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Baltic Sea ice seasons in the twentieth century

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ABSTRACT: We examine the evolution of ice seasons in the Baltic Sea during the 20th century based on a set of 37 time series from the coastal observation stations. The statistical question of combining data from sites with different ice probabilities is solved by using fractiles of the distributions. These 100 yr long time series, including date of freezing, ice break-up, number of days with ice, and maximum annual ice thickness, provide evidence of a general trend toward easier ice conditions; the largest change is in the length of ice season, which is decreasing by 14 to 44 d per century. The trends of a reduction of about 8 to 20 d per century to earliest ice break-up are in a good agreement with a warming trend in winter air temperature over Europe. A statistically significant decreasing trend in probability of ice occurrence in the southern part of the Baltic Sea was detected; however, there is no change in probability of ice occurrence in the northern part.

KEY WORDS: Baltic Sea · Ice conditions · Trend · Probability · Fractiles

1. INTRODUCTION

The Baltic Sea is located in the seasonal sea ice zone. The maximum annual ice extent is 10 to 100% of the Baltic Sea area; the length of ice season is 4 to 7 mo; and the maximum annual thickness of landfast ice is 50 to 120 cm. The long-term evolution of the Baltic Sea ice conditions is of high concern to the Baltic Sea countries, as it is expected that even small climatic changes will show up drastically in the ice conditions. The information of the past ice seasons is a key for the prediction of how the coming ice seasons will be.

The oldest documented records of ice conditions in the Baltic Sea are from 690 AD (Speerschneider 1915). Historical records of ice conditions have been used in several studies concerning climate reconstruction (Stakle 1936, Jurva 1944, Palosuo 1953, Betin 1957, Tarand 1993, Koslowski & Glaser 1995, Koslowski & Loewe 1996, Seinä & Palosuo 1996, Jevrejeva 2001).

Ice observations have been available since the early 1800s. The first sites were the Gulf of Finland at lighthouses Kronstadt (1814) and Vyborg (1861) (Rukachev 1886) and Helsinki (1829) (Leppäranta & Seinä 1985). A regular observation system was organized in 1860, based at the coastal lighthouses, and those observations were recorded in journals. The Main Hydrographic Office of Russia issued special instructions and observation forms in 1886. Along the Polish coast, regular ice observations have been performed since 1896 in Kolobrzeg and Zalew Szczecinski, and since 1900 in Ustka. Regular ice observations covering the German coastal region have been made since 1896. The ice observations included the dates of first and last ice and the number of days with ice.

The whole network of observation stations was set up by the end of the 19th century. The observation programme included information about the dates of the first freezing, the formation of the permanent ice cover,

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end of the permanent ice cover, the final disappearance of the ice, and the thickness of the ice. Air temperature measurements were also made.

After the network was set up, scientific papers began to discuss the Baltic ice conditions. An early description of the ice conditions in the western and southern parts of the Baltic Sea with some statistical data, published in German, can be found in 'Segel-Handbuch für die Ostsee mit der Einsegelung durch das Kattegat, den Sund und die Belte' from 1878 (Hydrographischen Bureau der Kaiserlichen Admiralität, Berlin). Some descriptions about ice conditions in the Gulf of Finland can be found in Rukachev (1886).

Ice conditions in the Baltic Sea have been examined by time-series analysis in order to study the natural variability of the ice conditions. Results show that there is large natural variability in the Baltic (Prüfer 1942, Betin 1957, Alenius & Makkonen 1981, Leppäranta & Seinä 1985, Drabkin et al. 1988, Kostjukov & Zaharchenko 1988, Leppäranta 1989, Schmelzer 1994, Sztobryn 1994, Girjatowicz & Kozuchowski 1995, Koslowski & Glaser 1995, Koslowski & Loewe 1996, Tinz 1996, Jevrejeva 2000, Jevrejeva & Leppäranta 2002, Jevrejeva et al. 2002).

The present authors have contributed to the Baltic ice time-series analysis since the 1970s. The purpose of this paper is to combine all our data and results for a comprehensive study of the ice climatology of the Baltic Sea. The ice conditions over the whole region and their evolution in the 20th century are examined using a joint data set, and the local variations around the general development are found for several parts of the Baltic Sea.

Table 1. Description of data sets from the coastal observation stations on the Baltic Sea (Finland, Russia, Estonia, Latvia, Poland, Germany)

Stn	Location	Date of freezing	Date of break-up	Number of days with ice	Ice thickness
Kemi	65° 44′ N, 24° 33′ E	1890–1995	1890–1995	1890–1995	1911–1995
Vaasa	63° 06′ N, 21° 36′ E	1889–1995	1889–1995	1889–1995	1897–1973
Rauma	61° 08′ N, 21° 28′ E	1889–1995	1889–1995	1889–1995	1907–1995
Utö	59° 47′ N, 21° 22′ E	1889–1995	1889–1995	1889–1995	
Helsinki	60° 09′ N, 24° 55′ E	1848–1995	1829–1995	1848–1995	1889–1995
Loviisa	60° 25′ N, 26° 16′ E	1896–1995	1894–1995	1897–1995	1910–1995
Vyborg	60° 43′ N, 28° 44′ E		1919–2000		
Ozerki (Stirsudden)	60° 11′ N, 29° 02′ E		1888–2000		
St. Petersburg (Nevskaya-Ust′evaya)	59° 55′ N, 30° 15′ E		1920–2000		
Ust′-Luga	59° 40′ N, 28° 19′ E		1920–2000		
Gogland Island	60° 06′ N, 26° 57′ E		1888–2000		
Narva-Jõesuu	59° 28′ N, 24° 31′ E	1903–2000	1903–2000	1903–2000	1922–2000
Pärnu	58° 23′ N, 24° 29′ E	1883–2000	1883–2000	1883–2000	1922–2000
Kihnu	58° 06′ N, 23° 58′ E	1898–2000	1898–2000	1898–2000	1898–2000
Vilsandi	58° 23′ N, 21° 49′ E	1908–2000	1908–2000	1922–2000	1964–2000
Salacgriva	57° 52′ N, 24° 22′ E	1922–2000	1922–2000	1922–2000	
Daugavgriva	57° 04′ N, 24° 02′ E	1922–2000	1922–2000	1922–2000	
Kolka	57° 45′ N, 22° 36′ E	1901–2000	1901–2000	1901–2000	
Ventspils	57° 24′ N, 21° 32′ E	1922–2000	1922–2000	1922–2000	
Liepaja	56° 29′ N, 21° 01′ E	1901–2000	1922–2000	1922–2000	
Gdańsk	54° 40′ N, 18° 70′ E	1922–2000	1922–2000	1922–2000	1946–2000
Ustka	54° 59′ N, 16° 85′ E	1900–2000	1900–2000	1900–2000	1946–2000
Kolobrzeg	54° 19′ N, 15° 55′ E	1896–2000	1896–2000	1896–2000	1946–2000
Swinoujscie	53° 55′ N, 14° 14′ E	1896–2000	1896–2000	1896–2000	1946–2000
Zalew Szczecinski	53° 45′ N, 14° 25′ E	1896–2000	1896–2000	1896–2000	1946–2000
Eckernförde	54° 29′ N, 09° 51′ E	1900–2000	1900–2000	1900–2000	1940–2000
Westermarkelsdorf	54° 32′ N, 11° 03′ E	1898–2000	1898–2000	1898–2000	1940–2000
Unterwarnow	54° 08′ N, 12° 05′ E	1900–2000	1900–2000	1900–2000	1947–2000
Warnemünde	54° 11′ N, 12° 05′ E	1900–2000	1900–2000	1900–2000	1947–2000
Vierendehlrinne	54° 24′ N, 13° 06′ E	1900–2000	1900–2000	1900–2000	1947–2000
Arkona	54° 40′ N, 13° 29′ E	1900–2000	1900–2000	1900–2000	1947–2000
Greifswalder Oie	54° 14′ N, 13° 56′ E	1900–2000	1900–2000	1900–2000	1947–2000

2. DATA SETS AND METHODS

In the present work, we focus on coastal observations for which long time series exist. They consist of the time series of date of freezing, date of ice break-up, number of days with ice and maximum annual ice thickness from Finland, Russia, Estonia, Latvia, Poland and Germany (Table 1, Fig. 1). Additionally, time series of the number of days with ice from 4 stations situated along the Swedish coast were used (Jevrejeva & Leppäranta 2002). The quality of the data sets and missing data are described in detail in Jevrejeva & Leppäranta (2002). For good comparisons, all time series were adjusted to 1900–2000 (the longer time series were cut down). In the present study, the date of freezing is the first day of ice occurrence; date of ice break-up is considered as the date of disintegration of the ice cover in the period with regular ice observations; and the number of days with ice is calculated as the real number of days on which ice occurred.

The study was subdivided into the Baltic Sea (the Bothnia Bay, the Gulf of Finland, the Gulf of Riga, central Baltic [Latvia, Sweden]) and the southern Baltic (Poland, Germany and southern part of Sweden).

The data were analysed by means of descriptive statistics (average, standard deviation, maximum and minimum), using frequency histograms, and for trends.

The first quantity found was the probability of ice occurrence. In the northern Baltic Sea, ice occurs every winter, while the further south one goes the more frequent ice-free seasons become. It is convenient to define a Bernoulli variable 'ice', *I*, for the ice occurrence at the site:

$$I(k) = \begin{cases} 0, \text{ if no ice occurs in winter } k \\ 1, \text{ if ice occurs in winter } k \end{cases}$$

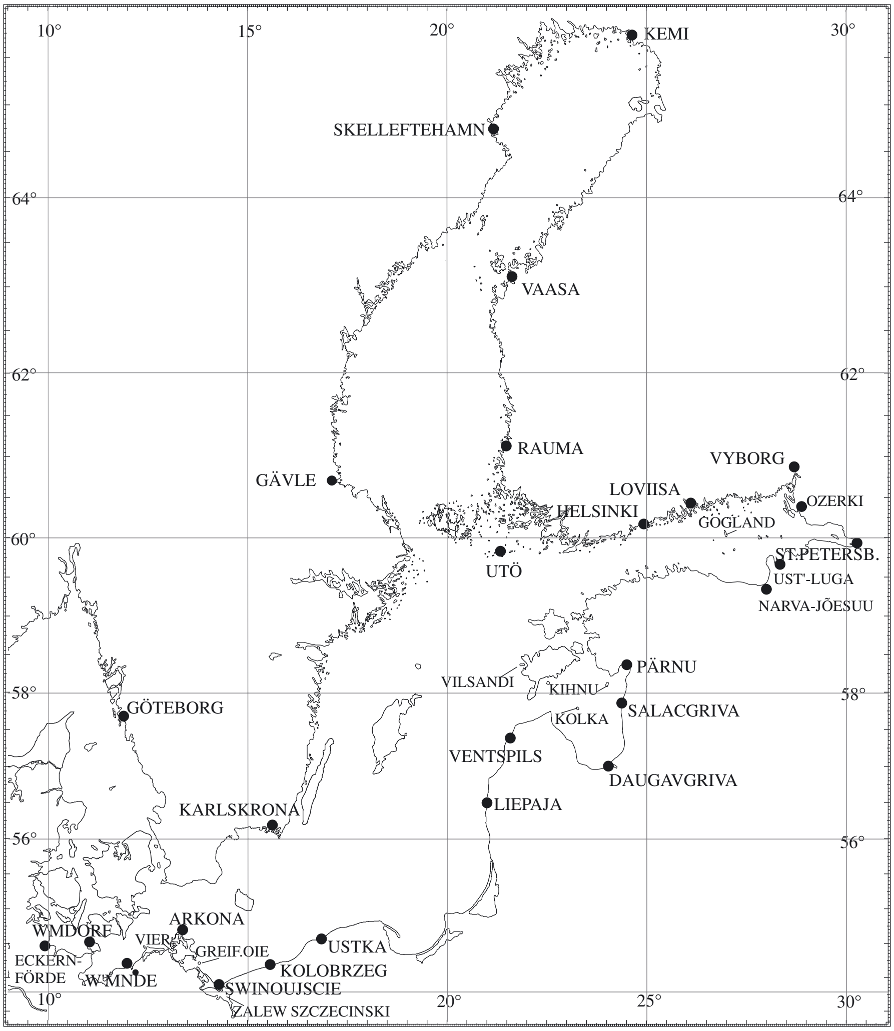

Fig. 1. Map of the Baltic Sea showing the location of observation stations. GREIF.OIE: Greifswalder Oie; VIER: Vierendehlrinne; WMDORF: Westermarkelsdorf; W'MNDE: Warnemünde

If the ice seasons are independent, clearly I follows the binomial distribution, and:

$$\mathrm{E}(I) = p,\ \mathrm{Var}(I) = p(1-p)$$

where the operator E stands for averaging and Var for the variance. For a time series of N winters with n ice winters, the best estimator for p is n/N and its variance is $p(1-p)/N$.

The quantity $I(k)$ can be examined for periodicities as well as for trends and spatial correlations. Its particular advantage is that it is a well-defined quantity whether the ice occurs or not, and all sites on the Baltic Sea are comparable.

A major question is naturally whether the $I(k)$ are independent; this can be estimated by various techniques. In particular, it is interesting to know whether $I(k)$ has a trend or periodicity or is made up of aperiodic changes.

The question of independence of winters is open, however. There are studies indicating cycles (in particular 7 to 8 yr cycles), but there are also studies showing no cycles.

When we come to ice climatology properties such as the date of freezing, the fundamental problem is how to treat seasons with no ice. A solution often applied is to take only ice cases, and then the statistics are performed under the condition that ice occurs. This is misleading. For example, it is possible that the date of freezing shows no trend, but the probability of ice occurrence is decreasing. Clearly, this means a milder climate; thus both features should be included.

The dates of freezing and break-up can be defined only when the sea freezes. The number of ice days and maximum annual ice thickness may be taken as zero when no ice occurs, but this is somewhat artificial, since zeros would then be realized in quite different kinds of winters. To produce statistics from the data is not so straightforward, since, for example, the average freezing date is not well defined if ice does not occur every winter. Let q_1 be an ice-season characteristic and define:

$$q(k) = \begin{cases} q_1(k), & \text{if ice occurs in winter } k \\ \mathrm{q}_0(k), & \text{if no ice occurs in winter } k \end{cases}$$

For the date of freezing q_0 is meaningless, but, for example, for the length of ice season (L), sometimes it may be useful to take $L = 0$ for ice-free winters. It is always possible to define ice statistics on the condition that ice occurs. The expected value under the condition that ice occurs is $\mathrm{E}(q \mid I = 1)$, but it would be the average of just severe enough winters, and a comparison between different qs at different sites would be not good based on the conditional averages.

A way to solve this problem is to use histograms and fractiles. The cumulative distribution is:

$$F(x) = P(q_1 \le x)$$

where P stands for the probability. A natural way to extend the cumulative distribution to include ice-free winters is the following: if no ice occurs in a given winter, let the date of ice freezing, $t_\mathrm{f} = \infty$, the date of ice break-up $t_\mathrm{b} = -\infty$, the number of days with ice $J = 0$ or $-\infty$, and the maximum annual ice thickness $H = 0$ or $-\infty$. Then F is a well-defined cumulative distribution, and its f fractiles are given by $q_\mathrm{f} = F^{-1}(f)$, $0 \le f \le 1$; for example, for $f = 0.5$ the median is obtained. Comparisons between sites with different freezing probabilities can be made using fractiles. If one is interested in time changes, the whole time series can be cut into parts and changes sought during these component parts.

3. RESULTS

3.1. Probability of ice occurrence

The probability of ice occurrence in the Baltic Sea varies drastically from 32% along the German coast (Arkona, Westermarkelsdorf) to 100% in Bothnia Bay (Kemi, Vaasa, Skelleftehamn). The probability of ice occurrence is also dissimilar for the open areas and shallow inner waters; even along the German coast the probability is confined between 32 and 92% (under the same weather or temperature conditions), and along the Polish coast between 54 and 93% (Fig. 2).

For the northern part of Bothnia Bay there are no changes in probability of ice occurrence, since the basin has frozen annually throughout the 20th century. Stn Utö (Finland) and German stations show statistically significant decreasing trends in probability, indicating that the open area in the northern and southern parts of the Baltic Sea are characterised by less winters with ice over time; this is in good agreement with a warming trend observed over Europe for the investigated period (Balling et al. 1998). However, the Gulf of Finland station, Loviisa, demonstrates a statistically significant increasing trend; Stn Narva-Jõesuu shows a similar trend, but it is statistically insignificant. Increasing trends in the Gulf of Finland can be explained by missing data in the earliest part of century and an increase in the freshwater influx to the gulf during recent decades (Jaagus 1996, Winsor et al. 2001). Along the Swedish coast, the trends were not statistically significant (Fig. 3).

We have constructed similar time series of (1,0) for the available air-temperature time series, assuming:

$$A(k) = \begin{cases} a_1(k), & \text{if winter air temperature is negative in winter } k \\ \mathrm{a}_0, & \text{if mean air temperature is positive in winter } k \end{cases}$$

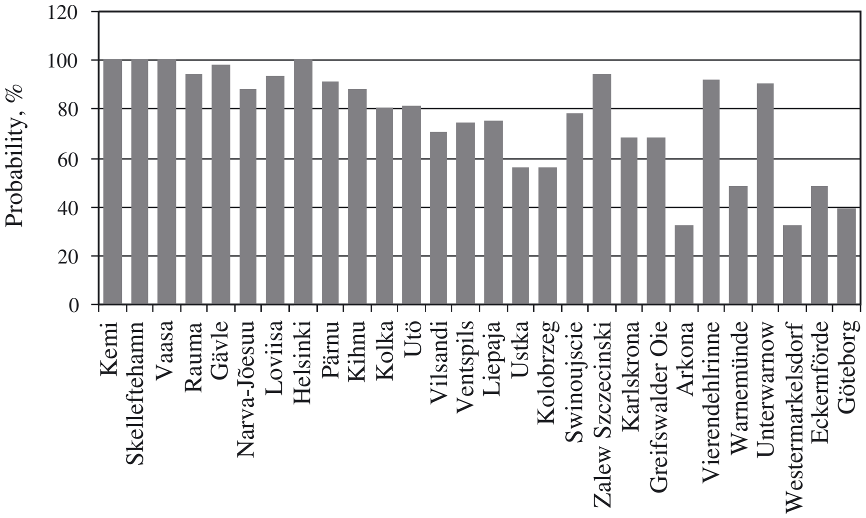

Fig. 2. Probability of ice occurrence in the Baltic Sea (1900–2000)

Correlation coefficients between time series of probability of negative mean winter air temperature and probability of ice occurrence were close to 0.9; however, for some stations (e.g. Vilsandi) correlation coefficients were rather low. Results for the open area of the Baltic show that the decrease in probability of ice occurrence is partly explained by the increase in winter air temperature.

3.2. Date of freezing

The mean date of freezing in the Baltic Sea is confined to between 10 November in Kemi and 25 January in Westermarkerlsdorf (Fig. 4). In general, mean date of freezing for the northern Baltic Sea (including the Gulf of Finland and the Gulf of Riga) falls between 10 November and 20 December; for along the Latvian coast (open area) between 21 December and 10 January; and for the southern Baltic Sea (Germany and Poland) between 10 and 30 January. The earliest freezing was observed at the beginning of October in the northern part of the Baltic Sea. Some of the earliest dates of freezing for the southern Baltic (Ustka, Kolobrzeg, Vierendehlrinne) were associated with the influence of cold air masses during the autumn, when ice formation is observed for a short time in shallow coastal areas. However, the earliest date of ice freezing is mostly related to

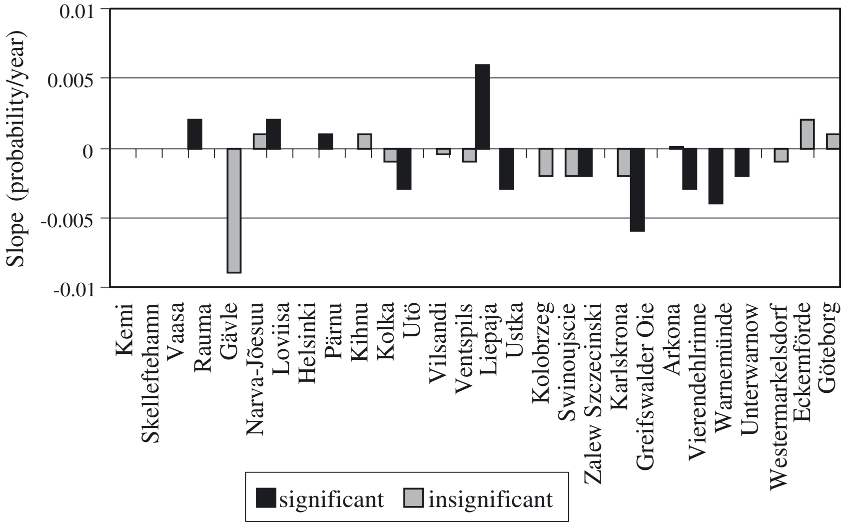

Fig. 3. Trends in the time series of probability of ice occurrence in the Baltic Sea (1900–2000); black and grey columns represent statistically significant ($p < 0.05$) and insignificant ($p > 0.05$) slopes, respectively

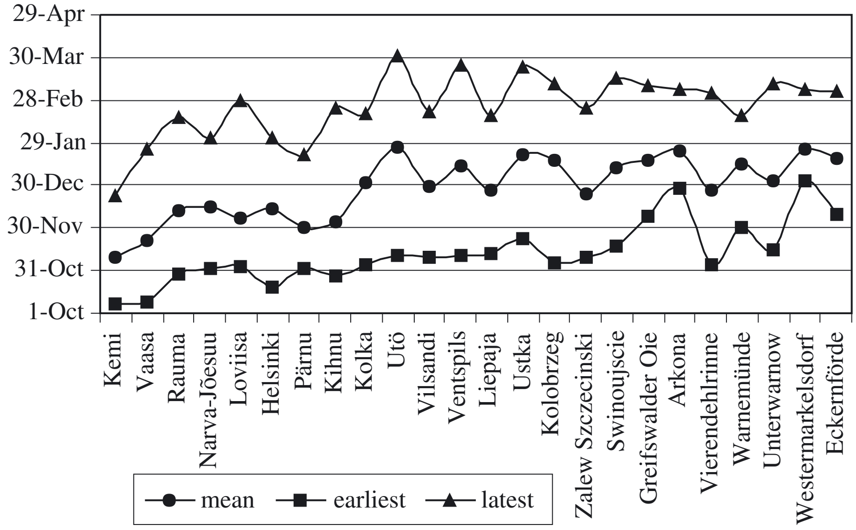

Fig. 4. Mean, earliest and latest dates in time series of date of freezing in the Baltic Sea (1900–2000)

average and mild winters, characterised by mixed-ice/no-ice periods.

The latest date of freezing was observed in Utö (31 March), Finland. This can be explained by the solar radiation balance; at such a high latitude the solar radiation balance is still negative in March, and ice formation may take place. For the southern Baltic, no freezing later than 10 March was reported.

The standard deviation in the time series for the date of freezing varies between 13 (Kemi) and 29 d (Ventspils); there are rather low values (16 to 23 d) for the southern Baltic. In the north, the winter comes fast, and therefore the standard deviation is at its lowest. On the other hand, in the south, only in the normal and severe winters does it freeze, which limits the standard deviation.

Cumulative probability curves of the date of freezing for selected stations representing all parts of the Baltic Sea are given in Fig. 5. Fractiles can be determined from these curves for the best comparison between different sites. The curves display a difference of about 2.5 mo for the 10% fractile in Kemi and Arkona (23 October and 5 January, respectively). In the northern part of the Baltic Sea there is a delay of 67 d for the 10% fractile (from Kemi to Utö), which increases to 106 d for the 75% fractile. Thus, in severe winters, freezing progresses more rapidly.

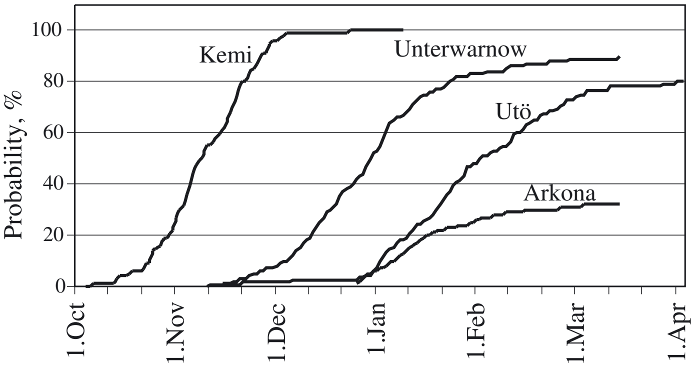

Fig. 5. Cumulative probability curves of time series of date of freezing in the northern (Kemi, Utö) and southern (Unterwarnow, Arkona) Baltic Sea

Along the Finnish coast, statistically significant increasing trends were found only for Vaasa (21 d per 100 yr), Utö (28 d per 100 yr) and Helsinki (14 d yr^{-1}); for other stations, trends were showing the same tendency to the later freezing, but significance was below the 95% level (Fig. 6a).

All Estonian stations show a tendency toward earlier freezing with time; however, only for the Gulf of Finland was the trend statistically significant. It may be explained by the increase in precipitation and increase in freshwater influx to the Gulf of Finland for the past 30 yr (Jaagus 1996). The same tendency is found in Latvian waters, but the results there are statistically insignificant.

In the southern Baltic the situation is opposite: on the Polish and German coast, all sites show later freezing, but the trends are not statistically significant.

3.3. Time series of date of ice break-up

The mean date of ice break-up occurred between 20 February (Warnemünde) and 21 May (Kemi) (Fig. 7). An extremely early date of ice break-up was found for the southern

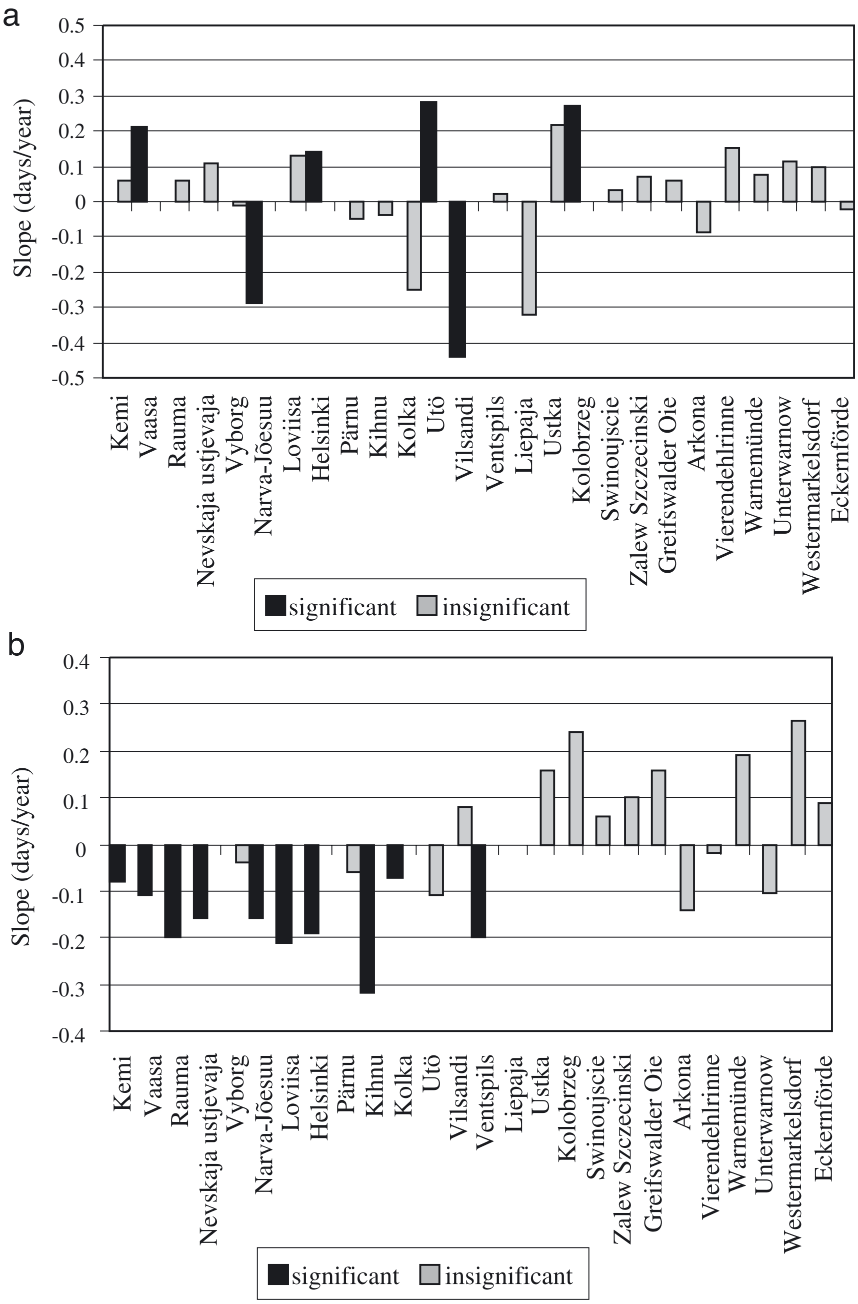

Fig. 6. Slopes sof the trends in time series of date of (a) freezing and (b) break-up in the Baltic Sea (1900–2000); black and grey columns represent statistically significant ($p < 0.05$) and insignificant ($p > 0.05$) slopes, respectively

Baltic time series. In shallow lagoons along the Polish coast, ice may form and disappear several times during an average or mild winter. During a mild winter, ice formation in the shallow coastal waters is limited to a few days, mostly occurring during a single cold spell (e.g. 1924–1925).

The standard deviation is higher in the southern part of the Baltic Sea. Furthermore, in the northern part, the standard deviation of freezing is higher than that for break-up, and in the southern part, the standard deviation for break-up is higher than that for freezing date. Cumulative probability curves demonstrate a substantial difference in the northern and southern parts of the Baltic Sea (Fig. 8).

Linear trends in time series of date of ice break-up for the northern Baltic Sea show evidence for break-up occurring earlier (8 to 20 d per century); however, some of them are statistically insignificant (Utö, Pärnu)

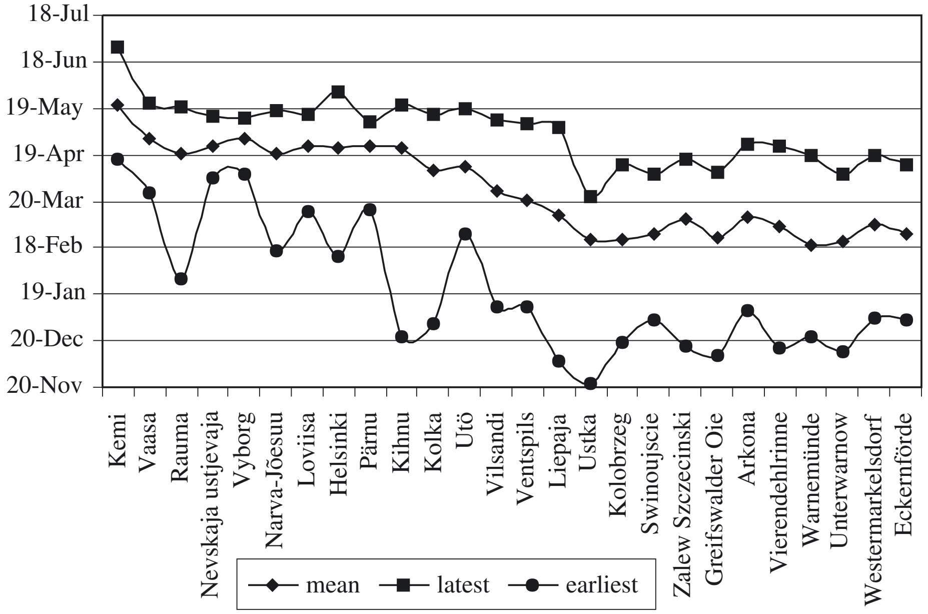

Fig. 7. Mean, earliest and latest break-up in the Baltic Sea (1900–2000)

(Fig. 6b). The results are in good agreement with grades regarding the date of ice break-up in Finnish rivers (Magnuson et al. 2000) and trends in winter air temperatures (Heino 1994, Balling et al. 1998).

We analysed the influence of large-scale atmospheric circulation on the date of ice break-up. Correlation coefficients between the time series of the North Atlantic Oscillation (NAO) winter index (Jones et al. 1997) and time series of date of ice break-up are between −0.4 and −0.7. However, they vary remarkably with time, showing that the relation is not stable and that other processes which are not included may have undergone changes over time. Most of them show increasing correlation coefficients since 1960 (Fig. 9). The results of our study are consistent with recently published papers (Girljatovicz 2001, Jevrejeva & Moore 2001, Omstedt & Chen 2001, Jevrejeva 2002).

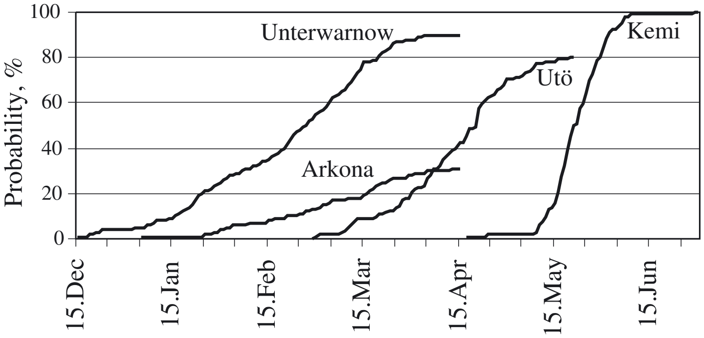

Fig. 8. Cumulative probability curves of date of ice break-up for northern (Kemi, Utö) and southern (Unterwarnow, Arkona) Baltic Sea

For the southern part of the Baltic Sea, all trends are statistically insignificant, however, displaying the tendency for a later break-up.

3.4. Number of days with ice

The year-to-year variation in time series of number of days with ice is remarkable. For the northern part, the mean number of days varies from 74 (Utö) to 193 (Kemi); however, for the southern part it is less than 50 d. The maximum number of ice days is 236 d in the north and 122 d in the south. Standard deviation varies from 17 d in Kemi to 45 d in Vilsandi, which shows that the variation in the time series of the number of days with ice in the open areas and in the central part of the Baltic Sea is higher than in coastal areas. Relatively low values of standard deviation in number of days with ice were found for the southern part (about 30 d).

For the northern part, statistically significant decreasing linear trends (14 to 44 d per century) were detected; for the southern part, the trends are statistically insignificant. Results support the hypothesis that there is a trend toward less prevalent ice conditions.

3.5. Maximum annual ice thickness

The time series of maximum annual ice thickness for the stations with a probability of ice

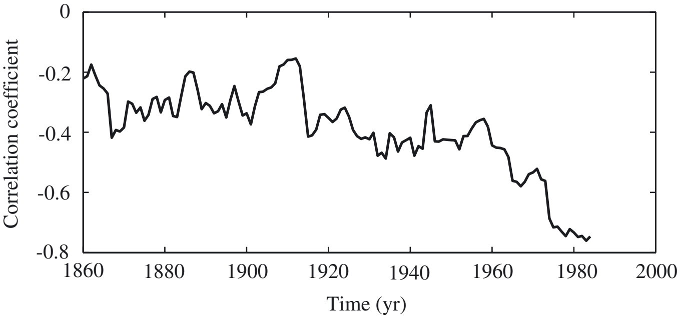

Fig. 9. Moving correlation coefficient between the date of ice break-up and the winter NAO index (window 30 yr)

occurrence higher than 70% were analysed. They do not show any general tendency. There is an increasing trend (statistically significant, 12 cm per century) in Kemi, and an increasing trend in Kihnu, just below the 95% level. The increasing trend in Kemi is in good agreement with the results of Haapala & Leppäranta (1996, 1997), who have shown that ice growth depends on snow thickness and is linked to an increasing trend in winter precipitation in the northern part of Finland.

In the Gulf of Finland, statistically significant trends showing a decline in the maximum annual ice thickness (25 cm per century; Helsinki, Loviisa) were found.

4. DISCUSSION

The decreasing trend in probability of ice occurrence found at most sites is in good agreement with a warming trend in winter air temperature over Europe (Balling et al. 1998). The opposite tendency in the Gulf of Finland and Gulf of Riga can be explained by increasing freshwater influx to the shallow semi-closed basins (Winsor et al. 2001).

For the freezing and break-up time series, we found a particular dissimilarity in statistical characteristics for the northern and southern parts of the Baltic Sea. The date of freezing is characterised by a low standard deviation, and the probability of ice occurrence is close to 100%; in addition, it is low in the southern Baltic, even where the probability of ice occurrence is only 32% (Arkona). We examined the relation between the probability of ice occurrence and standard deviation; a curve fit (not shown here) illustrates the decrease in the standard deviation with increasing probability, but not for the southern part of the Baltic. We propose that this is due to the difference in radiation balance and the consequent limited potential time for freezing in the southern part of the Baltic. The freezing date is related to the sea-surface temperature, which mainly depends on the mixed layer depth, radiation balance and the turbulent head exchange between sea and the atmosphere.

The standard deviation of the time series of the date of freezing is smaller than the standard deviation of the ice break-up for the northern part, and vice versa for the southern part. This difference is due to the radiation balance; the conditions for freezing and break-up in the southern part of the Baltic are potentially more limited (1 to 2 mo shorter from both ends in the south). The relatively small value of standard deviation for freezing date in the south can be explained by the fact that freezing cannot take place earlier than 4 November or later than 10 March due to the warmer climate. In the northern part of the Baltic, freezing can be observed from the beginning of October (Kemi) to the end of March (Utö).

Our results show that the date of ice break-up has a relatively small standard deviation in the north. However, in the southern part of the Baltic, the range of the date of break-up and standard deviation is remarkably larger. This is due to very short ice seasons in the south; occasionally, thin ice may appear in December and then melt, with no more ice occurring in the season.

Linear trends for the time series of the date of ice freezing in rivers in Finland over the 150 yr show a trend of from 0.7 to 5.7 d later freezing, but only one of them is statistically significant (Magnuson et al. 2000). Our results confirm the tendency for later freezing, with a maximum as high as 28 d per century. Nevertheless, most stations situated along the Baltic Sea are characterised by statistically insignificant trends.

The trends toward earlier ice break-up in the northern Baltic Sea can be explained by an increasing winter air temperature (Jones 1994, Balling et al. 1998), with weather conditions dominated during the past years by westerly circulation related to a positive NAO index (Winsor et al. 2001). Results from our study are consistent with other results (Loewe & Koslowski 1998, Girljatovicz 2001, Jevrejeva & Moore 2001, Omstedt & Chen 2001, Jevrejeva 2002), which demonstrate that large-scale atmospheric circulation patterns represented by NAO teleconnections have significantly controlled ice conditions in the Baltic Sea during the last 30 yr.

In the southern Baltic the tendency for a later break-up is related to the decreasing probability of ice occurrence. The combination shows less winters with ice, but ice is mostly observed with more and more severe winters (which are still reported). For the present sample, the early date of break-up for the mild winters disappears, which affects the statistical properties of the time series; the same effect can be seen for the standard deviation of the time series of the date of break-up.

5. CONCLUSION

The long-term time series of date of freezing, break-up, number of days with ice and maximum annual ice thickness of landfast ice in the Baltic Sea were examined by statistical methods. Results provide a new view of the rather complicated variability in ice conditions. The conclusions may be summarised as follows.

- The probability of ice occurrence is confined to between 32% in the southern part of Baltic Sea (Germany, Poland, southern part of Sweden) and 100% in the north and along the Finnish and Russian coasts.
- In the northern part of the Baltic Sea, there has been a change in the probability of ice occurrence. In the south Baltic Sea (Germany) and central areas, there is a statistically significant decreasing trend.
- Break-up in the north is characterised by a statistically significant decreasing trend showing earlier (8 to 20 d) break-up; in the south, trends are insignificant but have a tendency for a later date of ice break-up.
- Most sites show a tendency for shorter ice periods (maximum shortening is 44 d per century, Utö).
- There is no general conclusion concerning maximum annual ice thickness. Some sites (Kemi and Kihnu) show an increase (5 to 11 cm per century); however, most time series are characterised by a decreasing trend.

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