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The influence of the North Atlantic Oscillation on ice conditions in coastal lakes of the Southern Baltic Sea

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This paper focuses on relationships between the North Atlantic Oscillation Index (NAO) and the ice conditions in coastal lakes (Jamno, Bukowo, Gardno and Łebsko) of the southern Baltic Sea. The data on ice conditions included : date of first ice appearance (F), date of last ice disappearance (D), number of days with ice (N), length of the ice season (in days ; S) and maximum ice thickness (H) during the given winter. The period examined covers the winters from 1960/61 to 1999/2000. The monthly values of the NAO index for the same period were applied in accordance with Jones et al. (1997). Correlation and regression analysis methods were applied to determine and study the relationships between NAO (independent variable) and the parameters of ice conditions (dependent variables). The strongest relationships, with a linear correlation coefficient exceeding - 0.80, were obtained for the date of the last ice disappearance (D) in Łebsko Lake (- 0.853) and Gardno Lake (- 0.828) for the January-March period. In contrast, the relationships between the NAO index and the date of first ice appearance (F) are much weaker. They are statistically significant only in November and early winter (Nov.-Dec., Nov.-Jan.). The correlation coefficients in the coastal lakes of the Southern Baltic Sea coasts generally increase eastwards, a phenomenon related to the severity of winters and to the increasing continuity of ice phenomena during a given winter in this direction.

Keywords : Coastal lakes, southern Baltic, North Atlantic Oscillation, ice conditions.

Introduction

The thermal conditions, including the ice phenomena of the southern Baltic Sea coast, are highly dependent on the atmospheric circulation. One of the indices reflecting the circulation conditions over Europe, mainly over North-western and Middle Europe, including the southern Baltic Sea coast, is the North Atlantic Oscillation (NAO) index. As long ago as 1924 the British meteorologist Gilbert Walker noticed that a deep Iceland Low corresponds to a significantly developed Azores High and more intense zonal air masses inflow. The more active the two pressure centres are, the stronger is the inflow of warmer air masses over Europe in winter. A humid and relatively warm weather type dominates in Middle and Northern Europe during such periods (Hurrell & van Loon 1997, Kapala et al. 1998, Wibig 1999).

The relationships between the NAO index and the ice conditions are also significant. The period of high activity of the Iceland Low is characterised by relatively poorly developed ice phenomena in the Baltic Sea (Rogers & van Loon 1979). Similarly, Koslowski & Glaser (1999) observed that within a period of positive NAO phase, the development of ice phenomena in the Western Baltic Sea is limited. Conversely, severe ice conditions are observed during the negative NAO phase domination. This is supported by statistically significant correlation along the coasts of western Baltic (Koslowski & Glaser op. cit.). The relationship between NAO during the Dec.— Feb. period (1871-1992) and the mean ice index including ice concentration and thickness from stations in Kiel Bight and Mecklenburg Bay regions, show a correlation coefficient of -0.47 (Koslowski & Loewe 1994). Further eastward into the Baltic Sea, particularly in deeply cut bays and estua-

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ries of large rivers (Odra, Vistula), some of the correlation coefficients between NAO index and certain ice condition parameters exceeded -0.70. However, the strongest relationships occurred in the coastal lagoons along the Southern Baltic Sea coast, where some correlation coefficients, especially in Jan.-March and Dec.-March for the period 1960/61 to 1989/90 even reached values of -0.80 (Girjatowicz et al. 2002).

It is likely that the relationships between NAO and some characteristics of coastal lakes of the Southern Baltic Sea coast will also be statistically significant. The aim of this paper is to analyse the relationships between the NAO index and the ice condition parameters of the Jamno, Bukowo, Gardno and Łebsko lakes. Special attention will be paid to some factors that affect these relationships. The above mentioned lakes are the largest close to the southern coast of the Baltic Sea.

Materials and methods

The data on the ice condition of the Jamno, Bukowo, Gardno andŁebsko lakes were obtained from the Institute of Meteorology and Water Management (IMGW) in Gdynia for the period 1960/61 to 1999/2000. The morphometric and bathymetric data for the lakes studied are given in Table 1.

Five ice condition parameters were considered for the present study :

- date of first ice appearance (F),
- date of last ice disappearance (D),
- number of days with ice (N),
- length of the ice season (S), defined as the period of time between the day of first ice appearance and day of last ice disappearance inclusive (in days),
- maximum ice thickness (H, in cm) during the given winter.

The data on the North Atlantic Oscillation index used in this paper originate from the Internet materials of the East England University in Norwich. The NAO is defined here as the difference between the normalised values of the atmospheric pressure in Gibraltar and in the stations located in south-western Iceland, mainly in Reykjavik (Jones et al. 1997). Mean monthly values of the cold seasons (November - March) recorded from 1960/61 to 1999/2000 were used. In order to find the strongest relationships, not only the monthly values from November to March were applied, but also the mean values for longer periods including Nov.-Dec., Nov.-Jan., Dec.-Jan., Dec.-Feb., Dec.-Mar., Jan.-Feb., Jan.-Mar. and Feb.-Mar.

In order to explain strongly deviating NAO values from the ice condition parameters during extreme, i.e. very severe 1969/70 and very mild 1974/75 winters, some additional meteorological data were used. These were mean monthly air temperatures and mean monthly degree of cloudiness (0/10-10/10) originating from the IMGW station in Łeba. In addition, components of atmospheric circulation according to Lityński (1963, 1969) included in the «Calendar of atmospheric circulation types» (Stepniewska-Podrażka 1991) were used for the winters considered.

Correlation and regression analysis were used to determine and investigate the statistical dependence of relationships between the NAO index value for different months and periods, and the numerical values of accepted ice condition parameters. Linear regression equations were calculated. The ice condition parameters (F, D, N, S, H) were applied as the dependent variables (y), and the NAO index numerical value was used as the independent variable (x). The statistical significance of these relationships was verified by means of the Fisher-Snedecor test (F). The standard deviation, correlation coefficients (R), determination coefficients ($R^2 \cdot 100$ %) and variability coefficients, understood as a relation between standard deviation and the mean value, were also calculated. The type of the winter was determined following Betin (1957) by calculating the sum of air temperature monthly average deviations for multiyear, during the December to March period.

Table 1. Morphometric and bathymetric data of the coastal lakes from the southern Baltic Sea (after Choiński 1991).

Lakes	Surface area [km^2]	Volume [km^3]	Average depth [m]	Maximum depth [m]	Elevation at the water level [m a.s.l.]
Jamno	22.4	0.032	1.4	3.9	0.1
Bukowo	17.47	0.032	1.8	2.8	0.1
Gardno	24.68	0.031	1.3	2.6	0.3
Łebsko	71.4	0.118	1.6	6.3	0.3

Results

The circulation data for periods of several month show strong correlation with the thermal (Rogers 1984, Hurrell 1995) and ice conditions (Girjatowicz 2001).

The relationships between NAO and ice condition parameters in the coastal lakes of the southern Baltic Sea coasts are statistically significant, especially within the periods when ice phenomena are most frequent. The date of first ice appearance shows the strongest correlation with the NAO index during the first half of the winter (Nov.-Jan.), whereas the date of last ice disappearance is strongly correlated with the NAO index in the second half of winter (Jan.-March). The number of days with ice and the length of the ice season show the strongest correlation during the winter proper (Dec.-March), when the ice phenomena are the most frequent. The maximum ice thickness correlation is the strongest with the NAO index during the coldest part of winter (Jan.-Feb.), when the ice cover reaches its maximum thickness (Table 2).

Amongst these characteristics of the ice parameters, the strongest correlation with NAO index is recorded for the date of last ice disappearance and the number of days with ice, while the date of first ice appearance shows the weakest correlation. The highest correlation coefficient between the NAO index and the date of last ice disappearance occurred in the period of Jan.-March in Łebsko Lake and amounted to -0.853 (Table 2). The determination coefficient indicates that 73 % of the variability of the NAO index explains the variability of the last ice disappearance. A one unit rise of the NAO index results in earlier disappearance of the last ice, on average by 16 days (see the regression coefficient ; Fig. 1a).

The relationships between the NAO and the number of days with ice are slightly weaker. The highest correlation coefficient was also recorded in Łebsko Lake in the period of Dec.-March, and amounted to -0.833 (Table 2). The variability of the number of days with ice is explained at 69 % by the variability of the NAO index. A one unit increase of the NAO index results in

Table 2. Linear correlation coefficients for particular periods between the North Atlantic Oscillation and : date of first ice appearance (F), date of last ice disappearance (D), number of days with ice (N), length of ice season (S), maximum ice thickness (H), in some coastal lakes of the southern Baltic Sea during winters of the 1960/61 to 1999/2000 period. * significant value, $\alpha = 0.05$; ** significant value, $\alpha = 0.01$

Lakes	Nov.-Dec.	Nov.-Jan.	Dec.-Feb.	Dec.-Mar.	Jan.-Feb.	Jan.-Mar.	Feb.-Mar.
				F			
Jamno	0.369*	0.388*	0.227	0.199	0.186	0.158	0.065
Bukowo	0.477**	0.487**	0.254	0.218	0.208	0.172	0.059
Gardno	0.332*	0.375*	0.194	0.201	0.195	0.201	0.094
Łebsko	0.372*	0.429**	0.271	0.307	0.242	0.289	0.180
				D			
Jamno	-0.148	-0.352*	-0.670**	-0.744**	-0.703**	-0.786**	-0.746**
Bukowo	-0.107	-0.354*	-0.672**	-0.724**	-0.726**	-0.780**	-0.692**
Gardno	-0.210	-0.434**	-0.764**	-0.815**	-0.776**	-0.828**	-0.737**
Łebsko	-0.185	-0.412**	-0.747**	-0.815**	-0.782**	-0.853**	-0.775**
				N			
Jamno	-0.351*	-0.608**	-0.764**	-0.788**	-0.740**	-0.765**	-0.556**
Bukowo	-0.379*	-0.620**	-0.753**	-0.778**	-0.725**	-0.753**	-0.552**
Gardno	-0.406**	-0.644**	-0.783**	-0.825**	-0.740**	-0.790**	-0.597**
Łebsko	-0.399*	-0.629**	-0.773**	-0.833**	-0.735**	-0.807**	-0.632**
				S			
Jamno	-0.368*	-0.531**	-0.671**	-0.689**	-0.646**	-0.666**	-0.545**
Bukowo	-0.390*	-0.579**	-0.680**	-0.677**	-0.668**	-0.659**	-0.493**
Gardno	-0.343*	-0.534**	-0.679**	-0.721**	-0.687**	-0.730**	-0.603**
Łebsko	-0.337*	-0.527**	-0.673**	-0.742**	-0.682**	-0.758**	-0.644**
				H			
Jamno	-0.300	-0.580**	-0.712**	-0.664**	-0.698**	-0.635**	-0.365**
Bukowo	-0.288	-0.585**	-0.744**	-0.716**	-0.737**	-0.697**	-0.431**
Gardno	-0.220	-0.539**	-0.738**	-0.699**	-0.765**	-0.705**	-0.435**
Łebsko	-0.238	-0.559**	-0.778**	-0.738**	-0.794**	-0.735**	-0.466**

a decrease of the number of days with ice of up to 24 days (Fig. 1b).

The relationships between the NAO index and the maximum ice thickness are even weaker. The highest correlation coefficient occurred in the period of Jan.-Feb. in Łebsko Lake, and amounted to -0.794 (Table 2). The maximum ice thickness variability is at 63 % explained by the variability of the NAO index. A one unit increase of the NAO index results in a decrease of the maximum ice thickness by 5.8 cm (Fig. 1c).

The relationships between the NAO index and the length of the ice season are much weaker than the latter ones. The strongest correlation coefficient was recorded in the period of Dec.-March in Łebsko Lake and amounted to -0.758 (Table 2). The variability of the length of the ice season is explained at 57 % by the NAO index variability. A one unit increase of the NAO index results in shortening the length of ice season by 21 days (Fig. 1d).

The relationships between the NAO index and the date of first ice appearance are the weakest. They are statistically significant only in November and early winter (Nov.-Dec., Nov.-Jan., Table 2).

The strongest relationships between the NAO index and the ice condition parameters were reported in January and February. However, the relationships for monthly values of NAO are weaker in comparison to relationships calculated for periods of several months.

Analysis of the relationships illustrated in Fig. 1 reveals that some points of rectangular coordinates (winter) are distant from the regression line. Such a dispersion of points is mainly related to very severe or very mild winters. Some very severe winters are characterised by high values of ice condition parameters (particularly N, S, H and D), despite relatively high values of the NAO index. Relatively low air temperatures and extensive cloudiness can explain these deviations, by restricting the insolation effect on ice disintegration. Analysis of Figure 2 reveals that during the very severe 1969/70 winter, the ice phenomena in Łebsko Lake occurred on 27th of November, and disappeared the 17th of April. They persisted for a very long period of 142 days. However, the NAO index values were relatively high, as for an extremely severe winter, because the mean values of this index in February were positive and amounted to +1.06. In addition, from the second half of March up to the first half of April, cyclone circulation (c) was dominant, mainly from western (SW and NW) and southern (S) directions, resulting in warming up. The very low air temperatures, which occurred earlier (Dec.-Feb.) were mainly related to the anticyclone (a) circulation from the eastern (E, SE) directions, and resulted in a significant ice thickness increase (up to 40 cm in Łebsko Lake). As a result, the process of ice melting was significantly prolonged. The thick ice covers are characterised by a high inertia, especially during a cloudy period. It should be noted that at the end of this particular winter (March-April) there was an extensive cloud cover (high $C_Ł$), amounting to ca. 8/10, thus limiting the insolation influence on ice melting.

The 1969/70 winter was one of the most severe winters (in terms of temperature) in the southern Baltic Sea region in the 20th century. The polar-continental air mass flow dominated from the eastern directions (NE-SE ; 65 days - 43 %), whereas the frequency of air mass flow from western directions (SW-NW) amounted only to 25 % (38 days). The coldest periods occurring in the first half of the winter were connected with the High over Russia. However, during the December-April period, the cyclone circulation (76 days - 50 %) was insignificantly dominant over the anticyclone circulation (60 days - 40 % ; Fig. 2). Neither the cyclone nor anticyclone circulation affect the severity of the winter. The dominant factor determining the thermal conditions of a winter is the direction of air mass flow.

Some very mild winters (1974/75, 1987/88) are characterised by low values of the ice condition parameters despite relatively low values of the NAO index. Relatively high air temperatures and an intense impact of insolation can explain these deviations on ice disintegration.

An analysis of Figure 3 illustrates the example from Łebsko Lake, where during the very mild 1974/75 winter the ice appeared the 14th of December 1974, and disappeared the 26th of February 1975. The length of the ice season amounted to 75 days, and the number of days with ice to 13. During that time (Dec.-March) the mean value of the NAO index was relatively low and amounted to 1.28. In the second half of this winter, i.e. from mid-February, its value was even negative. Taking into account only the NAO index, the ice phenomena should have persisted for a longer time even in March, when the NAO index value was negative and amounted to -1.26. A decrease in the degree of cloudiness ($C_Ł$) beginning in January occurred, and continued until the end of the winter (Fig. 3). The decrease in cloud cover increased insolation, and thus ice melting intensity. Fast disappearance of ice was also enhanced by its low thickness (ca. 3 cm) in the near-shore area during this particular winter.

According to the classification of atmospheric circulation types of Lityński (1969), this exceptionally mild

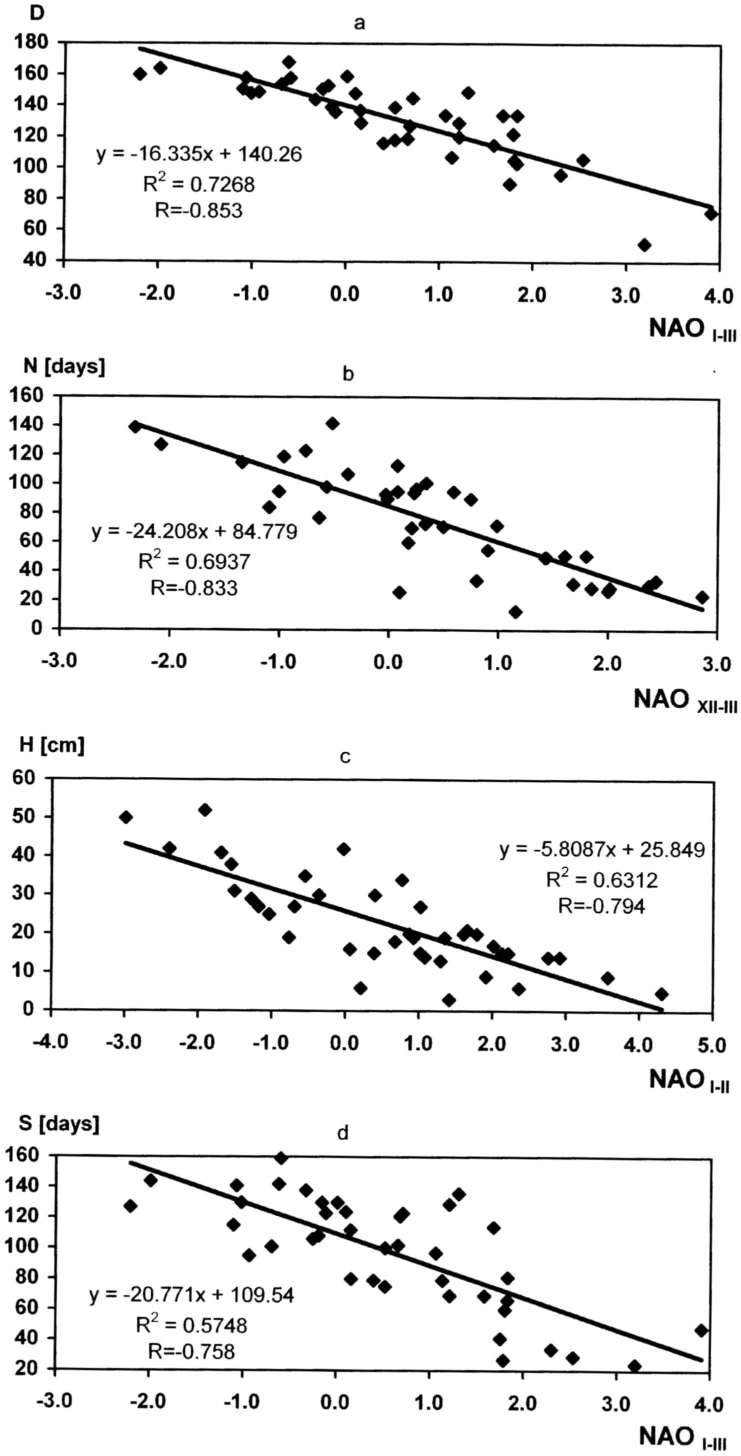

Fig. 1. Relationships between the North Atlantic Oscillation index (NAO) and : date of last ice disappearance (D ; a), number of days with ice (N ; b), maximum ice thickness (H ; c) and length of ice season (S ; d) in Łebsko Lake for the 1960/61 to 1999/2000 period.

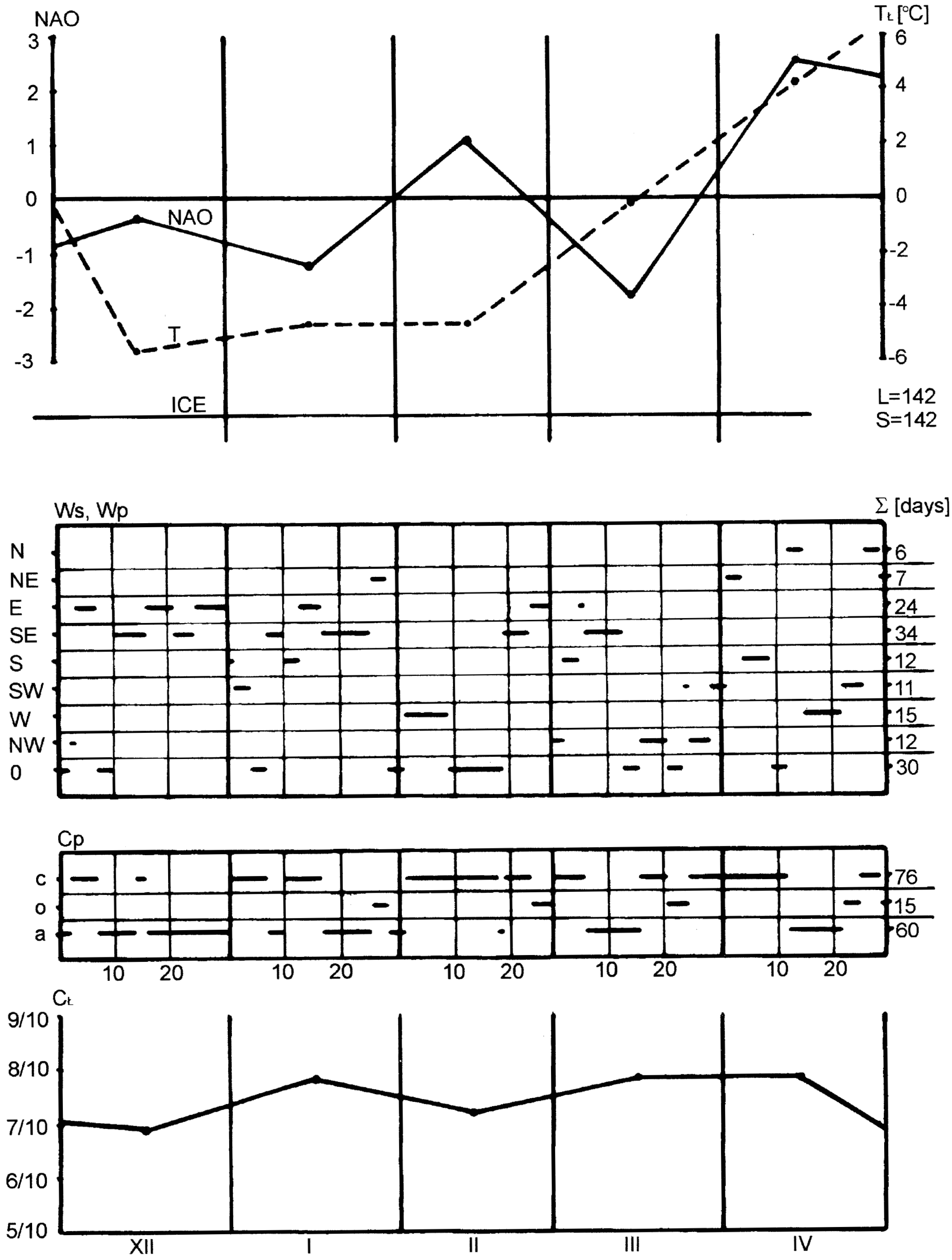

Fig. 2. Synchronised image of the North Atlantic Oscillation (NAO) with mean air temperature ($T_Ł$), ice condition (L, S) in Ł ebsko Lake, atmospheric circulation indicators according to Lityński (Ws, Wp, Cp), and mean cloudiness degree ($C_Ł$) in Łeba during the very severe 1969/70 winter.

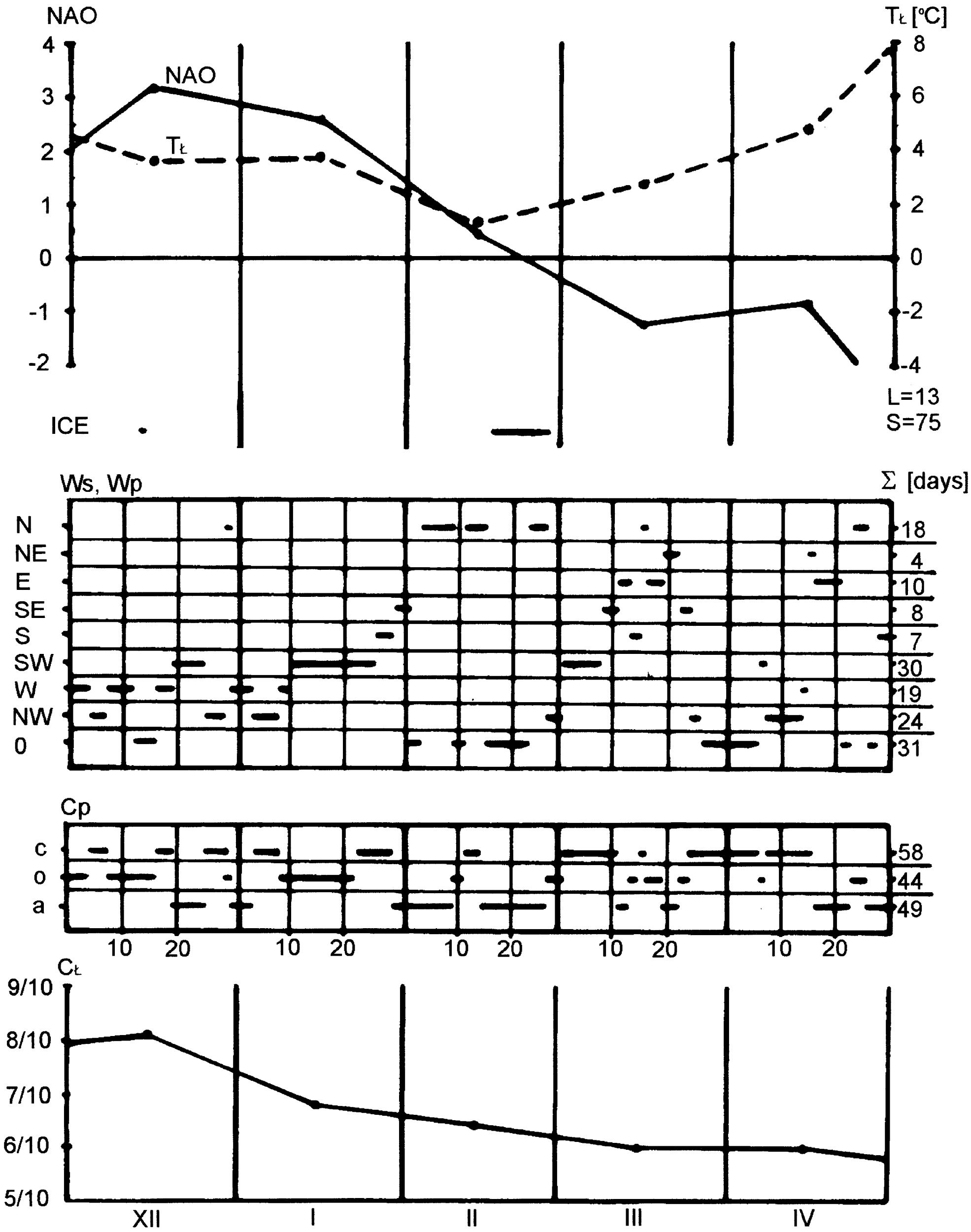

Fig. 3. Synchronised image of the North Atlantic Oscillation (NAO) with mean air temperature ($T_{Ł}$) and ice conditions (L, S) in Łebsko Lake, atmospheric circulation indicators according to Lityński (Ws, Wp, Cp), and the mean cloudiness degree ($C_{Ł}$) in Łeba during the very mild 1974/75 winter.

winter, particularly in December and January, was characterised by the dominance of warm polar-marine air masses flowing from western directions (48.3 % - 73 days). The frequency of air mass flow from eastern directions, especially in March, amounted to only 14.6 % (22 days). The cyclone (c) circulation (38.4 % - 58 days) dominated over the anticyclone (a) circulation (32.4 % - 49 days ; Fig. 3).

Coastal lakes along the southern shores of the Baltic Sea are characterised by fairly distinct geographical differentiation of correlation coefficients between the NAO index and the number of days with ice (N). The weakest coefficients were recorded in the western part on Lakes Jamno and Bukowo, whereas the strongest were found in the eastern part of the coast, i.e. in Gardno and Łebsko Lake (Table 2, Fig. 4). An average eastward directed gradient of correlation coefficient (R) in this part of the coast amounts ca. 0.05/100km. Such a differentiation of correlation coefficients primarily results from climate factors. This is due to the fact that the severity of winters and the continuity of ice phenomena during a given winter show a distinct eastward increase. This is also reflected by an increase of the severity of ice conditions in the same direction (Table 3). In average, an eastward increasing trend of some parameters is observed. The number of days with ice increases by 9 days/100km, the ice season length by 13 days/100km, and the maximum ice thickness during a given season by ca. 2 cm/100km. Similar considerations apply to the relationships between atmospheric circulation and ice conditions of the coastal lagoons on the southern coast of the Baltic Sea (Girjatowicz 2001b).

A distinct relationship between the correlation coefficients and the variability coefficients was recorded. The higher the variability coefficient, the weaker (usually) the correlation coefficient. The highest variability coefficients of ice condition parameters occur in Jamno and Bukowo Lakes, the lowest in Gardno and Łebsko Lakes (Table 3). The opposite differentiation was observed for the correlation coefficients of the NAO index with these parameters. These were usually the strongest in Łebsko and Gardno Lakes, and the weakest in Bukowo and Jamno Lakes (Table 2). Low variability of ice phenomena during a winter favours strong relationships between thermal factors, including the NAO index vs. the ice phenomena.

Conclusion

The North Atlantic Oscillation, reflecting the variability of atmospheric circulation affects not only the air temperature (Hurrell 1996, Marshall et al. 1997, Marsz 1999) and rainfall (Hurrell 1995, Wibig 2000), but supposedly also numerous other meteorological factors. It is thought that the NAO index is a complex indicator affecting (*inter alia*) the direction and velocity

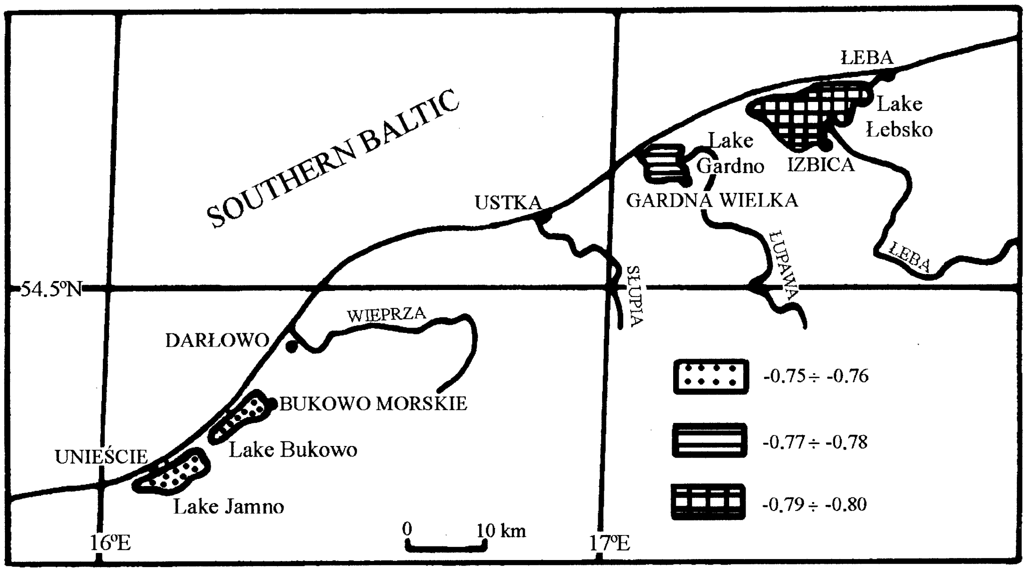

Fig. 4. Spatial differentiation of correlations between the NAO index and the number of days with ice on coastal lakes of the southern Baltic Sea during the 1960/61 to 1999/2000 period

Table 3. Mean and extreme values and variability measures of the date of first ice appearance (F), date of last ice disappearance (D), number of days with ice (N), length of ice season (S), maximum ice thickness (H) for the examined coastal lakes of the southern Baltic Sea during the 1960/61 to 1999/2000 period.

Lakes	Mean values	Maximum	Minimum	Standard deviation	Variability coefficient
			F		
Jamno	40.51	99	0	17.18	0.42
Bukowo	38.05	99	0	17.36	0.46
Gardno	34.78	98	1	19.73	0.57
Łebsko	34.43	96	1	20.18	0.59
			D		
Jamno	126.69	164	0	27.43	0.22
Bukowo	127.69	168	0	27.17	0.21
Gardno	131.93	170	54	26.47	0.20
Łebsko	130.95	168	52	25.56	0.20
			N		
Jamno	67.90	133	0	35.65	0.52
Bukowo	72.70	139	0	36.47	0.50
Gardno	76.98	142	15	35.49	0.46
Łebsko	74.40	142	13	35.55	0.48
			S		
Jamno	85.18	134	0	36.04	0.42
Bukowo	88.55	139	0	36.22	0.41
Gardno	98.35	160	30	35.56	0.36
Łebsko	97.70	159	24	36.54	0.37
			H		
Jamno	21.73	45	0	12.64	0.58
Bukowo	22.90	52	0	14.08	0.62
Gardno	23.55	48	4	11.31	0.48
Łebsko	22.55	52	3	12.23	0.54

of wind, cloudiness and sunshine, the intensity of solar radiation (air transparency). With the domination of either positive or negative phases of NAO, which are characterised by specific physical parameters and peculiar meteorological phenomena, these factors influence, to a certain extent, the development and disappearance of ice phenomena. Therefore, a strong correlation is recorded between the NAO index and the ice phenomena.

The relationships between the North Atlantic Oscillation and the ice conditions of the southern Baltic Sea coast show the strongest correlation in shallow water areas. Coastal lakes represent such areas. The correlation of the NAO index with the ice conditions in coastal lagoons is slightly weaker. In the open, neritic waters of the Baltic Sea located close to the deep water basins (Girjatowicz et al. 2002) these correlations are distinctly weaker. This is supported by Koslowski & Loewe (1994) who obtained a weaker correlation coefficient amounting to -0.47 for the coastal waters of the western Baltic Sea.

The strong relationships between the NAO index and ice phenomena in these shallow areas can be explained by rapid reaction of the coastal lakes to changing thermal conditions, which are determined by atmospheric circulation. Not only low depths enhance this, but also the weak influence of non-circulatory (non-thermal) factors (convection and currents) within the study area. It is noteworthy that during the winter season the strongest impact of NAO on the climatic conditions is observed in Central and Northern Europe (Rogers & Loon 1979, Hurrell & Loon 1997, Jones et al. 1997).

The strength of the NAO index correlation with ice condition parameters of the coastal lakes shows an eastward increase. This is affected by the climate conditions, due to the fact that the severity of winters and the continuity of ice occurrence during winter increase in that direction. An average air temperature in the study area shows an eastward decrease by ca. 0.5° C/100 km (Michalska 2001). Uninterrupted periods of ice occurrence and number of days with stable ice are also longer in the eastern part (Gardno and Łebsko lakes) than in the western one (Jamno and Bukowo, Girjatowicz 2001a). An eastward increase in the continuity of ice occurrence is also confirmed by the decrease in this direction of the variability coefficients of ice condition parameters (D, L, S, H).

Relationships between atmospheric circulation and the ice conditions, with similar statistical significance, were also reported from the Southern Baltic Sea lagoons. Application of Lityński's (1963, 1969) atmospheric circulation types combined with ice conditions revealed, particularly in Vistula Lagoon, correlation coefficients exceeding 0.80 (Girjatowicz 2001b). These relationships are distinctly stronger with zonal (SW-W-NW, NE-E-SE) directions than with meridional (N, S) ones. A similar eastward increase of correlation coefficients is also observed. Finally, although air and water temperatures were not taken into account in this study, it is likely that their use as predicators might reveal better relationships with ice conditions.

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