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Association Between Ice Conditions in the Baltic Sea along the Estonian Coast and the North Atlantic Oscillation

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Variations in time series of sum of negative degree-days, number of days with ice, date of ice break-up and maximum ice thickness on the Baltic Sea along the Estonian coast have been examined within context of the atmospheric circulation above the North Atlantic. It was found out that 20 –50 % of ice conditions along the Estonian coast might be explained by the state of the NAO winter index. However, correlation coefficients between time series of ice conditions and the NAO winter index varies with time; moving correlation coefficient can reach -0.98.

Introduction

Considerable evidence suggests that ice conditions on the Baltic Sea are closely related to the atmospheric circulation. Cooling during the severe winter seasons is determined by the travelling of anticyclones from the North. During average and mild winters warm air masses from Atlantic are prevailing.

Variation in winter weather in northern Europe is influenced by a fluctuation in atmospheric mass operating over the Atlantic Ocean called the North Atlantic Oscillation (NAO) (Rogers 1984; Lamb and Peppler 1987; Kozuchowski 1993; Jönsson and Bärring 1994). A positive relation between the NAO and the Northern European temperature has been pointed out by Roger (1985) and Hurrel (1995). Recently were published the results of analysis between the NAO and air temperature variability in Sweden (Chen and Hellström 1999).

There are several publications about relations between ice conditions and North

Atlantic Oscillation. For the western Baltic Sea the analysis of ice conditions in terms of a mass-related severity index: 1879-1992 and their relation with NAO was done by Koslowski and Loewe (1994). The NAO winter index has been used for describing air circulation patterns by Rogers (1984) and related to sea ice conditions in Hudson Bay (Wang 1994). Anomalies and trends of sea ice extent in the Nordic Seas during 1864-1998 with respect to atmospheric circulation were analyzed by Vinje (2000). However, there were no investigations about relation between ice conditions and NAO in the northern Baltic Sea or along the Estonian coast.

The objective of present study was to investigate the relation between the ice conditions along the Estonian coast and NAO. Since the NAO index is single, integrative index that quantifies winter precipitation, temperature and drives trends in precipitation and temperatures during winter through decadal phases (Hurrell 1995).

Data Sets

Time series from five stations situated in the Gulf of Riga and three situated in the Gulf of Finland along the Estonian coast with more than 100- year period were used in this study (Fig.1, Table 1). Those data have been collected from the archive of Estonian Meteorological and Hydrological Institute (EMHI).

Ice conditions were represented by severity of winter seasons defined by the sum of negative degree-days, number of days with ice, date of ice break-up and maximum ice thickness. Mean air temperature during December-March and mean air temperature of April have been also considered in order to get an understanding about the development of ice conditions and their implications for the NAO winter index. In previous studies (Jevrejeva 2000; Jevrejeva and Leppäranta 2002) detailed statistical analysis, including trend analysis, of time series of sum of negative degree-days, number of days with ice, date of ice break-up and maximum ice thickness was carried out.

In present study the winter index of the NAO from an internet (http://www.cgd.usar.edu/cas/climind/nao_winter.html) has been used. Winter (December through March) index of the NAO based on the difference of normalized sea level pressures (SLP) between Lisbon, Portugal and Stykkisholmur/Reykjavik, Iceland from 1864 through 1998. The SLP anomalies at each station were normalized by division of each seasonal pressure by the long-term (1864-1983) standard deviation. The values differ slightly from those in Hurrell (1995) because of continual updates to the data and a change in the base period. The SLP anomalies at each station were normalized relative to the 120- year period 1864-1983; Hurrell (1995) normalized relative to 1864-1994.

Classification of the index data is based on the definition of three categories: high, normal and low. A high index (NAO>1) is associated with strong westerly flow; a low index (NAO<-1) represents weak westerlies. A normal index covers (-1<NAO<1) and stands for a zonal circulation of average strength.

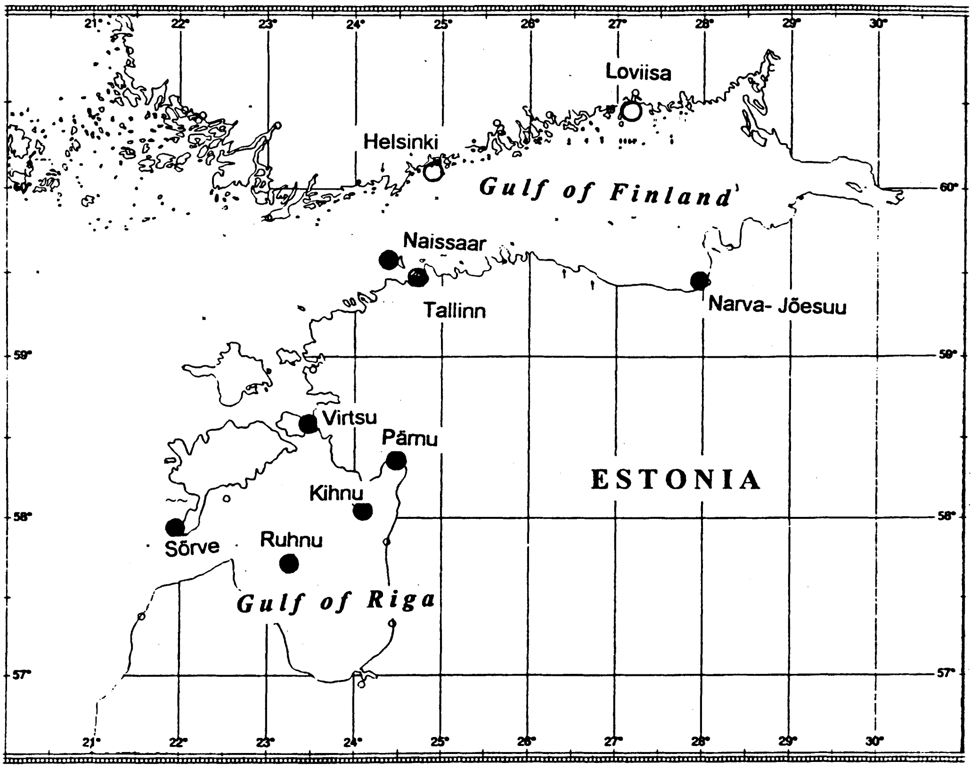

Fig. 1. Location map.

Results

Temporal Variations in the NAO Winter Index

Time series of the NAO winter index is characterized by average value 0.17, standard deviation 1.93, maximum 5.08 and minimum –4.89. Slightly increasing linear trend indicates tendency to the positive values. Histogram of the NAO winter index from 1864 to 1999 was plotted (not shown here). The shape of histogram is positively skewed, the strong western flow is dominated during the period 1864-1999.

From the course of polynomial fitting curve the period from 1864 to 1930 is characterized by a westerly flow. This period is associated with increasing of winter temperature (November- April) about 0.5-1.0 °C per century in Estonia (Jevrejeva 1999) and in Europe as well (Moses 1987). Period until 1970 is described by winters with weakened zonal circulation and characterized by the frequent occurrence of very severe winters. The last 30-year period is characterized by normal strength with a return to stronger westerlies in recent years, the same result is obtained by Flohn (1990).

Table 1 – Correlation coefficients between time series of ice conditions along the Estonian coast and the NAO winter index.

Data	Station	Period	R	P
Sum of negative degree -days	Narva-Jõesuu	1903-1990	-0.50	0.01
	Tallinn	1903-1990	-0.57	0.01
	Virtsu	1903-1990	-0.71	0.01
	Pärnu	1878-1990	-0.63	0.01
	Sõrve	1865-1990	-0.72	0.01
Date of ice break-up	Narva-Jõesuu	1903-1990	-0.51	0.01
	Tallinn	1903-1990	-0.52	0.01
	Naissaar	1888-1990	-0.52	0.01
	Virtsu	1903-1990	-0.55	0.01
	Pärnu	1883-1990	-0.54	0.01
	Kihnu	1898-1990	-0.55	0.01
	Ruhnu	1903-1990	-0.51	0.01
	Sõrve	1903-1990	-0.64	0.01
Number of days with ice	Narva-Jõesuu	1903-1999	-0.37	0.01
	Tallinn	1903-1999	-0.57	0.01
	Naissaar	1888-1987	-0.46	0.01
	Virtsu	1903-1999	-0.51	0.01
	Pärnu	1883-1999	-0.39	0.01
	Kihnu	1898-1999	-0.56	0.01
	Ruhnu	1903-1999	-0.44	0.01
	Sõrve	1903-1999	-0.66	0.01
Maximum ice thickness	Narva-Jõesuu	1922-1990	-0.36	0.01
	Naissaar	1922-1990	-0.34	0.07
	Virtsu	1922-1990	-0.37	0.01
	Pärnu	1922-1990	-0.39	0.01
	Kihnu	1898-1990	-0.47	0.01
	Sõrve	1922-1990	-0.41	0.01
Mean air temperature Dec-March	Narva-Jõesuu	1903-1999	-0.45	0.01
	Tallinn	1903-1999	-0.60	0.01
	Pärnu	1878-1999	-0.55	0.01
	Sõrve	1865-1999	-0.61	0.01
Mean air temperature in April	Narva-Jõesuu	1903-1999	-0.57	0.01
	Tallinn	1903-1999	-0.45	0.01
	Pärnu	1878-1999	-0.64	0.01
	Sõrve	1865-1999	-0.68	0.01

Sums of Negative Degree-days and the NAO Winter Index

The detailed results from statistical analysis of time series of sum of negative degree-days are published by Jevrejeva (2000). Jevrejeva (1999, 2000) classified three ice winter severity types for the coastal area in the Baltic Sea along the Estonian coast. Classification was made on the base of the data sets from five stations situated in the Gulf of Riga and three stations situated in the Gulf of Finland for the period 1890-1990, selected stations were located on the main land and on the islands as well. Time series of daily air temperature from the ice condition observation places were used to calculate the sum of negative degree-days for each of stations from the date of onset of freezing air temperatures to the date of onset of melting air temperatures. On the basis of obtained results the seasons used were classified as mild, if sum of negative degree-days was less than 380; as average, if sum was between 380 and 570; and as severe, if sum was more than 570 for the Gulf of Riga. Analogous classification was applied to the stations situated in the Gulf of Finland for the period 1890-1990: mild winter season if sum of negative degree-days is less than 470, average winter season if sum is between 470 and 830, and severe winter seasons if sum is more than 830.

Time series of sums of negative degree-days were treated as a dependent variable and the NAO winter index were treated as the independent variable in a regression analysis. Correlation coefficients were negative, from 0.50 to 0.72, $p<0.01$ (Table 1). The lowest value (0.50) was obtained for the eastern station Narva-Jõesuu situated in the Gulf of Finland and the highest value (0.72) for the station situated on the island in the Gulf of Riga.

Result for the Gulf of Riga (station Pärnu) is shown in Fig. 2. Mild winters with sums of negative degree-days (< 470) are associated with strong westerlies (NAO>1) and severe winters (> 830) are corresponded to the weak westerlies (NAO<-1). The less agreement is found out for the average winter seasons (-1< NAO<1). Extremely severe winter seasons, for example the winter 1941-42 or 1876-77 are stated with only -0.53 or 0.05 corresponding NAO winter indexes. From Koslowski (1994), Fraedrich (1990) and Parker (1983) there are discovered that in 1940s three of the most severe ice winters occurred in succession and concurrently with an extreme multiannual El Nino/Southern Oscillation (ENSO) warm episode (1939-42).

Correlation coefficients between time series of the NAO index less than –1 and more than 1 and time series of sum of negative degree-days were higher.
In general, from 25 to 50% of variation of severity can be explained by the state of the NAO winter index.

Number of Days with Ice and the NAO Winter Index

Results from the regression analysis are given in Table 1. In general, about 20- 40% of number of days with ice are defined by the state of the NAO. The best coefficients were obtained for the time series of Sõrve, Kihnu (islands in the Gulf of Riga) and

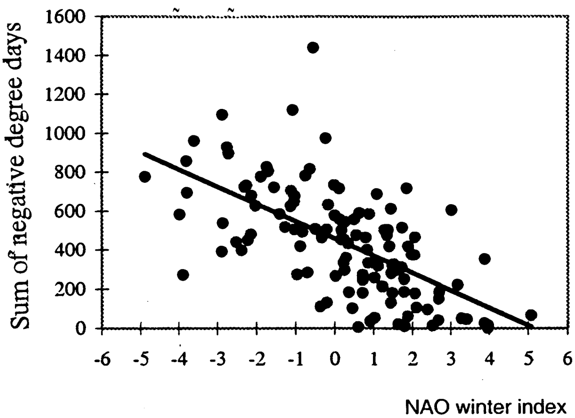

Fig. 2. Relation between time series of sum of negative degree-days in Pärnu and the NAO winter index.

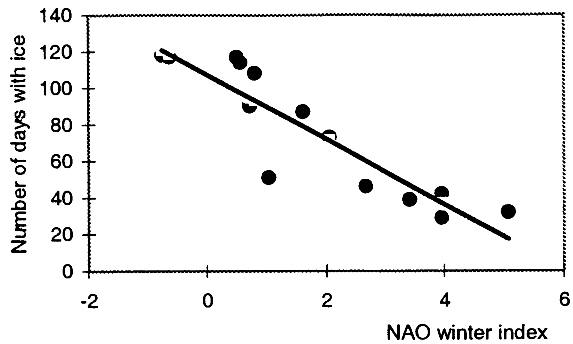

Fig. 3. Regression line between time series of number of days with ice and the NAO winter index (1979-1994).

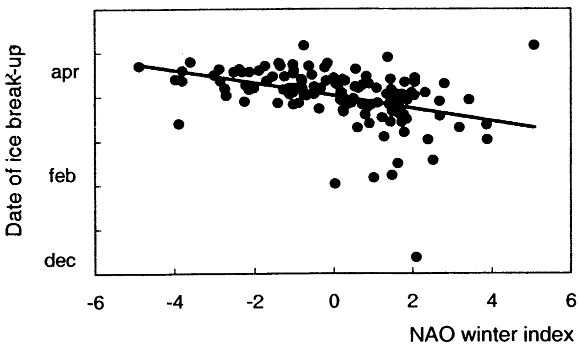

Fig. 4. Regression line between time series of date of ice break-up and the NAO winter index.

Tallinn. The highest values of standard deviation in time series of number of days with ice were stated for the same (Sõrve, Kihnu and Tallinn) time series of number of days with ice in previous study (Jevrejeva 2000).

The highest values of residuals were observed for the normal NAO winter index (-1<NAO<1), regression run performed for the time series without normal NAO winter index. The correlation coefficients were higher up to -0.75. The results of correlation for the positive phase of the NAO winter index (1979-1994) are given in Fig. 3. It shows that the correlation coefficient can reach -0.91 ($p<0.02$), in this case 80% of number of days with ice can be explained by the state of the NAO. Similar results were obtained for the negative phase of NAO winter index.

Chen and Hellström (1999) have mentioned the relation between the NAO and regional temperature anomalies for the period 1985-1994 are strong and can be used as a suitable candidate for statistical downscaling model of the regional temperature.

Maximum Ice Thickness and the NAO Winter Index

Maximum ice thickness is negatively correlated with the NAO winter index. The values of coefficients are less compared with results obtained for the time series of sum of negative degree-days, mean air temperature during December- March. The highest value of correlation coefficients (-0.47) was found for the Kihnu station time series.

Maximum ice thickness is defined as a function of sum of negative degree- days, the lower values of correlation coefficients can be explained due to the local effects in ice thickness development. Those effects seem to be more significant along the coast of main land than along the island.

The relation between maximum ice thickness and NAO winter index will be analysed more detailed with respect to snow cover, long-term change in salinity.

Time Series of Date of Ice Break-up and the NAO Winter Index

Statistical analysis of time series of date of break-up has been done in the previous study (Jevrejeva and Leppäranta 2002). Time series were characterized by high natural variability, no statistical significant trends were detected for the most stations situated along the Estonian coast during the investigated period. Time series of date of ice break-up divided according to severity of winter seasons were also analysed.

For all stations mild winter seasons are characterized by early date of ice break-up; a few weeks later the date of ice break-up is fixed for average winters and the latest the date of break-up for the severe winters is found.

Correlation coefficients between time series of date of ice break-up and the NAO winter index for eight stations were from -0.47 to – 0.64 ($p<0.01$). Regression line between date of ice break-p and the NAO winter index is given in Fig. 4. Screening of outlets was performed through the residuals analysis after an initial regression run. The reason was to get the results on the base of original data and compare those results from the time series where outliers were removed. After that the regression analysis was performed again; standardized residuals were checked, none of them exceeds ± 3.29. For the last 25 years standardized residuals showing the tendency to positive value.

Mean Air Temperature During December-March and the NAO Winter Index

In order to obtain a deeper understanding of an influence of the NAO winter index, relation between mean air temperature during December- March, mean air temperature in April and the NAO winter index were analysed. Performing a linear regression the correlation coefficients about -0.60 were obtained. It is a little bit less then the results published by Tomingas and Jagus (1999). However, they used the NAO winter index from Hurrell (1996).

Correlation between time series of mean air temperature in April and NAO winter index (December-March) resulted into the coefficient -0.45. It means that the state of NAO during December-March can affect the air temperature in April.

Moving Correlation

However, correlation analysis over different periods shows that the strength of the association varies with time. To investigate the evolution of the connections between the NAO winter index and ice conditions time series, 7-, 12-, 25-year moving correlations are calculated. This is done by sliding a window (7-, 12-, 25- years) along two time series and for each position of the window, Pearson's correlation coefficient is calculated for all observations within the window. The resulting correlation coefficient is assigned to the center point of the window. The windows size are 7,12 and 25 years and the windows are moved in one-year steps. There is a considerable fluctuation of the correlation for all time series.

For the time series of sum of negative degree-days (Fig. 5) the correlation coefficient (25 years) is decreasing from 1910 to 1930 (min –0.12) and later is increasing up to -0.81 during the last 25 years. Correlation coefficient with 12- year window shows two minimum about 1915 and 1935; maximum in 1982 (-0.92).

Similar tendency of evolution of the connections between NAO winter index time series and time series of number of days with ice was found. However, the minimum is observed for the period 1920-1930.

For the time series of date of ice break-up the evolution of coefficient in time is slightly different, there are two maximum in 1940 and 1983 (Fig. 6)

Discussion

The results support the idea that the NAO has an important impact on the ice conditions along the Estonian coast. However, the variation of the correlation coefficient between time series of ice conditions and NAO winter index implies that the relation between them is not stable and other processes must also be involved (water storage

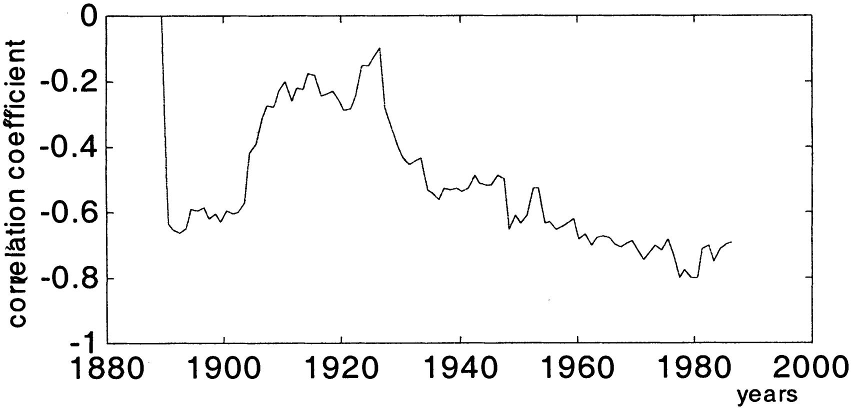

Fig. 5. Moving correlation coefficients (25-year window) between time series of sum of negative degree-days and NAO winter index.

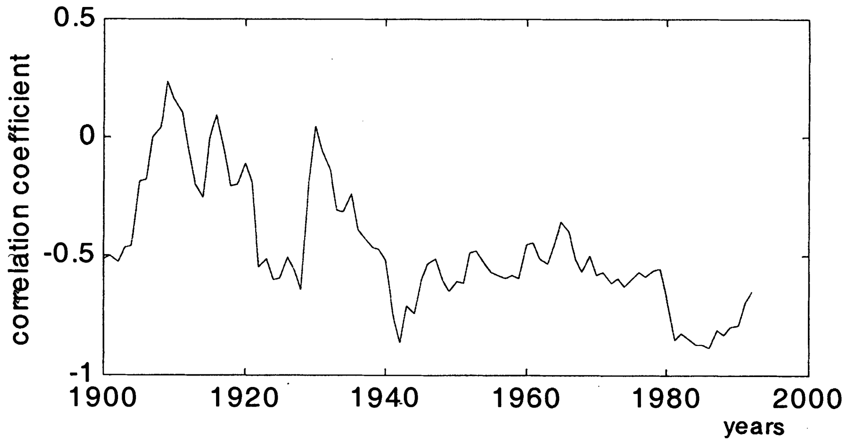

Fig. 6. Moving correlation coefficients (12-year window) between time series of date of ice break-up and NAO winter index.

variations in the Baltic Sea, thermohaline circulation, fresh water flux, inflow of highly saline water from the North sea and so on).

According to Koslowski and Loewe (1994) the Pearson's correlation coefficient between time series of accumulated areal ice volume from the Baltic coast of Schleswig- Holstein and the NAO winter index was –0.47. According to Tomingas and Jagus (1999) the correlation coefficients between snow cover duration and NAO winter index was –0.51. Moving correlations between the annual maximum ice extent in the Baltic Sea and the NAO index were recently published by Omstedt and Chen (2001). The analysis shows that the relationship between the NAO index and ice extent is not stationary over time. The highest correlations were found at the end of 1800s and during the last 31 years, which is in agreement with the results obtained in present study. The lowest values of correlation coefficients corresponded to the period around 1920. Omstedt and Chen (2001) related the increase of correlation coefficient during the last 100 years to the positive trend in the winter temperature. The time series analysed in the present study too short to make similar conclusion. However, the results of moving correlation with shorter windows (in Fig. 6 the window is 12 years) support the idea that higher values of correlations are mostly associated with stable positive phase of the NAO, for example the period 1900-13 and the last 30 years; low values were observed for periods characterized by large variability in NAO (for example the period 1954-1971).

Recently published analysis (Jevrejeva and Moore 2001) of the relationship between ice conditions in the Baltic Sea and the large-scale atmospheric circulation patterns represented by the NAO winter indices and Arctic Oscillation (AO) indices show the signature from AO is more clearly than that from NAO; in general it seems that the NAO can be viewed as a subset of the AO for the Baltic region.

Conclusion

Variations in time series characterising ice conditions in Baltic Sea along the Estonian coast have been examined within context of the atmospheric circulation above the North Atlantic. The results demonstrate that there is an influence of NAO on the ice conditions in the Baltic Sea along the Estonian coast:

- Time series of sum of negative degree-days are strongly correlated with NAO winter index (coefficients from –0.50 to –0.72, $p<0.01$);
- Correlation coefficients between time series of number of days with ice and NAO winter index were from –0.37 to –0.66 ($p<0.01$);
- The relation between mean air temperature during December-March and NAO winter index resulted into coefficients from -0.45 to -0.61;
- Correlation coefficient between time series of mean air temperature in April and NAO winter index are -0.45-0.64. This means that air circulation patterns determine the evolution of ice seasons longer than December –March;
- Results from statistical analysis of time series of date of ice break-up arranged according to the severity of winter seasons (severe, average and mild) show earliest break-up for mild winters, several weeks later for average and the latest for severe winters. The date of ice break-up of the different types of winter season depends on state of the NAO winter index;
- Between 20 and 50% of the ice condition is determined by the atmospheric circulation, the most significant effect was found for the islands located n the Gulf of Riga and Tallinn;
- Moving correlation coefficients for the time series of ice conditions and NAO winter index can reach -0.98, but can also be as low as 0.02.

- Disagreement between time series of ice conditions and normal NAO winter index (-1<NAO<1) was found.

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