limnological review

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Diversity and Variability of the Course of Ice Phenomena on the Lakes Located in the Southern and Eastern Part of the Baltic Sea Catchment Area

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Abstract: The aim of the study is to determine the scale of differentiation and variability of ice phenomena on the lakes in the south-eastern part of the Baltic Sea catchment area. The analysis was performed based on data from the period 1961–2020 from 15 lakes located in Poland (10) and Belarus (5). The characteristics of ice phenomena were characterized, i.e., the length of their occurrence and ice cover, the thickness of ice cover and the number of breaks occurring in the ice cover in the given years were characterized. The analysis of the course of ice phenomena made it possible to distinguish three regions with an increasing length of ice phenomenon occurrence from west to east. The zones were the west of the Vistula, the east of it and the eastern part of the Belarusian Lake District. In the analyzed multi-year period, a shortening of the duration of ice phenomena and ice cover, a decrease in the maximum thickness of the ice and an increasing number of breaks in ice cover were observed. These data correlate with the upward trend in air temperature.

Keywords: lakes in Poland and Belarus; ice phenology; variability

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Citation: Skowron, R.; Kirvel, P.; Choiński, A.; Kirvel, I. Diversity and Variability of the Course of Ice Phenomena on the Lakes Located in the Southern and Eastern Part of the Baltic Sea Catchment Area. *Limnol. Rev.* **2023**, *23*, 33–49. https://doi.org/10.3390/limnolrev23010003

Academic Editor: Piotr Rzymski

Received: 11 April 2023
Accepted: 19 April 2023
Published: 1 June 2023

1. Introduction

Research on the occurrence and variability of ice phenomena on lakes is basic, and in recent years, research problems in limnology have become more and more frequently discussed research. This is mainly due to the fact that lakes are perceived as an essential and important link of the natural environment, taking part in its changes. These changes occur in parallel with climate change, and are clearly noticeable in the northern hemisphere [1–3]. These changes mainly affect the biocenosis of an entire lake's ecosystem [4,5]. An important issue is still the differentiation of the course of the occurrence of ice phenomena depending on the geographical location of lakes. On the other hand, as examples of differentiation of lake icing in Europe, we can mention the works of Yoo and D'Odorico [6–8], for example.

2. Materials and Methods

The ice analysis conducted was based on data from 15 lakes located in the south-eastern part of the Baltic Sea catchment area, and they include five lakes west of the Vistula River (Osiek, Sławskie, Łebsko, Charzykowskie, and Biskupińskie), five lakes located in the Masurian Lake District (Jeziorak, Mikołajskie, Ełckie, Hańcza and Serwy), four lakes in Belarusian Poozerie (Naroch, Driviaty, Chervonoe and Lukomskoe) and one lake in Belarusian Polesie (Vygonoshchanskoe). Their selection was dictated by the existence of complete data series on lake ice (beginning of ice phenomena, beginning of ice cover, end of ice cover, end of ice phenomena, and maximum thickness of ice cover in individual years) in the period 1961–2020. Their extreme location is marked in the west by the Osiek Lake (15.68° E), in the east by the Lukomskoe Lake (29.08° E), in the north by the Driviaty Lake (55.6° N), and in the south by the Vygonoshchanskoe Lake (52.68° E). All the lakes, except the one located in Polesie, are of glacial origin (Figure 1).

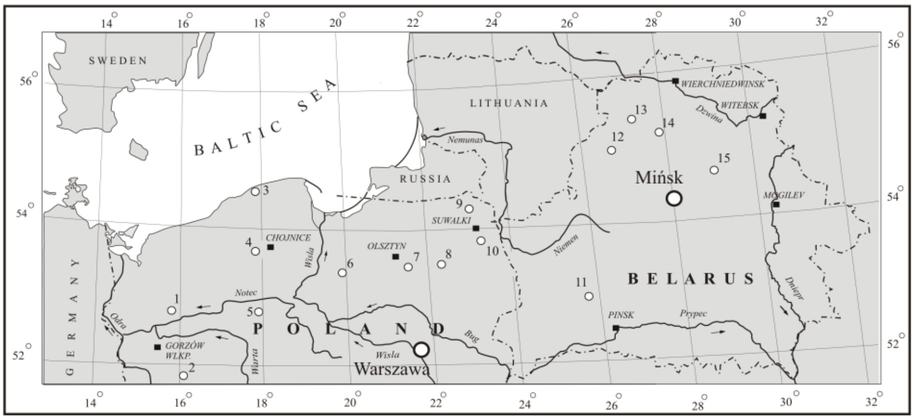

Figure 1. Location of lakes obtained during ice phenomena measurements in period 1961–2020 in Poland (1—Osiek, 2—Sławskie, 3—Łebsko, 4—Charzykowskie, 5—Biskupińskie, 6—Jeziorak, 7—Mikołajskie, 8—Ełckie, 9—Hańcza, and 10—Serwy) and in Belarus (11—Vygonoshchanskoe, 12—Naroch, 13—Driviaty, 14—Chervonoe, and 15—Lukomskoe) and meteorological stations (black points).

The largest lakes are Naroch (7960 ha) and Łebsko (7020 ha), while the smallest are Biskupińskie (107.0 ha) and Studzieniczne (244.0 ha). In terms of depth, the deepest are Lake Hańcza (106.1 m) and Ełckie (55.8 m), and the shallowest are Vygonoshchanskoe (2.3 m) and Chervonoe (2.6 m). The analyzed lakes are also clearly differentiated in terms of their capacity. The lakes with the largest capacity are Lake Naroch (710.4 million m^3) and Lukomskoe (249.0 million m^3), and those with the smallest are Biskupinskie Lake (6.4 million m^3) and Chervonoe (27.3 million m^3). A summary of the morphometric data is presented in Table 1.

Table 1. Location and basic morphometric data of the analyzed lakes in Poland and Belarus.

No.	Lake	Geographic Location		Area in ha	Maximum Depth in m	Mean Depth in m	Lake Volume in Million m^3	The Height of the Water Table in m a.s.l.	The Length of the Coastline in km
		Longitude	Latitude						
1	Osiek	15°40′ E	52°57′ N	**514.0**	35.3	9.3	50.06	52.5	27.8
2	Sławskie	16°01′ E	51°53′ N	822.5	12.3	5.2	42.7	57.0	24.6
3	Łebsko	17°23′ E	54°42′ N	**7020.0**	6.3	1.6	117.5	0.2	55.4
4	Charzykowskie	17°30′ E	53°47′ N	**1336.0**	30.5	9.8	134.5	120.0	31.0
5	Biskupińskie	17°44′ E	52°47′ N	107.0	13.7	5.5	6.4	78.6	5.6
6	Jeziorak	19°36′ E	53°43′ N	3152.5	12.9	4.1	141.6	99.2	49.0
7	Mikołajskie	21°35′ E	53°46′ N	424.0	25.9	11.2	55.74	115.7	14.6
8	Ełckie	22°20′ E	53°48′ N	385.0	55.8	15.0	57.4	119.9	18.6
9	Hańcza	22°48′ E	54°16′ N	291.5	106.1	38.7	120.4	227.3	11.8
10	Serwy	23°12′ E	53°54′ N	438.5	41.5	14.1	67.2	126.8	16.1
11	Vygonoshchanskoe [1]	25°56′ E	52°41′ N	2600.0	2.3	1.2	32.1	153.0	21.0
12	Naroch	26°44′ E	54°51′ N	7960.0	24.8	8.9	710.0	165.0	41.0
13	Driviaty	27°01′ E	55°36′ N	3614.0	12.0	6.1	223.5		37.6
14	Chervonoe	27°58′ E	52°24′ N	4032.0	2.9	0.7	27.3	136.4	30.0
15	Lukomskoe [2]	29°05′ E	54°40′ N	3771.0	11.5	6.7	243	165.1	36.4

Explanations: [1]—data from 1964, [2]—Lake Lukomskoe under the influence of a thermal power plant.

3. Results

The first studies of lake icing in the study area were carried out on four lakes and covered the years 1926–1937 [8]. They concerned the Gopło and Serwy lakes located in Poland and the Narocz and Drywiaty lakes located in the northern part of the Belarusian

Poozerie. The following lakes have the longest ice observation series: Gopło and Serwy (from 1924), Driviaty (from 1928), Lukomskoe (from 1932), Naroch (from 1944), Jeziorak, Mikołajskie and Studzieniczne (from 1947), Ełckie (from 1951), Sławskie, Biskupińskie, and Charzykowskie and Chervonoe (from 1956). Due to the numerous breaks in the observations, the synchronous period covering the years 1961–2020 was finally adopted in the study.

Lake icing was observed during the winter months every day at 7:00 a.m., noting the dates of the beginning and end of the occurrence of ice phenomena and ice cover, determining their extent within individual lakes, while the thickness of the cover was measured every 5 days, with an accuracy of 1 cm.

In this study, the results of the observations of the Institute of Meteorology and Water Management in Poland and the Hydrometeorological Service of the Republic of Belarus on the course of ice phenomena on 15 selected lakes in the period 1961–2020 were used. The dates of the beginning and end of ice cover, its duration and its maximum thickness in individual years were recorded. Air temperatures at posts located within the vicinity of the lakes were also taken into account. Moreover, the work involved synchronous measurements of the thickness of ice cover made in the winter of 2003/2004 on 33 lakes of the European Lowlands located between 8.02° E and 25.50° E [9].

The study uses data relating to the course of ice phenomena on the lakes of northern Poland and Belarus over the period of 60 years (1961–2020). The calculations of the individual parameters of icing (individual phases of icing) were made in the Excel and Corel Quattro Pro 8 computer programs, while graphic processing was presented using the Corel Draw 9 program.

The aim of the study is to present the changes in the course of icing in the selected lakes in Poland and Belarus and their spatial differentiation in the years 1961–2020 during the period of climate change.

Climatic conditions during the winter months are of particular importance for the formation of ice phenomena. These conditions are well represented by the course of the thermal winter, treated as the daily air temperature equal to or lower than 0 °C. The beginnings of thermal winters and their course in 1961–2015 confirm the very high variability of thermal conditions in the cold season. Only in the north-eastern part of Poland was thermal winter recorded each year. In the remaining areas, the course of thermal winter was most often interrupted by periods of warming [10]. The variability of the dates of the beginning and end of the thermal winter in the analyzed period does not show statistically significant changes. However, a slight tendency to shorten the thermal winter was found. Almost every winter, cold and frosty periods are interrupted by periods of thaws of varying intensity and duration. Climatological winter is, however, the season with the greatest inter-year fluctuations, but also the season with the greatest spatial variability of temperatures.

The dates defining thermal winter in Poland have fallen in the last 60 years within a very wide time span. The beginning of thermal winter was most often in the first decade in December, while its end was in the second decade in March [10]. There were years when thermal winter did not occur in Poland in three subsequent years—1988, 1989 and 1990—and also in two subsequent years—2007 and 2008. In general, the duration of thermal winter ranged from 40 days in the north-western part of Poland to 90–100 days in the Suwałki Lake District.

The spatial distribution of air temperature in the study area is marked by a gradual decrease in the average temperature from west to east during the winter months (December–March), especially in January (Table 2). In January, the average temperature in the years 1961–2020 varied from −0.9 °C in the west of Poland (Gorzów Wielkopolski) to −6.6 °C in the eastern part of the Belarusian Lake District (Vitebsk). During the winter months, a clear positive trend of the average air temperature was observed at all the considered posts, increasing to 0.08 °C·year^{-1} east of the meridian 26° E.

Table 2. Average air temperature in January and December–March and the trend in the thermal winter between December–March and annually in the multi-year period 1961–2020 at selected stations.

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

The confirmation of the significant influence of air temperature on the course of ice phenomena is their close correlation for the winter months (December–March) in the winter NAO index (DJFM) presented in the figure below (Figure 2). It is preserved regardless of the geographic location. Despite the significant distance between the meteorological posts (Gorzów Wielkopolski–Vitebsk)—almost 15° (approx. 1.15 km)—the correlation coefficient is above 0.7, with a statistical significance (α) of below 0.001.

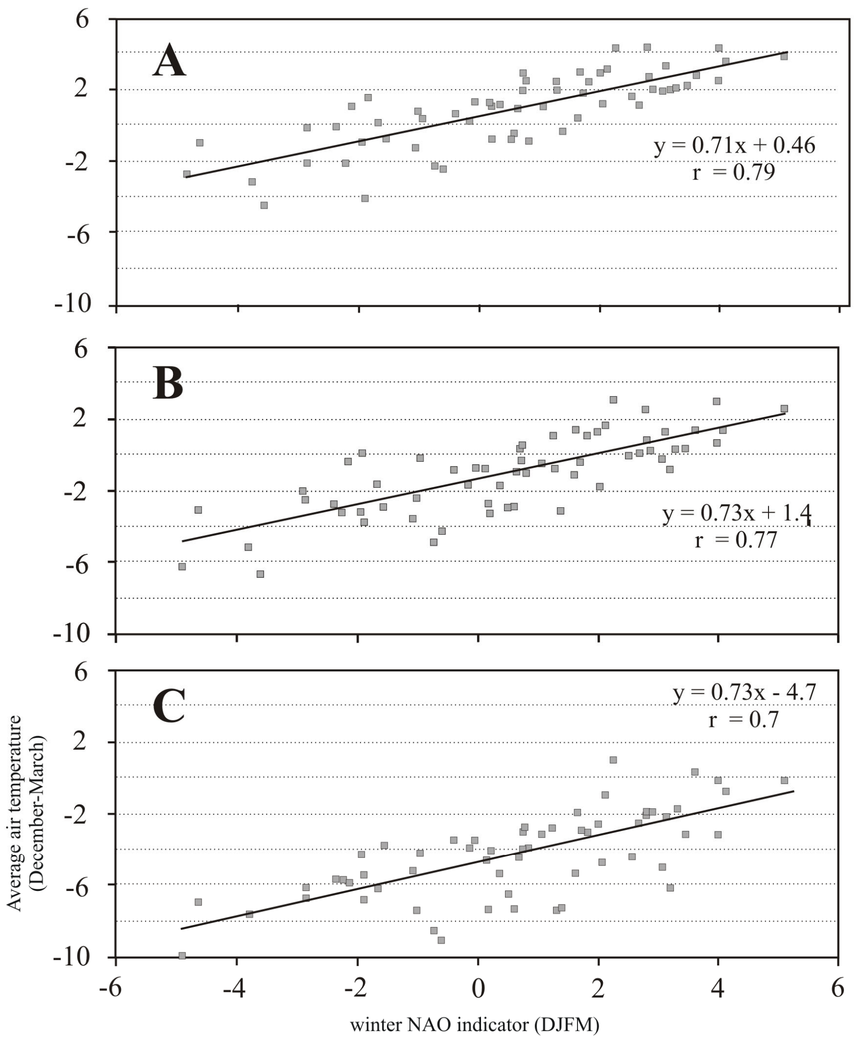

Figure 2. Relationship between the winter NAO index (DJFM) and the average air temperature in December–March in the multi-year period 1961–2020 at selected meteorological stations ((**A**)—Gorzów Wielkopolski, (**B**)—Olsztyn, (**C**)—Vitebsk).

It is well known that the course of ice phenomena on lakes depends on many factors, including the average depth and capacity. The average depth varies from less than 2 m (Chervonoe, Vygonoshchanskoe and Łebsko) to 38.7 m (Lake Hańcza). The lakes with the largest capacity are Lake Naroch (710 million m^3) and the Lukomskoe Lake (243 million m^3), while that with the smallest is Biskupińskie Lake (6.4 million m^3). The remaining morphometric data are presented in Table 1.

The temporal and spatial variability of the course of ice on the lakes was based on a 60-year series of observations covering the years 1961–2020 of 15 lakes. The data from these observations refer to the beginning and end of ice phenomena and ice cover, their duration, the maximum thickness of ice cover, the number of breaks in the occurrence of ice cover in the winter season and the percentage share of ice cover in the course of the occurrence of ice phenomena.

Particular attention was paid to the course of the occurrence of ice cover, which accounts for approx. 80% of various forms of ice, and at the same time creates new and different conditions for heat exchange between the lake and the atmosphere.

The first ice phenomena in the form of shore ice occurred on average between 17 November (Vygonoshchanskoe Lake) and 27 December (the Osiek and Charzykowskie lakes). Generally, their dates appear earlier and earlier in the eastern direction and depend also on the depth of the lakes. In the period 1961–2020, the earliest ice phenomena occurred on the lakes of the Belarusian Poozerie at the end of October 1987 and in 1988 (Czerwone, Driviaty and Vygonoshchanskoe). In the lakes located in the Polish Lowlands, the beginning of the occurrence of ice phenomena was much later in relation to the lakes located east of the meridian 26° E. The dates of the occurrence of ice phenomena on all lakes in the multi-year period 1961–2019 were characterized by a high degree of dispersion, as evidenced by the standard deviation (δ), which was on average 17.8 (Table 3. When analyzing the initial dates of the occurrence of ice phenomena on the lakes, a positive trend of 0.24 days·year^{-1} is noticeable (Table 4).

Table 3. Average values of ice characteristics in lakes in Poland and in Belarus in 1961–2020.

No.	Lake	Beginning of		End of		Duration of Days		Maximum Thickness of Ice Cover (cm)	Mean Proportional Part of Ice Phenomena in Longterm Period (%)
		Ice Phenomena	Ice Cover	Ice Cover	Ice Phenomena	Ice Phenomena	Ice Cover		
1	Osiek	27-Dec	3-Jan	11-Mar	16-Mar	66.5	59.0	20.5	81.8
2	Sławskie	13-Dec	24-Dec	3-Mar	4-Mar	68.6	59.2	21.9	80.1
3	Łebsko	11-Dec	23-Dec	1-Mar	8-Mar	69.2	55.6	22.2	74.6
4	Charzykowskie	27-Dec	4-Jan	14-Mar	21-Mar	73.9	62.3	24.5	77.7
5	Biskupińskie	15-Dec	20-Dec	8-Mar	12-Mar	79.2	69.2	25.5	85.3
6	Jeziorak	6-Dec	15-Dec	15-Mar	19-Mar	94.4	83.1	27.7	86.4
7	Mikołajskie	16-Dec	31-Dec	17-Mar	31-Mar	95.6	72.0	32.2	71.7
8	Ełckie	18-Dec	27-Dec	8-Mar	24-Mar	90.4	63.4	28.3	68.8
9	Hańcza	26-Dec	3-Jan	20-Mar	29-Mar	91.2	73.7	30.9	78.8
10	Serwy	19-Dec	28-Dec	21-Mar	29-Mar	98.1	81.6	30.5	81.2
11	Vygonoshchanskoe [1]	17-Nov	30-Nov	24-Mar	28-Mar	132.4	113.1	37.5	84.4
12	Naroch	29-Nov	17-Dec	08-Apr	12-Apr	137.2	113.0	46.5	81.1
13	Driviaty	28-Nov	8-Dec	07-Apr	13-Apr	139.9	120.1	45.7	83.4
14	Chervonoe	20-Nov	30-Nov	27-Mar	28-Mar	132.1	116.6	36.0	85.3
15	Lukomskoe [2]	7-Dec	18-Dec	26-Mar	02-Apr	120.2	97.5	36.2	76.7

Explanations: [1]—data from 1964, [2]—Lake Lukomskoe under the influence of a thermal power plant.

Table 4. The sizes of the standard deviation for the ice characteristics in selected lakes in Poland and Belarus in the years 1961–2020.

No.	Lake	Beginning of		End of		Duration of Days		Maximum Thickness of Ice Cover (cm)
		Ice Phenomena	Ice Cover	Ice Cover	Ice Phenomena	Ice Phenomena	Ice Cover	
1	Osiek	18.41	18.92	20.92	19.32	31.16	31.2	10.55
2	Sławskie	17.77	19.41	27.10	25.81	31.61	30.46	10.18
3	Łebsko	22.51	21.00	27.15	27.23	33.85	32.13	10.91
4	Charzykowskie	20.07	18.84	19.57	18.90	30.47	29.05	11.20
5	Biskupińskie	16.92	20.48	22.11	21.27	29.80	31.94	10.89
6	Jeziorak	14.72	17.78	21.90	20.94	28.01	30.79	11.87
7	Mikołajskie	17.33	18.97	22.98	18.41	31.61	32.28	13.88
8	Ełckie	18.02	19.64	25.78	21.54	30.74	32.39	10.02
9	Hańcza	20.74	19.62	24.13	22.49	29.75	28.66	14.26
10	Serwy	18.09	19.19	22.04	21.10	27.32	27.85	12.19
11	Vygonoshchanskoe [1]	14.69	17.62	18.28	18.41	22.01	23.56	11.88
12	Naroch	17.28	17.00	13.06	13.36	21.97	22.59	13.49
13	Driviaty	17.70	18.3	14.80	14.71	18.70	24.52	15.22
14	Chervonoe	14.64	16.77	15.55	16.61	19.5	21.83	11.11
15	Lukomskoe [2]	17.59	19.13	22.42	21.97	25.14	31.34	11.41

Explanations: [1]—data from 1964, [2]—Lake Łukomskie under the influence of a thermal power plant.

The average dates of the beginning of the occurrence of ice cover on the lakes varied considerably and ranged between 30 November (Vygonoshchanskoe and Chervonoe) and 4 January (Charzykowskie). The spatial distribution shows their definite later appearance on the lakes of the Polish Lowlands, which occurred most often in the second and third decade in December (Table 2). The earliest ice cover appeared at the beginning of November (Lake Vygonoshchanskoe and Chervonoe) in 1973 and 1988, respectively, while on the other lakes in the second and third decade in November, most often it was in 1994. In turn, the last dates of the appearance of ice cover in the multi-year period 1961–2020 were most often recorded in the second decade in February on lakes in the Polish Lowlands. Significant differences in the dates of the beginning of ice sheet formation refer to the air temperature course in the months from November to February (inclusive), and their confirmation is the standard deviation (δ), which was within 16.77 days (Lake Chervonoe) and 21.0 days (Lake Łebsko) (Table 4).

The dates of ice cover formation in all lakes were characterized by a positive trend at the level of 0.14 days·year^{-1} (Hańcza lake) an d0.36 days·year^{-1} (Biskupinskie Lake), but on the lakes in Belarus ice cover formation was less diversified (Figure 2, Table 3).

The average dates of the end of the occurrence of ice cover in the studied lakes were also characterized by considerable diversification. Their scope was determined by the dates between 1 March (Łebsko lake) and 7 and 8 April (Driviaty and Naroch lakes). In lakes located in Belarus, the average disappearance of ice cover occurred in the middle of the third decade of March. Their extreme dates varies considerably. The earliest ice cover disappeared in 1989 between December and January on eight lakes located within the Polish Lowlands. The latest ice cover disappeared at the end of the third decade of April 1963 on the lakes of the Belarusian Lake District (Lake Lukomskoe—30 April, and Naroch Lake—29 April). The end dates of their disappearance were highly dispersed, and the standard deviation (δ) ranged from 14.8 days (Driviaty Lake) to 27.15 days (Łebsko Lake), with an average of 21.2 days (Table 3).

The dates of the disappearance of ice cover on all analyzed lakes followed a negative trend (average at the level of −0.34 days·year^{-1}) from −0.09 days·year^{-1} (Lake Chervonoe) to −0.67 days·year^{-1} (Lake Lukomskoe). In the lakes of the Polish Lowlands, the trend for the end dates of ice cover was less diversified (Figure 3).

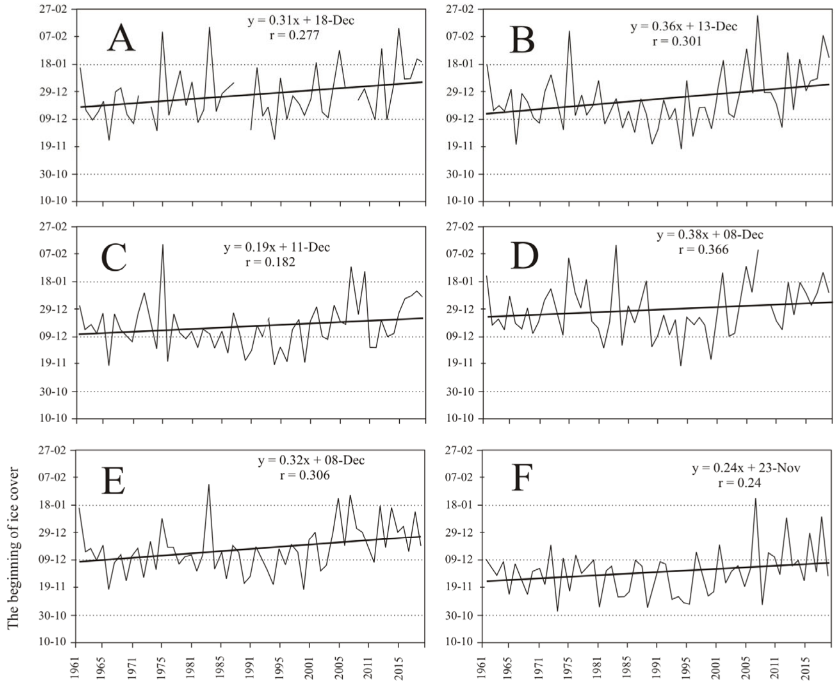

Figure 3. Course of initial dates of ice cover on selected lakes of Poland and Belarus in years 1961–2020 and trend line: (**A**)—Sławskie, (**B**)—Biskupińskie, (**C**)—Jeziorak, (**D**)—Serwy, (**E**)—Naroch, and (**F**)—Chervonoe.

The end of ice phenomena on lakes is also the beginning of the formation of the thermal structure of water after the period of thermal stagnation during winter. Throughout the aquatic ecosystem, there is a change in the direction of heat exchange flux between the atmosphere and the lake.

The end dates of ice phenomena on lakes fall on average between the second half of March for most lakes in Poland and the end of the first ten days of April in the lakes of the eastern part of the Belarusian Lake District. Their extreme dates fall on 4 March (Sławskie Lake) and 13 April (Driviaty Lake), which are characterized by a high degree of dispersion (standard deviation δ on average—20.1) and a negative trend of -0.52–0.6 days·year^{-1} (Figure 4).

The course of thermal winter is reflected in the length of ice cover on the lakes [11]. In the analyzed multi-year period, the average ice cover duration ranged from 55.6 days for Lake Łebsko to 121.0 days for Lake Driviaty (Table 3). For the others, it was usually in the range from 71 to 94 days, with the average being 83.3 days.

The length of its occurrence clearly related to the course of the thermal winter, where the correlation coefficient between the length of the thermal winter and the duration of ice cover for the lakes east of the Vistula was above 0.83, while for the lakes to the west it was below 0.71, with a high level of statistical significance: $\alpha < 0.001$.

The absolute maximum lengths of ice cover occurrence in the analyzed lakes were significantly diversified both in terms of their duration and in spatial terms. The longest ice cover was in 1996, when on Driviaty and Vygonoshchanskoe lakes it was 173 and 167 days, respectively. In Poland, the absolute record was recorded on Lake Jeziorak, which was 145 days (Figure 5).

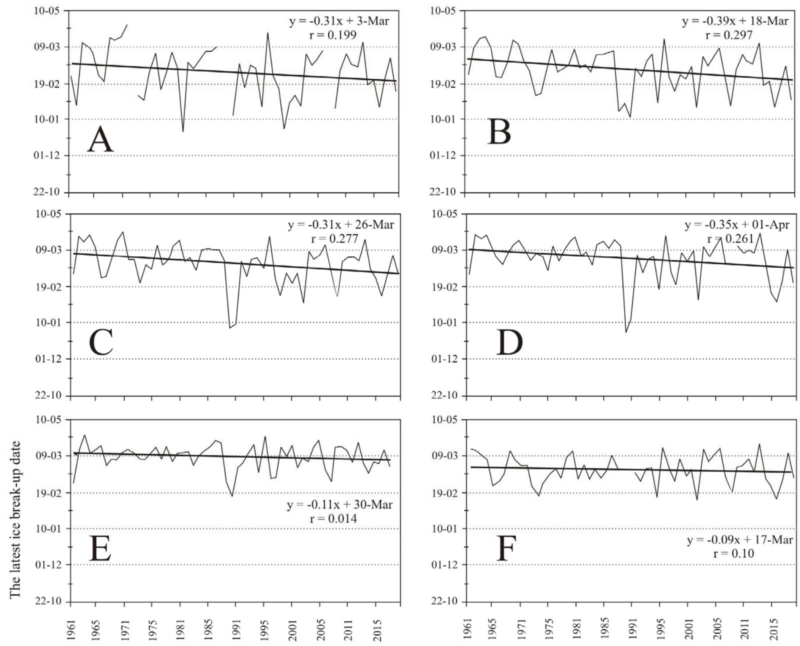

Figure 4. Course of end dates of ice cover on selected lakes of Poland and Belarus in years 1961–2020 and trend line: (**A**)—Sławskie, (**B**)—Biskupińskie, (**C**)—Jeziorak, (**D**)—Serwy, (**E**)—Naroch, and (**F**)—Chervonoe.

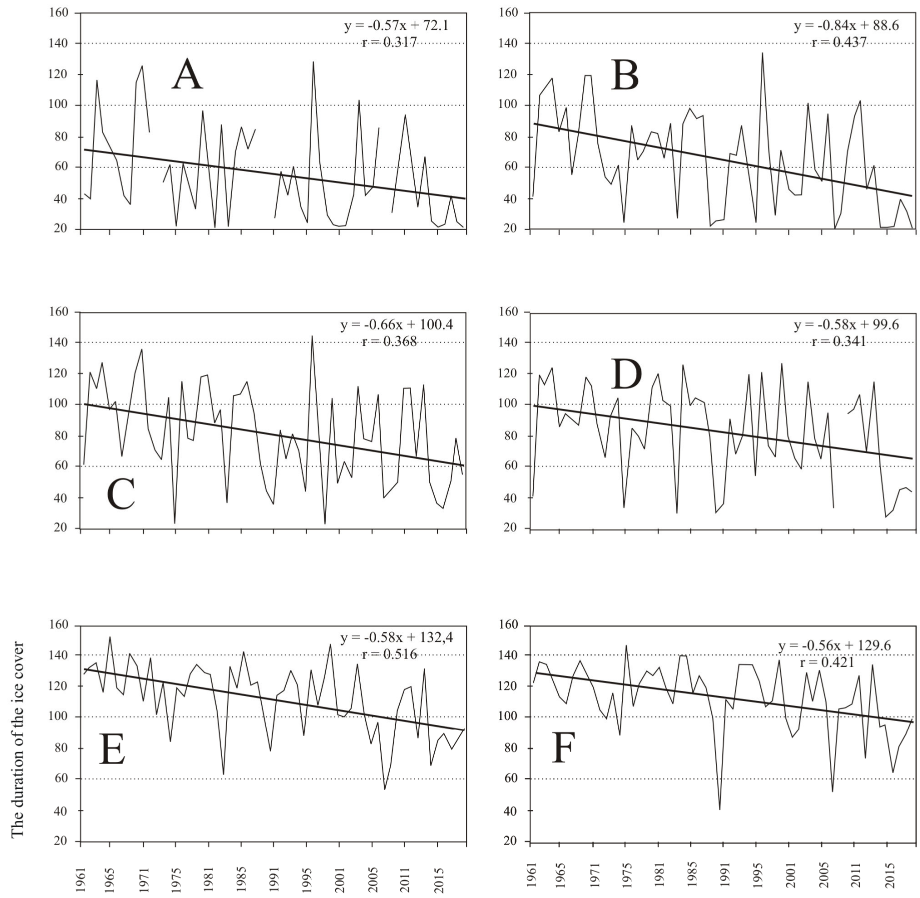

Figure 5. Course of duration of ice cover on selected lakes of Poland and Belarus in years 1961–2020 and trend lines: (**A**)—Sławskie, (**B**)—Biskupińskie, (**C**)—Jeziorak, (**D**)—Serwy, (**E**)—Naroch, and (**F**)—Chervonoe.

In the analyzed period, there were also years when ice cover did not occur at all. Such situations occurred only in the winter seasons of 1975, 1988, 1989 and 1990 on several lakes west of the Vistula (Sławskie, Gopło and Charzykowskie) and in the winter of 2020 on Belarusian lakes.

The length of ice cover in 10-year intervals in the multi-annual period 1961–2020 is interesting (Table 5). In general, in the lakes located west of the Vistula River, the average length of ice cover was over 18 days shorter than that in the lakes east of it. The period with the longest occurrence was 1961–1970 (102.1 days), and the period with the shortest was in the last decade, i.e., 2011–2020 (64.3 days).

Table 5. The course of ice cover occurrence (days) in 10-year intervals.

No.	Lake	1961–1970	1971–1980	1981–1990	1991–2000	2001–2010	2011–2020
1	Osiek	78.4	63.7	55.1	48.0	45.0	29.1
2	Sławskie	73.9	57.4	58.5	47.0	58.6	34.2
3	Łebsko	78.1	60.8	52.2	46.7	40.9	32.6
4	Charzykowskie	79.6	61.0	58.5	48.7	63.1	48.0
5	Biskupińskie	93.8	65.0	61.3	64.6	58.9	38.3
6	Jeziorak	104.1	85.3	78.7	73.8	73.5	65.9
7	Mikołajskie	91.4	80.4	66.3	60.3	61.8	56.3
8	Ełckie	95.6	69.4	62.7	54.4	60.9	66.1
9	Hańcza	87.9	74.1	64.9	70.9	70.6	58.9
10	Serwy	97.6	84.2	80.0	87.4	76.9	60.8
11	Vygonoshchanskoe [1]	128.6	120.2	115.5	124.1	109.3	93.9
12	Naroch	123.3	119.2	115.4	122.5	101.0	97.4
13	Driviaty	132.6	124.2	121.6	139.6	101.0	98.8
14	Chervonoe	130.1	125.0	119.3	124.0	111.5	94.5
15	Lukomskoe [2]	137.1	87.1	88.2	92.9	98.6	89.2

Explanations: [1]—data from 1964, [2]—Lake Łukomskie under the influence of a thermal power plant.

The duration of ice cover was characterized by a significant degree of dispersion of its duration, and the standard deviation ranged from 21.8 days (Lake Chervonoe) to 32.4 days (Lake Ełckie), with the highest standard deviations being found in the Polish Lowlands.

The duration of ice cover in all analyzed lakes was characterized by a significant shortening of the time of its occurrence. This was indicated by the change trends, ranging from -0.42 days·year^{-1} (Lake Vygonoshchanskoe) to -0.86 days·year^{-1} (Lake Osiek).

Due to the similar characteristics of the length of the occurrence of ice phenomena in relation to the occurrence of ice cover, the presentation of this element of ice was limited to the presentation of data in a tabular form (Tables 2 and 4).

The thickness of ice cover is a good indicator of climatic conditions and morphometric and catchment features, although there is no close relationship between its maximum thickness and the time of its presence [12].

In the analyzed multi-year period, ice thickness was very variable and generally increased towards the east. The average thickness varied from 20.5 cm in the Pomeranian Lake District (Lake Osiek) to 46.5 cm in the eastern part of the Belarusian Lake District (Lake Naroch). In the other lakes, it was from 29.4 cm in the Polish Lowlands to 40.4 cm in the Belarusian lakes [13].

The maximum thickness of ice cover was recorded in 1963, 1969, 1970 and 1996, when it was above 70 cm (Driviaty—79 cm, and Naroch—71 cm). In the lakes in Poland, the greatest thickness was recorded for the following lakes: Studzieniczne—65 cm, Nidzkie—62 cm, and Hańcza—61 cm, while in the western part of the Polish Lowlands they rarely exceeded 55 cm [14]. The maximum thickness of ice cover was recorded mostly from the second decade in February to the third decade in March (inclusive).

The general tendency of the shortening of the period with ice cover was also confirmed by the clear decrease in ice cover thickness, although there was no close relationship between them. All the lakes were characterized by a negative trend (average 0.2–0.4 cm·year^{-1}), and the size of the trend clearly increased towards the east.

An important feature of the lakes' ice regimes was also the numerous breaks in the occurrence of ice cover, which confirmed the degree of its durability [15,16]. In the analyzed period, there was a clear differentiation of this parameter. The average number of ice breaks on the lakes of the Polish Lowland was 0.41, clearly decreasing from west to east. The greatest number of ice breaks was found in lakes located in the western part of Poland. In turn, in the lakes in the eastern part of the Polish Lowlands, no breaks in ice cover were found until 1974. They did not appear until 1975 [9]. The lack of material for lakes from Belarus does not allow such an analysis to be made for them. It can be assumed that the above features of the Masurian Lake District may also apply to lakes located in the Belarusian Lake District.

Moreover, it was noticed that the maximum thickness of ice cover in all lakes was characterized by a significant dispersion of ice cover size, with the standard deviation (δ) being within a range between 10.18 cm (Sławskie Lake) and 14.26 cm (Hańcza Lake). Moreover, it is stated that this parameter showed a negative trend in all lakes, ranging from −0.05 cm year^{-1} to −0.58 cm·year^{-1} (Table 4, Figure 6).

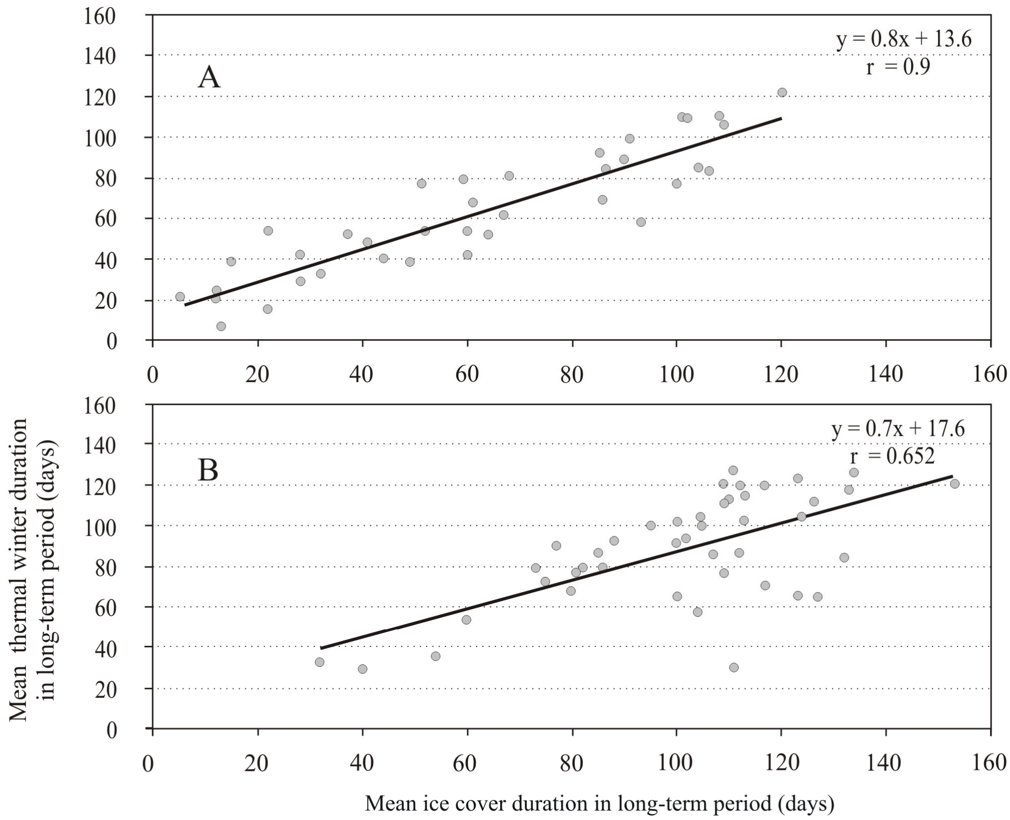

Figure 6. Relationship between duration of thermal winter and duration of ice cover for (**A**)—Łebsko and (**B**)—Serwy in the period 1956–2005.

The confirmation of the variation in the thickness of ice cover is the synchronous studies carried out on 30–31 January 2004 on 33 lakes of the European Lowlands. The lakes covered by this research were located on a strip of a length of approx. 1200 km (8.02° E–25.50° E). At that time, the thickness of the ice sheet clearly increased to the east from 3 to 33 cm, and the results of the research confirmed the increasing importance of zonal atmospheric circulation (Table 6, Figures 7 and 8).

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

No	Lake	Beginning of		End of		Duration of Days		Maximum Thickness of Ice Cover (cm)
		Ice Phenomena	Ice Cover	Ice Cover	Ice Phenomena	Ice Phenomena	Ice Cover	
1	Osiek	0.14	0.32	**−0.45**	−0.33	**−0.65**	−0.86	**−0.20**
2	Sławskie	0.18	0.31	−0.31	−0.18	−0.46	**−0.57**	−0.08
3	Łebsko	**0.56**	0.19	−0.42	**−0.56**	**−0.88**	**−0.82**	**−0.20**
4	Charzykowskie	0.22	0.14	−0.33	**−0.48**	**−0.65**	−0.46	−0.17
5	Biskupińskie	0.14	**0.36**	**−0.39**	−0.26	**−0.58**	**−0.84**	−0.16
6	Jeziorak	0.16	0.19	−0.36	−0.29	**−0.55**	**−0.66**	**−0.26**
7	Mikołajskie	**0.37**	0.16	−0.37	−0.23	**−0.61**	**−0.68**	**−0.34**
8	Ełckie	0.19	0.18	−0.37	−0.35	**−0.55**	−0.56	−0.13
9	Hańcza	0.09	0.14	−0.27	−0.11	−0.22	−0.44	**−0.48**
10	Serwy	**0.38**	0.18	−0.35	−0.35	**−0.65**	**−0.58**	**−0.35**
11	Vygonoshchanskoe [1]	0.15	0.32	−0.21	−0.28	−0.32	**−0.42**	**−0.35**
12	Naroch	**0.49**	**0.32**	−0.11	−0.20	**−0.83**	**−0.58**	**−0.26**
13	Driviaty	0.16	0.24	**−0.40**	**−0.31**	**−0.41**	**−0.69**	**−0.58**
14	Chervonoe	0.04	0.24	−0.09	−0.34	**−0.48**	**−0.56**	**−0.32**
15	Lukomskoe [2]	**0.41**	**0.35**	**−0.67**	−0.22	**−0.63**	**−0.76**	0.05

Explanations: [1]—data from 1964, [2]—Lake Łukomskie under the influence of a thermal power plant.

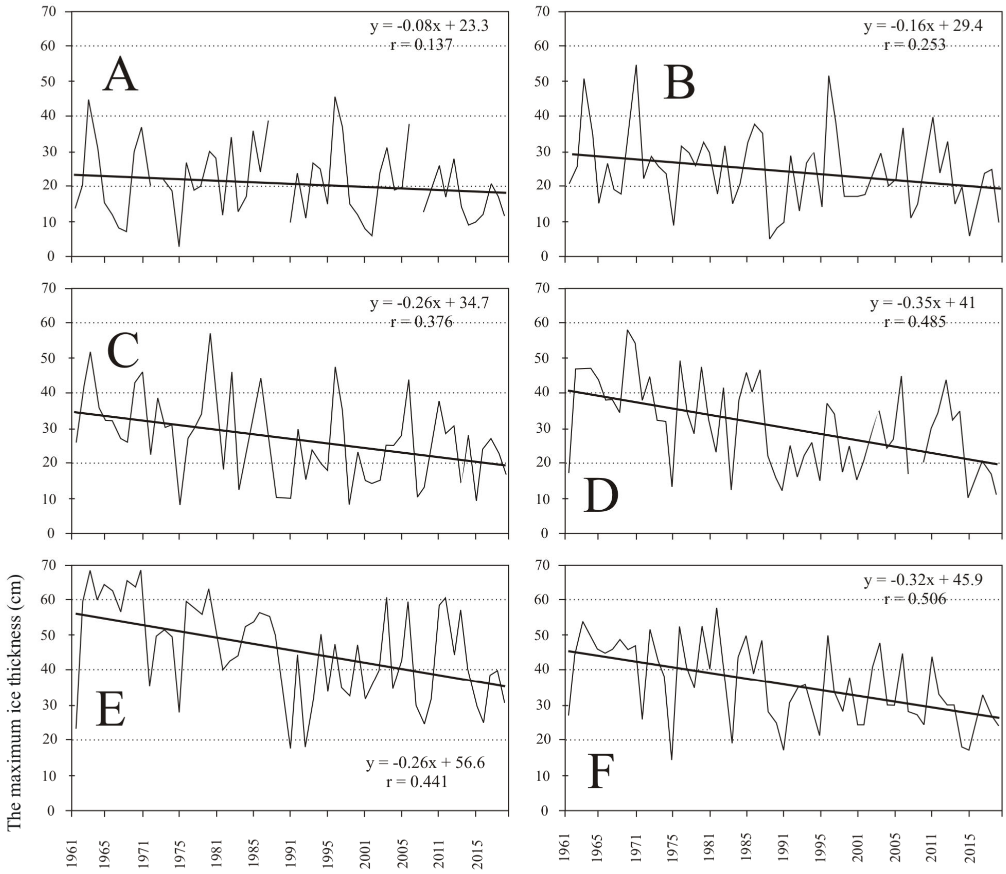

Figure 7. Course of maximum thickness of the ice sheet in selected lakes of Poland and Belarus in years 1961–2020 and trend lines: (**A**)—Sławskie, (**B**)—Biskupińskie, (**C**)—Jeziorak, (**D**)—Serwy, (**E**)—Naroch, and (**F**)—Chervonoe.

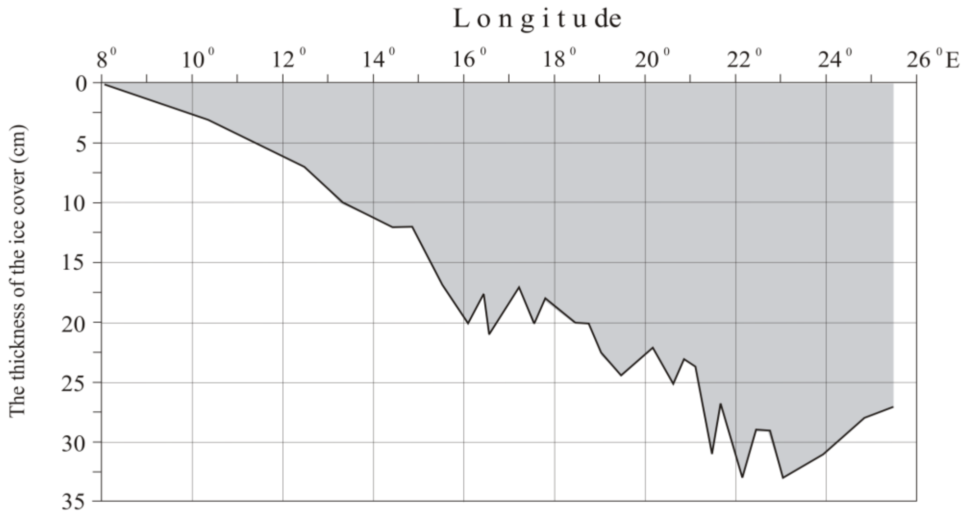

Figure 8. Course of thickness of ice cover, 30 and 31 January 2004 [9].

4. Discussions

Many climatologists take the view that after 1980, winter periods were generally warmer than earlier winters were [17–19]. They agree that the main and fundamental cause of climate variability is the variability of atmospheric circulation and the properties of air masses that shape the climate of Central Europe.

The main problem concerning the phenology of lake ice in Poland, presented after 2000, was the long-term changes in the course of individual ice stages. This applies to single lakes [20–23], as well as a selected group of lakes [8,11,14,24,25]. These issues also concerned the aspect of spatial differentiation of individual forms of ice and the impact of the climate, especially the winter NAO index, on the course of ice [26–30].

Climate warming caused changes in the thermal and ice regime of the lakes in the northern hemisphere [2,31]. Researchers carefully analyzed the course of ice for many lakes and rivers around the world. Observations of the icing of lakes and rivers in the northern hemisphere in the years 1846–1995 over 150 years showed the later freezing and earlier breakdown of ice cover [32]. For Lake Kallavesi and Lake Nàsijàrvi in Finland, freezing was on average 5.8 days later per 100 years, while the average dates of ice cover disappearance in the period 1833–1995 were on average earlier by 9.2 and 8.8 days per 100 years, respectively [33–36].

This is confirmed by the course of ice phenology for eight lakes in Karelia (north-west Russia) for the years 1950–2009, in which statistical relationships between the phenology of lake ice, air temperature and the north atlantic oscillation index (NAO) were found [37]. Research has shown that the freezing of all lakes takes place later and later, while their disappearance is occurring earlier and earlier in relation to the long-term average. On Lakes Ladoga and Onega, an earlier disappearance of ice cover was observed [38], while in recent decades of the 20th century, on the largest freshwater lakes in Russia located at high latitudes, there was a decrease in the thickness of ice cover [39–41]. Examples of the decrease in the maximum thickness of ice cover at the same time were also observed on Russian lakes (Ladoga, Onega and Taymyr) [3]. Additionally, all analyzed lakes show a negative tendency confirming the decrease in the maximum thickness of ice cover, especially after 1980.

Similarly, A. Reinart and O. Pärn [42] showed that the ice cover on Lake Peipus in Estonia lasts 115 days (from 9 December to 4 April) and is characterized by an earlier breakdown, similarly to many other lakes in the northern hemisphere. Additionally, on Lake Ladoga, its disappearance is earlier (14 days out of 100 years) [38]. On the other hand, on Lake Onega, the phenomenon of shortening of the the duration of ice cover causes the extension of the ice-free period from 217 to 225 days [43].

This is also confirmed by the results of the average values of the parameters of the forms of ice in Lithuanian lakes [44]. As shown by I. Danilovish [45], as a result of an increase in air temperature by 1.1 °C in 1988–2002, there was a significant reduction of the period with water temperature in the range of 0 and 2°C and the duration of ice phenomena by 5 days and the ice by 6 days [46]. These observations are confirmed by the observations of significant drops in ice thickness by an average of 4–9 cm·year^{-1} [13,47]. Statistical relationships between lake ice phenology (ice freezing and decay dates, ice duration), air temperature and the North Atlantic Oscillation Index (NAO) were analyzed for eight lakes in Karelia in 1950–2009. It has been shown that in the last 20 years the trends in the chronology of ice phenomena are clearer than in the entire 60-year period [7,37].

Similar situations were observed on lakes in central Norway (Øvre Heimdalsvatn) [48] and on lakes in central and southern Sweden [49]. Many years of observations of ice phenology on 101 Norwegian lakes, located at an altitude of up to 1400 m above sea level and under the influence of various climatic conditions (from oceanic to continental), showed that the beginning of freezing of the lakes was correlated with an increase in altitude above sea level as well as latitude and longitude. The area and volume of the lakes also had a significant impact on the freezing dates of the lakes. On the other hand, the average dates of the disappearance of the ice sheet were becoming earlier [50]. Over the past 40 years, mountain lake Øvre Heimdalsvatn in central Norway has been characterized by a 9-day delay in the freezing dates and a 6-day delay in the ice sheet breakdown dates [48]. Additionally, K. Takács et al. [51] found that the dates of first occurrence of ice and frost in Hungary were delayed by 12–30 and 4–13 days within 100 years. In contrast, the disappearance of the ice sheet shifted to earlier dates by 7–13 days within 100 years. It was found that in Switzerland's lakes, ice cover on lakes has been significantly shortened over the past 40 years. This is consistent with the temperature increase observed in the winter in this period [52].

The impact of NAO has also been proven in relation to the phenology of lake ice in the northern hemisphere [53–56]. As J. Yoo and O. D'Odorico [6] indicate, the winter NAO index mainly affects the late winter temperature (January–March), and also that of the spring period (April–May), when the air temperature is strongly correlated with the dates of the ice age. The analysis of data in the Baltic Sea region indicates the existence of similar fluctuations in the winter air temperature (JFM) with fluctuations in the winter NAO index.

The course of ice cover in the areas west of Poland's border was compared to that on Lake Müggel in the period 1977–1998 [57]. It was similar to those found in the western part of Poland. Research conducted on two small lakes located in the Berlin Brandenburg Lake District in the years 1961–2007 showed an earlier end to the period of ice cover and a shorter duration of ice cover [58].

The impact of the North Atlantic Oscillation (NAO) on changes in ice phenomena is also noticeable on mountain lakes in Europe. An example of such an impact is the Morskie Oko lake in the Polish Tatra Mountains, where for the years 1971–2010, the following were observed: a reduction in the duration of ice phenomena by 9 days·decade^{-1}, reduction in ice cover duration by 9.5 days·decade^{-1} and reduction in maximum cover thickness by 2.2 cm·decade^{-1} [59]. Additionally, for three mountain lakes in Spain located above 2000 m above sea level, a reduction in the duration of ice cover was observed [60].

In studies of ice phenomena on Polish lakes for the years 1951–2010, it was found that during this period the average duration of ice cover was reduced by 0.55 days·year^{-1} and the maximum thickness of ice cover was reduced by 0.21 cm·year^{-1} [25]. These results are consistent with those of earlier Polish studies on the course of the occurrence of ice phenomena on lakes in shorter time intervals [27,61]. The spatial analysis of the course of the occurrence of ice phenomena showed that the maximum thickness of ice cover, the degree of durability of ice cover and the number of breaks in ice cover had a clear distribution.

5. Conclusions

The period of the last 200 years over the area of Central Europe and the Baltic Sea was characterized by large changes in air temperature and the occurrence of positive trends in average annual temperatures [62]. For Warsaw, it was 0.65 °C per 100 years, and for Vilnius and Tallinn it was 0.56 °C per 100 years [63–65]. The diversification of the NAO effect on the course of lake icing resulted not only from the influence of the degree of continentalism, especially in the eastern parts of the study area, but also from the individual characteristics of the individual lakes.

When analyzing the course of the occurrence of ice phenomena, the authors distinguished three characteristic regions on the basis of the average values of lake ice indexes in the multi-year period 1961–2020:

- The first region—located west of the Vistula—is distinguished by the shortest ice cover time (61.1 days), which appeared on average on December 28 and disappeared on March 8, having the smallest thickness (22.9 cm). Ice cover accounts for 79.9% of the duration of all ice phenomena,
- The second region is the eastern part of the Polish Lowlands (east of the Vistula), characterized by a much longer duration of ice cover on the lakes (74.8 days on average), which lies here from December 27 to March 17, and has an average maximum thickness of 29.9 cm. Ice cover has a similar share in the duration of all ice phenomena (79.9%).
- The third region includes lakes located in the eastern part of the Belarusian Lake District. Ice cover remains there for the longest, 114 days, from December 9 to March 31. Its thickness reaches an average of 40.4 cm, while in some seasons it reaches over 70 cm and accounts for 82.2% of all ice phenomena.

In the analyzed multi-annual period, a shortening of the duration of ice phenomena and ice cover, a decrease in the maximum thickness of the ice and an increasing number of breaks in ice cover were observed in all lakes. These data clearly correlate with the upward trend in air temperature in this part of Europe.

In general, in the lakes located in the study area, the average dates of the beginning of the occurrence of ice phenomena appear 10.6 days earlier from the beginning of ice cover, while their ending occurs 6.5 days later. It should be remembered, however, that the study used mainly average values of ice indexes in the multi-year period 1961–2020, while all stages of lake icing and their features in individual winter seasons created a very diverse mosaic, as indicated by the standard deviation.

Author Contributions: Conceptualization, R.S.; methodology A.C. and R.S.; investigation, R.S., P.K. and I.K.; writing—original draft preparation, R.S. and A.C.; writing—review and editing, R.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Primary data from the territory of Poland and Belarus (the results of measurements at hydrological and meteorological stations in Poland and Belarus) are unavailable for downloading in accordance with the policy of Hydrometeorological Service of the Poland and Republic of Belarus.

Conflicts of Interest: The authors declare no conflict of interest.

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