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Ice Conditions along the Estonian Coast in a Statistical View

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The paper presents the results from analysis of long-term (100-year) time series of freezing, fast ice formation, disappearance of fast ice, break-up and ice thickness for eight stations situated along the Estonian coast in the Gulf of Finland and Gulf of Riga. Most of the data have not been published yet. Basic statistics: average, standard deviation, maximum, minimum and frequency histograms are given. On average ice has formed in the Gulf of Finland three weeks later compared with the Gulf of Riga. The range of variation of the freezing date is very large, 3-4 months, with maximum value of standard deviation 29 days (Tallinn). The average ice seasons last 4-5 months; the range is 0- 7 months. Statistically significant trends are found in time series of date of freezing for Sõrve and Virtsu and in time series of ice break-up for Kihnu and Virtsu, both trends toward shorter ice seasons. Correlation coefficients of different time series are varied through 0.03-0.90.

Introduction

The coastal areas along the Estonian coast in the Gulf of Finland and Gulf of Riga are covered by ice nearly every winter. The ice seasons last from November to May. Ice conditions have a large importance as the main factor restricting the winter navigation. The safety and efficiency of sea transportation, offshore operations, and fisheries encouraged the development of the sea ice monitoring and forecasting service in Estonia. There is a long tradition of ice observations in this country. The oldest written documents about ice break-up are from the 14th century, found in the Tallinn Town Archive (Tarand 1993).

A number of reports exist on the statistical properties of ice conditions in the Baltic Sea as time series, tables and ice atlases. Jurva (1937), Palosuo (1953), Makkonen et al. (1984), Seinä (1993), Leppäranta and Seinä (1985), Haapala and Leppäranta (1996) have examined the Baltic ice extent and ice conditions along the coast of Finland. For the western Baltic Sea ice conditions have been analysed in terms of a mass-related severity index (Koslowski and Loewe 1994; Koslowski and Glaser 1995). Girjatowicz and Kozuchowski (1995) and Sztobryn (1994) have presented ice statistics along the coast of Poland.

Such work is largely lacking for the Estonian waters. There are some earlier publications, mostly from the time before the Second World War. More recently, long-term continuous time series of ice break-up at the port of Tallinn based on historical chronicles has been re-constructed by Tarand (1993). There are also some publications in Russia, describing the general features of ice regime in the Baltic Sea but without any detailed analysis of ice conditions along the Estonian coast (Betin 1957). A few internal reports have been produced in the Estonian Meteorological and Hydrological Institute (EMHI).

The ice conditions are investigated here for the Estonian coast during the period 1890-1990. In a previous study an analysis of the sum of negative degree-days, air temperature, onset of freezing and onset of melting, and the number of ice days has been carried out (Jevrejeva 1999, 2000). The relation between the time series of the sum of negative degree-days and number of ice days was investigated, resulting correlation coefficients being from 0.61 to 0.76. A new more detailed study has now been completed. The objective is to analyse the temporal variability of the date of the freezing, fast ice formation, fast ice break-up, ice break-up and maximum ice thickness.

The Data Material

In Estonia regular ice observations were commenced in the 1800s at several lighthouses: *e.g.*. Sõrve in 1865, Tallinn and Naissaar in 1889, Narva in 1889 and Kihnu in 1895 (Table 1, Fig.1). The observation programme included information about the date of the first freezing, the formation of the permanent ice cover, the date of the end of the permanent ice cover, the final disappearance of the ice and the thickness of the ice. During the ice seasons also air temperature measurements were made. These observations were recorded in journals and preserved to the present day in the archive of EMHI.

Since 1959 the observation programme has changed remarkably. New detailed measurements of ice drift, ice thickness and development of ice were introduced. At present the ice conditions are daily reported from 21 coastal stations.

Table 1 – The availability of ice data on the Estonian coast (EMHI archives)

N	Station	Periods of observations
1.	Abruka	1910-13, 1922-40, 1946-63
2.	Aegna	1930-40
3.	Haapsalu	1922-31, 1931-40, 1947-57
4.	Heltermaa	1947-50, 1950-90
5.	Häedemeeste	1930-39, 1939-40
6.	Keri	1906-07, 1908-14, 1922-40
7.	Kihnu	1894-97, 1898-1914, 1916-17, 1921-40, 1949-90
8.	Kunda	1948-49, 1950-90
9.	Kõpu	1903-07, 1908-14, 1922-40
10.	Loksa	1923-24, 1925-30, 1950-58
11.	Merise	1949-63
12.	Mohni	1903-14, 1922-40
13.	Naissaar	1888-1906,1908-09,1910-17, 1922-40,1949-90
14.	Narva-Jõesuu	1903-14, 1922-40, 1948-64, 1964-90
15.	Osmussaar	1903-17,1922-40,1952-72
16.	Pakri	1903-09, 1910-14, 1922-40, 1950-90
17.	Paldiski	1923-26, 1954-90
18.	Prangli	1949-56, 1966-90
19.	Puise	1932-40

N	Station	Periods of observations
20.	Purtse	1930-33, 1933-40, 1946-64
21.	Põõsaspea	1929-35, 1939-40, 1949-90
22.	Pärnu	1893-1907, 1908-11, 1920-40, 1944-90
23.	Raugi	1923-40, 1947-90
24.	Ristna	1922-23, 1924-25, 1929-40, 1948-90
25.	Roomassaare	1922-24, 1925-40
26.	Rohuküla	1949-50, 1950-90
27.	Rohuneeme	1949-50, 1955-90
28.	Ruhnu	1903-14, 1922-40, 1947-90
29.	Suurpea	1960-90
30.	Suurupi	1916-17, 1922-40, 1947-55
31.	Sõrve	1903-14, 1922-40, 1951-90
32.	Sõru	1923-35, 1947-90
33.	Tallinn	1903-07, 1908-17, 1923-40, 1948-90
34.	Tahkuna	1903-14, 1922-40, 1950-67
35.	Toolse	1929-40
36.	Vaindloo	1888-95, 1903-04, 1906-17, 1923-40
37.	Viirelaid	1888-93, 1894-96, 1897-98, 1899-1902, 1903-17, 1922-40
38.	Vilsandi	1908-14, 1922-40, 1949-90
39.	Virtsu	1904-17,1922-24,1929-30,1932-40, 1947-90
40.	Vormsi	1892-1914, 1915-17, 1922-40,

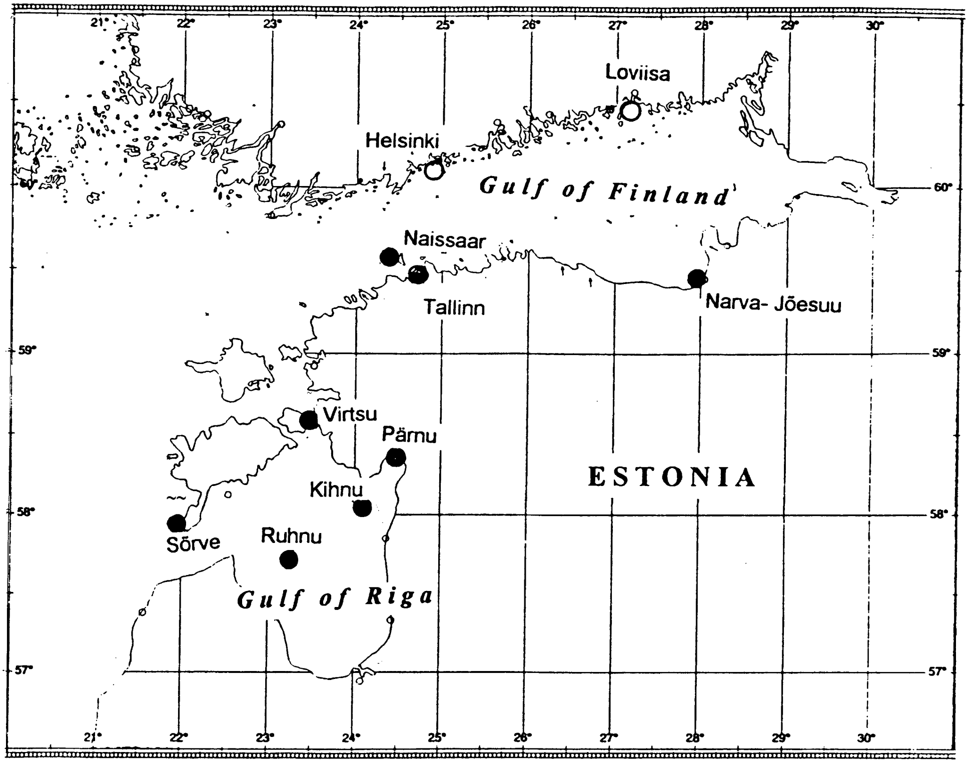

Fig. 1. Location of the observation stations used in the investigation.

The archive of EMHI thus includes daily ice observations and measurements spanning 120 years. There were some gaps during the First and Second World Wars. The following eight stations were selected for the time-series analyses based on at least 80 years of observations: Narva, Tallinn and Naissaar in the Gulf of Finland, and Sõrve, Ruhnu, Kihnu, Virtsu and Pärnu in the Gulf of Riga.The time series include the date of the first freezing, the date of formation and end of permanent ice cover, the final disappearance of ice, number of days with ice, ice thickness and air temperature. For comparison the results for Helsinki and Loviisa along the Finnish coast of the Gulf of Finland (Leppäranta and Seinä 1985) were utilized.

The data were analysed for descriptive statistics (average, standard deviation, maximum and minimum) and frequency histograms. For trends analysis, the results for regression fit, correlation coefficients, and the significance level (by use of a t-test) are given.

In a site where sea ice does not form every winter, the definition of ice season characteristics may be difficult. The length of ice season comes out as zero and the dates of freezing and break-up do not exist. To examine such time series it is necessary to include the probability of ice occurrence. This is made as follows: let $I(n)=0$ if ice does not form; or $I(n)=1$ if ice forms in winter n. Then the average of I is the probability of ice occurrence, and by establishing the trend of I it is possible to say whether winters with no ice become more common or rare.

Table 2 – Statistics of time series of date of freezing, date of fast ice formation, date of fast ice break-up and date of ice break-up (Gulf of Finland), N- number of years ice observations, Ntotal- total number of years.

	Narva	Tallinn	Naissaar
Date of freezing			
Probability of freezing	82%	71%	77%
Mean	15.Dec	5. Jan	19.Jan
St. dev. (days)	21	29	21
Earliest	2. Nov	3.Nov	26.Nov
Latest	1. Feb	12.March	3.March
N/ N total	71/87	64/90	75/98
Date of fast ice formation			
Probability of fast ice formation	77%	71%	60%
Mean	2. Feb	14.Jan	3.Feb
St. dev. (days)	17	22	18
Earliest	15.Dec	7.Nov	6.Dec
Latest	4.March	7.March	2.March
N/ N total	60/86	60/84	33/78
Date of fast ice break-up			
Mean	12.April	7.April	6.April
St. dev. (days)	21	18	25
Earliest	17.Jan	8.Feb	15.Jan
Latest	14.May	8.May	10.May
N/ N total	67/86	57/84	47/78
Date of break-up			
Mean	21.April	8.April	15.April
St. dev. (days)	18	24	23
Earliest	16.Feb	9.Jan	15.Jan
Latest	18.May	14.May	30.May
N/ N total	70/87	66/90	72/98
Ice thickness (cm)			
Mean	42		40
St. dev.	17		15
Min	10		3
Max	88		83
N/ N total	56/86		29/78

Table 3 – Correlation coefficients of time series of date of freezing and date of ice break-up (Gulf of Finland)

	Loviisa	Narva	Tallinn	Naissaar
Date of freezing				
Helsinki	0.54	0.25	0.21	0.20
Loviisa		0.25	0.03	0.15
Narva			0.49	0.45
Tallinn				0.27
Date of break-up				
Helsinki	0.60	0.46	0.59	0.67
Loviisa		0.63	0.55	0.52
Narva			0.54	0.58
Tallinn				0.77

Results

Gulf of Finland

Freezing

The time series of date of freezing are characterized by a very high natural variability (Table 2). The freezing front comes from Narva to Tallinn in the time of three weeks, with standard deviation 21 -29 days and range 3-4 months. The correlation coefficients (Table 3) are low: 0.49 for Narva-Tallinn, 0.45 for Narva-Naissaar and 0.27 for Naissaar-Tallinn. Also across the Gulf of Finland correlations are low, at best 0.25 for Loviisa-Narva. On the other hand, the correlation coefficients in mean air temperature for the period November-April for the same stations are about 0.97-0.99 (Jevrejeva 1999, 2000).

Attempts to find any regularity in the time series of the date of freezing by classifying them according to the severity of winter were inadequate with persistent statistical 'noise'. A mild winter can start at any time, late or early. The range of standard deviations is wide for the different types of winter seasons. The highest values (26 days, Tallinn and 25 days, Helsinki, Narva) were found for mild winters. For normal winters the standard deviations is 13-26 days, and for severe winters the standard deviations is 12-23 days.

The histograms of freezing date are asymmetrical and shifted toward the beginning of winter season *i.e.* positively skewed, with clearly indicated peak (Fig. 2). Freezing starts from the Finnish coast (Helsinki, Loviisa), and two weeks later the ice appearance is observed in Narva. In Tallinn freezing starts later with lower frequency, the rest of the histograms are rather uniform. Ice appearance around the island of Vaindlo (which is situated in the middle of the Gulf of Finland between Helsinki and Tallinn) occurs with a delay of 30 days from Helsinki and 10 days from

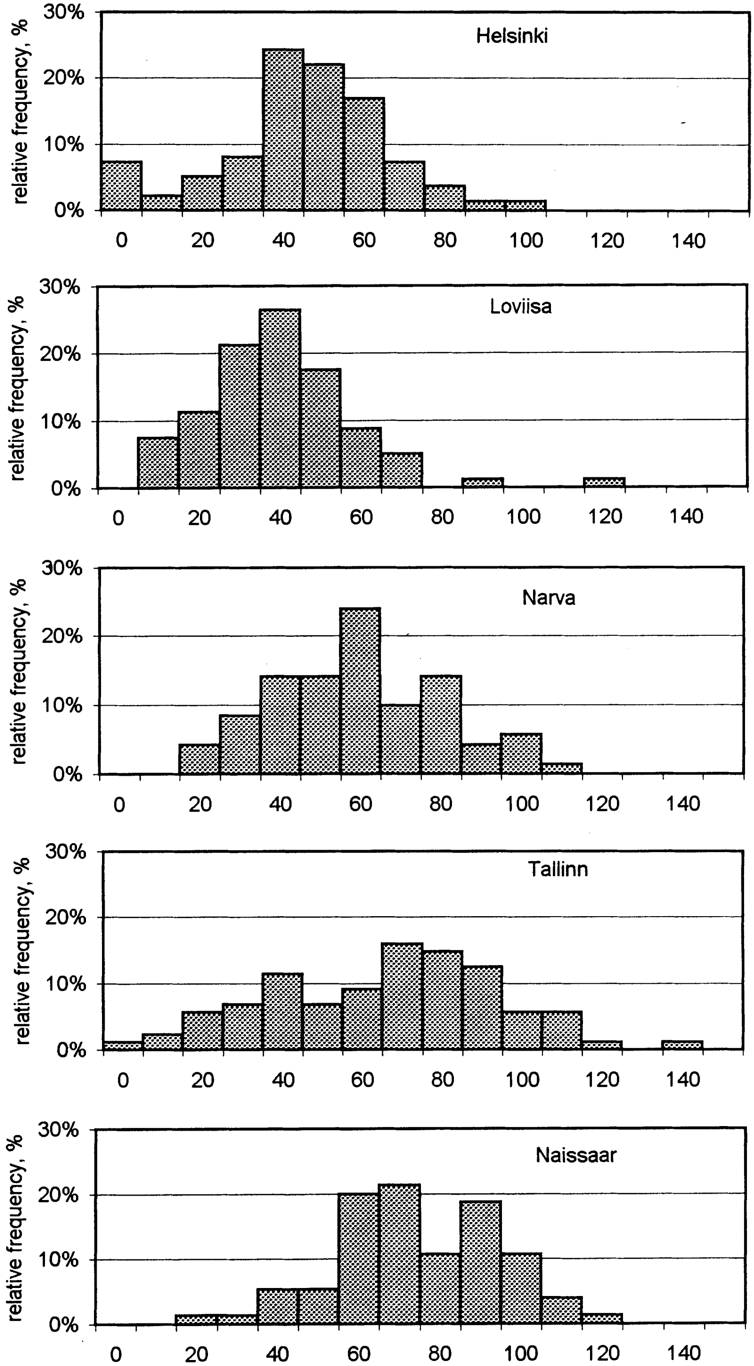

Fig. 2. Histograms of date of freezing in the Gulf of Finland.

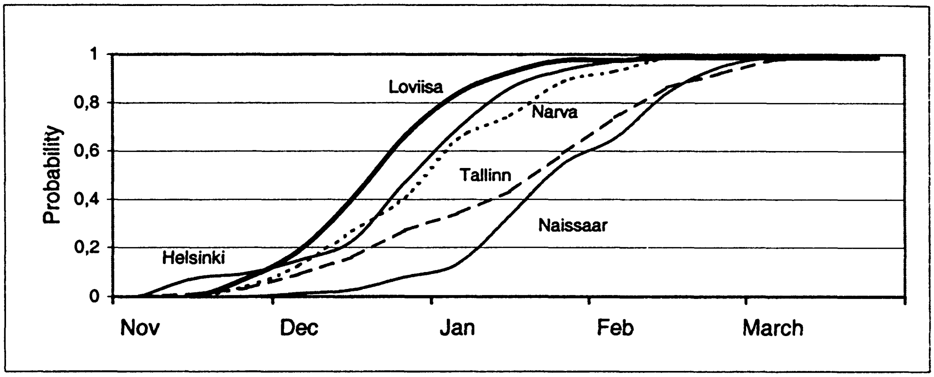

Fig. 3. Cumulative probability curves for the stations situated in the Gulf of Finland

Tallinn. The time series is shorter than others, but it is important to assess its location in order to understand the freezing in the Gulf of Finland. At the same time (with a delay also of around 30 days) freezing starts around island Naissaar, which is situated not far northwest from Tallinn.

Cumulative probability curves for each station in the Gulf of Finland are shown in Fig. 3. They are confined between the curves of Loviisa and Naissaar. At the same cumulative probability level the time range is 50 days for those stations. There is a similar tendency for the three stations Loviisa, Helsinki and Narva. For Naissaar the shape of the curve is the same but shifted; for Tallinn the slope of the shape much differs from the rest.

Trend analysis by linear regression showed that the probability of freezing is increasing in Narva and Tallinn (significant trend), *i.e.* more winters with ice is expected to come; insignificant at Naissaar. Statistically insignificant increasing linear trends were found for the time series of freezing on the Estonian coast. However, the time series of Helsinki shows the later freezing (Leppäranta and Seinä 1985).

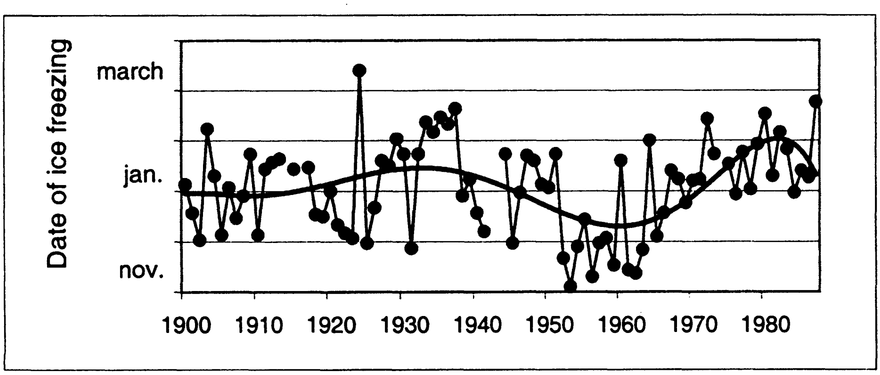

Fig. 4. Polynomial fitting curves for the time series of date of freezing in the Gulf of Finland

A fifth degree polynomial fit (Fig. 4) shows aperiodic oscillations during 1900-1990. They are similar as the tendencies found for the sums of negative degree- days and for the mean air temperature for the period November-April (Jevrejeva 1999). A tendency toward later freezing occurred from the beginning of the 20th century until 1940, then freezing became earlier until 1960, and thereafter again the freezing appeared later.

Table 4 – Statistics of time from the zero downcrossing of air temperature to the date of freezing and statistics of time from zero upcrossing of air temperature to the date of break-up (Gulf of Finland); unit in day.

	Narva	Naissaar	Tallinn
Freezing			
Mean	20	30	34
St. dev.	24	20	27
Max	77	81	103
Min	-40	0	0
Break-up			
Mean	25	14	13
St. dev.	13	10	16
Max	58	29	39
Min	-21	-15	-44

Fast Ice Formation and Break-up

The specific date for the zero down-crossing of air temperature was defined by the method given in "Guideline for the construction of climatological time series"(1969). The number of days elapsed after the downcrossing to the date of freezing was analysed (Table 4). The first appearance of ice along the Estonian coast is usually related to the formation of ice from the freezing of water, rarely the first ice is non- local drift ice. Only in Narva the drift ice from the Narva river is recorded as the first ice in some years, confirmed by the fact that ice was observed earlier than air temperature became negative. In calm and cold weather freezing may occur on the same day when air temperature passes through zero, while in the other extreme the delay may be as much as 103 days (station Tallinn).

In general, fast ice is observed every ice season, even during a mild winter. The natural variability in the time series of the formation of fast ice is less than in the time series of freezing (Table 2). There are two peaks in histograms of date of fast ice formation, most probably due to formation of fast ice in winters with different severity.

In 1900-1990 there is a statistically significant increasing trend in the probability of fast formation. In regards with timing the data show a tendency toward later formation of fast ice (5-15 days per 100 years) but these trends are not statistically significant (only 75-90% level).

The average annual maximum ice thickness is about 40 cm in Narva and Naissaar (Table 2). There was a quite low correlation (0.32) between these two time series. The observed maximum ice thickness is 88 cm, occurred in winter 1925/26. Trends in time series are statistically insignificant.

The date of fast ice break-up is on average 6-12 April with standard deviation of 18-25 days (Table 2). There are no statistically significant trends in these time series.

Break-up

The time series of date of ice break-up are characterized by high natural variability, but less than in the time series of the date of freezing (Table 2). The highest correlation was obtained for Tallinn and Naissaar (Table 3).

The histograms (Fig. 5) show that in general the disappearance of ice runs in reverse order compared with its appearance. Ice break-up starts from Naissaar, and there after it is observed in Tallinn, Narva, Helsinki and Loviisa. Ice break-up occurs at Loviisa mostly 1-20 May, close to the situation at Narva. The Tallinn histogram is quite flat spanning through 10 March-10 May.

Analysis of the time elapsed after the date of zero upcrossing of air temperature until the date of break-up shows that in some winters ice break-up was even earlier than the zero upcrossing (Table 4); *e.g.* Naissaar in 1972/73 and 1973/74, Narva in 1909/10 and in ice season 1929/30 the ice break-up was on the 8th of February in Tallinn, 44 days before the upcrossing. The likely explanation is that the ice disappearance may result from dynamic factors (strong wind, sea level fluctuations, currents), which are connected with the cyclone activity dominated during the mild and normal winters (Betin 1957; Myrberg 1998). In addition, there is a low correlation coefficient ($R = 0.39$) between the time series of air temperature zero upcrossing and time series of date of ice break-up in Tallinn.

The break-up is more uniform at Naissaar, according to the quite strong correlation with date of air temperature zero upcrossing (0.91). There is the largest range (140 days) between the earliest and latest break-up in the Gulf of Finland: from the last days of January to the end of May, the latest case being due to the ice drifted from the sea. Very early disappearance of ice can be found also for Tallinn (the beginning of February), Narva (the end of February) and Helsinki (the end of February). These stations are situated at the climatological ice edge.

In regards with different winter types, the average dates of break-up are for mild winters between the 26th of March (Naissaar) and the 21st of April (Loviisa), for normal winters between the 13th of April (Tallinn) and the 28th of April (Loviisa), and for severe winters between the 28th of April (Helsinki) and the 6th of May (Loviisa).

Cumulative curves of date of break-up are flattest for Tallinn and Naissaar. Slightly decreasing trends were found mostly indicating the break-up coming earlier by 5-

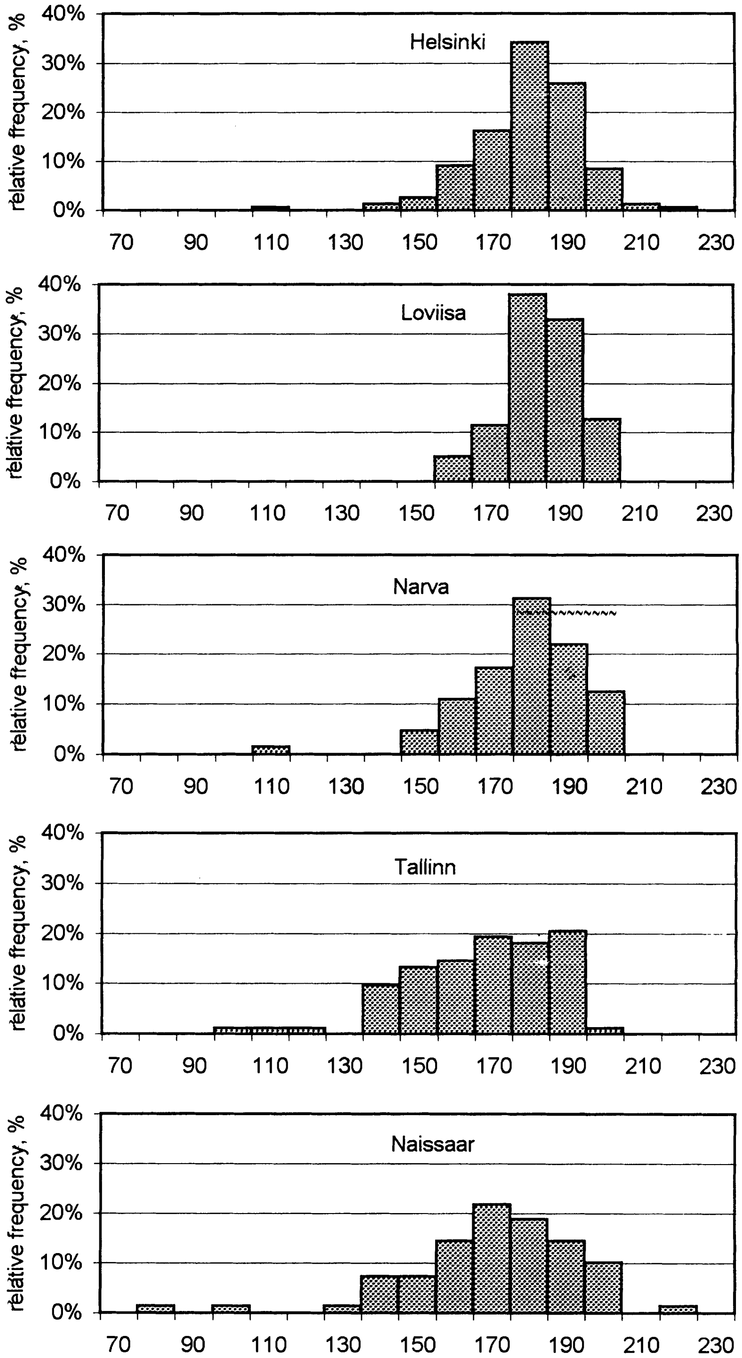

Fig. 5. Histograms of date of break-up in the Gulf of Finland.

15 days during the 100-year period (statistical significance of those trends are close to the limit). No trends were found for the time series of the time elapsed after the air temperatures upcrossing to the date of ice break-up.

The relation between the time series of sum of negative degree -days and time series of date of ice break-up was investigated by regression analyses, the former treated as the independent variable. The correlation coefficient was 0.70 for Tallinn and 0.90 for Narva. The correlation coefficient between the time series of the air temperature zero upcrossing and date of break-up was 0.39 for Tallinn, 0.91 for Naissaar and 0.70 for Narva.

Summary for the Gulf of Finland

The first appearance of ice along the Estonian coast in the Gulf of Finland is usually related to the local freezing of sea water. Only in Narva drift ice coming from the river Narva has been observed as the earliest ice in some years.

In the calm and cold weather freezing may occur on the same day when the air temperature downcrosses zero, but delay may be as much as 103 days. No statistically significant linear trends were found in the time series of the dates of freezing and fast ice formation. A polynomial fit shows periods of late freezing (from the beginning of the 20th century until 1940 and also from 1960 onward) and a period with early freezing (from 1940 until 1960).

Ice break-up runs in reverse order when compared to its appearance depending mostly on thermal conditions. But during mild and normal winters break-up may occur earlier than air temperature upcrosses zero, indicating the dominant influence of dynamical factors (wind, sea level fluctuations, currents). The correlation coefficients between the dates of upcrossing and break-up range from 0.31 to 0.91.

Decreasing trends (5-15 days per century) indicate that the ice break-up has become earlier along the Estonian coast of the Gulf of Finland during the investigated period.

Freezing along the Finnish coast starts about two weeks earlier compared with the Estonian coast (Leppäranta and Seinä 1985); the earliest freezing has been observed in Loviisa (8^{th} of October) and the latest freezing at Tallinn (12^{th} of March).

Break-up two weeks later occurs on the Finnish coast compared with the Estonian coast, the latest break-up has been observed at Helsinki (31^{st} of May).

Statistics of the ice thickness along the Estonian coast are quite similar to those obtained by Leppäranta and Seinä (1985) for the Finnish coast.

Gulf of Riga

Freezing

The time series of five stations located in the different parts of the Gulf of Riga were selected for the analysis (Fig.1). The Estonian coast there freezes earlier, on average 24 November –10 December, than the Gulf of Finland coast (Table 5).

Freezing starts from the eastern part of the Gulf of Riga. First ice appears near

Table 5 – Statistics of time series of date of freezing, date of fast ice formation, date of fast ice break-up and date of ice break-up (Gulf of Riga), N- number of years with ice observations, N total-total number of years of observations.

	Virtsu	Kihnu	Ruhnu	Pärnu	Sõrve
Date of freezing					
Probability of freezing	72%	83%	73%	84%	78%
Mean	25.Nov	10.Dec	8.Dec	24.Nov	4.Dec
St. dev. (days)	23	19	22	16	23
Early	28.Oct	27.Oct	15.Nov	1.Nov	8.Nov
Latest	30.Jan	29.Jan	10.March	19.Jan	14.March
N/ N total	60/86	80/94	62/87	79/95	68/87
Date of fast ice formation					
Prob. of fast ice form.	69%	74%	53%	90%	69%
Mean	2.Jan	15.Jan	1.Feb	20.Dec	14.Jan
St. dev. (days)	21	21	18	24	24
Early	6.Nov	10.Dec	6.Jan	12.Nov	7.Dec
Latest	15.Feb	1.March	1.April	22.March	1.March
N/ N total	59/86	63/85	37/84	63/70	43/87
Date of fast ice break-up					
Mean	10.April	9.April	11.April	16.April	27.March
St. dev. (days)	19	20	22	14	20
Early	27.Jan	30.Jan	20.Jan	6.March	3.Feb
Latest	4.May	9.May	11.May	9.May	23.April
N/ N total	59/86	62/85	46/87	62/69	60/87
Date of ice break-up					
Mean	23.April	27. April	23. April	25. April	6. April
St. dev. (days)	18	21	19	11	29
Early	7.Feb	17.Jan	28.Jan	15.March	5.Jan
Latest	19.May	21. May	21. May	19. May	17. May
N/ N total	62/86	78/94	63/87	80/95	67/87
Ice thickness (cm)					
Mean	42	44			37
St.dev.	11	18			15
Min	19	6			13
Max	66	105			75
N/Ntotal	46/86	62/85			46/87

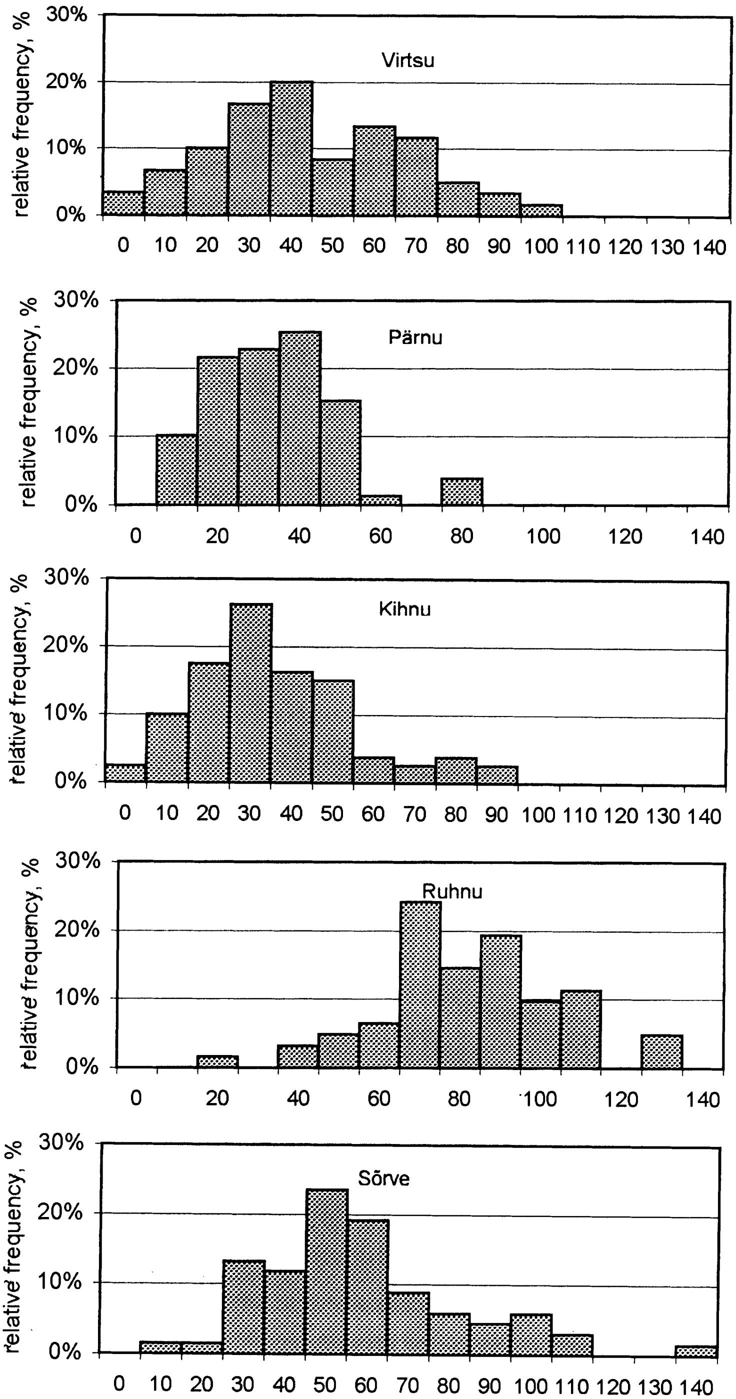

Fig. 6. Histograms of date of freezing in the Gulf of Riga

Table 6 – The correlation coefficients of time series of date of freezing and date of ice break-up in the Gulf of Riga

	Kihnu	Pärnu	Ruhnu	Sõrve
Freezing				
Pärnu	0.65			
Ruhnu	0.09	0.19		
Sõrve	0.42	0.45	0.38	
Virtsu	0.55	0.46	0.12	0.70
Break-up				
Pärnu	0.74			
Ruhnu	0.75	0.61		
Sõrve	0.78	0.76	0.72	
Virtsu	0.90	0.82	0.75	0.75

Pärnu, in a small bay. The lowest value of the standard deviation was obtained for this site. Quite early freezing occurs also in Virtsu and Kihnu. The ice formation at Kihnu occurs mostly at the end of November, the shape of the histogram being positively skewed with a clearly indicated peak (Fig. 6). Histogram of Virtsu is rather flat; with large standard deviation (23 days). A large value is also found out for Sõrve, situated in the Irbe Strait, connecting Gulf of Riga and Baltic Sea. Considerable difference between the dates of freezing is found along the island Ruhnu, situated in the central part of the Gulf of Riga.

The correlation coefficients between the stations were low, the highest value (0.70) was found for Virtsu and Sõrve and the lowest value (0.09) for Ruhnu and Kihnu (Table 6).

The date of freezing shows the highest values of standard deviation for mild winters at Ruhnu and Sõrve (31 day); for normal winters the values are between 12 days (Pärnu) and 20 days (Virtsu); and for severe winters between 13 days (Pärnu) and 17 days (Ruhnu).

There were no statistically significant linear trends; only for stations Virtsu and Sõrve the decreasing linear trends of about 20 days per century were detected, statistical significance at the 99.9% level.

There are few periods of early and late freezing in the Gulf of Riga similar to the results obtained for the Gulf of Finland. The trends with similar tendencies were found for the time series of freezing arranged according to the winter severity.

The trend in probability of freezing is increasing at 99% level for time series of Sõrve and Pärnu and statistically insignificant for the rest stations.

Fast Ice Formation and Break-up

Probability of fast ice occurrence was between 90% for Pärnu and 53% for Ruhnu (Table 5). Standard deviations for Kihnu, Pärnu and Sõrve were higher than in the

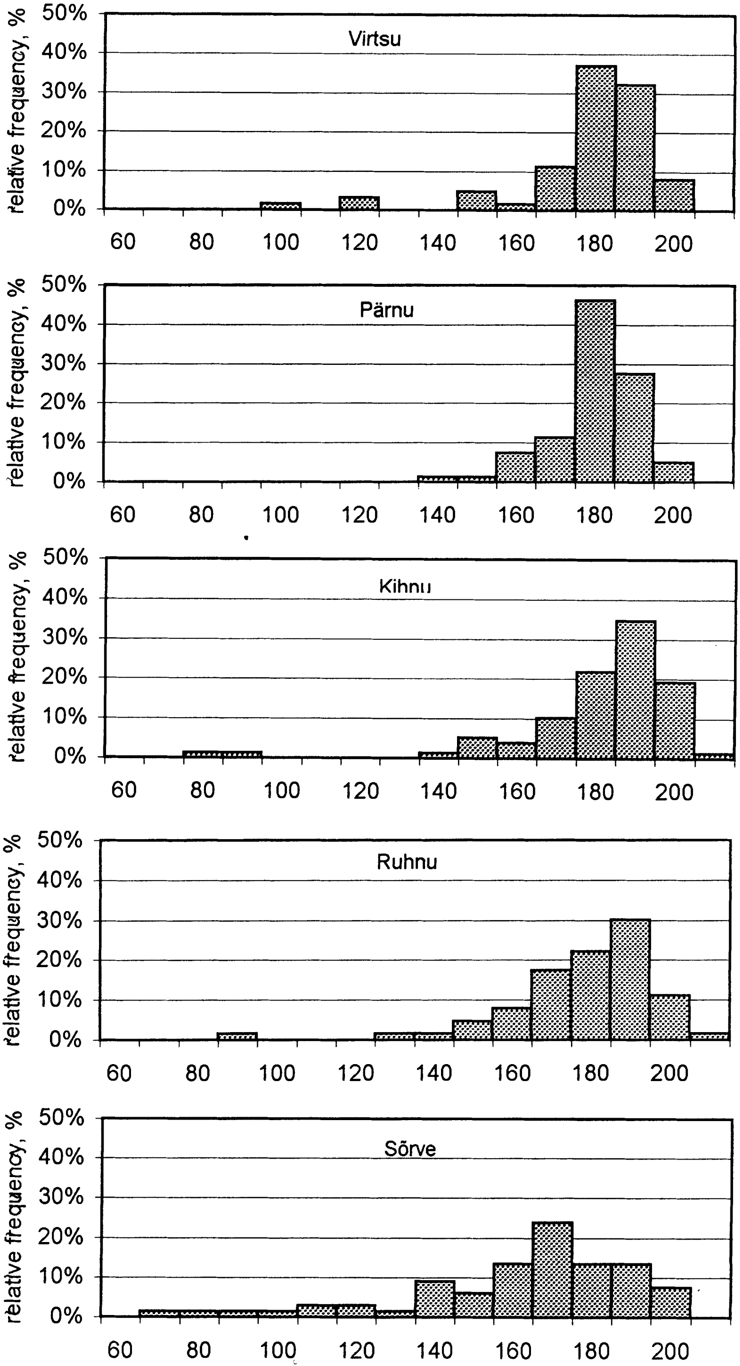

Fig. 7. Histograms of date of break-up in the Gulf of Riga

Table 7 – Correlation coefficients of time series of ice thickness

	Kihnu	Naissaar	Narva	Virtsu
Sõrve	0.79	0.72	0.51	0.66
Kihnu		0.56	0.69	0.72
Naissaar			0.32	0.49
Narva				0.58

case of date of freezing. The trend in probability of fast ice formation is increasing and statistically significant only for station Sõrve at 99% level.

Only for Kihnu an increasing trend was detected for the date of fast ice formation (99% level), showing the later fast ice formation of about 21 days per century.

Fast ice break-up starts from Sõrve at the end of March and only two weeks later fast ice break-up is observed along the eastern part of the gulf (Table 5).

The time series of ice thickness from three stations (Sõrve, Virtsu, Kihnu) were analysed (Table 5). Correlation coefficients were highest between Kihnu and Sõrve (Table 7). The maximum (105 cm) ice thickness was observed near the island Kihnu at the winter season 1900/01. No trends were found in time series of ice thickness.

Break-up

The average break-up date is 6-27 April (Table 5). The highest correlation between stations (0.90) was found for Virtsu and Kihnu (Table 6).

Histograms of the date of ice break-up are shown in Fig. 7. Break-up occurs about the same time along the continental part (Pärnu, Virtsu), and there the shape of histograms is negatively skewed with a clear peak in the first ten days of May. For Ruhnu and Kihnu the peaks are shifted toward the middle of May, while a rather spread

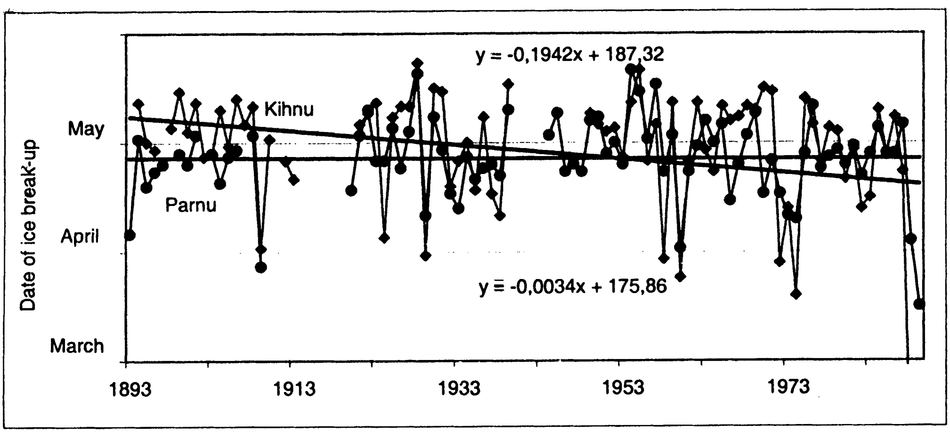

Fig. 8. Trends of time series of date of break-up (Gulf of Riga)

and flat histogram comes out for Sõrve. Cumulative probability curves (not presented here) show similar tendencies for the all stations except Sõrve, where the curve is shifted two weeks forward earlier dates.

In mild winters the break-up was on an average between 16th of March (Sõrve) and 16th of April (Pärnu), with standard deviations of 12-30 days. In normal winters the break-up was a little bit smoother and occurred from the 13th of April (Sõrve) to 3rd of May (Kihnu); there was a quite high value of standard deviation for the station Virtsu (25 days). In severe winters ice break-up can be characterized by average date from 1st of May (Sõrve) to 10th of May (Kihnu), with the standard deviations between 5 and 7 days, except station Sõrve where it was 14 days.

Statistically significant trend (99% and 98% levels), indicating about 20 days earlier break-up per 100 years were detected for the time series of Kihnu and Virtsu (Fig. 8).

Alternating periods of the early and late break-up were obtained by polynomial fits, but the fluctuations are insignificant and rather chaotic.

Relation between sum of negative degree-days and date of ice break-up was examined; correlation coefficients were for Pärnu 0.7, for Virtsu 0.8, for Sorve 0.8.

Summary for the Gulf of Riga

Estonian coastal areas of the Gulf of Riga are covered by ice nearly every winter. In spite of its comparatively small size, the ice conditions along the coastal line show large spatial variations.

The date of freezing is characterized by the low spatial correlation and large standard deviation. Cumulative probability of freezing is confined between the curves of Pärnu and Ruhnu. Significant decreasing trends were found only for Virtsu and Sõrve. However, there are a few periods of early and late freezing in the Gulf of Riga, with clearly distinguishable maximum and minimum values and varied time intervals between them.

Variations in date of break-up are smaller compared with those in freezing date. Correlation coefficients between stations are 0.61-0.90. The standard deviations are usually lower than the standard deviation of date of freezing. The results from trend analysis are quite different. No periods of early and late break-up were found, the fluctuations in time series are rather chaotic.

Conclusion

The results obtained from the analysis were carefully compared with the information from "Climatological ice atlas for the Baltic Sea, Kattegat, Skagerrak and Lake Vänern" (1982). Statistical characteristics were calculated for the period 1963-1979 with respect to the period shown in the atlas and quite large differences resulted of about two weeks for the average date of freezing in Tallinn, four weeks in Kihnu, five weeks in Ruhnu and Pärnu and four weeks in Sõrve. Large differences for earliest and latest dates of the freezing were also found. There were no possibilities to compare the data from Narva, Virtsu and Naissaar.

For the average date of ice break-up difference only of about a few days were detected in the Gulf of Finland (data from Narva station are not included) and of about one week in the Gulf of Riga. Relevant difference between date of earliest and latest break-up for both areas were found. The reason is likely that not so detailed information was available for the Estonian coast when the ice atlas was prepared.

The present results for the ice conditions along the Estonian coast indicate the wide variations in the processes of ice formation and break-up. Climatic changes in ice conditions during the last 100 years are not always detected compared with results of the analysis of meteorological conditions (Jevrejeva 1999, 2000). The following conclusions are made for the present ice time series:

- In general, natural variability is very high, less in the date of ice break-up than in the date of freezing.
- Statistical characteristics of time series of fast ice formation are similar for the Gulf of Finland and the Gulf of Riga
- On average ice has formed in the Gulf of Finland from the 15th of December (Narva) to the 19th of January (Naissaar) and in the Gulf of Riga from the 24th of November (Pärnu) to the 10th of December (Kihnu). The range of variation of the freezing date is very large, 3-4 months, with maximum value of standard deviation 29 days (Tallinn).
- Correlation coefficients between stations were quite low for freezing: 0.03-0.49 in the Gulf of Finland and 0.09-0.70 in the Gulf of Riga.
- In calm and cold weather the freezing can occur on the same day when the air temperature downcrosses zero; in mild weather and strong wind the freezing may start even as latest 103 days from downcrossing zero (Tallinn).
- Statistically significant trends in the date of freezing were found only for Sõrve and Virtsu. However, periods with late freezing (from the beginning of the 20th century until 1940 and from 1960 onward) and a period with early freezing (from 1940 until 1960) were detected for both areas.
- There are no trends in time series of fast ice formation, only for Kihnu an increasing trend indicates the later fast ice formation being 21 days per century
- On average, the break-up occurred in the 6th to 27th of April in the Gulf of Riga and in 8th to 21st of April in the Gulf of Finland.

- For the date of break-up spatial correlation coefficients were higher for the Gulf of Riga (0.61-0.90) than for the Gulf of Finland (0.46-0.77).
- Decreasing significant trends were detected for time series of ice break-up at Kihnu and Virtsu.
- The correlation coefficients between the zero upcrossing of air temperature and break-up were 0.31-0.91; the correlation coefficients between time series of sum of negative degree-days and time series of date of break-up were 0.70-0.90.

Further investigations have to be done concerning ice thickness and its relation to the winter weather conditions.

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References

Betin, V.V. (1957) Ice conditions in the different parts of the Baltic Sea and its variations, *State Oceanological Institute Publications, Vol.41 (in Russian),* pp. 54-124.

Girjatowicz, J., and Kozuchowski, M. (1995) Contemporary changes of Baltic Sea ice, *Geographia Polonica, Vol. 65*, pp. 43-50.

State Oceanographical Institute (1969) *Guideline for the construction of climatological time series,* Leningrad, Russia.

Haapala, J., and Leppäranta, M. (1997) The Baltic Sea ice season in changing climate. *Boreal Env. Res., Vol. 2*, pp. 93-108.

Jevrejeva, S. (1999) Some results from the analysis of long-term time series regarding ice conditions along the Estonian coast. Proceeding of Conference POAC'99, Vol. 1, pp. 354-363.

Jevrejeva, S. (2000) Long-term variability of sea ice and air temperature conditions along the Estonian coast, *Geophysica, Vol 36*, pp.17-30.

Jurva, R. (1937) Über die Eisverhältnisse des Baltischen Meeres an den Küsten Finnlands. Merentutkimuslaitoksen Julk./Havsforskningsinst, Skr. No. 114, Helsinki, pp. 67-112.

Koslowski, G., and Glaser, R. (1995) Reconstruction of the ice winter severity index since 1701 in the Western Baltic, *Climate Change, Vol. 31*, pp. 79-98.

Koslowski, G., and Loewe, P. (1994) The Western Baltic Sea ice seasons in terms of a mass-related severity index 1879-1992. Part I. Temporal variability and association with the North Atlantic oscillation, *Tellus, Vol. 46A*, pp. 66-74.

Leppäranta, M. (1989) On climatic variations of the Baltic Sea ice conditions. Conference on Climate and Water, Vol. 1, publications of the Academy of Finland, Helsinki, 9/89, pp. 63-72.

Leppäranta, M., and Seinä, A. (1985) Freezing, maximum annual ice thickness and breakup of ice on the Finnish coast during 1830-1984, *Geophysica, Vol. 21,* pp. 87-104.

Makkonen, L., Launiainen, J., Kahma, K., and Alenius, P. (1984) *Long-term variations in some physical parameters of the Baltic Sea.* In: Mörner N.-A. and Karlen W.(eds.), Reidel, pp. 391-399.

Merejää vaatlused 1923/24- 1938/39 talvel Eestis. Tartu University, 1939-40.

Myrberg, K. (1998) Analysing and modelling the physical processes of the Gulf of Finland in the Baltic Sea, *Boreal Env. Res., Vol. 10,* pp19-25.

Palosuo, E. (1953) A treatise on severe ice conditions in the Baltic Sea. Merentutkimuslaitoksen Julk./Havsforskningsinst, Skr. No. 156, Helsinki, pp. 130-31.

Seinä, A. (1993) Ice time series of the Baltic Sea Ice Climate, Report Series in Geophysics 27, Dept. of Geophysics, University of Helsinki.

SMHI and FIMR (1982) *Climatological ice atlas for the Baltic Sea, Kattegat, Skagerrak and Lake Vänern 1963-1979,* Norrköping, Sweden.

Sztobryn, M. (1994) Long-term changes in ice conditions at the Polish coast of the Baltic Sea. Proc. IAHR Ice Symposium, Norwegian Institute of Technology, Norway, 1994, pp. 345-354.

Tarand, A. (1993) The Tallinn time series of break-up as climate indicator. Report Series in Geophysics 27, Dept. of Geophysics, University of Helsinki.

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