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Secular fluctuations of ice phenomena in Upper Radunia Lake, Kashubian Lakeland

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Abstract: The paper is an attempt at reconstructing multiannual fluctuations of the duration of ice phenomena on Upper Radunia Lake, using their close dependence on the index of winter North Atlantic Oscillation (NAO). Against the secular changes there were analysed the fluctuations of particular phases of the development of ice phenomena in the last 40 years, which proved to be the period of the greatest transformations of the ice regime of the lake. In the years 1961-2004 there was observed a tendency of a shortening of the ice cover duration (9.8 days/10 yrs) and the duration of ice phenomena (9.0 days/10 yrs). The percentage share of the ice cover duration with respect to the total duration of ice phenomena decreased at a rate of 6.3%/10 ys. There are also observed shifts of dates of the beginning and end of individual phases of the ice regime manifested in gradients of a range of 1.7–4.9 days/10 years.

Key words: ice phenomena, ice cover, North Atlantic Oscillation.

Introduction

The occurrence of ice phenomena, widespread in lakes of temperate climatic zone, is one of the basic characteristics of the thermal regime of each lake. Moreover, the intensity of these processes as well as their duration are significant factors shaping the ecological conditions of lakes and factors which may have socio-economic consequences.

The investigation of ice regimes of Polish lakes was started in the late 1930's by Matusewicz (1939) and for many years after that the problem was only marginally dealt with. Its main directions were basically determined by (1) regional description of the diversity of the course of ice phenomena (Gołek, 1957; Pasławski, 1982; Skowron and Szczepanik, 1988), (2) forecasting parameters of ice regime (Li-tyńska, 1966, 1969; Pasławski, 1982) and (3) determination of the course and natural conditions of ice phenomena in chosen lakes (Chojnowski, 1964; Grześ, 1974). Regional research was performed on the basis of short measurement series covering data sets of periods no longer than 25 years. Only the recent years brought studies which used data series of the years 1961–2000 (Skowron, 1997, 2003; Sziwa, 2002), significantly enriching the knowledge of spatial and temporal deversity of ice regimes of Polish lakes. Alhough they present a new approach to the discussed problem, concentrating basically on the analysis of multiannual changes of chosen parameters of ice regime of lakes, they still reveal basic interpretation limitations caused by restricting the measurement series to a period of maximum 40 years (Sko-wron, 2003). Hence, there arises the question if the tendencies of changes observed at present in Polish lakes are a persistent process or only a peculiar disturbance in the secular cycle.

The aim of this study is determined by the search for answers to the above questions and covers an attempt at the reconstruction of multiannual fluctuations of the duration of ice phenomena in

Upper Ra-dunia Lake from the beginning of the 19th century, at the determination of characteristic periods in their course and comparing the obtained results with the tendencies in the course of this phenomenon observed presently in other lakes of Polish Lowland.

Area of study

Upper Radunia Lake is situated in the catchment of the upper river Radunia (Kashubian Lakeland) at an altidude of 162 m and covers an area of 387.2 ha. Its maximum depth is 43 m, with mean depth reaching 15.5 m and capacity is 60.2 mln m^3. The morphology of the lake bottom is characterised by the occurrence of overdeepenings, bottom bars and islands dividing the basin into three clearly distinctive parts. The lake is a flowthrough reservoir with the intensity of horizontal water exchange of FR = 0.467 and retention time RT = 2.14 (Borowiak, 2000), which indicates a passive hydrological type. A characteristic feature of the lake is its special structure of water balance in which the dominating role on the side of income is played by undergournd inflow, constituting over 50% of the total supply value.

Kashubian Lakeland is a characteristic region in young glacial landscape. In terms of climate it belongs to the province of Pomerania Lakeland distinguished by a big number of frosty days, on the averige 130 (Kwiecień, 1979). As the region is the highest situated within the European Lowland (Wieżyca 329 m above sea level), mean air temperatures are here lower (about 1.5°C) than in the adjacent areas. Upper Radunia Lake situated in a postglacial channel is subject to characteristic wind operation. Winds occur mainly along the longitudinal axix of the lake from SW or NE differing in speed and frequency of occurrence in comparison with winds on the morainic plateau (Okulanis, 1981). Winds blowing along the channel axis constitute in total as much as 73.3% of the sum of winds. Also wind speeds show a similar tendency. The highest speeds are of southern and south-western winds: 4.5 and 4.4 m/s respectively (Barańczuk and Marchlewicz, 2003).

Measurements of water temperature and ice phenomena have been performed in the Limnological Station of the University of Gdańsk, situated in the north-western Borucno Basin, continuously since 1961.

Results

Ice conditions between 1961–2004

The analysis of archival data results in the conclusion that the course of ice phenomena in Upper Radunia Lake reveals considerable year to year fluctuations manifested in large oscillations in dates of formation, disappearance and duration of various forms of ice (Fig. 1).

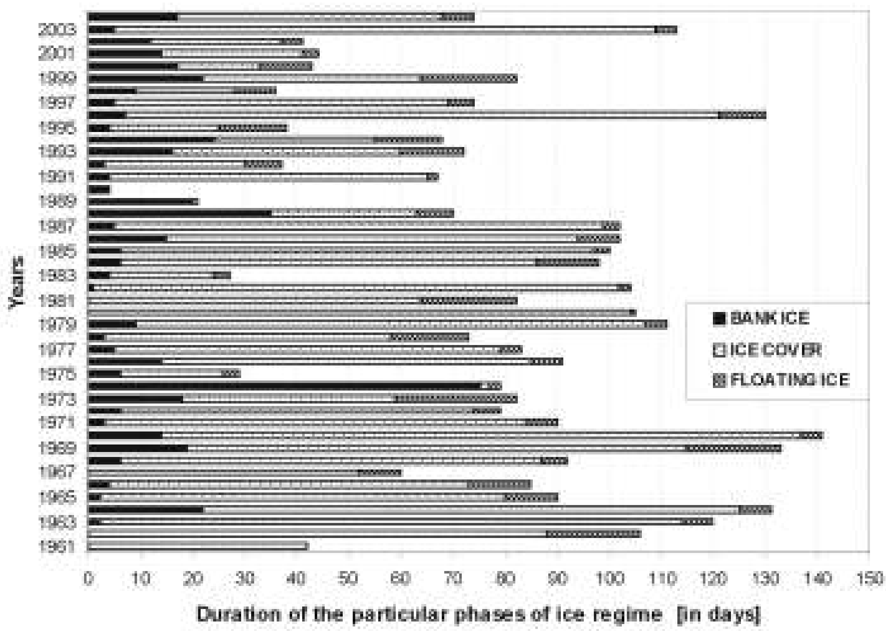

Fig. 1. Duration of the ice phenomena phases in Upper Radunia Lake in the years 1961–2004

The beginning of ice phenomena on the lake, formation of bank ice, occurs after 1st December (years 1989, 1994, 1999), but not later than on 15th February (1975). The mean date of bank ice appearance marks the 28th December (SD /standard deviation/ = 18.1 days). The stabilisation of ice cover occurs only about two weeks later, on 10th January (SD = 20.6 days). Extreme dates of occurrence of continuous ice cover fall on the following extreme dates: 7th December (1981) and 3rd March (1988). However, a stable ice cover may not form at all, as it was the case in 1990, while in 1989 its occurrence was limited to one day only, and ice thickness was then just 1 cm. The disappearance of ice cover takes place between 21st January (2002) and 21st April (1970), whereas the mean date of the end of ice cover falls on 18th March (SD = 21.5 days). The termination of ice phenomena occurs only about 27th March (SD = 20.7 days), and threshold dates are 8th January (1990) and 30th April (1969). Hence, theoretically, the length of the period with ice phenomena may even be four months, i.e. 151 days in total. In fact, the longest duration of ice phenomena, close to the theoretical one, was recorded in 1970 and it was 141 days, and a stable ice cover remained for 123 days. The shortest duration of ice phenomena was in 1990 (4 days in total), and a continuous ice cover did not occur at all. The mean ice cover duration on Upper Radunia Lake is 61 days, which is 77.2% of the whole ice phenomena period.

In five years (1961, 1962, 1967, 1980, 1981) the ice cover was not preceded by the occurrence of bank ice and/or floating ice. Bank ice remained the longest in 1974, for 75 days, while the shortest in 1982 – only one day. The mean duration of bank ice was 11 days, which is 13.9% of the total duration of ice phenomena. Floating ice on Upper Radunia Lake occurred in 42 examined periods. It did not occur in 1961 and 1990. The largest number of times it appeared in 1973 and it was recorded on 23 days in total. The mean duration of floating ice on the lake was 7 days – 8.9% of the duration of ice phenomena.

In the period 1961–2004 there were observed tendencies of changes of individual phases of the ice regime of the lake. They were mainifested basically in changes in the duration of particular phases as well as a shift of the dates of their beginning and/or ending. The total duration of ice phenomena gradually decreased by 9.0 days/10 years on the average. At the same time, there was observed an earlier ending of ice phenomena with a simultaneous earlier beginning, by 4.9 days/10 years and 1.7 days/10 years respectively. Whereas, the ice cover duration decreased by 9.8 days/10 years on the average. In this case, there was not observed a clear tendency of a shift of the day of ice cover appearance, though the dispersion from the mean expressed as standard deviation is here as much as 20.6 days. On the other hand, there is clearly marked change in the dates of the ice cover disappearance. The ice cover disappears earlier, and the intensity of these changes is manifested in the gradient of about 4.9 days/10 years. The resultant of the above observed tendencies is also the change in the stability of the duration of ice cover. The percentage share of the ice cover duration with regard to the total duration of ice phenomena reduced at a rate of 6.3%/10 years.

The mean of the maximum thicknesses of ice, for the examined period, was 23.3 cm (SD = 11.9). Conditions the closest to the mean occurred in the years 1967, 1993, 1997. The highest value of the ice cover was observed in 1970 when it was as much as 50 cm and occured for subsequent 44 days between 25th February and 9th April. Extreme was also the year 1990 (lack of ice cover) and 1989 with ice cover of only 1 cm of thickness. The mean ice thickness in the whole period was 16.5 cm (SD = 8.6). The most typical, in this respect, were the years 1966, 1967, 1977, 1994 and 2003.

Fluctuations of elements of the ice regime of Upper Radunia Lake in the years 1825–2004

In the research concerning the icing of lakes, air temperature and lake depth were indicated as the main factors shaping the conditions of the ice cover formation (Lityńska, 1966, Pasławski, 1982). As air temperature is shaped by the directions and intensity of advection of air masses, it may be indirectly determined by gradients of the pressure field or indices describing them (Kożuchowski and Żmudzka 2002). One of such indicators, strongly conditioning the circulation of air masses over northern Europe and also significantly influencing air temperature distributions in Poland, especially in winter, is the index of winter North Atlantic Oscillation (NAO) (Hurrell, 1995; Marsz, 1999; Marsz and Styszyńska, 2001). In this paper there was used winter NAO index (mean value for period December – March) determined by Jones (Jones *et al.*, 1997; CRC 2004). In turn, the mean depth of the lake indirectly characterises the capacity of heat storage in the period preceding ice phenomena and may be substituted for by a parameter describing the quantity of the accumulated heat resources in the surface water layer. In the case of examining the course of ice phenomena in only one reservoir, adopting the index of heat resources is more justified as depth is, in such a case, a constant value not influencing the result of forecasting. Since, as it was shown earlier, ice phenomena start on Upper Radunia Lake at the beginning of December, the sum of mean monthly temperatures of water surface of the period October – November was adopted as the index of heat resources of the lake.

As a result of calculations there were obtained equations of linear regression for such elements of ice regime as the duration of ice phenomena, duration of ice cover and mean ice thickness (Tab. 1). As the degree of explanation of the variability of the ice regime elements on the basis of equations with one and two predictors is similar, and in the case of determining the ice thickness, the degree of explaining of the dependent variable of one-parameter equation is over 50%, and due to a lack of available observations of water temperatures, which is a decisive reason, one-parameter equations were used to reconstruct ice conditions in the lake in the years 1825–2004. This approach is the more acceptable as the level of information loss in the case of reconstructing the duration of ice phenomena (the biggest differences between both equations) is very small, and calculated values similar (Fig. 2). Finally, there was reconstructed the chronological course of ice phenomena from 1825. It indicates a high inter-annual diversity of ice phenomena in the discussed 180 years period. However, smoothing of the diagram and removing fluctuations of high frequency (short duration) allows for distinguishing several distinctive periods of the development of ice phenomena characterised by different values of ice regime parameters, as well as different tendencies of occurring changes (Fig. 3).

Table 1. Equations describing selected parameters of the ice regime of Upper Radunia Lake (DIP – duration of ice phenomena, DIC – duration of ice cover, MIT – mean ice thickness) as a function of the index of winter North Atlantic Oscillation (NAO) and the sum of mean monthly temperatures of water surface in October and November (WST). Calculations for the period 1961–2003

EQUATION	R^2
DIP = -23,074*NAO – 4,957*WST + 174,300	0.667
DIC = -22,431*NAO – 2,022*WST + 105,140	0.576
MIT = -5,258*NAO – 0,453*WST + 26,549	0.498
DIP = -21,796*NAO + 87,553	0.613
DIC = -21,904*NAO + 69,854	0.567
MIT = -5,282*NAO + 19,196	0.527

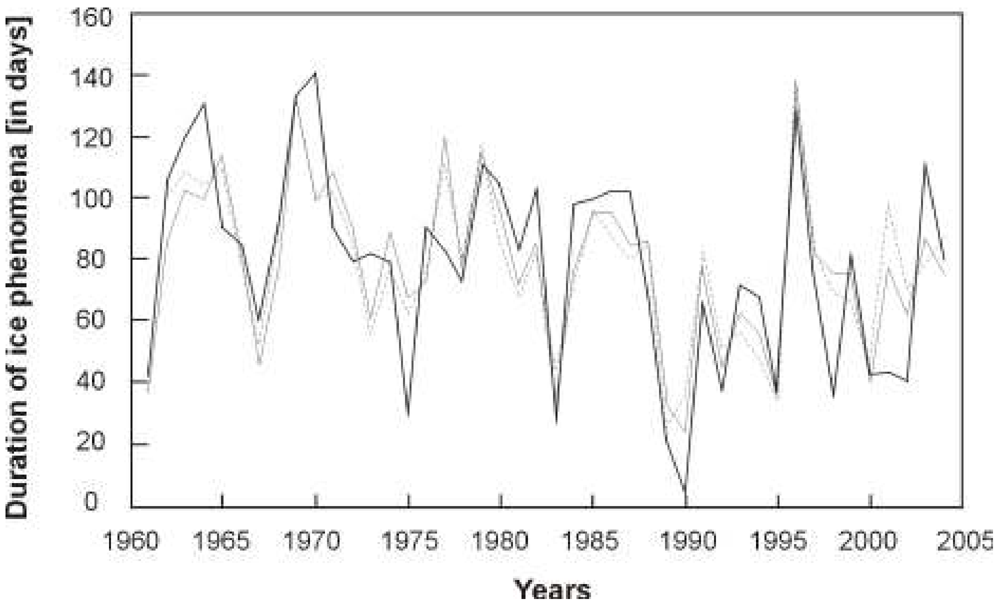

Fig. 2. Observed (thick solid line) and calculated values of the duration of ice phenomena. Solid line denotes NAO model and broken line NAO–WST (water surface temperature) model

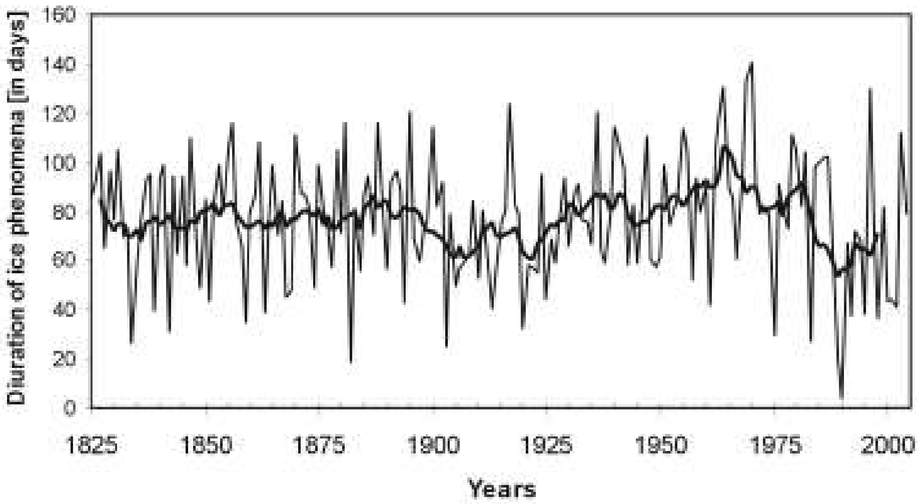

Fig. 3. Ice phenomena in Upper Radunia Lake in the years 1825-2004. Moving average (7 years step) is marked in thick line

Discussion

The research on icing of lakes of Polish Lowland performed by Skowron (2003) unambiguously prove the occurrence in the years 1961–2000 of a tendency of shortening of the duration of ice cover and ice phenomena. There are also marked clear changes of dates of the beginning and end of individual phases of the development of ice phenomena. These changes are manifested through ever earlier beginning and end. There is also a noticeable decrease in the share of the duration of ice cover with respect to the length of the whole period of ice phenomena. Against this background, Upper Radunia Lake does not differ from other Polish lakes. The character of the changes observed in this lake is very close to the tendencies occurring in the majority of lakes of Pomerania and Masurian Lakelands (Tab. 2). Only with reference to the date of the beginning of the ice cover formation there were not observed significant changes. In the quoted research also this parameter revealed a highly ambiguous character of changes. There can be listed numerous lakes on which the formation of ice cover was delayed (Lakes Osiek, Lubie, Charzykowskie, Bukowo) or relatively stable (Lake Żnińskie Duże). The shortening of the ice cover duration is also reflected in a gradual reduction of the ice cover thickness. The maximum ice thickness is decreasing at a rate of 3.9 cm/10 years and fall within the range obtained in earlier research (Skowron, 2003).

Table 2. Mean values of the duration of particular phases of ice phenomena (in days) and maximum ice thickness (in cm) in Upper Radunia Lake in the years 1961–2004 divided into decades

YEARS	BANK ICE	ICE COVER	FLOATING ICE	ICE PHENOMENA	ICE THICKNESS
1961–1970	6.9	84.4	8.7	100.0	32.8
1971–1980	13.9	61.4	6.9	82.2	24.0
1981–1990	9.6	55.8	5.6	71.0	19.9
1991–2000	11.1	43.9	9.7	64.7	19.1
2000–2004	12.0	51.8	4.3	67.8	17.3

However, these tendencies had a varied course during the years 1825–2004 (Fig. 3). Till the end of the 19th century, ice phenomena showed a relative stability, and their fluctiations were short-term. In that period the elements of the regime were close to the mean values ($\overline{DIP}$=77 days, $\overline{DIC}$=60 days, $\overline{MIT}$=17 cm) and they were DIP = 78 days (SD = 23.5), DIC = 60 days (SD = 23.6) and MIT = 17.2 cm (SD = 5.6) respectively. At the beginning of the 20th century (1919–1930) there occurs a clear warming caused by the intensification of western circulation, which is reflected, among others, in shortening of the duration of ice phenomena by about 10 days (DIP = 68 ±20.6 days, DIC = 50 ±20.7). Simultaneously, the mean ice thickness is decreasing; its value in that period fell to 14.7 ±4.9 cm. After that period, up to 1980 there occurs an intensification of ice phenomena. Their duration increases to 86 ±23.8 days. The ice cover, in comparison with the value obtained for the whole analysed period, occured on the average 7 days longer (DIC = 67 ±21.3). The mean thickness of ice cover increases to 18.8 ±5.0 cm. The height of the intensification of ice phenomena fell on the years 1961–1970 when the length of individual phases of the ice regime increased by over 20% in comparison with the mean values (DIP = 99 ±31.0 days, DIC=74 ±25.7 days), and the ice cover thickness increased by 20.5% (MIT = 20.5 ±6.0 cm). The end of the 20th century is distinguished by another increase in the intensity of western circulation, and ice regime parameters reveal similarity to the ones recorded at the beginning of the century (DIP = 68 ±31.8 days, 53 ±25.4 days, 15.5 ±6.0 cm).

As can be seen from the presented survey, the evaluation of the tendencies of changes of elements of the ice regime of Polish lakes based on data of the years 1961–2000 concerns a special period in their secular fluctuations. It covers the period of the strongest intensification of ice phenomena (1960–1970), followed a phase of winter warming strongly limiting their development in the years 1981–2000. Thus, this is a period of the occurrence of the largest gradients of individual elements of the regime. Hence, this period can be treated as an ideal one for the identification and evaluation of the influence of factors disturbing the development of ice phenomena on Polish lakes. The reversal or strong reduction of the observed trends must be a result of various local conditions overlapping with the general picture of changes caused by extraregional influences.

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Streszczenie

Ostatnie prace dotyczące rozpoznania przebiegu zjawisk lodowych na jeziorach Polski choć prezentują nowe podejście do omawianego zagadnienia, koncentrując się na analizie wieloletnich zmian wybranych parametrów reżimu lodowego jezior, wciąż ujawniają zasadnicze ograniczenia interpretacyjne spowodowane redukcją serii pomiarowych do okresu maksimum 40-letniego (Skowron, 2003). Pojawia się zatem pytanie czy obserwowane współcześnie w jeziorach polskich tendencje zmian są procesem trwałym, czy stanowią jedynie swego rodzaju zaburzenie w cyklu sekularnym? Cel opracowania wyznacza zatem poszukiwanie odpowiedzi na postawione powyżej pytanie i obejmuje próbę odtworzenia wieloletnich, poczynając od początku XIX wieku, wahań czasu trwania zjawisk lodowych na Jeziorze Raduńskim Górnym, wyznaczenie charakterystycznych okresów w ich przebiegu oraz odniesienie uzyskanych wyników do obserwowanych współcześnie tendencji.

Z dokonanej analizy danych archiwalnych wynika, że przebieg zjawisk lodowych w Jeziorze Raduńskim Górnym wykazuje znaczne fluktuacje międzyroczne, przejawiające się dużymi wahaniami w terminach powstania, zaniku i czasu trwania różnych form zlodzenia (rys. 1). Początek zjawisk lodowych na jeziorze, formowanie się lodu brzegowego, następuje nie wcześniej aniżeli 1 grudnia (lata 1989, 1994, 1999) i nie później niż 15 lutego (1975). Zakończenie zjawisk lodowych następuje w Jeziorze Raduńskim dopiero około 27 marca (SD = 20,7 dnia), a daty progowe wyznaczają: 8 stycznia (1990) oraz 30 kwietnia (1969). W latach 1961–2004 zaobserwowano tendencje zmian poszczególnych faz reżimu lodowego. Przejawiały się one zasadniczo zmianami w czasie trwania poszczególnych faz jak też przesunięciem dat ich początku i/lub zaniku. Całkowity czas trwania zjawisk lodowych ulegał stopniowemu skróceniu średnio o 9,0 dni/10 lat. Jednocześnie zaobserwowano wcześniejsze zanikanie zjawisk lodowych przy wcześniejszym ich pojawianiu się, odpowiednio o 4,9 dni/10 lat oraz 1,7 dni/10 lat. Z kolei czas zalegania pokrywy lodowej skrócił się przeciętnie o 9,8 dnia/10 lat.

Wykorzystując dane zlodzenia jeziora z lat 1961–2003 oraz zimowy indeks NAO (średnia wartość za okres grudzień–marzec) opracowano modele pozwalające na predykcję wybranych charakterystyk reżimu lodowego jeziora (tab. 1). Ponieważ stopień wyjaśniania zmienności elementów reżimu lodowego na podstawie równań jedno- i dwuparametrowych jest zbliżony (rys. 2) do rekonstrukcji warunków lodowych panujących w jeziorze w latach 1825–2004 wykorzystano równania jednoparametrowe. Analiza sekularnych wahań parametrów reżimu lodowego pozwala na wydzielenie kilku odrębnych okresów rozwoju zjawisk lodowych cechujących się odmiennymi wartościami średnimi parametrów, a także różnymi tendencjami zachodzących zmian (rys. 3).

Uprzednie badania Skowrona (2003) dowodzą występowania w ostatnim 40-leciu tendencji skracania czasu zalegania pokrywy lodowej oraz trwania zjawisk lodowych. Wskazują też na czytelne przesunięcia dat początk-

ku i końca poszczególnych faz rozwoju zjawisk lodowych. Na tym tle jezioro Raduńskie Górne nie odbiega od pozostałych jezior Polski, a charakter zmian obserwowanych na tym jeziorze jest zbliżony do tendencji obserwowanych na większości jezior Pojezierza Pomorskiego jak i Mazurskiego (tab. 2).

Jednakże tendencje te różnie kształtowały się na przestrzeni lat 1825–2004 (rys. 3). Do końca XIX w. zjawiska lodowe wykazywały względną stałość, a ich wahania były krótkookresowe. Na początku wieku XX (1991–1930) zaznacza się ocieplenie powodowane intensyfikacją cyrkulacji zachodniej, co manifestuje się skraceniem czasu trwania zjawisk lodowych o około 10 dni (DIP = 68 dni, DIC = 50 dni). Jednocześnie redukcji, do 14,7 cm, ulega średnia grubość pokrywy lodowej. Po fazie tej, aż do roku 1980, ma miejsce intensyfikacja zjawisk lodowych. Czas ich trwania wydłuża się do 86 dni. Pokrywa lodowa zalega przeciętnie o 7 dni dłużej a średnia grubość pokrywy lodowej wzrasta do 18,8cm. Apogeum przypada na lata 1961-1970 kiedy to długość poszczególnych faz reżimu lodowego ulega wydłużeniu o ponad 20% w porównaniu z wartościami średnimi. Koniec wieku XX zaznacza się ponownym wzrostem natężenia cyrkulacji zachodniej, a parametry reżimu lodowego ujawniają podobieństwo do notowanych na początku stulecia (DIP = 68 dni, DIC = 53 dni, MIT = 15,5 cm).

Ocena tendencji zmian elementów reżimu lodowego jezior polskich oparta na danych z lat 1961-2000 odnosi się zatem do specyficznego okresu w ich sekularnych fluktuacjach. Obejmuje bowiem okres o najsilniejszej intensyfikacji zjawisk lodowych (1960-1970), po którym z kolei następuje faza zimowego ocieplenia silnie ograniczająca ich rozwój w latach 1981-2000. Tym samym jest to okres największych gradientów poszczególnych elementów reżimu, może więc być potraktowany jako idealny do identyfikacji i oceny wpływu czynników zakłócających rozwój zjawisk lodowych na jeziorach polskich.