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The surface temperature of water in Polish and Belarusian lakes during the period of climate change

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Abstract: The paper presents the results of surface water temperature measurements from 17 lakes located in northern Poland and Belarus over the period of 50 years (1971-2020). Using the Excel computer program, Corel Quattro Pro 8 and the graphic Draw 9, annual and monthly averages, extreme values, annual and monthly trends were calculated and presented. It is supplemented by the monthly average air temperatures for 13 weather stations. The research showed that the temperature in all lakes is characterized by a positive trend at the level of 0.044°C $year^{-1}$. The largest lake is characteristic for Chervonoe Lake – 0.066°C $year^{-1}$, and the smallest 0.029°C $year^{-1}$ for the deep Lake Hańcza. In the course of the average monthly surface water temperatures, a positive trend is also observed, ranging from 0.015°C $year^{-1}$ in January to 0.069°C $year^{-1}$ in May. These values correlate with the average air temperatures in the winter months (December-March) and with the winter NAO index (DJFM).

Key words: lake, Poland and Belarus, temperature

Introduction

The temperature of surface water in lakes is one of the basic abiotic features of the lake ecosystem, determining the dynamics and rate of metabolism in water bodies, and determines the intensity of mixing of water masses. It is also an important parameter in shaping the trophy of individual reservoirs (Lampert and Sommer 1996). It also becomes the most sensitive element, susceptible to any changes in the natural environment, especially climatic conditions, both seasonal and long-term. The surface layer of water in lakes, including, as it is commonly accepted, a layer up to a depth of 1-2 m. It is a boundary layer through which the exchange of energy and mass occurs between the lake and its surroundings, the solar radiation absorption zone, the water circulation zone, the layer in which the mechanisms shaping the thermal structures waters are of fundamental importance for the heat balance and the hydrological regime, the layer in which the course of both short-term and long-term changes is characterized by the greatest variability and differentiation (Skowron 2011; Sobolewski et al. 2014).

The long-term results of surface water temperature measurements were used to distinguish periods in the annual cycle. The dates of the formation and disappearance of the ice cover, the permanent transition of the surface water temperature by the value of 4 and 15°C, both in spring and autumn, and the dates of the minimum and maximum water temperatures were taken into account (Tikhomirov 1982; Skowron 2001, 2011).

The differences in water temperature in the surface layer (1-2 m thick) between the littoral (shore) and deep-water parts of the lake, carried out on lakes of various shapes and degrees of formation of individual elements of the lake basin, showed that the greatest differences between the coastal and deep (profundal) parts were occur during the spring warming up of water, they rarely exceeded 3-4°C, most often oscillating within the range of 1.5-2.5°C (Skowron 2007).

The aim of the study is to present changes in the course of the surface water temperature in selected lakes in Poland and Belarus and its spatial differentiation in the period 1971-2020 during the period of climate change.

Material and methods

Out of the 17 analyzed lakes covered by surface water temperature measurements, 2 are located in the Greater Poland-Kuyavian Lakeland (Gopło, Sławskie), 5 lakes in the Pomeranian Lakeland (Charzykowskie, Gardno, Lubie, Łebsko, Raduńskie Górne), 5 in the Masurian Lakeland (Jeziorak, Mikołajskie, Nidzkie, Hańcza, Studzieniczne), 3 in the Belarusian Lake District (Narocz, Drywiaty, Łukomskoe) and 2 in the Polesie area (Wygonoszczanskoe, Czerwonoe) (Fig. 1). All the lakes, except those located in Polesie, are of post-glacial origin. Their location is marked by Lake Lubie in the west (15.9°E), and in the east by Lake Lukomskoe (29.1°E), while in the north by Lake Drywiaty (55.6°N), and in the south by Lake Czerwonoe (52.4°N). The distance between the position of the extreme lakes from west to east is approx. 1,130 km (13.2°).

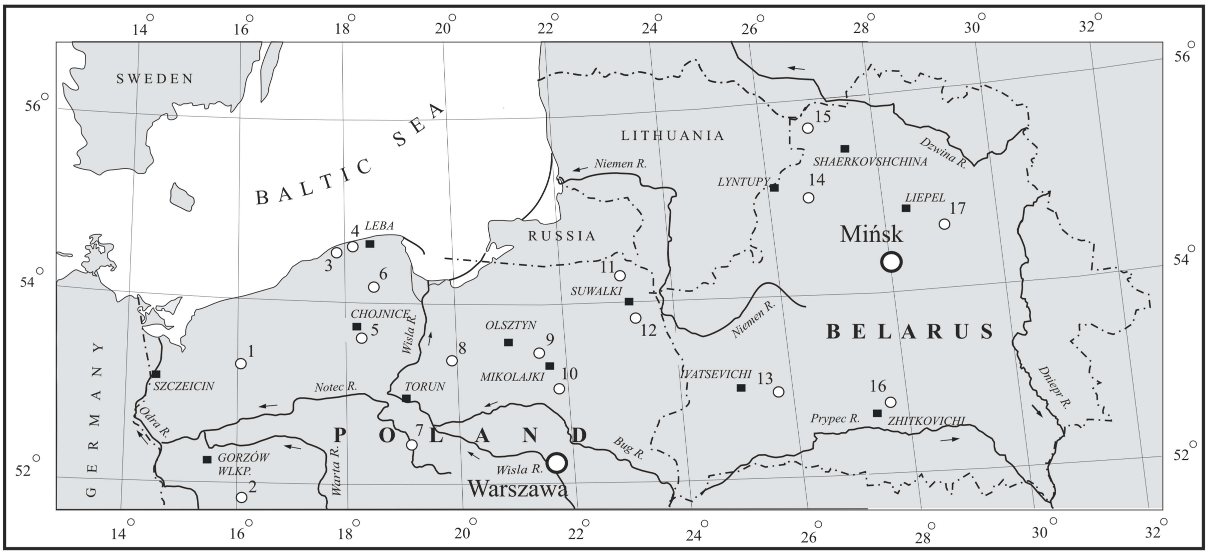

Fig. 1. Location of lakes on which surface water temperature measurements in period 1971-2020 in Poland: (1 – Lubie, 2 – Sławskie, 3 – Gardno, 4 – Łebsko, 5 – Charzykowskie, 6 – Raduńskie Górne, 7 – Gopło, 8 – Jeziorak, 9 – Mikołajskie, 10 – Nidzkie, 11 – Hańcza, 12 – Studzieniczne) and Belarus: (13 – Vygonoshchanskoe, 14 – Naroch, 15 – Driviaty, 16 – Chervonoe, 17 – Lukomskoe) and meteorological stations (black squars)

The largest lake is Naroch (7 960 ha) and Łebsko (7 020 ha), while the smallest ones are Studzieniczne (244.0 ha) and Hańcza (291.5 ha). In terms of depth, the deepest is Lake Hańcza (106.1 m) and Lubie (46.2 m), and the shallowest is Vygonoshchanskoe (2.3 m) and Chervonoe (2.6 m). The analyzed lakes are also clearly diversified in terms of their capacity. The largest capacity is Lake Naroch (710.4 hm^3) and Lake Lukomskoe (249.0 hm^3), the smallest lake Studzieniczne (22.07 hm^3) and Lake Chervonoe (27.35 hm^3). The remaining morphometric data are presented in Table 1.

The analysis of the surface water temperature for 17 lakes was presented on the basis of daily temperature measurements from the Institute of Meteorology and Water Management in Warsaw and the Hydrometeorological Service of the Republic of Belarus in Minsk taken at a depth of 0.4 m in the coastal zone at 7:00 (6:00 GMT) in the 50 years 1971-2020. On this basis, decade averages, monthly averages and annual averages in the aforementioned multiannual period were calculated. These data were also the basis for determining the extreme values, determining the tendency of changes and decade-long increases and decreases in surface water temperature.

The calculated parameters of water and air temperature in lakes were presented on the basis of the Excel and Corel Quattro Pro 8 computer programs, while the graphic processing was presented using the Corel Draw 9 program.

Table 1. Location and morphometry of the studied lakes (Choiński 2007; Vlasov et al. 2004)

No	Lake	Geographic location [°]		Area [ha]	Volume [hm³]	Depth [m]		Average width [m]
		latitude	longitude			Maximum	Mean	
1	Lubie	52.5	15.9	1 487.5	169.88	46.2	11.6	1 040
2	Sławskie	51.9	16.0	822.5	42.66	12.3	5.2	898
3	Gardno	54.7	17.1	2 337.5	30.95	2.6	1.3	3 682
4	Łebsko	54.7	17.4	7 020.0	117.52	6.3	1.6	4 366
5	Charzykowskie	53.8	17.5	1 336.0	134.53	30.5	9.8	1 360
6	Raduńskie Górne	54.2	18.0	362.5	60.16	43.0	15.5	521
7	Gopło	52.6	18.4	2 121.5	78.5	16.6	3.6	295
8	Jeziorak	53.7	19.6	3 152.5	141.59	12.9	4.1	1 172
9	Mikołajskie	53.8	21.6	424.0	55.74	25.9	11.2	866
10	Nidzkie	53.6	21.6	1 750.0	113.87	23.7	6.2	790
11	Hańcza	54.3	22.8	291.5	120.36	106.1	38.7	688
12	Studzieniczne	53.9	23.1	244.0	22.07	30.5	8.7	730
13	Vygonoshchanskoe	52.7	26.0	2 600.0	32.1	2.3	1.2	3 710
14	Naroch	54.9	26.8	7 960.0	710.4	24.8	8.9	6 200
15	Driviaty	55.6	27.0	3 614.0	223.52	12.0	6.1	3 570
16	Chervonoe	52.4	28.0	4 032.0	27.35	2.9	0.7	3 500
17	Lukomskoe	54.7	29.1	3 771.0	249.0	11.5	6.6	3 500

Results

The analyzed area, where the analyzed lakes are located, is characterized by transitional climate features; from more oceanic in the western part to more continental in its eastern part, which is expressed by a distinct distinctiveness of climatic conditions. This character is presented for the monthly and annual mean air temperatures and their amplitudes in the years 1971-2020 (Table 2).

The average annual air temperature west of the Vistula River was over 8.2°C, in the Masurian Lake District 7.1°C, clearly decreasing in the northern part of the Belarusian Lake District to 6.0°C (Lyntupy). Only in the area of Polesie it was about 7.3°C. The differentiation is even clearer for the average monthly temperatures. In the winter months (December, January, February), the area east of the Vistula River, when the temperature is clearly negative, while to the west of this river, it rarely drops below 0°C. In the area of the Belarusian Lake District, it drops below 4.3°C, reaching –6.2°C at the Liepel station in January. This spatial variation in air temperature is emphasized by the mean annual amplitudes. East of the Vistula River, the amplitude is always higher than 22.4°C, exceeding 24.0°C at some stations. On the other hand, at the checkpoints in the Belarusian Lake District, it reaches an average of 23°C (Table 2). Thus, the areas located to the east of the meridian of 23°E are characterized by a much greater degree of continentalism.

Table 2. Average monthly and annual air temperatures and amplitude (Ampl.) at selected meteorological stations in Poland and Belarus in the period 1971-2020 (calculated on the basis of data from the Institute of Meteorology and Water Management in Poland and Republican Center for Hydrometeorology, Control of Radioactive Contamination and Environmental Monitoring)

Station	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Year	Ampl.
Szczecin	4.5	1.2	–0.4	0.4	3.5	8.2	13.1	16.4	18.2	17.7	13.8	9.2	**8.8**	**20.6**
Gorzów Wielkopolski	4.0	0.5	–1.0	0.1	3.5	8.5	13.5	16.8	18.5	18.1	13.9	9.0	**8.8**	**21.4**
Łeba	4.6	1.2	–0.6	–0.1	2.2	6.1	10.7	14.5	16.9	16.9	13.5	9.2	**7.9**	**19.0**
Chojnice	3.0	–0.6	–2.4	–1.5	1.7	7.0	12.2	15.4	17.2	16.8	12.7	7.9	**7.4**	**21.5**
Toruń	3.6	–0.2	–-2.0	–1.0	2.6	7.9	13.4	16.7	18.5	17.9	13.4	8.5	**8.3**	**22.7**
Olsztyn	2.7	–1.0	–2.8	–2.0	1.5	6.5	11.7	14.6	16.7	16.1	12.0	7.5	**7.0**	**22.8**
Mikołajki	3.0	–1.2	–3.4	–-2.5	0.9	6.9	12.8	16.1	18.0	17.5	13.1	8.0	**7.4**	**23.4**
Suwałki	2.0	–2.2	–4.4	–3.7	0.1	6.5	12.4	15.6	17.3	16.7	12.0	6.8	**6.6**	**24.0**
Liepel	0.6	–3.7	–6.2	–5.5	–1.0	6.3	12.9	16.3	17.9	16.7	11.6	5.9	**6.1**	**24.1**
Lyntupy	1.0	–3.2	–4.9	–4.8	–0.6	6.1	12.2	15.3	17.3	16.2	11.3	5.9	**6.0**	**22.2**
Sharkovshchina	1.2	–2.7	–4.1	–4.0	0.1	7.1	12.8	16.2	18.5	17.2	12.1	6.2	**6.8**	**22.7**
Ivatsevichi	2.1	–2.0	–3.6	–2.9	1.5	8.1	14.0	17.1	18.8	18.0	12.9	7.4	**7.7**	**22.4**
Zhitkovichi	1.9	–2.5	–4.9	–3.8	0.8	8.1	14.1	17.3	18.8	17.8	12.7	7.1	**7.3**	**23.7**

The spatial thermal system over the discussed area also emphasizes the course of ice phenomena on the lakes. It also determines the influence of air temperature on the course of the surface water temperature, especially in the winter months (December-March). Preliminary information about the occurrence of the ice cover in the analyzed area indicates a significant diversity of its dates. In all the lakes analyzed in this study, in the years 1971-2020, the dates of its appearance were more and more late, with the trend of 0.26-0.39 days $year^{-1}$. The beginning of the appearance of the ice cover on the lakes was slightly diversified and was recorded from December 14 on the lakes in the Belarusian Lake District to December 28 in the lake districts in Poland. In turn, the dates of its disappearance are from March 8 in the lakes west of the Vistula River, to March 17 east of it and March 22 in the Belarusian Lake District. Their dates are characterized by earlier decay dates with a negative trend of 0.5-0.6 days $year^{-1}$. This spatial differentiation is emphasized by the time of its occurrence, which ranges from 61 days in the lakes west of the Vistula River, 75 days in the Masurian Lake District to 108 days in the lakes located in the Belarusian Lake District.

The mean annual surface water temperatures in the analyzed multi-year period 1971-2020 were clearly differentiated and ranged from 8.6°C for Lake Hańcza to 11.0°C for lakes: Sławskie and Gopło (Table 3). Towards the east it decreased to below 9.0°C in lakes in the Belarusian Lake District.

In particular years of the analyzed multi-year period, the highest values were characteristic for the years 1990, 2002 and 2007, and 2007 was the warmest year. In all lakes, the mean annual water temperature was below 9.5°C.

In the course of monthly mean surface water temperatures, the highest values were recorded most often in July, and less frequently in August. They ranged from 18.4°C in Lake Gardno to 21.8°C in Lake Chervonoe (Table 3). The highest values of the average monthly surface temperature of water on lakes in Poland occurred in July 1994, when the monthly average exceeded 24°C (Jeziorak 25.2°C, Gopło 24.3°C and Sławskie 24.1°C). Generally, the highest values of surface water temperature in summer, with few exceptions, were found in the shallowest lakes located in the Greater Poland Lakeland. On the other hand, for decade intervals (10 days). the highest average temperatures in the analyzed 50-year period occurred in the first decade of August (average for Polish lakes is 20.6°C, while the lowest in the third decade of January (1.28°C) and the first decade of February (1.31°C).

Table 3. Average monthly and annual surface water temperatures in selected lakes of Poland and Belarus in the period 1971-2020

No	Lake	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Year
1	Lubie	6.05	2.66	1.42	1.47	2.94	6.71	12.87	17.62	19.79	19.63	15.54	10.80	**9.79**
2	Sławskie	6.46	2.81	1.76	2.07	4.15	8.90	15.22	19.43	21.16	21.19	17.23	12.06	**11.04**
3	Gardno	4.63	2.12	1.26	1.28	2.79	7.13	12.95	16.75	18.53	17.90	13.74	8.97	**9.02**
4	Łebsko	4.98	2.46	1.60	1.62	3.38	7.88	13.31	16.93	18.91	18.37	14.08	9.33	**9.41**
5	Charzykowskie	6.55	3.11	1.50	1.31	2.43	5.98	12.70	17.46	19.62	19.61	15.81	11.28	**9.78**
6	Raduńskie Górne	6.29	3.27	1.73	1.54	2.49	5.41	11.24	16.45	18.59	18.81	15.23	10.67	**9.31**
7	Gopło	7.04	3.93	2.46	2.56	4.35	8.24	14.49	19.01	20.64	20.41	16.63	12.10	**11.04**
8	Jeziorak	5.24	2.17	1.30	1.34	2.95	7.97	14.96	19.34	21.05	20.88	16.25	10.61	**10.40**
9	Mikołajskie	6.94	2.85	1.13	0.96	1.77	5.17	12.27	17.68	19.91	20.31	16.53	11.80	**9.81**
10	Nidzkie	5.44	1.88	0.90	0.94	2.38	7.08	14.13	18.67	20.58	20.51	16.25	10.82	**9.97**
11	Hańcza	4.75	2.35	1.13	0.89	1.48	3.73	9.76	16.91	19.32	19.28	14.70	9.47	**8.65**
12	Studzieniczne	5.40	2.14	1.23	1.20	1.95	5.84	13.72	18.58	20.44	20.32	15.87	10.45	**9.76**
13	Wygonoszczanskoe	2.74	0.62	0.19	0.20	1.20	7.71	14.65	18.61	20.00	19.16	13.85	8.36	**8.99**
14	Narocz	3.18	0.66	0.18	0.14	0.43	4.78	12.58	17.70	19.90	19.72	14.90	8.42	**8.55**
15	Drywiaty	2.72	0.62	0.20	0.15	0.71	5.02	12.24	17.83	19.93	19.27	14.62	8.12	**8.45**
16	Chervonoe	2.85	0.55	0.15	0.24	1.58	7.93	15.66	20.18	21.84	20.98	15.55	8.45	**9.66**
17	Łukomskoe[#]	4.26	1.32	0.32	0.33	1.46	6.51	13.88	19.06	21.35	20.85	16.12	10.27	**9.49**

Explanations: # – Lake Lukomskoe is under the influence of a thermal power plant

Two directions of the energy flow in the annual heat exchange cycle between the lake and the atmosphere. The first one is directed to the lake and is related to the absorption of heat by the surface layer of water. The heating of this layer in the lakes of the Polish Lowlands usually takes place from the second decade of February and lasts until the second decade of August. The second period, on the other hand, concerns the emission of heat and is directed to the atmosphere. It usually falls from the second decade of August and lasts until the second decade of February. Both periods are separated by the moment of equilibrium in heat exchange, the dates of occurrence and length of which in particular years are clearly different. The duration of these periods is well illustrated by the average dates of selected temperatures in the annual course (Efremova et al. 2016).

The different course of surface water temperature between the lakes was obtained by analyzing the average dates of specific water temperatures (Table 4).

The absolutely highest surface water temperatures in the analyzed lakes were recorded usually at the turn of July and August. The highest temperature, 32.7°C, was measured on July 15, 2014 in the Chervonoe lake and 30.1°C in the Lukomskoe lake, while the lowest was 0.0°C, many times in all analyzed lakes (Table 5) (Skowron 2008, State water cadaster 1971-2021).

Table 4. Average dates when the surface water temperature passed through selected limit values in lakes in Poland and Belarus in the period 1971-2020 (based on data from the Institute of Meteorology and Water Management, PIB and the Hydrometeorological Service of the Republic of Belarus in Minsk)

No	Lake	Spring					Max	Autumn				
		2 °C	4 °C	10 °C	15 °C	20 °C		20 °C	15 °C	10°C	4°C	2 °C
1	Lubie	8-03	25-03	4-05	27-05	30-06	27-07	19-08	20-09	22-10	2-12	26-12
2	Sławskie	22-02	12-03	22-04	14-05	12-06	24-07	1-09	29-09	27-10	3-12	26-12
3	Gardno	9-03	23-03	30-04	30-05	24-06	25-07	10-08	7-09	10-10	20-11	13-12
4	Łebsko	1-03	20-03	27-04	25-05	19-06	24-07	15-08	10-09	13-10	23-11	19-12
5	Charzykowskie	12-03	1-04	6-05	29-05	26-06	30-07	18-08	20-09	24-10	9-12	29-12
6	Raduńskie Górne	8-03	3-04	12-05	3-06	3-07	23-07	12-08	17-09	21-10	9-12	4-01
7	Gopło	23-02	10-03	28-04	20-05	20-06	14-07	25-08	28-09	30-10	14-12	24-12
8	Jeziorak	7-03	24-03	26-04	16-05	11-06	27-07	27-08	22-09	21-10	25-11	19-12
9	Mikołajskie	18-03	8-04	8-05	28-05	19-06	29-07	25-08	28-09	28-10	8-12	25-12
10	Nidzkie	13-03	28-03	29-04	21-05	16-06	26-07	26-08	23-09	21-10	25-11	14-12
11	Hańcza	23-03	19-04	18-05	4-06	2-07	1-08	15-08	14-09	13-10	23-11	23-12
12	Studzieniczne	15-03	6-04	3-05	22-05	15-06	24-07	23-08	21-09	19-10	27-11	15-12
13	Vygonoshchanskoe	–	6-04	28-04	–	–	15-07	–	–	11-10	10-11	–
14	Naroch	–	20-04	11-05	–	–	18-07	–	–	11-10	13-11	–
15	Driviaty	–	15-04	7-05	–	–	16-07	–	–	10-10	09-11	–
16	Chervonoe	–	4-04	28-04	–	–	20-07	–	–	13-10	11-11	–
17	Lukomskoe#	–	5-04	3-05	–	–	17-07	–	–	17-10	19-11	–

Explanations: # – Lake Lukomskoe is under the influence of a thermal power plant

Table 5. Extreme water temperature values in the analysed lakes in the period 1971-2020 (based on the data obtained from the Institute of Meteorology and Water Management and the Hydrometeorological Service of the Republic of Belarus in Minsk)

No	Lake	Mean annual		Extremal
		Maximal (year)	Minima (year)	Maximal (date)
1	Lubie	11.74 (2016)	7.93 (1980)	26.9 (17.07.2010)
2	Sławskie	12.35 (2014)	9.47 (1980)	27.8 (27.07.2007)
3	Gardno	10.26 (2016)	7.54 (1996)	25.4 (15.07.1995)
4	Łebsko	10.56 (2014)	8.18 (1987)	26.2 (30.07.1994)
5	Charzykowskie	11.98 (2018)	8.23 (1984)	26.7 (04.08.2018)
6	Raduńskie Górne	10.38 (2014)	7.85 (1980)	24.8 (12.07.2010)
7	Gopło	13.05 (2009)	9.25 (1974)	27.8 (29.07.1994)
8	Jeziorak	11.67 (2014)	8.56 (1984)	29.2 (16.08.1994)
9	Mikołajskie	12.05 (2014)	8.39 (1980)	27.6 (01.08.1994)
10	Nidzkie	11.85 (2018)	8.06 (1980)	27.6 (03.08.2018)
11	Hańcza	9.66 (2010)	7.18 (1977)	26.4 (06.08.1994)
12	Studzieniczne	11.83 (2014)	8.17 (1980)	27.4 (18.07.2010)
13	Vygonoshchanskoe	10.50 (2019)	7.27 (1993)	28.5 (18.07.2010)
14	Naroch	10.39 (2020)	6.62 (1976)	29.7 (16.08.2010)
15	Driviaty	10.00(2019)	6.88 (1977)	28.8 (31.07.1994)
16	Chervonoe	11.66 (2019)	7.18 (1980)	32.7 (15.07.2014)
17	Lukomskoe#	11.03 (2010)	7.83 (1980)	30.1 (23.07.2010)

Explanations: # – Lake Lukomskoe is under the influence of a thermal power plant

It was unequivocally found that the course of the mean annual surface water temperatures in all lakes presented in this study is characterized by a positive trend at the level of 0.044°C $year^{-1}$. The largest lake is characteristic for Lake Chervonoe – 0.066°C $year^{-1}$, and the smallest 0.029°C $year^{-1}$ for the deep Lake Hańcza. In the course of the monthly mean water temperatures, a positive trend is also noticed on the level from 0.015°C $year^{-1}$ in January to 0.069°C $year^{-1}$ in May. Their extreme values range from –0.021°C $year^{-1}$ for Lake Gopło in December to 0.130°C $year^{-1}$ for Lake Chervonoe in May (Table 6).

Table 6. Average monthly and annual trend of surface water temperatures in selected lakes of Poland and Belarus in the period 1971-2020 (based on IMiGW PIB and the Hydrometeorological Service of the Republic of Belarus in Minsk. Statistical significance <0.001 is shown in bold

No	Lake	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Year
1	Lubie	**0.064**	**0.051**	**0.033**	**0.030**	**0.050**	**0.074**	**0.088**	**0.083**	**0.067**	**0.065**	**0.070**	**0.062**	**0.061**
2	Sławskie	**0.054**	**0.037**	**0.023**	**0.028**	**0.032**	**0.054**	**0.056**	**0.056**	**0.055**	**0.056**	**0.051**	**0.046**	**0.045**
3	Gardno	**0.037**	0.027	0.016	0.017	0.029	**0.053**	**0.044**	**0.041**	0.034	0.044	**0.048**	**0.039**	**0.034**
4	Łebsko	0.021	0.010	0.009	0.012	0.018	**0.058**	**0.050**	**0.047**	**0.044**	**0.041**	**0.045**	0.029	**0.031**
5	Charzykowskie	**0.043**	**0.043**	**0.036**	**0.036**	**0.048**	**0.066**	**0.064**	**0.053**	**0.050**	**0.049**	**0.051**	**0.034**	**0.047**
6	Raduńskie Górne	**0.034**	**0.034**	**0.031**	**0.027**	**0.036**	**0.053**	**0.080**	**0.063**	**0.038**	**0.041**	**0.040**	**0.026**	**0.042**
7	Gopło	–0.020	–0.021	0.020	**0.039**	**0.065**	**0.095**	**0.108**	**0.067**	**0.042**	**0.055**	**0.036**	–0.007	**0.044**
8	Jeziorak	**0.046**	**0.025**	0.008	0.007	0.026	**0.048**	**0.043**	**0.053**	**0.057**	**0.065**	**0.073**	**0.046**	**0.047**
9	Mikołajskie	**0.034**	**0.030**	0.016	**0.017**	**0.027**	**0.046**	**0.047**	**0.044**	**0.046**	**0.052**	**0.048**	**0.034**	**0.036**
10	Nidzkie	**0.043**	**0.024**	0.011	0.013	0.027	**0.059**	**0.051**	**0.055**	**0.053**	**0.063**	**0.051**	**0.038**	**0.039**
11	Hańcza	0.015	–0.010	0.003	0.011	**0.026**	**0.048**	**0.073**	**0.074**	0.038	**0.043**	0.026	**0.035**	**0.029**
12	Studzieniczne	**0.041**	**0.032**	0.015	0.016	**0.028**	**0.059**	**0.052**	**0.049**	**0.046**	**0.052**	**0.053**	**0.043**	**0.039**
13	Vygonoshchanskoe	**0.054**	0.015	0.006	0.009	**0.060**	**0.097**	**0.078**	**0.079**	**0.091**	**0.082**	**0.054**	**0.034**	**0.051**
14	Naroch	**0.063**	**0.030**	0.008	0.004	0.024	**0.076**	**0.070**	**0.076**	**0.083**	**0.070**	**0.033**	**0.042**	**0.048**
15	Driviaty	**0.062**	**0.031**	0.007	0.001	0.028	**0.043**	**0.068**	**0.068**	**0.041**	**0.030**	**0.043**	**0.018**	**0.037**
16	Chervonoe	**0.057**	0.025	0.005	0.013	**0.075**	**0.102**	**0.130**	**0.110**	**0.109**	**0.084**	**0.039**	**0.042**	**0.066**
17	Lukomskoe#	**0.047**	**0.033**	0.012	0.010	**0.041**	**0.060**	**0.064**	**0.080**	**0.094**	**0.085**	**0.086**	0.016	**0.052**

Explanations: # – Lake Lukomskoe is under the influence of a thermal power plant

Discussion

Already the first results of water temperature measurements in lakes in Europe confirmed the increasing influence of zonal atmospheric circulation, especially since the beginning of the 1990s (Hurrell 1995; Straile et al. 2003; Naumenko et al. 2006; Dokulil 2013). The intensity of the inflow of air masses to the area of Western Europe, the Baltic Coast and the East European Lowlands is determined by the activity of permanent atmospheric pressure systems – the Icelandic Lowlands and the Azores Highlands, expressed by the NAO (North Atlantic Oscillation) coefficient. Research has shown that the North Atlantic Oscillation has a large impact on the air temperature and the temperature of lake waters in Poland, especially in winter (Skowron 2011, 2020, 2021; Wrzesiński et al. 2015).

The analysis of long-term changes in surface water temperature in many lakes in the northern hemisphere shows that from the 1990s and the first 1920s, a significant increase in both air temperature and surface water temperature in lakes was observed (Gronskaya et al. 2002; Järvet 2004; Pernaravičiūtė 2004; Naumenko et al. 2006; Nõges et al. 2010; Dokulil 2013; Woolway et al. 2017). In Poland, research in this area conducted in the years 1961-2020 on a dozen lakes also confirmed a similar trend (Dąbrowski et al. 2004; Skowron 2011; Sobolewski et al. 2014).

The increase in air temperature causes significant changes in the functioning of the entire lake ecosystem, especially in the course of the surface water temperature in lakes, its thermal structure of water (increase in the temperature of the epilimnion and its range, deepening the location of the thermocline, increasing temperature gradients in the thermocline) (Kilkus 2000; Skowron 2011; Choiński et al 2015; Woolway et al 2017).

This tendency is confirmed by the increase in surface water temperature in many lakes located in the western part of Europe (Dokulil 2013). The author reports that Lake Windermere (England) increased by 1.4°C in 1960-2000, and Lake Lough Feeagh (West Ireland) increased by 0.7°C in 1960-1997. The average water temperature in Lake Zurich in Switzerland from 1950 to 1990 increased at a rate of 0.16°C per decade, and in Lake Constance by about 0.1°C (Strajle et al. 2003). This trend is complemented by exceptionally high increases of 1.6°C per decade in Lake Stensjön in Sweden (Adrian et al. 2009). Also, the surface water temperature in many lakes in Finland, Austria and Switzerland during the summer increased by 0.38, 0.43 and 0.29°C per decade, respectively (Arvola et al. 2010; Dokulil 2013). These conclusions are confirmed by more detailed results of regional studies (Livingstone and Dokulil 2001; Lieberherr and Wunderle 2018; Sukhovilo 2019).

In the lakes of Latvia in 1946–2002, the long-term average annual surface water temperature showed a statistically significant positive trend of 0.4-0.8°C (Apsīte et al. 2014). This is confirmed by studies on large lakes in Estonia (Peipus and Võrtsjärv), where the temporal variability of climatic seasons in the years 1946-2000 was determined (Järvet 2004). The most significant trend was obtained for winter (the ice cover period), which was shortened by 17 days. In Lake Ladoga, a positive trend was found at the level of 0.05-0.07°C year^{-1} (Naumenko et al. 2006, 2008).

The results of research carried out on Lithuanian lakes showed that the average annual surface water temperature in 1991-2000 was 0.6°C higher than the average for the years 1981-1990 (Pernaravičiūtė 2004). In turn, Kilkus and Valiuskevicius (2001) indicate that this increase in Lithuanian lakes began in the years 1981-1985 and continues to this day.

An increase in air temperature by 1.1°C in 1988-2002 caused changes in basic processes in lakes and artificial reservoirs (Danilovish 2004, 2005). The effect of these changes is the earlier occurrence of water temperature of 0.2, 4.0 and 10.0°C in spring, even from 5 to 11 days, and in autumn by 7 days.

The surface water temperature studies carried out on lakes in Poland, covering the period 1961-2000, also confirm the trend in the lakes of Europe. For most lakes, it ranges from 0.2°C to 0.9°C and only in Łebsko and Jeziorak do they exceed 1°C per decade (Skowron 2001, 2009, 2011; Sobolewski et al. 2014).

Conclusions

The results of measurements of water temperature in lakes in Europe confirmed the growing importance of zonal atmospheric circulation, especially since the beginning of the 1970s (Naumenko et al. 2008; Dokulil 2013). This is confirmed by the relationship between air temperature in December-March and the winter NAO index (DJFM) (Fig. 2).

The water temperature in lakes in northern Poland in the winter and spring seasons is clearly higher than the average in the positive NAO phase (DJFM) than in the negative phase. The spatial distribution of air temperature changes is different than that of water temperatures in lakes. The observed changes concern not only the size of the differences in water and air temperature values, but mainly their temporal and spatial variability. These differences result from the location and morphometry of the lakes. An important parameter controlling the reaction of thermal features of lake waters to changes in air temperature is the average depth of the lakes. The lakes with the greatest average depths (over 15 m) are more "resistant" to air temperature changes, while shallower lakes with polymictic features are more sensitive (Skowron 2011; Wrzesiński et al. 2015).

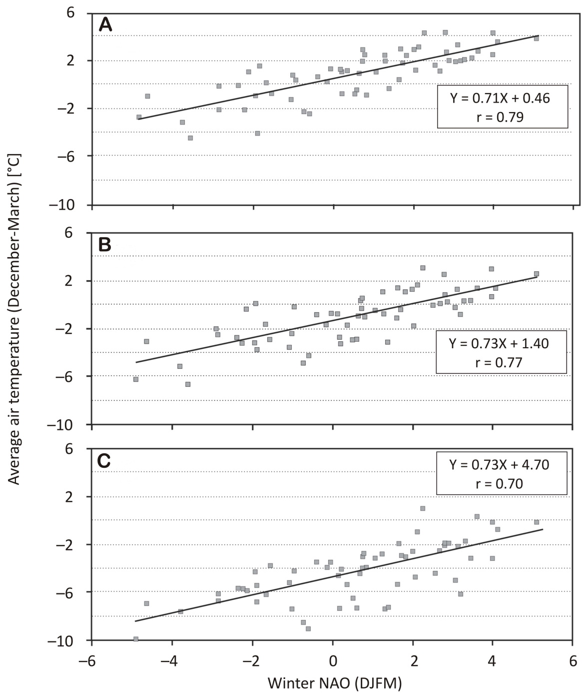

Fig. 2. The relationship between the average air temperature in December-March and the winter NAO index (DJFM) in the period 1971-2020 for the stations: A – Gorzów Wielkopolski, B – Olsztyn, C – Vitebsk

It has been noticed that the greatest increases in surface water temperature in lakes in the annual course occur on average in the temperature range of 9.7-14.7°C at the turn of April and May, while its greatest drops are on average in the range of 7.6-9.6°C at the turn of October and November. The results of calculating temperature trends in the course of the decade averages are consistent with the average increases and decreases in water temperature in the decade intervals.

The observed increase in water temperature in lakes caused, among others. things, through the intense North Atlantic Oscillation, it can lead to a gradual transformation of lake ecosystems. The transformation may affect both their physical and chemical processes and phenomena, as well as the living conditions in the aquatic environment different than before. This can lead to changes in the biocenosis of the entire lake ecosystem (Schindler 1996; Blenckner 2001).

In the context of the obtained results, the average temperatures in the surface layer of water and the dates of the occurrence of certain water temperatures justify the division of the annual course into four periods; winter with the phase of winter cooling and the phase of winter heating, spring with the early and late phase of spring heating, summer with the phase of summer heating and cooling, and autumn with the first and second phases of autumn cooling (Skowron 2011).

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