ORIGINAL ARTICLE

Relationships between air temperature and ice conditions on the southern Baltic coastal lakes in the context of climate change

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ABSTRACT

Shallow, lagoonal coastal lakes of the Southern Baltic are exceptionally susceptible to atmospheric factors. This work examines the influence of winter air temperatures on ice parameters (dates of first ice occurrence and last ice disappearance, ice season duration, number of days with ice, and annual maximum ice thickness) on Southern Baltic coastal lakes (Jamno, Bukowo, Gardno, Łebsko), and trends displayed by changes in these parameters over the period spanning 1960/61-2019/20. The research data was retrieved from the archives of Institute of Meteorology and Water Management – National Research Institute. As a first step of the analysis, we investigated the statistical relationships in spatial and temporal variations in winter air temperature and coastal lake ice parameters. Correlation and regression method was employed to determine the influence of air temperature on coastal lake ice conditions. Correlation coefficients were calculated, and linear regression equations were determined. The statistical significance of the observed relationships was assessed using Fisher-Snedecor test. Additionally, linear trend models were constructed. Our analysis indicates that from 1960/61 to 2019/20, the average rate of increase in winter temperature (December-March) equalled 0.04°C–year^{-1}. The correlation coefficients for air temperature versus ice parameters were highly statistically significant (α<0.001). The strongest relationships (with correlation coefficients below -0.90) occurred between air temperature and number of days with ice. Ice season duration and number of days with ice are both closely linked with last ice disappearance date and ice thickness. Our analysis shows that a 1°C increase in average seasonal air temperature will result in the number of days with ice on the studied coastal lakes becoming reduced by 16-17 days. All trends in ice parameters indicate a mildening of ice conditions. The assessed trends are statistically significant, except for L (date of last ice disappearance) for Lake Jamno and H (annual maximum ice thickness) on lakes Jamno and Bukowo, at least at α=0.05 level. Their correlation coefficients are usually in the range from -0.35 to -0.50. The strongest trends were observed for ice season duration. Ice season duration shortens in an eastward direction by 0.66 day·year^{-1} (Lake Jamno) to 1.16 day·year^{-1} (Lake Łebsko). All correlation coefficients for ice trends were found to increase eastward, which could be explained by an increasing influence of the warming climate over the Southern Baltic in this direction. The strong relationships between air temperature and Southern Baltic coastal lake ice parameters, and the determined rate of changes may have a significance for forecasting, as the shifting dates of ice formation and disappearance on lakes are highly important for the lake hydrodynamics, and the functioning of aquatic ecosystems.

INTRODUCTION

Lakes Jamno, Bukowo, Gardno and Łebsko are among the largest lakes along the southern Baltic coast. These lagoonal lakes are linked to the sea via channels, and strongly influenced by the sea. They are very shallow, especially when compared to their relatively large areas. Their surface areas equal: 22.3, 16.4, 23.4 and 70.2 km^2, respectively, and their average depths equal: 1.4, 1.8, 1.3 and 1.6 m, respectively (Tab. 1). Lake exposure indices defined as the ratio of surface area expressed in hectares to average depth expressed in meters (ha/m) are very high, and equal, respectively, 1593, 911, 1800 and 4387 ha/m, compared to an average value of ~30 ha/m for the lakes of Poland (Choiński, 1995). The lake exposure index value reflects how strongly atmospheric conditions influence a lake's thermal and ice conditions. Lakes characterized by higher exposure index values are more susceptible to atmospheric forcing. Lakes characterized by low heat capacity due to low volume, especially shallow ones, warm and cool quickly, depending on air temperature changes. On such lakes, ice phenomena develop earlier than on deeper lakes (see e.g., Scott, 1964; Leppäranta, 2010).

Ice conditions on coastal lakes are considerably harsher than on neighboring basins (Baltic Sea and Szczecin Lagoon). Ice cover lasts longer, and attains considerable thicknesses. Notably, winters with no ice phenomena occur sporadically. Some ice parameter values for these lakes are presented in papers by Girjatowicz

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Key words: coastal lakes; southern Baltic Sea; ice conditions; air temperature; statistical relationships; trends.

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(2003), Marszelewski and Skowron (2006), Ptak (2013) and Choiński *et al.* (2014). More severe thermal and ice conditions concern those lakes located further toward the east, which results from the meridional distribution of winter isotherms over Europe at latitudes 47–56°N, i.e., including the study area. The number of days with subzero temperatures in a year increases toward the east (Schönwiese and Rapp, 1997). In the period 1950/51 - 2019/20 a clear increase in ice parameter values from the west to the east was also observed in coastal lagoons of the southern Baltic Sea (Girjatowicz and Świątek, 2021). In Szczecin and Vistula lagoons, the average number of days with ice was respectively 51 and 80; the ice season duration was 64 and 94 days, and the annual maximum ice thickness was 17 and 28 cm.

To date, few papers focused on the ice phenomena on the southern Baltic coastal lakes. These few papers usually concern the variability in selected ice parameters, mostly ice season duration, number of days with ice, and annual maximum ice thickness only for some lakes, and over various study periods. In addition to the analysis of trends (Sziwa and Jańczak, 2009; Ptak, 2013; Choiński *et al*., 2014), the papers on ice phenomena on coastal lakes also present the frequency and spatial variability in ice parameters (Girjatowicz, 2002), the links between ice parameters and air temperature, especially with regard to the occurrence of positive thermal trends (Marszelewski and Skowron, 2006), relationships between ice thickness and lake depth (Pasławski, 1982; Sziwa and Jańczak, 2009; Choiński, 2010), as well as changes in ice phenology related to location and morphometry (Choiński *et al*., 2015).

Papers on lakes located in northern Poland, including coastal lakes, include analyses of the North Atlantic Oscillation impact on ice conditions on these lakes (Girjatowicz, 2003b; Skowron, 2009; Wrzesiński *et al*., 2015). The impacts of weather conditions, including air temperature, wind speeds and rainfall on ice cover thickness and duration on Lake Gardno are studied by Bartosiewicz *et. al.* (2021). Marszelewski and Skowron (2006) present the relationships of both the number of days with ice and maximum ice thickness, with winter air temperature for Lake Łebsko. Ptak and Sojka (2021) show a successive decline in the ice extent on lakes Jamno and Łebsko due to climate warming. Shortening ice cover periods on Polish coastal lakes due to air temperature warning expected in the 21st century is confirmed by numerical studies (Piccolroaz *et al*., 2021).

Relationships between air temperature and lake ice parameters were studied in other countries of the Baltic Sea basin – in Finland (Palecki and Barry, 1986; Kornhonen, 2006), Sweden (Weyhenmeyer *et al*., 2008; Livingstone *et al*., 2010), Estonia (Nôges and Nôges, 2014), and in north-eastern Germany (Bernhardt *et al*., 2012). Collective analyses of ice phenomena in European lakes are also available (Nôges *et al*., 2009; Leppäranta, 2010; Livingstone *et al*., 2010). None of these works, however, concerned coastal lakes, which are highly unusual due to their morphometry (including shallow depth), and the impact of the sea.

Investigating the impact of climate warming on ice parameters is highly significant, for instance due to the fact that a longer ice-free period in a year, and an earlier disappearance of ice cover leads to changes in lacustrine ecosystems (i.e., assemblage structure – plant and animal population), such as quantitative and qualitative changes among the dominant phytoplankton taxa, succession turnover, decrease in taxonomic diversity of biota, and a shift from macrophyte-dominated to less transparent water colonized mostly by phytoplankton (Nôges, 2009). The impact of warming on the shifts in dates of ice phenomena formation and disappearance on lakes is highly significant for lake hydrodynamics, e.g., water circulation. It also enables photosynthesis, which would otherwise be blocked by the presence of an ice cover with a superjacent layer of snow (Salonen *et al*. 2009). The research described in the present article is important also because of the especially strong changes regarding ice cover on lakes located in temperate latitudes (Weyhenmeyer *et al*., 2004). Thus, another aim of the present work is to show how strongly climate warming impacts the changes in ice cover duration, the date of its formation and disappearance, and ice thickness in shallow coastal lakes, as exemplified by the southern Baltic coastal lakes.

METHODS

This paper is based on materials concerning the lakes Jamno, Bukowo, Gardno and Łebsko, located on the

Tab. 1. Morphometric and bathymetric data for coastal lakes of the southern Baltic Sea (after Jańczak 1997; Choiński 2006).

Lakes	Elevation (m asl)	Surface area (km^2)	Volume (m m^3)	Average depth (m)	Maximum depth (m)	Shoreline lenght (km)	Exposure indicator
Jamno	0.1	22.30	31.53	1.4	3.9	28.3	1593
Bukowo	0.1	16.44	32.07	1.8	2.8	23.2	911
Gardno	0.3	23.37	30.95	1.3	2.6	23.3	7800
Łebsko	0.3	70.02	117.52	1.6	6.3	55.9	4387

southern Baltic coast, over the period spanning 1960/61 to 2019/20. Ice monitoring stations for these lakes were located as follows: in Unieście for Lake Jamno; in Bukowo Morskie for Lake Bukowo; in Gardna Wielka for Lake Gardno; and in Izbica for Lake Łebsko (Fig. 1). The materials were collected by the Institute of Meteorology and Water Management – National Research Institute (IMWM-NRI, in Polish: IMGW-PIB). Data for the period 1960/61-2019/00 were published in "*Catalogue of ice conditions* …" (Girjatowicz, 2007). Data for the period 2000/01-2019/20 were retrieved directly from the archives of IMWM-NRI. Examined in this study were five ice parameters, including: date of first ice occurrence (F), date of last ice disappearance (L), number of days with ice (N), ice season duration (S), and annual maximum ice thickness (H). Those are the most commonly used parameters characterizing ice conditions in a given basin in individual winters (cf. Janérus and Jansson, 1982; Leppäranta *et al*., 1988; Schmelzer and Holfort, 2012). Mean values for N, S and H were calculated for the entire 60-year period. For Lakes Gardno and Łebsko, average F and L were calculated for a 59-year period, and for lakes Jamno and Bukowo – for a 58-year period. Additionally, the ratio of the number of days with ice in a given season (N) to the ice season duration (S), i.e. N/S, is presented, which is a measure of the stability (permanence) of ice occurrence during a given winter.

In order to gain a quantitative perspective on the timing of ice phenomena occurrence and disappearance, dates were converted into successive days of the water year, which begins on 1 November. Ordinal dates used in calculations were the observed days of first ice occurrence and last ice disappearance in a given water year. Mean monthly air temperature values were retrieved from the IMWM-NRI (IMGW-PIB) weather station at Ustka, located in the central part of the Polish Baltic Sea coast (Fig. 1). This work includes data from meteorological winter, i.e., from the months from December to March (hereafter abbreviated as Dec-Mar), and ice parameter values for a given winter season were correlated with an average air temperature from that period. However, in order to obtain the strongest relationships between the dates of the first ice occurrence, the last ice disappearance, and air temperature (T; for disambiguation, temperature is spelled out in full when referring to water temperatures), various different definitions of the winter period were also tested in addition to the above, which is the one most commonly used in analyses of ice phenomena in temperate latitudes (cf. Omstedt and Chen, 2001; Jevrejeva, 2002; Jaagus, 2006). These alternative winter period definitions included: December (Dec), November-December (Nov-Dec), November-January (Nov-Jan), March (Mar), November-April (Nov-Apr), February-March (Feb-Mar), and February-April (Feb-Apr).

The aim of the present paper was to examine the impact of winter air temperature (following the standard practice, average temperature for the December-March (Dec-Mar) period was used; average temperature for the period November-December (Nov-Dec) was used for the determination of air temperature influence on the date of first ice appearance; average temperature for the period February-March (Feb-Mar) was used for the date of last

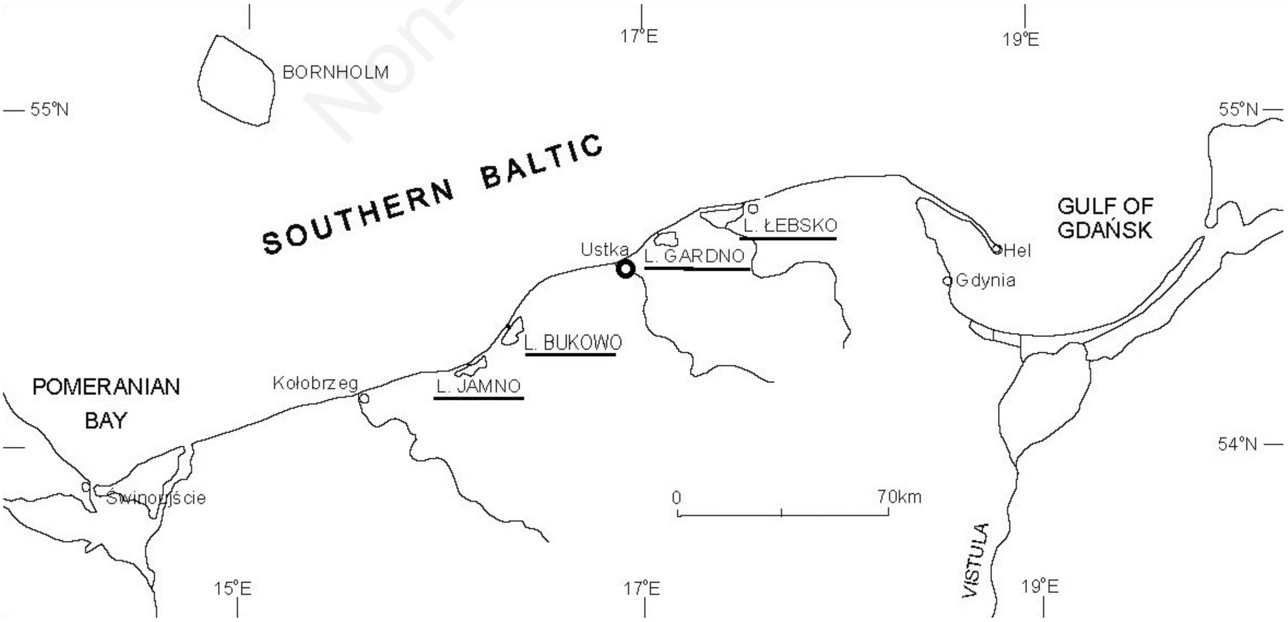

Fig. 1. Location of the studied southern Baltic coastal lakes. The location of Ustka weather station is also provided.

ice disappearance) on all the basic ice parameters, such as: dates of first ice appearance and last ice disappearance, number of days with ice, ice season duration and annual maximum ice thickness for four of the largest southern Baltic coastal lakes: Jamno, Bukowo, Gardno and Łebsko, over a study period spanning 1960/61 through 2019/20. Further, variability in these ice parameters is presented against winter air temperature, along with the trends. Probability of ice occurrence on the studied lakes was also determined.

In order to assess the sample distribution, stemplots with class intervals were established, in which abundance and frequency were determined. In order to describe statistical principles in spatial and temporal variability of the studied parameters, main estimators of statistical measures were computed. These included: arithmetic mean, standard error of the mean, standard deviation, extreme values, median, and lower and upper quartile. Interquartile range (i.e., the difference between the upper and lower quartile values) indicated the portion of the range of variation of a feature that included the middle 50% of the measurements.

The links between winter air temperature, predominantly from the Dec-Mar period, and ice parameters (F, L, S, N, H), were investigated using the correlation and regression method. Ice parameters were assumed as dependent variables (predicted variables), and air temperature was the assumed independent variable (predictor variable). Linear regression was applied, with regression lines plotted in figures based on least squares method, and their equations determined. The observed relationships were assessed statistically by calculating correlation coefficients (R), and by performing the Fisher-Snedecor test, which enables a verification of statistical significance (α) of the resultant relationships (Time series analysis, 2010). The probability of ice occurrence on the studied lakes was estimated in accordance with the principles formulated in Jevrejeva *et al*. (2004), Leppäranta (2014) and Karetnikov *et al*. (2017). Probability and standard deviation were calculated using the following equations:

$$p = \frac{1}{N}\sum_{n=1}^{N} I(n) \quad ; \quad SD = \sqrt{\frac{p(1-p)}{N}} \qquad (1)$$

Where p is the ice occurrence probability, N is the total number of years (winters), n is the successive number of a winter; I(n) is a binary designation of ice occurrence; I(n)=0 signifies lack of ice in a given winter no. n, and I(n)=1 signifies the presence of ice in a given winter, SD is the standard deviation of the estimator, i.e., the ice occurrence probability. Methods used in this study follow methodology described earlier in the study by Girjatowicz i Świątek (2021).

Cluster analysis was employed in order to detect mutual links between ice parameters. The clustering procedure was based on Ward's method, which estimates the distance between clusters by means of variance analysis approach (Ward, 1963). The formula 1-R, where R is Pearson's correlation coefficient, was used as the distance measure. The resultant dendrogram shows the clusters. The smaller the taxonomic distance (D) the stronger the links between the variables.

RESULTS

Air temperature during periods of ice phenomena occurrence on coastal lakes

Ice phenomena are noted on Polish coastal lakes irregularly from November to April, which is associated with a number of factors, including the annual variability of mean air temperature in the Baltic coastal zone. In the ice seasons spanning 1960/61 through 2019/20, mean $T_{Nov\text{-}Apr}$ equaled 2.6°C, with a standard deviation of 1.5°C. The lowest $T_{Nov\text{-}Apr}$ was noted in the 1962/63 and 1969/70 seasons (-0.9°C and -0.7°C, respectively). The warmest seasons, with T exceeding 5.0°C, were the years 2019/20, 2006/07 and 1989/90. Most frequently, ice phenomena were noted from Dec to Mar. In the 1960/61 through 2019/20 ice seasons, mean T for these months equaled 1.1°C. In individual years, the values of this variable deviated from the arithmetic mean by an average of ±2.0°C. As in the case of the Nov-Apr period, the lowest $T_{Dec\text{-}Mar}$ was noted in 1962/63 and 1969/70 (-3.7°C and -3.6°C, respectively). The warmest seasons, with temperature exceeding 4.5°C, were the winters of 2019/20, 2006/07 and 1989/90. January was the coldest month in the study period, with an average air temperature equal to -0.1°C (Fig. 2).

Negative average T_{Jan} values were noted for 28 winters (46.7% cases), and T_{Feb} for 27 winters (45.0% cases). In

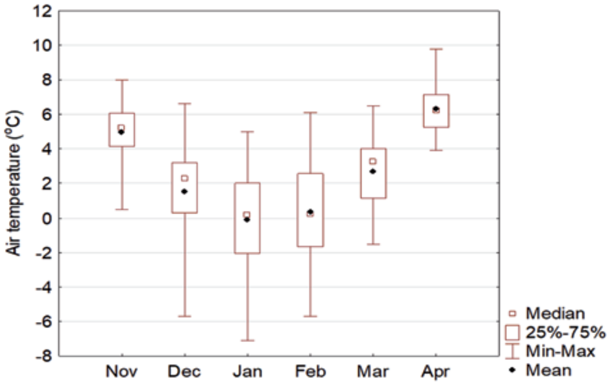

Fig. 2. Box and whisker plot presenting descriptive measures for mean air temperature over the period from November to April (1960/61-2019/20).

negative average T_{Dec} and T_{Mar} values were observed for 13 and 8 winter seasons, respectively. Negative average $T_{Dec\text{-}Mar}$ values were noted for 17 ice seasons (28.3% cases).

Notably, if the study period is considered as two consecutive 30-year subperiods (subperiod A spanning 1960/61 through 1989/90 and subperiod B spanning 1990/91 through 2019/20), both the average T, quartile values and extreme values increase in subperiod B (Fig. 3). Average $T_{Nov\text{-}Apr}$ and $T_{Dec\text{-}Mar}$ increased by 1.2°C. In subperiod B, negative average T values were significantly less frequent than in subperiod A. Negative average $T_{Dec\text{-}Mar}$ values were noted only for 6 ice seasons.

An increase in average T in the ice seasons spanning 1960/61-2019/20 is corroborated by the linear trend equations observed in the present study. $T_{Dec\text{-}Mar}$ rose by 0.04°C×year^{-1} over the period 1960/61-2019/20 (Figs. 4 and 5), with a correlation coefficient equal to 0.38. The standard error of estimate is 1.8°C. The statistically significant increasing trend (a=0.002) suggests that through the 60 year-long study period, the average $T_{Dec\text{-}Mar}$ increased by 2.6°C. In Jan, the average rate of change through the discussed 60 year-long study period equaled 0.05°C×year^{-1}, which, coupled with the statistically significant (a=0.02) trend indicates a 2.8°C T increase through the discussed period.

Description of ice conditions, and probability of ice occurrence on coastal lakes

On southern Baltic shallow coastal lakes, fast ice cover is definitely the dominant ice phenomenon (over 90% of the ice occurrence duration). Such ice cover is usually interrupted by current polynyas next to points of riverine water inflow and next to the outflow of lake waters to the sea. During periods of sustained landward winds and storm surges, more saline marine waters from the outlet stretches of the channels enter the lakes. In winter, these marine waters are warmer than the lake waters. During inflows of marine waters into the lakes via channels (backflow episodes) in winter, lake waters become warmer. In such hydrological conditions, the current polynyas in the outlet stretches of the channels enlarge. Fast ice survives the longest within bays, and disappears more quickly directly adjacent to the outlets of rivers and channels. At the end of winter, the dominant wind direction is from the SW-W, owing to which ice may persist slightly longer in northeastern and eastern parts of the lakes. During periods of SW-W wind occurrences, ice floes and brash ice may drift toward the east. Consequently, during periods of strong winds and rising temperatures that facilitate ice cover breakage and disintegration, forms of rafted ice and piled ice may occur along the eastern banks of the studied lakes.

During periods of cooling, manifested by the occurrence of negative T values, first ice occurs as early as after 2-3 days. It is usually a thin layer of ice rind forming in the coastal part of the lake, that quickly disperses over the entire lake. First ice phenomena occur – on average – in mid-Dec (Tab. 2, Fig. 6a), which is relatively early for the discussed climatic zone. In the eastern part of the study area (lakes Gardno and Łebsko), ice phenomena occur earlier (12 Dec) than in the western part (lakes Jamno and Bukowo – 16 Dec). Considering the variability of weather conditions during individual winters, the earliest first occurrence of ice was observed in early Nov (1-15 Nov), and the latest first occurrence of ice was observed in Feb (4-22 Feb). Last ice phenomena disappear on average in the second pentad of Mar (Tab. 2, Fig. 6b). The disappearance date is slightly later in the eastern (8-9 Mar) than in the western part of the study area (5-7 Mar). The earliest date of ice disappearance in the study period was in Dec (10-24 Dec), and the latest– in April (13-19 Apr). The last ice is usually in the form of brash ice, which disappears during periods of warming (T>0°C). The dates of first ice appearance (F) and last ice disappearance (L) determine the ice season duration (S) (Fig. 7a). On the studied lakes, the average S ranged from 78-79 days in the western part (lakes Bukowo and Jamno) to 86-87 days in the eastern part of the coast (lakes Gardno and Łebsko). S equalled most frequently 90-120 days. The highest S value was 134 days recorded on Lake Jamno (in the 1963/1964 season), and 160 days recorded for Lake Gardno (1979/80 season). The average number of days with ice (N) ranged from 64 days in the western part to 70 days in the eastern part of the coast (Fig. 7b). Both ice season duration (S) and number days with ice (N) are closely linked to last ice disappearance (L). The correlation coefficients between S and L exceeded 0.78. The observed highly statistically significant correlations between N and L ranged from 0.79 for

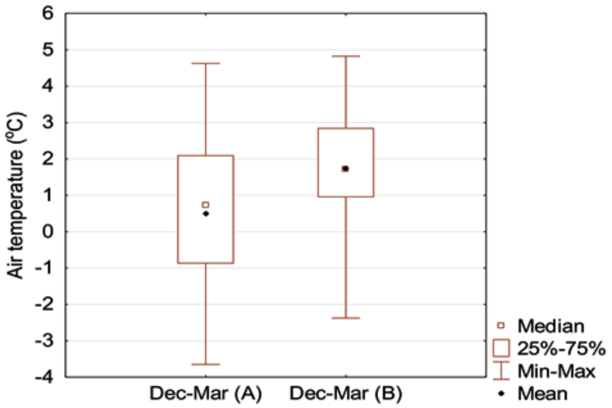

Fig. 3. Box and whisker plot presenting descriptive measures for mean air temperature (Dec-Mar) in subperiod A (1960/61-1989/90) and subperiod B (1990/91- 2019/20).

Lake Jamno to 0.84 for Lake Łebsko. The ratio of number of days with ice (N) to ice season duration (S) reflects the ice cover stability. On coastal lakes, where ice forms relatively rapidly, and becomes thick and stable. The ice stability ratio (N/S) often equals 100%, or at least is close to this value. The mean value of N/S is in the range of 79 to 85% whereas the minimum value is in the range of 17 to 32% (Fig. 8, Tab. 2). Relatively large values of N/S are favored by large ice thickness, weak water motion, or physiographic conditions of the lake (shallow depth, enclosure).

Mean annual maximum ice thickness (H) equaled ca. 21 cm in three of the studied lakes, and ca. 20 cm in Lake Jamno (Fig. 9, Tab. 2). H reached 45 cm for Lake Jamno,

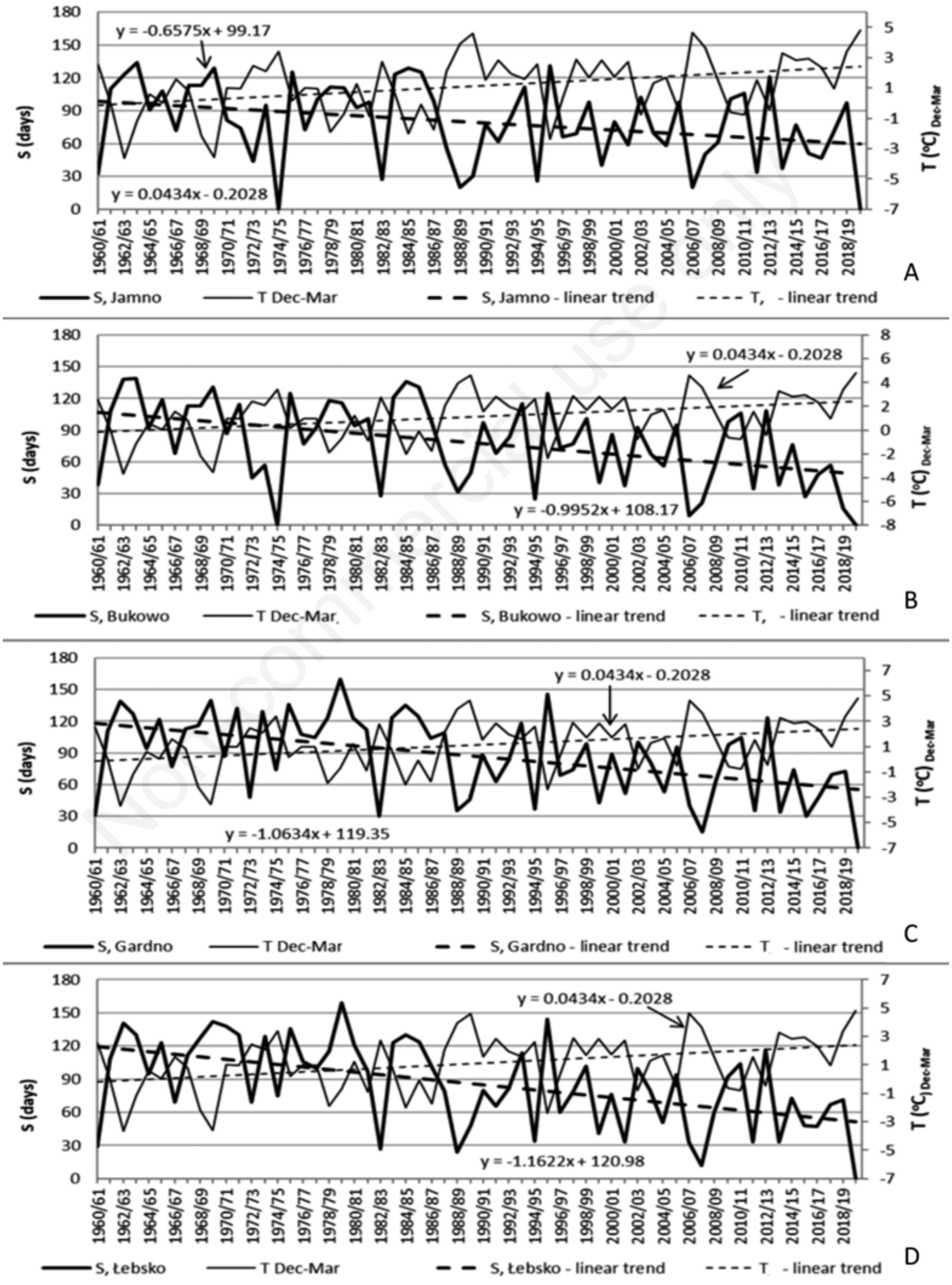

Fig. 4. Ice season duration (S) variability and trend lines for lakes: A) Jamno, B) Gardno, C) Bukowo and D) Łebsko, and winter (Dec-Mar) air temperature (T), (1960/61-2019/20), along with regression line equations.

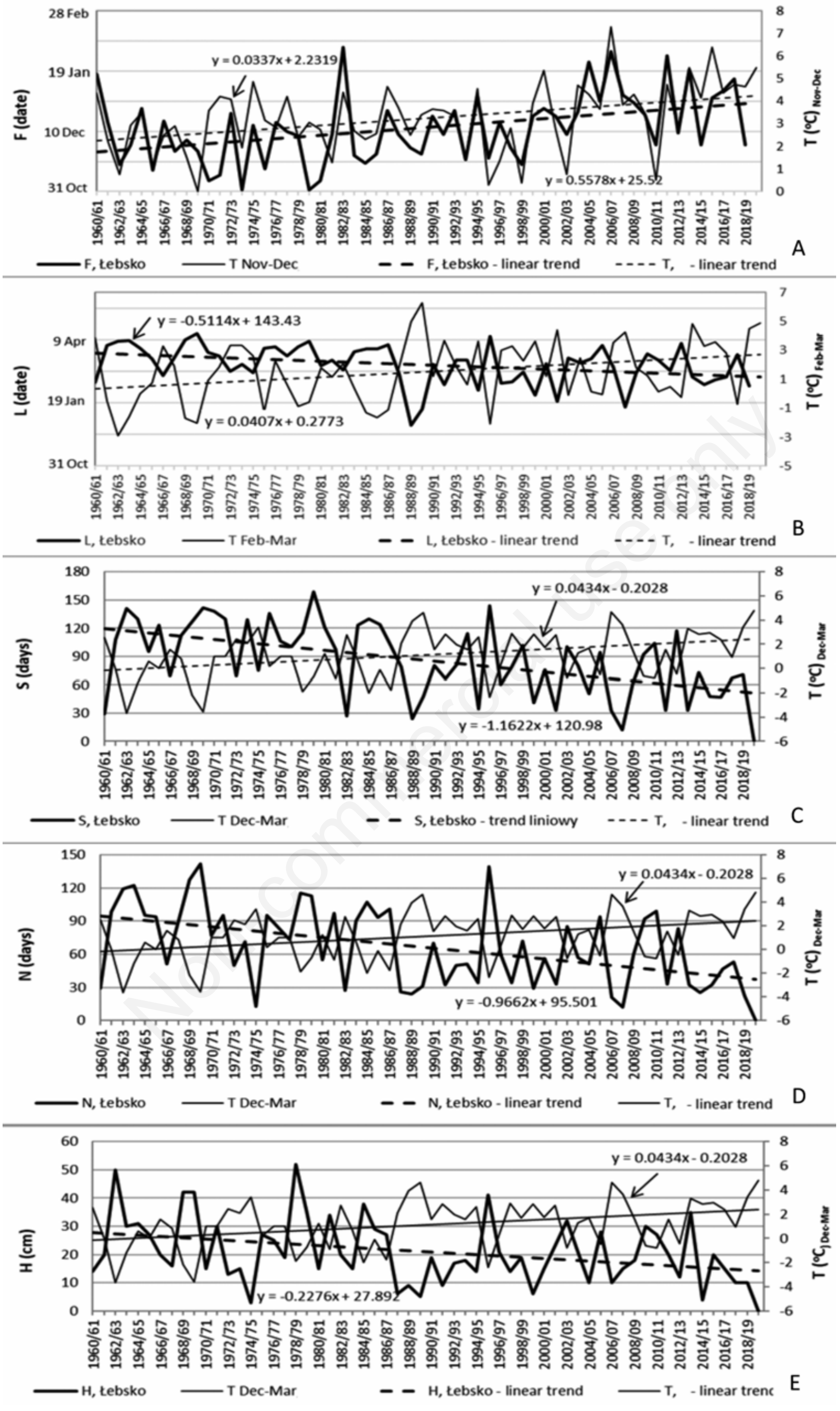

Fig. 5. Variability and trend lines for: A) first ice occurrence date (F), B) last ice disappearance date (L), C) ice season duration (S), D) number of days with ice (N), and E) annual maximum ice thickness (H) for lake Łebsko, and air temperature (T) from selected periods (Nov-Dec, Feb-Mar and Dec-Mar) in seasons 1960/61 to 2019/20, along with regression line equations.

48 cm for Lake Gardno and 52 cm for lakes Bukowo and Łebsko. Notably, H remains closely linked to N. The observed highly statistically significant correlations between both variables ranged from 0.77 for lake Bukowo through 0.79 for lakes Jamno and Łebsko, to 0.83 for Lake Gardno. Statistically significant correlation coefficients between H and L ranged from 0.58 for Lake Jamno to 0.66 for Lake Gardno. The strongest correlation coefficients for these lakes concern N and S. These range from 0.85 (Lake Jamno) to 0.9 (Lake Bukowo). The close relationship between S and N, further linked to L, and H, is corroborated by cluster analysis. On one hand, F values are closely linked with one another (taxonomic distance D = 0.2), but on the other hand, they are not linked with other ice parameters (D = 7.7). The remaining parameters (L, S, N, H) formed a distinct cluster (D = 1.3), which included smaller clusters. The closest relationships were obtained between S and N values (D = 0.5). L values were

Tab. 2. Mean and extreme values of ice parameters: date of first ice occurrence (F), date of last ice disappearance (L), number of days with ice (N), ice season duration (S), annual maximum ice thickness (H) and the ratio of the number of days with ice to the ice season duration (N/S) in southern Baltic coastal lakes (1960/61-2019/20).

Ice parameters		Jamno	Bukowo	Gardno	Łebsko
F (day)	Earliest	15 Nov	11 Nov	1 Nov	1 Nov
	Mean	16 Dec	16 Dec	12 Dec	12 Dec
	Latest	11 Feb	22 Feb	6 Feb	4 Feb
L (day)	Earliest	10 Dec	22 Dec	24 Dec	22 Dec
	Mean	7 Mar	5 Mar	9 Mar	8 Mar
	Latest	13 Apr	17 Apr	19 Apr	17 Apr
N (days)	Minimum	0	0	0	0
	Mean	64	65	70	66
	Maximum	133	139	142	142
S (days)	Shortest	0	0	0	0
	Mean	79	78	87	86
	Longest	134	139	160	159
H (cm)	Lowest	0	0	0	0
	Mean	20	21	21	21
	Highest	45	52	48	52
N/S	Minimum	0.27	0.32	0.20	0.17
	Mean	0.81	0.85	0.81	0.79
	Maximum	1.00	1.00	1.00	1.00

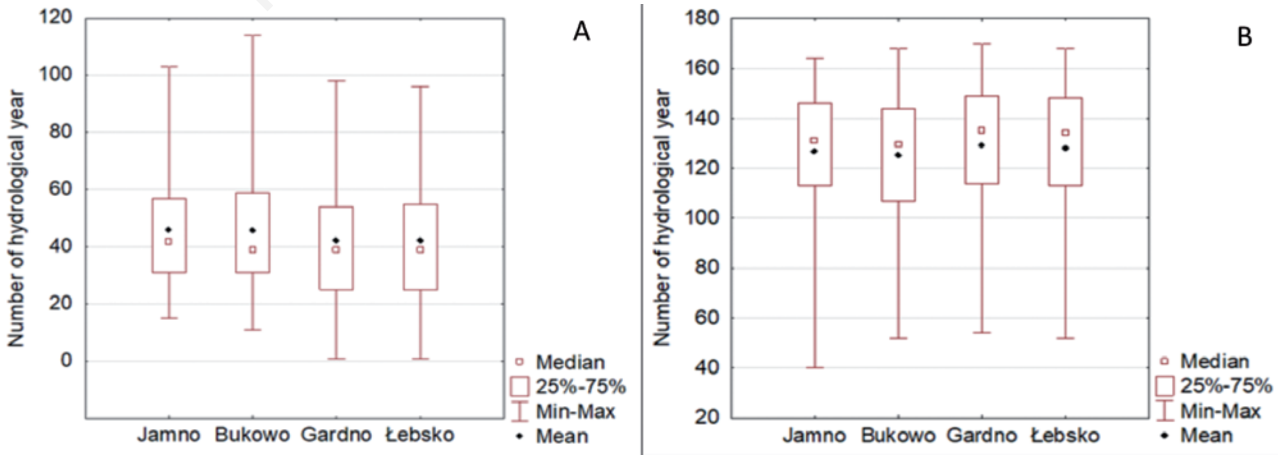

Fig. 6. Box and whisker plots presenting descriptive measures for: A) first ice occurrence date (F), B) last ice disappearance date (L) on coastal lakes (1960/61-2019/20).

linked with S and N only slightly weaker (D = 0.7). The studied lakes are characterized by the lowest diversity of the N parameter variability (D = 0.06), and the highest diversity of the F parameter (D = 0.2). The resultant dendrogram indicates certain diversity (distinctly separate clusters with a high degree of mutual correlation) in ice conditions in the western (lakes Jamno and Bukowo), and eastern part of the coast (lakes Gardno and Łebsko; Fig. 10). Ice occurred on the studied coastal lakes during nearly every winter. Through the study period, lakes Gardno and Łebsko were entirely ice-free only once, in the winter of 2019/20. Lakes Jamno and Bukowo were ice-free twice, in the winters of 1974/75 and 2019/20. The analysis performed here indicates an eastward increase in ice occurrence probability (p) on the studied lakes: for lakes Jamno and Bukowo it equals 0.967, and for lakes Gardno and Łebsko it is slightly higher, and equals 0.983 (Tab. 3). Standard deviations (SD) of p, however, are higher for the lakes located in the western part of the southern Baltic coast (0.023) than in the eastern part (0.017), as shown in Tab. 3.

Considering two consecutive 30 year-long subperiods separately, a shift in F is noted. In subperiod B compared to subperiod A, ice started occurring on Lake Jamno 11 days later; on lakes Bukowo and Gardno - 16 days later, and on Lake Łebsko - 19 days later. On the other hand, L occurred from 8 days earlier on Lake Jamno to 15 days earlier on Lake Gardno. In subperiod B, S was 18 shorter than in subperiod A on Lake Jamno, 27 days shorter on Lake Bukowo, 34 days shorter on Lake Gardno and 36

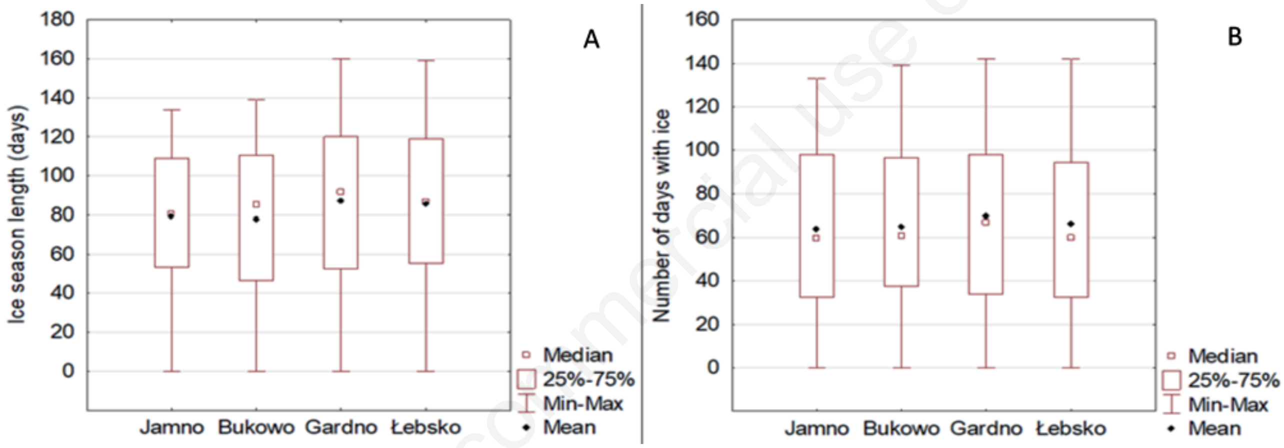

Fig. 7. Box and whisker plots presenting descriptive measures for: A) ice season duration (S) and B) number of days with ice (N) on coastal lakes (1960/61-2019/20).

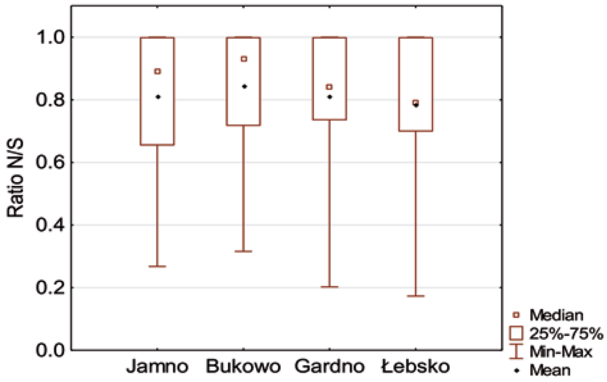

Fig. 8. Box and whisker plots presenting descriptive measures for the ratio of the number of days with ice to ice season duration (N/S) on coastal lakes (1960/61 - 2019/20).

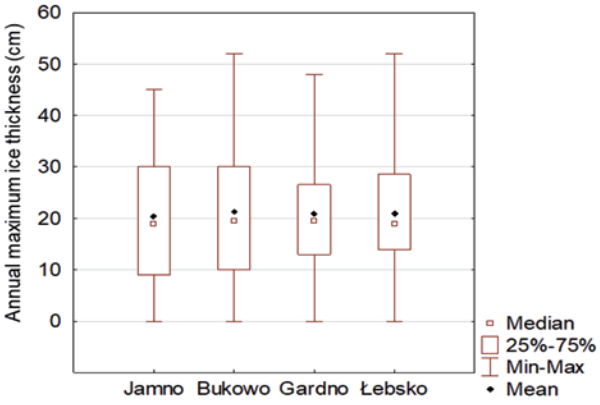

Fig. 9. Box and whisker plot presenting descriptive measures for annual maximum ice thickness (H) on coastal lakes (1960/61-2019/20).

days shorter on Lake Łebsko. Also N is reduced by 18-28 days. H in subperiod B is from 4 cm (Lake Jamno) to 8 cm lower (Lake Gardno) compared to subperiod A.

Analysis of links between ice parameters on coastal lakes and winter thermal conditions

Coastal lakes have similar morphometric, hydrodynamic and hydrothermal properties (Tab. 1). Differences concerning atmospheric circulation and thermal conditions with respect to individual lakes are small due to their location in close proximity to one another, and most of all, at a similar latitude (i.e., within the same climatic zone). Thus, these factors have a minor influence on the disparity in ice parameters between individual coastal lakes, and consequently the correlation coefficients obtained for the relationships between T and ice parameters on individual lakes are similar. The differences among correlation coefficients for relationships between T and individual ice parameters do not exceed 0.1 and range from 0.03 (-0.86 for Lake Jamno and -0.89 for Lake Bukowo) for L through 0.09 (0.62 for Lake Łebsko and 0.71 for Lake Bukowo) for F (Tab. 4). F and L were correlated not only with average $T_{Dec-Mar}$, but also with mean T values for the following periods: Dec, Nov-Dec, Nov-Jan and Mar, Feb-Mar, Feb-Apr, during which months first or last ice phenomena occurrences were observed the most frequently. The strongest correlation between F and T was achieved using $T_{Nov-Dec}$ values, when correlation coefficients ranged from 0.6 (for lakes of the eastern part of the study area) to 0.7 (for lakes of the western part). A 1°C increase in air temperature (Nov-Dec) will cause a 9-day delay in the date of first ice occurrence on lakes Gardno and Łebsko, and a 10-day delay on lakes Jamno and Bukowo. The strongest correlation between F and T was obtained using $T_{Feb-Mar}$ values, when correlation coefficients exceeded -0.85. A 1°C increase in air temperature (Feb-Mar) will accelerate the last ice disappearance date by 10 days on lakes Jamno and Łebsko and by 11 days on lakes Bukowo and Gardno.

Table 3. Ice occurrence probability (p) and its standard deviation (SD) on coastal lakes of the southern Baltic in the period from 1960/61 to 2019/20.

	Jamno	Bukowo	Gardno	Łebsko
p	0.967	0.967	0.983	0.983
SD	0.023	0.023	0.017	0.017

A higher diversity among correlation coefficients occur between T and individual ice parameters (F, L, S, N, H). For average values, the difference equals 0.28

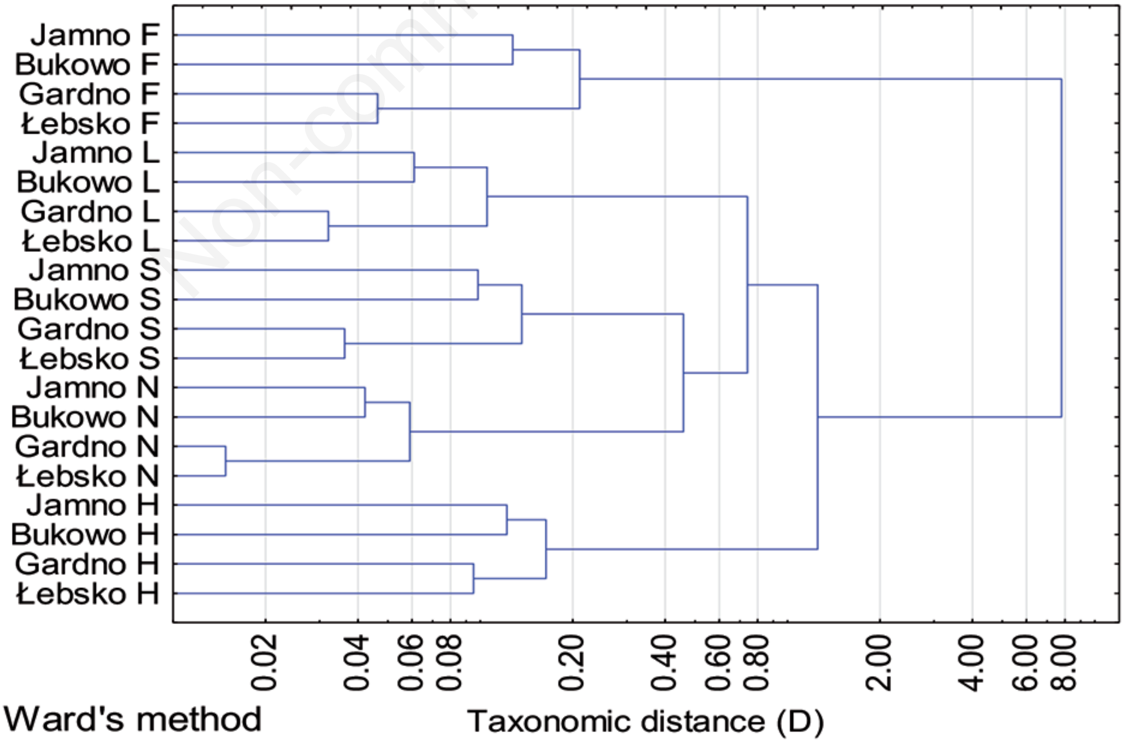

Fig. 10. Cluster analysis dendrogram showing the grouping of ice parameters on coastal lakes (1960/61-2019/20); D values are presented on a logarithmic scale.

(0.67 for date of first ice occurrence (F) through Nov-Dec period and -0.95 for number of days with ice (N) through Dec-Mar period; Tab. 4). The relatively low value of average correlation coefficient (equal to 0.67) for F and $T_{Nov-Dec}$ is caused by the influence of numerous factors on the date of water freezing in coastal lakes. Although T plays the most important part, the first episode of water freezing (i.e., ice formation) in a season, is to some extent influenced also by water temperature, wind (water mixing), marine water incursions. Physiographic (bathymetric) conditions of the studied lakes play a significant part. The high value of correlation coefficient (-0.95; the highest among all the examined relationships) for the relationship between N and mean $T_{Dec-Mar}$, indicates that T is essentially the strongest factor controlling ice conditions on lakes. N, in contrast to S, is a definitive reflection of ice conditions on lakes, as it includes only those days on which ice actually occurred. The ice season, however, lasts from the day of first ice occurrence to the day of last ice disappearance, and there may be ice-free days within this period, especially in the study area, where T frequently changes from negative to positive and vice versa. Shallow lakes react to such changes strongly and rapidly.

Of all the ice parameters considered here, the one that correlates the strongest with T is N (Tab. 4). The correlation coefficient values for the link between N and T range from -0.93 for Lake Łebsko to -0.97 for Lake Jamno (Tab. 4). This means that variations in T explain the variability of N for Lake Łebsko in 87% and for Lake Jamno in 94%. As indicated by the regression equation, a 1°C increase in T over the Dec-Mar period reduces N on Lake Jamno on average by 16 days, and on Lake Łebsko by 17 days (Fig. 11). For the remaining lakes (Bukowo and Gardno), correlation coefficients for the relationship between N and T all equal 0.94. All these relationships are highly statistically significant, at $\alpha<0.001$ level (Tab. 4). The links between H and T are also relatively strong. Their average correlation coefficient equals -0.84 (Tab. 4). The strongest relationship was observed for Lake Gardno, with a correlation coefficient equal to -0.87 (Tab. 4). A 1°C increase in T will cause a reduction in H by an average of 5 cm. Such high strength of this link compared to other correlations is influenced by the physiography of Lake Gardno, as it is the shallowest lake studied here (Tab. 1). Of all the examined lakes, Lake Bukowo in particular displays the strongest relationships between T and ice parameters (except for number of days with ice (N) on Lake Jamno and annual maximum ice thickness (H) on Lake Gardno). All relationships between ice parameters and T for Lake Bukowo are statistically significant at $\alpha<0.001$ level (Tab. 4). In the case of this lake, the highest value of correlation coefficient is 0.94 (T-$N_{Dec-Mar}$ relationship). This means that variations in T explain the variability in F in 50%, and variability in N in 87%. The regression equation indicates that a 1°C increase in T over the Nov-Dec period will delay F in a given winter season on lake Bukowo on average by 10 days (Fig. 12). A 1°C increase in T over the Dec-Mar period will cause a reduction in N on Lake Bukowo on average by 17 days (Fig. 12). The weakest links between F and T may be influenced, albeit to a limited extent, by a number of factors, such as: water temperature or factors other than temperature, e.g., wind, precipitation, marine water incursions through the straits linking a given lake with the sea. Further, the occurrence of first ice is not strongly associated with the severity of a winter. This is associated with the high climatic variability. First ice occurs in November, December, January, or even in February. To the contrary, N is clearly related to the degree of a winter's severity, and therefore also to T, because ice oc-

Tab. 4. Linear correlation coefficients for relationships of date of first ice occurrence (F), date of last ice disappearance (L), number of days with ice (N), duration of ice seasons (S) and annual maximum ice thickness (H) in southern Baltic coastal lakes with mean air temperature in certain seasons (1960/61-2019/20).

Ice parameters	Jamno	Bukowo	Gardno	Łebsko	Mean
$L_{DEC-MAR}$	-0.78**	-0.82**	-0.81**	-0.82**	-0.81
$S_{DEC-MAR}$	-0.82**	-0.84**	-0.79**	-0.78**	-0.82
$N_{DEC-MAR}$	-0.97**	-0.94**	-0.94**	-0.93**	-0.95
$H_{DEC-MAR}$	-0.83**	-0.84**	-0.87**	-0.82**	-0.84
F_{DEC}	0.51**	0.51**	0.40*	0.4*	0.46
$F_{NOV-DEC}$	0.70**	0.71**	0.63**	0.62**	0.67
$F_{NOV-JAN}$	0.58**	0.63**	0.57**	0.57**	0.59
L_{MAR}	-0.74**	-0.75**	-0.75**	-0.76**	-0.75
$L_{FEB-MAR}$	-0.86**	-0.89**	-0.87**	-0.88**	-0.88
$L_{FEB-APR}$	-0.83**	-0.87**	-0.87**	-0.88**	-0.86

**Coefficient significant at level $\alpha<0.01$; **coefficient significant at level $\alpha<0.001$.*

currence is closely linked to periods of cooling. As the studied lakes are entirely freshwater, variations in salinity makes virtually no influence on the values of individual ice parameters (no variability exists, it oscillates very close to null value). The lakes are freshwater because of the low salinity of the Baltic Sea, which equals as little as 7.5‰ off the Polish Baltic coast (https://www.marinefinland.fi/). Furthermore, the lakes

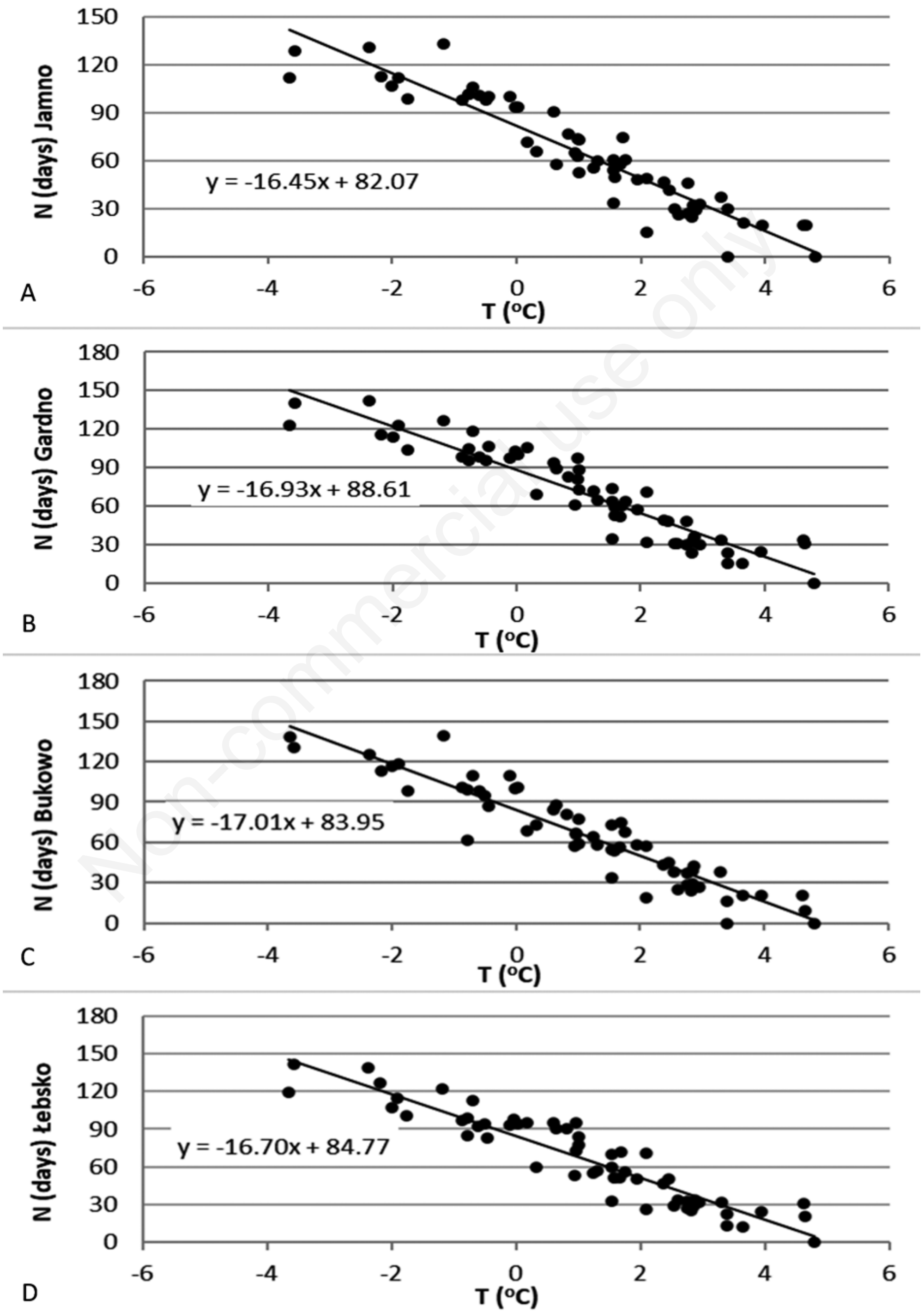

Fig. 11. Relations between winter (Dec-Mar) air temperature (T, 1960/61-2019/20) and number of days with ice (N) on lakes: A) Jamno, B) Gardno, C) Bukowo and D) Łebsko, along with regression line equation.

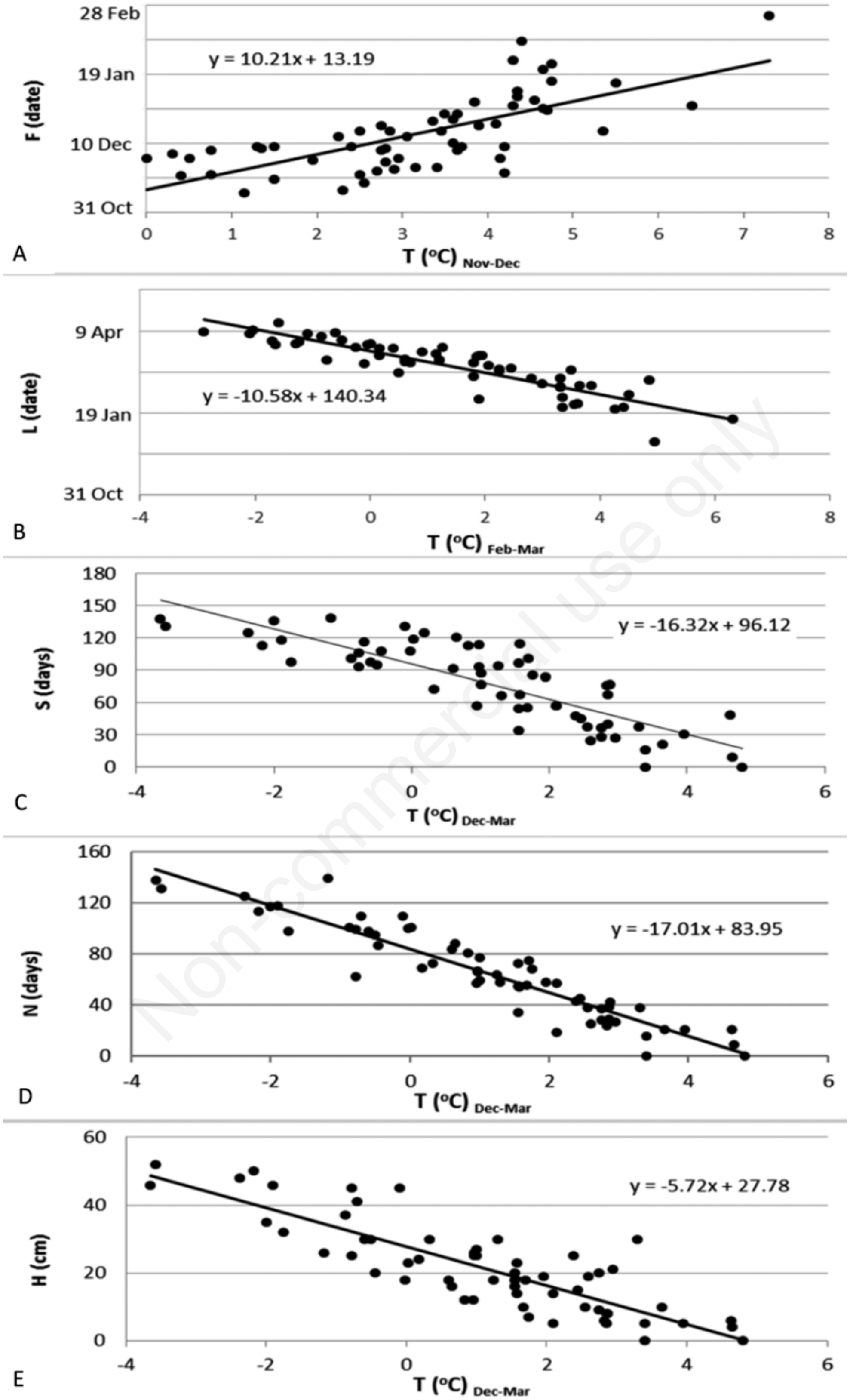

Fig. 12. Relations between air temperature from selected periods (Nov-Dec, Feb-Mar, Dec-Mar; 1960/61-2019/20) and: A) first ice occurrence date (F), B) last ice disappearance date (L), C) ice season duration (S), D) number of days with ice (N) and E) annual maximum ice thickness (H) on Lake Bukowo, along with the regression line equation.

have a restricted link to the sea. This results in a minimum, negligible influence of sea currents and other types of water motion in the sea on the variability of ice parameters on the studied lakes.

Analysis of trends in coastal lake ice parameters with winter thermal conditions

Ice occurrence is directly dependent on climatic conditions, and especially on T. The scatter of empirical points in Figs. 4 and 5 shows that in the 1960s, there were numerous severe winters characterized by very low T values, and concomitant high values of ice parameters (L, S, N, H). From the 1980s to the present, however, and especially in the last two decades of the study period, there is a clear dominance of mild winters, with relatively high temperatures, and low ice parameter values.

Considering the statistical significance of trends in ice parameters (Tab. 5), it is clear that most of the trends for the studied lakes are significant, and together they point to a distinct mildening of ice conditions, especially in the last decade (Figs. 4 and 5). Of all the analyzed ice parameters (F, L, N, S, H), the strongest trends concern ice season duration (S), and number of days with ice (N). Their correlation coefficients equal on average -0.45 and -0.43, respectively (Tab. 5). Correlation coefficients for these parameters for individual lakes range from -0.32 and -0.34, respectively, for Lake Jamno to -0.52 and -0.48, respectively, for Lake Łebsko. The weakest trend for S, albeit statistically significant at $\alpha<0.05$ level, concerns Lake Jamno (Tab. 5). An analysis of the spatial distribution of the linear trend coefficient values for S reveals an eastward trend toward increasingly negative values (Fig. 4). This means that in an eastward direction, on successive lakes: Jamno, Bukowo, Gardno and Łebsko, S will be gradually shorter, by 0.66, 0.99, 1.06 and 1.16 day-year^{-1}. Ice will also occur later and disappear earlier, and both N and H will be reduced in an eastward direction.

Of all the examined lakes, the strongest trends in ice condition changes concern Lake Łebsko - mean absolute value of correlation coefficients characterizing linear trends in the studied ice parameters equals 0.43 (Tab. 5). Correlation coefficients describing multiannual changes in the studied ice parameters for Lake Łebsko range from -0.35 annual maximum ice thickness (H) to -0.52 ice season duration (S). As indicated by the trend equation, H diminishes by 0.23 cm·year^{-1}, and S becomes reduced by 1.16 day·year^{-1} with the passage of time (Fig. 5). All trends observed for Lake Łebsko are statistically significant at least at $\alpha<0.01$ level (Tab. 5). The values of linear trend coefficient for all ice parameters generally increase toward the east. This indicates a stronger impact of the warming climate on ice conditions along the southern Baltic coast toward the east. Multiannual changes (year to year) in ice parameters, except for F and L, are larger for the lakes located in the eastern part of the study area (lakes Gardno and Łebsko) than for those located in the west (lakes Jamno and Bukowo; Tab. 2).

The analysis of dynamics in changes of 30-year long ice condition data series indicated a mildening of ice conditions on the coastal lakes in the second 30-year period, especially on lakes Bukowo and Gardno. On Lake Bukowo, first ice occurrence was noted earlier in the period 1960/61 through 1989/90 (trend coefficient value equalled -0.19 day·year^{-1}). In contrast, a delay in first ice occurrence was detected in the period 1990/91-2019/20 (1.23 day·year^{-1}, a relationship statistically significant at $\alpha<0.05$ level). Furthermore, an accelerated, statistically significant shortening of the ice season was noted in the second 30-year period (from -0.85 to -1.75 day·year^{-1}). On lake Gardno, in the period 1990/91-2019/20 a statistically significant delay in the date of first ice occurrence was detected (0.94 day·year^{-1}), while in the first 30-year period the trend coefficient equalled -0.39 day·year^{-1} (an earlier first ice occurrence). The trends in changes of the remaining ice parameters in the second 30-year period proved statistically insignificant. The performed analysis indicates that the increased rate of change in the second 30-year period may be linked to the increase in air temperature in winter months.

Tab. 5. Correlation coefficients for linear temporal trends of date of first ice occurrence (F), date of last ice disappearance (L), number of days with ice (N), duration of ice seasons (S) and annual maximum ice thickness (H) in southern Baltic coastal lakes (1960/61-2019/20).

Ice parameters	Jamno	Bukowo	Gardno	Łebsko	Mean
F	0.27*	0.41***	0.37**	0.42***	0.37
L	-0.21	-0.32*	-0.33**	-0.36**	-0.31
S	-0.32*	-0.45***	-0.49***	-0.52***	-0.45
N	-0.34**	-0.44***	-0.45***	-0.48***	-0.43
H	-0.16	-0.24	-0.41***	-0.35**	-0.29
Average of absolute values	0.26	0.37	0.41	0.43	0.37

**Coefficient significant at level $\alpha<0.05$; **coefficient significant at level $\alpha<0.01$; ***coefficient significant at level $\alpha<0.001$.*

DISCUSSION

Relationships between T changes and lake ice parameters were analyzed by numerous researches, who found certain patterns. Leppäranta (2014) reported that a 1°C increase in T during meteorological winter causes a 5-day delay in F, and a 10 cm decrease in H. These conclusions were based on the analysis of ice cover on a large (478.1 km^2 surface area) and deep (average depth: 9.65 m, maximum depth: 75 m) lake Kallavesi, located in the southern part of Finland, at an altitude of 82 m asl, and linked by straits with numerous other large lakes. Thus, Lake Kallavesi is multiple times larges and incomparably deeper than those examined in the present work. Benson *et al.* (2012) have also published on the progressively later formation of ice cover, and its earlier disappearance, and – as a consequence – a shorter S on the Northern Hemisphere lakes. That work studied changes taking place from the mid-19th century to 2005, but not everywhere were the changes statistically significant. Estimates of Benson *et al.* (2012) indicate that a 1°C increase in mean winter T caused 3.9-day delay in F in season, and a 5.6-day shift in L toward earlier dates. The study was based on an analysis of 75 lakes located in North America (mostly along the U.S.-Canada border), Scandinavia, Russia (Lake Baikal), and in Japan. The lakes varied with respect to morphometry, surface area (both lakes smaller than 20 km^2 and larger than 30,000 km^2 were selected for study), depth and altitude. None of the studied lakes was a coastal lake. A study performed on lakes of Brandenburg (Germany) indicated, however, that a 1°C increase in mean winter T will delay F by 3.8 days, and will shift L by as much as 9 days earlier (Bernhardt *et al*., 2012). The study was based on data from lakes Műggelsee and Stechlin. The former is relatively shallow (average depth: 4.8 m, maximum depth: 8.9 m), rather small (7.6 km^2 surface area), highly eutrophicated, polymictic flow-through lake located in the southeastern part of Berlin. Lake Stechlin is smaller (4.1 km^2 surface area), but considerably deeper (average depth 24.1 m, maximum depth: 69.5 m), oligotrophic and endorheic (drainageless), located 100 km north of Berlin. Previous research by Palecki and Barry (1986) showed that due to a 1°C increase in T in Nov and Apr, F occurs about 5 days later, and L occurs about 5 days earlier. These conclusions were drawn from an analysis of data from postglacial lakes, highly diverse with respect to size and morphometry, 59 of which are located in the southern part of Finland (Finnish Lakeland), with 4 located in northern Finland.

Changes in lake parameters presented in the cited works were considerably lower than those found in the present study. This points to a higher vulnerability of shallow coastal lakes to climate changes, in comparison to appreciably deeper lakes of other types, located within the same climatic zone, and being influenced by the same air temperature changes. The considerably stronger impact of T changes on the mildening of ice conditions on coastal lakes located along the southern Baltic coast was due to the relatively high exposure index of the studied lakes, and therefore their higher susceptibility to T changes, which results mostly from their very shallow depths. Lake depth has a particularly strong influence on F in a given season. Every additional meter of lake depth makes the time between the onset of sub-zero air temperatures and F on a given basin longer (Kirillin *et al*., 2012). As in the present work, Palecki and Barry (1986) have shown that an increase in T has a stronger influence on ice disappearance than on ice formation. Other authors publishing on trends in ice parameter changes (Korhonen, 2006; Jensen *et al*., 2007) have also discussed the influence of T on shifts in dates of ice disappearance, which is often stronger than the impact that T exerts on the timing of ice formation. The fact that air temperature makes a stronger influence on ice disappearance than on first ice occurrence, may be facilitated by solar factors. Insolation, especially during the winter-spring transition, facilitates an earlier ice disappearance. Research conducted in Sweden (Livingstone *et al*., 2010) indicated a stronger impact of T changes on changes in ice phenology (ice conditions) on lakes, in which ice cover lasts relatively short (such as the lakes studied in the present paper) than on those lakes on which ice cover lasts for a longer period in a year. The impact of warming on lake ice cover was considerably stronger in lakes of southern Sweden than in those of northern Sweden. Studies from the northern USA (Mishra *et al*., 2011) showed that the strongest influence on F was exerted by temperatures over the October-December period. L was influenced the strongest by temperatures over the period from March to May. Links between these parameters were not as strong as in the case of lakes studied in the present work. Studies on lake ice phenomena were conducted also in Poland. There are important papers that present spatial variability in some ice parameters (Gołek, 1987; Skowron and Szczepanik, 1988). There are also papers that characterize ice parameters, links between these parameters, and the frequency of ice phenomena occurrences (Girjatowicz, 2003a). Relationships between T and ice conditions from a forecasting perspective were presented in papers by Pasławski (1982) and Marszelewski and Skowron (2006), and for coastal lagoons – by Girjatowicz and Świątek (2021). As in the case of coastal lakes, a distinct acceleration in the mildening of ice conditions on the coastal lagoons was observed in the last two decades (2000-2020). The relationships between $T_{Dec\text{-}Mar}$ and both N and H on Lake Łebsko over the period 1961-2000 obtained by Marszelewski and Skowron (2006) are slightly different from the results of the present study. The differences between correlation coefficients obtained in both studies for N and H are minor, and equal 0.01 and 0.08, respectively. These are due to the difference in study period duration: the present work is based on a longer time series (1960/61-2019/20). The relationships between T and F obtained in the present study are distinctly weaker compared to the remaining ice parameters studied. The values of this parameter depend not only on air temperature, but also on water temperature, among other factors. Water temperature is considered in constructing forecasting relationships. In such cases, water temperature values are taken from the period immediately preceding the occurrence of ice (Maliński, 1971; Abuzyarov *et al*., 1988). Other ice parameters are not strongly influenced by water temperature, as following the ice formation, water temperature is nearly stable and oscillates close to 0°C. In addition to T_{air}, H is influenced by the thickness of snow cover on the ice cover. L is influenced, in addition to those two factors, by H attained in a given season, and solar radiation quantity dependent on insolation in the final period of a given ice season (Leppäranta, 2014). Leppäranta (2010) noted that a 1 cm increase in H causes the delay of ice disappearance by 1 day. Ice cover disappearance (acceleration of disappearance) is also influenced by rain occurrence (liquid precipitation) and strong wind (Kirillin *et al*., 2012).

The mildening of ice conditions taking place from the second half of the 19th century to the present is manifested not only on the southern Baltic coastal lakes (Dąbrowski *et al*., 2004; Heino et al., 2008), but also on the lakes of the whole Northern Hemisphere (Magnuson *et al*., 2000, Arai, 2000; Dibike *et al*., 2011; Benson *et al*., 2012; Kirillin, 2012; Leppäranta, 2014). It has manifested itself the most clearly in the final decades of the 20th century (Gronskaya 2000, Kratz *et al*., 2000, Vuglinsky *et al.* 2002). In Finnish (Nasijarvi, Oulujarvi) and Norwegian lakes (Mjosa), S has shortened by about 20 days from mid-19th century to the 1990s. Ice phenomena started occurring later and disappearing earlier (Kuusisto and Elo, 2000). Also a decrease in H has been observed on the lakes of southern Finland, especially through the period from the 1960s to 2003 (Kornhonen, 2006). In Sweden, changes in ice parameter values, and especially a significant shift in dates of ice cover disintegration and disappearance on lakes was observed since 1979 (Weyhenmeyer *et al*., 2008). Since then, also the frequency of winters during which no ice cover occurs on lakes of southern Sweden, has been increasing. The results of the present study indicate even more clearly the progressive mildening of thermal and ice conditions, especially in the second decade of the 21st century (2010/11-2019/20).

Changes in ice parameters do not point to strong mildening of ice phenomena everywhere. For instance, the degree of mildening on Estonian lakes (Nôges and Nôges, 2014) was minor. In the case of some basins it was even statistically insignificant. Changes in ice parameter values were not observed there, despite a large increase in both T values (especially in spring), and in water temperatures, which were relatively high, particularly since 1961. Modeling of changes in ice phenomena on European lakes (Nôges *et al*., 2009), indicated that lakes of Poland are transitioning from being ice-free in some winters to being always ice-free in winters.

CONCLUSIONS

The performed analysis leads to the following conclusions:

1) On the studied lakes, the intensity of ice phenomena increases toward the east. Ice cover stability increases (i.e., the ratio of number of days with ice to ice season duration), as well as ice occurrence probability and ice occurrence period duration (expressed both as ice season duration, and the number of days with ice), and finally – ice thickness.
2) Ice occurrence probability is very high and close to 1 (1-2 years without ice in the analyzed 60-year period). Trends indicate a mildening of ice conditions and a larger number of winters with no ice phenomena occurring on the studied lakes should be expected in the future.
3) Ice season duration and number of days with ice are both closely linked to the date of last day with ice, and to annual maximum ice thickness. Date of first ice occurrence is not linked to these parameters.
4) Shallow coastal lake ice conditions, characterized by a relatively short period of ice phenomena occurrences, are highly susceptible to climate change, especially to climate warming.
5) Air temperature and its multiannual variations, expressed as linear trends, very strongly impact the values and changes in ice parameters on the southern Baltic coast. This is due to their very shallow depth, and the resultant polymictic character of these lakes, causing them to react quickly to air temperature changes. This impact is considerably stronger than for other, deeper lakes.
6) The parameter that characterizes ice conditions in a given winter that shows the strongest link to air temperature is the number of days with ice. The correlation coefficient for the relationship between this parameter and air temperature equals -0.93 for Lake Łebsko to -0.97 for Lake Jamno. It can therefore be considered as the most accurate descriptor of lake ice conditions, and is strongly linked to the severity of a winter.
7) A weaker relationship was detected between air temperature and the date of first ice occurrence (correlation coefficient equals about 0.70). This is caused by

the contribution of other factors, mostly water temperature. The remaining parameters characterizing ice cover on individual basins are not strongly influenced by water temperature, as it remains nearly constant, close to 0°C.

8) On the studied lakes, a 1°C air temperature increase (Dec-Mar) will cause the following: a reduction in the number of days with ice by an average of 16-17 days; a reduction in ice season duration by 15-16 days; a reduction in annual maximum ice thickness by 5-6 cm. A 1°C air temperature increase in the period Nov-Dec will delay the date of first ice occurrence by an average of 9-10 days. Finally, a 1°C air temperature increase in the period Feb-Mar will accelerate the last ice disappearance by 10-11 days.
9) Local (physiographic) conditions exert an exceptionally strong influence on the strength of relationships between ice parameters and air temperature on coastal lakes. In these very shallow polymictic (coastal) lakes, the impact of air temperature on ice cover is considerably stronger than on lakes of different provenances.
10) Water exchange between the sea and coastal lakes, especially inflows of warmer marine waters in autumn and winter, may weaken the impact of air temperature on the lake ice cover. This relationship may also be weakened by strong wind, which contributes not only to the disintegration of ice cover, but may also set the ice in motion, causing its inflow or outflow.
11) Trends in ice season duration, number of days with ice, annual maximum ice thickness, and dates of first and last ice phenomena occurrence in a given season are statistically significant, even at $\alpha<0.001$ level (nearly all). These trends are decreasing, which points to a mildening of ice conditions. An exception is the increasing trend observed for the date of first ice occurrence, pointing to a progressively later occurrence of first ice on a given basin. A distinct acceleration in ice conditions mildening is manifested in the last two decades of the study period (2000/01-2019/20), which results from the ongoing climate warming.
12) The analysis of trends in changes through the 60-year study period indicated a shortening of the ice season on the studied lakes by an average of -0.97 day·year^{-1}, and a decrease in number of days with ice by -0.98 day·year^{-1}. The strongest trends are noted for Lake Łebsko (-1.16 day·year^{-1} and -0.97 day·year^{-1}, respectively). This is due to progressively later occurrence of first ice (on average by 0.47 day·year^{-1}), and gradually earlier last ice disappearance (on average by 0.51 day·year^{-1}).
13) Ice season duration and number of days with ice on lakes Jamno, Bukowo, Gardno and Łebsko become progressively shorter in an eastward direction, ranging from by about 0.7 to 1.0 day·year^{-1}. This testifies to an eastward, gradually stronger impact of the warming climate along the southern Baltic coast.
14) The relationships between ice parameters and air temperature, and trends in ice parameters characterized by high correlation coefficients, and high statistical significance ($\alpha<0.001$), may have a utility in forecasting occurrences of ice phenomena.

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