Oceanologia, 67 (2)/2025, 67404
Polish Academy of Sciences
Institute of Oceanology
Open access article under the CC BY license
https://doi.org/10.5697/ZVAO7632

Dynamics of ice phenomena on the lake shores based on ice scars method – study from the Southern Baltic Sea coast

Józef P. Girjatowicz, Tomasz A. Łabuz*, Małgorzata Świątek

Abstract

This paper analyses how ice pile-ups affect lake shores, how far ice thrusts reach and the height of ice pilings, while also determining the regions that are most vulnerable to the destructive impact of ice on reservoirs located in a coastal zone. This was achieved by a field survey examining ice scars on trees growing along the lakes of the southern Baltic Sea. The ice scars were mainly measured in terms of elevation and length, the distance of the damaged trees from the shore, geographic coordinates, the geographic direction the scars were facing and the elevation of the ground above the water level. A t-test was used to determine whether the tree scars on the individual lakes varied from the average in elevation or distance from the shore.

The furthest traces of ice pile-ups observed on trees were 38 m inland, while the maximum height of the ice piles was 3.8 m. These maximum scores were found at lakes located further east, on their northeastern shores, probably because the most frequent and strongest winds tend to be westerly. Based on the research findings, some conclusions can be drawn about the dynamics of ice phenomena, especially in areas where systematic observations of this type were not carried out. The results can be used to design shore protection and may be relevant for investment plans for municipal housing, transport and recreational infrastructure.

Keywords

Piled ice; Ice scars; Coastal lakes; Shore erosion; Baltic Sea's coast

Institute of Marine and Environmental Science, University of Szczecin, Mickiewicza 16, 70–383 Szczecin, Poland

***Correspondence**: tomasz.labuz@usz.edu.pl (T.A. Łabuz)

Received: 22 October 2024; **revised:** 2 September 2025; **accepted**: 3 September 2025

1. Introduction

Due to climate change, hydrological and meteorological phenomena on lake and sea shores are becoming increasingly violent and less predictable. The number of ice days has decreased in all observed areas of moderate to cold climates (Duguay et al., 2006; Livingstone et al., 2009; Kozlov et al., 2020). The ice season has shortened, and the maximum ice thickness on coastal lakes has shrunk. This also applies to ice phenomena affected by these changes, which are also more difficult to forecast. Negative trends in terms of the formation and duration of ice cover (length of the ice season, maximum ice thickness, etc.) in coastal areas due to global warming do not exclude the possibility that very harsh winters may occur due to changing atmospheric circulation patterns in temperate latitudes. Observations of ice cover have only been conducted at certain spots. Short-term ice pile-ups on the banks of water bodies cause significant damage to infrastructure and buildings (c.f. Kraus, 1930; Reinhart, 1955; Correns, 1973; Barnes et al., 1994; Orviku et al., 2011).

Global climate change is manifested not only as rising temperatures and less severe ice conditions but also as an increase in the frequency and intensity of extreme weather events (e.g. storms and severe gales), as well as more frequent alternation between sub-zero and above-zero air temperatures during winter. This strongly affects the variability and intensification of ice dynamics (Jevrejeva et al., 2004; Livingston et al., 2009; Sztobryn et al., 2012; Haapala et al., 2015). Increased variability in the intensity and duration of ice phenomena, frequent (often occurring multiple times over the course of one winter) ice breakup events, and ice thrusts caused by wind and shifting ice pose a significant threat to the coastal zone.

Coastal lakes play an important role in the environment, economy and society. Fishing and sailing marinas, tourism facilities with recreational infrastructure as well as residential buildings are often constructed there, in low-

---

lying areas, either on the shore or within its immediate vicinity. Ice cover is formed during the winter period on lakes located in the temperate climate zone. Meteorological and hydrological conditions can lead to ice drift and sheets of ice being thrust onto the shore. Ice thrusting on land causes bank erosion, damages the vegetation (including trees) and poses a threat to infrastructure such as ports, beacons, hydraulic engineering and other coastal facilities (Christensen, 1994; Orviku et al., 2011; Girjatowicz and Łabuz, 2020).

Studies of ice pile-up may be conducted remotely, mainly through satellite imagery (e.g., Kozlov et al., 2020) or by observing the thermal conditions of a water body (e.g., Sztobryn et al., 2012), or directly via field reconnaissance (Girjatowicz and Łabuz, 2020); either during the event (Uunila and Church, 2014) or retrospectively, based on traces left behind (Smith and Reynolds, 1983). The method applied in this study was to determine the extent of ice pile-ups along shores based on tree damage. This enabled an estimation of their range regardless of when the ice phenomena occurred. Ice pile-up is a dynamic, short-lived process, and researchers often do not have the opportunity to reach the site quickly and document its extent, especially since access is difficult in winter. Measurement is also hindered by the early onset of darkness at higher latitudes. In contrast, during the summer season, extended fieldwork is much easier, enabling a more thorough and complete analyses. However, indirect analyses are not as precise and reliable as in situ measurements.

Due to global warming, ice phenomena on coastal lakes have started to occur later and disappear earlier. Ice thrusting and piling on the shores of coastal lakes in the southern Baltic Sea has never been monitored by the hydrological and meteorological services. In the past, these phenomena were observed as ice pile-ups near the shores in shallow water or as ice thrusts on the shore. Some insight can be gained by measuring ice scars formed on trees as a result of ice thrusts.

In the coastal zones of lakes, reservoirs, bays or rivers, damage to tree trunks caused by ice can be observed from the water side. These reflect certain ice dynamics, especially thrusting and piling. These signs of damage offer more information about thrusting and piling ice, and the locations where such events occur (Sui et al., 2005; Cyberski et al., 2006). Ice scars on trees have mainly been studied along riverbanks (Smith and Reynolds, 1983; Lederer and Garver, 1996; Pawłowski, 2019), where they indicate the height of flood surges caused by ice jams (Engström et al., 2011; Lind et al., 2014; Uunila and Church, 2014). Tree trunk damage along riverbanks may reach several meters above the average water level in the river. For example, during the ice jam on the Mohawk River in 1996, ice scars were formed on tree trunks 5 m above the normal water level (Lederer and Garver, 1996). The maximum elevation of the ice scars may indicate the highest water and ice levels in the river during an ice jam.

Damaged trees and riparian vegetation destroyed by ice sheets thrusting onshore also occur on the shores of coastal lagoons, bays and straits, reservoirs, and on large lakes. Frequent cases of damaged and sometimes uprooted trees have been observed on the Szczecin Lagoon (Banzhaf, 1931; Girjatowicz et al., 2024), Vistula Lagoon (Girjatowicz, 2015) and the Curonian Lagoon (Kozlov et al., 2020). In the Gulf of Riga area (Estonia), ice sheets advancing onshore caused extensive damage to the pine forest (Orviku et al., 2011). Significant harm has also been observed in the Luodonselkä Strait area (Finland), where many older and younger trees were destroyed (Alestalo and Häikiö, 1976). Similar damage has also been noted on the banks of reservoirs (Gatto, 1984).

Few studies have been devoted to tree ice scars in the vicinity of lake shores. Tree damage has been mentioned when discussing erosion, sediment transport and lake shoreline formation. Such studies were mainly conducted in Canada and the USA. Ice sheets thrusting onto the shores of lakes destroy not only shoreline vegetation (Dione, 1979; Bégin and Payette, 1991; Pyökäri, 2011), but also cause windthrow damage (Gatto, 1984; Lemay and Bégin, 2012; Pyökäri, 2011). Some trees are even uprooted by the ice (Gatto, 1984; Pyökäri, 2011). The elevation of tree ice scars can be used to infer the height of ice jams (Lederer and Garver, 1996). The water level during an ice jamming event has been found to correlate to the maximum ice scar elevation. The elevation of ice scars can be used to assess the danger of flooding due to ice jams. So far, there has been no precise information on the areas at risk of ice thrusting on the coastal lakes of the southern Baltic Sea.

The aim of this paper is to present the extent of ice pile-ups on the shores of coastal lakes. The area covers the coastal lakes of the southern Baltic Sea coast. The method was based on investigations of ice scars on trees. This paper discusses the negative impact on lake shores in temperate zones caused by ice phenomena. It analyses the circumstances under which ice tree scars are formed on shores.

2. Material and methods

2.1 Field investigation

A unique method was used to assess the possibility of ice pile-up on the basis of ice scars on tree trunks. The methodology presented in this paper for determining the maximum extent of ice thrusts onto land was used to determine potential threats associated with these phenomena in other temperate climate zones. A field survey was carried out to find ice scars on trees growing along the coastal lakes of the southern Baltic in Poland. Based on the results, the sections of lake shores most vulnerable to destructive ice activity were determined.

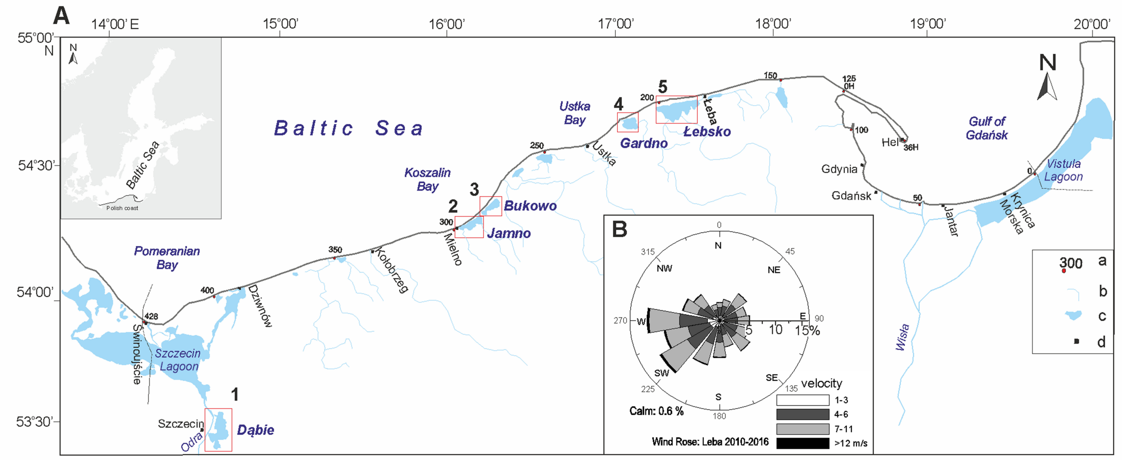

Figure 1. Location of the study area on the southern Baltic coast. A – coastal lakes with ice scars included in the study: 1 – Dąbie, 2 – Jamno, 3 – Bukowo, 4 – Gardno, 5 – Łebsko; a – length of the coast (km), b – rivers, c – lakes, d – main towns. B – the compass rose for the central coast, Łeba town, 2010–2016 (Łabuz 2019, based on IMGW data).

Shores with forest or trees were selected based on satellite images. Trees do not always grow along the shores of coastal lakes, as they mostly consist of wetlands and reed belts. As part of this research, field surveys were conducted on the shores of 7 lakes located along the southern Baltic Sea coast: Dąbie, Resko Przymorskie, Jamno, Bukowo, Wicko, Gardno and Łebsko. Other lakes on the southern shore of the Baltic Sea were excluded from the scope of this research due to their small area. No ice scars were observed on the smallest of the group of lakes examined: Wicko and Resko Przymorskie. However, some were found on the shores of the 5 largest lakes: Dąbie, Jamno, Bukowo, Gardno and Łebsko (Figure 1).

Measurements documented with photographs were conducted during field surveys on selected sections of the shore. Due to the number of lakes covered in the analysis and the size of the area, the surveys were conducted between 2021 and 2023. Results from a pilot study on Lake Dąbie in 2017 were also considered. The equipment used included measuring tapes, ranging rods, an optical level (Ni20), a compass, and a GPS receiver. Measurements were taken with an accuracy of up to 1 cm. Fieldwork was conducted during the warm half of the year, at average water levels for each lake, and in calm weather to ensure that the water levels did not influence the measurements of scar distance from the shoreline. The age of the scars was not determined, so exactly when the ice thrusts occurred is unknown. Data were collected on the following: the species of the damaged trees, their geographical coordinates, the distance from the shore, the elevation of tree scars above ground and water level, their length, the scars' geographic orientation (azimuth) and, in some cases, their width. Photographic documentation of the scars showing the extent of ice damage to the trees was enclosed in the research. The fieldwork consisted in searching for ice scars on trunks, branches or exposed roots of the trees growing along the shores of the lakes. Scars indicating animal activity (e.g., beaver teeth marks), human interference (especially in recreational areas), or those located on the land-facing side of trees were excluded. Observations of ice pile-ups forming in forested shoreline sections in previous years were also used (notably in the winters of 1978/79, 2001/02, 2005/06, and 2010/11).

2.2 Material and analysis

During the field survey, 152 ice scars were identified. Based on geographical coordinates, their distribution and quantity on the surveyed banks were determined. It was found that the location of the ice scars on the trees in relation to the waterline, geographical coordinates and azimuth corresponded with wind factors causing the ice to thrust and pile, which made it possible to determine the approximate hydrological and meteorological conditions during which the ice scars formed on trees.

To formulate accurate conclusions, appropriate statistical methods were applied. The most important factors were found to be the distance of the scars from the shore and the maximum elevation of the scars on a given tree. These were measured around coastal lakes and specific spots, and described in detail using descriptive statistics. The first step was to verify the similarity of the probability distribution of the empirical data values to a normal distribution. A non-parametric Shapiro-Wilk normality test (Kaptein and van der Heuvel, 2022) was used for this purpose. Measures of central tendency (arithmetic mean and median), as well as lower (1st) and upper (3rd) quartile values, were then determined. A Student's t-test of the difference between the means for independent samples was used to determine whether the scars on the trees on the individual lakes were at different elevations or at dif-

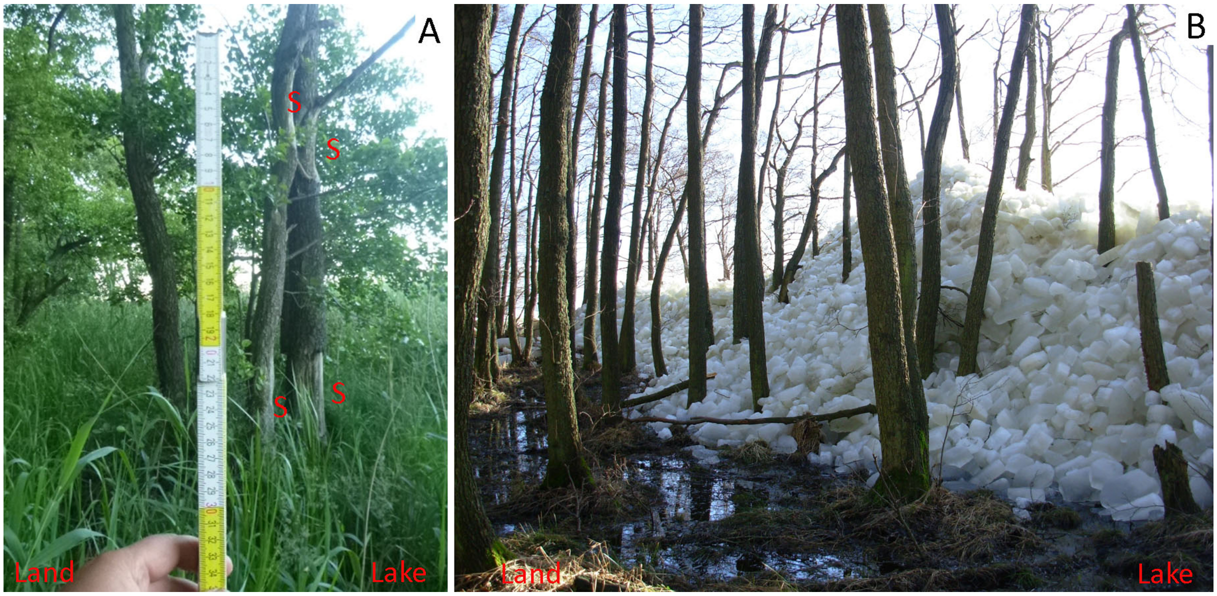

Figure 2. Observation of tree ice scars, the same area of the northern coast of Lake Łebsko (S – ice scar). A – ice scars on trees (06.2022). B – ice ridge shifted to the coast with trees (02.2011), photo by D. Staniaszak.

ferent distances from the shore than the average. The null hypothesis was that there were no significant differences between the average distances of damaged trees from the shore and the maximum elevations of tree scars. The results of both the Shapiro-Wilk and Student's t-tests were considered statistically significant at the standard significance level of 0.05. The length and maximum width of the identified scars were also compared. In addition, the geographic orientation of the scars was analysed, related to the direction from which the ice thrusted onto the shore, and, by analogy, to the wind direction, which causes ice to thrust and pile onto the shore (Figure 2).

3. Characteristic features of the lakes included in the study

The following lakes, where ice phenomena have been observed to occur, were included in the research: Dąbie, Jamno, Bukowo, Gardno and Łebsko (Figures 1, 3). These lakes are connected to the sea by channels and estuaries. Their surface area ranges from 16.44 km^2 (Bukowo) to 70.40 km^2 (Łebsko). They are all very shallow (medium depth ranging from 1.3 to 2.6 m) coastal lakes, with a high exposure index (ratio of the basin area to its average depth) ranging from 913 ha m^{-1} to 4400 ha m^{-1}, while the average for Polish lakes is approx. 30 ha m^{-1} (Choiński, 1995). This results in a rapid rate of water cooling in reaction to air temperature change and the formation of ice phenomena (Choiński, 1995; Leppäranta, 2010). The morphometric features of these lakes are presented in Table 1.

Table 1. Morphometric parameters of the studied lakes (measurements for Dąbie: Jańczak, 1997; other lakes: Cieśliński, 2011).

Studied lake	Surface [km^2]	Medium depth [m]	Exposure ind. [ha m^{-1}]
Dąbie	54.08	2.6	2080
Jamno	22.32	1.4	1594
Bukowo	16.44	1.8	913
Gardno	23.38	1.3	1798
Łebsko	70.40	1.6	4400

The analysed coastal lakes, except for Dąbie, are influenced by the Baltic Sea. Intrusions of seawater with a salinity of 7.5 PSU (Leppäranta and Myrberg, 2009) through narrow channels have little effect on the overall salinity of these water bodies, which is below 1 PSU. Higher salinity levels are observed in the estuaries where lake waters meet the sea (Cieśliński et al., 2009). Very low salinity means that the process of surface water freezing resembles that observed on freshwater lakes. The characteristics of ice events on the lakes in question have been analysed in numerous scientific studies (Skowron, 2009; Choiński et al., 2015; Wrzesiński et al., 2015). The first ice in the form of frazil ice, slush grease ice and ice rind tends to occur most frequently in the second half of December. On average, ice forms earliest on lakes on the east coast (12 December), while further west, it tends to appear later (16 December; Girjatowicz et al., 2022). Ice cover is formed from the buildup of ice rind and does not easily break up. This type of ice mostly accumulates in a regular manner with a uniform, cohesive structure and a smooth surface. The permanence of such ice sheets, their considerable thickness and the small movements of water on the lakes all increase their stability. They disintegrate after the ice has sufficiently

Figure 3. Examples of ice pile-up on the shores of lakes of the southern Baltic coast. A – Dąbie, NE shore, 14.03.1979. B – Gardno, E shore, 18.03.2005. C – Łebsko, N shore, 10.12.2005. D – Łebsko, SE shore, 19.03.2005

melted. This process is often accelerated by strong winds, causing the ice to pile-up. Ice thrusting and piling can occur in shallow water (Figure 3) or several metres from the waterline inland.

The ice cover disintegrates at the end of February and beginning of March on average (or during the first half of April at the latest). The last ice usually disappears a few days earlier on lakes in western Poland than on those located further east. Due to the prevailing westerly wind, ice cover tends to last longest on the eastern shores of the lakes, mainly in the northeast of the country. The maximum ice thickness in individual winter periods is slightly larger on the lakes in the east (21 cm on average) than in the west (less than 20 cm), and in extreme cases, can reach up to 52 cm (Skowron, 2009).

The slight increase in the severity of ice phenomena in the eastern part of Poland is due to climatic conditions. As Schönwiese and Rapp (1997) found, in central Europe (47–56°N), including the surveyed area, there are more days with air temperatures below 0°C in the east, where ice phenomena are also more intense, not only on lakes, but also on the lagoons of the southern Baltic coast (Girjatowicz, 2014). The mean annual water temperature in the coastal lakes in the 1961–2000 period ranged from 8.6 to 9.1°C, while the winter (December–February) mean temperature fluctuated between 1.3 and 1.5°C. The minimum monthly mean values were lowest in February, ranging from 0 to 0.1°C (Girjatowicz, 2011).

In the Lake Dąbie area, the dominant wind direction is from the southwest (about 14% of the year), followed by WSW (13%) and west (11%). In the area of the Jamno and Bukowo lakes, the most frequent wind direction is westerly (12% of days), but northerly and southerly winds are also quite common (approx. 10% of days per year each). In the vicinity of Gardno, westerly winds clearly dominate (approx. 16%), followed by WSW (Wibig, 2021). In the case of Łebsko Lake (in Łeba), the most frequent wind directions are W (20%), SW (ca. 17%) and S (16%; Baranowski and Chlost, 2009).

The highest wind velocities are recorded in the winter period. The multiannual mean wind velocity in winter in the areas of the examined lakes increases as we move eastward – from about 4 m s^{-1} over Lake Dąbie, 4.5 m s^{-1} over Jamno and Bukowo, slightly above 5 m s^{-1} over Gardno (Tomczyk and Bednorz, 2022) and 5.8 m s^{-1} over Łebsko (Baranowski and Chlost, 2009). The highest average daily wind speeds over Lake Łebsko occurred in February (8.8 m s^{-1}) and in January (8.7 m s^{-1}; Baranowski and Chlost, 2009). In spring, on the other hand, wind velocities are lower (approx. 3.5 m s^{-1} over Dąbie, Jamno and Bukowo, 4.5 m s^{-1} over Gardno (Tomczyk and Bednorz, 2022) and 4.8 m s^{-1} over Łebsko (Baranowski and Chlost, 2009).

The dynamics of ice phenomena may be affected by higher near-surface wind velocity over Gardno and Łebsko. Over the other surveyed lakes, the mean wind velocity (between 1966–2018) did not change, while the

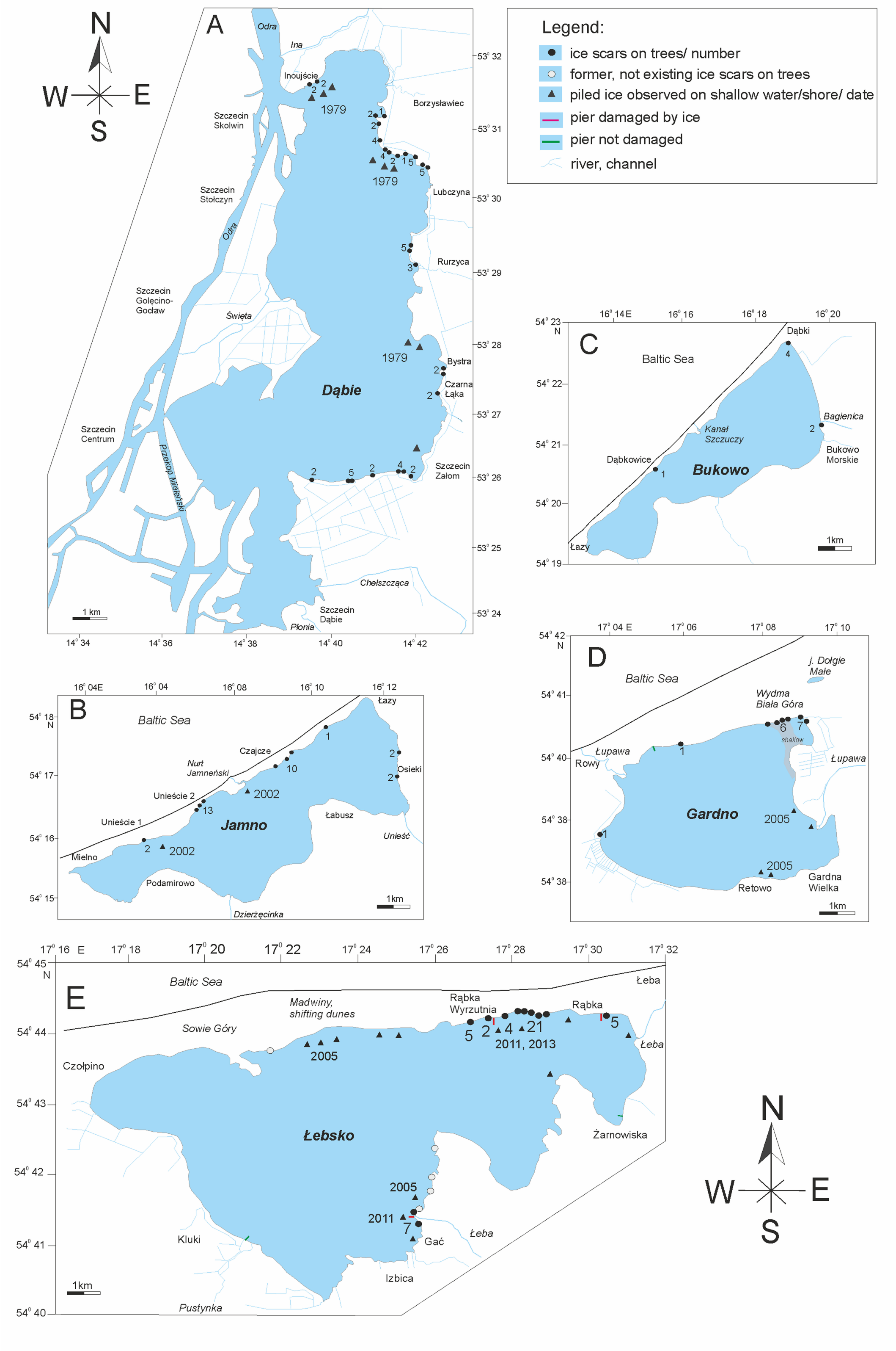

Figure 4. Lakes with trees bearing ice scars (black points) and their number (location on Figure 1). A – Dąbie. B – Jamno. C – Bukowo. D – Gardno. E – Łebsko.

maximum wind velocity decreased (Wibig, 2021). At the beginning of the 21st century, the western and central coast of the southern Baltic Sea was dominated by SW, W and NW winds (Łabuz, 2019). More than 40% of the wind was southwesterly or westerly (Figure 1C). Almost 90% of strong winds, with velocities exceeding 10 m s^{-1}, blew from the south and west (Łabuz, 2019). Strong wind on the Polish coast is most often accompanied by a northwest circulation, regardless of the type of pressure system, as well as a west and north anticyclonic circulation and often also a southwest cyclonic circulation in winter (Tarnowska, 2011).

Wind directions have an impact on the salinity and water levels in the examined lakes. They may cause seawater to form a barrier at the estuary, preventing the outflow of water from the lake basin. Often, this can also result in water backing up into the lake basin. On the southern shore of the Baltic Sea, strong northerly winds cause so-called wind surges as seawater is pushed towards the shore. This forces the seawater deep into the coastal lake through a channel connecting it with the sea. Wind directions are not always the same for all lakes. For example, sea waters generally flow into Lake Łebsko with a westerly wind, and into the nearby Lake Gardno with a northerly and northwesterly wind (Cieśliński et al., 2009). The intrusion of seawater into the lake depends on the angle of the seawater inflow into the estuary sections connecting the lakes with the sea. Seawater intrusion is particularly rapid during winter storm periods (Cieśliński et al., 2009).

4. Results

4.1 Distribution of ice scars on lake shores

Ice pile-up on the shores of the examined lakes was observed on their northern (Figure 3A,C) or eastern shores (Figure 3B,D) Tree ice scars mostly occur on the northern, northeastern and eastern shores (Figure 4). This phenomenon is most frequent on the northern shores of long, narrow lakes situated along a southwest-northeast axis, namely Jamno and Bukowo (Figure 4B,C) and ones running east to west, i.e. Gardno and Łebsko (Figure 4D,E). On Lake Dąbie, which is a large body of water stretching southward, many scars were found on the northern, eastern and southern shores (Figure 4A). Their occurrence is likely due to the exposure of the shore to the dominant westerly and northwesterly winds. No scars were found on the southern shores of the other lakes. They were unlikely to have occurred there due to the wide reed belt inhibiting the thrusting of ice. However, ice scars from ice thrusts were observed on their southeastern shores.

A correlation was identified between the elevation of the observed scars and their distance from the lake shore (Figure 5). The highest scars (>3.5 m) are found close to the shore. They are unevenly distributed because of the narrowing of the western area of the lakes (Jamno, Bukowo and Łebsko) and stretches of shore without trees (e.g. eastern shores of lakes Łebsko and Gardno). Lack of vegetation is also characteristic of the central part of the northern shore of Lake Łebsko due to the presence of moving dunes (known as Madwiny) descending into the lake (Figures 3C, 4E) The western shores of the examined lakes are sheltered by land from westerly winds, and ice thrusting onto the western shores is unlikely due to infrequent easterly winds in winter, which additionally tend to have lower velocities. The greatest number of scars was observed on trees growing directly on the shore, including eroded sections with no reed belt (the northern shore of Lake Jamno; Figure 4B). The shores of the studied lakes are low-lying, just above the water level. Most scars (55% of cases) were found on shores located up to 0.25 m above the average water level. More than 25% of cases occurred up to 0.5 m, and 20% between 0.5 and 1 m above the water level.

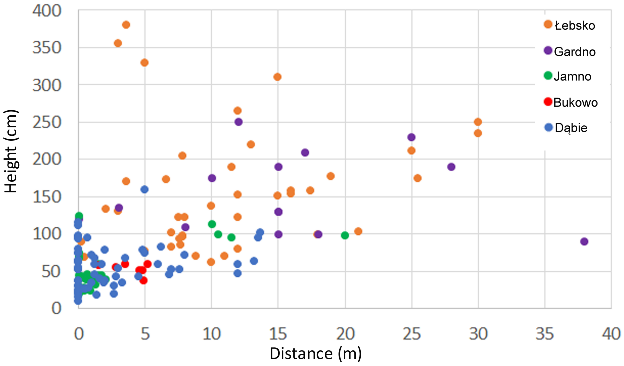

Figure 5. Relationship between the distance from the shore at which tree ice scars occur and their maximum height above average water level (a.w.l.) on coastal lakes of the southern Baltic Sea.

4.2 The distance of ice advance onto the shore based on scars

During this study, large discrepancies were observed in the distance of scars from the shore, depending on shore exposure (Figure 6A) and how far the ice advanced inland (Figure 5). Dense walls of forest prevented further ice advance inland, which can be observed especially on the northeastern shore of Lake Łebsko, where the distances of ice scars from the waterline ranged from 0 to 30 m.

The Shapiro-Wilk test was used to verify the normality of the probability distribution regarding specific distances of trees with ice scars from the shoreline. In most lakes, there was no similarity to normal distribution (making it necessary to reject the null hypothesis of normality of the distribution at the assumed significance level of $p = 0.05$). The statistical values ranged from 0.53 for Jamno to 0.93 for Łebsko. Only in the case of lakes with a very small number of observed scars (i.e. Bukowo and Gardno) were there no grounds for rejecting the hypothesis of distribution nor-

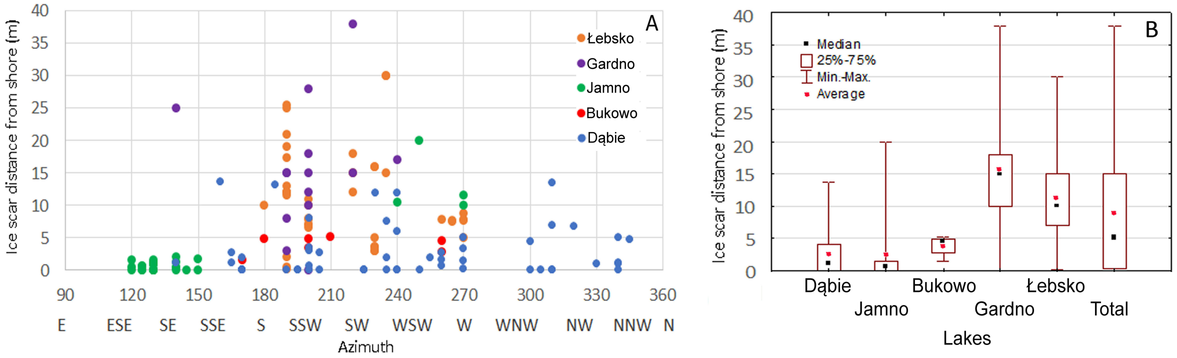

Figure 6. Distance of scars on trees from the shoreline of the studied lakes. A – distance versus ice azimuth. B – quartiles, extremes and average values of the distance of ice-damaged trees from the shoreline on the separate lakes and the entire data set (Total).

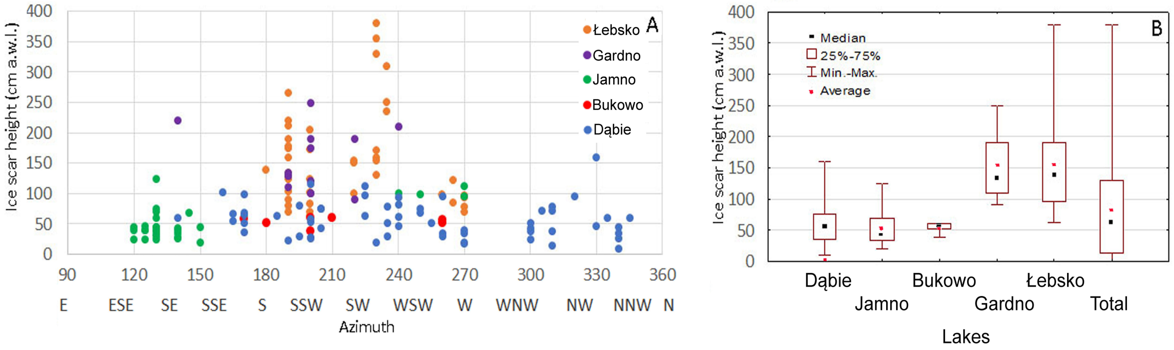

Figure 7. Height of ice scars on the damaged trees from the shoreline on the separate lakes. A – distance versus ice azimuth. B – quartiles, extremes and average values of the heights for ice scars a.w.l. on trees on the entire shore of the lakes (Total).

mality. It can therefore be assumed that the distances of scarred trees from the shore of these two lakes have a distribution close to normal, whereas the others do not. Consequently, in addition to the classic measure of central tendency (arithmetic mean), positional measures such as lower, middle (median) and upper quartiles were also calculated to determine measures of central tendency and variability (Figure 6B).

The furthest ice scar from the shore (at 38 m) was observed on a tree on the northeastern shore of Lake Gardno. The median distance of tree ice scars on this lake was 15 m, and the average was 15.64 m. The long advance of the ice was due to the low-lying, flat ground (at 0.2 m above the water level), as well as the total area of the reservoir and exposure to southwesterly winds. On the other coastal lakes, tree ice scars occurred much closer to the shore. Almost half of the damaged trees on lakes Jamno and Dąbie were found on the shoreline (Figures 6, 8A,B). On lakes Jamno, Dąbie and Bukowo, the damage occurred at extreme distances of 20, 14 and 5 m, medial distances of 0.63 m, 1.1 m and 4.6 m and mean distances of: 2.25, 2.7 and 3.9 m, respectively (Figure 6B). Ice scars were also observed relatively far from the shore on Lake Łebsko (maximum: 30 m, median: 10 m, mean: 11 m). The interquartile range (difference between the upper and lower quartiles; Figure 6B). and the interquartile deviation shows the greatest variation in the distance from the waterline of the damaged trees on the shores of lakes Gardno and Łebsko (4 m each) and the least variation on the shores of Lake Jamno (0.75 m).

Table 2. Student's t-test for mean distances of tree ice scars from the shoreline on individual coastal lakes (L) versus the mean distance of tree ice scars from the shoreline for all lakes (total – T).

Studied lake	Average, L [m]	Average, T [m]	t	p
Dąbie and T	2.70	8.87	−4.79	0.00
Jamno and T	2.25	8.87	−3.67	0.00
Bukowo and T	3.90	8.87	−1.36	0.18
Gardno and T	15.64	8.87	2.50	0.01
Łebsko and T	11.24	8.87	1.45	0.15

t – test value; p – significance level.
Statistically significant differences are underlined.

The shorter distances of ice thrusts from the shore,

Figure 8. Different ice scar positions on trees (S – ice scar). A – horizontal ice scars on the roots on an eroded shore (Jamno). B – large scars on the roots and trunk close to a shore covered by a reed belt (Dąbie). C – small scars far from shore (20 m) covered by a reed belt (Jamno). D – scars at different heights (Łebsko). E – large scar on a thick tree (Dąbie). F – four scars at various distances from the shore (Łebsko).

compared with coastal lagoons, are due to the smaller size of these lakes (small wind fetch) as well as the shore morphology. The longest distances of ice thrusts onto the shore were associated with frequent and strong SW, SSW and SW winds. This is evidenced by the azimuths of the ice scars on the trees furthest from the shore, ranging between 195° and 250°.

To precisely calculate the quantitative deviation of the distance from the waterline of ice scars near individual coastal lakes from the average (mean) for these lakes, a Student's t-test was performed for independent samples. The results of the test are presented in Table 2.

The t-test indicated that tree ice scars occurred significantly closer to the shoreline on lakes Dąbie and Jamno and significantly further from the shoreline on Lake Gardno, implying that the ice had advanced further up the shore.

4.3 Ice scar elevations on tree trunks

The elevation of the scars on the trees near each lake varied (Figures 5, 7A), which is due to the height of ice pile-up on the shore and the direction in which it advanced. Scars at the highest elevations were found on the northern and north-eastern shores of the lakes. Their maximum elevation above the ground surface (a.g.l.) ranged from 0 to 270 cm, and above the water level (a.w.l.), from 0 to 380 cm. The highest elevation (380 cm a.w.l.) of tree ice scarring was observed on the north-eastern shore of Lake Łebsko (Figures 7A, 8D). The scar was 3.6 m from the waterline, and was found on a tree growing 45 cm a.w.l. It was formed by ice advancing with a southwesterly wind.

The average elevation of the ice scars was 114 cm a.g.l. and 158 cm a.w.l. On both Lake Łebsko and Lake Gardno, ice scars occurred on the north-eastern shores of the lake and were formed during strong SSW-SW winds. A significant proportion of ice scars was identified at water or ground level (67% in the case of Lake Dąbie and up to 80% in the case of Lake Jamno). In some cases, scars were observed on neighboring, or even the same, trees at different elevations (Figure 8D,F). Scars identified at the highest elevations were found to have an azimuth between 195° and 240°; therefore, they must have been exposed to SSW-WSW winds. Figure 7A shows the relationship between the azimuth of tree ice scars and their elevation at the lakes included in the study.

Table 3. Student's t-test parameters for mean maximum heights of tree ice scars on individual coastal lakes (H) versus mean heights of tree ice scars for all lakes (total – T).

Studied lake	Average, H [cm]	Average, T [cm]	t	p
Dąbie and T	57.50	84.97	−2.46	0.01
Jamno and T	51.93	84.97	−2.12	0.04
Bukowo and T	53.71	84.97	−0.98	0.33
Gardno and T	15.64	84.97	−3.07	0.00
Łebsko and T	157.73	84.101	4.84	0.00

t – test value; p – significance level.
Statistically significant differences are underlined.

Analysis of the similarity of the probability distribution of the occurrence of a specific maximum elevation of tree ice scars to a normal distribution showed, as in the case of the distance from the shore, that only in the case of lakes Bukowo and Gardno were there no grounds to reject the hypothesis regarding this similarity. For the remaining lakes, the significance level of the test was much lower than 0.05, and the test value ranged from 0.84 for Jamno to 0.95 for Dąbie. Thus, it can be tentatively concluded that the maximum elevation of ice scars only features a near-normal distribution on the shores of Bukowo and Gardno. For this reason, positional statistics were used to establish the maximum elevations of the scars. The median elevation for all ice scars was 62 cm, and the mean was 84.97 cm. Scars with the highest elevations were found on lakes Łebsko and Gardno (medians of 138 and 132.5 cm, respectively), while the lowest elevations were measured on Lake Jamno (median of 41.5 cm; Figure 7B). t-tests showed that on lakes Gardno, Jamno and Dąbie the scars were significantly lower than average, while they were significantly higher on Lake Łebsko (Table 3). Ice pile-ups causing tree damage were so high that they largely influenced the mean value of the maximum elevation of scars around all the lakes surveyed.

4.4 Length and width of tree ice scars

Most of the examined scars were also measured in terms of their length and width, which varied on the surveyed lake shores (Figure 8). The longest ice scars were recorded on Lake Dąbie, where in most cases they occurred at water or ground level (Figure 8B). The longest scar measured 180 cm, the shortest 17 cm, and the mean was 64 cm. The longest scar was observed in the southeastern part of Lake Dąbie. It had been formed during an ice advance from the NW or NNW. Long scars, up to 165 cm, were also observed on Lake Łebsko (Figure 8D). Shorter scars occurred on lakes Jamno and Gardno, with maximum lengths of 125 and 110 cm, and mean lengths of 37 and 60 cm, respectively. Some were very short but located close to one another (Figure 8C). The longest scars were measured on the northeastern shores of the lakes and had been formed during ice advance from the south. The shortest tree ice scars occurred on Lake Bukowo, ranging in length from 6–25 cm, with a mean of 16 cm. The longest ice scar (25 cm) was formed on the northeastern shore during ice advance from the SSW (azimuth 200°), while the others had been formed during ice advance from the SW (azimuths 170–260°).

On lakes Łebsko and Dąbie, the maximum width of tree ice scars were also partially measured for 27 and 20 cases, respectively, and proved to be similar: 55 and 65 cm, respectively. On Lake Łebsko, a scar (55 cm) was found on an alder tree with a trunk circumference of 75 cm, growing on the north-eastern shore of the lake, while in the case of Lake Dąbie, one was found on a willow tree on the eastern shore of the lake (Figure 8E). These scars had been exposed to SW and WNW winds, respectively, with azimuths of 225° and 300°. The average widths of these scars were 28 and 14 cm, respectively, while the minimum widths were 6

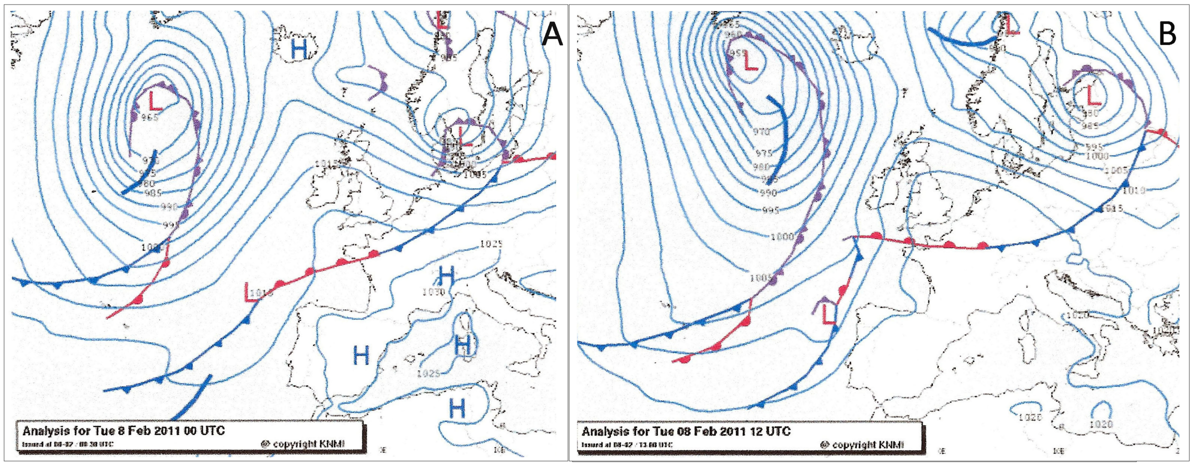

Figure 9. Synoptic chart analysis for the 8.02.2011, 00 UTC (A) and 12 UTC (B).

Figure 10. Damaged and broken trees as a result of ice thrusting on the northeastern shore (A – 8.02.2011, photo by D. Staniaszak) and on the eastern shore (B – 25.01.2002) of Lake Łebsko.

and 3 cm. The narrowest scars were generally old and overgrown.

4.5 Meteorological and hydrological conditions conducive to the formation of tree ice scars

On coastal lakes, as on other bodies of water, ice thrusting and piling damage trees. These ice phenomena are caused by high velocity winds, generated in intense and active low-pressure areas. Such lows are not only accompanied by strong winds but also usually associated with warm air (Ta > 0°C) and rising water levels (Leckebusch and Ulbrich, 2004; Sepp et al., 2005; Wiśniewski and Wolski, 2011). These factors weaken the ice cover and, during strong winds, the surface tangential tension force causes ice run, resulting in ice thrusting and piling on the shore.

One example of circumstances causing ice thrusting and piling on the shoreline, resulting in tree damage, is the anemobaric situation that occurred on 8 February 2011 (Figure 9). On that day, the southern coast of the Baltic Sea was affected by a deepening low pressure system moving rapidly (75 km h^{-1}) latitudinally from west to east across the Central Baltic Sea. At 00 UTC, the centre of this low, with a pressure below 985 hPa, was over southwestern Sweden and by 12 UTC it had moved over northern Estonia, where the pressure dropped further to 976 hPa. A pressure gradient of 7–8 hPa over the southern Baltic coast was recorded at that time. Large differences in atmospheric pressure generated westerly storm winds of 20 m s^{-1}. As the cold front passed, strong gusts of wind (25 m s^{-1}) were formed and the water level rose, which caused ice thrusting and piling, not only on the coastal lakes, but also on the coastal lagoons of the southern Baltic Sea. There was an influx of warm 5°C air of a north-westerly cyclonic (NWc) atmospheric circulation type. As a result of ice thrusting and piling on the north-eastern shore of Lake Łebsko, many trees were damaged (Figure 10A). Ice scars on these trees were formed at various elevations, from the base of the trunk up to 3.8 m a.w.l.

Similar hydrological and meteorological conditions, leading to ice thrusting and piling and, consequently, damage to trees, occurred in January 2002. In the second half of January, an active low-pressure system moved eastwards with a central pressure mostly below 990 hPa. It was accompanied by strong winds from westerly directions, which caused ice run on Lake Łebsko and then thrust onto the land. On the eastern shore of Lake Łebsko, ice piling occurred among trees to a height of about 2 m a.w.l. As a result of the pressure of pushing ice, some trees approximately 10–15 metres from the shore were damaged (Figure 10B). During the period of ice thrusting, the water levels on the lake were higher than average due to the effect of the onshore wind. There was an influx of warm air above 0°C (maximum 9°C) of a northwesterly cyclonic (NWc) atmospheric circulation type. Ice damage to trees in this section was also observed in 2005 (Figures 3C, 4E). In addition, in 2002, small piles of ice were observed on the shallow water of the northern shore of Lake Jamno, which could also have scarred the shore of the lake due to erosion (Figure 4B). In turn, in March 2005, an ice pile-up 1.5–2.5 m high was observed on the northern and eastern shores of lakes Łebsko and Gardno (Figure 3B–D).

5. Discussion

Tree ice damage may occur on the shores of various bodies of water and rivers in temperate and subarctic climate zones. Such damage on trees has been observed on rivers (Lederer and Garver, 2000; Lind et al., 2014; Vandermause et al., 2021), bays (Alestalo and Häikiö, 1976; Orviku et al., 2011), lagoons (Banzhaf, 1931; Kozlov et al., 2020), reservoirs (Gatto, 1984) and lakes (Barnes et al., 1994; Duguay et al., 2006; Lemay and Bégin, 2012). The height of ice pile-ups and the extent of inland ice thrusting along the shores of Canada and Alaska are generally determined based on tree damage (Uunila and Church, 2014; Vandermause et al., 2021). Tree damage along the Peace River in

Canada (Uunila and Church, 2014) reached heights of up to 2 m, while on the Susitna River in Alaska (Vandermause et al., 2021), damage was observed up to 1.8 m above the maximum water level. In the sheltered waters of the southern Baltic Sea in particular, high ice pile-up heights and inland thrust distances were recorded on the Szczecin Lagoon (Girjatowicz et al., 2024). On the Rów Peninsula, ice scars reached 4.3 m above sea level, and ice thrusts inland extended up to 64 m (Girjatowicz et al., 2024).

Pyökäri (2011) conducted research on the damage to vegetation and trees by ice on Labrador Peninsula lakes, noting that the greatest damage occurs mainly on the shores of large lakes, compared with smaller lakes, where there is little damage. This damage occurs in the spring when the ice is pushed onto the shore by the wind. The pushing ice moves not only shoreline material and large stones but also uproots trees and moves them far inland. The erosive effect, the damage to vegetation or trees, is mainly due to the thrusting of the ice onto the shore, caused, in the case of rivers, by the water current (cf. Beltaos et al., 2006; Lind et al., 2014; Vandermause et al., 2021), while in the case of lakes, by wind acting on the ice surface (tangential stresses; Orviku et al., 2011; Leppäranta, 2013). The larger the surface area of the lake, and thus the ice field, and the stronger the wind, the thicker the ice that can be thrusted and piled-up on the shores. In turn, the thicker the ice, the higher the pile-ups that can form (Kraus, 1930; Alestalo and Häikiö, 1976). On the Mohawk River, ice scars were observed to reach a maximum elevation of 5 m a.w.l. (Lederer and Garver, 1996) – likewise on the Vistula Lagoon (Girjatowicz, 2015), reflecting maximum ice pile-up heights. In recent years, 6–8 m high ice pile-ups have been observed on the eastern shore of Lake Peipus in Estonia in 2022 (Saart, 2022).

On the examined coastal lakes, with smaller ice-field areas, ice pile-ups were much lower, as evidenced by the height of tree ice scars. On the largest of these lakes (Łebsko, Dąbie and Gardno), ice scars were observed up to 3.8 m a.w.l. while on the other, smaller lakes (Bukowo and Jamno), such scars were lower (0.6–1.2 m a.w.l.). These observations are in line with the conclusions presented by Pyökäri (2011) for the Labrador Peninsula lakes. The size of the lake area and the area of the ice field are correlated with the distance of the ice thrusting onshore. On larger bodies of water, such as in the Gulf of Parnava (part of the Gulf of Riga), ice sheets have been observed to advance up to the distances of 312 m (Kraus, 1930), while for the Szczecin and Vistula lagoons, they proceeded 120 and 140 m from the shore, respectively (Girjatowicz, 2014). On the coastal lakes in question, due to their much smaller areas, the maximum distances of ice advance onshore were noticeably shorter. On lakes Łebsko and Gardno, the longest distances were 30 and 38 m, respectively, and on the other lakes (Bukowo, Dąbie and Jamno) they occurred from 5 to 20 m from the shore. In general, the larger the water body, the higher and further from the shore the ice scars are found, due to a longer wind fetch. However, on Lake Gardno, scars were observed further inland than on the larger Lake Dąbie because of its orientation (north–south), which limits the fetch for the dominant westerly winds. Wind speeds are also reduced due to this lake's location further from the seashore compared to the other studied lakes.

Lemay and Bégin (2012) conducted research on tree ice scars and on the impact of ice on the shores of Lake Corvette (Canada), emphasising the role of environmental factors such as wave fetch, wind direction and velocity, and shore slope. In the study presented in this paper, the formation of tree ice scars was found to be influenced by other local factors in addition to those mentioned above, such as the width of the reed belts, the presence of trees and bushes, and human activity (shoreline fortifications or dykes), which slow down ice advance, limiting the possibility of tree ice scars forming.

The distance of ice thrusting and the height of ice pile-ups damaging trees are influenced by hydrological factors, including water level, ice type and strength. According to Gatto (1984), on Lakes Michigan and Franklin Falls Reservoir, shore erosion and ice damage to vegetation and trees is largely determined by water level. At high water levels, the destructive impact of ice on the shore can be significant. On Canadian lakes, ice thrusts onto the shore have most often been observed during spring floods (Lemay and Bégin, 2012). Similar observations, related to the impact of water levels, also apply to bodies of water in the Baltic Sea. High water levels facilitate the thrusting of ice onto the shore (cf. Alestalo and Häikiö, 1976; Orviku et al., 2011). Hence, at high water levels, tree damage can occur even far inland from the shore. In contrast, with low and medium water levels, the incoming ice tends to pile-up on the shore, where tree damage is most likely to occur.

Rising water levels have a significant impact on the distance of ice advance in the coastal lagoons of the southern Baltic Sea. High water levels and raised ice fields reduce the friction of the sliding ice and allow it to advance far inland. On the low shores of the lakes and coastal lagoons of the southern Baltic Sea, which are frequently flooded, ice fields can advance onshore without much hindrance and not only damage trees but also other objects that are located there.

Global warming has significantly reduced the number of ice cover days on lakes located along the southern coast of the Baltic Sea (Girjatowicz et al., 2022). The maximum ice thickness during the ice season has also decreased. In the decade 1960/61–1969/70, the average maximum ice thickness on lakes Jamno, Bukowo, Gardno, and Łebsko was 27, 27, 28, and 29 cm respectively, whereas in the decade 2010/11–2019/20 this dropped to a mere 18, 16, 14, and 15 cm respectively. The downward trends in maximum ice thickness have also been confirmed by time series analyses. Trend line slopes for the period 1960/61–2019/20 are negative and statistically significant at $p < 0.01$. On the largest lake, Łebsko, the maximum seasonal ice thickness declined on average by 0.23 cm per year over this period (Girjatowicz et al., 2022).

As a result of the shorter ice cover duration, the sailing and fishing seasons begin earlier and end later. Climate change does not mean a complete absence of ice cover, as relatively short periods of severe frost still occur. Warming also leads to mid-winter thaws, and more frequent storms increase the destructive impact of breaking ice cover. Lake shores continue to be exposed to erosion, require protection and are excluded from certain types of development, such as tourism and recreational infrastructure.

Signs of the progressing global warming can be seen in phenomena such as increasing frequency and velocity of westerly, or particularly southwesterly, winds, as well as shorter and more frequent periods of alternating cooling ($Ta < 0°C$) and warming ($Ta > 0°C$) and associated ice-free periods. Ice cover that repeatedly forms and disintegrates 2–3 times within a single winter season is conducive to the formation of piles on shores and will pose a threat to any recreational and port infrastructure located there.

6. Summary and conclusions

Based on the conducted field survey and analysis of the results of measurements of tree ice scars located on the shores of coastal lakes in the southern Baltic Sea, the following conclusions can be drawn.

1. Ice scars on trees provide some insight into the dynamics of ice phenomena, especially regarding the distance of ice advance from the waterline and the height of ice pile-ups. The observed regularities can be applied to other lakes located in the temperate climate zone, where western and southwestern winds prevail.
2. The distance of the ice advance onshore depends mainly on the type, thickness and strength of the ice, the shape (mainly slope) of the shore, the presence of trees and width of the reed belt, as well as the water level, the wave fetch, wind direction and velocity, and anthropogenic factors such as shoreline fortifications or dykes.
3. It is not possible to deduce the height of the water level on the lakes during ice thrusting and piling solely based on the elevation of the ice scars on the trees. It can, however, be said that higher water levels facilitate onshore ice thrusts.
4. The height of the ice pile-up, as identified by the height of the scars, is indicative of the dynamics of the ice phenomena and the threat it poses to nature and anthropogenic infrastructure.
5. The distances from the shore and the maximum elevations of tree ice scars present great variation. Tree ice scars formed by thrusting ice are most often found on bare shores, either completely devoid of, or with just a narrow strip of, reed belts.
6. The density of tree ice scars on individual lake shores mainly correlates with the direction and frequency of strong winds and their fetch during the winter-spring period. Shores exposed to the most frequent wind directions, where the highest wind velocities are recorded, have the highest incidence of ice scars.
7. On the coastal lakes surveyed, the greatest number of ice scars was found on the eastern and northern shores, especially in the north-eastern region, which is related not only to the prevailing wind direction from the SW, but also to the warming that occurs with air circulation from this direction during the winter-spring period.
8. A wide reed belt makes it difficult for the ice to push onshore, stopping its advance and causing it to pile-up there. Hence, on shores with a wide reed belt, there are no tree ice scars.
9. On steep lake shores, tree ice scars are mostly found along the shoreline, where ice usually piles-up to the highest elevations.
10. On low-lying and flat shores, ice advances further onto the land. In such cases, tree damage can be found even far from the shoreline, and ice scars are mostly at ground level, at the base of the tree trunk.
11. Ice thrusting mainly involves large ice sheets. The thicker the ice, the higher the ice piles that are formed, which can damage tree trunks at higher elevations.
12. The larger the lake, the greater the likelihood of ice thrusting onto the shore. On lakes with larger ice fields and longer wind fetch, ice thrusting and piling occurs more often than on smaller lakes.
13. Dykes, shoreline fortifications and steep shores prevent the advance of ice sheets and cause them to break and pile-up at their base.
14. Based on ice scar measurements, conclusions can be drawn on the dynamics of ice phenomena in areas where no systematic ice observations have been carried out. In addition, the results of the research can be used in design work for the protection of the shores of coastal lakes and in other similar bodies of water.
15. Given the vulnerability of water body shores in temperate and polar zones to ice thrust-related damage, it is necessary to avoid non-essential development, particularly in low-lying and high-risk areas.

In places with critical infrastructure like hydrological, port, or navigation facilities, the shoreline should be protected against damage using riprap, earthen embankments, breakwaters or vegetative buffers along the shore.

Acknowledgements

The authors would like to thank the anonymous reviewers for their help in improving the quality of the manuscript.

Professor Józef Girjatowicz praises God for the care and protection he experienced during 54 years of his oceanographic studies on the southern Baltic coast.

Co-financed by the Polish Minister of Science under the “Regional Excellence Initiative” Program for 2024–2027 (RID/SP/0045/2024/01).

Conflict of interest

None declared.

References

Alestalo, J., Häikiö, J., 1976. *Forms created by the thermal movement of lake ice in Finland in winter 1972–1973*. Fenia 157 (2), 51–92.

Banzhaf, W., 1931. *Ice pileups on the Szczecin Lagoon*. Nature und Museum 61 (12), 491–494 (in German).

Baranowski, D., Chlost, I., 2009. *Hydro-meteorological conditions in the catchment of the Łebsko Lake*. Baltic Coastal Zone 13, 109–119.

Barnes, P.W., Kempema., E.W., Reimnitz, E., McCormick M., 1994. *The influence of ice on southern Lake Michigan coastal erosion*. J. Great Lakes Res. 20 (1), 179–195. https://doi.org/10.1016/S0380-1330(94)71139-4

Bégin, Y., Payette, S., 1991. *Population structure of lakeshores willows and ice-push events in subarctic Québec, Canada*. Holarctic Ecol. 14, 9–17.

Beltaos, S., Prowse, T.D., Carter, T., 2006. *Ice regime of the lower Peace River and ice-jam flooding of the Peace-Athabasca Delta*. Hydrol. Process. 20 (19), 4009–4029. https://doi.org/10.1002/hyp.6417

Correns, M., 1973. *Eisverhältnisse des Peenestrom – Haffgebietes – ein Beitrag zur Hydrogrphie der Gewässer an der Sűdlichen Ostseekűstr*. Petermanus Geographischen Mitteilungen 174, 4 (in German).

Cieśliński, R., 2011. *Geographical conditions of hydrochemical variability of lakes on the southern Baltic coast*. Gdańsk Univ. Publ., Gdańsk (in Polish).

Cieśliński, R., Drwal, J., Chlost, I., 2009. *Sea water intrusions to the lake Gardno*. Baltic Coastal Zone 13, 85–95.

Choiński, A., 1995. *Outline of physical limnology of Poland*. Wyd. Nauk. Uniw. Adama Mickiewicza (in Polish).

Choiński, A., Ptak, M., Skowron, R., Strzelczak, A., 2015. *Changes in ice phenology on Polish lakes from 1961 to 2010 related to location and morphometry*. Limnologica 53, 42–49. https://doi.org/10.1016/j.limno.2015.05.005

Christensen, F.T., 1994. *Ice ridge-up and pile-up on shores and coastal structures*. J. Coast Res. 10 (3), 681–701.

Cyberski, J., Grześ, M., Gutry-Korycka, M., Nachlik, E., Kundzewicz, Z.W., 2006. *History of floods on the River Vistula*. Hydrolog. Sci. J. 51 (5), 799–817. https://doi.org/10.1623/hysj.51.5.799

Dione, J.C., 1979. *Ice action in the lacustrine environment – A review with particular reference to subarctic Quebec, Canada*. Earth Sci. Rev. 15 (3), 185–212.

Duguay, C.R., Prowse, T.D., Bonsal, B.R., Lacroix, M.P., Ménard, P., 2006. *Recent trends in Canadian lakes ice cover*. Hydrolog. Process. 20, 781–801. https://doi.org/10.1002/hyp.6131

Engström, J., Jansson, R., Nilsson, C., Weber, C., 2011. *Effects of river ice on riparian vegetation*. Freshwater Biol. 56, 1095–1195. https://doi.org/10.1111/j.1365-2427.2010.02553.

Gatto, L.W., 1984. *Reservoir Bank erosion caused by ice*. Cold Reg. Sci. Techn. 9, 203–214.

Girjatowicz, J.P., 2011. *Effects of the North Atlantic Oscillation on water temperature in southern Baltic coastal lakes*. Annales Limnol. – Int. J. Lim. 47, 73–84. https://doi.org/1051/Limn/2010031

Girjatowicz, J.P., 2014. *Ice thrusting and hummocking on the shores of the Southern Baltic Sea’s coastal lagoons*. J. Coast. Res. 30 (3), 456–464. https://doi.org/10.2112/JCOASTRES-D-12-00032.1

Girjatowicz, J.P., 2015. *Forms of onshore ice thrusting in coastal lagoons of the Southern Baltic Sea*. J. Cold Reg. Eng. 29 (1), 1–17. https://doi.org/10.1061/(ASCE)CR.1943-5495.0000069

Girjatowicz, J.P., Łabuz, T. A., 2020. *Forms of piled ice at the southern coast of the Baltic Sea*. Est. Coast. Shelf Sci. 239. https://doi.org/10.1016/j.ecss.2020.106746

Girjatowicz, J.P., Świątek, M., Kowalewska-Kalkowska, H., 2022. *Relationships between air temperature and conditions on the southern Baltic coastal lakes in the context of climate change*. J. Limn. 81, 2060. https://doi.org/10.4081/jlimnol.2022.2060

Girjatowicz, J.P., Świątek, M., Łabuz, T.A., 2024. *The range of sliding and piling ice on the basis of ice scars on trees in coast of the coastal lagoons on the example of the Szczecin Lagoon*. Quaest. Geogr. 43 (1), 93–110. https://doi.org/10.14746/quageo-2024-0006

Haapala, J., Ronkainen, I., Schmelzer, N., Sztobryn, M., 2015. *Recent change – sea ice*. [In:] The BACC II Author Team (Eds.), *Second assessment of climate change for the Baltic Sea basin*, International Baltic Sea Secretariat, Springer, Geesthacht, 145–153.

Jańczak, J., 1997. *Atlas of Polish Lakes*. Wyd. Inst. Meteorol. Gosp. Wod., Poznań (in Polish).

Jevrejeva, S., Drabkin, V.V., Kostjukov, J., Lebedev, A.A., Leppäranta, M., Mironov, Y.U., Schmelzer, N., Sztobryn, M., 2004. *Baltic Sea season in the twentieth century*. Climate Res. 25 (23), 217–227. https://doi.org/10.3354/cr025217

Kaptein, M., van den Heuvel, E., 2022. *Statistics for data scientists: an introduction to probability, statistics and data analysis*. Springer, Berlin, Heidelberg, New York.

Kozlov, I.E., Krek, E.V., Kostianoy, A.G., Dailidienė, I., 2020. *Remote sensing of ice conditions in the southeastern Baltic Sea and in the Curonian Lagoon and validation of SAR-based ice thickness products*. Remote Sens. 12 (20), 3754, 20 pp. https://doi.org/10.3390/rs12223754

Kraus, E., 1930. *Over ice pileups*. III Hydrological Conference of the Baltic Countries, Warsaw, Poland, 1–44 (in German).

Leckebusch, G.C., Ulbrich, W., 2004. *On the relationship between cyclones and extreme windstorm events over Europe under climate change*. Global Planet. Change 44, 181–193. https://doi.org/10.1016/j.gloplacha.2004.06.011

Lederer, J.R., Garver, J.I., 1996. *Ice jams inferred from tree scars made during the 1996 mid-winter flood on the Mohawk River*. Geology Department Union College, New York, USA.

Lederer, J.R., Garver, J.I., 2000. *Ice jams on the lower Mohawk River (Crescent, NY) formed during the 2000 mind-winter flood*. Geology Department Union College, New York, USA.

Lemay, M., Bégin, Y., 2012. *Using ice-scars as indicators of exposure to physical lakeshore disturbances, Corvette Lake, northern Quebec, Canada*. Earth Surface Processes and Landforms 37 (13), 1353–1361. https://doi.org/10.1002/esp.3244

Leppäranta, M., 2010. *Modelling of formation and decay of lake ice*. [In:] George, G., (Ed.), *The impact of climate change on European lakes*, Springer, 63–83. https://doi.org/10.1007/978-90-481-2945-4_5

Leppäranta, M., 2013. *Land-ice interaction in the Baltic Sea*. Estonian J. Earth Sci. 62 (1), 2–14. https://doi.org/10.3176/earth.2013.01

Leppäranta, M., Myrberg, K., 2009. *Physical Oceanography of the Baltic Sea*. Springer. https://doi.org/10.1007/978-3-540-79703-6

Lind, L.C., Nilsson, C., Povli, L.E., Weber, C., 2014. *The role of ice dynamics in shaping vegetation in flowing waters*. Biolog. Rev. 89, 791–804. https://doi.org/10.1111/brv.12077

Livingstone, D.M., Adrian, R., Blenckner, T., George. G., Weyhenmeyer, G.A., 2009. *Lake ice phenology*. [In:] George, G. (Ed.), *The impact of climate change on European lakes*. Aquat. Ecol. Ser. Vol. 4, Springer, Dordrecht, 51–61. https://doi.org/10.1007/978-90-481-2945-4_4

Łabuz, T.A., 2019. *Storm surges in the 21st century (2000–2019) and their impact on the erosion of the dune coast in Poland, 28–29*. [In:] *Abstracts of 2nd Scientific Conference of Polish Sea Researchers: State and trends in seas and oceans*, Gdynia (Poland) 24-25.09.2019.

Orviku, K., Jaagus, J., Tõnisson, H., 2011. *Sea ice shaping the shores*. J. Coast. Res. 64 (Sp. Iss.), 681–685. https://www.jstor.org/stable/26482258

Pawłowski, B., 2019. *Ice jams: causes and effects*. [In:] Maurice, P.A. (Ed.), *Encyclopedia of water: science, technology and society*. John Willey & Sons Inc. https://doi.org/10.1002/9781119300762

Pyökäri, M., 2011. *Ice action on lake shores near Schefferville, central Quebec – Labrador, Canada*. Can. J Earth Sci. 18 (10), 1629–1634. https://doi.org/10.1139/e81-149

Reinhard, H., 1955. *Eispressungen an der Kũste*. Weissenschaftliche Zeitschrift der Ernst Moritz Arndt Universität Greifswald, Jahr. 4, 6/7 (in German).

Saart, P., 2022. *Peipus Lake*. https://www.youtube.com/watch?v=SYIrxoY08zs

Schönwiese, Ch., Rapp, J., 1997. *Climate trend atlas of Europe based on observations 1891–1990*. Kluwer Acad. Publ.

Sepp, M., Post, P., Jaagus, J., 2005. *Long-term changes in the frequency of cyclones and their trajectories in Central and Northern Europe*. Nordic Hydrol. 36, 297–309. https://doi.org/10.2166/nh.2005.0023

Skowron, R., 2009. *Changeability of the ice cover on the lakes of northern Poland in the light of climatic changes*. Bull. Geogr. Phys., Geogr. Ser. 1 (1), 103–124. https://doi.org/10.2478/bgeo-2009-0007

Smith, D.G., Reynolds, D.M., 1983. *Trees scars to determine the frequency and stage of high magnitude river ice drives and jams, Red Deer, Alberta*. Can. Water Res. J. 8 (3), 77–94.

Sui, J., Karney, B.W., Fang, D., 2005. *Variation in water level under ice-jammed conditions – field investigation and experimental study*. Nordic Hydrol. 36, 65–84.

Sztobryn, M., Wójcik, R., Miętus, M., 2012. *Ice cover in the Baltic Sea – current status and expected changes in the future*. [In:] *Climatic and oceanographic conditions in Poland and the Southern Baltic Sea. Expected changes and guidelines for the development of adaptation strategies in the national economy*, Monograph Ser., IMGW-PIB Publ., 189–215.

Tarnowska, K., 2011. *Strong winds on the Polish coast of the Baltic Sea*, Prac. Stud. Geogr. WGiSR UW 47, 197–204 (in Polish).

Tomczyk, A., Bednorz, E., (Ed.), 2022. *Climate atlas of Poland (1991–2020)*. Bogucki Sci. Publ. (in Polish).

Uunila, R., Church, M., 2014. *Ice on Peace River: Effects on Bank Morphology and Riparian Vegetation*. [In:]

Church, M. (Ed.), *The regulation of Peace River: a case study for river management*. Willey & Sons Inc., 391–420. https://doi.org/10.1002/9781118906170.ch6

Vandermause, R., Harvey, M., Zevenbergen, L., Ettema, R., 2021. *River-ice effects on bank erosion along the middle segment of the Susitna River, Alaska*. Cold. Reg. Sci. Techn. 185, 103239. https://doi.org/10.1016/j.coldregions.2021.103239

Wibig, J., 2021. *Change of wind*. [In:] Falarz, M., (Ed.), *Climate change in Poland. Past, present, future*. Springer, 391–420. https://doi.org/10.1007/978-3-030-70328-8

Wiśniewski, B., Wolski, T., 2011. *Physical aspects of extreme storm surges and falls on the Polish coast*. Oceanologia 53 (1 TI), 373–390. https://doi.org/10.5697/oc.53-1-TI.373.

Wrzesiński, D., Choiński, A., Ptak, M., Skowron, R., 2015. *Effect of the North Atlantic Oscillation on the pattern of lake ice Phenology in Poland*. Acta Geophys. 63, 1664–1684. https://doi.org/10.1515/acgeo-2015-0055