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CHANGEABILITY OF THE ICE COVER ON THE LAKES OF NORTHERN POLAND IN THE LIGHT OF CLIMATIC CHANGES

Abstract: The study is based upon instrumental observations of ice covers which formed on the lakes in northern Poland in the period 1956–2005 and records of air temperature measured at 9 meteorological stations in the period 1960–2005. Relations between mean dates of ice cover freeze-up, ice cover duration, maximum ice thickness, and also other properties of ice regime indicate obvious dependency upon air temperatures in winter months (December-February). Both air temperatures and main properties of ice covers revealed definite trends, showing the increase in air temperature in winter (0.04–0.06°C year^{-1}), earlier disappearance of ice cover (0.5–0.6 day year^{-1}), its shorter duration (0.6–0.7 day year^{-1}), and decreases in maximum thickness of the ice cover (0.2–0.25 cm year^{-1}). The author shows considerable statistical relations between main properties of the course of the ice cover, air temperatures in winter and the NAO winter indexes. Therefore, changeability of the ice covers on the lakes in northern Poland in the latter half of the twentieth century may be treated as another proof and an indirect indicator of climatic changes undergoing in this part of Europe.

Key words: lakes, ice cover, trends, climatic changes

Introduction

Investigations of ice cover formation and its changeability belong to fundamental, and in recent years, more frequently undertaken research problems in limnology. This primarily results from the fact that the lake has become to be perceived as an essential link in the natural environment, which participates in its transformations. These changes occur simultaneously with climatic changes, clearly noticeable on the northern hemisphere (Stefan and Fang 1997; Magnuson et al. 2000; Vuglinsky 2000), particularly in the moderate and transitional climatic zone (Jaagus 1997; Kilkus 1997; Danilovich 2004). This influence causes most frequently shortening of ice cover duration and decreases in its maximum thickness (Gronskaya 2000; Yoo and D'Odorico 2002; Vuglinsky et al. 2002; Skowron 2003; Skowron and Marszelewski 2005; Marszelewski and Skowron 2006).

It is generally assumed that over Central Europe and Southern Baltic Sea the period of last 200 years was characterised by considerable changes in air temperature and the occurrence of positive trends for mean annual values. The increase in mean annual air temperature is primarily influenced by the temperature of the winter period (Marsz 1999; Przybylak et al. 2003) with its biggest changeability.

Study area and source materials

The lakes presented in this study are different with respect to basic morphometric parameters (Table 1). The area of the lakes ranges from 107 ha (Lake Biskupińskie) to 7 020 ha (Lake Łebsko), whereas their mean depths are from 1.3 m (Lake Gardno) to over 38 m (Lake Hańcza). The character of the basin expresses the mean inclination of the lake bed, which is higher than 3.5° for deeper lakes (Osiek, Ełckie, Studzieniczne, Serwy and Hańcza), and lower than 0.5° for the most shallow lakes (Gardno, Łebsko, Bukowo, Jamno and Drużno).

Extensiveness of the littoral zone and its percentage share in the lake volume play an important role in the freeze-up and break-up processes. This property is well expressed in the percentage share of the volume of the lake to the depth of 2.5 m. The biggest share (> 50%) is characteristic of the coastal lakes and lakes: Gopło, Sępoleńskie, Drużno and Jeziorak, whereas the smallest share (< 20%) is recorded in the deepest lakes (Ełckie and Serwy). This character is also clearly underlined by the relative depth index (C_R).

The study is based upon the results of the measurements conducted by the Institute of Meteorology and Water Management, and concerns a fifty-year series of observations of ice covers on 15 lakes (Fig. 1). It comprises

Table 1. Location and basic morphometric and resistance related features of the analysed lakes. (determined on the basis of the data from the Inland Fisheries Institute and the Institute of Meteorology and Water Management).

No.	Lake	Lake surface in ha	Lake volume in m. of m^3	Lake volume up to 2.5 m (%) deep	Maximum depth of lake in m	Mean depth of lake in m	Mean inclination of lake bottom	Relative depth index $C_R = D_{av.} / W_{av.}$
1	Sławskie	822.5	42 665	42.4	12.3	5.2	1° 44’	0.006
2	Gopło	2.221.5	78 497	55.2	16.6	3.6	1° 25’	0.004
3	Biskupińskie	107	6 397	39.6	13.7	5.5	1° 47’	0.008
4	Żnińskie (Duże)	420.5	29 493	33.3	11.1	6.8	1° 04’	0.005
5	Charzykowskie	1 336.0	134 533	27.2	30.5	9.8	2° 11’	0.007
6	Jamno	2 231.5	31 528	99.8	3.9	1.4	0° 15’	0.0006
7	Łebsko	7 020.0	117 521	91.6	6.3	1.6	0° 09’	0.0004
8	Ostrzyckie	296.0	20 785	25.3	21.0	6.7	3° 07’	0.014
9	Drużno	1 147.5	17 352	100.0	2.5	1.2	0° 08’	0.0007
10	Jeziorak	3 152.5	141 594	72.4	12.9	4.1	1° 14’	0.003
11	Drwęckie	780	50 140	40.6	22	5.7	2° 56’	0.01
12	Mikołajskie	424.0	55 740	21.1	25.9	11.2	2° 46’	0.013
13	Ełckie	385.0	57 420	15.8	55.8	15.0	5° 37’	0.016
14	Studzieniczne	244.0	22 074	28.8	30.5	8.7	3° 35’	0.012
15	Serwy	438.5	67 182	15.6	41.5	14.1	5° 50’	0.021

Explanation: [1] – $D_{av.}$ – mean lake depth in m, $W_{av.}$ – mean lake width in m.

the longest series of instrumental measurements conducted in Poland. The following definitions of the parameters characterising ice covers – earlier determined by (Stefan and Fang 1997; Vuglinsky et al. 2002; Skowron 2003; Williams et al. 2004; Marszelewski and Skowron 2006 and altered slightly) are considered in this work:

– the earliest freeze-up date (E_{fd})—the first day with the ice cover in winter season, when 100% of lake area within a visible measurement sector was covered with ice, considered as the beginning of ice cover in the article;

– the latest ice break-up date (L_{bd})—the last day with the ice cover in winter season (the day before the date of disintegration of the ice cover), considered as end of ice cover in the article;
– the duration of the ice cover (D_{ic})—the total number of days with the lake covered by ice during a winter;
– the total period of the ice cover ($L_{bd} - E_{fd}$)—days between the earliest freeze-up and latest ice break-up dates;
– maximum ice thickness (M_t)—measured over the winter ice cover period;
– continuous ice cover ratio ($I = D_{ic}/E_{fd} - L_{bd}$ *100%*) – the duration of the ice cover divided by the total period of the ice cover (%);
– mean ice-in date in a long-term period (M_{UD});
– mean ice-out date in a long-term period (M_{IOD});
– mean ice cover duration in a long-term period (M_{ICD});
– mean maximum ice thickness in a long-term period (M_{MID});
– mean number of disruptions in the ice cover in the winter season in a long-term period;
– mean share of ice cover duration in the course of ice phenomena in a long-term period.

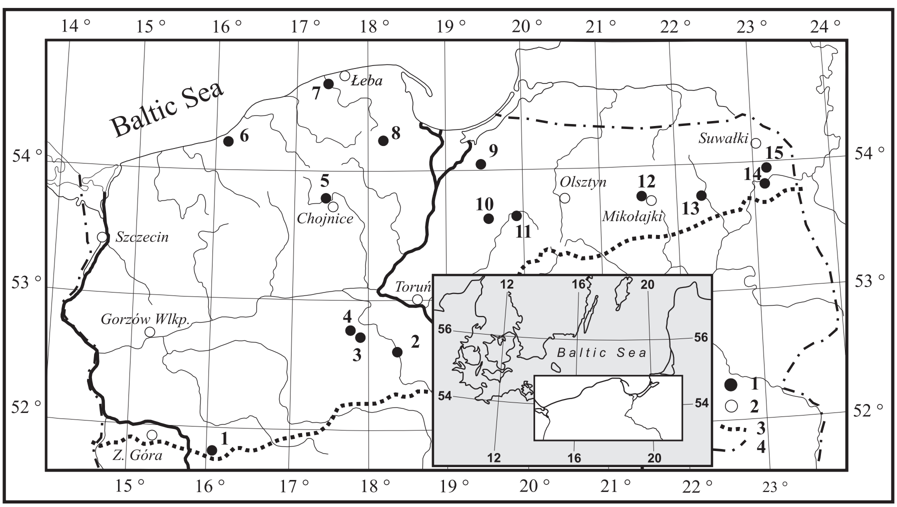

Fig. 1. Location of the lakes studied: 1 – lakes, 2 – meteorological stations, 3 – limits of the Vistulian (Weichselian) Glaciation, 4 – Polish border

The study aims at presenting spatial and time diversity in the course of the ice cover on the lakes of the Polish Lowland in the period 1956–2005, and tendencies of the changes in the context of climatic changes undergoing in this part of Europe.

Discussion of the results

The area of the Polish Lowland (the Vistulian Glaciation) is characterised by distinct spatial diversity of air temperature (Table 2). This mainly refers to mean annual values, mean temperatures in the winter season, as well as to annual amplitudes. Generally, the highest air temperatures in the winter season are recorded in the western part of the Pomerania and Wielkopolska Lakelands, and their mean values in the long-term period of 1961–2005 are higher than 0°C. While to the east of the River Vistula valley, their values are lower than –1°C, reaching the values below –2.5°C in the eastern limits of Poland. An observable increase in annual air amplitudes ranging from 19°C

Table 2. Mean annual values (5-year), mean values in the cold period (Dec-March) and annual amplitudes (A) of air temperature (°C) at the selected stations in the period 1961–2005 (calculations based upon the data obtained from the National Climatic Data Center Global Historical Climate Network version 2; http://www.ncdc.noaa.gov)

Station	1961–1965	1966–1970	1971–1975	1976–1980	1981–1985	1986–1990	1991–1995	1996–2000	2001–2005	1961–2005	A
Zielona Góra	8.1	8.4	8.8	7.8	8.3	8.6	9.0	8.6	9.5	0.55	21.5
Gorzów Wlkp.	7.9	8.0	8.7	7.8	8.4	8.7	9.1	8.8	9.2	0.5	21.4
Szczecin	8.0	8.2	8.9	8.0	8.7	9.0	9.3	8.7	9.4	1.0	20.6
Łeba	7.3	7.2	7.9	6.9	7.6	8.0	8.2	7.8	8.3	0.48	19.0
Chojnice	6.7	6.7	7.4	6.5	7.1	7.3	7.7	7.5	7.9	-0.96	21.5
Toruń	7.3	7.4	8.2	7.3	8.1	8.2	8.6	8.3	8.8	-0.4	22.7
Olsztyn	6.8	6.8	7.6	6.3	7.2	7.5	7.7	7.3	7.9	-1.29	22.8
Mikołajki	6.6	6.6	7.7	6.3	7.0	7.4	7.8	7.4	7.9	-1.77	23.4
Suwałki	6.1	5.8	6.7	5.3	6.2	6.4	6.9	6.5	6.8	-2.77	24.0

in Łeba to 24°C in Suwałki confirms intensifying continental character of the climate in the eastern direction.

The winter season in the long-term period of 1961–2005 was also diverse with respect to thermal conditions. The coldest winters (Dec. – Feb.) in the analysed 50-year long period occurred in the years 1961–65 and 1966–70, when the mean values ranged from –0.5°C (Szczecin) to –3.9°C (Suwałki) and from –0.2°C (Z. Góra) to –4.8°C (Suwałki) respectively. The warmest winters, on the other hand, were observed in the years 1991–95 and 1971–75. The mean values for the 5-year long periods ranged from –1,1°C (Suwałki) to 2,3°C (Szczecin) and from 1.2°C (Suwałki) to 2.2°C (Szczecin) respectively (Table 2).

The lowest air temperatures in particular years of the winter season (Dec. – Feb.) in the analysed long term period of 1956–2005 were recorded in Suwałki in 1969 (-8.3°C), whereas the highest values in Szczecin in 1990 (4.9°C). The trend for the mean value of air temperature in winter months showed a positive value at the level of 0.04–0.06°C year^{-1} at all stations, and was close to the values quoted by other authors (Degirmendžić et al. 2000; Fortuniak et al. 2001).

On average, the thermal winter (with the mean daily air temperature < 0°C) in the Polish Lowland occurred earliest in northeast Poland at the turn of November and December (Suwałki 2 December), and latest in the Baltic Coastland (after 10 January). The end of the thermal winter in the study area occurred between mid-February (Gorzów Wlkp. – 13 February) and mid-March (Suwałki – 12 March). The duration of the thermal winter was below 10 days in the Baltic Coastland, approximately 60 days in the River Vistula valley to over 100 days in eastern Poland.

It must be clearly stated that the winter season in the Polish Lowland shows repeated exceeding mean daily air temperature over the value of 0°C. After a December decline in air temperature below 0°C there is its very frequent increase, mainly in January or February, and then another decline. These properties are related to the recovery of the zonal atmospheric circulation and rising oceanic properties of the climate, which result in warmer winter seasons, particularly in January and February (Marsz 1999; Degirmendžić et al. 2000). The influence of the Northern Atlantic Oscillation upon climatic conditions in Poland has been a subject of numerous publications. Their analysis indicates strong relations between air temperature and the NAO winter index (Table 3).

Table 3. Matrix of correlation coefficients between the NAO winter index (A-Hurrell 1995) and mean air temperature in winter periods (Dec-Mar) at the selected meteorological stations in the period 1956–2005. Statistical sensitivity α < 0.01 marked in bold).

Station	Dec	Jan	Feb	Mar	Dec-Mar
Zielona Góra	0.522	0.475	0.470	0.607	0.677
Gorzów Wlkp.	0.549	0.571	0.526	0.668	0.760
Szczecin	0.551	0.568	0.548	0.690	0.754
Łeba	0.540	0.555	0.584	0.674	0.750
Chojnice	0.535	0.575	0.674	0.634	0.764
Toruń	0.548	0.565	0.584	0.586	0.771
Olsztyn	0.392	0.571	0.579	0.560	0.747
Mikołajki	0.477	0.583	0.599	0.618	0.749
Suwałki	0.361	0.587	0.615	0.603	0.762

The ice cover formation. The mean dates of the ice cover freeze-up on the lakes of the Polish Lakeland occur earliest between 11 and 13 December in the shallowest lakes (Drużno – 11 Dec., Jeziorak – 13 Dec.), whereas they are observed latest on the deepest lakes in the western part of the analysed area (Charzykowskie – 5 Jan., Duże Żnińskie – 29 Dec. and on the deepest lakes of the Mazury Lake District (Mikołajskie – 29 Dec. and Ełckie – 27 Dec.). On the remaining lakes the mean dates of ice cover freeze-up stabilised most frequently between 15 and 20 December (Table 4).

The dates of the ice cover formation in the area of the Polish Lowland proceeded with a distinct spatial and time diversity in the analysed 50-year long period. The ice cover occurred earliest in 1966 and 1994, as early as in November (Drużno – 12 Nov., Biskupińskie, Studzieniczne and Serwy – 17 Nov.). On the other hand, it froze up latest in 1975, 1983 and 1994, as late as in mid February (Sławskie – 10 Feb., Łebsko – 19 Feb.).

Time diversity among the lakes mainly resulted from the depth and volume of a lake and its location. The biggest time diversity was recorded in 1994 and 1999 and equaled: 97 and 86 days respectively, and in 1984–83 days. On the other hand, the smallest differences were observed in 1993 and 1971 and equaled 9 and 12 days respectively.

Table 4. Mean dates of ice cover formation in the analysed lakes in the period 1956–2005

Lake	Beginning of ice cover (E_{fd})	End of ice cover (L_{bd})	Duration of ice cover (D_{ic})	Maximum thickness of ice cover (M_t)	The number of winter periods without ice-cover break-ups[1]	Degree of its durability ($I = D_{ic}/E_{fd} - L_{bd}$ 100%)
Sławskie	25.12	4.03	58	22	0.60	85
Gopło	17.12	4.03	67	21	0.54	88
Biskupińskie	18.12	9.03	71	26	0.70	86
Duże Żnińskie	29.12	7.03	63	26	0.58	91
Charzykowskie	5.01	14.03	62	24	0.38	90
Jamno	20.12	27.02	55	22	0.91	79
Łebsko	21.12	3.03	58	23	0.73	82
Ostrzyckie	19.12	21.03	84	26	0.57	90
Drużno	11.12	14.03	83	29	0.57	87
Jeziorak	13.12	16.03	85	28	0.45	91
Drwęckie	21.12	15.03	78	29	0.31	94
Mikołajskie	29.12	19.03	76	33	0.36	94
Ełckie	27.12	12.03	72	30	0.33	94
Studzieniczne	18.12	28.03	100	37	0.12	99
Serwy	24.12	23.03	89	32	0.12	99

Explanation: [1] – after Marszelewski and Skowron (2006)

The calculated line trends for the period of 1956–2005 (Table 5) prove the author's earlier suggestions of earlier ice cover freeze-ups on most lakes in Poland (0.2–0.3 day · year^{-1}).

The ice cover break up. The dates of the ice cover break up indicate, similarly to the dates of its freeze-up, considerable spatial and time diversity. The mean ice break-up dates occur most frequently on shallow lakes in the Baltic Coastland (Jamno – 27 Feb., Łebsko – 3 Mar.) and in the reservoirs located in the western part of Poland (Sławskie and Gopło – 4 Mar., Duże

Table 5. Trend of the selected properties of the ice cover in the analysed lakes in the period 1956–2005

Lake	Beginning of ice cover (E_{fd})	End of ice cover (L_{bd})	Duration of ice cover (D_{ic})	Maximum thickness of ice cover (M_t)	Degree of its durability (I)
Sławskie	-0.03	**-0.54**	-0.45	-0.01	-0.12
Gopło	-0.1	**-0.61**	**-0.91**	**-0.21**	**-0.6**
Biskupińskie	-0.01	**-0.51**	**-0.67**	-0.13	-0.3
Duże Żnińskie	0.1	-0.31	**-0.67**	-0.15	**-0.36**
Charzykowskie	-0.06	**-0.46**	**-0.61**	**-0.22**	**-0.43**
Jamno	-0.2	-0.44	-0.48	0.02	-0.4
Łebsko	-0.13	**-0.74**	**-0.78**	-0.18	-0.37
Ostrzyckie	-0.09	**-0.57**	**-0.82**	**-0.26**	**-0.46**
Drużno	-0.23	**-0.66**	-0.42	**-0.25**	-0.04
Jeziorak	-0.18	**-0.56**	**-0.64**	**-0.32**	**-0.34**
Drwęckie	0.1	**-0.7**	**-0.81**	**-0.3**	-0.07
Mikołajskie	0.04	**-0.65**	**-0.83**	**-0.3**	**-0.28**
Ełckie	-0.08	**-0.64**	**-0.88**	**-0.2**	**-0.29**
Studzieniczne	-0.11	**-0.53**	-0.47	**-0.33**	-0.05
Serwy	-0.17	**-0.56**	**-0.48**	-0.39	-0.04

Explanation: Statistical significance (α) < 0.05 presented in bold.

Żnińskie – 7 Mar.). They disappear latest on the lakes located to the east of the River Vistula in late March (Studzienniczne – 28 March, Serwy – 23 March). In the remaining lakes the ice cover diappears in mid March.

The ice cover disappeared earliest, on average in late December, in the years 1988, 1989 and 1990, whereas it broke up latest, on average, in mid April in 1970, 1974 and 1996.

The biggest time differences among the lakes were observed in 1988 and amounted to 111 days (Jamno – 17 Dec. and Mikołajskie – 7 Apr.), while the smallest differences were noted in 1975 – 15 days (Jamno – 23 Feb. and Jeziorak – 10 Mar.).

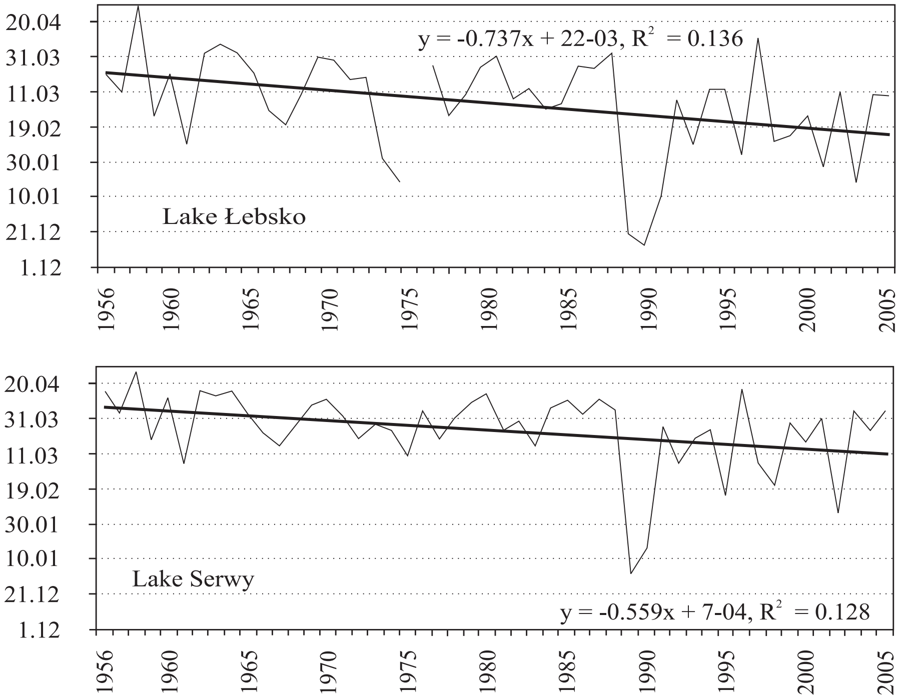

Fig. 2. Course and trend line of final dates with ice cover on the selected lakes in the period 1956–2005.

The calculated trend for the ice out dates indicated a negative value for all the lakes, at the level of 0.5–0.6 day year^{-1} (Table 6, Fig. 2). The highest trend values were characteristic of the shallowest lakes (Gopło –0.61 day year^{-1}, Łebsko –0.75 day year^{-1}, Drużno –0.66 day year^{-1}, Drwęckie –0.7 day year^{-1}) with very few exceptions from that rule.

The ice cover duration. The reflection of the initial and final dates with the ice cover can be seen as its duration. The mean ice cover duration amounts from 55 days for Lake Jamno to 100 days for Lake Studzienniczne. It ranges from 60 to 75 days for the remaining lakes. The ice cover stayed longest on the lakes located to the east of the River Vistula. As for the ice cover duration, it showed significant spatial and time diversity on the lakes of the Polish Lowland in the studied 50-year long period.

In general, the mean duration of the ice cover was 8 days higher on the lakes located to the east of the River Vistula than to the west of it. Its

Table 6. Matrix of correlation coefficients between the NAO winter index (A-Hurrell 1995, B-Jones et al. 1997) and basic properties of ice regime (ice cover) of the selected lakes in the period 1956–2005. Statistical significance $\alpha < 0.01$ marked in bold)

Lake	NAO winter index	Beginning of ice cover (E_{fd})	End of ice cover (L_{bd})	Maximum thickness of ice cover (M_t)	Duration of ice cover (D_{ic})	Degree of its durability (I)	Number of winter periods without ice-cover break-ups	Share of durability of ice cover in the course of ice phenomena
Sławskie	A	0.134	0.548	0.48	0.659	0.359	0.281	0.261
	B	0.143	0.558	0.556	0.69	0.343	0.236	0.237
Gopło	A	0.193	0.506	0.683	0.626	0.297	0.305	0.181
	B	0.229	0.473	0.674	0.613	0.287	0.249	0.263
Biskupińskie	A	0.078	0.648	0.617	0.693	0.525	0.552	0.224
	B	0.0	0.613	0.636	0.675	0.46	0.499	0.223
Duże Żnińskie	A	0.251	0.598	0.57	0.754	0.456	0.321	0.074
	B	0.204	0.648	0.617	0.736	0.417	0.247	0.098
Charzykowskie	A	0.29	0.582	0.709	0.69	0.343	0.135	0.382
	B	0.299	0.612	0.753	0.719	0.362	0.153	0.351
Jamno	A	0.102	0.615	0.483	0.708	0.225	0.017	0.288
	B	0.066	0.606	0.562	0.705	0.272	0.072	0.298
Łebsko	A	0.028	0.649	0.665	0.76	0.289	0.132	0.393
	B	0.036	0.646	0.68	0.73	0.231	0.124	0.359
Ostrzyckie	A	0.056	0.703	0.679	0.675	0.483	0.376	0.28
	B	0.069	0.741	0.669	0.683	0.481	0.362	0.26
Drużno	A	0.148	0.632	0.695	0.648	0.484	0.564	0.424
	B	0.188	0.677	0.693	0.616	0.42	0.512	0.36
Jeziorak	A	0.1	0.646	0.663	0.668	0.472	0.528	0.485
	B	0.071	0.687	0.71	0.702	0.46	0.477	0.46
Drwęckie	A	0.107	0.626	0.679	0.644	0.3	0.255	0.461
	B	0.074	0.683	0.677	0.667	0.319	0.23	0.498
Mikołajskie	A	0.204	0.618	0.731	0.658	0.332	0.195	0.485
	B	0.176	0.679	0.737	0.692	**0.362**	0.222	0.524
Elckie	A	0.113	0.655	0.625	0.712	0.346	0.292	0.461
	B	0.061	0.672	0.63	0.692	0.343	0.264	0.447
Studzieniczne	A	0.024	0.672	0.725	0.573	0.144	0.195	0.255
	B	0.075	0.695	0.77	0.614	0.098	0.124	0.2
Serwy	A	0.061	0.651	0.733	0.532	0.297	0.211	0.293
	B	0.045	0.694	0.725	0.572	0.249	0.195	0.283

duration clearly referred to the course of thermal conditions of the thermal winter, when the correlation coefficient between the duration of the thermal winter and the duration of the ice cover was above 0.83 for the lakes located to the west of the River Vistula, and above 0.71 for the lakes located to the east of the Vistula, at the level of statistical significance of $\alpha < 0.001$.

The ice cover stayed longest in the years: 1958, 1962, 1964, 1969, 1970 and 1996, and lasted over 120 days. The absolute record was noted in 1996 when it lasted for 145 days on Lake Drużno and Jeziorak. During the analysed period there were years when there was no ice cover at all. Such situations occurred in a few lakes located to the west of the River Vistula (Sławskie, Gopło i Charzykowskie) in the winter seasons of 1975, 1988, 1989 and 1990.

The duration of the ice cover was characterised by a negative trend in the analysed long-term period (0.8–0.9 day $year^{-1}$) and proved definite shortening (Fig. 3).

The maximum thickness of the ice cover. The ice cover thickness is a good indicator of morphometric and basin conditioning as well as climatic conditions. However, there is no close dependency between the maximum thickness of the ice cover and its duration.

During the analysed 60-year period the maximum thickness of the ice cover was very changeable and generally increased eastwards. Its mean values changed from below 24 cm on the lakes located to the west of the River Vistula (Gopło – 18.4 cm, Osiek – 20.0 cm) to over 32 cm in the east part of Poland (Studzieniczne – 37.4 cm, Mikołajskie – 33.8 cm).

The maximum values of the ice cover thickness were recorded in the years: 1963, 1969, 1970 and 1996, when they reached beyond 60 cm (Mikołajskie – 65 cm, Studzieniczne – 65 cm), while in the western part of the Polish Lowland the values rarely exceeded 50 cm.

The general tendency of shortening the duration of the ice cover can also be proven by its declining thickness. All the lakes (except for Lake Jamno) are characterised by a negative trend (0.2–0.4 $year^{-1}$), and these trend values clearly increase eastwards (Table 6).

The fact of the repeated freeze-ups of the ice cover in a winter season distinctively corresponds to the duration of the thermal winter, thermal conditions and its stability. These values are well expressed by the degree of the ice cover durability ($I = D_{ic}/L_{bd} - E_{fd}\ 100\%$), where: D_{ic} – is the mean (real) duration of the ice cover in days; L_{bd} – is the mean date of the ice cover freeze-up, and E_{fd} – is the mean date of the ice over break-up.

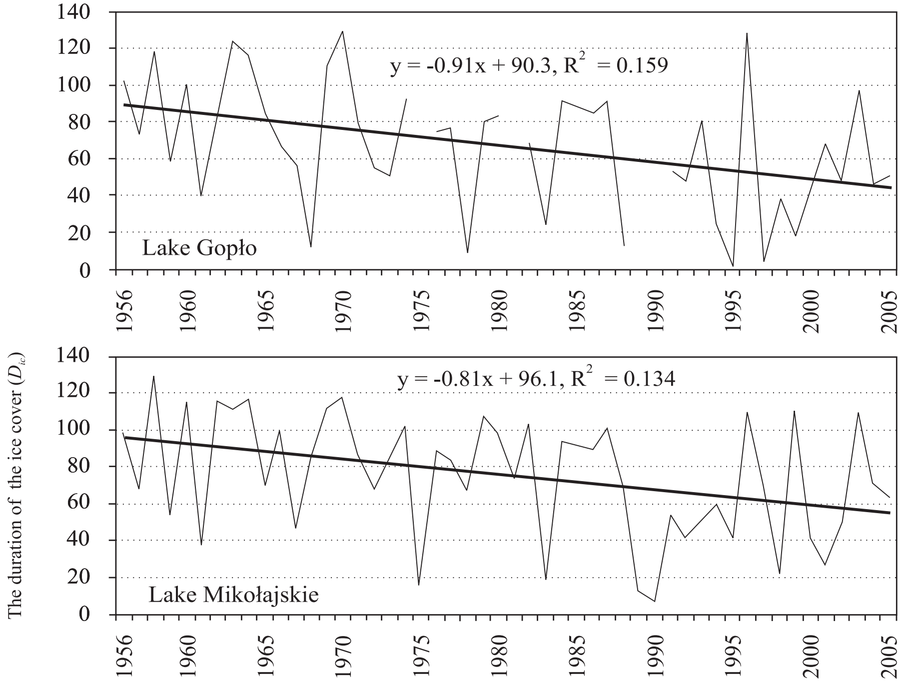

Fig. 3. Course and trend line of ice-cover duration (D_{ic}) on the selected lakes in the period 1956–2005

The continuous ice cover ratio is of a similar importance. It defines the quotient of the duration of the ice cover divided by a total period of ice cover (Stefan and Fang 1997).

The biggest durability of the ice cover occurs on the lakes located to the east of the meridian 19°E, where it exceeds 92%. The lowest values (< 85%), on the other hand, are recorded in the shallowest lakes located to the east of the River Vistula.

Changeability of the ice cover formation in the light of climatic changes

The formation and the course of the ice cover on the lakes of the Polish Lowland are characterised by considerable time span and spatial diversity both in particular seasons and for the mean values during the long term period. Significant differences among extreme lakes mainly result from diverse thermal conditions of the thermal winter in the study area, and further depend upon morphometric conditions and the character of the basin of particular lakes.

The analysis of instrumental observations of the ice cover on the lakes proved apparent relations of its course with thermal climatic conditioning during the winter season, and particularly with air temperature in winters (Dec – Mar), the duration of the thermal winter and the frequency of negative air temperatures in the area of the Polish Lowland. In particular decades of the studied 50-year long period there is a distinct increase in frequency of negative temperatures in the east direction, from 38.3% in Łeba in the years 1991–2000 to 93.3% in Suwałki in the years 1961–1970. The results of the measurements proved the growing importance of the zonal atmospheric circulation in this part of the continent, which has been mentioned in several climatic studies (Degirmendžić et al. 2000; Przybylak et al. 2003).

The works presenting the influence of the North Atlantic Oscillation upon the conditions of the thermal regime prevailing in the Baltic waters and ice conditions of the Polish Coastland are particularly interesting (Girjatowicz 2003, 2005). A new perception of the influence of the North Atlantic circulation upon the aquatic environment of the lakes is presented in the works discussing the formation of the temperature of water and ice phenomena (Górniak and Pękala 2001; Skowron 2003; Marszelewski and Skowron 2006; Skowron and Marszelewski 2005).

The consequence of the influence of the zonal atmospheric circulation upon the course of harshness of winters can be seen in the increase of air temperature in the December-March period and shorter duration of the thermal winter. There is a very strong dependency between winter duration and ice cover duration. This dependency is underlined by a correlation coefficient (r) which ranges from 0.6–0.9 (Fig. 4). It must be emphasised that the value of this coefficient decreases in the east direction, particularly in case of the deeper lakes.

The conducted statistical calculations between the NAO winter indexes (Hurrell 1995; Magnuson et al. 2000) and the basic parameters defining ice regime in the lakes of the Polish Lowland indicate close dependencies. The lowest correlation coefficients occurs between the NAO winter index and the formation of the ice cover ($0.03<r<0.25$), which mainly results from considerable changeability of thermal conditions which prevail in December (Table 6).

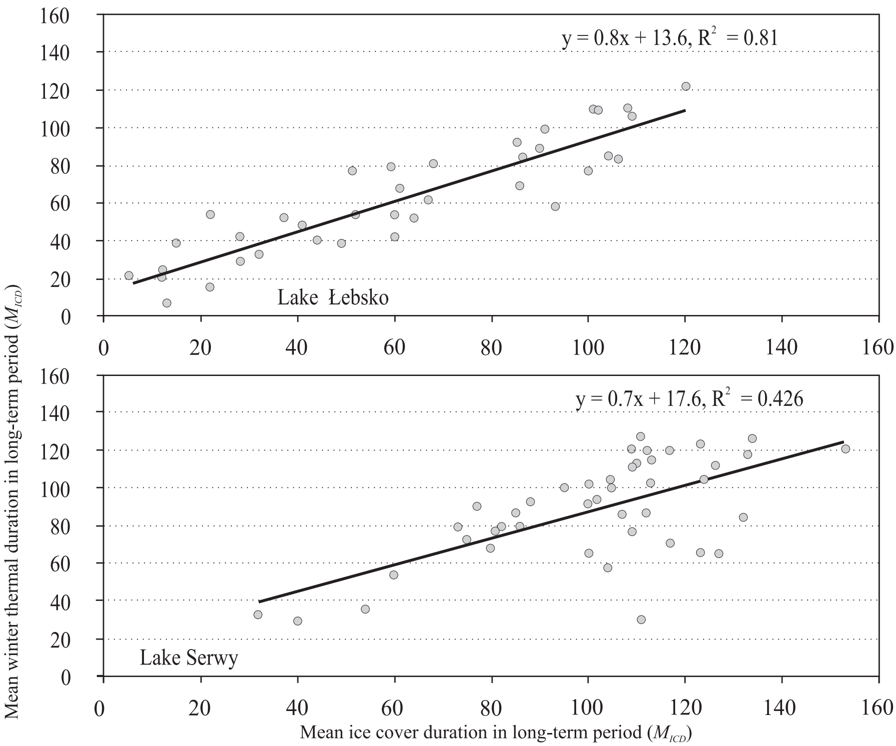

Fig. 4. Dependency between the duration of thermal winter and the duration of ice cover in the selected examples in the period 1956–2005

The highest dependencies occur between the NAO winter indexes and the dates of ice cover break-ups and ice phenomena and the parameters characterising the course of the ice cover: the maximum thickness of the ice cover and its duration ($0.6<r<0.75$), at the high level of statistical sensitivity ($p<0.01$) for all the lakes, regardless of their location (Figs 5 and 6). Similar dependencies characterise the NAO index and the maximum thickness of the ice cover.

The parameters characterising the duration of the ice cover, i.e. the degree of its durability and the mean number of disruptions are correlated to a weaker or mediocre degree. The correlation coefficient of the winter index with both parameters ranged most frequently between 0.15–0.35 and did not prove regional diversity.

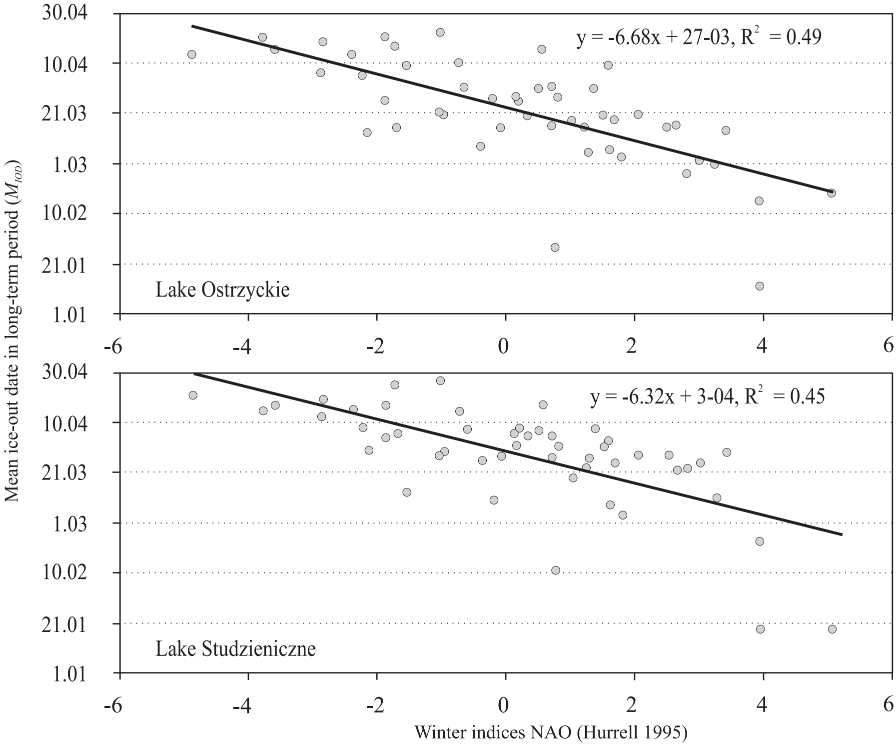

Fig. 5. Dependency between the NAO winter index (Hurrell 1995) and the disappearance of ice over on the selected lakes in the period 1956–2005

Observations of the ice cover thickness were carried out with respect to 33 lakes located in the Central European Lowland in the belt between φ = 53.20°-55.26°N and α = 8.02°-25.50°E (18). The ice cover thickness increased noticeably from 3–8 cm in the western part of the Mecklenburg Lakeland to 27–31 cm in the Vilnius Lakeland, and corresponded to the course of the thermal winter.

It must be assumed that the NAO winter indexes (Hurrell 1995; Jones et al. 1997) undeniably determine the course of the ice cover freeze-ups on the lakes of the Polish Lowland. The soundness of these conclusions was also confirmed by the investigations the author had conducted with respect to the selected Polish lakes in another period (Marszelewski and Skowron 2006).

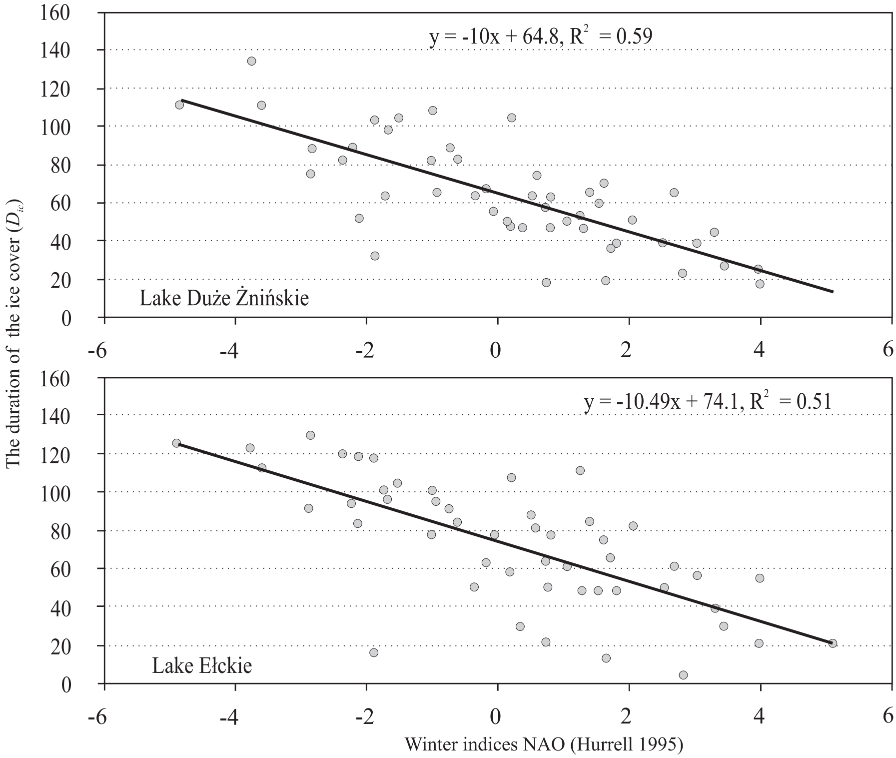

Fig. 6. Dependency between the NAO winter index (Hurrell 1995) and the duration of ice cover on the selected lakes in the period 1956–2005

The thermal conditioning of the winter months (Dec. – Mar.) in the Polish Lowland cause that the course of the ice cover on the lakes is also characterised by noticeable changes, particularly in the west-east direction. This character is proven by changeability of the selected properties of ice regime in the lakes together with the longitude (Fig. 7). The high correlation coefficient ($0.75< r<0.9$) proves the above observations and exposes the influence of thermal properties upon spatial differences in ice cover formation in this part of Europe.

Results

Climate warming occurring over the area of northern and central Europe, and particularly observable in the region of the European Lowland in the

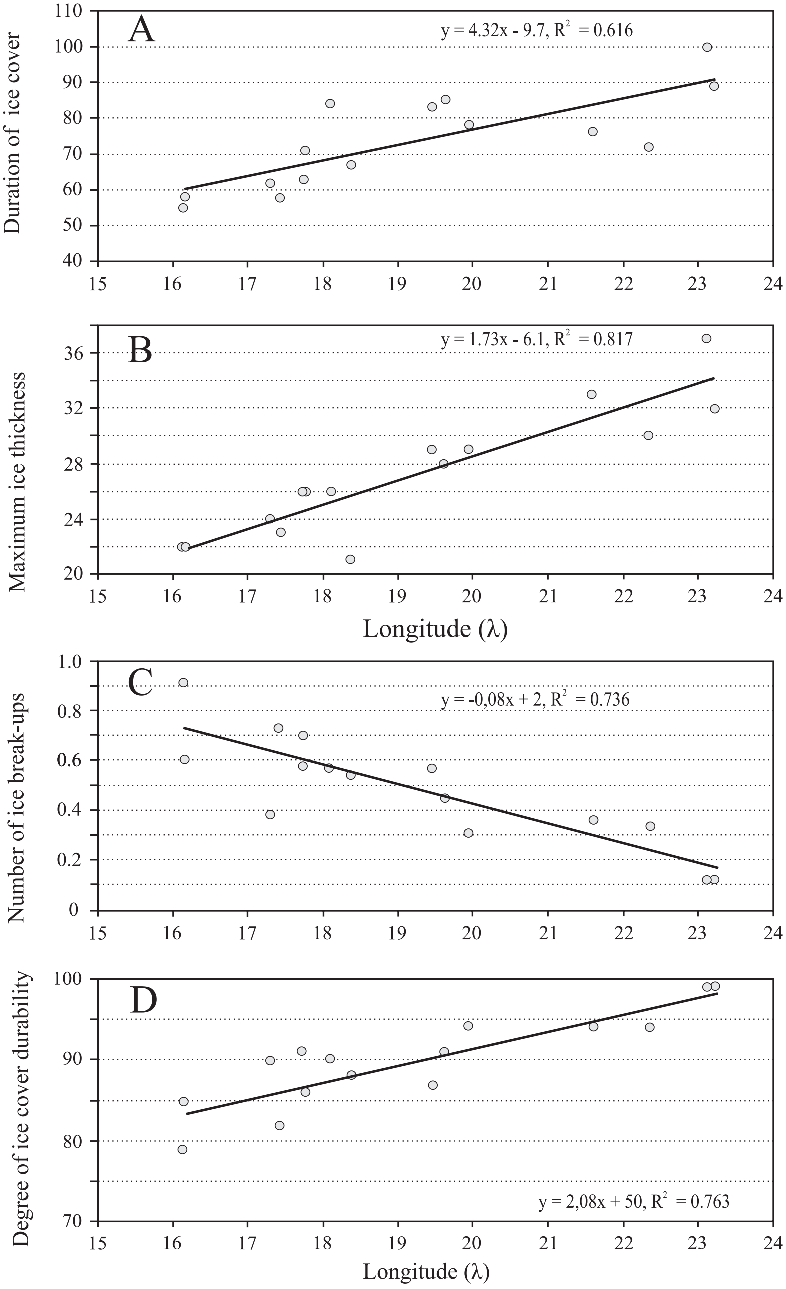

Fig. 7. Dependency between longitude (λ) and selected properties of ice regime in the analysed lakes: A – duration of ice cover, B – maximum ice thickness, C – number of ice break-ups, D – degree of ice-cover durability

latter half of the twentieth century resulted in considerable changes in lake ecosystems. Changes in water stages, water temperatures and the course of the ice cover are best recognised (Palecki and Barry 1985; Magnuson et al. 2000; Vuglinsky et al. 2002; Girjatowicz 2003; Skowron 2003; Marszelewski and Skowron 2006). The analysis of the 50-year long observations of the ice cover indicate that:

– they constitute sufficiently long series of data for the characteristics of changeability and determination of tendencies of changes
– the course of initial ice-in dates on most lakes was characterised by a negative trend at the level of 0.2–0.3 day year^{-1}, marking its earlier appearance
– the biggest changes in the analysed period occurred within the dates of ice cover break-up, which fall between 28 February and 26 March on average and show a negative trend for all the lakes at the level of 0.8–0.9 day year^{-1}
– the ice cover duration shortened in all 15 lakes (0.8–0.9 day year^{-1}) and the maximum thickness of the ice cover decreased (0.2–0.4 cm year^{-1})
– tendencies of changes in main properties of the ice cover on the analysed lakes were similar but they occurred with different intensity
– changes in the ice cover are well characterised by the degree of the ice cover durability (*I*)
– disruptions in the ice cover show unstable thermal conditions of the thermal winter, more and more frequently observed since the mid-1970s
– there is a distinct border of spatial distinctiveness in the course of the ice cover in the area of the Polish Lowland running along the 19 °E meridian, which matches climatic dissimilarity of these regions
– in the light of the presented material the ice cover regime on the lakes of the Polish Lowland clearly corresponds to the changes in the climate, particularly in the period from mid December to the end of March.

Refereces

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