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Thermal regimes of lakes in the southern and eastern part of the Baltic Sea catchment area during the period of climate change

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Abstract. The study covered eleven lakes located in northern Poland and Belarus, aiming to determine the degree and trends of surface water temperature changes for the years 1971–2020 and lake ice cover for the period of 1961–2020 under the influence of ongoing climate changes. The analysis focused on changes and trends in average monthly surface water temperatures (SWT), as well as changes in the onset and end, duration and maximum thickness of ice cover. The average annual surface water temperature increased in the lakes by an average of 0.044°C per year. The lake with the highest trend is Chervonoe, at with 0.066°C per year, while the lowest is 0.029°C per year in Lake Hańcza. The ice cover duration showed a decrease of 0.6 days per year, and there was a reduction in maximum ice thickness of 0.27 cm per year.

Introduction

There is no doubt that in recent decades we have observed the phenomenon of climate warming. This is indicated by average global air temperature trends. Since 1998, the years have been decidedly the warmest in the history of global air temperature observations. Out of the 20 warmest individual years since 1850, as many as seventeen occurred in the last two decades, and a clear sign of warming is the shrinking cryosphere.

It is widely accepted that, after 1980, winter periods in Central Europe generally became warmer compared to earlier winters (Przybylak et al. 2005; Kaszewski 2015). The authors unanimously agree that, in the southern and eastern part of the Baltic Sea basin (the area of Poland and Belarus), the main cause of climate change is the variability of atmospheric circulation and the characteristics of air masses that shape the climate of Central Europe.

These features are associated with the intensification of zonal atmospheric circulation and the increase in oceanic climate characteristics, resulting in warming during winter periods, especially in January and February (Kożuchowski and Żmudzka 2001).

Materials, methods and study area

All the lakes are basins of post-glacial origin. The location of the studied lakes is defined by Lake Sławskie to the west (16.0°E), Lake Łukomskoe to the east (29.1°E), Lake Drywiaty to the north (55.6°N) and Lake Czerwonoe to the south (52.4°N).

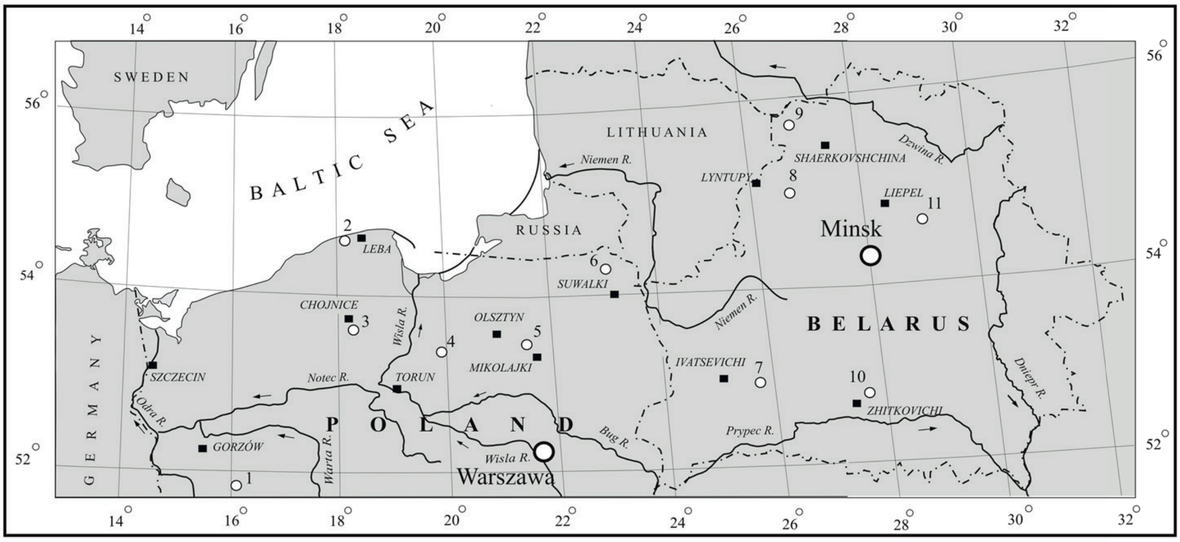

Fig. 1. Location of lakes for surface water temperature measurements recorded in 1971–2020 and for ice phenomena measurements recorded in 1961–2020 in Poland: 1 – Sławskie, 2 –Łebsko, 3 – Charzykowskie, 4 – Jeziorak, 5 – Mikołajskie, 6 –Hańcza; and in Belarus: 7 –Vygonoshchanskoe, 8 – Naroch, 9 – Driviaty, 10 – Chervonoe, 11 – Lukomskoe); and meteorological stations (black points).

The distance between the extreme lakes from west to east is ~1,130 km (13.2°) (Fig. 1).

The largest lakes are Lake Naroch (7,960 ha) and Łebsko (7,020 ha), while the smallest is Lake Hańcza (291.5 ha). In terms of depth, Lake Hańcza is the deepest (106.1 m), and the shallowest are Vygonoshchanskoe (2.3 m) and Chervonoe (2.6 m). The analysed lakes also show significant variation in capacity, with Lake Naroch (710.4 million m^3) and Lake Lukomskoe (249.0 million m^3) having the highest capacity and Lake Chervonoe (27.35 million m^3) having the lowest. Other morphometric data are presented in Table 1.

The analysis of air temperature is based on data from eight meteorological stations in Poland and nine stations in Belarus for the period of 1971–2020 (Table 1). These data encompass average annual and

Table 1. Location of wells with high-precision temperature logs made by the first author in Alberta and Saskatchewan, Canada

No.	Lake	Geographic location		Area in ha	Lake volume in millions m^3	Maximum depth in m	Mean depth in m	Average width (m)
		latitude	longitude					
1	Sławskie	51.9	16.0	822.5	42.66	12.3	5.2	898
2	Łebsko	54.7	17.4	7 020.0	117.52	6.3	1.6	4 366
3	Charzykowskie	53.8	17.5	1 336.0	134.53	30.5	9.8	1 360
4	Jeziorak	53.7	19.6	3 152.5	141.59	12.9	4.1	1 172
5	Mikołajskie	53.8	21.6	424.0	55.74	25.9	11.2	866
6	Hańcza	54.3	22.8	291.5	120.36	106.1	38.7	688
7	Vygonoshchanskoe	52.7	26.0	2 600.0	32.1	2.3	1.2	3 710
8	Naroch	54.9	26.8	7 960.0	710.4	24.8	8.9	6 200
9	Driviaty	55.6	27.0	3 614.0	223.52	12.0	6.1	3 570
10	Chervonoe	52.4	28.0	4 032.0	27.35	2.9	0.7	3 500
11	Lukomskoe	54.7	29.1	3 771.0	249.0	11.5	6.6	3 500

Source: after Skowron et al. (2023)

monthly temperatures, as well as annual amplitudes in those years.

The surface water temperature trends were depicted for eleven lakes based on data from the Institute of Meteorology and Water Management in Warsaw and the Hydrometeorological Service of the Republic of Belarus in Minsk over a 50-year period (1971–2020). Additionally, the ice-related phenomena (ice cover) were analysed for the same lakes over a 60-year period (1961–2020). Calculations for individual ice parameters were performed using Excel and Corel Quattro Pro 8 computer programs, and graphic representation was done using Corel Draw 9.

The goal of the study was to present the main features of the thermal regime, surface temperature, and ice cover for eleven (11) lakes in northern Poland and Belarus and determine their variability in the period of 1961–2020.

Results

The average annual air temperature in the area west of the Vistula River was 8.2°C, while east of the river it was 7.1°C and decreased notably on the Belarusian Lakeland to 6.0°C (Lyntupy). In the winter months (December, January, February) east of the Vistula River, the air temperature is distinctly negative, whereas west of this river, it rarely drops below 0°C. The spatial variation in air temperature is highlighted by the average annual amplitudes. East of the Vistula River, the amplitudes are always higher than 22.4°C, exceeding 24.0°C at some stations. On the other hand, stations on the Belarusian Lakeland achieve an average of 23°C (Table 2). Areas located east of the 23°E meridian are characterised by a significantly higher degree of continentality.

The spatial distribution of air temperature directly influences the surface water temperature (SWT) in lakes. The average annual values of SWT in the analysed period from 1971 to 2020 were distinctly diverse, ranging from 8.6°C for Lake Hańcza to 11.0°C for Lake Sławskie (Table 3). In the eastern direction, this value decreased to below 9.0°C in lakes on the Belarusian Lakeland.

The highest average monthly surface water temperatures were recorded most frequently in July and less frequently in August. These temperatures ranged from 18.91°C in Lake Łebsko to 21.84°C in Lake Chervonoe (Table 3).

The course of average annual surface water temperatures in all lakes shows a positive trend at the level of 0.044°C per year. Lake Chervonoe has the highest trend at 0.066°C per year, while the

Table 2. Average monthly and annual air temperatures and amplitude (A) at selected meteorological stations in Poland and Belarus in the period 1971–2020

Station	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Year	A
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 Wlkp.	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**
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**
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**
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**
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**

Source: after Skowron et al. (2023)

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

No	Lake	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Year
1	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**
2	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**
3	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**
4	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**
5	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**
6	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**
7	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**
8	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**
9	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**
10	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**
11	Łukomskoe[1]	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**

Source: Explanations: [1]Lake Lukomskoe is under the influence of a thermal power plant

Table 4. Average monthly and annual trend of 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	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**
2	Łebsko	0.021	0.010	0.009	0.012	0.018	**0.058**	**0.05**	**0.047**	**0.044**	**0.041**	**0.045**	0.029	**0.031**
3	Charzykowskie	**0.043**	**0.043**	**0.036**	**0.036**	**0.048**	**0.066**	**0.064**	**0.053**	**0.05**	**0.049**	**0.051**	**0.034**	**0.047**
4	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**
5	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**
6	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**
7	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**
8	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**
9	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**
10	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**
11	Lukomskoe[1]	**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**

Source: (based on IMiGW PIB data)

Explanations: 1 Lake Lukomskoe is under the influence of a thermal power plant, statistical significance < 0.001 is shown in bold.

smallest is 0.029°C per year in Lake Hańcza. The trend in average monthly water temperatures is also positive, ranging from 0.015°C per year in January to 0.069 °C per year in May (Table 4).

Climate conditions during winter months play a crucial role in the formation of ice phenomena. The onset of thermal winters and their courses in the years 1961–2015 confirm significant variability in thermal conditions in the cold season (Czarnecka and Nidzgorska-Lencewicz 2017).

The spatial distribution of air temperature during the winter months (December–March) gradually decreased from west to east (Table 5). In January, the average temperature in the multi-year period of 1961–2020 ranged from −0.9°C in western Poland (Gorzów Wielkopolski) to −6.6°C in the eastern part of the Belarusian Lakeland (Vitebsk) (Fig. 2).

The average dates of the onset of ice cover formation on lakes were significantly diverse and ranged between November 30th (Vygonoshchanskoe, Chervonoe) and January 4th (Charzykowskie). The spatial distribution shows significantly later appearances on lakes in the Polish Lowland.

The average dates of the end of ice cover on the studied lakes varied significantly. Their range fell between March 1st (Lake Łebsko) and April 7th and 8th (Lake Driviaty and Lake Naroch). The dates of ice cover disappearance on all analysed lakes showed

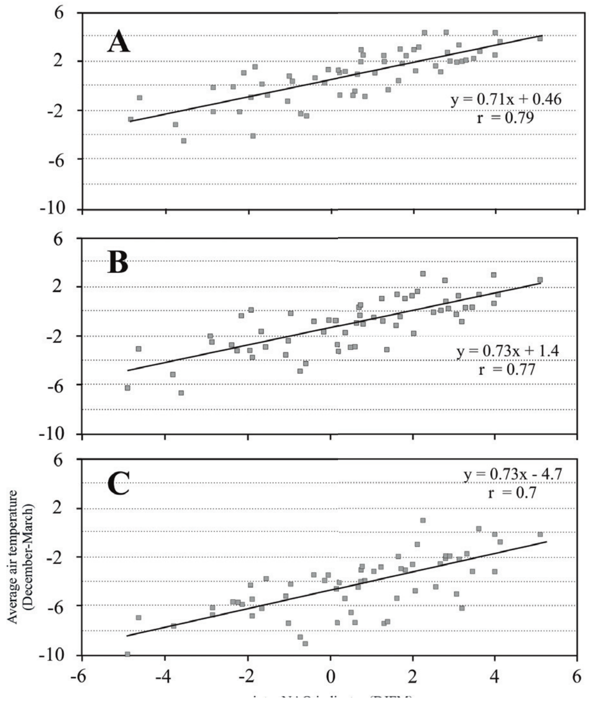

Fig. 2. Relationship between average air temperature in Dec–Mar and winter NAO index (DJFM) at the designated stations: A – Gorzów Wielkopolski, B – Olsztyn, C – Vitebsk, 1971–2020

a negative trend (average –0.34 days per year), ranging from –0.09 days per year (Lake Chervonoe) to –0.67 days per year (Lake Lukomskoe). For lakes in the Polish Lowland, the trend for the end dates of ice cover is less varied (Fig. 3).

In the analysed period, the average duration of ice cover varied from 55.6 days for Lake Łebsko to 121.0 days for Lake Driviaty (Table 6). For the others, it mostly ranged from 71 to 94 days, with an average of 83.3 days.

Ice thickness in the analysed period was very variable and generally increased towards the east. Average thickness varied from 21.9 cm (Lake Sławskie) to 46.5 cm in the eastern part of the Belarusian Lakeland (Lake Naroch). On other lakes, it ranged from 29.4 cm in the Polish Lowland to 40.4 cm on Belarusian lakes (Kirvel 2007). All lakes showed a negative trend (on average 0.2–0.4 cm per year), with the trend magnitude clearly increasing eastward (Table 7).

Discussion

Climate warming has led to changes in the thermal and ice regime of lakes in the northern hemisphere (Magnuson et al. 2000; Benson et al. 2012). Observations of lake and river freezing from 1846 to 1995 (over 150 years) have shown later freezing and earlier breakup of ice cover. Results of water temperature measurements in numerous lakes in Europe have confirmed the increasing importance of zonal atmospheric circulation, especially since the early 1970s (Hurrell 1995; Dokulil 2013). In Poland, studies in this area were conducted over the multi-year period of 1961–2020 on several lakes (Dąbrowski et al. 2004; Sobolewski et al. 2014; Wrzesiński et al. 2015; Ptak et al. 2018, 2019).

Based on long-term direct measurements of surface water temperature from twenty (20) lakes in Central Europe, it was found that the widespread increase in water temperature over the past fifty (50) years aligns with global lake trends (Silow 2012; Magee et al. 2016; Woolway et al. 2017). Confirmation of this trend includes an increase in surface water temperature in many lakes across Europe. Lake Windermere in England experienced

Table 5. Average air temperature in January & December–March, comparison of annual and thermal winter (December–March) mean trend observed at designated stations, 1961–2020

Stations	Average air temperature		Mean trend	
	in January	in December–March	in December–March	Year
Gorzów Wlkp.	-0.9	0.8	0.05	0.04
Chojnice	-2.3	-0.6	0.05	0.04
Olsztyn	-2.9	-1.0	0.05	0.03
Suwałki	-4.3	-2.4	0.05	0.03
Pińsk	-4.4	-4.4	0.08	0.05
Wierchniedwińsk	-5.9	-4.0	0.07	0.04
Vitebsk	-6.6	-4.4	0.08	0.05
Mogilev	-6.5	-4.3	0.06	0.03

Table 6. Average values of ice features of selected lakes in Poland and Belarus in the years 1961–2020

No.	Lake	Beginning of ice cover	End of ice cover	Duration of days ice cover	Maximum thickness of ice cover (cm)	Percentage of cover ice in the course of phenomena ice cream (%)
1	Sławskie	24 Dec	3 Mar	59.2	21.9	80.1
2	Łebsko	23 Dec	1 Mar	55.6	22.2	74.6
3	Charzykowskie	4 Jan	14 Mar	62.3	24.5	77.7
4	Jeziorak	15 Dec	15 Mar	83.1	27.7	86.4
5	Mikołajskie	31 Dec	17 Mar	72.0	32.2	71.7
6	Hańcza	3 Jan	20 Mar	73.7	30.9	78.8
7	Vygonoshchanskoe[1]	30 Nov	24 Mar	113.1	37.5	84.4
8	Naroch	17 Dec	08 Apr	113.0	46.5	81.1
9	Driviaty	8 Dec	07 Apr	120.1	45.7	83.4
10	Chervonoe	30 Nov	27 Mar	116.6	36.0	85.3
11	Lukomskoe[2]	18 Dec	26 Mar	97.5	36.2	76.7

Source: after Skowron and Sukhowilo (2022)
Explanations: 1 data from 1964, [2] Lake Lukomskoe is under the influence of a thermal power plant.

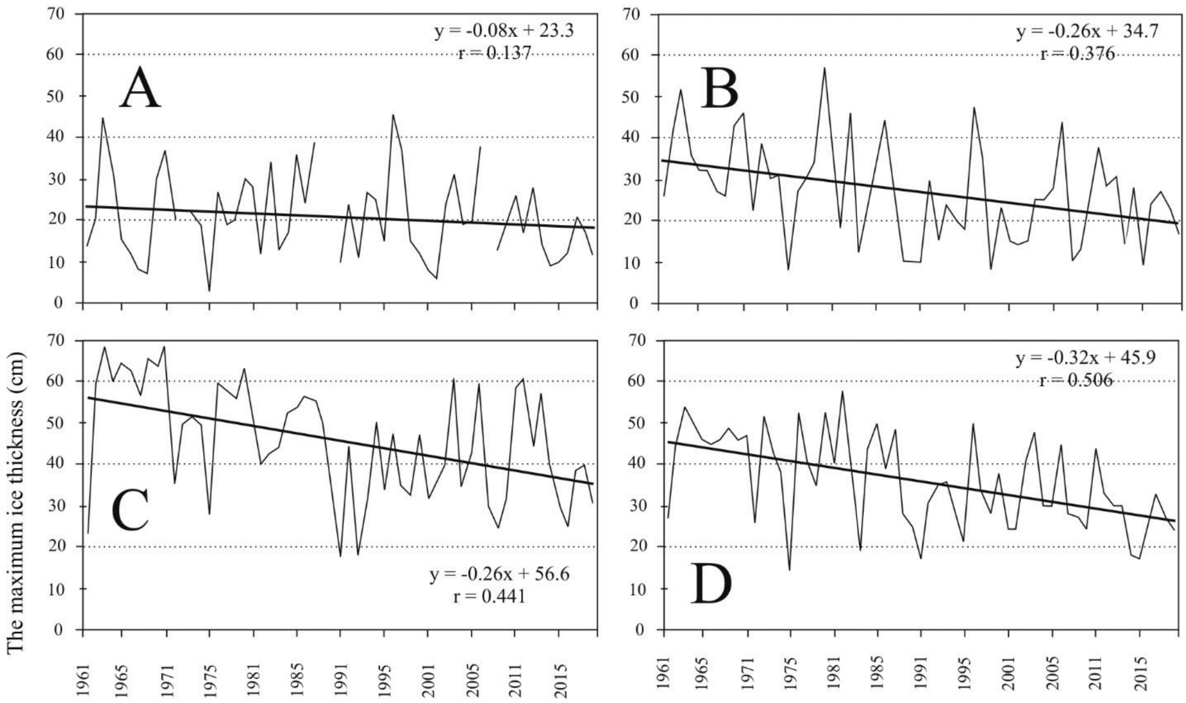

Fig. 3. Course of the maximum thickness of the ice sheet in selected lakes of Poland and Belarus in the years 1961-2020 and trend lines:A-Sławskie, B-Jeziorak, C-Naroch, D-Chervonoe.

a rise of 1.4°C between 1960 and 2000, and Lake Lough Feeagh in western Ireland saw an increase of 0.7°C between 1960 and 1997 (Dokulil 2013). The average water temperature in Lake Zurich, Switzerland, increased at a rate of 0.16 °C per decade from 1950 to 1990, and Lake Constance increased by about 0.1°C (Straile et al. 2003). This trend is complemented by exceptionally high increases of 1.6°C per decade in Stensjön Lake in Sweden (Adrian et al. 2009). Surface water temperature in many European lakes in Finland, Austria, and Switzerland during the summer increased by 0.38°C, 0.43°C, and 0.29°C per decade, respectively (Arvola et al. 2010).

Table 7. Trend values for features of selected lakes in Poland and Belarus in the years 1961–2020

No.	Lake	Beginning of ice cover	End of ice cover	Duration of days ice cover	Maximum thickness of ice cover (cm)
1	Sławskie	0.31	–0.31	**–0.57**	–0.08
2	Łebsko	0.19	–0.42	**–0.82**	**–0.20**
3	Charzykowskie	0.14	–0.33	–0.46	–0.17
4	Jeziorak	0.19	–0.36	**–0.66**	**–0.26**
5	Mikołajskie	0.16	–0.37	**–0.68**	**–0.34**
6	Hańcza	0.14	–0.27	–0.44	**–0.48**
7	Vygonoshchanskoe[1]	0.32	–0.21	**–0.42**	**–0.35**
8	Naroch	**0.32**	–0.11	**–0.58**	**–0.26**
9	Driviaty	0.24	**–0.40**	**–0.69**	**–0.58**
10	Chervonoe	0.24	–0.09	**–0.56**	**–0.32**
11	Lukomskoe[2]	**0.35**	**–0.67**	**–0.76**	0.05

Source: after Skowron and Sukhowilo (2022)

Explanations: 1 data from 1964, [2] Lake Lukomskoe is under the influence of a thermal power plant, statistical significance < 0.001 is shown in bold

There is compelling evidence of an increase in surface water temperature since the early 1990s (Livingstone 1993; George 2007; Lieberherr and Wunderle 2018; Zhang et al. 2020). Results of water temperature measurements in European lakes have confirmed the growing importance of zonal atmospheric circulation, especially since the early 1970s (Naumenko et al. 2008; Dokulil 2013). An example of these changes is the average annual surface water temperatures in Latvian lakes, which, during the period of 1946–2002, showed a significant positive trend ranging from 0.4 to 0.8 °C (Järvet 2002; Dokulil 2013; Apsīte et al. 2014). A 1.1°C increase in air temperature from 1988 to 2002 led to fundamental changes in processes in lakes and artificial reservoirs in Belarus (Danilovish 2004). This resulted in earlier occurrences of water temperatures of 0.2°C, 4°C and 10°C in spring (5 to 11 days earlier) and in autumn (7 days earlier). The duration of ice phenomena decreased significantly by five (5) days, and ice cover reduced by 6 days.

Studies on Lithuanian lakes showed that the average annual surface water temperature from 1991 to 2000 was 0.6°C higher compared to the average from 1981 to 1990 (Pernaravičiūtė 2004). The increase in water temperature in Lithuanian lakes began in the years 1981–1985 and continues to this day (Kilkus and Valiuškevičius 2001). In Lake Ladoga, a positive trend of 0.05–0.07°C per year was observed (Naumenko et al. 2008). Research conducted on lakes in northwestern Russia and Finland from 1961 to 1990 also showed earlier occurrences of 4 and 10 °C surface water temperatures in spring and later occurrences in autumn (Gronskaya et al. 2002; Mitikka and Ekholm 2003).

The increase in the temperature of the surface layer of water in lakes causes the transfer of heat through convection and turbulence to deeper layers, ultimately affecting the temperature in the hypolimnion (HWT) (Mazumder and Taylor 1994). In Lake Maggiore in northern Italy, from 1963 to 1998, water temperature consistently increased at all depths, especially below 300 m (Ambrosetti and Barbanti 1999). Similar increases were observed in several other lakes in northern Italy, and, in Lake Garda, from 1990 to 2003 the temperature in the hypolimnion increased by 0.7°C per decade (Salmaso and Mosello 2010). A similar increase in hypolimnion temperature was observed in four Swiss lakes north of the Alps, ranging from 0.1 to 0.5°C per decade (Livingstone 1993). Temperature variations in the hypolimnion were observed in Lake Geneva, where the upper hypolimnion was distinguished up to a depth of 90 m, below which the lower hypolimnion had a more stable water temperature (Michalsky and Lemmin 1995). An analysis of thirty nine (39)-year temperature profiles (1969–2008) in Lake Kinneret in Israel showed that the average temperature of the epilimnion increased by 0.028°C per year, and the thermal gradient in the metalimnion also increased (Rimmer et al. 2011).

The increase in hypolimnion temperature in the second half of the 20th century by approximately

0.1–0.2°C per decade was significantly linked to the winter North Atlantic Oscillation (NAO) index (Dokulil et al. 2006). In some cases, the warming of water had episodic characteristics and was characterised by a slow increase in hypolimnion temperature (Ambrosetti and Barbanti 1999; Skowron and Sukhovilo 2022). In Lake Mond in Austria, the period of thermal stratification has now become 26 days longer (Dokulil et al. 2010), and in shallow Lake Erken in Sweden, the duration of summer stratification increased by 28 days (Arvola et al. 2010).

Research on surface water temperature in lakes in the Polish Lowland covering the years 1961–2000 confirms the trend observed in lakes across Europe. For most lakes, the increase ranges from 0.2°C to 0.9°C per decade (Skowron 1997, 1999, 2001, 2007; Marszelewski and Skowron 2006).

Significant changes have occurred in the course of ice phenomena. Observations of lake and river freezing from 1846 to 1995 (over 150 years) have shown later freezing and earlier breakup of ice cover (Magnuson et al. 2000). For Lake Kallavesi and Lake Näsijärvi in Finland, freezing occurred on average 5.8 days later per 100 years, while the average dates of ice cover disappearance from 1833 to 1995 were on average 9.2 and 8.8 days earlier per 100 years, respectively.

These trends are confirmed by ice phenomena for eight (8) lakes in Karelia (northwestern Russia) from 1950 to 2009, where statistical dependencies between lake ice phenology, air temperature and the NAO index were observed (Efremova et al. 2013). The research showed that freezing of all lakes occurs increasingly later, while their ice cover disappearance has shifted to an earlier date compared to the multi-year average. On Lake Ladoga and Lake Onega, earlier disappearance of ice cover was observed (Karetnikov and Naumenko 2008), while, in the last decades of the 20th century, the largest freshwater lakes in Russia located at high latitudes experienced a reduction in ice cover thickness (Lemeshko and Gronskaya 2004).

Analysis of the course of ice cover for several Finnish lakes, especially for Lakes Kallavesi, Näsijärvi and Oulujärvi, indicates a slight tendency towards earlier breakup in many lakes (Kuusisto and Elo 2000; Korhonen 2004). Similar situations were observed in lakes in central Norway (Øvre Heimdalsvatn) (Kvambekk and Melvold 2010) and in lakes in central Sweden (Bengtsson 1986).

The ice cover on Lake Peipus in Estonia lasts for one hundred fifteen (115) days (from December 9th to April 4th) and is characterised by earlier breakup, similarly to many other lakes in the northern hemisphere (Reinart and Pärn 2006). Also, on Lake Ladoga, there is an earlier disappearance (14 days per 100 years) (Karetnikov and Naumenko 2008). On Lake Onega, the phenomenon of shortening the duration of ice cover leads to an extension of the ice-free period from two hundred seventeen (217) to two hunder twenty five (225) days (Salo and Nazarova 2011).

Similar features were observed in the course of average ice cover values for Lithuanian lakes (Bukantis et al. 2001). As a result of the 1.1°C increase in air temperature from 1988 to 2000, there was a clear shortening of the period with water temperatures in the range of 0 and 2°C and the duration of ice phenomena by five (5) days and ice cover by six (6) days (Danilovish 2004). These observations confirm the significant decreases in ice thickness, averaging 4–9 cm per year (Kirvel 2007). Statistical dependencies between lake ice phenology (freezing and breakup dates, ice duration), air temperature and the NAO index were analysed for eight lakes in Karelia from 1950 to 2009. It was shown that, in the last twenty (20) years, trends in the chronology of ice phenomena are more pronounced than in the entire sixty (60)-year period (Efremova et al. 2013).

The influence of NAO has also been proven in relation to lake ice phenology in the northern hemisphere (Mahrer et al. 2005; George 2007; Soja et al. 2014). The winter NAO index mainly affects late-winter temperatures (Jan–Mar) and also the spring period (Apr–May), when air temperature is strongly correlated with ice phenomena dates (Yoo and D'Odorico 2002). Data analysis in the Baltic Sea region indicates similar fluctuations in winter air temperature (JFM) with fluctuations in the winter NAO index.

In studies of ice phenomena on Polish lakes from 1951 to 2010, it was established that, during this period, the average duration of ice cover shortened by 0.55 days per year and the maximum ice cover thickness decreased by 0.21 cm per year (Choiński et al. 2014; Ptak et al. 2019). These results are consistent with earlier Polish studies on the course of ice phenomena on lakes in shorter time intervals (Marszelewski and Skowron 2006). Spatial analysis of the course of ice phenomena showed that the only clear distributions are for maximum ice cover thickness, the degree of ice cover persistence, and the number of breaks in the ice cover distribution.

Conclusions

The transient nature of the climate in the northern part of Poland is marked by changes in surface temperature (Skowron 2001) and varied dates of occurrence, durations and degrees of persistence of ice cover (Wrzesiński et al. 2015; Skowron 2021). During the positive phase of the NAO, in warm and humid winters, the duration and thickness of ice cover were significantly less than in winters with a negative NAO index. The transient nature of Poland's climate is clearly evident in the spatial distribution of lake ice phenomena. West of the Vistula River, the occurrence of ice phenomena is notably shorter, and the thickness of the ice cover is smaller.

In the course of surface temperature in all lakes in Poland and Belarus, distinct positive trends have been observed for the average annual temperature, as well as in the spring and autumn months. This has led to temperatures of 4 and 10°C appearing increasingly earlier in spring and later in autumn. In Polish lakes, the period of thermal stratification (above 15°C) typically begins around the third decade of May and ends in the middle of the third decade of September. The length of the period with temperatures above 15°C ranges from 100 to 135 days and is characterised by a clearly positive trend at a level of 0.15–0.25 days per year (Skowron and Sukhovilo 2022).

Disclosure statement

No potential conflict of interest was reported by the authors.

Author contributions

Study design: RS; data collection: RS; statistical analysis: RS, TS; result interpretation: RS, TS; manuscript preparation: RS, TS; literature review: RS, TS.

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