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Ice phenomena in investigations of Polish lakes

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Abstract. The paper presents nearly 150 years of history of ice research conducted on Polish lakes. In the first stage, these were observations and expedition studies that had an exploratory purpose. It was not until the 1920s that stationary measurements on several lakes were introduced. Unfortunately, the outbreak of World War II interrupted these observations. After the war, they were resumed in 1946, but the real beginning of investigations of ice phenomena on lakes is taken to be 1960. At present, stationary measurements of ice phenomena are conducted on about 70 lakes located mainly in northern Poland. Besides the purely explorative purpose, experimental research on ice phenomena on lakes has also contributed to the development of a measurement methodology. The author of this paper took part in numerous experimental studies conducted on over 30 lakes for which the ice results are partially presented below.

Key words:
Poland,
lake,
history of ice phenomena research

Introduction

Ice phenomena occur on lakes in a process closely related with meteorological conditions and the processes of thermal exchange between water and atmosphere. In lakes of the temperate zone, the presence of ice on lakes is a common phenomenon and depends on many factors, such as: geographic location, local climatic conditions, the hydrological and morphometric features of the lake, and anthropogenic activities.

Generally speaking, research on lake ice phenomena can be divided into experimental and stationary investigations. The first experimental research on lakes in Poland was conducted as early as the 17th century and was limited to *ad hoc* measurements related to people's living needs. One of these needs was the gathering of ice from rivers, ponds and lakes for the construction of so-called icehouses, which were used to store crops, meat, dairy products and fish. Fragments of some of these have survived to the present day and serve as simple storage cellars (Fig. 1).

Fig. 1. Former ice house in Bachanowo in the Podlasie voivodeship (photo by author)

Measurements of ice phenomena in lakes in Poland

Lakes in the temperate transitional climate zone are diverse in the course of biotic and abiotic water properties. Certainly, these properties include water temperature and ice phenomena on lakes in Poland. The aim of the work is to present an almost 150-year history of research on ice phenomena conducted on Polish lakes.

The first measurements of lake icing

The first studies of ice phenomena on lakes were carried out at the turn of the 20th century, mainly by geographers (Bojanowicz 1970; Skowron 2017). They mainly concerned the lakes in the Tatra Mountains, and in the early 20th century the lakes in Kuyavia and the lakes in the eastern borderlands of Poland (Pasławski 1993). At the turn of the 20th century, ice-cover investigations were conducted on several lakes in the Tatra Mountains, such as Czarny Staw, Morskie Oko and others. It was noted that the differences in the dates of ice-cover formation and disappearance on the lakes were conditioned by insolation, the topography of the surroundings, and the influence of inflows on the thermal conditions of the ponds (Lencewicz 1926).

On the basis of observations of the ice cover on the Tatra lakes, Lityński (1913) identified the freeze-up and break-up periods of the lakes, also giving their duration. Moreover, he also described the layered structure of lake ice. Observations of ice phenomena showed that the ice cover on Tatra lakes was not homogeneous (Szumny 2017).

Early 20th century to World War I

More or less systematic observations of ice phenomena on lakes in Poland were carried out from the mid-19th century, especially under the Prussian partition. However, no significant records on this subject have been preserved to the present day. Such measurements were made for the needs of fishing companies operating at the time and mainly concerned ice cover thickness, and less frequently the dates of its formation and disappearance. The material was very often scattered, unsystematic and, therefore, of low scientific value. The first measurements of ice phenomena on the Masurian lakes were conducted periodically on Tałty Lake (in 1901, then from 1904 to 1910 and from 1937 to 1939) (Korolcówna 1961).

It is worth noting that ice phenomena observations were carried out on Lake Serwy, which was then under the Russian partition. Although the results of observations conducted from 1888 to 1910 were published in a Russian journal, due to certain difficulties, it is difficult to retrieve these materials (Matusewicz 1939).

The inter-war period (systematic measurements begin)

After Poland regained its independence, research on lakes was conducted by the Hydrographic Office, and beginning in 1934 by the Hydrographic Institute (Bojanowicz 1970; Pasławski 1993). The Hydrobiological Station at Lake Wigry and the Polesie Biological Station in Pińsk (Koźmiński and Wiszniewski 1935) made great contributions to the studies of ice phenomena. The results of these valuable measurements were included in a paper presented at the General Assembly of the International Association for Scientific Hydrology in Washington in 1939. Unfortunately, the results of the measurements were irretrievably lost in the turmoil of war, and only valuable research on ice phenomena in the lakes Gopło, Wigry, Światez, Narocz and Drywiaty survived (Matusewicz 1939).

At this point, the significant contribution of Polish geographers to the knowledge of ice-covered lakes located within the borders of contemporary Poland should be emphasised. These studied lakes included: Świtaź in Polesie Wołyńskie (today's Ukraine) with an area of 25.2 km², Narocz in the Narocko-Wilejska Plain (in the northern part of today's Belarus) with an area of 79.6 km², and Drywiaty in the Drujka river basin (in the northern part of today's Belarus) with an area of 36.1 km²

Table 1. Average parameters of course of ice phenomena on lakes studied in Poland, 1926–1937 (based on data from Matusewicz [1939])

Lake Parameters	Gopło	Wigry	Świtaź	Narocz	Drywiaty
Beginning of ice phenomena	12-Dec	13-Dec	15-Dec	10-Dec	8-Dec
End of ice phenomena	19-Mar	7-Apr	29-Mar	16-Apr	18-Apr
Duration of ice phenomena (days)	97.5	114.6	104.2	126.8	131.2
Maximum ice thickness (cm)	30.8	42.1	38.9	40.8	59.9

(Fig. 2). The research on ice phenomena carried out on five lakes within the borders of Poland at that time, covering the years 1926–37, made it possible to conclude with certainty that their course and dates of occurrence result from the geographical location of the lakes and the zone of abrasion of the continental and oceanic air influence (Matusewicz 1939). Closer differences between the studied lakes are shown in Table 1.

The greatest differences were observed between Lake Gopło and Drywiaty, and related to the duration of ice phenomena (in Lake Drywiaty they lasted 34 days longer), while the thickness of ice cover was 29 cm greater than in Lake Gopło. The thickness of ice cover was also interesting, when on Gopło Lake during the cold winter of 1928/29 it reached the highest recorded value of 75 cm. Unfortunately, the war interrupted observations of these interesting phenomena.

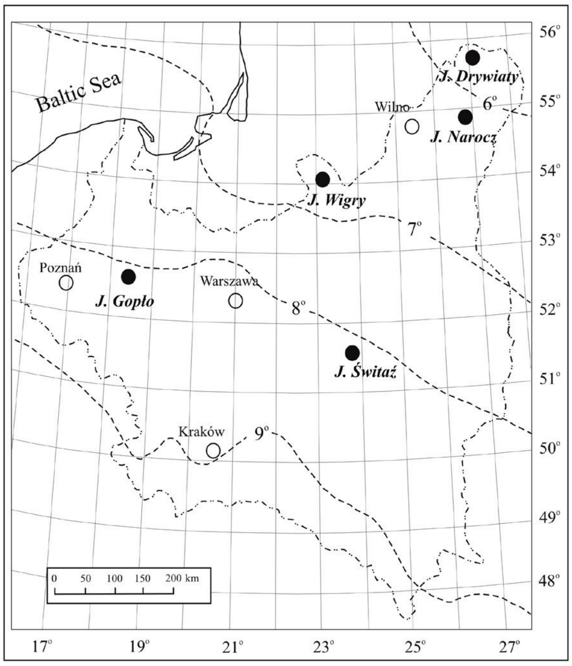

Fig. 2. Location of lakes from 1939 where research was conducted on ice phenomena in Poland, after Matusewicz (1939) (dashed lines – medium isothermal machines, 1926–37)

End of World War II to 1975 (stationary research continues)

After the Second World War, hydrological measurements were resumed on many lakes as part of a new network of stations of the Polish Hydrological and Meteorological Institute (PIHM) and several research stations. They were created as an outcome of the Limnological Conference on Limnological Research held in 1953 in Poznań. The programme and organisation of limnological research stressed the need for various scientific centres to cooperate with PIHM (now the Institute of Meteorology and Water Management - National Research Institute IMGW-PIB) and hydrobiological and fisheries centres (Galon 1954).

The year 1960 is considered to be the proper beginning of stationary observations of ice phenomena, when systematic measurements were made on more than 20 lakes representing the most important lake districts. In the years 1961–1970 there were 21 measuring stations concerning ice phenomena on lakes (Bojanowicz 1970; Kowalska 1972). In the following years (1971–1980), the network of measuring stations was extended. Only two lakes (Gopło and Studzienniczne) have a full 65-year (1956–2020) measurement series. Observations of lake ice cover are made at the water level readings (at the gauges) by recording the freeze-up and break-up dates of ice phenomena and ice cover, and the thickness of ice cover every 5 days, with 1-cm accuracy.

The first studies presenting the results of post-war lake ice observations based on stationary measurements were carried out by Gołek (1957, 1986). They referred to four lakes (Serwy, Tałty, Jeziorak and Gopło), for which the freeze-up and break-up dates of ice phenomena and ice cover, and their duration and ice thickness were determined.

Longer data series compiled by Pasławski (1982) concerned stationary measurements from 25 lakes for the years 1956–1980. The author determined the extreme and average dates of the appearance and disappearance of ice phenomena and ice cover, as well as the duration of their occurrence. He found that the duration of ice cover accounted on average for 79% of the duration of ice phenomena. The results of the study provided a basis for determining the dates of ice cover onset depending on the mean depth of the lake. Knowing the average number of freezing days and the mean depth of the lake, the theoretical freeze-up date and the duration of ice cover were determined using a mathematical equation.

Analysing data for 1951–2010 for five lakes in northern Poland, Choiński et al. (2014) found a reduction in the mean duration of ice phenomena (by 0.50 days·year^{-1}) and ice cover (by 0.55 days·year^{-1}), and a reduction in the maximum ice thickness per season (by 0.21 cm·year^{-1}). It was also observed that the spatial distribution of ice phenomena was related to the increasing influence of the continental climate – especially for the maximum ice cover thickness, duration and number of ice breaks.

Another subject of interest for Polish limnologists was the dependence of ice cover thickness and duration on meteorological conditions, geographical location, degree of continentalism and water pollution. Noteworthy works are by Skowron and Szczepanik (1988); Skowron (1997, 2003, 2009); Sziwa (2002); Girjatowicz (2003, 2004, 2005); Marszelewski and Skowron (2006, 2009); Barańczuk and Borowiak (2005) and Choiński et al. (2014).

The extreme dates of ice phenomena and ice cover in 1961–2005 for ten lakes in northern Poland were the subject of a study by Marszelewski and Skowron (2009). The authors analysed the courses of ice phenomena and highlighted all the properties that deviate most from the mean values. During this period, the ice cover formed earliest on 15 November on lakes Bukowo, Jamno and Necko, and latest on 28 February (Lake Hańcza). On the other hand, the absence of ice cover in winter seasons was recorded many times. It occurred most frequently: four times in Lake Gopło (1975, 1981, 1989 and 1990) and Lake Lubie (1988, 1989, 1990 and 1995). The longest duration of ice cover was recorded on Lake Jeziorak and lasted 145 days (1996). Its extremes of thickness ranged from 0 to 65 cm.

On the basis of the available stationary material on ice phenomena in Polish lakes in the years 1976–2000, Skowron (2008a) selected two winter seasons 1989/90 and 1995/96 with extreme courses of ice formation. The extreme character of ice phenomena was shown on the basis of its spatial variability in 74 selected lakes in the Polish Lowlands. The course of ice cover showed a clear correlation with the course of thermal conditions during winter months (Dec–Mar) and with the winter NAO indices (Hurrell 1996).

The analysis of the course of ice cover in 1961–2000 on six selected lakes in northern Poland confirmed different trends of dates of ice-cover onset (Marszelewski and Skowron 2006). However, the ice cover disappeared earlier and earlier in all the lakes, from 0.6 to 0.8 day·year^{-1} on average. The length of the period with ice cover was characterised by a negative trend, from 0.8 to 0.9 day·year^{-1}. A similar negative trend was observed for maximum ice cover thickness (from 0.26 to 0.60 cm·year^{-1}).

1975–2020 (research into the impact of climate change on the course of ice phenomena)

Since 1975, new testing methods have been introduced in the form of calibrated thermistor thermometers, thermal gradient probes (RTW 8), thermal imaging cameras (Flir SC 660), miniature

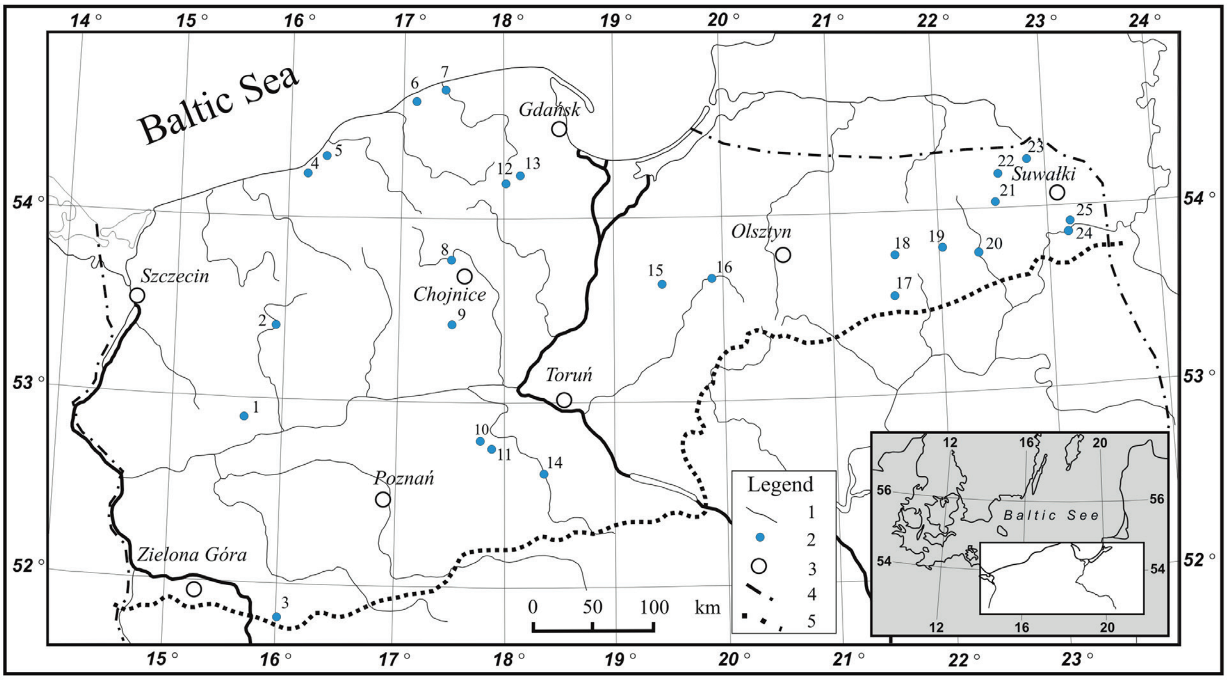

Fig. 3. Distribution of lakes subject to ice phenomena observation: 1 – rivers, 2 – lakes, 3 – major cities, 4 – Polish border, 5 – maximum extent of Vistulian glaciation (list of lakes as per Table 2)

thermistors integrated with data loggers, and echo sounders with integrated GPS and a side scanner (Szumny 2017).

An extended study of ice phenomena was presented for 34 lakes and covered the period 1961–2000 (Skowron 1997, 2003). A clear correlation relationship was observed between the duration of the ice cover and the degree of thermal continentalism. This fact, according to the author, is due to a clear warming of the thermal winter and corresponds with the dates of its disappearance, the maximum thickness and the degree of durability of the ice cover.

The above-mentioned views are confirmed by conclusions related to the 50-year data series (1956–2005) for 15 lakes in northern Poland (Skowron 2009). The calculated mean dates of the ice cover formation and destruction shows a clear bipartite character for the whole area. The border between the two separate parts runs along the Vistula River valley. The variability in the occurrence of lake ice cover in northern Poland in the second half of the 20th century may be regarded as further evidence – and an indirect indicator – of climate change in this part of Europe.

The main problem presented in the works published after 2000 are the issues connected with long-term changes in the course of ice phenomena. Apart from a few works mentioned above, it is worth citing those that refer to analyses of the ice cover of individual lakes (Chojnowski and Ciszewski 1964; Górniak 1999; Borowiak and Barańczuk 2004; Dąbrowski 2008; Pius and Marszelewski 2016) and groups of lakes (Barańczuk and Marchlewicz 2003; Girjatowicz 2003, 2004; Barańczuk and Borowiak 2005), as well as in the supra-regional aspect (Marszelewski and Skowron 2006, 2009). These problems mostly concerned the spatial differentiation of individual forms of ice phenomena and their temporal occurrence (Skowron 2003; Skowron and Marszelewski 2005; Sobolewski et al. 2014), differentiation of ice thickness (Sziwa 2002; Choiński et al. 2006), the occurrence of extreme values (Skowron 2008b; Marszelewski and Skowron 2009), the influence of climate – especially the winter NAO index on the course of ice cover (Girjatowicz 2003, 2005; Borowiak and Barańczuk 2004; Skowron 2008a, 2009; Wrzesiński et al. 2013, 2015).

The initial dates of the appearance of the ice cover were characterised by a negative trend at the level of 0.2–0.3 days·year^{-1}, while their end also had a negative trend within the range of 0.6–0.8 days·year^{-1}. The consequence of these events was a significant shortening of the time of its occurrence by 0.8–0.9 days·year^{-1} with a clear decrease in its thickness by 0.2–0.4 cm·year^{-1} (Skowron 1997, 2003, 2009; Choiński 2007). It should be emphasised, however, that research on ice phenomena is also conducted in order to explain some mechanisms of the formation of the cover or its distinctiveness and its differentiation in particular winter seasons (Grześ 1974; Barańczuk and Borowiak 2005; Choiński et al. 2006; Choiński 2007).

While studying lakes in the Kashubian Lakeland in 1961–2000, Barańczuk and Borowiak (2005) found that the total duration of ice phenomena in Lake Raduńskie Górne declined at an average rate of 1.2 days·year^{-1}, while the duration of the ice cover decreased at an average rate of 1.5 days·year^{-1}, and maximum ice thickness was reduced by 0.39 cm·year^{-1} on average. For 21 lakes in the Polish Lowlands in 1961–2000, a decrease in maximum thicknesses of between 2 and 4 cm per 10 years was determined (Skowron 2003). On the other hand, for 18 lakes in northern Poland during the 50-year period (1961–2010), the duration of ice cover was found to have declined on average by 0.56 days·year^{-1}, and the maximum ice thickness decreased by 0.61 cm·year^{-1} (Choiński et al. 2015).

The results of a long-term study on ice phenomena for 25 lakes in Poland in the period 1961–2020 are presented for the first time in Figure 3 and Table 2 in this paper. The results of these measurements differ slightly from the data presented in the previous Polish literature (Pasławski 1982; Skowron 2011; Choiński et al. 2014; Sobolewski et al. 2014).

As can be seen from Table 2, the average dates of the occurrence of ice phenomena were recorded between 6th December (Lake Jeziorak) and 7th January (Lake Lubie). On the other hand, the average dates of ice cover occurrence were recorded between 24th and 30th December. The average terminal dates of the ice cover occurrence were recorded between 26th February (Lake Jamno) and 28th March (Lake Studzieniczne).

The nature of the ice cover on the lakes, apart from the dates of the formation and disappearance of ice phenomena, is complemented by: maximum thickness of cover, mean share of ice cover in duration of ice phenomena, degree of durability of ice cover (%), and number of ice breaks (%). These data are supplementary to those in Table 2.

The data from Lake Morskie Oko provide different properties of ice phenomena. The average dates of the beginning and disappearance of ice phenomena range between 18th November and 14th May, while the average dates of ice cover occurrence fall between 27th November and 1st May (Table 3). These data are slightly different from those previously cited in the literature (Choiński 2007, 2010; Choiński et al. 2013).

In general, the number of lakes included in the research on ice phenomena in Poland after the Second World II underwent considerable changes due to the expansion of the research base and organisational changes. At present, stationary ice measurements are conducted on about 70 lakes.

Experimental research has provided an important supplement over the last half-century in this area. These were studies conducted on individual lakes, and sometimes on a larger number of them. Their aim, apart from the purely exploratory aspect, was to develop a measurement methodology, determine differences in the dates of ice cover occurrence and its thickness in the lake and also in relation to other lakes. On the basis of thorough studies of the ice cover on Lake Mikołajskie carried out in 1952–57, Korolcówna (1961) presents the measurement methodology and the results of the first measurements. The measurements of ice cover thickness on this lake indicated that its thickness is clearly differentiated, and the differences can reach up to 12 cm.

In her research on the lakes of the Masurian Lake District, Lityńska (1969) made an attempt to predict the dates of ice cover formation on the basis of the duration of homothermia, i.e. the period from the moment when the whole water mass reached the temperature of 4°C until the moment when the lake became frozen. Chojnowski (1964); Chojnowski and Ciszewski (1964) carried out observations of ice phenomena on Lake Mikołajskie with the aim of tracing the influence of air temperature on the cooling and freezing of water, and to study the conditions of formation, growth and disappearance of ice cover. Meanwhile, Grześ (1974), based on observations of ice phenomena on Lake Gopło,

Table 2. Average values of ice characteristics in lakes in Poland,1961–2020

No.	Lake	Beginning of		End of		Duration in days		Maximum thickness of ice cover (cm)	Duration of ice cover divided by total period of ice cover	Degree of durability of ice cover (%)	Mean proportional part of ice phenomena in long-term period (%)
		ice phenomena	ice cover	ice cover	ice phenomena	ice phenomena	ice cover				
1	Osiek	28-Dec	05-Jan	09-Mar	15-Mar	63.5	54.5	19.2	0.64	89.1	80.5
2	Lubie	07-Jan	11-Jan	09-Mar	08-Mar	57.7	54.8	22.8	0.11	97.9	87.3
3	Sławskie	13-Dec	26-Dec	03-Mar	05-Mar	67.1	55.1	20.9	0.63	85.6	75.9
4	Jamno	18-Dec	22-Dec	26-Feb	07-Mar	62.0	52.2	21.0	0.84	79.5	76.7
5	Bukowo	18-Dec	26-Dec	27-Feb	03-Mar	63.3	53.7	24.7	0.53	86.9	88.7
6	Gardno	10-Dec	19-Dec	28-Feb	09-Mar	69.4	55.2	20.7	0.85	79.3	74.3
7	Łebsko	14-Dec	24-Dec	28-Feb	07-Mar	65.7	52.1	21.7	0.72	83.0	73.5
8	Charzykowskie	29-Dec	05-Jan	12-Mar	18-Mar	69.8	60.2	23.8	0.33	91.9	79.3
9	Sepoleńskie	21-Dec	25-Dec	09-Mar	14-Mar	74.8	66.8	23.9	0.56	91.0	85.7
10	Biskupińskie	17-Dec	23-Dec	06-Mar	11-Mar	76.2	64.1	24.6	0.71	87.3	80.6
11	Żnińskie Duże	21-Dec	29-Dec	06-Mar	11-Mar	71.1	61.4	25.1	0.52	91.2	89.2
12	Raduńskie Górne	30-Dec	09-Jan	16-Mar	27-Mar	73.3	58.4	23.1	0.60	91.0	73.3
13	Ostrzyckie	19-Dec	21-Dec	19-Mar	20-Mar	85.1	80.9	25.2	0.53	90.3	94.0
14	Gopło	14-Dec	21-Dec	28-Feb	09-Mar	74.1	59.0	19.7	0.62	84.8	74.5
15	Jeziorak	06-Dec	16-Dec	15-Mar	19-Mar	93.0	80.9	27.1	0.51	90.7	85.3
16	Drwęckie	12-Dec	23-Dec	11-Mar	17-Mar	84.4	73.3	27.4	0.31	94.0	79.9
17	Nidzkie	08-Dec	20-Dec	19-Mar	29-Mar	102.5	84.9	29.0	0.26	95.4	81.4
18	Mikołajskie	18-Dec	01-Jan	16-Mar	30-Mar	93.4	69.6	31.1	0.53	93.0	71.0
19	Orzysz	13-Dec	28-Dec	17-Mar	27-Mar	99.1	75.9	28.2	0.29	95.5	74.7
20	Ełckie	21-Dec	29-Dec	12-Mar	24-Mar	89.7	68.2	29.7	0.29	95.0	73.0
21	Olecko Wielkie	14-Dec	28-Dec	20-Mar	28-Mar	90.9	74.1	29.3	0.35	92.7	78.2
22	Rospuda	29-Dec	01-Jan	25-Mar	29-Mar	92.9	82.6	27.1	0.06	97.5	87.2
23	Hańcza	27-Dec	04-Jan	19-Mar	28-Mar	89.5	71.4	28.6	0.18	96.3	77.1
24	Studzieniczne	15-Dec	22-Dec	28-Mar	01-Apr	103.8	93.2	34.2	0.10	98.9	89.0
25	Serwy	19-Dec	28-Dec	21-Mar	29-Mar	98.1	81.6	30.5	0.10	98.6	81.2
26	Morskie Oko [a]	18-Nov	27-Nov	01-May	14-May	171.7	150.2	69.3	0.50	97.0	87.4

Explanation: a – observations in the period 1962–2020 (after IMGW-PIB)

Table 3. Characteristics of ice cover and ice phenomena on the Lake Morskie Oko in various periods 1962–2020

Period	Duration of ice phenomena (days)	Duration of ice cover (days)	Maximum thickness of ice cover (cm)
1962–1970	177	156	76
1971–1980	193	170	72
1981–1990	177	157	69
1991–2000	166	156	61
2001–2010	166	139	65
2011–2020	148	130	73
1962–2020	172	150	69

Table 4. Ice cover thickness on selected lakes, Jan 29 to Feb 1, 1996, and ranges of water temperature and heat content (after author's unpublished materials)

Lake	T_{ice} (cm)	D_{ice} (cm)	$T_{0,2}$	T_b	$J \cdot cm^{-3}$
Powidzkie	37	6	0.92	3.5	10.70
Gopło	41	5	0.91	3.5	10.31
Skulskie	40	3	0.88	3.4	7.16
Skulska Wieś	44	6	0.75	4.1	10.79
Popielewskie	31	6	1.15	3.3	11.52
Wiecanowskie	42	2	1.00	3.7	10.00
Szydłowskie	30	5	1.18	3.2	10.11
Kamienieckie	32	4	0.80	2.6	8.70
Ostrowskie	31	2	1.12	3.9	9.73
Bachotek	36	4	0.13	3.1	6.11
Jeziorak	31	1	2.09	3.2	11.69
Dadaj	31	2	1.77	3.2	11.88
Narie	25	7	2.01	3.1	11.29

Explanations: T_{ice} – mean thickness of ice cover, D_{ice} – differences in thickness of ice cover (cm), $T_{0.2}$ – water temperature at depth of 0.2 m, T_b – water temperature at bottom (°C), $J \cdot cm^{-3}$ – Heat content ($J \cdot cm^{-3}$)

described forms of ice on the lake and drew attention to the relationship between the duration and variability of ice phenomena and the influence of meteorological conditions.

Several publications present the course of lake ice formation in an area with little variation in climatic conditions. In such cases, other factors such as lake basin morphometry and exposure, water circulation in the lake, and the chemical composition of the water may also determine the variability of ice formation in lakes (Pietrucień and Skowron 1984). Expeditionary research in the Kashubian Lakeland covered short measurement series of up to 10 years (Okulanis 1977). Subsequent publications concerned the lakes of the Kashubian Lake District (Barańczuk and Marchlewicz 2003; Borowiak and Barańczuk 2004). A paper by Barańczuk and Marchlewicz (2003) presents spatial variability of ice cover on Lake Raduńskie Dolne, while a paper by Barańczuk and Borowiak (2005) presents ice cover on several lakes of the Radunia, Łeba and Słupia spring zone. There is a relatively large number of studies on ice cover thickness. Their aim, apart from the purely exploratory aspect, was to determine the reasons for these differences, but also the degree of safety and suitability for the people residing on it. The thickness of the ice cover in a lake varies minimally (up to 4–6 cm maximum), despite the relatively high fragmentation and depth variation (e.g., Gopło, Jeziorak, Popielewskie, Ostrowskie) (Skowron 1997).

However, the measurements of ice cover thickness made on several selected lakes during the cold and snowy winter of 1995/96 presented in Table 4 are very interesting.

The influence of a cold, snowy winter on the thickness of ice cover on and among the lakes was insignificant. The lowest thickness occurred on Lake Narie (25 cm), and the highest on Lake Skulska Wieś (44 cm). On the other hand, the differences in thickness among particular lakes varied from 2 cm (Wiecanowskie, Ostrowskie and Dadaj) to 6 cm (Powidzkie, Skulska Wieś and Popielewskie).

The measurements made by the author in the last ten days of February 2003 in 11 lakes of the Brodnica Lakeland also prove that ice thickness is determined mainly by the mean depth of the lake and the presence of snow cover. Ice thickness values ranged from 33 cm (Zbiczno) to 38 cm (Dębno), while differences in the perimeter of particular lakes ranged from 2 cm (Strażym) to 7 cm (Dębno). Further measurements made on six lakes of the Kashubian Lakeland at the beginning of March 2003 and 2004 by Barańczuk and Marchlewicz (2003) showed clearly different thicknesses of ice cover: Raduńskie Dolne 16–31 cm, Ostrzyckie 10–20 cm, Zamkowisko 22–26 cm, Kaniewo 22–26 cm, Boruckie 16–20 cm and Żuromińskie 17–20 cm. The authors concluded that one of the reasons was the presence or absence of snow cover. Similar observations are reported by Choiński (2007) for Lake Niepruszewskie (differences up to 6 cm), Lake Charzykowskie (differences up to 11 cm) and Lake Jaroszewskie (differences up to 10 cm).

Bearing in mind that the maximum thickness of ice on lakes in the temperate zone occurs on average at the threshold of January and February, the measurements of this parameter were made on lakes located over a wide area. Synchronous studies on the thickness of ice cover were performed from 30 January to 2 February 2004 on 33 lakes in northern Germany, Poland and south-eastern Lithuania (Marszelewski and Skowron 2006) (Figs. 4, 5). The study area was about 1,200 km long (8.02–25.50°E) and about 250 km wide (52.87–55.26°N). The results of the measurements confirmed its increasing thickness from 3–8 cm in the western part of the Mecklenburg Lakeland to 27–31 cm in the Vilnius Lakeland, which correlated with the course of the thermal winter (Skowron and Marszelewski 2005). It can be concluded that due to large changes in climatic conditions in this part of Europe, the course of ice phenomena on the lakes varied both in space and time.

Due to the limited volume of the paper (editorial requirements), the author could not include several papers concerning ice phenomena on various lakes, for which he sincerely apologises.

Fig. 4. Distribution of studied lakes in European Lowlands (after Skowron and Marszelewski 2005)

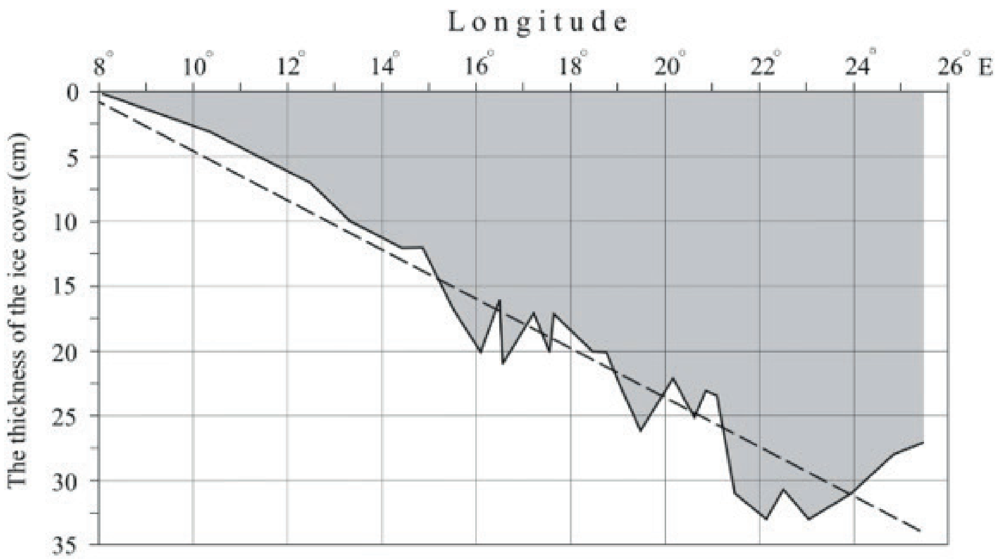

Fig. 5. Course of thickness of ice cover, 30 and 31 Jan 2004 (after Skowron and Marszelewski 2005) Bearing in mind that the maximum thickness of ice on lakes in the temperate zone occurs on

Discussion

Changes in climatic conditions have led to closer scrutiny of their effects on lake ecosystems. It is widely known that winter periods were generally warmer after 1850 than before (Fortuniak et al. 2001; Przybylak et al. 2003; Kaszewski 2015). The changeability of the circulation and properties of air masses that shape the climate of Central Europe should be considered to be the main and fundamental cause of climate variability. According to Kożuchowski and Żmudzka (2001), the mean annual air temperature calculated for 51 meteorological stations amounted to 9.5°C, and was the highest in the years 1951–2000, and probably the highest in the area of Poland since the beginning of instrumental observations. The conclusions concerning the course of air temperature during winter months are particularly interesting (Przybylak et al. 2003). No potential conflict of interest was reported by the authors.

The publication of Hurell (1996) on the influence of the atmospheric circulation (NAO) on air temperature during the winter months led to a closer examination of its influence on the course and variation of ice phenomena in the northern hemisphere in particular years (Magnuson et al. 2000; Grirjatowicz 2005; Benson et al. 2012; Wrzesiński et al. 2013, 2015).

Meaningful evidence for changes in lake ice in Europe is provided by the research conducted by Korhonen (2006) in Finland. Based on a series for the period 1885–2002, he finds the average trend of later ice cover formation to be 7.9 days every one hundred years in southern Finland, 3.6 days in central Finland, and 4.6 days in northern Finland. In contrast, the average trend for earlier ice break-up is 8.6 days every one hundred years in southern Finland, 6.6 days in central Finland, and 7.5 days in northern Finland. This results in a decline in ice cover duration of 16.8 days every one hundred years in southern Finland, 11.1 days in central Finland, and 12.8 days in northern Finland. A similar trend is identified by Kärkäs (2000) for the deep Lake Pääjärvi (southern Finland) when comparing data from the multiyear periods 1910–30 and 1971–88.

Similarly, Reinart and Pärn (2006) show that the ice cover on Lake Peipus in Estonia lasts 115 days (from 9 December to 4 April) and is characterised by an earlier ice cover break-up, as in many other lakes in the northern hemisphere. Also, on Lake Ladoga there is an earlier break-up (14 days every 100 years) (Karetnikov and Naumenko 2008). On Lake Onega, on the other hand, the phenomenon of shortening of the ice cover duration extends the ice-free period from 217 to 225 days (Salo and Nazarova 2011).

The results of the mean values of ice cover in Lithuanian lakes confirm this fact (Bukantis et al. 2001). The average ice-in dates are two weeks later, and the duration of the ice cover is on average 15 days longer than the lakes located in north-eastern Poland (Skowron 2011). Also, lakes and artificial reservoirs in Belarus, as indicated by Danilovish (2004), show that the 1.1 °C increase in air temperature in 1988–2002 resulted in earlier occurrence of spring and a marked shortening of five days in the period with water temperatures between 0 and 2 °C and the duration of ice phenomena, and six days in the duration of ice cover.

Statistical correlations between lake ice phenology (dates of ice freeze-up and ice break-up, ice duration), air temperature and the North Atlantic Oscillation (NAO) index were analysed for eight lakes in the Karelia between 1950 and 2009. The trends in the chronology of ice phenomena in the last 20 years are shown to be more distinctive than in the whole 60-year period (Efremova et al. 2013).

The course of the ice cover occurrence in the areas west of the Polish borders was traced on the example of Müggel Lake in the period 1977–98 (Adrian and Hintze 2000). The values were similar to those in western Poland. The studies conducted on two lakes located in the Berlin-Brandenburg Lake District showed an earlier ice cover break-up and its shorter duration in the period 1961–2007 (Bernhardt et al. 2012).

Fig. 6. Ice fishing on Masurian lakes (photo R. Skowron)

The investigations carried out on the three Masurian lakes in 2006–10 (Jagodne, Śniardwy and Roś) showed that the parameters of ice phenomena did not vary much (Wira and Ptak 2015). Only the earlier appearance of ice phenomena on Śniardwy Lake in comparison to the other two lakes should be associated with morphometry (lower mean depth) and earlier cooling of the water mass of the lake.

It is interesting to compare the mean data of ice observations for two lakes in Poland (Gopło and Wigry) for 1924–33 with the mean values for 2001–20. The mean properties of ice phenomena show significant differences compared to the data after 75 years. Both in Lake Gopło and Lake Wigry, the disappearance of ice phenomena in the first two decades of 21st century occurs 14 days earlier. The consequence of such a course is a shortened duration of ice phenomena in both lakes by 27.5 and 26.1 days, respectively. Also, the maximum thickness of ice cover decreased by 11.9 and 13.5 cm (Table 5).

Conclusion

The conducted research confirmed the noticeable influence that changing climatic conditions, caused by different intensity of the North Atlantic Oscillation, had on the regime of lake ice phenomena in the temperate zone (Hurrell 1996; Magnuson

Table 5. Comparison of average course of ice phenomena on Lakes Gopło and Wigry:

Lake	Period	Average ice values of lakes			
		Beginning of ice phenomena	End of ice phenomena	Duration of ice phenomena (days)	Maximum ice thickness (cm)
Gopło	A	13-Dec	20-Mar	98.0	30.8
	B	16-Dec	07-Mar	70.5	18.9
Wigry	A	12-Dec	07-Apr	109.0	42.1
	B	25-Dec	23-Mar	82.9	28.6

A – in 1926–1938 and B – 2001–2020 (after IMGW-PIB) et al. 2000; Benson et al. 2012). The transitional character of the climate in northern Poland was marked by the varied dates of ice cover occurrence, its duration, and the degree of ice cover duration (Girjatowicz 2003, 2005; Skowron 2003; Wrzesiński et al. 2013, 2015). In the positive phase of the North Atlantic Oscillation, during warm and moist winters, the duration of the ice cover and its thickness were significantly smaller than for winters with a negative NAO index (Marsz 1999). The transitional character of the Polish climate is clearly marked in the spatial distribution of ice phenomena in lakes. To the west of the River Vistula, the occurrence of ice phenomena is clearly shorter and the thickness of the ice cover is less.

Numerous research studies have confirmed this, especially in the latter half of the 20th century in the area of Pomerania, where a positive trend of air temperature occurred, e.g., in the winter season. Analysing the course of air temperature in Poland, Kożuchowski (2011) showed an increasing trend of climate oceanism. It also resulted in a softening of the winter period in the South Baltic Coastal Strip (Łukaszewicz and Jawgiel 2016).

The increase in mean annual air temperature is most strongly influenced by the temperature of the winter period in which the greatest variability is observed. The occurrence of so-called "coreless" winters, in which a short decrease in air temperature is followed by a several-fold increase, is becoming common. These characteristics should be associated with a revival of the zonal atmospheric circulation and an increase in oceanic climate properties (Marsz 1999; Kożuchowski and Żmudzka 2001), causing warming of winter seasons, especially in January and February (Fortuniak et al. 2001).

The transitional character of the Polish climate characterised by a high fluctuation in its course in the winter months results in significant differences in the dates of occurrence of ice phenomena on lakes. Therefore, their occurrence is characterised by high variability, which is confirmed by standard deviation values. They average ±19.0 and ±18.9 days for the initial dates of ice phenomena and ice cover occurrence, and ±21.3 and ±22.7 days for their break-up. On the other hand, the standard deviation for the duration and maximum thickness of the ice cover are ±30.1 days, ±30.2 days and ±11.6 cm, respectively. Hence, in order to determine the correct assessment of the occurrence of their trends, long measuring series of at least 50 years should be taken into account.

The ever thinner ice cover and more frequent breaks in ice cover duration make it impossible to hold traditional ice boat races and also limit fishing opportunities for numerous ice-fishing enthusiasts (Fig. 6).

Disclosure statement

No potential conflict of interest was reported by the authors.

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