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Effect of Teleconnection Patterns on Changes in Water Temperature in Polish Lakes

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Abstract: The objective of the paper was the determination of the effect of teleconnection patterns (North Atlantic Oscillation (NAO), Arctic Oscillation (AO), East Atlantic pattern (EA), East Atlantic/Western Russia (EAWR), and Scandinavian pattern (SCAND)) on changes in air and water temperature in Polish lakes. Correlations of circulation indices with air and lake water temperature were analysed in the monthly cycle. Deviations of values of such components in different phases of the analysed atmospheric circulations types from mean average from the years 1971 to 2015 were also determined. The research showed a variable effect of the atmospheric circulations types. The strongest effect on water temperature was observed in winter, when AO and NAO circulation showed particularly evident influence. Deviations of water temperature from mean values from the analysed multi-annual period generally oscillated around 1.0 °C, reaching a maximum value of 1.4 °C. The presented research shows the complexity of processes determining changes in lake water temperature, the course of which depends on many factors with both regional (e.g., ice cover on lakes) and local range (conditions of water exchange, human pressure).

Keywords: teleconnection patterns; air temperature; water temperature; lakes; Central Europe

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1. Introduction

Due to the strong dependency of hydrological processes on climatic conditions, in the context of the climate warming observed over the last decades, an extensive transformation of the functioning of lakes is observed. This refers to water level fluctuations [1], ice phenomena [2], as well as water temperature [3]. In addition to the research trend concerning the assessment of long-term tendencies of changes in the hydrosphere in the times of global warming, numerous studies refer to the effect of types of macroscale circulation of the atmosphere on its different components. Such research has been conducted in many regions of the world [4–8]. In the case of Central Europe, one of the main macroscale atmospheric circulation patterns determining climatic conditions is the North Atlantic Oscillation (NAO). Changes in its intensity affect, among other things, the course of precipitation and air temperature [9,10]. Whereas in the case of NAO the relationships are relatively thoroughly investigated, in the case of other circulation patterns, such an approach still requires more detailed research [11,12]. In addition to the aforementioned circulation type, climatic conditions in Europe (with variable intensity) are affected by other circulation patterns, including the Arctic Oscillation (AO), East Atlantic pattern (EA), East Atlantic/Western Russia (EAWR), and the Scandinavian pattern (SCAND). The analysis of the effect of many types of atmospheric circulations is undertaken in reference to both climatic and hydrological conditions [13–16].

Temperature is one of the primary water parameters [17,18]. Its distribution and variability determines the course of many processes occurring in lakes. The key role of temperature is evident in reference to biotic [19–22]. Temperature deviations caused by the effect of macroscale circulation will determine seasonal changes in the functioning of lake ecosystems. In the case of Lake Washington (USA), Winder and Schindler [23] observed that long-term climate warming and variability of macroscale climate indices (PDO and ENSO) prolonged the stratification period by 25 days over 40 years. Van Cleave et al. [24] identified a change in the regime of Lake Superior related to El Niño referring among others to water temperature and ice cover. Molinero et al. [25] determined that water temperature in Lake Geneva in the summer period was sensitive to teleconnection patterns, and as a consequence had an effect on among others the abundance of particular zooplankton species. In the case of 38 lakes in Finland, it was determined [26] that benthic organisms responded to short-term teleconnection patterns (NAO). The above examples show how conditions resulting from atmospheric circulation can transform the physical and biological parametres of lakes. It is key to refer to water temperature as one of its elementary parameters determining the general functioning of lake ecosystems through numerous interactions with other phenomena and processes. The effect of NAO on thermal conditions of lakes in Europe is confirmed by many studies [27–31]. In the context of functioning of lake ecosystems in Europe, other teleconnection patterns were also considered [32–34], showing their complex dependencies.

According to the above, the role of teleconnection patterns can be considerable for the functioning of lake ecosystems, and the results obtained in the paper will constitute a reference point for broader interdisciplinary research in the future. The issue discussed in the paper, namely the effect of teleconnection patterns, refers to postulates emphasising the need of more detailed investigation of the effect of different patterns of atmospheric circulation in this part of Europe. In this context, the obtained results enrich the knowledge in reference to air and lake water temperature.

The objective of the paper was the determination of the temporal and spatial effect of teleconnection patterns (NAO, AO, EA, EAWR, SCAND) on changes in water temperature in Polish lakes. It was implemented by means of determination of correlations of circulation type indices with air and lake water temperature, and determination of deviations of values of the components in different phases of the analysed atmospheric circulations types from average values from the years 1971 to 2015.

2. Materials and Methods

2.1. Study Lakes

The data were compared for 10 lakes (Figure 1, Table 1) located in the area of three main lakelands in Poland. In terms of their genesis, the majority of lakes represent the post-glacial type, with the exception of Lake Gardno that developed as a result of cutting off a sea bay.

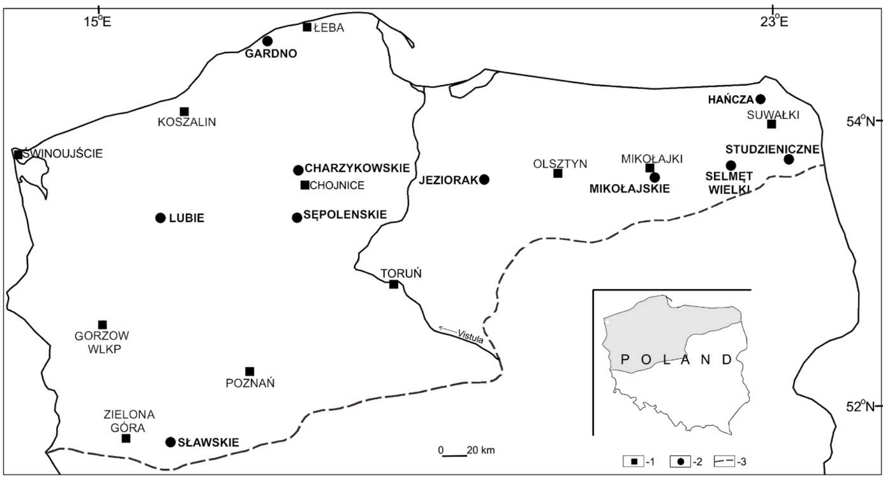

Figure 1. Location of study objects: 1—meteorological stations, 2—lakes, 3 (dashed line)—maximum range of the last glaciation.

Table 1. Morphometric data of the studied lakes.

No.	Lake	Area (ha)	Volume (thous.m^3)	Depth (m)	
				Average	Max
1	Sławskie	822.5	42,664.8	5.2	12.3
2	Lubie	1487.5	169,880.5	11.6	46.2
3	Sępoleńskie	157.5	7501.6	4.8	10.9
4	Charzykowskie	1336	134,533.2	9.8	30.5
5	Gardno	2337.5	30,950.5	1.3	2.6
6	Jeziorak	3152.5	141,594.2	4.1	12.9
7	Mikołajskie	424	55,739.7	11.2	25.9
8	Selmęt Wielki	1207.5	99,463.9	7.8	21.9
9	Studzieniczne	244	22,073.6	8.7	30.5
10	Hańcza	291.5	120,364.1	38.7	106.1

2.2. Data

The study applied data on surface water temperature in 10 lakes, and mean daily air temperatures in 11 meteorological stations from the collection of the Institute of Meteorology and Water Management—State Research Institute from the years 1971 to 2015. In limnological studies, surface water temperature is associated with the epilimnion, i.e., water layer remaining in contact with the atmosphere [35]. Point measurements of lake water temperature were conducted at a depth of 0.4 m, every day at 7:00 (GMT + 1). Mean daily air temperature constitutes the result from four measurements.

The paper applied monthly indices of five macroscale atmospheric circulations types, namely the NAO, AO, EA, EAWR, and SCAND. Data for the years 1971–2015 were obtained from databases of the Climate Prediction Centre of NOAA (CPC NOAA) (http://www.cpc.ncep.noaa.gov/data/teledoc/telecontents.shtml). The aforementioned website also includes diagrams of particular teleconnections providing the basis for many studies concerning teleconnection patterns [36–38], similarly as this paper. The loading patterns for January, April, July, and October, are displayed so that the plotted value at each grid point represents the temporal correlation between the monthly standardized height anomalies at that point and the teleconnection pattern time series valid for the specified month. The methodology of designation of teleconnection patterns (except for AO) at the baric height of 500 hPa is based on the principal components analysis with rotation of principal components, applied by Barnston and Livezey [39].

2.3. Analysis

Mean monthly air temperature and mean lake water temperature was calculated based on daily values of air temperatures and lake water temperatures. The calculated mean value is the arithmetic mean.

The first stage of works involved the calculation of the Spearman's coefficient of correlation between mean monthly air and lake water temperature. Then, statistical significance was analysed at a level of $p = 0.05$ and $p = 0.01$

The next stage of works involved the calculation of the Spearman's rank correlation coefficient between monthly indices of the analysed atmospheric circulations types and mean monthly air and lake water temperature. The Spearman's rank correlation test is a non-parametric test applied in analyses of correlations between quantitative parameters in the case of a low number of observations or those with statistic distribution deviating from normal. The test employs the linear regression method (similarly as in the case of the Pearson's correlation coefficient), however, the correlation coefficient is calculated based on ranks ascribed to variables. The calculations were performed with Statistica 12 software (Statistica, Tulsa, OK, USA).

Changes in monthly air and lake water temperatures in different phases of the analysed macroscale atmospheric circulations types were determined based on differences of such parameters in the positive and negative phase in comparison to mean values from the years 1971 to 2015. At the first stage, monthly temperatures were calculated for the entire study period 1971–2015, and then for 11 years with high, and 11 years with low values of indices of the discussed atmospheric circulations types. The threshold values correspond to the first and third quartile from the entire collection of indices in the years 1971–2015. The statistical significance of differences was analysed by means of *t*-test for dependent samples. Each time hypothesis $H_0{:}\mu = \mu_0$ with equality of expected values was tested against $H_1{:}\mu \neq \mu_0$. Rejection of the hypothesis suggests significant differences between mean temperatures observed in different phases and their mean values from the years 1971 to 2015. The verification of the hypothesis involved the application of a test for a small sample based on Student's t distribution, with $n - 1$ degrees of freedom:

$$t = \left| \frac{\overline{x} - \mu_0}{s} \sqrt{n} \right| \quad (1)$$

where n is the sample abundance, s is the standard deviation, $\overline{x}$ is the mean from the sample, and μ_0 is the mean from the population.

Since sequences of hydro-meteorological data can suggest autocorrelation, the preliminary data analysis involved the determination of autocorrelation in monthly sequences of air and lake water temperatures with a time step from 1 to 12 time units (months). In the case of air temperature series, significant autocorrelation coefficients were obtained only for series in April, and for lake water temperatures also in August. Statistical significance can be overestimated in the case of series with considerable autocorrelations, and results of statistical analyses should be interpreted with caution.

The spatial variability of the observed changes in temperature was presented in the form of a table and figure. The graphic representation applied Surfer 10 software (Golden Software, Golden, CO, USA), and the construction of isoline maps was based on the kriging procedure.

3. Results

The dependency between air and water temperature in all of the analysed cases is very strong. In the monthly cycle, lake water temperatures correlated positively and statistically significantly ($p < 0.01$; except for November in the case of Lake Hańcza) with air temperatures. The strongest correlations were recorded in July, where in several cases the correlation coefficient was higher than 0.90. In the annual cycle, the strongest effect of air temperature on water temperature is observed in the case of Lake Gardno (the shallowest among the analysed lakes), and the weakest in the case of Lake Hańcza (the deepest of the lakes).

3.1. Correlations

3.1.1. NAO

Correlations were analysed between monthly air temperature and monthly NAO index. The analysis showed a positive correlation. The strongest effect of NAO on thermal conditions was observed in the period from December to March. The calculated correlation coefficients were high (in December and January in the majority of stations >0.60) and statistically significant at a level of $\leq$0.01 (Table 2a). Correlations between monthly lake water temperature and monthly NAO index from December to March were statistically significant at a level of $\leq$0.05. The strongest correlation, however, was determined in January. The calculated correlation coefficients were high, and varied from 0.39 to 0.62. The correlations were particularly high in the western part of the study area. The analysis showed a positive correlation (Table 2b).

Table 2. Spearman's coefficient of correlation between indices of macroscale atmospheric circulations types and air (**a**) and lake water temperature (**b**) in Poland, orange color—positive correlation, $p < 0.01$; yellow color—positive correlation, $p < 0.05$; dark-blue—negative correlation, $p < 0.01$; light blue—negative correlation, $p < 0.05$.

(a)

	Meteorological Station \ Month	January	February	March	April	May	June	July	August	September	October	November	December
NAO	Chojnice	0.65	0.47	0.52	0.17	0.13	0.22	0.16	0.11	0.22	0.20	0.25	0.66
	Gorzów Wlkp	0.69	0.49	0.49	0.23	0.08	0.08	0.21	0.12	0.23	0.17	0.26	0.70
	Koszalin	0.64	0.53	0.55	0.26	0.19	0.16	0.12	0.07	0.23	0.21	0.31	0.64
	Łeba	0.62	0.49	0.54	0.17	0.11	0.24	0.12	0.04	0.23	0.22	0.31	0.59
	Mikołajki	0.65	0.52	0.43	0.09	0.03	0.15	0.09	0.08	0.19	0.20	0.16	0.65
	Olsztyn	0.66	0.52	0.46	0.10	0.04	0.20	0.11	0.01	0.19	0.24	−0.11	0.47
	Poznań	0.69	0.49	0.47	0.16	0.08	0.04	0.16	0.02	0.19	0.16	0.19	0.68
	Suwałki	0.61	0.52	0.50	0.02	0.00	0.16	0.04	0.08	0.16	0.13	−0.14	0.47
	Świnoujście	0.68	0.50	0.55	0.30	0.09	0.24	0.19	0.13	0.27	0.24	0.32	0.65
	Toruń	0.67	0.52	0.45	0.17	0.10	0.23	0.13	0.04	0.20	0.10	0.16	0.65
	Zielona Góra	0.66	0.47	0.41	0.21	0.08	0.04	0.17	0.07	0.26	0.18	0.19	0.58
AO	Chojnice	0.71	0.42	0.54	0.04	0.28	0.18	0.23	0.25	0.47	0.37	0.33	0.54
	Gorzów Wlkp	0.67	0.42	0.51	0.05	0.30	0.06	0.21	0.27	0.55	0.35	0.29	0.54
	Koszalin	0.69	0.42	0.53	0.08	0.34	0.15	0.21	0.19	0.50	0.35	0.34	0.51
	Łeba	0.73	0.44	0.57	0.10	0.41	0.19	0.25	0.18	0.49	0.40	0.37	0.56
	Mikołajki	0.68	0.46	0.52	0.10	0.19	0.11	0.21	0.22	0.46	0.37	0.31	0.52
	Olsztyn	0.70	0.47	0.55	0.06	0.15	0.17	0.22	0.21	0.48	0.41	0.15	0.41
	Poznań	0.65	0.41	0.49	0.03	0.27	0.00	0.18	0.20	0.50	0.30	0.24	0.52
	Suwałki	0.68	0.47	0.57	0.09	0.09	0.13	0.21	0.22	0.42	0.33	0.13	0.43
	Świnoujście	0.68	0.45	0.56	0.19	0.37	0.22	0.23	0.26	0.50	0.37	0.34	0.54
	Toruń	0.67	0.43	0.51	0.10	0.25	0.20	0.21	0.25	0.48	0.35	0.25	0.50
	Zielona Góra	0.64	0.41	0.47	0.10	0.30	0.03	0.14	0.25	0.52	0.32	0.27	0.41
EA	Chojnice	0.27	0.36	0.28	0.43	0.29	0.19	0.31	0.33	0.63	0.57	0.53	0.04
	Gorzów Wlkp	0.24	0.37	0.35	0.42	0.30	0.17	0.22	0.34	0.69	0.57	0.55	0.07
	Koszalin	0.26	0.33	0.26	0.36	0.34	0.27	0.37	0.38	0.64	0.56	0.48	0.09
	Łeba	0.30	0.31	0.23	0.45	0.37	0.25	0.39	0.32	0.61	0.50	0.41	–0.04
	Mikołajki	0.27	0.32	0.25	0.39	0.23	0.13	0.44	0.33	0.60	0.53	0.53	0.04
	Olsztyn	0.28	0.32	0.30	0.48	0.26	0.17	0.41	0.40	0.62	0.57	0.19	0.06
	Poznań	0.27	0.41	0.34	0.48	0.34	0.17	0.29	0.38	0.70	0.60	0.58	0.11
	Suwałki	0.20	0.31	0.24	0.43	0.13	0.10	0.48	0.32	0.54	0.52	0.16	−0.03
	Świnoujście	0.22	0.31	0.34	0.48	0.42	0.21	0.27	0.27	0.63	0.57	0.42	0.00
	Toruń	0.26	0.36	0.36	0.48	0.31	0.21	0.32	0.41	0.64	0.57	0.61	0.07
	Zielona Góra	0.24	0.44	0.35	0.49	0.33	0.14	0.16	0.32	0.72	0.60	0.53	0.11

Table 2. *Cont.*

(a)

	Month / Meteorological Station	January	February	March	April	May	June	July	August	September	October	November	December
EAWR	Chojnice	0.07	0.03	0.10	0.07	0.02	−0.15	0.16	0.12	−0.41	−0.05	−0.18	0.29
	Gorzów Wlkp	0.03	−0.03	0.09	0.15	0.09	0.00	0.20	0.11	−0.31	−0.06	−0.16	0.30
	Koszalin	0.09	−0.04	0.08	0.08	0.01	−0.04	0.19	0.03	−0.34	−0.06	−0.13	0.31
	Łeba	0.09	0.00	0.01	0.03	−0.16	−0.16	0.16	−0.03	−0.43	−0.02	−0.16	0.39
	Mikołajki	0.06	−0.02	0.05	−0.16	−0.16	−0.20	0.06	0.04	−0.44	−0.15	−0.30	0.25
	Olsztyn	0.02	−0.01	0.13	−0.14	−0.18	−0.18	0.05	0.04	−0.44	−0.05	−0.36	0.17
	Poznań	0.01	−0.06	0.13	0.02	0.05	0.05	0.14	0.09	−0.37	−0.10	−0.23	0.25
	Suwałki	0.11	−0.03	0.11	−0.18	−0.23	−0.26	0.01	−0.01	−0.50	−0.18	−0.39	0.14
	Świnoujście	0.07	0.01	0.01	0.14	0.00	−0.12	0.26	0.06	−0.37	0.01	−0.16	0.38
	Toruń	0.00	−0.05	0.11	−0.04	−0.03	−0.13	0.13	0.09	−0.39	−0.10	−0.23	0.25
	Zielona Góra	0.01	−0.01	0.14	0.14	0.22	0.13	0.28	0.13	−0.33	−0.03	−0.18	0.23
SCAND	Chojnice	−0.42	−0.49	−0.23	0.28	0.33	0.15	0.17	0.09	0.10	0.25	0.16	0.00
	Gorzów Wlkp	−0.38	−0.49	−0.28	0.22	0.17	−0.07	0.12	0.00	0.01	0.25	0.14	−0.06
	Koszalin	−0.41	−0.47	−0.23	0.22	0.33	0.08	0.18	0.14	0.12	0.27	0.17	−0.02
	Łeba	−0.42	−0.49	−0.23	0.18	0.20	0.10	0.25	0.12	0.03	0.21	0.12	−0.03
	Mikołajki	−0.43	−0.51	−0.36	0.24	0.40	0.24	0.23	0.10	0.07	0.18	0.17	−0.06
	Olsztyn	−0.45	−0.50	−0.19	0.25	0.46	0.23	0.19	0.10	0.02	0.17	0.18	−0.03
	Poznań	−0.35	−0.46	−0.25	0.21	0.23	−0.10	0.15	0.03	0.07	0.30	0.21	−0.02
	Suwałki	−0.50	−0.47	−0.21	0.26	0.46	0.30	0.23	0.15	0.09	0.14	0.16	−0.08
	Świnoujście	−0.40	−0.51	−0.36	0.07	0.03	−0.02	0.17	0.12	0.12	0.27	0.11	−0.05
	Toruń	−0.42	−0.48	−0.27	0.22	0.31	0.07	0.17	0.09	0.06	0.17	0.19	−0.07
	Zielona Góra	−0.34	−0.44	−0.29	0.18	0.11	−0.16	0.07	−0.05	0.02	0.28	0.12	0.05

(b)

	Month / Lakes	January	February	March	April	May	June	July	August	September	October	November	December
NAO	Sławskie	0.62	0.54	0.43	0.18	−0.04	0.06	0.09	−0.04	0.31	0.04	0.21	0.47
	Lubie	0.44	0.46	0.37	0.32	−0.06	0.08	−0.04	−0.13	0.21	−0.04	0.13	0.41
	Gardno	0.57	0.57	0.44	0.12	0.18	0.24	0.13	−0.05	0.27	0.23	0.28	0.53
	Sępoleński	0.54	0.42	0.49	0.20	−0.07	0.16	0.08	0.08	0.27	−0.06	0.18	0.43
	Charzykowskie	0.62	0.44	0.41	0.26	−0.03	0.11	0.08	0.07	0.31	−0.03	0.29	0.40
	Jeziorak	0.39	0.29	0.48	0.13	−0.03	0.12	0.08	0.07	0.14	−0.03	0.28	0.36
	Mikołajskie	0.52	0.32	0.41	0.11	−0.02	0.14	0.03	−0.04	0.26	−0.14	0.19	0.27
	Studzieniczne	0.39	0.38	0.34	0.03	−0.04	0.13	0.02	−0.06	0.31	−0.15	0.07	0.34
	Selmęt Wielki	0.48	0.50	0.52	0.01	0.00	0.19	0.05	−0.18	0.30	−0.13	0.14	0.29
	Hańcza	0.46	0.39	0.44	0.15	−0.10	0.07	0.15	0.04	0.23	−0.06	0.23	0.34

Table 2. *Cont.*

(b)

	Lakes \ Month	January	February	March	April	May	June	July	August	September	October	November	December
AO	Sławskie	0.54	0.57	0.53	0.34	0.32	0.04	0.10	0.24	0.56	0.18	0.30	0.26
	Lubie	0.36	0.50	0.48	0.33	0.37	0.08	0.17	0.16	0.38	0.13	0.29	0.33
	Gardno	0.62	0.50	0.49	0.17	0.37	0.20	0.15	0.04	0.34	0.35	0.35	0.48
	Sępoleński	0.59	0.44	0.50	0.26	0.27	0.11	0.21	0.25	0.43	0.07	0.23	0.38
	Charzykowskie	0.51	0.47	0.48	0.30	0.23	0.04	0.11	0.22	0.47	0.01	0.36	0.40
	Jeziorak	0.45	0.36	0.52	0.21	0.26	0.06	0.18	0.25	0.42	0.17	0.29	0.42
	Mikołajskie	0.46	0.37	0.44	0.27	0.30	0.09	0.24	0.10	0.41	−0.02	0.25	0.26
	Studzieniczne	0.39	0.43	0.43	0.22	0.24	0.06	0.21	0.08	0.34	−0.10	0.28	0.27
	Selmęt Wielki	0.44	0.54	0.54	0.24	0.28	0.11	0.21	0.05	0.43	0.00	0.24	0.24
	Hańcza	0.43	0.44	0.44	0.31	0.26	0.06	0.25	0.16	0.41	0.00	0.22	0.27
EA	Sławskie	0.23	0.33	0.32	0.26	0.33	0.17	0.21	0.43	0.48	0.45	0.17	0.23
	Lubie	0.41	0.23	0.24	0.37	0.30	0.23	0.35	0.42	0.39	0.45	0.19	0.18
	Gardno	0.43	0.27	0.30	0.21	0.26	0.13	0.39	0.24	0.45	0.47	0.42	0.19
	Sępoleński	0.23	0.06	0.14	0.10	0.28	0.10	0.27	0.31	0.37	0.41	0.14	0.14
	Charzykowskie	0.30	0.26	0.23	0.25	0.20	0.07	0.27	0.27	0.52	0.37	0.19	0.21
	Jeziorak	0.20	−0.03	0.29	0.12	0.12	0.18	0.37	0.44	0.49	0.41	0.26	0.27
	Mikołajskie	0.31	0.21	0.19	0.16	0.19	0.21	0.47	0.40	0.37	0.34	0.15	0.10
	Studzieniczne	0.44	0.18	0.24	0.24	0.09	0.14	0.45	0.41	0.36	0.22	0.24	0.21
	Selmęt Wielki	0.50	0.13	0.16	0.22	0.17	0.14	0.50	0.50	0.33	0.31	0.20	0.26
	Hańcza	0.19	0.19	0.12	0.13	0.05	0.11	0.40	0.28	0.32	0.44	0.11	0.09
EAWR	Sławskie	0.00	0.08	−0.01	0.20	0.13	−0.03	0.21	0.01	−0.34	−0.19	−0.23	0.15
	Lubie	−0.22	0.10	0.12	0.24	0.08	−0.22	0.21	0.01	−0.23	−0.29	−0.14	0.26
	Gardno	0.04	0.11	−0.05	0.01	0.04	−0.23	0.16	−0.01	−0.37	−0.13	−0.15	0.30
	Sępoleński	0.00	0.08	−0.06	0.17	0.18	−0.16	0.26	0.03	−0.30	−0.40	−0.10	0.09
	Charzykowskie	0.04	0.06	0.16	0.05	0.08	−0.07	0.24	−0.06	−0.30	−0.34	−0.21	0.23
	Jeziorak	0.04	0.26	0.06	0.11	−0.04	−0.02	0.16	−0.13	−0.37	−0.33	−0.08	0.30
	Mikołajskie	0.10	0.18	0.01	−0.01	0.00	−0.08	0.05	−0.16	−0.37	−0.37	−0.16	0.08
	Studzieniczne	−0.09	0.04	0.01	−0.07	−0.14	−0.14	−0.01	−0.12	−0.45	−0.45	−0.16	0.12
	Selmęt Wielki	−0.04	0.20	0.00	0.00	0.00	−0.15	0.01	−0.18	−0.37	−0.30	−0.24	0.00
	Hańcza	−0.24	0.10	0.15	0.05	0.06	−0.17	0.08	0.02	−0.30	−0.35	−0.22	0.26
SCAND	Sławskie	−0.39	−0.43	−0.46	−0.01	−0.07	−0.15	0.12	−0.13	0.03	0.20	0.08	0.21
	Lubie	−0.21	−0.50	−0.59	0.02	−0.05	−0.18	0.07	0.02	0.22	0.18	0.02	0.18
	Gardno	−0.32	−0.47	−0.36	0.10	0.16	0.26	0.34	0.23	0.16	0.17	0.20	0.19
	Sępoleński	−0.32	−0.46	−0.25	0.06	0.07	−0.01	0.18	−0.02	0.14	0.14	0.12	0.17
	Charzykowskie	−0.12	−0.46	−0.42	−0.14	0.16	0.09	0.23	0.04	0.15	0.22	0.06	0.28
	Jeziorak	−0.21	−0.62	−0.25	0.18	0.30	0.12	0.17	−0.11	0.23	0.21	0.16	0.03
	Mikołajskie	−0.27	−0.45	−0.40	0.04	0.26	0.16	0.18	0.03	0.17	0.16	0.10	0.20
	Studzieniczne	−0.18	−0.49	−0.29	0.05	0.22	0.16	0.31	0.15	0.17	0.14	0.12	0.25
	Selmęt Wielki	−0.25	−0.64	−0.36	0.05	0.23	0.10	0.22	0.02	0.16	0.10	0.08	0.22
	Hańcza	−0.21	−0.38	−0.39	−0.04	0.02	0.04	0.28	0.12	0.15	0.15	0.09	0.09

3.1.2. AO

The strongest effect of AO on thermal conditions was observed in the period from January to March, and in September and December (Table 2a). The calculated correlation coefficients were high and statistically significant at a level of $\leq$0.01. Moreover, statistically significant ($p \leq 0.05$) correlations were recorded in October. The most intensive effect of AO was observed in the northern part of the study area. Changes in AO intensity affect lake water temperature in Poland the strongest in the winter-spring season (from December to April), and in September (Table 2b). The correlations of monthly water temperatures (January–March) with AO indices for all lakes are positive, and for the majority of lakes (with the exception of lakes in the east), very statistically significant ($p \leq 0.01$). Somewhat weaker correlations were determined for September. The calculated correlation coefficients are high (from 0.35 to 0.62).

3.1.3. EA

The correlation coefficient between monthly air temperature and monthly EA index showed that this type has the strongest positive effect from September to November ($p \leq 0.01$; except the northeast in November), in April and May ($p \leq 0.05$), as well as in February, March, July, and August ($p \leq 0.05$) (Table 2a). The calculated correlation coefficient between monthly lake water temperature and monthly EA index showed that the type had statistically significant effect ($p \leq 0.05$) in January and from July to October with a maximum in September (Table 2b).

3.1.4. EAWR

The calculated coefficient of correlation between monthly air temperature and monthly EAWR index showed that this circulation type has the strongest effect in September (negative correlation) and December (positive correlation) (Table 2a). The calculated correlation coefficients in the majority of stations are statistically significant at a level of $\leq$0.05. The correlations between monthly lake water temperature and monthly EAWR index were statistically significant in September and October ($\leq$0.05) (Table 2b).

3.1.5. SCAND

The correlation coefficient between monthly air temperature and monthly SCAND index showed that this circulation type has the strongest (statistically significant) effect in February ($p \leq 0.01$) and January ($p \leq 0.05$). The calculated correlation coefficient r in the aforementioned months was negative. Moreover, statistically significant positive correlations were also determined in May, and covered the majority of the study area (with the exception of coastal and western stations) (Table 2a). The calculated correlation coefficient between monthly lake water temperature and the monthly SCAND index showed that the type has the strongest (the most statistically significant) effect in February ($p \leq 0.01$) and March ($p \leq 0.05$) (Table 2b).

3.2. Differences in Air and Lake Water Temperature in Comparison to Mean Values in Different Phases of Macroscale Types of Atmospheric Circulation

3.2.1. NAO

In the positive NAO phase, evidently higher than average air temperature was observed (Figure 2). The most statistically significant differences in air temperature occurred in December ($p < 0.001$ except for Suwałki, $p < 0.01$), as well as in February and March ($p < 0.001$ or $p < 0.01$). Differences in air temperature increased from the west to the east. The greatest air temperature deviations from multi-annual mean were recorded in February. They varied from more than 2 °C in the west to more than 3 °C in the east of the study area. In the remaining months, the differences varied from more than 1 °C to more than 2 °C.

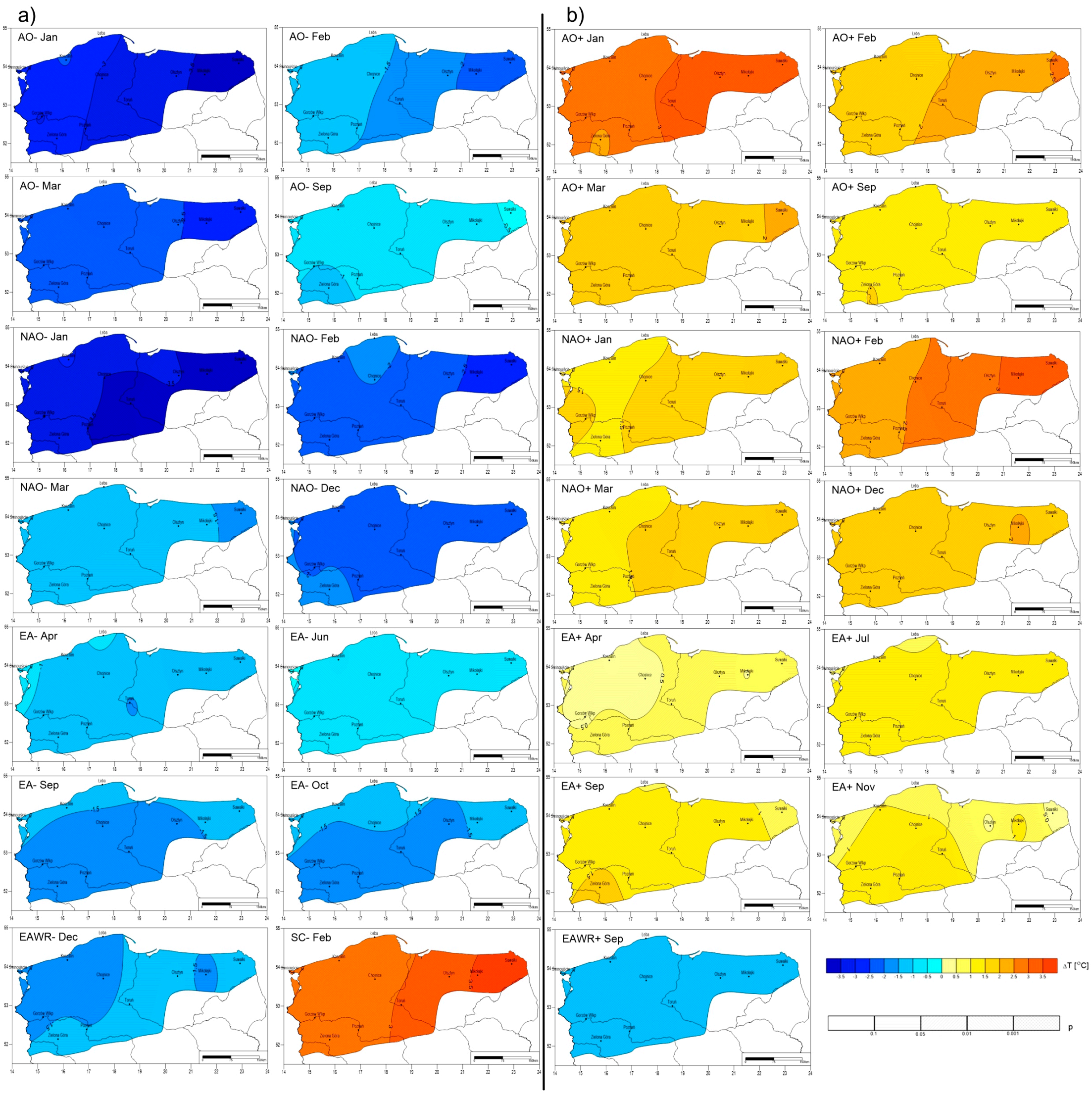

Figure 2. Spatial distribution of differences (ΔT) in air temperature in comparison to mean values in different phases of macroscale types of atmospheric circulation and significance (*p*); (**a**) negative phase; and (**b**) positive phase.

In the negative NAO phase, evidently lower than average air temperature was observed (Figure 2). The most statistically significant air temperature differences were recorded in January (except for the eastern part of the study area at a level of <0.001), as well as in December and February (at a level of <0.05 or <0.01). In March, in the south and in the vicinity of Mikołajki, the analysed differences were not statistically significant. Similarly as in the positive NAO phase, the differences increased from the west to the east. The greatest air temperature deviations from the multi-annual mean were recorded in January. Over the major part of the study area, they exceeded 3.5 °C. In February, the differences were somewhat lower, and exceeded 2.5 °C only in the east.

The effect of NAO on changes in lake water temperature is observed in the period from December to March and in September (Figure 3). In the negative NAO phase, lake water temperatures in the period are lower than mean values by a value from 0.2 to 0.9 °C. With the exception of December, when statistically significant differences are only observed on lakes in the western part of the area, in the remaining months the differences are more significant, and particularly in January ($p < 0.001$). In the positive NAO phase, lake water temperatures in the period from December to March are higher than average by a value from 0.4 to 1.1 °C whereas, in January, considerably lower differences of up to 0.5 °C, not statistically significant, are observed. In the remaining months, the observed differences in water temperatures in the analysed lakes are significant at a level of $p < 0.05$.

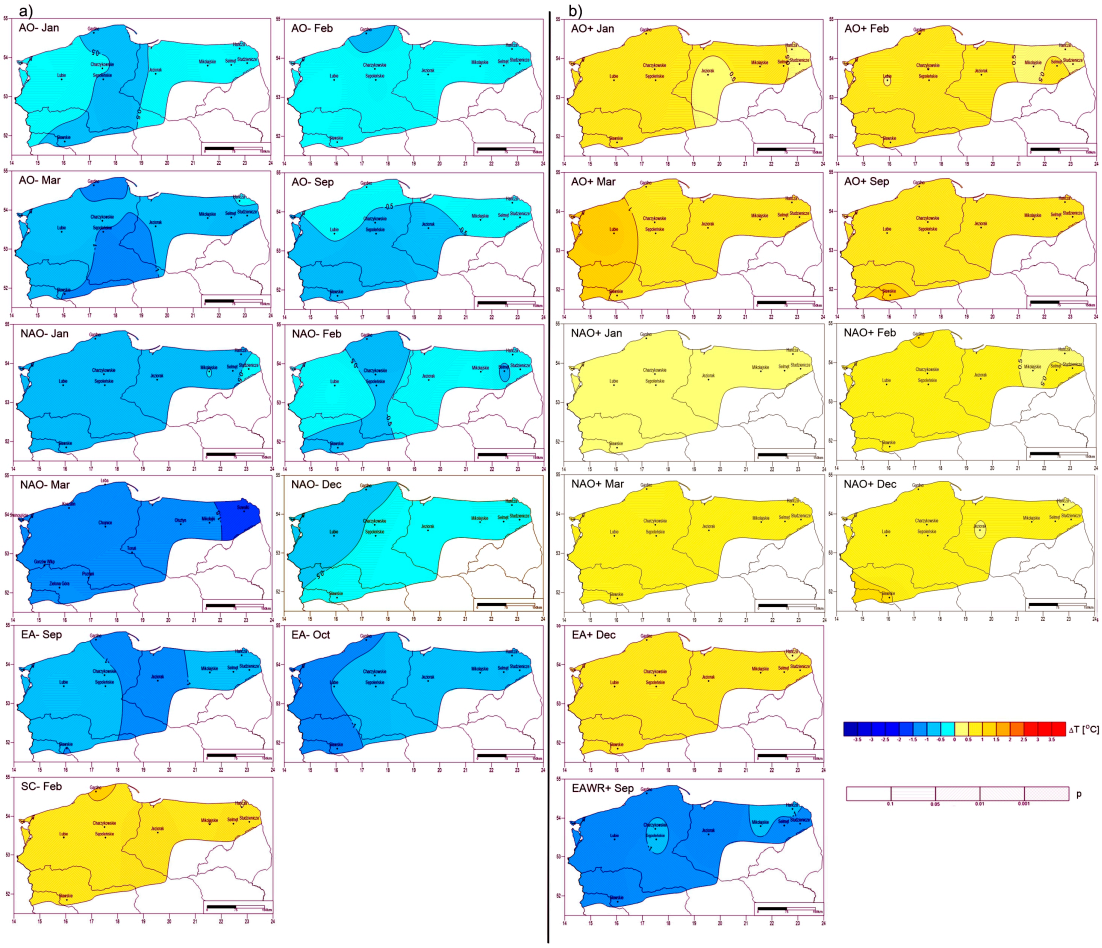

Figure 3. Spatial distribution of differences (ΔT) in lake water temperature in comparison to mean values in different phases of macroscale types of atmospheric circulation and significance (p); (**a**) negative phase; and (**b**) positive phase.

3.2.2. AO

In the positive AO phase, considerably higher than average air temperature was recorded (Figure 2). The most significant differences in air temperature were observed in January ($p < 0.001$) and in March ($p < 0.001$ except for three stations: Łeba, Mikołajki, and Suwałki—$p < 0.01$). In January, air temperature deviations east of the Vistula River exceeded 3 °C, and in March they were somewhat lower, and exceeded 2 °C only in the Suwałki region. An approximate spatial distribution of air temperature deviations was recorded in February. East of the Vistula River, they amounted to more than 2 °C, and in the east of the study area 2.5 °C. In February and December, the statistical significance of the analysed differences was lower, and over the majority of the area it was statistically significant at a level of <0.05.

In the negative AO phase, evidently lower than average air temperature was recorded (Figure 2). The highest deviations from the multi-annual occurred in January. In the east of the area they exceeded 3.5 °C. The most statistically significant ($p < 0.01$) differences were observed in March. Somewhat less significant differences occurred in January ($p < 0.01$) and December ($p < 0.05$, except for Zielona Góra). Similarly as in the positive AO phase, a decrease in air temperature differences occurred towards the west. Except for Suwałki, no statistically significant ($p < 0.05$) differences in air temperature were recorded in February.

In the negative AO phase, lake water temperatures are lower than mean values, in January and February by a maximum of 0.7 °C (Figure 3). The observed differences are statistically significant on the majority of lakes ($p < 0.05$), whereas they are the most significant in February on five lakes. Considerably greater differences are observed in the case of temperatures in March. Water temperature is then lower than average by a value from 0.4 °C (Lake Hańcza) to 1.2 °C (Lake Gardno). The observed differences in temperatures in that month are also very statistically significant ($p < 0.01$) on all lakes in the northeast (with the exception of Hańcza). In the negative AO phase, water temperatures lower than average by a value from 0.3 to 0.8 °C are also observed in September. The greatest and most statistically significant differences in temperatures are observed on lakes in the southern and central part of the lakeland area (Sławskie Lake, Charzykowskie Lake, and Sępoleńskie Lake). In the positive AO phase, lake water temperatures are higher than average, in January and February from 0.3 to 1.0 °C (Figure 3), and in March and September from 0.5 to 1.2 °C, and from 0.7 to 1.0 °C, respectively. The significance of the observed differences, however, is lower, and evidently decreases from the west to the east. The greatest deviations of temperatures from mean values are determined in March in the west of the country (more than 1 °C), and the observed difference in the case of Lake Lubie is very statistically significant ($p < 0.01$).

3.2.3. EA

In the positive EA phase, lower than average air temperature was observed. The most statistically significant differences in air temperature occurred in September. The significance level decreased from the west ($p < 0.001$) to the east ($p < 0.05$). The greatest differences in air temperature were recorded in the south west >1.5 °C, and the lowest in the east <0.5 °C (Figure 2). In November, differences in air temperature were statistically significant outside of the eastern part of the study area, and on the majority of the area west of the Vistula River they exceeded 1 °C. In April, air temperature deviations from multi-annual mean did not exceed 1 °C.

In the negative EA phase, lower than average air temperature was observed. The greatest deviations from multi-annual mean occurred in September and October. Over the majority of the area they exceeded 1.5 °C. In the aforementioned months, air temperature differences were statistically significant at a level of <0.001. Equally statistically significant temperature differences were recorded in April. Except for the northwestern part of the analysed area, they exceeded 1 °C (Figure 2). In June, differences in air temperature varied from 0.5 to 1 °C.

A deviation of lake water temperatures in Poland related to changes in EA intensity is observed throughout the year on different lakes. In the negative EA phase, the greatest changes, however, occur in autumn months, namely September and October. Lake water temperature is then from 0.5 to 1.4 °C lower than average (Figure 3). The most statistically significant differences in temperatures are observed in October on lakes located in the western and northern part of the lakeland ($p < 0.001$).

In the positive EA phase, lake water temperature is higher than average, and the lowest and most statistically significant differences are observed in December. In that month, temperatures are higher than average by a maximum of 1 °C (Figure 3), but they are statistically significant only in the case of half of the analysed lakes ($p < 0.05$).

3.2.4. EAWR

In the positive EAWR phase, lower than average air temperature was observed, however, only in September statistically significant differences were recorded. In the study area, deviations varied from 1 to 1.5 °C. In the negative EAWR phase, statistically significant differences in air temperature occurred in December, and covered the northwestern part of the study area. The greatest deviations from the mean value exceeded 1.5 °C. Moreover, in the northeastern part of the area, statistically significant differences in air temperature were recorded in November, and the deviations oscillated around 1.5 °C.

Changes in EAWR circulation intensity have the weakest effect on changes in lake water temperature. In the negative EAWR phase, no significant changes in water temperatures are observed throughout the year, and in the positive phase, the greatest and most statistically significant differences in lake water temperatures are observed in September. Water temperatures are then from 0.9 (Hańcza Lake, Charzykowskie Lake) to more than 1.3 °C (Gardno Lake) lower than average, and the observed differences on the majority of lakes are very statistically significant ($p < 0.01$).

3.2.5. SCAND

In the positive SCAND phase, lower than average air temperature was observed. The greatest deviations from the multi-annual mean occurred from January to March. They usually exceeded 1.5 °C, and in March in Mikołajki even 2.2 °C (Figure 2). Except for Mikołajki and Świnoujście, in March, differences in air temperature were not statistically significant. In the negative SCAND phase, higher than average air temperature was observed. Statistically significant ($p < 0.001$) differences in air temperature, however, were only recorded in February. Air temperature deviations increased from the west (more than 2.5 °C) to the east (more than 3.5 °C). Moreover, in the negative phase, statistically significant ($p < 0.05$) air temperature deviations in the east of the study area were observed in April and May.

The effect of SCAND on changes in lake water temperatures is observed in the negative phase. In February, lake water temperature is from 0.5 to 1.1 °C higher than average (Figure 3). The observed differences are very statistically significant ($p < 0.05$).

4. Discussion and Summary

The obtained results show a variable response of lake ecosystems in Poland to the effect of macroscale atmospheric circulations types. This concerns both particular circulation types and months in which they influence water temperature (the winter period is dominant). The spatial distribution in the case of water temperature (Figure 3) is less transparent than in the case of the effect of macroscale atmospheric circulations types on air temperature (Figure 2), where certain patterns are evident in the distribution of isolines with meridional orientation (resulting from the features of transitional climate: stronger effect of continental climate in the east of Poland, and effect of marine climate in the west, [40]). It should also be emphasised that correlations resulting from the location of lakes exist. In the majority of cases (NAO, AO, EA, SCAND), deviations of water temperatures from mean values decrease with an increase in latitude. They are the greatest in the west of the study area, and the lowest in the east. Such patterns are the most evident in the positive NAO and AO phase in winter and spring months, SCAND in March, and the negative EA phase in October.

The determined statistically significant correlations suggest that all the cases were compatible as to the direction of effect (Table 2). Therefore, each decrease or increase in air temperature translated into an analogical process in the case of water. The strength of effect of particular circulations on both centres was observed to be quite often different and, in some situations, also somewhat shifted in time. The suppression of the effect of macroscale atmospheric circulations in the case of water should be associated with its properties, and particularly with its higher heat capacity and internal processes occurring in the lake system. Such a situation particularly depends on water circulation in the lake. This is emphasised by among others Gerten and Adrian [41], referring to the effect of NAO on water temperature in three lakes in Germany. In the case of the analysed lakes, the value of deviations of lake water temperatures from mean values in different phases of the studied teleconnections are determined by the morphometric parameters of lakes—depth and surface area. They are considerably higher in shallow and larger lakes, where water mass has more contact with the atmosphere.

The key role there was that of conditions related to water mixing, depending on the dynamics recording the signal of the macroscale circulation from previous seasons in different times. The occurring vertical circulation disturbs the effect of atmosphere on waters in the epilimnion, and as emphasised by Livingstone [42], it can even constitute a buffer in the context of climate warming.

In the case of NAO, lakes in Poland were observed to respond at a similarly strong level to the effect of the circulation in the period from January to March. A certain differentiation occurred in December, when part of the lakes showed more significant correlations than other lakes. A characteristic regional pattern was observed in which lakes in the eastern part of the analysed lakelands showed less significant, or a lack of statistically significant, correlations with NAO. Such a situation is related to the development of the ice cover that appears faster in the east, and the difference between its persistence between the eastern and western part of the study area exceeding 30 days [43]. The ice cover is one of components affecting the climatic conditions of lakes of the moderate zone [44]. In reference to the situation presented above, due to the existing ice cover, lakes in the eastern part in December responded to atmospheric factors differently than those still free from ice. The situation in the case of Lake Jeziorak in February is quite characteristic. It was the only lake whose correlations with NAO were not statistically significant. Such a situation can result from the human impact on the thermal conditions of the lake. The role of human pressure in obscuring signals of teleconnection patterns was emphasised by among others Hernández et al. [32] in the case of Lake Las Madres in Spain. Changes in the thermal regime in the case of the analysed lake can be caused by pollutants supplied from the city directly neighbouring on the lake. As observed in the study on the state of cleanliness of lakes [45], the southern part of Lake Jeziorak (where the limnological station was located) can be subject to such threats. In the case of relationship of water temperature with AO, a similar situation is observed as for the previous teleconnection pattern. Apart from evident dependencies in months from January to March and division of lakes into two groups in December, an impact on water temperature in September is recorded. In the case of EA pattern in January, lakes in the eastern as well as western part of the analysed region, both shallow and deep, show a similar response. It is, therefore, difficult to find any patterns in the response of lakes to this teleconnection pattern, and the observed situation was determined by individual parameters of lakes and their surroundings. The key role of the latter is emphasised by Wrzesiński et al. [46] for Lake Morskie Oko (Tatra Mountains), where local factors obscured the effect of macroscale atmospheric circulation. A greater effect of EA pattern occurs in the period from July to October. Here a more evident pattern is observed, i.e., the first two months of the period show stronger correlations with water temperature in the eastern, and two last ones in the western part of the study area. It should be emphasised, however, that it is not identical in both areas, and different situations occur even in lakes located at a relatively short distance from each other. EAWR pattern has an effect on the analysed lakes, particularly in September and October. Two cases are characteristic here, where water temperature showed no response to the aforementioned teleconnection patterns (Lake Lubie), and where strong correlations were recorded (Lake Studzieniczne). In the first case, lack of response of surface water to atmospheric circulation should be associated with its vertical circulation (period of stratification decomposition) and inflow of masses with different thermal parameters from the hypolimnion. In the case of Lake Studzieniczne, horizontal movement of water masses was probably the deciding factor. The lake is located along a waterway (Augustów Channel), and due to the related water exchange, it is not able to fully adopt parameters resulting from the impact of teleconnection patterns. SCAND pattern showed the strongest correlations with water temperature in February, covering all lakes. In January, significant correlations were particularly observed for shallower lakes located in the western part of the analysed area.

Pursuant to presumptions (see: Introduction), water temperature in Polish lakes was considerably affected by NAO circulation. Such a situation is in accordance with earlier studies concerning the effect of the circulation on water temperature in Polish lakes. Research conducted on lakes in the lowland area so far [47–49] showed strong correlations with this type of circulation also in months from December to March. In reference to the remaining teleconnection patterns, no such research has been conducted in Poland before. The expansion of information on their effect (term of occurrence of significant correlations, deviations, and mean values) on temperature of lake water—one of its basic parameters, can constitute a new source of interpretation in many interdisciplinary studies on lakes. Such knowledge is important in the case of the discussed area (northern part of Poland), where a high number of lakes affects the functioning of the natural environment (hydrological regime, bioclimatic conditions, biological diversity), and is an important component of economic development (tourist, fishery, transport).

In the case of lakes in Europe, numerous research is conducted considering the effect of different (not only NAO) teleconnection patterns. Such analyses concern among others hydrobiological conditions [50], physical processes [51], or changes in the water balance of lakes [52], and as a consequence changes in water resources. In the case of Poland, particularly the last issue is interesting and requires possibly fast detailed investigation with consideration of all processes affecting the water balance. Due to the occurrence of water deficits in Poland [53], activities are implemented (among others through governmental agendas) aimed at an increase in water retention. Lakes are one of the main components of natural water retention. Current research [54] analysing the course of natural components affecting changes in surface areas of lakes, i.e., precipitation and air temperature (and as a consequence increase in evaporation) showed an increase in the latter with relative stability of the former. Such a situation should be considered unfavourable and requiring further detailed research (among others with consideration of teleconnection patterns) aimed at the development of solutions hindering the reduction of easily available water resources accumulated in lakes (e.g., through the expansion of hydrotechnical infrastructure, etc.).

The paper concerns the effect of macroscale types of atmospheric circulation on changes in surface water temperature in Central European lakes. Studies to date particularly focused on the correlations of water temperature with NAO, and as results from the presented data also other atmospheric circulations types affect this parameter, although the strength and time of the effect are varied. The highest number of statistical correlations with water temperature at the annual scale was determined for AO circulation which apart from the winter season also occurred in September. Changes in water temperature in comparison to mean values from the multi-annual 1971–2015 oscillated around 1.0 °C, reaching a maximum value of 1.4 °C.

The presented study shows the complexity of processes occurring in lakes whose course is determined by many factors, with both regional and local range. The paper constitutes another step towards the investigation of the importance of changes in intensity of different types of atmospheric circulation on water temperature in Polish lakes. The knowledge is important in the context of the observed climate changes and the resulting transformation of lake ecosystems. The assessment and potential counteracting their negative effects is a difficult task requiring possibly detailed information regarding changes in water temperature. It is particularly important in the case of Polish lakes. Their transformations can considerably affect not only the environmental conditions, but also the volume of water resources (simultaneously exploited by man [55]), that are among the lowest in Europe.

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