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Relationships between the Baltic Sea ice extent and ice parameters in the sheltered basins of the southern Baltic coast

by

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Abstract

In the study, archive data on the maximum annual ice extent in the Baltic Sea (MIB) for the period 1961–2018 were used. They were obtained from the FIMR database. Data on ice parameters for the four largest southern Baltic coastal lakes: Jamno, Bukowo, Gardno and Łebsko, and for Szczecin, Puck, and Vistula Lagoons, come from the Maritime Branch of Institute of Meteorology and Water Management – National Research Institute (in Polish: Instytut Meteorologii i Gospodarki Wodnej – Państwowy Instytut Badawczy, IMGW-PIB) in Gdynia. The time series for the lakes cover the years from 1960 to 2018, and for the lagoons – from 1946 to 2018. Three ice parameters were selected for this study: the number of days with ice, the duration of the ice season and the maximum ice thickness for a given winter. Relationships between the selected ice parameters for the studied basins and the MIB were examined using correlation and regression methods.

Correlations between the MIB and values of the ice parameters for the lakes and the southern Baltic coastal lagoons do not differ significantly. Considerable differences are observed amongst the correlation coefficients for individual ice parameters and the MIB.

Larger differences are found in relationships between the values of individual ice parameters in the sheltered basins and the MIB. The strongest correlation with the MIB is observed for the maximum ice thickness and the number of days with ice.

Key words: southern Baltic, sheltered basins, correlation, MIB, ice parameters

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Introduction

Values of ice parameters (for example ice thickness, ice season duration, or the probability of ice occurrence) in the Baltic Sea are affected by the large latitudinal extent of the basin, as well as distinct climatic differences between its northern and southern regions. Ice occurrence probability increases toward the north. The probability varies from about 30% along the southern coast, e.g. in the Hel, Arkona or Westermarkelsdorf area, up to even 100% in the northern part of the Baltic Sea, i.e. in the Gulf of Bothnia (Janérus & Jansson 1982; Jevrejeva et al. 2004). The Baltic Sea ice cover (i.e. the basin area covered by ice) varies on a year-to-year basis, largely due to the type of atmospheric circulation prevailing during a given winter – usually the North Atlantic Oscillation (NAO). Since the 1980s, however, the ice extent is comparable to, smaller, or definitely smaller than in the period 1720–1995 (Omstedt & Chen 2001; Vihma & Haapala 2009; Haapala et al. 2015). Forecasts indicate that by the end of the 21st century, the ice extent in the Baltic Sea will be limited to the northernmost parts of the Gulf of Bothnia.

The ice conditions in the northern regions of the Baltic Sea are much more severe (longer ice season and thicker ice cover) than in the south. While the ice along the southern Baltic coast disappears in early March, it continues to develop in the north (Leppäranta & Myrberg 2009). Along the northern Baltic coast, the first ice occurs on average before 15 November, and disappears after 15 May. Due to longer and more severe winters, the ice season in the north lasts more than 180 days and the maximum ice thickness in the season is larger than 70 cm (Lepparänta et al. 1988). In Kemi (Finland) in the 20th century, the last ice melted on average on 21 May, ranging from 16 April to 27 June (Leppäranta & Myrberg 2009).

The ice conditions along the southern Baltic coast are considerably milder and more dynamic. Ice usually appears at individual research stations in January, while in the Hel region it is not observed until early February. It tends to disappear in late February through early March. The average ice season duration, i.e. the number of days from the first to the last day with ice, ranges from 10 to 30 days for most stations along the southern Baltic coast, and the mean maximum ice thickness in the winter season for the period from 1954/1955 to 1999/2000 ranges from 5 to 12 cm (Girjatowicz 2007). This variation in ice conditions is mainly due to the seabed bathymetry and the river ice influx.

The Baltic Sea ice conditions are characterized by seasonality and large annual variability in the ice extent. During very severe winters, the entire Baltic Sea is often covered by ice, as evidenced by winters of 1939/40, 1941/42, and 1946/47 (Seina & Palosuo 1993; Koslowski & Loewe 1994; Omstedt et al. 2014). In 1987, 96% of the Baltic Sea was covered by ice. Even during such severe winters, the sea ice in the Gotland Sea was very thin and fragile, i.e. easy to break (Leppäranta & Myrberg 2009). During very mild winters, however, only the northernmost areas of the Baltic Sea and the bays are covered with ice. This is exemplified by winters of 1924/25, 1988/89, and 2007/08, when ice developed only in the coastal zones of the Gulf of Bothnia and along the northern coasts of the Gulf of Finland and the Gulf of Riga (Betin 1957; Seina & Palosuo 1996; Styszyńska 2010). In recent years, the 2014/2015 season witnessed a very mild winter. The ice appeared in the Gulf of Bothnia in mid-November, but December and January were exceptionally warm. The last ice melted in the first half of May, approximately two weeks earlier than usual. The ice season was also unusually short in 2015/16, when the Gulf of Finland was completely free of ice already in mid-April (Janecki et al. 2018).

In the coastal lagoons of the southern Baltic Sea, the ice conditions are milder than in the northern Baltic regions, but are more severe than in the southern unsheltered waters of the Baltic Sea (Preobraženskij 1960; Janérus & Jansson 1982; Girjatowicz 1990). Differences in ice conditions between sheltered and unsheltered basins of the southern Baltic are influenced by both climatic and morphometric (bathymetric) factors. On the one hand, unsheltered basins located further to the north experience more severe winters, but on the other hand, surface water cooling, conducive to more intense ice development, progresses faster in shallower basins with a higher exposure coefficient (i.e. surface to water depth ratio). Further, sheltered basins are less prone to water mass motion, e.g. due to wind-driven waves or currents. In the open sea, ice formation and ice durability are hindered because of frequent winter storms associated with the west to east migration of low pressure systems (Brayshaw 2005).

The first ice in the lagoons appear already in December. In the Vistula Lagoon, it occurs at the beginning of December, and in the Puck Lagoon and in the Szczecin Lagoon – at the end of December. The last ice disappears from the lagoons in March: in the middle of March in the Vistula Lagoon, and at the beginning of March in the Puck Lagoon and in the Szczecin Lagoon. The average ice season duration clearly increases toward the east. In the Szczecin Lagoon, the ice season lasts for 73 days, in the Puck Lagoon – 77 days, and in the Vistula Lagoon – 104 days. The maximum ice thickness in the season is: 18, 22, and 31 cm, respectively (Girjatowicz 2007). The lagoons in questions considerably vary in terms of ice conditions. This is particularly evident when the Szczecin Lagoon is compared to the Vistula Lagoon, as the ice conditions in the latter are considerably more severe (see Łazarienko & Majewski 1975; Majewski 1980; Szefler 1993). In these basins, the dominant form of ice is permanent ice cover (Maliński 1971; Zorina & Maliński 1975; Szefler 1993).

In the present study, the inner part of Puck Bay (i.e. the western part of the Gulf of Gdańsk) is referred to as the Puck Lagoon due to considerable shoaling of the Seagull Sandbar (depth range: from 0.9 to 1.6 m) and the Rewa Cape projecting toward the sandbar. These features together clearly distinguish this part of the gulf from the remainder, effectively making it a lagoon with respect to water circulation, biota, temperature and ice conditions. There is a dredged passage between the sandbar and the cape, which enables vessels to sail from Gdynia to Puck. The term "Puck Lagoon" was used, among others, by Nowacki (1976), Musielak (1983), and Majewski (1990). The Puck Lagoon is also termed "Little Puck Bay", or "Inner Puck Bay" in the literature.

Ice conditions in the coastal lakes of the southern Baltic Sea are milder than in the northern Baltic regions, but are more severe than in the southern part of the Baltic (open sea). The first ice appears on average in early December and disappears in early March. The average ice season duration ranges from 85 to 100 days and the mean maximum ice thickness is 22–24 cm (Girjatowicz 2003; Skowron 2009). For the open southern Baltic, these parameters range from 10 to 30 days and from 5 to 12 cm, respectively. The coastal lakes are covered with permanent ice even during very mild winters (Girjatowicz 2003; Choiński et al. 2014). The ice conditions are slightly more severe in the eastern part of the coast, although these lakes show little variation in the ice conditions (Girjatowicz 2003; Skowron 2009; Ptak 2013). The eastward increase in the severity of ice conditions is even more pronounced for the other lakes of northern Poland, especially with regard to the date on which the last ice disappears, the duration of the ice season and the maximum ice thickness (Marszelewski & Skowron 2009).

The fact that the ice conditions in the coastal lakes are more severe than in the open southern Baltic results from the shallow depth of these lakes – the maximum depths of Jamno, Bukowo, Gardno and Łebsko lakes are only 3.9, 2.8, 2.6 and 6.3 m, respectively (Jańczak 1997; Choiński 2006).

Although values of the ice parameters in the lakes and coastal lagoons differ from the corresponding values observed for the open Baltic, it can be assumed that there are statistically significant correlations between them. The objective of the present work is to analyze the relationships between the ice parameters (ice season duration, number of days with ice, and maximum ice thickness for a given winter) in the southern Baltic lagoons and the coastal lakes, and the maximum annual ice extent in the entire Baltic Sea expressed in km^2 (hereafter abbreviated as MIB – Maximum Ice Extent in the Baltic Sea). The MIB parameter, which refers to the ice-covered area of the Baltic Sea as a whole, is a good descriptor of the Baltic Sea ice conditions in a given winter. An additional objective is to emphasize the variation in the strength of connections between individual sheltered basins and to characterize the factors affecting this variation. It is likely that the similarity of climatic conditions, especially the similarity between the climatic trends observed in the entire Baltic Sea basin, will impact the strong relationships between the ice conditions in the lagoons and coastal lakes, and the Baltic Sea ice cover (MIB). Strong and statistically highly significant correlations can be used to estimate values of the selected ice parameters. In the case of discontinuous data series, due to lack of any given observation, it will be possible to estimate a variable for a given winter based on the observed relationships.

Materials and methods

Archive data on MIB for the period 1961–2018, expressed in km^2, were obtained from the Finnish Institute of Marine Research (FIMR) database. Data for the period 1720–1995 were published by Seina & Palosuo (1996). The MIB was used in this study as a parameter characterizing the ice conditions in the Baltic Sea, given that the ice cover extent best characterizes the ice conditions in the Baltic Sea, even though the state of sea ice is basically described by the extent, thickness and drift directions (Haapala et al. 2015).

Data on the ice parameters for the four largest southern Baltic coastal lakes: Jamno, Bukowo, Gardno and Łebsko, and for Szczecin, Puck, and Vistula lagoons come from the Maritime Branch of the Institute of Meteorology and Water Management – National Research Institute (IMGW-PIB) in Gdynia (Poland). The time series for the lakes covers the period from 1960 to 2018, and for the lagoons – from 1946 to 2018. Ice observations of individual basins were performed in the following fixed points: Unieście (Lake Jamno), Bukowo Morskie (Lake Bukowo), Gardna Wielka (Lake

Gardno), Izbica (Lake Łebsko), Trzebież (Szczecin Lagoon), Puck (Puck Lagoon), and Tolkmicko (Vistula Lagoon; Fig. 1). The availability of continuous time series of data on the ice occurrence during the ice season (i.e. ice occurrence on nearly annual basis) was taken into account when selecting the coastal lakes and lagoons. The basins selected for the analysis are characterized by similar morphological and climatic conditions of ice formation. The main morphometric and bathymetric data for these basins are presented in Table 1.

The analysis started with an estimation of the probability of ice occurrence in the coastal lagoons and coastal lakes based on the principles used in the works by Jevrejeva et al. (2004), Leppäranta (2014) and Karetnikova et al. (2017). The sea ice occurrence probability for the studied basins and its standard deviation were calculated using the following equations (Leppäranta 2014):

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

where:

p – probability of ice occurrence,
N – the total number of seasons (years),
n – the season number,
I(n) – binary variable,
I(n) = 0 – season n is ice free,
I(n) = 1 – season n is with ice,
SD – standard deviation of the estimator.

Three ice parameters were selected for the detailed analysis: the number of days with ice (N), i.e. days during which any form of ice was observed; the ice season duration (S), i.e. the period from the day when the first ice was observed to the day when the last ice disappeared, but including possible ice-free periods between days with ice (expressed in days); and the maximum ice thickness (H) in a given winter. Mean values of the ice parameters, their standard deviation and ranges (extreme values of the ice parameters as well as the season and the basin of their occurrence)

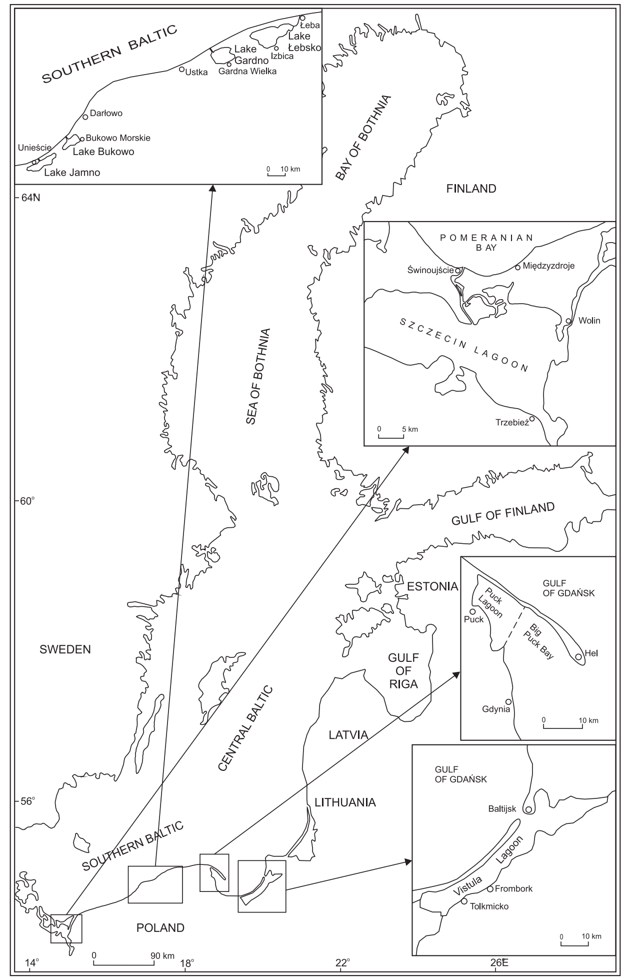

Figure 1

The Baltic Sea basin and the study site

Table 1

Morphometric and bathymetric data for the sheltered basins of the southern Baltic Sea coast (after Łazarienko & Majewski 1975; Majewski 1980; Nowacki 1993; Jańczak 1997; Choiński 2006)

Basins	Elevation (m a.s.l.)	Surface area (km^2)	Volume (km^3)	Average depth (m)	Maximum depth (m)	Shoreline length (km)
Lagoons						
Szczecin	0.0	686.9	2.582	3.8	8.6	243.0
Puck	0.0	102.7	0.320	3.1	9.7	52.0
Vistula	0.0	838.0	2.300	2.6	5.1	270.0
Lakes						
Jamno	0.1	22.30	0.032	1.4	3.9	28.3
Bukowo	0.1	16.44	0.032	1.8	2.8	23.2
Gardno	0.3	23.37	0.031	1.3	2.6	23.3
Łebsko	0.3	70.02	0.118	1.6	6.3	55.9

in the groups of coastal lagoons and coastal lakes are tabulated in Table 2. Mean and maximum values of these ice parameters for both the selected coastal lagoons and lakes and are tabulated in Table 3.

were assumed as dependent variables (y), while MIB values were treated as independent variables (x). Ice parameter relationships were also calculated between individual lagoons (within the group of three coastal

Table 2

Mean, standard deviation (SD) and extreme values (per season and basin) of selected ice parameters: ice season duration (S), number of days with ice (N), maximum ice thickness (H) in groups of southern Baltic coastal lagoons (1946/1947 through 2017/2018) and lakes (1960/1961 through 2017/2018)

Ice parameters	Mean	SD	maximum			minimum		
			values	season	basin	values	season	basin
Lagoons								
S (days)	77.5	39.8	151	1962/63	Vistula	0	repeatedly	
N (days)	63.9	37.6	138	1969/70	Vistula	0	repeatedly	
H (cm)	22.5	15.0	70	1962/63	Puck	0	repeatedly	
Lakes								
S (days)	84.1	36.3	160	1979/80	Gardno	0	1974/75	Jamno, Bukowo
N (days)	68.3	34.3	142	1995/96	Gardno	0	1974/75	Jamno, Bukowo
H (cm)	21.7	12.1	60	2009/10	Jamno	0	1974/75	Jamno, Bukowo

Table 3

Mean and extreme values of selected ice parameters: ice season duration (S), number of days with ice (N), maximum ice thickness (H) in southern Baltic coastal lagoons (1946/1947 through 2017/2018) and lakes (1960/1961 through 2017/2018)

Ice parameters		Lagoons			Lakes			
		Szczecin	Puck	Vistula	Jamno	Bukowo	Gardno	Łebsko
S (days)	shortest	0	0	16	0	0	15	12
	mean	66.1	70.5	96.2	80.2	80.2	88.7	87.3
	longest	135	139	151	134	139	160	159
N (days)	minimum	0	0	11	0	0	15	12
	mean	51.9	57.5	82.4	65.3	66.8	73.3	67.9
	maximum	123	128	138	133	139	142	142
H (cm)	lowest	0	0	3	0	0	4	3
	mean	17.7	21.0	28.9	21.6	22.1	21.6	21.5
	highest	60	70	70	45	52	48	52

Correlations (especially those where outliers were observed in regression plots) were interpreted based on mean monthly and mean winter (December through February) air temperature values from Szczecin (for the western Baltic coast), Ustka (central coast), and Gdynia (eastern coast) for winters from 1946/47 to 2017/2018. On the basis of these data, the deviation from the mean air temperature for the whole study period was calculated for each winter.

Relationships between the selected ice parameters for the studied basins and the MIB were analyzed using the correlation and regression method. Linear regression equations (y = ax + b) were determined. The ice parameters for the lakes and lagoons (N, S and H)

lagoons), individual lakes (within the group of four coastal lakes), and between average values for the lagoon group and average values for the lake group.

The strength of these correlation relationships was examined using the correlation coefficient (*r*) and the determination coefficient (r^2 100%), and their statistical significance was evaluated using the Fisher–Snedecor test (Łomnicki, 2014; Time Series Analysis 2010). The correlation coefficients estimated in this study were high, and all proved to be statistically significant at $p < 0.001$. For linear relationships presented in the Cartesian coordinate system, a 99% confidence interval was applied.

Results

Ice occurrence probability in the coastal lagoons and lakes, and its relationship with the maximum ice extent in the Baltic Sea (MIB)

Ice phenomena occur commonly in the basins described in the present work. During our research, ice occurred on the Vistula Lagoon as well as on Gardno and Łebsko lakes in each season. No ice was observed on Jamno and Bukowo lakes during only one season (winter of 1974/1975), in the Puck Lagoon – during three seasons, and in the Szczecin Lagoon – during six seasons. These differences are due to milder winters in the western part of the southern Baltic coast compared to the eastern part, and due to the lower heat capacity of the lakes caused by their smaller areas and slightly shallower depths relative to the lagoons. The higher isolation of the lakes from the sea compared to the lagoons may also affect the probability of ice occurrence. However, the differences in the ice occurrence probability in individual basins are not high. There is a distinct eastward increase in the ice occurrence probability. Exact values of the ice occurrence probability are listed in Table 4 along with the standard deviation.

During seasons with no ice in at least one of the analyzed basins, the MIB was considerably below the average derived from all the analyzed seasons. The average MIB for the seasons from 1946/47 to 2017/2018 ($\bar{x}$) was 182.31 km^2. During seasons with no ice, the MIB was as low as 85.43 km^2. The latter value is slightly lower than the difference between the average MIB and the standard deviation (SD = 90.46 km^2; $\bar{x}$ – SD = 91.84 km^2). The minimum MIB, equal to 49 km^2, was observed for the season 2007/2008 when no ice phenomena were observed in the Puck Lagoon. This represents nearly ten times lower ice extent compared to the maximum MIB of 420 km^2 observed in the season of 1946/47. The mildest ice conditions in the sheltered basins of the southern Baltic coast were observed in the season of 1974/75. No ice occurred in Szczecin and Vistula lagoons, or on Jamno and Bukowo lakes. The MIB for that season was also relatively low, i.e. 75 km^2.

Table 5

Linear correlation coefficients between the following ice parameters: ice season duration (S), number of days with ice (N) and maximum ice thickness (H) in southern Baltic coastal lagoons in the period from 1946/1947 to 2017/18

Ice parameters	Lagoons	Szczecin	Puck	Vistula
S	Szczecin	1		
	Puck	0.89	1	
	Vistula	0.80	0.85	1
N	Szczecin	1		
	Puck	0.93	1	
	Vistula	0.87	0.91	1
H	Szczecin	1		
	Puck	0.85	1	
	Vistula	0.88	0.88	1

Relationships between the ice parameters in the coastal lagoons, coastal lakes, and between lagoons and lakes

Values of the ice parameters for the ice seasons in individual coastal lagoons and coastal lakes are comparable. These basins are located within the same climatic zone and in similar physiographic conditions (location along the coast, similar degree of isolation from the sea, and comparable depth). The similarity of the long-term variability in the values of the ice parameters was estimated by means of a correlation coefficient. The correlation between the ice parameters in the coastal lagoons shows that the highest similarity is observed for the number of days with ice (Table 5), especially for Szczecin and Puck lagoons, which may be explained by similar bathymetry (Table 1). A smaller similarity between the lagoons is observed for the duration of the ice season, usually for geographically distant basins (Szczecin and Vistula lagoons). Apart from bathymetry, also climatic conditions influence the strength of these relationships (Table 5): the eastern part of the Baltic coast has a more continental climate, with more severe winters compared to the western part.

Table 4

Probability of ice occurrence (p) and its standard deviation (SD) in southern Baltic coastal lagoons (1946/1947 through 2017/2018) and lakes (1960/1961 through 2017/2018)

statistical	Lagoons			Lakes			
parameters	Szczecin	Puck	Vistula	Jamno	Bukowo	Gardno	Łebsko
p	0.92	0.96	1	0.98	0.98	1	1
SD	0.032	0.028	0	0.019	0.019	0	0

The coastal lakes are characterized by similar values of the ice parameters regardless of the analyzed parameter. The lowest correlation coefficient indicates a slightly lower similarity for the maximum ice thickness (Table 6). Slightly greater dispersion of the relationship strength is observed between individual lakes – the greatest similarity in the variability of the ice parameters was found for the lakes located closest to each other (Jamno and Bukowo, Gardno and Łebsko).

The correlation coefficient values calculated for the group of the coastal lagoons and the group of the coastal lakes (i.e. between individual basins belonging to each group) were very high. For this reason, the values for basins belonging to each group were averaged before further statistical analysis to determine general relationships between the lagoons and the lakes, and to compare their respective ice parameters with the MIB.

The correlations between individual average ice parameters characterizing the lagoons and the lakes from the 1960/61 season to the 2017/18 season are high, ranging from 0.93 for the ice season duration, through 0.95 for the maximum ice thickness, up to 0.97 for the number of days with ice. This testifies to the very high similarity in the long-term variability between the southern Baltic coastal lagoons and coastal lakes.

Relationships between the ice parameters in the coastal lagoons and the ice extent in the Baltic Sea

Although climatic conditions vary between the southern Baltic coastal lagoons and the Baltic Sea as a whole, especially in the northern part, they show similar trends. Usually, the severity of winter in the Baltic Sea is paralleled by the severity of winter in the coastal lagoons. This is reflected in statistically significant correlations between the ice parameters observed in the coastal lagoons and the MIB.

Table 6

Linear correlation coefficients between the following ice parameters: ice season duration (S), number of days with ice (N) and maximum ice thickness (H) in southern Baltic coastal lakes in the period from 1960/1961 to 2017/18

Ice parameters	Lakes	Jamno	Bukowo	Gardno	Łebsko
S	Jamno	1			
	Bukowo	0.95	1		
	Gardno	0.88	0.89	1	
	Łebsko	0.87	0.88	0.96	1
N	Jamno	1			
	Bukowo	0.96	1		
	Gardno	0.88	0.86	1	
	Łebsko	0.96	0.96	0.90	1
H	Jamno	1			
	Bukowo	0.88	1		
	Gardno	0.87	0.88	1	
	Łebsko	0.83	0.89	0.91	1

Correlations between average values of the ice parameters (calculated based on values from the three lagoons) and the MIB are high. The correlation value for the ice season duration is 0.81 and for the number of days with ice and the maximum ice thickness is 0.82 (Table 7). This indicates that the ice processes in the southern Baltic coastal lagoons and the maximum ice extent in the Baltic Sea (MIB) are very similar. The correlations between individual lagoons and the MIB are not as strong. This is due to the local effects on the ice parameters in individual basins in certain ice seasons. These local ice conditions are less strongly correlated with the overall Baltic Sea ice conditions (e.g. ice seasons corresponding to outliers in Figure 2a, b).

Table 7

Linear correlation coefficients between the maximum annual ice extent in the Baltic Sea (MIB) and ice parameters: ice season duration (S), number of days with ice (N) and maximum ice thickness (H) in southern Baltic coastal lagoons in the period from 1946/1947 to 2017/18

Ice parameters	Lagoons			
	Szczecin	Puck	Vistula	All lagoons (average)
S	0.72	0.73	0.69	0.81
N	0.73	0.79	0.73	0.82
H	0.80	0.79	0.79	0.82

The analysis of the relationships between the MIB and values of the ice parameters in individual lagoons shows that the strongest correlation occurs between the MIB and the maximum ice thickness (Table 6). Of all the basins considered here, the strongest correlation was observed for the Szczecin Lagoon – the variability in the maximum ice thickness is explained by the variability in MIB in 64% (Fig. 2a). An increase in the MIB by a single unit (10^3 km^2) will cause an increase in the ice thickness in the Szczecin Lagoon by 0.1 cm on average (Fig. 2a).

A strong positive correlation was also found between the MIB and the number of days with ice in selected lagoons. The strongest correlation was observed for the Puck Lagoon (Table 6). The variability in the number of days with ice is explained by the MIB variance in 62% (Fig. 2b). Such strong coexistence of

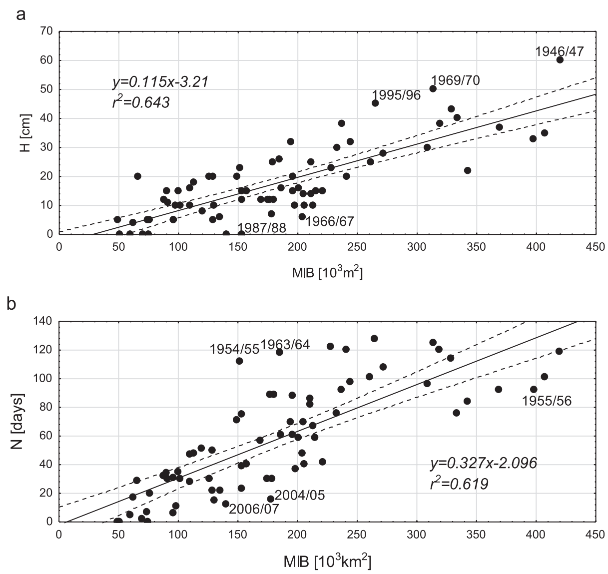

Figure 2

Relationships between the maximum annual ice extent in the Baltic Sea (MIB) and: the maximum ice thickness (H) in the Szczecin Lagoon (a) and the number of days with ice (N) in the Puck Lagoon (b) in 1946/1947–2017/2018

variability in the discussed ice parameters is associated with a similar course of the heat loss during periods of negative air temperatures in these basins. Late in the cooling period (the period with air temperature T < 0°C), both the maximum ice thickness and the maximum ice extent reach the highest values.

Slightly weaker correlations were found between the MIB and the ice season duration (Table 7). Determination coefficients for these correlations are about 50%. Correlation and regression coefficients for these relationships are positive, which indicates that an increase in the MIB will be reflected in an increase in values of these ice parameters. The ice season duration is not an accurate representation of ice conditions, as the ice season may actually include several periods of ice presence separated by ice-free periods. This may reduce a correlation between the MIB and the ice season duration. High co-occurrence of individual ice parameter values and the MIB is due to similar thermal conditions that directly impact the ice formation. The increase in ice thickness and ice season duration depends mainly on air temperature.

Some data outliers can be observed in Figures 2a, b. Such scatter of data points relates to unusual cases, mostly extreme winters, either very mild or very severe. Figure 2a shows the relationship between the maximum ice thickness and the MIB for the Szczecin Lagoon. Outliers represent winters that were very severe (1969/70, 1995/96 and 1946/47) or very mild (1987/88 and 1966/67) along the southern Baltic coast. For these severe winters (December–February), air temperature deviations from the mean value (1.0°C) for the period 1946/47–2017/18 are very low: −4.8, −4.0 and −5.3°C, respectively. Very low air temperatures contributed to an intensive increase in ice thickness. The maximum ice thickness in the Szczecin Lagoon during these winters was very high: 50, 45 and 60 cm, respectively. During the mild winters of 1987/88 and 1966/67, air temperature deviations from the mean value (1.0°C) were positive and equal to 1.7 and 1.4°C, respectively. Therefore, the maximum ice thickness in the Szczecin Lagoon in the winter of 1966/67 was only 6 cm. No ice was observed in the winter of 1987/88.

Figure 2b shows the relationship between the number of days with ice and the MIB for the Puck Lagoon. Outliers represent severe winters (1963/64 and 1955/56), mild winters (2004/05 and 2006/07) and the temperate winter of 1954/55. Air temperature deviations from the mean value (0.9°C) for the severe winters and the temperate winter are negative and are −1.9, −2.1 and −0.9°C, respectively. Such low air temperatures were conducive to intensive ice development. Thus, the number of days with ice in the Puck Lagoon was very high and amounted to 118, 92 and 112 days, respectively. During the mild winters of 2004/05 and 2006/07, air temperature deviations from the mean value (0.9°C) were positive: 0.8 and 3.3°C, respectively. During these warm winters, the ice was poorly developed. Thus, the number of days with ice in the Puck Lagoon was low: 16 and 12 days, respectively.

Correlations between the ice parameters in the coastal lakes and the ice extent in the Baltic Sea

The southern Baltic coastal lakes are located at approximately the same latitude, hence in the same climatic zone as the coastal lagoons under study. Thus, the relationships between the Baltic Sea ice conditions and the ice parameters of the lakes are similarly strong as those observed for the coastal lagoons. However, in the case of the ice season duration and the maximum ice thickness, the relationships between average values of the ice parameters and the MIB for the lakes are slightly weaker than the corresponding relationships for the lagoons. The correlation coefficients for the MIB and the average number of days with ice are 0.82 for both lakes and lagoons.

The correlation coefficients between the values of the ice parameters for the selected coastal lakes and the MIB are slightly lower than for mean values for the group of coastal lakes and range from 0.67 to 0.80 (Table 8). The strongest relationships were observed between the number of days with ice and the MIB (Table 8). For Jamno and Bukowo lakes, the variability in the number of days with ice is explained by the MIB variability in 65% (Fig. 3a). The increase by 1000 km^2 in the MIB will be reflected in a 0.3 day increase in the number of days with ice (Fig. 3a). In these shallowest basins, the number of days with ice (i.e. days during which any form of ice was observed) is most strongly affected by the thermal conditions, similarly to the MIB. Although these parameters are expressed in different units (number of days versus area in km^2), they are effected by similar thermal conditions in any given time throughout the ice season, especially by air temperature.

Rather strong relationships were also observed between the MIB and the maximum ice thickness and between the MIB and the ice season duration in the selected lakes (Table 8). An increase in the MIB is reflected in increased values of these ice parameters. The strongest relationships (with a correlation coefficient r = 0.77 and a 60% determination coefficient) were determined for the MIB and the maximum ice thickness in Lake Gardno. The increase by 1000 km^2 in the MIB is reflected on average in a 0.1 cm increase in the ice thickness (Fig. 3b).

Similarly to the regression plots for the coastal lagoons (Figs 2a, b), several outliers are also observed in the regression plots for the southern Baltic coastal lakes (Figs 3a, b). The observed data point scatter concerns extreme winters, both very severe and very mild ones.

Figure 3a shows the relationship between the number of days with ice on Lake Jamno and the MIB. The outliers represent mostly severe (1963/64, 1995/96, 1986/87) and mild winters (1987/88, 1974/75). Air temperature deviations from the mean value (0.8°C) for these severe winters are high and negative: −2.0, −3.2 and −2.6°C, respectively. Such low air temperatures were conducive to the development of ice. Therefore, the number of days with ice on Lake Jamno was high for these winters, amounting to 133, 131 and 99 days, respectively. During mild winters of 1987/88 and 1974/75, air temperature deviations from the mean value (0.8°C) were positive: 1.3 and 2.6°C, respectively. Thus, during these warm winters, the number of days with ice on Lake Jamno was as low as 15 days in the winter of 1987/88. No ice occurred on Lake Jamno during the winter of 1974/75.

Figure 3b shows the relationship between the maximum ice thickness on Lake Gardno and the MIB. The outliers also represent severe winters (1969/70, 1995/96 and 1962/63), and mild winters (2006/07 and 1987/88). For severe winters, air temperature deviations from the mean value (0.8°C) are highly negative: −4.4, −3.2 and −4.5°C, respectively. Very low temperatures were conducive to the intensive development of ice. Therefore, during these severe winters, 47, 45 and 48 cm (respectively) thick ice was observed on Lake Gardno. For the mild winters of 2006/07 and 1987/88, air temperature deviations from the mean value (0.8°C) are positive: 3.8 and 1.3°C, respectively. During these warm winters, the thickness of ice on Lake Gardno was small and equal to 5 and 7 cm, respectively. The outliers are affected not only by thermal conditions, but also by the high inertia of ice in the shallow basin due to the presence of thicker ice, which takes longer to melt. The intensive development of thicker ice, which lasts relatively long, takes place in these basins during severe winters. Such basins are more sensitive to air temperature changes than the sea, which is characterized by a higher heat capacity due to the greater depth of water (i.e. larger volume of water).

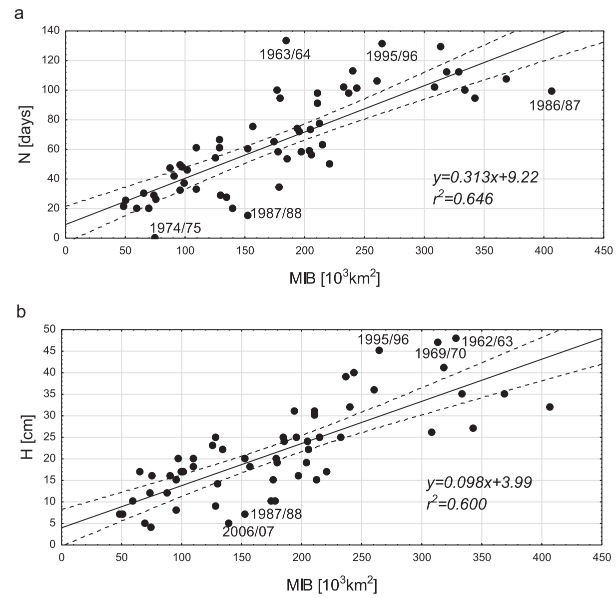

Figure 3

Relationships between the maximum annual ice extent in the Baltic Sea (MIB) and: the number of days with ice (N) in Lake Jamno (a) and the maximum ice thickness (H) in Lake Gardno (b) in 1960/1961–2017/2018.

Comparison of the relationships between the ice parameters of the southern Baltic coastal lagoons and lakes and the ice extent in the Baltic Sea

In general, the correlations between the MIB and the ice parameters for the southern Baltic coastal lagoons and between the MIB and the ice parameters for the coastal lakes do not vary significantly. These relationships are more varied depending on individual ice parameters (Tables 7 and 8). The correlations between the MIB and the maximum ice thickness are stronger for the lagoons than for the lakes (Tables 7 and 8). Whereas, the correlations between the MIB and the number of days with ice are weaker for the lagoons than for the coastal lakes. The strength of the correlation between the MIB and the ice season duration are similar for the lagoons and lakes (Tables 7 and 8) – correlation coefficients do not differ by more than 0.06.

The small differences between the correlation coefficients for the MIB and values of the ice parameters for the coastal lagoons and the lakes are due to similar hydrological regimes of both types of basins. Further, ice conditions in these basins are shaped by climatic factors of similar magnitude.

Table 8

Linear correlation coefficients between the maximum annual ice extent in the Baltic Sea (MIB) and ice parameters: ice season duration (S), number of days with ice (N) and maximum ice thickness (H) in southern Baltic coastal lakes (from 1960/1961 to 2017/18)

Ice parameters	Lakes				
	Jamno	Bukowo	Gardno	Łebsko	All lakes (average)
S	0.74	0.75	0.72	0.70	0.76
N	0.80	0.80	0.78	0.80	0.82
H	0.67	0.72	0.77	0.72	0.75

Discussion

In the sheltered basins analyzed in the present work, the ice occurrence probability is very high (ice occurs during nearly every season), considerably higher than along the open coast – the ice occurrence probability in Ustka and Kołobrzeg (located in the close vicinity of the studied basins) was 0.58 (Jevrejeva et al. 2004). The ice occurrence probability estimated for the Szczecin Lagoon is comparable to the value estimated by Jevrejeva et al. 2004, calculated on the basis of data from the period 1900–2000.

To date, relationships between ice conditions in the sheltered basins of the southern Baltic coast and the open Baltic Sea have not been studied. Previous studies focused on ice parameter correlations between study sites located within individual basins, but also between individual basins along the southern Baltic coast.

The correlation coefficients established in this study (between MIB and S, N and H, respectively) are weaker than those determined by previous researchers for the ice parameters (S, N and H) between the study sites located within individual basins, or between basins of the southern Baltic coast.

The strongest relationships are reported between sites located in the Szczecin Lagoon between Trzebież and Podgrodzie stations. Correlation coefficients for these sites were usually above 0.90 (Girjatowicz et al. 1995). Strong correlations at these sites are due to their location within the same basin and in close proximity to each other. For this reason, ice conditions at these sites are shaped by similar climatic and hydrological factors.

The strength of the correlation between the ice parameters was already studied for Jamno and Łebsko lakes (Girjatowicz 2003). The correlations reported by Girjatowicz (2003) were also stronger than in the present work. The highest correlation coefficients between these lakes exceeded 0.90 and were observed for the number of days with ice ($r = 0.96$), the number of days with fast ice ($r = 0.97$) and for the maximum ice thickness ($r = 0.90$). The lowest correlation coefficients between Jamno and Łebsko lakes were determined for the number of days with floating ice (0.60) and the first ice appearance date ($r = 0.71$). All correlations were statistically significant at $p < 0.001$. The correlations between the MIB and the ice parameters for the southern Baltic sheltered basins are weaker than between the individual sheltered basins of the southern Baltic. This is obviously due to the varying degree of climatic and morphometric (bathymetric) similarities. Nonetheless, the differences in the strength of the correlations are lower than would result from the latitudinal differences. The weaker relationships determined for the number of days with floating ice were associated with higher fluctuations in the presence of floating ice, largely depending on anemometric conditions, i.e. wind direction regulating the ice inflow and outflow. Similarly, weaker relationships concerning the first ice appearance date may be associated with high variability in this parameter, especially along the southern Baltic coast (cf. Sztobryn et al. 2012). In the southern Baltic basins, the first ice may occur throughout the winter, i.e. from November to March (Girjatowicz 2007).

Strong ice parameter correlations exceeding *r* = 0.90 are also observed between such basins as the Szczecin Lagoon or the Vistula Lagoon, and between some river mouths, straits and harbors (Girjatowicz 2011). The strongest correlations were determined for the number of days with ice between Świbno (Vistula river mouth) and Tolkmicko (Vistula Lagoon, *r* = 0.94), the ice season duration between Świnoujście and Ueckermünde harbors (Szczecin Lagoon, *r* = 0.94), and the maximum ice thickness between Puck (Puck Lagoon) and Tolkmicko (*r* = 0.92). The weakest relationships, mostly characterized by correlation coefficients lower than 0.90, were found for the ice season duration (Girjatowicz 2011). The lowest correlation coefficients were found between the Świnoujście harbor and Trzebież (Szczecin Lagoon, *r* = 0.81), Ueckermünde and Trzebież (Szczecin Lagoon, *r* = 0.83), and between Baltiysk (Strait of Baltiysk) and Krasnoflotskoye (Vistula Lagoon; *r* = 0.84). These weaker relationships are influenced by relatively high variability of ice conditions, associated with coastal currents at sites located at the river estuaries, i.e. in Świnoujście, Trzebież and Ueckermünde, and within straits – in Baltiysk.

The low strength of the relationships concerning the ice season duration is associated with the observation that the ice season may in fact comprise several periods with the presence of ice separated by ice-fee periods. The variability of these periods is not only due to fluctuations in alternating cooler ($T < 0°C$) and warmer periods ($T > 0°C$), but may also be caused by dynamic factors such as ice inflow and outflow. The number of such ice periods during the ice season can be up to six in the Vistula Lagoon (Łazarienko & Majewski 1975), and even up to eight in the Szczecin Lagoon (Girjatowicz 2011).

On the local scale in the Baltic Sea basin, the severity of winter is connected with the prevailing type of atmospheric pressure systems. The prevalence of lows during winter favors mild ice conditions in a given basin, while the prevalence of highs is conducive to severe ice conditions (Omstedt et al. 2004). This explains why in the sheltered basins of the southern Baltic, during some winters (represented as outliers in the regression plots), ice conditions are milder or severer than the Baltic average. For instance, during the unusually severe winter of 1995/96, air masses from the Arctic moved from the Norwegian Sea to the Szczecin Lagoon and the Pomeranian Bay (SW Baltic Sea) as early as mid-November, and the high pressure belt covered Western and Central Europe including the southern Baltic Sea, which caused the air temperature in Szczecin to drop to –7°C. The anticyclone in December contributed to a decrease in the minimum temperature in Szczecin to –13.3°C, while on the coast the temperature was about 1°C higher. In mid-March, the high pressure system over Scandinavia and Central Europe caused the air temperature over the Szczecin Lagoon to drop to –11°C. Anticyclonic systems and the inflow of Arctic air masses over the southern Baltic contributed to an unusually long ice season and more intensive development of ice during that winter (Schmelzer et al. 1996).

Conclusions

Based on the analysis of relationships between the maximum annual sea ice extent in the Baltic Sea (MIB) and the ice parameters recorded for the sheltered basins of the southern Baltic Sea (first ice appearance date, last ice disappearance date, number of days with ice, ice season duration and maximum ice thickness in season), we conclude the following:

- For the sheltered basins covered by the present work, the ice occurrence probability is close to 1 (i.e. ice occurs in almost every analyzed season), which is considerably higher than along the open coast.
- Both individual coastal lagoons and individual coastal lakes are characterized by very similar long-term variability in the ice parameters.
- Long-term variability of the ice parameters in the group of coastal lagoons and the group of coastal lakes is very similar, nearly identical.
- Ice conditions throughout the Baltic Sea basin may be affected by similar climatic conditions. Whether a given winter is mild or severe in the lagoons and coastal lakes of the southern Baltic, it reflects the overall winter conditions in the Baltic Sea basin. This is indicated by statistically highly significant correlations between the ice parameters for the southern Baltic lagoons and coastal lakes, and the MIB.
- The variation in the strength of the correlation between the MIB and the ice parameters for the lagoons and coastal lakes depends on local conditions, especially bathymetry and climatic factors.
- Average values of the ice parameters for the group of coastal lagoons and the group of coastal lakes show slightly stronger correlations with the MIB than the values of ice parameters for individual basins. This results from the elimination of extreme values (i.e. atypical seasons in a given basin) by averaging. Such atypical seasons are represented

on the regression plots (showing the relationship between MIB and any given ice parameter for a given basin) as outliers.

- The relationships between the maximum ice extent in the Baltic Sea and the ice parameter values are similar for the coastal lakes and lagoons of the southern Baltic Sea. The coexistence of variability in particular ice parameters is not only due to the close proximity of these basins and their similar climatic conditions, but also due to similar hydrologic, morphometric and bathymetric conditions such as low average and maximum depths and limited water exchange with the open sea.
- Values of individual ice parameters for the sheltered basins correspond to the MIB to a varying degree. The maximum ice thickness and the number of days with ice show a considerably stronger relationship with the MIB than the ice season duration (counted from the day when the first ice is observed to the day when the last ice disappears in a given winter). This is because ice periods are interrupted by ice-free periods due to rather frequent alternating periods of temperatures below (T < 0°C) and above freezing (T > 0°C) during a given winter in the coastal lagoons and lakes of the southern Baltic.
- As the Baltic Sea ice conditions are best characterized by the maximum ice extent, the strongest correlations between the MIB and both the maximum ice thickness and the number of days with ice for the lagoons and coastal lakes may indicate that these parameters will equally well characterize ice conditions (and indirectly also winter severity) in these basins.
- Unusually mild or severe winters, whose ice parameters considerably deviate from the theoretical ranges (i.e. outliers in regression plots) are influenced by local factors, mostly relatively high or low air temperatures. These, in turn, are influenced by the pressure systems (highs and lows) prevailing in a given time interval. Ice inertia in shallow, sheltered basins may also be a factor. Such basins are more sensitive to air temperature changes compared to deeper basins with a larger heat capacity of water.
- The strongest correlations can be used to estimate the intensity of ice development in shallow, sheltered basins. Knowing the MIB forecast, it will be possible to predict values of ice parameters for the southern Baltic lagoons and coastal lakes.
- The results of the present study may be used, for example, in designing and/or adjusting the parameters of existing or future hydrotechnical constructions in lagoons and coastal lakes.

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