2 days, merely 7% days in the month).

In order to explain a substantial deviation of the average surface water temperature (SST) in the winter of 2006/2007 from a regression line (Figure 3A), only the winters (11 cases) with the similar number of days (from 49 to 59) featuring SW + W + NW atmospheric circulation were analysed. The analysis, with a focus placed on deviations from the average value and relations with SST, concerned the following factors of the selected winters: water temperature in November, winter insolation in Gdynia, average air temperature in winter in Gdynia and the number of days featuring N, S, 0, SW, S + SW, SE + S and NE + E + SE circulation patterns. It

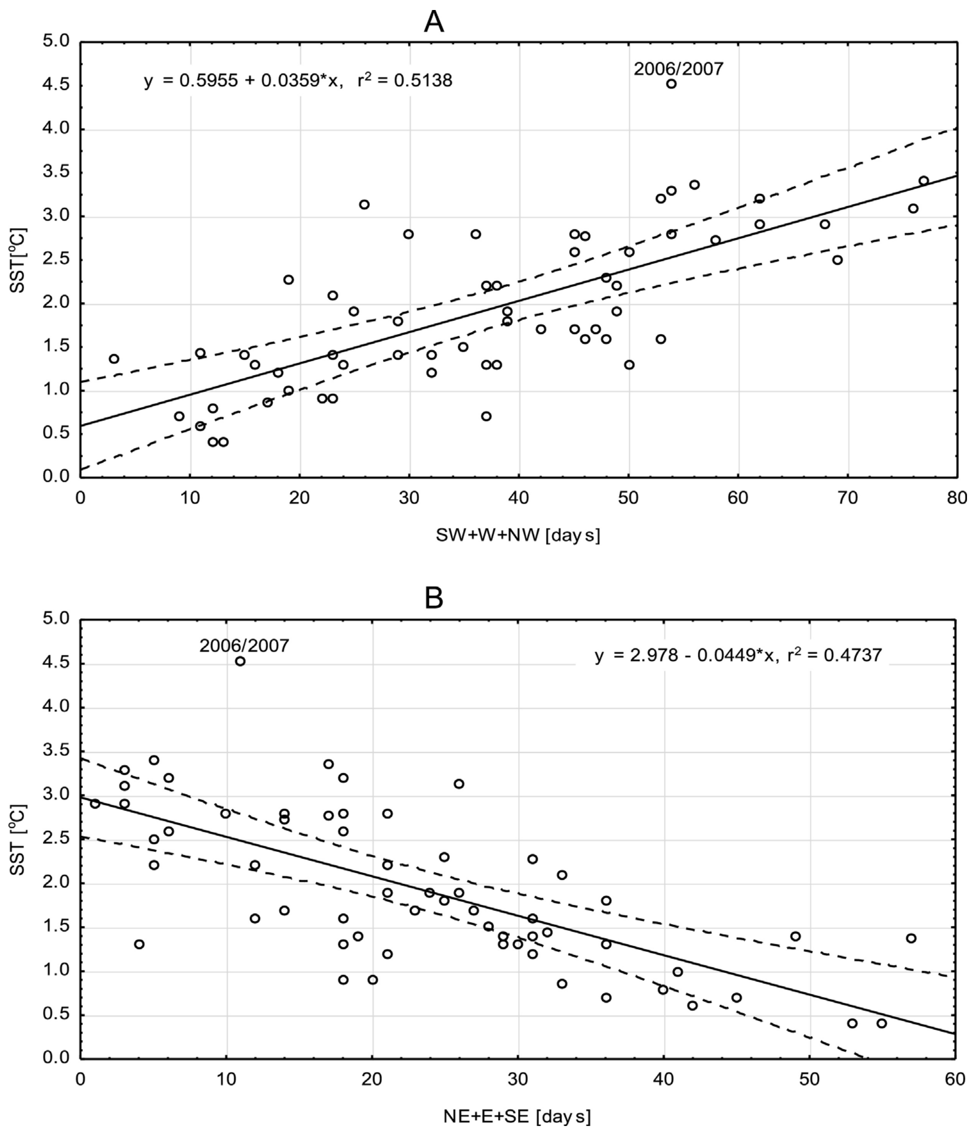

Figure 3 Linear regression estimated for the relationship between water temperature at Władysławowo with the number of days with atmospheric westerly circulation patterns for (A) and easterly ones (B) during December—February (1951—2010). Curves presented 99% confidence interval.

was found, that in the selected group of 11 atypical winters the one of 2006/2007 had the highest deviations from average values among the group, regarding such factors as: air temperature (deviation from the average air temperature of the selected winters was 1.7°C), water temperature in November (deviation from the selected winters average value was equal to 2.0°C), and the number of days with S circulation (deviation from the group's average value amounted to 4 days). For that group, correlation coefficients between SST and the air temperature, the water temperature in November as well as the number of days with S circulation amounted to 0.94, 0.45 and 0.56, respectively, and were statistically significant only with air temperature (α = 0.001). It was also observed that an increase in air temperature in Gdynia by 1°C resulted in an increase in SST in Władysławowo by an average of 0.713°C. Summing up, it can be assumed that the relatively high air temperatures in the winter of 2006/2007 and in November 2006 are responsible for a significant deviation of the actual water temperature from the value obtained from the regression equation.

3.2. Asynchronous relationships between water temperature and atmospheric circulation patterns

Relationships between surface water temperatures and the number of days with atmospheric circulation patterns were studied. Both the western (SW + W + NW) and the eastern (NE + E + SE) circulation patterns were considered, preceded by one, two or three seasons during which water temperature (SST) was analysed. It was found that asynchronous relationships are weaker than simultaneous (synchronous) relationships. The strength of such relationships decreased as time intervals increased, within the interval of just two seasons they were typically statistically insignificant (Table 3). The strongest relationships are the ones regarding the relation

Table 3 Correlation coefficients between the number of days with selected atmospheric circulation pattern SW + W + NW and NE + E + SE with lagged water temperature (SST) one (A), two (B) and three (C) seasons (1951—2010).

Variables	Świnoujście	Międzyzdroje	Kołobrzeg	Władysławowo	Hel	Gdynia
A						
SW + W + NW_{winter}, SST_{spring}	0.54[c]	0.62[c]	0.64[c]	0.67[c]	0.63[c]	0.62[c]
SW + W + NW_{spring}, SST_{summer}	0.35[b]	0.52[c]	0.39[b]	0.30[a]	0.44[c]	0.56[c]
SW + W + NW_{summer}, SST_{autumn}	−0.29[a]	−0.23	−0.22	−0.26[a]	−0.27[a]	−0.24
B						
SW + W + NW_{winter}, SST_{summer}	−0.07	0.20	0.25	0.41[b]	0.14	0.14
SW + W + NW_{spring}, SST_{autumn}	0.23	0.19	0.17	0.20	0.35[b]	0.29[a]
C						
SW + W + NW_{winter}, SST_{autumn}	−0.06	−0.01	0.01	−0.03	0.05	−0.07
A						
NE + E + SE_{winter}, SST_{spring}	−0.54[c]	−0.53[c]	−0.62[c]	−0.60[c]	−0.60[c]	−0.57[c]
NE + E + SE_{spring}, SST_{summer}	−0.12	−0.30[a]	−0.26[a]	−0.24	−0.39[b]	−0.50[c]
NE + E + SE_{summer}, SST_{autumn}	0.20	0.25	0.22	0.24	0.16	0.13
B						
NE + E + SE_{winter}, SST_{summer}	0.01	−0.18	−0.18	−0.26[a]	−0.17	−0.20
NE + E + SE_{spring}, SST_{autumn}	−0.04	−0.06	−0.14	−0.20	−0.34[b]	−0.29[a]
C						
NE + E + SE_{winter}, SST_{autumn}	0.01	−0.07	−0.08	−0.05	−0.11	0.00

[a] Values significant at the level $\alpha = 0.05$.
[b] Values significant at the level $\alpha = 0.01$.
[c] Values significant at the level $\alpha = 0.001$.

between water temperature in spring (SST_{spring}) and the number of days with atmospheric circulation in winter. These relationships were slightly stronger for the days with SW + W + NW_{winter} circulation than for days with the NE + E + SE_{winter} circulation. All of them were, however, statistically significant, even at a level of $\alpha = 0.001$. The strongest relationship of water temperature in spring (SST_{spring}) and the number of days with western atmospheric circulation (SW + W + NW_{winter}) in winter occurred in Władysławowo, resulting in a correlation coefficient of 0.67. The determination coefficient of 0.45 means, that water temperature variability in spring can be explained by the variability of the number of days with western circulation in winter in 45%. As demonstrated by a regression coefficient, an increase in the number of days with western circulation in winter by 1 day will cause a rise of water temperature in spring in Władysławowo by an average of 0.04°C.

The coefficients determining the relationship between the number of days with western circulation (SW + W + NW_{winter}) in winter and water temperature in spring (SST_{spring}), summer (SST_{summer}) and autumn (SST_{autumn}) are weaker (Table 3). The determination coefficients of the number of days with eastern circulation (NE + E + SE_{winter}) in winter with subsequent seasonal water temperatures (SST_{spring}, SST_{summer} and SST_{autumn}) decrease in a similar fashion (Table 3). Such drop in strength of asynchronous relationships can be explained by the sea water masses thermal inertia. The thermal conditions of water masses strengthened by the atmospheric conditions in winter are still being reflected in the following seasons. The thermal effects of winter circulation encoded in water masses die down with time, while asynchronous relationships become statistically insignificant.

4. Discussion

The water temperature variability depends on the thermal properties of the incoming air masses, especially in winter. In this paper, the atmospheric circulation patterns developed by Lityński (1969) constitute the measure of air mass advection. The numbers of days with circulation patterns were added up for chiefly two sectors: SW + W + NW and NE + E + SE as they influenced water temperature variability the most. The proper generalisation of circulation patterns, involving their combination into sectors, provides a better reflection of their occurrence real frequency since there are sometimes unjustified significant differences in their occurrence between neighbouring patterns. On the other hand, excessively wide sectors deteriorate the relationship, because they may contain the conflicting circulation patterns with an opposite effect on water thermal conditions (Girjatowicz, 2001).

Comparing previous studies by Girjatowicz (2008) regarding the impact of the NAO index on the SST along the southern Baltic Sea shores, with this work, one can notice some differences in the statistical significance of the compounds. The NAO index (reflecting the intensity of the polar-marine air masses advection) corresponds to the SW + W + NW type of atmospheric circulation according to the Lityński's classification. The SST compounds with the NAO index and the number of winter and autumn SW + W + NW circulation days. Furthermore, both are characterized by similar statistical significance. However, these relationships clearly differ for summer and even more so for spring. In spring, the SST associations with the SW + W + NW atmospheric circulation were usually statistically significant, while for the NAO index none of them was. A similar situation occurs for the NE + E + SE circulation days and the NAO index association with SST. The Lityński's classification provides more detailed and precise information about the relationship between atmospheric circulation and SST than the NAO index, thus it has been used in this work.

It was determined that directions of air masses advection significantly influence water temperature along the southern coast of the Baltic Sea. The strongest relationships occurred in winter, which may be explained by more intensive atmospheric activity (resulting from stronger baric gradients over Europe during the winter season (Löptien et al., 2008; Sepp et al., 2005) and by the limited influence of solar radiation (low real insolation — Koźmiński and Michalska, 2005). One must remember, that the European thermal conditions in winter are determined by the heat coming from lower latitudes, transported by the Gulf Stream and accumulated in the northern Atlantic. Above all, oceans feature high thermal inertia ("thermal memory"), characterised by a gradual heat transfer in thermal exchange processes (e.g. through latent heat) between water and atmosphere (Marsz, 1999). The heated air mass is, in turn, carried from Atlantic to the east through the proper atmospheric circulation (western flow), the most intensive in temperate geographic latitudes during winter (Andersson, 2002; Lamb, 1978). Similarly, in the Gulf of Gdańsk, where the heat accumulated during spring, as a result of atmospheric circulation, particularly in the deeper water layers, influences water temperature in certain regions of the southern Baltic Sea coast in autumn. It can be explained by the greater thermal inertia of deeper water layers of the Bay of Gdańsk in comparison to the remaining regions of the southern Baltic Sea coast. In the water masses of the Bay of Gdańsk, the effects of earlier atmospheric circulation are better "remembered", which are later manifested.

The conducted research confirmed, that winter thermal features are related to the atmospheric circulation activity over northern Europe and the Baltic Sea (cf. Leckebusch and Ulbrich, 2004; Löptien et al., 2008; Sepp et al., 2005). At this time of the year, the frequency of deep low-pressure systems over the Baltic Sea increases (Bengtsson et al., 2006; Brayshaw, 2005; Walther and Bennartz, 2006). In the subsequent seasons, the atmospheric circulation activity is weaker, as is the strength of the studied correlational relationships. At the same time, the influence of the solar radiation differentiation depending on the sunshine duration (cloudiness) increases, reaching its maximum in summer.

During summer, especially the eastern (NE + E + SE) circulation is frequently accompanied by high pressure, cloudless weather or the weather with little cloudiness. Days with western anticyclonic circulation may also be relatively sunny, however, the most solar energy arrives during the eastern anticyclonic circulation, mainly in the spring and summer (Rozwadowska, 1992). In such circumstances, solar radiation has a significant impact on water temperature. According to Miętus (1999), summer water temperature is determined by anticyclonic forms of atmospheric circulation, which are contributing to the increased amount of direct sun radiation to the surface of the sea. Thus, in summer the relationships of water temperature with atmospheric circulation are weak and typically statistically insignificant.

In summer, during western circulation, inflowing polar-sea air masses are colder than the continental air mass (cf. Kożuchowski and Marciniak, 1988; Marsz and Styszyńska (eds.), 2002). In turn, during eastern circulation, warm, polar-continental air masses arrive over the southern Baltic Sea region (Miętus (ed.), 1997).

The factors interfering with the relationships of water temperature with atmospheric circulation are the solar radiation described earlier and a phenomenon of upwelling. The upwelling is an upward current caused by the wind blowing parallel to the coast located on its left (Bychkova and Victorov, 1987; Gidhagen, 1987; Leppäranta and Myrberg, 2009). Along the southern coastline of the Baltic Sea, it is mostly the eastern wind that gives rise to the upwelling, most strongly manifested during the warm season (May—September), occurring with the frequency of approximately 30% (Krężel, 1997; Urbański, 1995). In the warm season, water temperature rise is generated during eastern circulation, which is accompanied by cloudless weather or the weather with little cloudiness, and the high solar radiation inflow. The eastern circulation corresponds approximately to similar wind directions giving rise to an upwelling. Siegel et al. (2008) noticed that along the German and Polish Baltic Sea coasts (with the exclusion of the Oder estuary zone) upwelling occurs when eastern winds blow at speeds higher than 15 m/s. The greatest negative anomalies of surface water temperature caused by upwelling occur alongside the Hel Peninsula (at the side of the open sea) and in the most northern part of the Polish coast (Kowalewski and Ostrowski, 2005). In summer, cooler water coming to the surface from deeper sea layers reduces the surface water temperature. Consequently, upwelling weakens the relationships between water temperature and atmospheric circulation. In the region of Hel, Kołobrzeg and Łeba, the upwelling phenomena are more frequent than in the other regions of the Polish Baltic Sea coast (Lehmann et al., 2012). The maximum water-temperature difference between the centre of upwelling and water surrounding it was observed. It amounted to 14°C in Hel, 12.5°C in Łeba and 8.9°C in Kołobrzeg (Krężel et al., 2005). Inflows of cool water from the deeper layers (upwellings) do not occur in bays due to their shallow depths (cf. Kowalewska-Kalkowska and Lejman, 2002/2003). Downwellings appear far more frequently than upwellings along the Baltic Sea southern coast (Kowalewski and Ostrowski, 2005; Myrberg and Andrejev, 2003), a result of the western and south-western winds domination in that part of the Baltic Sea (Miętus (ed.), 1997). However, downwellings do not have a greater impact on the variability of the surface water temperature.

An upwelling may slightly weaken the influence of atmospheric circulation on water temperature in the cold season as well. However, owing to a lower vertical gradient of water temperature than in summer, the impact is slightly weaker. In winter, during eastern circulation, frosty and dry polar-continental air masses arrive, causing a decrease of water temperature. Similarly, sea-surface wind directions accompanying this circulation pattern cause warmer waters to resurface from deeper sea layers causing the slight surface water temperature rise (cf. Girjatowicz, 1987; Łomniewski, 1960).

5. Conclusions

The objective of this work was to analyse the influence of western (SW + W + NW) and eastern (NE + E + SE) atmospheric circulation patterns during individual seasons of the year (December—February, March—May, June—August, September—November) on the surface water temperature of the Baltic Sea southern coast. The focus was also placed on the strength difference of those relationships in this particular geographical region for each season separately. Long-term (1951—2010) water temperature data from the following stations: Świnoujście, Międzyzdroje, Kołobrzeg, Władysławowo, Hel and Gdynia were used. Circulation types were adopted from "Calendar of atmospheric circulation patterns" prepared by IMGW-PIB according to Lityński's method. In order to examine the strength of these relationships, the analytical methods of correlation and regression were employed. Statistical significance of the relationships was analysed with Fisher-Snedecor test.

The relationships obtained for winter seasons demonstrate the high statistical significance (α = 0.001). The correlation and regression coefficients of the SST and a number of days with SW + W + NW circulation are positive, indicating that an increase of SW + W + NW circulation frequency corresponds to a rise in the water temperature. This circulation has an opposite effect on water temperature during summer, however, these relationships are usually statistically insignificant. The relationships that are statistically significant have a negative correlation and regression coefficients. A rise in the frequency of the SW + W + NW circulation pattern, which is accompanied by an advection of cool air masses from the Atlantic and cloudiness, results in water temperature drop.

Strong relationships in winter can be explained by the thermal influence of the air masses incoming from the west or east. The westerly air masses (coming from the Atlantic), mostly the polar-sea air masses, are much warmer, while the easterly ones (from the Eurasian continent) the polar-continental air masses, are much cooler compared to the coastal waters of the southern Baltic Sea. A clear thermal difference between the westerly and easterly air masses distinctly affects the respective increases and decreases of water temperatures, which are reflected by the strong correlational relationships between these variables.

The relationships of the water temperature with the NE + E + SE circulation in winter are slightly weaker than with the SW + W + NW circulation, but they are also statistically significant at a level of α = 0.001. An upwelling (the inflow of warmer waters) may weaken these relationships, especially under the NE + E + SE circulation in winter. The correlations and regression coefficients are negative, which indicates that a greater frequency of the NE + E + SE circulation in winter corresponds to the water temperature decrease. That circulation has the opposite effect on the water temperature in summer. During the summer season, relatively small thermal differences between the incoming air masses are observed, and thereby small water temperature variations are present, which may affect weak relationships. Simultaneously, a significant influence of the eastern anticyclonic circulation (NEa + Ea + SEa) on the water temperature in bays is noticeable, particularly in the relatively shallow Pomeranian Bay. The NEa + Ea + SEa circulation is frequently accompanied by cloudless weather or weather with low cloud cover, favouring an increase of the solar radiation inflow affecting the water temperature rise.

Atmospheric circulation of a different type than SW + W + NW or SE + E + SE occurs during approximately 34% (i.e. 31) of days. On these days, with circulation 0 (14%, 13 days), N (10%, 9 days) and S (10%, 9 days) the advection of air with a distinctly different temperature can happen. Advection from the N direction brings cold air masses, while from the S direction — warm ones. This will have an effect on the weakening correlations between the average water temperature and the number of days with SW + W + NW or with NE + E + SE circulation.

The water temperature in February and May has a significant impact on the water temperature in spring (March—May) and summer (June—August). In other words, the water temperature in the months directly preceding a given season (spring or summer) directly influences the water temperature of that season. At the same time, the influence of atmospheric circulation on the water temperature weakens in those two seasons. In turn, the water temperature in winter and autumn is not significantly affected by the water temperature in the months preceding those seasons. The atmospheric circulation is of greater influence at the time (particularly in winter). It affects both air and water temperature. Average seasonal air temperatures exert a significant influence on the seasonal water temperatures, and the correlation coefficient is the highest in winter and spring. Average water temperature values in individual seasons and appropriate seasonal average air temperatures show stronger relationships than between average water temperature values and the number of days with SW + W + NW or NE + E + SE circulation.

No distinct spatial differentiation of the correlation coefficient value was found in winter, with the number of days of both the SW + W + NW and NE + E + SE circulation patterns alongside the southern Baltic Sea coast. Still, the correlation coefficients on the eastern coast, particularly in Władysławowo and in Gdynia, are slightly higher (in these stations variabilities of average water temperature in winter are explained by the number of days with SW + W + NW circulation in 51% and 50% respectively). That coefficient variability could have been caused by increases of continentalism and the degree of winter severity in the eastern direction. The influence of continentalism on the strength of relationships is most visibly demonstrated in the relation between the number of days with NE + E + SE circulation pattern and the accompanying intensity of the cooler weather in winter, in the eastern direction. However, a differentiation of these coefficients (SST and circulation) between sheltered waters (bays) and non-sheltered waters in summer is evident. During this season, in Pomeranian Bay and the Bay of Gdańsk, the relationships are statistically significant, whereas alongside the open (unsheltered) Baltic Sea coast they are statistically insignificant. The difference in strength is chiefly affected by local conditions, such as upwellings and the inflows of river waters. Upwellings reducing surface water temperature occur alongside the open shores during eastern circulation in summer. The influence of an upwelling on water temperature is, thus, opposite to the influence exerted by circulation factors. In summer the upwelling, next to poor atmospheric circulation activity and strong insolation, is one of the factors weakening the relationships of water temperature with the number of days with NE + E + SE circulation. The phenomenon of upwelling does not occur in Pomeranian Bay and the Bay of Gdańsk, therefore, it does not disturb the correlational relationships. At the same time, the inflow of river waters to those bays has a positive effect on the relationships. In summer, during NE + E + SE circulation (especially of the anticyclonic types), accompanied by the weather with the cloudless sky (or with a little cloud cover) and high solar radiation, the water temperature rises. At the same time, a discharge from rivers brings warm water masses into the bays. Conversely, during the SW + W + NW circulation pattern, when cold air masses from the ocean come in accompanied by cloudy weather (especially during the cyclonal circulation), water temperature decreases. Concurrently, colder river waters flow in. Hence, atmospheric circulation factors together with the river water inflow have a similar effect on the water temperature of the bays. Consequently, it translates to statistically significant correlational relationships, despite the poor circulation activity in summer.

Asynchronous relationships between water temperature and the number of days with atmospheric circulation may offer a certain prognostic possibility. It is based on winter and spring correlations of water temperature with the number of days with atmospheric circulation, and averaged water temperature of the preceding season. These are all statistically highly significant relationships (α = 0.001) for both circulation patterns — NE + E + SE and SW + W + NW — presented in a number of days. As time intervals (seasonal intervals) increase between the variables, their relationships weaken. However, two-season intervals continue to be significant, i.e. between the number of days with spring circulation and water temperature in autumn in the stations located closer to deeper regions of the Baltic Sea (Hel, Gdynia).

Statistical significance of asynchronous relationships may be affected by ongoing atmospheric circulation, i.e. occurring while the seasonal temperature data is gathered. The circulation synchronised time-wise with water temperature may either improve or deteriorate correlation relationships. Other factors, both meteorological and hydrological ones, can have a similar effect.

Many other factors, aside from atmospheric circulation, can affect the statistical significance of synchronous and asynchronous relationships. Those relationships would be stronger if circulation patterns accounted for advection intensity. As it is, the significance of such relationships depends on, inter alia: intensity of solar radiation, air temperature, upwelling or river water inflow of differing thermal properties. However, the examination of the impact of those factors on water temperature was omitted, as it would exceed the envisaged scope of the paper.

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References

Andersson, H., 2002. Influence of long-term regional and large-scale atmospheric circulation on the Baltic sea level. Tellus A 54 (1), 76—88, http://dx.doi.org/10.1034/j.1600-0870.2002.00288.x.

Bengtsson, L., Hodges, K.I., Roeckner, E., Brokopf, R., 2006. On the natural variability of the pre-industrial European climate. Clim. Dynam. 27 (7—8), 743—760, http://dx.doi.org/10.1007/s00382-006-0168-y.

Bradtke, K., Herman, A., Urbański, J., 2010. Spatial and interannual variations of seasonal sea surface temperature patterns in the Baltic Sea. Oceanologia 52 (3), 345—362, http://dx.doi.org/10.5697/oc.52-3.345.

Brayshaw, D., 2005. Storm Tracks Under Climate Change. rdg.ac.uk.

Bychkova, I.A., Victorov, S.V., 1987. Use of satellite data for identification and classification of upwelling in the Baltic Sea. Oceanology 27 (2), 158—162.

Cyberska, B., 1994. Water temperature. In: Majewski, A., Lauer, Z. (Eds.), Atlas of the Baltic Sea, Wyd. IMGW, Warszawa, 214 pp., (in Polish).

Cyberska, B., Launer, Z., Trzosińska, A (Eds.), 1986. Environmental conditions of the Polish zone of the southern Baltic Sea, Mater. IMGW, Gdynia, (in Polish).

Gidhagen, L., 1987. Coastal upwelling in the Baltic Sea — satellite and in situ measurements of sea-surface temperatures indicating coastal upwelling. Estuar. Coast. Shelf. Sci. 24, 449—462.

Girjatowicz, J.P., 1987. Hydrological and meteorological causes of the occurrence of ice cover inversion in the southern Baltic. Ann. Sci. Stetinenses 2 (2), 45—51, (in Polish).

Girjatowicz, J.P., 1999. The influence of atmospheric circulation on water temperature at the Polish Baltic in cold half-year, Inż. Mor. Geotech. 1, 4—7, (in Polish).

Girjatowicz, J.P., 2001. Effects of atmospheric circulation on ice conditions in the Southern Baltic coastal lagoons. Int. J. Climatol. 21 (13), 1593—1605, http://dx.doi.org/10.1002/joc.698.

Girjatowicz, J.P., 2008. The relationships of the Nord Atlantic Oscillation to water temperature along the southern Baltic Sea Coast. Int. J. Climatol. 28, 1071—1081, http://dx.doi.org/10.1002/joc.1618.

Gurova, E., Lehmann, A., Ivanov, A., 2013. Upwelling dynamics in the Baltic Sea studied by a combined SAR/infrared satellite data and circulation model analysis. Oceanologia 55 (3), 687—707, http://dx.doi.org/10.5697/oc.55-3.687.

Hagen, E., Feinstel, R., 2005. Climatic turning points and regime shifts in the Baltic sea region: the Baltic winter index (1659—2002). Boreal Environ. Res. 10, 211—224.

Hydrographic Yearbook of the Baltic Sea, 1950–1970, Wyd. Komunik. Łącz., Warszawa, (in Polish).

Hydrological and Meteorological Marine Bulletin, 1961–1990, Wyd. IMGW, Warszawa, (in Polish).

Kowalewska-Kalkowska, H., Lejman, J., 2002/2003. Changes of water physical features as indicators of the convection movements in the Coastal Zone of the Pomeranian Bay. Baltic Coast. Zone (7), 5—20.

Kowalewski, M., 2016. Water Temperature (PM3D model). www.satbaltyk.pl.

Kowalewski, M., Ostrowski, M., 2005. Coastal up- and downwelling in the southern Baltic. Oceanologia 47 (4), 453—475.

Kozlov, I., Kudryavtsev, V., Johannessen, J., Chapron, B., Dailidiene, I.I., Myasoedov, A., 2012. ASAR imaging for coastal upwelling in the Baltic Sea. Adv. Space Res. 50 (8), 1125—1137, http://dx.doi.org/10.1016/j.asr.2011.08.017.

Koźmiński, Cz., Michalska, B., 2005. Sunshine in Poland. Akad. Rol., Szczecin 110 pp., (in Polish).

Kożuchowski, K., Marciniak, K., 1988. Variability of mean monthly temperatures and semi-annual precipitation totals in Europe in relation to hemispheric circulation patterns. J. Climatol. 8 (2), 191—199, http://dx.doi.org/10.1002/joc.3370080206.

Krężel, A., 1997. Recognition of mesoscale hydrophysical anomalies in a shallow sea using broadband satellite teledetection methods. Uniw. Gdańsk., Gdańsk, 173 pp., (in Polish).

Krężel, A., Ostrowski, M., Szymelfenig, M., 2005. Sea surface temperature distribution during upwelling along Polish Baltic coast. Oceanologia 47 (4), 415—432.

Krzymiński, W, Łysiak-Pastuszak, E, Miętus, M (Eds.), 1999. Environmental conditions in the Polish Zone of the southern Baltic Sea, Mater. IMGW, Gdynia, (in Polish).

Lamb, H.H., 1978. Climate: Present, Past and Future. Methuen, London, 825 pp.

Leckebusch, G.C., Ulbrich, U., 2004. On the relationship between cyclones and extreme windstorm events over Europe under climate change,. Global Planet. Change 44 (1—4), 181—193, http://dx.doi.org/10.1016/j.gloplacha.2004.06.011.

Lehmann, A., Myrberg, K, Höflich, K., 2012. A statistical approach to coastal upwelling in the Baltic Sea based on the analysis of satellite data for 1990—2009. Oceanologia 54 (3), 369—393, http://dx.doi.org/10.5697/oc.54-3.369.

Leppäranta, M., Myrberg, K., 2009. Physical Oceanography of the Baltic Sea. Springer and Praxis Publishing, Berlin, 371 pp.

Lityński, J., 1969. A numerical classification of circulation patterns and weather types in Poland. Prace Państwowego Instytutu Hydrologiczno-Meteorologicznego, 3—15, 97 pp., (in Polish).

Löptien, U., Zolina, O., Gulev, S., Latif, M., Soloviov, V., 2008. Cyclone life cycle characteristics over the Northern Hemisphere in coupled GCMs. Clim. Dynam. 31 (5), 507—532, http://dx.doi.org/10.1007/s00382-007-0355-5.

Łomnicki, A., 1999. Introduction to Statistics for Naturalists. Wydawnictwo Naukowe PWN, Warszawa, 263 pp. (in Polish).

Łomniewski, K., 1960. Thermohaline relations in the coastal zone of the southern Baltic Sea, Zeszyty Geograficzne 2. Wydawnictwo Wyższej Szkoły Pedagogicznej, Gdańsk, 45—74, (in Polish).

Marsz, A., 1999. The North Atlantic Oscillation and the thermal regime of waters in the area of north—west Poland and the Polish coast of the Baltic Sea. Przegl. Geogr. 71 (3), 225—245, (in Polish).

Marsz, A.A., Styszyńska, A. (Eds.), 2002. North Atlantic Oscillation and its role in shaping of variability of climate and hydrological conditions in Poland. Akad. Mor., Gdynia, 222 pp., (in Polish).

Miętus, M (Ed.), 1997. The climate of the Baltic Sea basin, WMO/TD-No. 933. IMGW, Gdynia, 185 pp.

Miętus, M., 1999. The role of atmospheric circulation over Europe and north Atlantic in forming climatic and oceanographic conditions in the Polish coastal zone, Mater. Bad., ser. Meteorologia 29. IMGW, Warszawa, 157 pp., (in Polish).

Miętus, M, Łysiak-Pastuszak, E, Zalewska, T., Krzymiński, W (Eds.), 2002—2010. Southern Baltic Sea — environmental conditions, Mater. IMGW, Gdynia, (in Polish).

Myrberg, K., Andrejev, O., 2003. Main upwelling regions in the Baltic Sea — a statistical analysis based on three-dimensional modelling,. Boreal Environ. Res. 8, 97—112.

Omstedt, A., Elken, J., Lehmann, A., Leppäranta, M., Meier, H.E.M., Myrberg, K., Rutgersson, A., 2014. Progress in physical oceanography of the Baltic Sea during the 2003—2014 period. Prog. Oceanogr. 128, 139—171, http://dx.doi.org/10.1016/j.pocean.2014.08.010.

Paszkuta, M., Stoń-Egiert, J., Stramska, M., Zapadka, T., 2012. Practical applicability and preliminary results of the Baltic Environmental Satellite Remote Sensing System (SatBaltic), Geophys. Res. Abstracts 14, EGU2012-12987.

Pianko-Kluczyńska, K., 2006. New calendar of types of atmospheric circulations according to J. Lityński. IMGW, Warszawa, 123 pp., (in Polish).

Rozwadowska, A., 1992. The variability of solar energy inflow to the southern Baltic Sea, typescript of PhD dissertation, IO PAS, Sopot. 140 pp., (in Polish).

Sepp, M., Post, P., Jaagus, J., 2005. Long-term changes in the frequency of cyclones and their trajectories in Central and Northern Europe. Nord. Hydrol. 36 (4—5), 297—309.

Siegel, H., Gerth, M., Schmidt, T., 1996. Water exchange in the Pomeranian Bight investigated by satellite data and shipborne measurements. Cont. Shelf Res. 16 (14), 1793—1817, http://dx.doi.org/10.1016/0278-4343(96)00012-X.

Siegel, H., Gerth, M., Tiesel, R., Tschersich, G., 1999. Seasonal and interannual variation in satellite derived sea surface temperature of the Baltic Sea in the 1990s. German J. Hydrogr. 51 (4), 407—422, http://dx.doi.org/10.1007/BF02764163.

Siegel, H., Gerth, M., Tschersich, G., 2006. Sea surface temperature development of the Baltic Sea in the period 1990—2004. Oceanologia 48 (S), 119—131.

Siegel, H., Gerth, M., Tscherisich, G., 2008. Satellite-derived sea surface temperature for the period 1990-2005. In: Feistel, R., Nausch, G., Wasmund, N. (Eds.), State and evolution of the Baltic Sea. Wiley Interscience, Warnemünde, 207—217.

Stramska, M., Białogrodzka, J., 2015. Spatial and temporal variability of sea surface temperature in the Baltic Sea based on 32-years (1982—2013) of satellite data. Oceanologia 57 (3), 223—235, http://dx.doi.org/10.1016/j.oceano.2015.04.004.

Time Series Analysis. Section III, 2010, Department of Statistics, Univ. Oxford, Oxford, 47 pp.

Uiboupin, R., Laanemets, J., 2009. Upwelling characteristics derived from satellite sea surface temperature data in the Gulf of Finland, Baltic Sea,. Boreal Environ. Res. 14, 297—304.

Urbański, J., 1995. Upwellings along the Polish coast of the Baltic Sea. Przegl. Geofiz. 40 (2), 141—153, (in Polish).

Walther, A., Bennartz, R., 2006. Radar-based precipitation type analysis in the Baltic area. Tellus A 58 (3), 331—343, http://dx.doi.org/10.1111/j.1600-0870.2006.00183.x.

Woźniak, B., Bradtke, K., Darecki, M., Dera, J., Dudzińska-Nowak, J., Dzierzbicka-Głowacka, L., Ficek, D., Furmańczyk, K., Kowalewski, M., Krężel, A., Majchrowski, R., Ostrowska, M., Paszkuta, M., Stoń-Egiert, J., Stramska, M., Zapadka, T., 2011a. SatBałtyk — a Baltic environmental satellite remote sensing system — an ongoing project in Poland, Part 1: Assumptions, scope and operating range. Oceanologia 53 (4), 897—924, http://dx.doi.org/10.5697/oc.53-4.897.

Woźniak, B., Bradtke, K., Darecki, M., Dera, J., Dudzińska-Nowak, J., Dzierzbicka-Głowacka, L., Ficek, D., Furmańczyk, K., Kowalewski, M., Krężel, A., Majchrowski, R., Ostrowska, M., Paszkuta, M., Stoń-Egiert, J., Stramska, M., Zapadka, T., 2011b. SatBałtyk — a Baltic environmental satellite remote sensing system — an ongoing project in Poland, Part 2: Practical applicability and preliminary results. Oceanologia 53 (4), 925—958, http://dx.doi.org/10.5697/oc.53-4.925.

Woźniak, B., Krężel, A., Darecki, M., Woźniak, S., Majchrowski, R., Ostrowska, M., Kozłowski, Ł., Ficek, D., Olszewski, J., Dera, J., 2008. Algorithm for remote sensing of the Baltic ecosystem (DESAMBEN). Part 1: Mathematical Apparatus. Oceanologia 50 (4), 451—508.