THE RANGE OF ICE THRUSTS AND ICE PILES AS REFLECTED BY ICE SCARS ON TREES GROWING ON THE SHORES OF COASTAL LAGOONS: THE CASE OF THE SZCZECIN LAGOON

Józef Piotr Girjatowicz, Małgorzata Świątek, Tomasz Arkadiusz Łabuz

Institute of Marine and Environmental Sciences, University of Szczecin, Szczecin, Poland

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Abstract: We studied the phenomena associated with the thrusting of ice onto the shore of the Szczecin Lagoon based on the occurrence of tree ice scars. The measurements concerned mostly the maximum height, length and width of ice scars on trees, and the distance of these trees from the shore in the period 2017–2022. It was observed that sheets of ice advanced up to 64 m inland, and piled to form hummocks reaching up to 4.3 m above the water level. These maximum values occurred mostly on eastern shores, which is where the highest numbers of damaged and broken trees were observed. This should be associated with the strongest and most frequently occurring wind blowing from the western direction in the winter-spring period. To the contrary, the lowest number of damaged trees were observed on the western shore. This is due not only to the lower frequency of wind blowing from the east, and the associated cooling (Ta < 0°C) and ice cover stabilization, but also due to the presence of extensive reed belts. Our results enable an indirect insight into the ice phenomena dynamics, especially in areas lacking systematic ice observations. Similar conclusions may be extended for all the sheltered basins as lakes or lagoons.

Keywords: ice thrusting, damaged trees, coast erosion, Szczecin Lagoon, Baltic coast

Corresponding author: Tomasz Arkadiusz Łabuz, tomasz.labuz@usz.edu.pl

Introduction

The dynamics of ice phenomena in the coastal zone, especially ice thrusting and ice piling, may be reflected by ice scars on trees. These represent damage to the lower parts of the trunks of trees growing along the shore. Such damage usually arises following the disintegration of fast ice and the resultant ice drift.

To date, tree ice scar-based studies on the dynamics of ice phenomena were performed mainly on rivers (cf. Smith, Reynolds 1983, Lederer, Garver 1996, 2000, Engström et al. 2011, Uunila, Church 2014, Pawłowski 2019). Tree ice scars are observed the most frequently along river banks, due to the permanent occurrence of a current in the river and the presence of trees growing near the waterline (Cyberski et al. 2006). On marine shores, especially along the southern Baltic coast, there are a wide number of beaches which act against ice (ice floe, sheet ice), advancing far inland. Further, a grease ice ridge forms earlier along a marine shoreline, which also acts as an obstacle to ice floe advancement (Girjatowicz, Łabuz 2020). The effects of tree damage by floe thrusting on rivers become the clearest during an ice jam. Pressured floe blocks the discharge of water, causing a considerable water level rise in the river (Beltaos et al. 2006, Lind et al. 2014, Vandermause et al. 2021). At the peak of the high water event, floe advances up the bank and may damage tree trunks. The damaged (abraded) tree trunks may reach several meters above the average water level in the river. This is evidenced by ice scars on trees growing along rivers in North America (Smith, Reynolds 1983, Lederer, Garver

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1996, 2000), Canada (Uunila, Church 2014) and Alaska (Vandermause et al. 2021), and in Europe, for instance along the lower reaches of the Wisła River (Grześ 2005, Pawłowski 2005, 2019). For instance, 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, Garver 1996). It was observed that the water level during the surge was matched by the ordinate of the maximum elevation of an ice scar on a tree trunk.

Similar damage to trees, induced by ice being thrusted on land, was observed also along the shores of coastal lagoons, straits and marine gulfs, retention reservoirs or on large lakes. Ice scars on trees are observed less frequently on these basins, however, than along rivers. In the case of lagoons, a strong wind is necessary to cause ice floe thrusting onto land. Studies on how the scale of ice floe advances onto lake shores based on tree ice scars were performed mostly in North America, Canada and the USA, where such phenomena are common due to the high number of very large lakes (Gilbert, Glew 1986, Futter 2003, Duguay et al. 2006). Sheets of ice being pressured and thrusted inland had caused large damage in the forests around the Pärnu Bay (Estonia; Orviku et al. 2011). Considerable damage had also been caused along the shores of the Luodonselkä (Finland), where grey alder trees were strongly damaged, and young Scots pines were totally destroyed (Alestalo, Häikiö 1976). Frequent cases of trees that were damaged or ploughed out together with the ground by advancing sheets of ice were also recorded in the Szczecin Lagoon area (Banzhaf 1931, Girjatowicz 2004). Similar tree damage and destruction were also observed along the shores of the Curonian Lagoon (Lundbeck 1931) and the Vistula Lagoon (Girjatowicz 2015). On the shores of the Vistula Lagoon, ice scars occurred on tree trunks not only at the ground level but also at an elevation of up to 5.5 m above the water level. Trees damaged by sheet ice thrusting were also observed around large coastal lakes of the southern Baltic region, including Łebsko and Dąbie lakes (Girjatowicz 2017), or on the shores of retention reservoirs (Jaguś, Rzętała 2000).

The elevation of the identified ice scars above the ground may be a measure of river ice jam and an ice-thrusting threat onto the bank (Beltaos et al. 2006, Pawłowski 2011, Lind et al. 2014). Ice thrusting on land causes bank erosion, damages the substratum and vegetation (including trees) and poses a threat to the infrastructure such as ports, beacons, buildings and roads and may contribute to flooding along river banks (Beltaos et al. 2006, Orviku et al. 2011, Kolerski et al. 2019).

To date, no precise information was available on ice scars on trees growing along the shores of the southern Baltic coastal lagoons, which could be used to determine the scale of the threat. The first partial study of tree ice scars was performed on the Polish part of the Szczecin Lagoon (Girjatowicz 2017). Examining the hydrological conditions of the Szczecin Lagoon is especially important as this particular basin plays an important part in transport, fishing and tourism. Numerous small ports are situated along the shores of the Szczecin Lagoon. Due to its attractive location, there is an increasing number of private investments, including houses, marinas and recreational infrastructure. All these facilities are situated on a ground that is barely raised above water, at the shore or in its immediate surroundings. The construction works are performed – not entirely reasonably – down to the shoreline, and therefore, estimating the threat degree is highly relevant, as it may enable the proprietors to avoid increased spending on protective measures in the future.

The aim of the present work is to establish which part of the coast is the most prone to the destructive impact of the ice, based on the distribution of ice scars on trees growing along Szczecin Lagoon shores. Based on the spatial analysis of the occurrence of ice-scarred trees, it was determined which shores are the most threatened by the destructive impact of sheet ice thrusting. It also obtained information on how far inland ice thrusting may reach and pose a threat. Further, the density of occurrence, distance from shore and the elevation of ice scars on tree trunks provided information on the intensity of ice impact in those regions where ice thrusting and onshore piling is the most frequent.

Study area

The present study covered the entire shore of the Szczecin Lagoon, named as Oder Lagoon (Fig. 1) in Germany, which comprised the Great Szczecin Lagoon, located entirely within Polish borders, and the Small Szczecin Lagoon, located on the German part of the border (Fig. 1B). The Szczecin Lagoon is a shallow basin (average depth: 3.8 m) connected with the Pomeranian Bay of the Baltic Sea via three narrow and very shallow straits (Figs 1A and 1B). It occupies an area of 687 km^2, with a volume of 2.5 km^3, and its shoreline is 243 km long (Majewski 1980). Due to its very shallow depth combined with a relatively large area, the Szczecin Lagoon is characterised by a high lake exposure index value, defined as a ratio of the basin area to its average depth, equal to 191 km^2 m^{-1} (Girjatowicz, Świątek 2021). This results in a rapid rate of water cooling (in reaction to air temperature change) and the formation of ice phenomena. The greatest natural depth of the Lagoon is only 8.5 m, and the fairway crossing the Lagoon is 12.5 m deep.

The average annual influx of fluvial waters equals 18 km^3 (Radziejewska, Schernewski 2008). Marine water influx is not known due to the bidirectional exchange of waters with the sea (depending on the wind direction, water flows from the Szczecin Lagoon to the Pomeranian Bay or the opposite way). It is estimated that about 69% of water discharge from the Lagoon to the Baltic Sea occurs via Świna and its branches, 17% via Peenestrom and 14% via Dziwna (Mohrholtz, Lass 1998). As the Baltic Sea has very low salinity (on average 7.5‰ in the Pomeranian Bay; Leppäranta, Myrberg 2009) and the Szczecin Lagoon is connected to the sea via narrow and

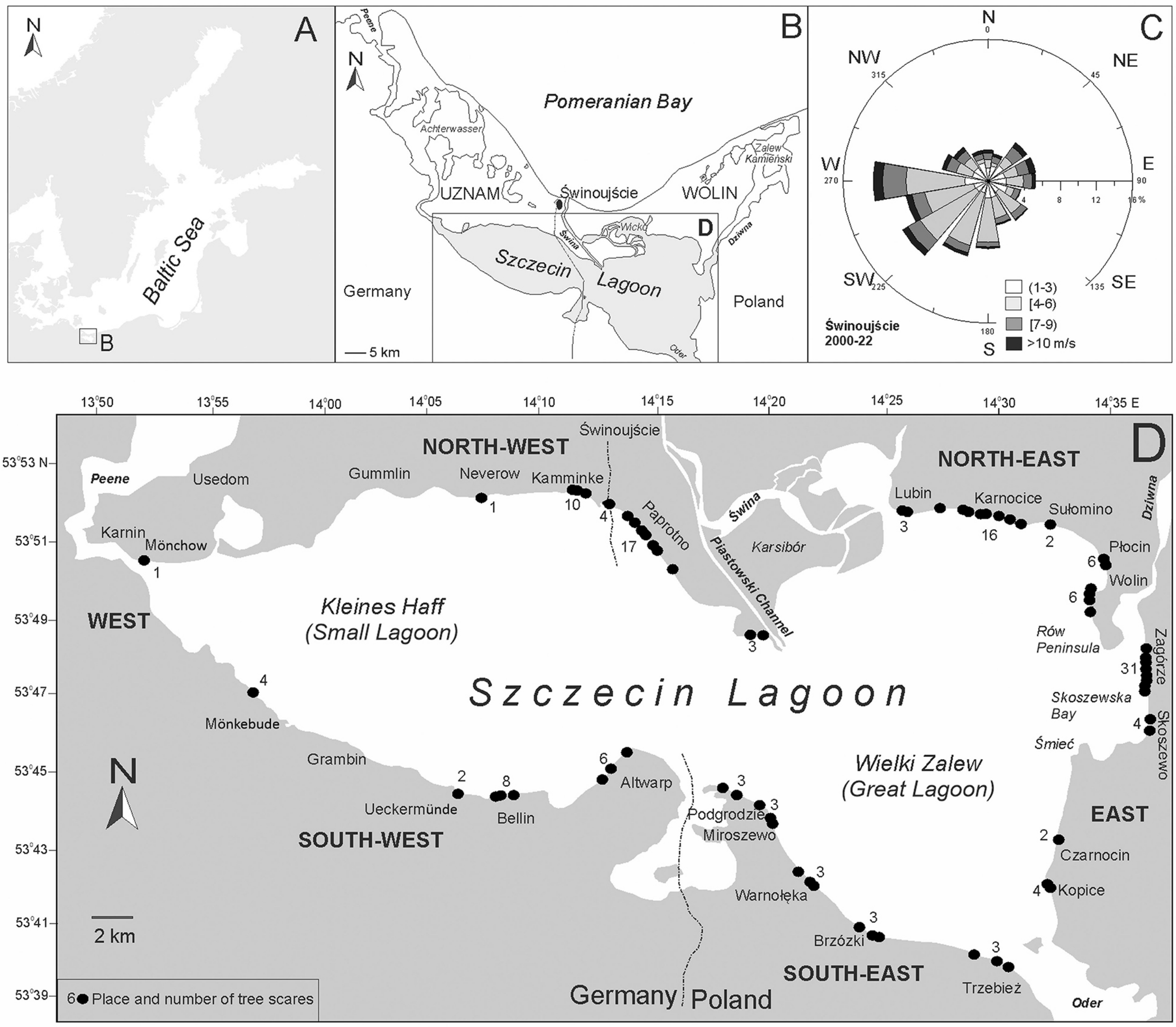

Fig. 1. Szczecin Lagoon. A – location on the South Baltic Sea coast; B – lagoon location between land and Uznam and Wolin Islands; C – wind rose at station Świnoujście, 2000–2022 (complied after Łabuz 2022); D – Lagoon coastline with the location of trees with ice scars (black points) and their number.

shallow straits, the lagoon is virtually a freshwater basin, with salinity ranging from 0.3 to 4.5‰ (on average, 1.4‰). The salinity is the highest in winter, when strong landward winds occur at the southern end of the Piast Canal (an artificial branch of the Świna and the main connection between the lagoon and the Pomeranian Bay). The lowest salinity occurs next to the Odra River mouth in summer (Bangel et al. 2004). The very low salinity of the lagoon enables the process of freezing of its surface waters to resemble those observed on freshwater lakes.

The mean annual water temperature in the lagoon is ca. 11°C (Schernewski et al. 2006), and the mean annual air temperature is 8.7°C, with a multiannual mean monthly air temperature reaching a minimum of 0.8°C and a maximum of 17.9°C. The mean annual precipitation sum equals 550 mm (Koźmiński et al. 2004, Radziejewska, Schernewski 2008). Mean wind velocities over the study area are the highest in winter (especially in February) and early spring (Świątek 2012), which favours the formation of ice hummocks, and thrusting ice onshore during periods of air temperature increase within this time. On the Szczecin Lagoon, ice occurs on average for 51 days. The earliest ice phenomena appear on average on 25th December (in individual years ranging from 13 November to 27 February), and the last ice in a given season disappears on average on 5th March (ranging from 13 January to 10 April), average annual maximum ice thickness equals 17 cm and the peak value reaches 50 cm (Girjatowicz, Świątek 2020).

Winds blowing from the directions ranging from the south to the west occur for 58% of the time (Fig. 1C). Wind velocity ranging from 3 $m \cdot s^{-1}$ to 5 $m \cdot s^{-1}$ occurs for about 50% of the time. Strong winds (with velocities exceeding 10 $m \cdot s^{-1}$) are basically those blowing from the southern and western sectors; they represent more than 90% of the strong winds (Koźmiński et al. 2004, Łabuz 2022). Damage caused by ice floes is also impacted by water levels. On the Szczecin Lagoon, the highest water levels are observed when storm winds are blowing from the W, NW and N. Maximum water levels, recorded during winter high-water events in January 2002, 2005 or 2007 reached 0.65–0.95 m above the average water level for the southern lagoon coast in Trzebież (Kowalewska-Kalkowska, Kowalewski 2005, 2008).

Materials and methods

Measurements, along with photographic documentation, were performed by the authors during on-foot reconnaissance campaigns along the entire lagoon. Due to the large geographic extent of the study area, fieldwork was carried out in various years in the period from 2017 to 2022. In order to facilitate the analysis and interpretation of the ice scar distribution, the Szczecin Lagoon shore was divided into six segments characterised by approximately uniform exposure: western, south-western, south-eastern, eastern, north-eastern and north-western (Fig. 1D).

Field measurements involved five key parameters of damage to trees:

a) distribution along the shore of the Szczecin Lagoon and tree kind,
b) distance of the scars on a damaged tree from the shore,
c) minimum and maximum elevation of the scars above the water level,
d) geographic direction the scar is facing (exposure),
e) shape parameters, including length and maximum width.

Additionally, the tree species were noted, along with the tree circumference, information on fallen trees bearing scars and the scale of damage to the shore and vegetation caused by ice thrusting onshore. Geographic coordinates and the exposure of ice scars on the examined tree trunks were also noted. The aim was to determine the hydrometric conditions under which the ice scars were probably formed. The documentation was supplemented by photographs presenting the scale of the examined phenomena.

During the field campaigns, it was recorded that 147 ice scars on growing trees were distributed around the Szczecin Lagoon. Ice scars were found also on numerous trees previously uprooted by ice or due to shore erosion. Such damage was not considered in the present study, as the displaced and fallen trees did not indicate the maximum ice scar elevation, nor the distance from shore.

The distance of the fallen tree from the shore and the maximum elevation of an ice scar on a given tree were deemed the most important parameters of damage to trees. For the entire shore of the Szczecin Lagoon and for each of the segments distinguished herein, the values of these parameters were characterised in detail by means of descriptive statistics. The first stage involved a verification of the similarity of the distribution of the empirical data to normal distribution. This was achieved using the non-parametric Shapiro–Wilk normality test (Kaptein, van den Heuvel 2022). Next, central tendency measures were determined (classical – arithmetic mean and positional – median) as well as values of the lower (1) and upper (3) quartile. In order to determine whether the damage to trees in individual segments of the lagoon shore occurred at a different than average distance from the shore or were located at a different than average elevation, a difference between means test for independent samples was applied (Student's *t*-test). The null hypotheses for this test were no significant differences among average distances of damaged trees from the shore or among maximum elevations of scars on trees. Those test results (both Shapiro–Wilk test and Student's *t*-test) that yielded the standard significance level of 0.05 were deemed statistically significant. As part of this study, the dimensions (lengths and maximum widths) of ice scars from individual segments of the lagoon shore were compared. Further, it was attempted to determine the density of ice scar occurrence along the Szczecin Lagoon shore, following the scale proposed by Lederer and Garver (2000). These authors put forward a six-degree scale of ice scar distribution density, as follows: 0 – no ice scars; 1 – minor, exceedingly rare damage; 2 – minor, rare damage; 3 – moderate, several damaged trees; 4 – large, widespread damage, a common occurrence of scars and 5 – extreme, most trees damaged, broken trees present.

Results

Distribution of scars relative to the exposure and geometry of the Szczecin Lagoon shore

This subsection includes a characteristic of the Szczecin Lagoon shore segments distinguished here in order to facilitate a more detailed analysis and interpretation. The shore subdivision was based on the exposure of the shore to the dominant wind direction, which influences ice motion and its thrust onto the shore.

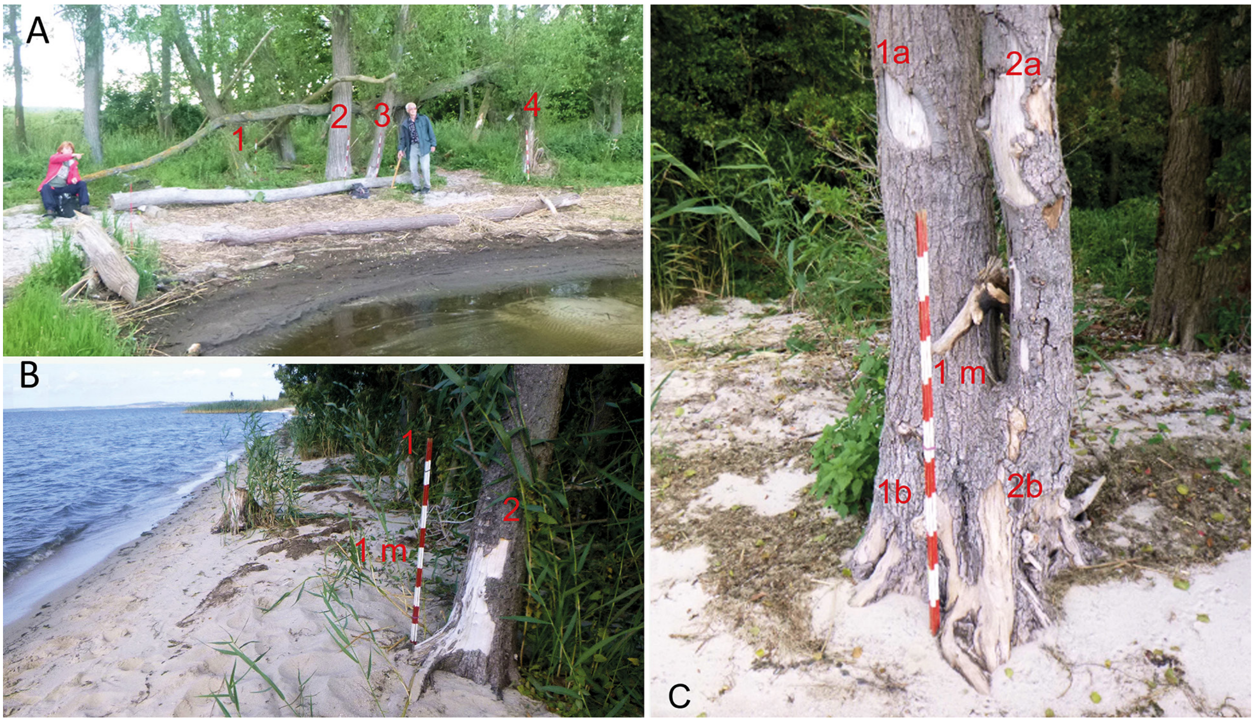

Fig. 2. Examples of ice scars on trees on the lagoon shore. A – a cluster of trees (1–4) bearing ice scars, growing in a small bay, Mönkebude, 25 May 2022; B –trees bearing ice scars (1–2) close to the eroded shoreline, Zagórze, 26 September 2022; C – double scars, Zagórze, 26 September 2022, 1a–1b – north-western thrust direction, 2a–2b – south-western thrust direction.

The part of the shore located entirely within the Small Szczecin Lagoon, on the German side of the border, is here considered as the western shore. It is the narrowest part of the Lagoon, tapering in a funnel-shaped manner toward the west, and connected with the channel and Peene (one of the three straits connecting the lagoon to the sea) outlet in the vicinity of Karnin. The northern part of the western shore extends from Gummlin to Karnin in the outlet of the Peene Strait, and the southern part extends from Karnin to Grambin (Fig. 1D). The shores are mostly represented by wetlands and marshes in this part of the lagoon, with a broad reed belt, extending from 50 to 100 m. The southern side of these shores is protected over long distances by flood embankments. Sparse trees are growing adjacent to the basin, at an elevation of 0.3–0.4 m a.w.l. (above water level). Only five ice scars were observed in this part of the shore. These occurred on willow trees growing next to an outlet of a 25-m wide bay cut into the reed belt extending along the entire shore in this segment (Fig. 2A). Damage to trees may have arisen not only due to ice advance but also due to ice floe-wave interaction, especially at higher water levels.

The south-western shore segment was also designated along the small Szczecin Lagoon. It extends from Grambin through Bellin, Ueckermünde and further eastward, through Altwarp Siedlung to Altwarp (Fig. 1D). It is a low, marshy shore, with a broad reed belt along the shoreline (Fig. 3A). The reed belt is cut by coastal facilities of towns and ports and by rivers draining into the lagoon, including Uecker in Ueckermünde and Zarow in Gramlin. Ice scars were found only on trees growing on the shores of small bays that lacked reed. On these low, marshy shores, such areas were usually flooded during periods of occurrence of strong winds blowing from NW–N directions. This facilitated the advance of ice far inland and resulted in damage to trees. Ice scars positioned high on trees originated via ice thrusting and piling processes. Sixteen trees damaged by ice were observed in this region. Ice scar-bearing trees were growing on a substratum located on average 0.5 m a.w.l. (ranging from 0.2 to 1.1 m).

The south-eastern shore segment is located within the large Szczecin Lagoon, on the Polish side of the border. It extends eastward from Podgrodzie, through Miroszewo, Warnołęka, Brzózki, to Trzebież (Fig. 1D). The shore includes both low sections and cliffs. A low cliff occurs close to Miroszewo and Trzebież. Until recently, the cliff was partly (Miroszewo) active, free from vegetation and reed belt shelter. At present (from 2013), it is artificially reinforced by a stone band.

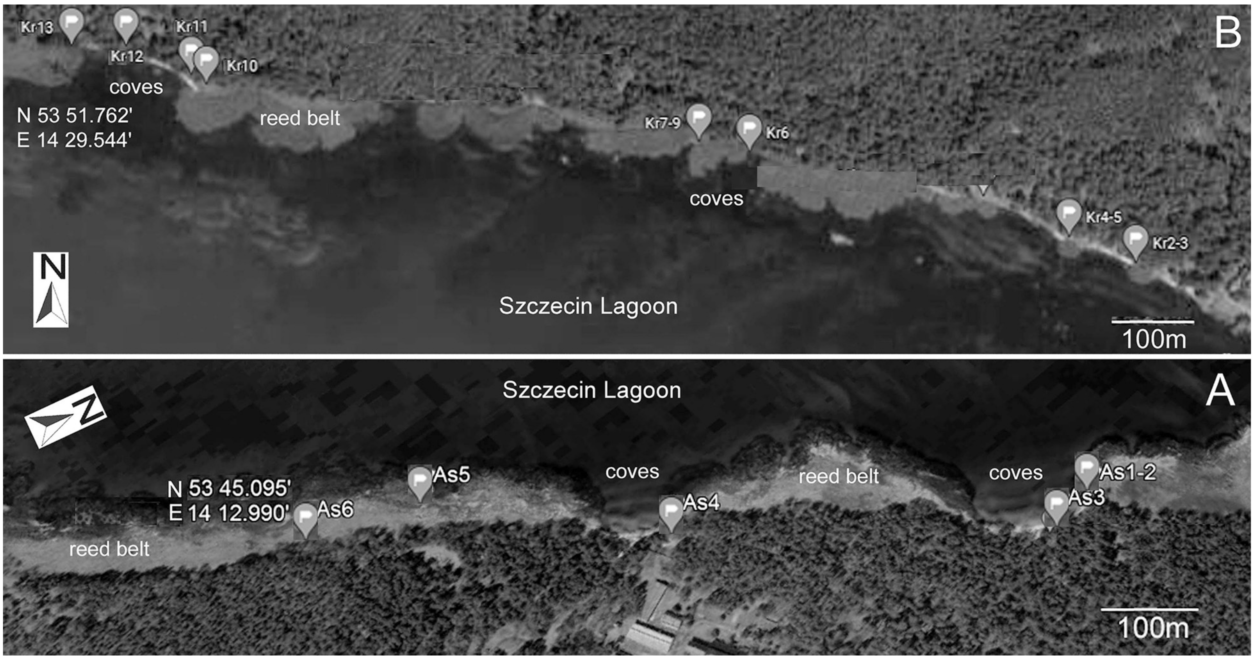

Fig. 3. Distribution of trees with scars (flags) on: A – the south-western shore, Altwarp-Siedlung region (As1 ÷ As6); B – a north-eastern shore, Karnocice region (Kr2 ÷ Kr13).

Low shores appear to the west of Brzózki and are protected by a flood embankment. Shores with broad reed belts also occur in this area. Low-lying areas, especially those on the proximal sides of flood embankments, were frequently flooded, which enabled ice floe to advance far inland. A total of 15 trees bearing ice scars were observed in this segment. Ice-scarred trees occur there at an average elevation of 0.4 m a.w.l., ranging from 0.1 to 0.6 m.

The segment designated as the eastern shore extends along the coast of the large lagoon, in Poland, north of Kopice, through Czarnocin, the Śmiec Peninsula, Skoszewo, Zagórze, to the western shore of the Rów Peninsula (Fig. 1D). Within this shore segment, approximately 16 km long, it was observed that there were as many as 47 ice scars on trees (Fig. 2B and 2C). Scars on fallen trees, or those eroded away from the substratum, were not measured. The elevations of the shores on which the scarred trees are growing are rather variable, ranging from 0 to 1.6 m a.w.l. (on average 0.4 m a.w.l.). The lowest shores are found on the Rów Peninsula: their elevation is below about 0.5 m a.w.l. Very low shores extend between Czarnocin and Skoszewo. A broad reed belt occurs at many points over this stretch of the shore. Trees growing within this reed belt bore no ice scars. The broadest reed belt occurs adjacent to the Śmiec Peninsula. The eastern part of the lagoon is exposed to frequent and strong wind blowing from the western sector, characterised by a long fetch. The highest ice hummocks develop there from a relatively thick ice floe. The ice floe advances the furthest inland in this low and flat, marshy area from different direction (Fig. 2C).

As the north-eastern shore, it was designated the part of the lagoon shore located within Polish borders, extending west of Płocin, through Sułomino, Karnocice, Lubin, to the Karsibór Island (Fig. 1D). It is the most diverse and relatively high shore segment. The shore is mostly represented by cliffs, up to 50 m high, especially between Karnocice and Lubin. At many points, the high cliff shore is preceded at its base by a low terrace, covered by a reed stand (Fig. 3B). In the vicinity of Lubin, there is an active cliff, abraded by waves, and lying at its base are the trees that had slid from the cliff slope. The lowest-lying shores, protected by flood embankments, occur in the vicinity of Płocin and Karsibór. Broad reed belts occur there as well (Fig. 3B). Ice scars were identified mostly on the shores with no reed. Trees bearing ice scars, 29 of which were recorded, are growing at an elevation of 0–1.7 m a.w.l., on average 0.6 m a.w.l.

The north-western shore extends westward from the entrance to the Piast Canal, through Paprotno, the state border, Kamminke and Neverow to Gummlin (Fig. 1D). Over this segment, more than 23 km long, 34 ice scars on trees growing mostly in the vicinity of Paprotno (Świdny Las) were observed. It is the western bank of the Świna Reverse Delta, exposed to the winds blowing from the SW. This shore segment is characterised by low shores, mostly wetlands and swamps with broad belts of reed. To the west of Kamminke, there are cliffs up to 30 m high. At the base of the cliff, there is an accumulation terrace with a gathering of riparian thickets, with common alder being the dominant tree, and a reed belt up to 100 m wide. From Neverow to Gummlin, the dominant type of shore is a low wetland with scattered ground moraine elevations, where the shore is protected by a belt of reed. The reed stands are cut by small outlets of drainage channels and small private harbours (e.g. in Gummlin, Pratenow, Dargen). The ice-scarred trees in this area occurred at an elevation ranging from 0.3 to 1.0 m a.w.l., on average 0.4 m a.w.l.

Distances of ice-scarred trees from the shore

On the Szczecin Lagoon, ice-scarred trees occurred at a variable distance from the shore, ranging from 0 to 64 m (Fig. 4). Some of the trees with identified ice scars were growing next to the shoreline on an eroded shore. This was most commonly observed on the eastern shore of the lagoon. This is also where ice-scarred trees uprooted due to erosion caused by waves or ice occurred the most frequently. Figure 4, in addition to the distance from the shore, presents also the maximum elevations of ice scars.

Ice-scarred trees located the furthest from the shore were observed at a distance of 40–64 m from the shore (Figs 4 and 5). All such trees were identified on shores exposed to the SW–NW wind directions. The two scars that were located the furthest from the shore (63 and 64 m) were

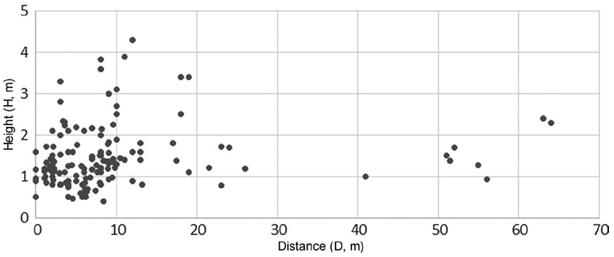

Fig. 4. The relationship between the distance from the shore of ice damage on trees and their maximum height above water level.

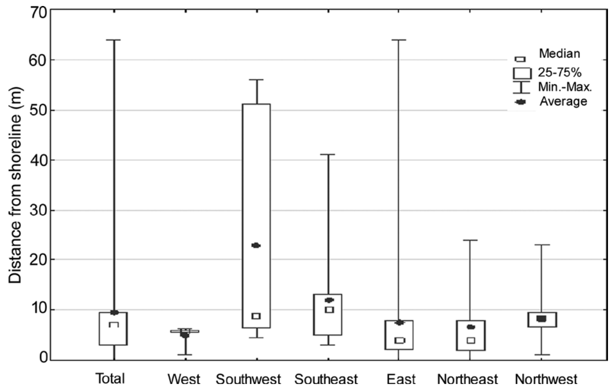

Fig. 5. Quartiles, extremes and average values of the distance of ice-damaged trees from the shoreline on the entire shore of the lagoon (Total, T) and in its separated parts.

found on trees growing on the Rów Peninsula. Five ice scar-bearing trees located 51–56 m from the shore were recorded on the south-western shore, in Bellin (Fig. 5). These scars, as indicated by their azimuth (325°), were formed during a period of strong wind blowing from the NW. One ice-scarred tree was identified at a distance of 41 m from the shore in Podgrodzie, which is located on the south-eastern shore and exposed to a rare but strong wind blowing from the NE. Ice scar-bearing trees located 20–30 m from the waterline occurred on the northern (Wydrzany and Karnocice, Fig. 3B) and southern (Podgrodzie and Miroszewo, Fig. 3A) shores. Ice-scarred trees located 10–20 m away from the shore appeared on a shore exposed to the west (Sułomino, Wydrzany and Altwarp Siedlung). The far advances of ice floe on land, apart from strong wind, is favoured also by the high water level, which reduces friction. High water levels in the Szczecin Lagoon are caused by strong wind blowing from the western sector, especially from the NW.

The value of the Shapiro–Wilk test, employed here for determining the similarity of distribution of empirical values (distances of trees damaged by ice measured in the field) to a theoretical normal distribution, equalled 0.606. For the studied sample size, this is sufficient to reject the hypothesis on the normality of distribution. For this reason, positional central tendency measures (quartiles: lower, central [median] and upper) were computed in addition to the classical one (arithmetic mean; Fig. 5).

The tree ice scars located the furthest from the shore were formed on a shore segment exposed to the winds blowing from the SW and W, on the eastern and north-eastern shores of the lagoon, especially on the Rów Peninsula. This area features, e.g. double scars, located on the same tree trunk (Fig. 2C) but formed by ice advancing in different directions.

Ice scars were observed on trees relatively far from the shore also at the south-eastern shore of the lagoon. The scar located the furthest from the waterline was observed in Podgrodzie, at a distance of 41 m from the shore (Fig. 5). On the north-eastern shore of the lagoon, the scar that was the furthest away from the waterline (a distance of 24 m) was observed in Karnocice. It was formed on a willow tree growing on a flat wetland. Distances of tree ice scars similar to those on the north-eastern shore were observed also on the north-western shore of the lagoon (Fig. 5). Also, the shore types and wind directions inducing ice thrusting onto the shore are similar. The furthest ice scar was found on a tree located 23 m from the shore. Also, this particular scar was formed during a period of strong wind blowing from the SW direction.

Ice scars occurred the closest to the waterline – at distances of just a few meters – on the whole western shore of the lagoon. The furthest of those was an ice scar observed in Mönkebude, formed on a willow tree growing 6 m from the shore.

For the purpose of precise verification of quantitative deviation of the distance of ice scars on trees from the waterline from average values for the entire coast, a Student's *t*-test for independent samples was performed. The results of the test are presented in Table 1.

The *t*-test indicated that the south-western shore segment stands out with respect to the distance of damaged trees from the waterline. In this segment, damaged trees are located

Table 1. *T*-test parameters for average distances of ice-damaged trees from the individual shore segments (labelled using the respective geographic directions) against the average distance of damaged trees from the shoreline (Total, *T*). Average, *a* – average for a given shore segment, Average, *T* – average for the entire lagoon shore, *t* – *t*-test value, *p* – *t*-test significance level; *t*-test parameters indicating statistically significant differences between averages are underlined.

Area	Average, *a* [m]	Average, *T* [m]	*t*	*p*
West and T	4.84	9.57	−0.88	0.38
Southwest and T	22.93	9.57	3.85	0.00
Southeast and T	11.87	9.57	0.72	0.47
East and T	7.64	9.57	−0.95	0.34
Northeast and T	6.59	9.57	−1.31	0.19
Northwest and T	8.23	9.57	−0.65	0.52

considerably further (on average, about 23 m) than in the remaining segments of the Szczecin Lagoon shore.

Ice scar elevations on tree trunks

On the shores of the Szczecin Lagoon, the maximum elevations of ice scar occurrences on trees above the water level are considerably varied (Fig. 4), ranging from 0.5 to 4.3 m a.w.l. (Figs 4 and 6). The Shapiro–Wilk test, employed here for determining the similarity of the distribution of empirical values (maximum elevation of ice scars on tree trunks) to a normal distribution, yielded a value of 0.868. For the studied sample size, this is sufficient to reject the hypothesis on the normality of the distribution of empirical data. For this reason, similar to the analysis of the distance of ice-scarred trees from the shore, it was computed

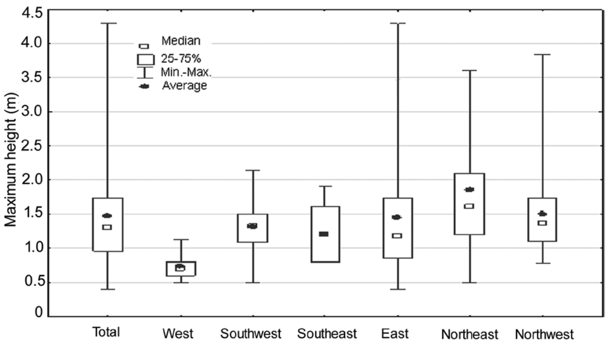

Fig. 6. Quartiles, extremes and average values of the heights for ice scars above water level on trees on the entire shore of the lagoon (Total, T) and in its separated parts.

quartiles for the maximum ice scar elevation. The results, along with mean and extreme values, are presented in Figure 6.

The scar that occurred at the highest elevation (4.3 m a.w.l.) was measured on the eastern shore of the lagoon, in Kopice. It formed on a poplar tree growing on a scarp at 1.6 m a.w.l. and 11.5 m from the shore. Two more ice-scarred poplar trees grew next, with scars positioned at 2.7 and 3.9 m a.w.l. The azimuth of the scar (250°) indicates it was formed during a period of wind blowing from the western sector (SW–W). The highest average ice scar elevations were observed in the north-eastern segment of the lagoon shore. The highest of these (3.6 m a.w.l.) was measured in Karnocice, on a pine tree growing on a scarp elevated 1.4 m a.w.l. and 8 m from the shore. Next to it, there was another pine tree bearing an ice scar at an elevation of 3 m a.w.l. (Fig. 7A).

In the north-western shore segment, the highest ice scar elevation (3.8 m a.w.l.) was measured in Paprotno. This particular scar was observed on an alder tree growing on a ground located 0.5 m a.w.l. and 8 m away from the shore. The trunk of that tree was damaged in several places, with the longest scar located at an elevation of 1.7 m. On the south-western shore, the highest scar elevation (2.2 m a.w.l.) was observed in the Altwarp Siedlung vicinity, on an oak tree growing at an elevation of 1.1 m a.w.l., 8 m from the shore. The highest ice scar elevation recorded on the south-eastern shore, in Trzebież, was 1.9 m a.w.l., at a distance of just 1 m from the shore. The azimuth of that scar (330°) indicates

Table 2. *T*-test parameters for average values of maximum tree ice scar elevations in individual shore segments (labelled using the respective geographic directions) against average maximum tree ice scar elevation (Total, T). Average, *a* – average for a given shore segment, Average, *T* – average for the entire lagoon shore, *t* – *t*-test value, *p* – *t*-test significance level; *t*-test parameters indicating statistically significant differences between averages are underlined.

Area	Average, *a* [m]	Average, *T* [m]	*t*	*p*
West and T	0.74	1.48	−2.15	0.03
South-western and T	1.31	1.48	−0.87	0.38
South-eastern and T	1.20	1.48	−1.40	0.16
East and T	1.45	1.48	−0.21	0.84
North-eastern and T	1.86	1.48	2.36	0.02
North-western and T	1.51	1.48	0.19	0.85

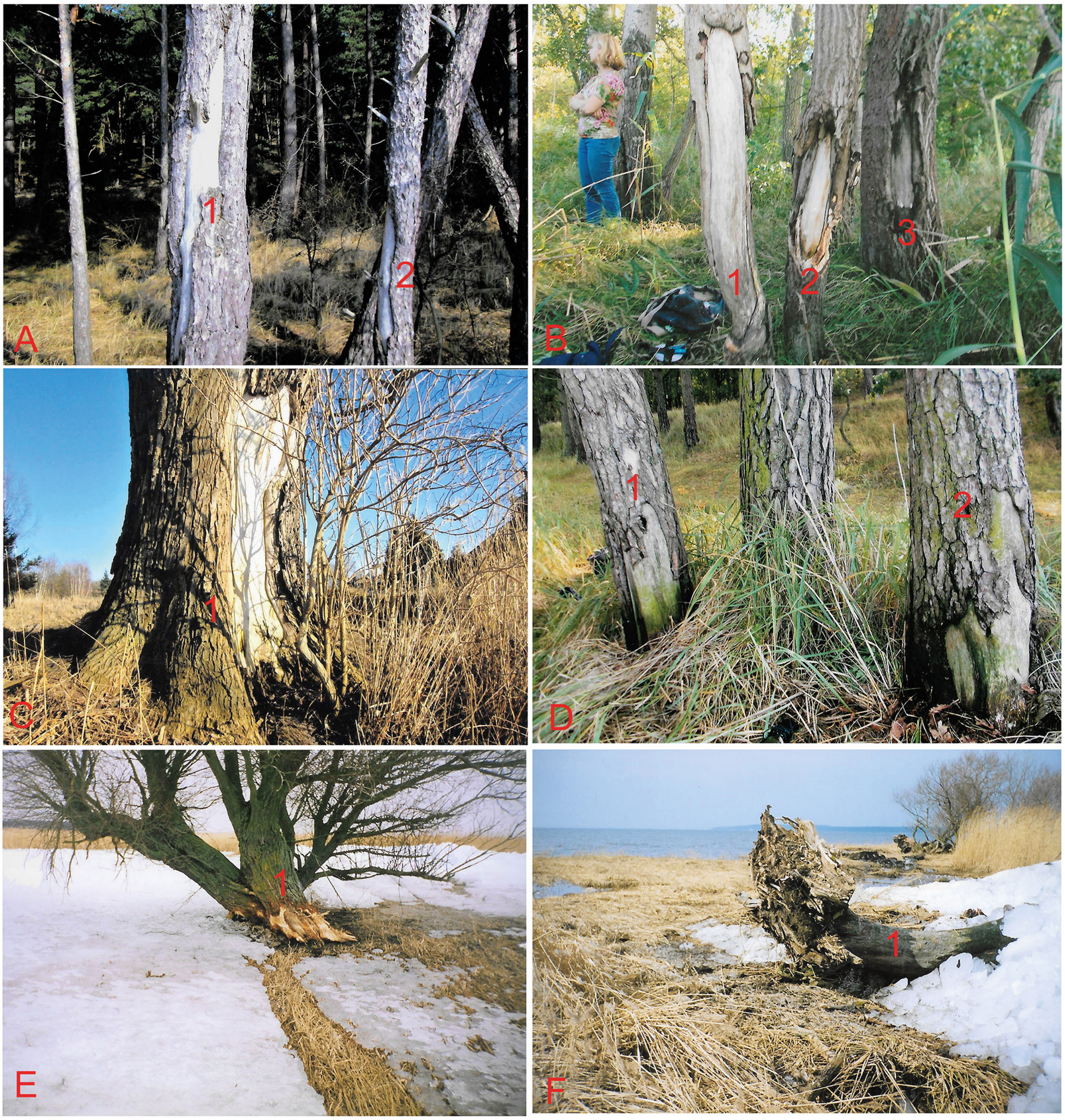

Fig. 7. Examples of ice scars on trees on the Lagoon shore: high-lying and long (A, B), low-lying and long (C), low-lying and short (D, E), on an ice-fallen tree (F). A – pines, north-eastern shore, Karnocice, 13 March 2017; B – poplars, south-western shore, Bellin, 29 September 2020; C – poplar, eastern shore, Kopice, 15 February 2017; D – pines, south-western shore, Altwarp Siedlung, 29 September 2020; E – willow, eastern shore, Rów Peninsula, 18 March 2003; F – willow, eastern shore, Rów Peninsula, 18 March 2003.

it was formed during a period of strong wind blowing from the NNW.

The lowest ice scar elevations were measured on the western shores of the lagoon. The highest of these, with a maximum elevation of 1.1 m a.w.l., was observed in Mönchow. This scar was recorded on a willow tree growing on a ground elevated 0.3 m a.w.l., 1 m from the shore. This funnel-shaped basin is adjacent to the Peene outlet; it has a relatively small area and is sheltered by land on three sides, thus restricting the possibility of ice thrusting onshore and hummocking.

Using Student's *t*-test for independent samples, it verified the occurrence of scars deviating from the average value for the entire shore with respect to the maximum elevation of ice scars on trees in a given shore segment (Table 2). On the western shore of the lagoon, ice scars occur at unusually low elevations: the average of their maximum elevation is 74 cm lower than average for all the analysed cases (Table 2). On the north-eastern shore – to the contrary – ice scars occur exceptionally high: the average of their maximum elevation is 38 cm higher than average for all scars. This difference is corroborated by t-test values, statistically significant at $p < 0.05$ level (Table 2).

Length and width of ice scars on trees

Ice scar lengths and widths were also measured during fieldwork. The length of ice scars on trees around the Szczecin Lagoon varied within a broad range, from 9 to 280 cm (Fig. 7). The largest tree ice scars, both with respect to maximum width and length, were observed on the eastern shore of the lagoon (Fig. 8). In the remaining segments of the lagoon shore, the scars had similar dimensions.

The longest ice scar (280 cm) was observed in the vicinity of Kopice (eastern shore). It was measured on a poplar tree growing on a scarp elevated 1.8 m a.w.l., 12 m from the waterline. Similar, albeit, shorter scars occurred on the neighbouring trees. The azimuth of these scars (240–250°) indicates that they were formed during a period of strong wind blowing from the WSW.

The maximum width of ice scars on trees growing along the Szczecin Lagoon shore is also very variable, ranging from 1 cm (healing scar) to 210 cm. The widest scar (210 cm) was measured on the Rów Peninsula (eastern shore). This scar, 220 cm long, was formed on a willow tree growing on a ground elevated 0.5 m a.w.l., 18 m from the shore. The remaining ice scars on the Rów Peninsula were also rather wide, from 30 to 60 cm. One of these is pictured in Figure 7F. It was found that the azimuth of these scars displayed a remarkably broad range, from 210 to 340°.

Ice-scarred tree occurrence density

By applying the six-degree scale of tree ice scar occurrence density by Lederer and Garver (2000), it determined the relationship between the scar density and shore exposure to the most frequent wind direction. The highest value on the scale was assigned to the shores exposed to the winds blowing from the W and SW directions. These are the eastern and northern shores of the Szczecin Lagoon (Fig. 1D). The western shore of the Rów Peninsula (eastern part of the lagoon) was assigned a value of five: all trees were damaged, and some were broken, uprooted or displaced landward. These were facilitated by the low and flat, often flooded terrain, enabling ice to penetrate far inland. The remaining part of the eastern shore of the lagoon (Kopice-Zagórze) may be assigned a value of four. On this shore segment, numerous trees closest to the shore were damaged. The north-western and north-eastern shores of the lagoon, especially in the vicinity of Karnocice and Paprotno, where forests display high density, were also assigned a grade 4 ice scar occurrence density. Further, this shore is exposed to winds blowing from the S–SW–W directions, which occur the most frequently in the ice run period, mostly in February and March. On the south-eastern and south-western shores, however, ice scars on trees were considerably fewer, and their occurrence density varied, with a mean

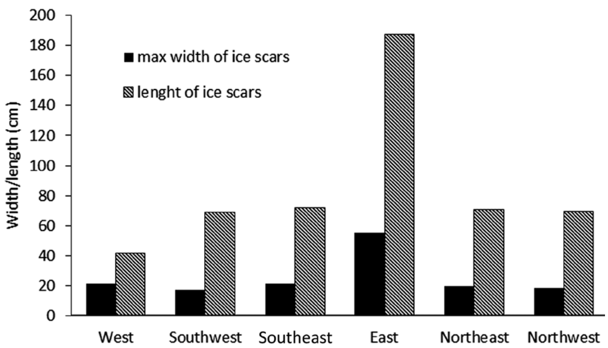

Fig. 8. Average lengths and widths of ice scars on trees in separated parts of the shore of the Szczecin Lagoon.

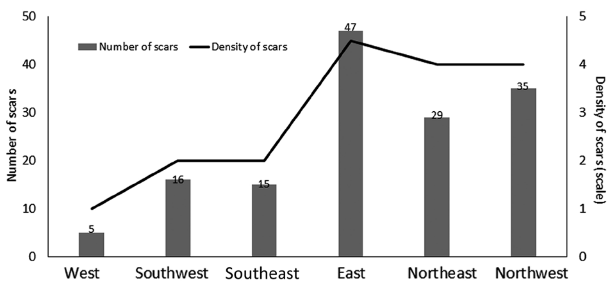

Fig. 9. The number of ice-scarred trees and their density scale in the designated segments of the Szczecin Lagoon (according to the method of Lederer, Garver 1996).

estimate of 2.5. A value of two was assigned to the south-eastern shore segment (Podgrodzie-Trzebież). The western shore was characterised by the lowest ice scar density (Fig. 9).

Discussion

On the southern Baltic shores, the wide beaches and the presence of grease ice ridge prevent ice floes from advancing on land (cf. Girjatowicz, Łabuz 2020). The advancing ice floe crumbles and piles before the coastal grease ice ridge, and thus, the trees growing on the dunes are protected from damage. On the Baltic Sea shores, ice scars on trees are observed only over some segments of the shores of the Gulf of Riga and the Gulf of Finland (Orviku et al. 2011). On the shores of the coastal lagoons, trees growing adjacent to the shore are relatively highly exposed to damage from advancing ice floe. Following the disintegration of fast ice cover, sheets of ice readily undergo thrusting onto flat shores (cf. Kraus 1930, Dionne 1979, Gatto 1984, Lemay, Bégin 2012, Girjatowicz 2017). Trees growing along river banks are the most vulnerable to destructive ice activity. Ice floe carried by the river and ice jams forming on rivers, especially at high water levels, readily damage trees (cf. Lederer, Garver 1996, Pawłowski 2005, Uunila, Church 2014, Vandermause et al. 2021).

The average maximum ice scar elevation observed on the trees surrounding the Szczecin Lagoon equalled 1.5 m a.w.l., with a maximum elevation equal to 4.3 m a.w.l. Effects of ice thrusting represented by ice scars on trees were most frequently found on open shores or in bays free of reed or on shores with a narrow reed belt. The ice scar elevation on trees was influenced by the specifics of the hummocking process, dependent on ice type and thickness, area of the ice field or floe, wind force and water level, which facilitates ice thrusting.

Scars located high on a tree trunk are formed during the ice hummocking process (Girjatowicz 2014). As the sheet of ice thrusts up a windward slope, the ice crumbles to form brash ice on the leeward side, causing an increase in the width and height of the ice hummock. As the hummocking process progresses, the sheet of ice causes damage to tree trunks even several meters above water level. as it undergoes thrusting. Trees growing along the shore are usually an obstacle for a thrusting ice field; so, hummocking mostly occurs within such tree stands.

The largest tree damage was observed in the eastern segment of the shore (Figs 8 and 9). In this area, the damage was not only the most extensive but also the most frequent: it was documented in 47 cases, which represented nearly 1/3 of all the observed cases of damage to trees caused by ice thrusting. This is favoured predominantly by the shore exposure to the frequent western wind (Koźmiński et al. 2004, Łabuz 2022) (Fig. 1D), which has the longest fetch. Within the Skoszewo Bay, located between the Rów Peninsula and the Śmiec Peninsula (a distance of 4 km), was measured 35 ice scars on 31 trees, the most frequently, those growing close to the shoreline (Fig. 2B), including double scars characterised by different geographic exposure on four trees (Fig. 2C). Within this segment, due to shore erosion, many ice-scarred trees were already fallen or dragged onto the shore by ice and waves. The scars characterised by the highest elevation were formed in that part of the shore which is exposed to the wind from the SW direction, which favours ice run, as well as thrusting and hummocking. Wind blowing from this direction (and also from the W) is the most frequent and the strongest, especially in the winter-spring period (Koźmiński et al. 2004), causing the formation of high ice hummocks. Further, it brings warming in winter (the air temperature Ta > 0°C), thus favouring ice run and ice thrusting onto the shore. Wind blowing from the west causes ice piling. For instance, in late January 2004, on the sheltered basins of the nearby Rügen Island, a wind blowing from the SW caused the formation of ice piles up to 2 m high along the eastern shore (Schmelzer et al. 2004). On the southern Baltic coastal lagoons, wind blowing from the W sector usually brings warming and causes ice run (cf. Girjatowicz 1977). It causes ice drift and thrusting of sheets of ice onto the shore. Stronger wind may thrust thicker ice sheets that will form higher hummocks (cf. Orviku 1965, Girjatowicz 2014).

Ice scars positioned especially high on trees arise where ice hummocks develop. The thicker the ice floe, the higher wind speed is required to cause ice thrusting and piling. On the other hand, the ice hummock height increases with increasing ice floe thickness. For instance, on the southern Baltic coastal lagoons, 10 cm-thick ice floes may form hummocks up to 3 m high, and 20 cm-thick ice floes may form hummocks as high as 5 m (Girjatowicz 2014).

Ice-induced tree damage was especially abundant on the Rów Peninsula. It is a flat, low-lying area, frequently flooded during high-water events. During periods of strong wind blowing from western directions (SW, W and NW) in conjunction with elevated water levels, an ice field is readily thrust inland, thus causing damage to tree trunks. Figure 10 shows two separate ice thrusts onto the shore of the Rów Peninsula. Map A shows the range of the thrust and ice hummocking caused by the wind blowing from the WNW. Map B shows the same for the wind blowing from the SW. In this part of the lagoon, especially in the vicinity of Skoszewo and Zagórze villages, in recent years, the ongoing shore erosion caused the destruction of the reed belt and subsequently – also of the tree belt, up to several meters wide, including the ice-scarred trees.

Relatively large damage was caused on the northern shore. In this segment, ice scars on trees occurred especially high (Table 2). This shore segment is exposed to frequent wind blowing from the S–SW and W directions, which causes the breakup of fast ice. For this segment of the shore, this is a landward wind, causing ice thrusting onto the shore. Additionally, wind blowing from this direction causes warming (Koźmiński et al. 2004), which in turn causes ice run (Ta > 0°C). Damaged trees were located at a relatively short distance from the water line due to the dominance of steep shores in the northern part of the lagoon, which does not favour ice penetration inland. The NW segment of the shore, in the vicinity of Paprotno (a district of Świnoujście town), is exposed almost perpendicularly to the wind blowing from the SW direction. As the most frequent wind direction is from the SW, such shore exposure favours ice thrusting onto the shore.

Numerous ice scars characterised by moderate elevation and located on trees growing relatively far from the waterline were observed on the southern shore. These were formed during periods of strong wind blowing from the W through NW to N, causing the largest water surges on the lagoon, reaching 0.7–1 m, and storm waves (Kowalewska-Kalkowska, Kowalewski 2005, 2008). For comparison, on Lake Ontario, wind blowing at 8 $m \cdot s^{-1}$ caused the formation of ice piles reaching a height of up to 2.5 m a.w.l. on the shore (Gilbert, Glew 1986).

The fewest (only five) tree scars formed due to ice activity were identified in the western segment of the shore (Fig. 9). Ice scars on trees were located at exceptionally low elevations (Table 2) and were the smallest (Fig. 8). Sparse occurrence and a short distance of ice scars from the water line may be explained by the basin physiography and the associated wind conditions. The western part of the Szczecin Lagoon is characterised by strong land exposure, a relatively small area and a short fetch of wind from the western sector. The exposure of this part of the lagoon to wind from the eastern sector does not favour ice thrusting

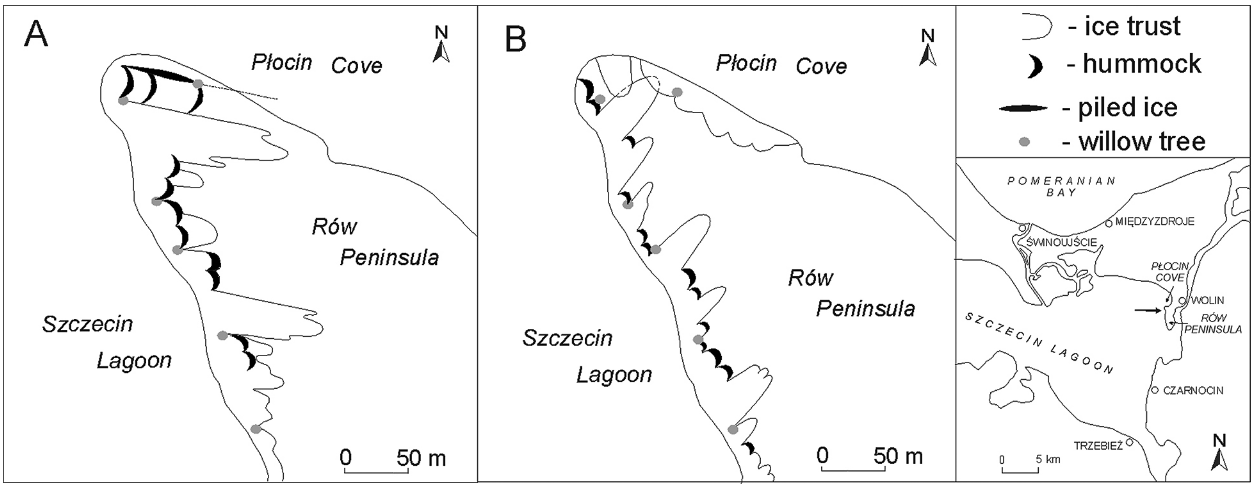

Fig. 10. Thrust ice fields with ice sheets in the northwest part of Rów Peninsula. A – 28 January 2003; B – 1 February 2004 (based on Girjatowicz 2015).

on land. Such wind brings cooling (Ta < 0°C) and stabilization or increase of thickness of an ice cover. Such ice cover is stable and lasts for a long period. In spring, it rots and disintegrates *in situ* (in water).

Numerous papers describe the results of sheet ice piling and thrusting onto lake shores and river banks and their impact on the nearby vegetation, including trees (e.g. Barnes et al. 1994, Engström et al. 2011, Lind et al. 2014). Maximum ranges of ice on shore may be analysed based on the identification of ice scars left behind on trees. Few researchers have applied this method to date (Lederer, Garver 1996, 2000, Pawłowski 2005, Lemay, Bégin 2012, Vandermause et al. 2021). Damaged vegetation and trees growing significantly above the river level are the most frequent evidence for the elevations reached by ice piles on rivers (Lederer, Garver 1996, Uunila, Church 2014, Vandermause et al. 2021). Ice scars on trees have been used to interpret the maximum time of breaking and piling of the ice cover on the rivers (Smith, Reynolds 1983, Vandermause et al. 2021).

The studies by Leder and Garver (1996, 2000), performed along the lower reaches of the Mohawk River (New York), indicated that the ordinate of the ice scar position on trees is equal to or lower than the ordinate of surge culmination during an ice jam. Similarly, on the lower course of the Wisła River, the ordinate of the water level reached during an ice jam is usually matched by the ordinate of the maximum elevation of ice scars (Pawłowski 2005). Ice damage to trees along the banks of the Peace River in Canada was observed up to 2 m above the maximum river level (Uunila, Church 2014). In Alaska, during an ice jam and an associated surge, damaged roots and trunks, as a result of substratum erosion, occurred to an elevation of 1.8 m (Vandermause et al. 2021). On the southern Baltic lagoons, ice hummocks may reach a height of up to 10 m (Zimdars 1941, Girjatowicz 2004) and in sheltered bays of the Baltic Sea, up to 16 m (Slaucitajs 1929, Kraus 1930, Orviku 1965). Along the southern Baltic coast, the dominant form of piled ice are grease ice ridges, whose height may reach up to 5 m (Girjatowicz 2001a, Girjatowicz, Łabuz 2020).

On rivers, water current is the factor responsible for piling ice floes and brash ice to form ice jams (Beltaos et al. 2006, Lind et al. 2014). On coastal lagoons, however, the factor responsible for piling sheets of ice within the ice field to form hummocks is the wind (Girjatowicz 2001b, Orviku et al. 2011, Leppäranta 2013). The influence of the wind (tangential stress) on a large area of an ice field causes the ice to become strongly pressured, to thrust inland and to undergo hummocking (Fig. 11A). The larger the ice field surface and the stronger the wind, the thicker ice will undergo hummocking. Further, higher ice thickness will form higher hummocks (cf. Kraus 1930, Alestalo, Häikiö 1976, Girjatowicz 2014). High hummocks arise due to a specific ice hummocking process. Sheets of ice advancing from the windward side become rafted and may even attain a vertical position. On the leeward side of a hummock, sheets of ice crumble under their own weight, forming brash ice (Fig. 11B). Brash ice accumulating on

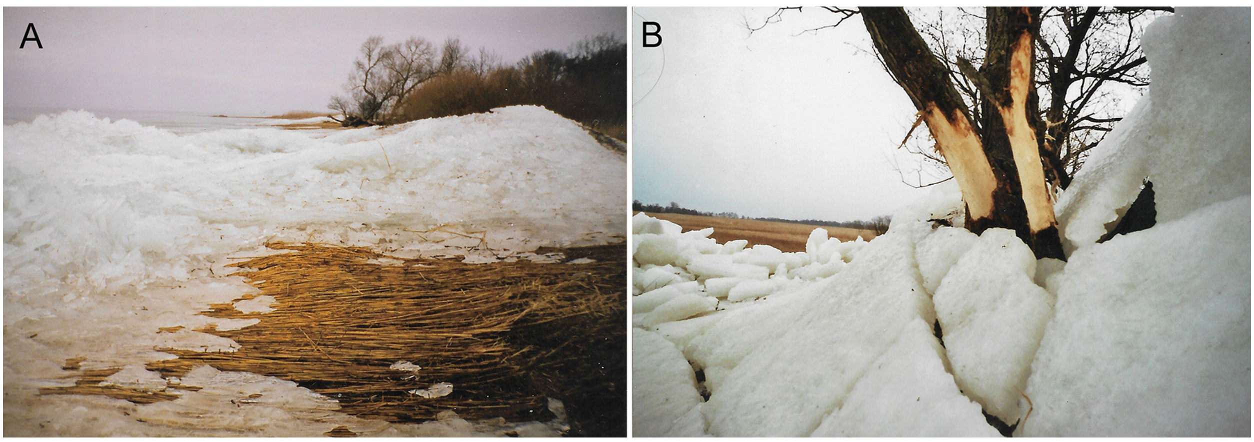

Fig. 11. Ice hummocks in the near-shore zones of coastal lagoons. A – in a destroyed reed belt, resting against the tree line, eastern shore of the Szczecin Lagoon, Czarnocin, 6 February 2004; B – the peak of a hummock next to a tree trunk bearing a fresh ice scar, formed on 8 February 2011, southern shore of the Vistula Lagoon, Frombork, 11 February 2011.

the leeward side causes a gradual deflection of the ice sheet as it advances through the apical part of the hummock, and thus, the height of the hummock is simultaneously rising. In the final phase of hummocking, the advancing sheet of ice attains a vertical position and may even deflect towards the windward side and crumble into brash ice there as well (Girjatowicz 2019).

The highest values of the ice damage ordinate on trees occur when the peak of a hummock aligns with the position of a tree trunk (Fig. 11B). This is where an advancing sheet of ice may damage the tree, marking the maximum elevation of a scar, and at the same time, it is the maximum height of an ice hummock. Ice being hummocked next to such a tree may damage it from the base of the trunk all the way up to the maximum height of the hummock. This is why an ice scar may be so long and reach so high. A tree damaged up to an elevation of 5.5 m by ice thrusting and hummocking due to strong wind over the Vistula Lagoon (Fig. 11B) is a good example of this. This scar marked the maximum height of a hummock. It should be emphasised that neither the scar elevation nor the hummock height should be linked with the water level ordinate during a surge on coastal lagoons. Surges do facilitate sheet ice thrusting onto the shore, however.

The spatial diversity of ice scar occurrence on trees is affected also by shore morphology, in addition to wind direction (cf. Pawłowski 2005). The shores of the southern Baltic coastal lagoons are mostly flat, with extensive areas of swamps, peatlands or marshes. On such shores, sheets of ice may advance over distances of even 100 m inland (Alestalo, Häikiö 1976, Leppäranta 2011, Girjatowicz 2015). Thus, ice scars may occur relatively far from the shore and, usually, at the base of a tree trunk.

The lagoon water level also has a major influence on the distance over which sheets of ice may be thrust inland (cf. Alestalo, Häikiö 1976, Orviku et al. 2011, Girjatowicz 2015). At low and moderate water levels, the advancing ice is usually hummocked at the lagoon shore. Under such hydrological conditions, trees are usually damaged only very close to the shoreline. At higher water levels, however, trees may get damaged further away from the shore. In such cases, due to reduced friction, ice thrusting is facilitated, and sheets of ice may advance further inland.

The ongoing climate change, manifested for instance by increased wind velocity and frequent alternations of positive and negative air temperatures, influences the high variability and dynamics of ice phenomena (cf. Jevrejeva et al. 2004, Livingstone et al. 2009, Sztobryn et al. 2012, Haapala et al. 2015, Girjatowicz, Świątek 2021). A given winter may witness several periods of ice phenomena occurrence on the lagoons, for instance, six on the Vistula Lagoon (Łazarenko, Majewski 1975) and up to eight uninterrupted series of days with ice on the Szczecin Lagoon (Girjatowicz, Świątek 2020). Repeated ice cover disintegration, caused usually by strong wind, enables repeated ice damage to trees in individual winter seasons.

Summary and conclusions

Based on analysis of the occurrence of ice scars on tree trunks on the Szczecin Lagoon shores performed here, the following conclusions are drawn:

- ice scars on trees may be a proxy for the dynamics of ice phenomena, especially concerning the distance over which ice is thrust inland, and the height of ice piles on shores,
- based on the elevation of ice scars on trees and the height of ice hummocks alone, it is not possible to reconstruct the water level during a surge on coastal lagoons or large lakes; elevated water levels, however, facilitate the thrusting of ice field on land,
- the density of ice scar occurrences on trees is associated with wind direction and the frequency of occurrence of strong wind, along with wind fetch in the winter-spring period; on shores exposed to the most frequent wind directions, in conjunction with the highest wind velocities, the number of ice scars is the highest and the scars are the largest and may reach high elevations,
- the maximum elevations of ice scars on trees and their distances from the shore display a high diversity; traces of ice thrusting represented by scars on trees most frequently occur on unsheltered shores or in bays devoid of reed and on shores with a narrow reed belt,
- a broad reed belt acts against thrusting of ice field onto the shore. Ice rafting and piling frequently occur on ice 'anchored' (immobilised)

by reed; for this reason, shores that do have a broad reed belt usually lack ice scars on trees,
– on steep shores, ice scars on trees usually occur mostly along the shoreline; this is where – the most frequently – ice undergoes hummocking; hummocks reach large heights, and thus, ice scars are present at high elevations,
– on flat shores, sheets of ice advance the furthest inland; thus, damaged trees may be growing at considerable distances from the waterline, and ice scars occur mostly on the ground level (at the base of the tree),
– only large ice forms undergo thrusting onto land, mainly ice fields with advancing thick sheets of ice; such ice builds high ice piles such as hummocks, which may damage tree trunks at significant elevations,
– the larger the basin (e.g. a lagoon, large lake), the higher the probability of ice being thrust onshore; such basins have larger ice fields and offer longer wind fetch, which is why ice thrusting and hummocking occur more frequently there than on smaller basins,
– flood embankments, breakwaters or steep shores are obstacles for an advancing ice field, which usually piles at their bases,
– measurements of ice scars may indirectly reflect the dynamics of ice phenomena in regions where no systematic ice observations have been performed; further, the results of this study may be used in planning and designing shore protection on the Szczecin Lagoon, or on other, similar basins.

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Authors' contribution

Józef Piotr Girjatowicz: concept, field work, theory, text, Małgorzata Świątek: text, statistical analyses, field work, Tomasz Arkadiusz Łabuz: text, graphic, analyses, field work.

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