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FREEZING, MAXIMUM ANNUAL ICE THICKNESS AND BREAKUP OF ICE ON THE FINNISH COAST DURING 1830–1984

by

MATTI LEPPÄRANTA and ARI SEINÄ

Finnish Institute of Marine Research
P.O. Box 33, SF–00931 Helsinki, Finland

Abstract

Long time series of ice conditions on the Finnish coast and the ice extent in the Baltic Sea are presented. Most of the data have been earlier published in a large number of publications and are now combined together. A basic statistical analysis is done. The length of ice season has had a significant decreasing trend of 20–30 days per one century, and the thickness of ice has generally been randomly varying. The spectra of ice season characteristics are almost all even.

1. *Introduction*

Long climatological time series are the basic data to the understanding of the variability of our climate from the purely descriptive level to advanced modeling. Such information is rare since most scientific observation stations have been founded only in this century. Observation series were earlier originated for various, often practical, reasons.

Ice in the Baltic Sea is and has been very important to economic life in Finland being the main factor regulating winter navigation. In addition its annual formation and breakup have been often noted down by people interested in nature. Consequently, it is possible to construct long time series on ice conditions. *E.g.*, using historical records R. Jurva was able to construct a time series on the annual maximum ice extent in the Baltic Sea as far back as to 1720 (PALOSUO, 1953).

Here we present the following time series on ice conditions on the Finnish coast: the dates of freezing and breakup, length of ice season, maximum annual ice thickness, and the maximum annual ice extent in the Baltic Sea. The earliest observations concern the ice season 1829/30 for the ice extent, 1848/49 for freezing date, 1829/30 for breakup date, and 1889/90 for ice thickness. Some of the observations have not been published, and those which have been are distributed in a large number of various publications. Hence it was considered necessary to publish the time series also in numerical form (LEPPÄRANTA & SEINÄ, 1985).

The value of long climatological time series has been emphasized in the World Climate Programme. Especially at least one hundred years long time series are considered very useful. Many of the series below are of such length and each in its own way tells us of the severity of the winters in the Baltic Sea area.

2. *The material*

Eight observation stations have been selected from the Finnish coast: Kemi, Vaasa and Rauma in the Gulf of Bothnia, Mariehamn, Bogskär/Jungfruskär and

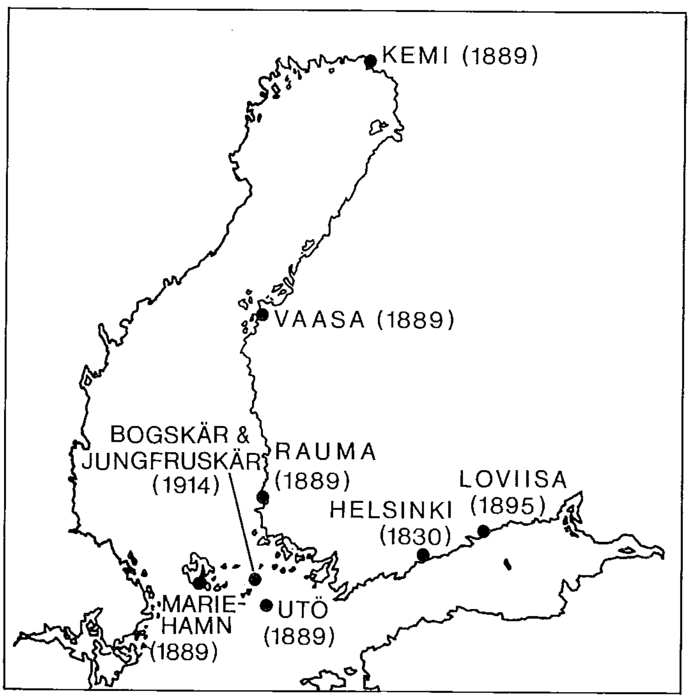

Fig. 1. The locations of the observation sites. The first observation year is given in parenthesis.

Utö in the Archipelago Sea, and Helsinki and Loviisa in the Gulf of Finland. These sites with their earliest observation years are shown in Fig. 1.

The time series have been constructed mainly on the basis of earlier publications. Some gaps in the published data could be filled using the archived material at the Finnish Institute of Marine Research. There are, however, winters for which it was not possible to find direct information. Especially, for the winter 1909/10 even the archived material is very limited. For that winter we made estimates for our stations based on information from nearby stations. Another winter which was difficult to reconstruct was 1917/18 due to the abnormal times of the Russian revolution and the Finnish Civil War. However, all observation stations except Loviisa actually never stopped their work, and archived data could be found.

The availibility of data is presented in graphical form in Fig. 2. It is seen that the time series contain the date of freezing from the year 1889, the date of breakup from 1891, and the maximum ice thickness from 1912 at Kemi, in its outer

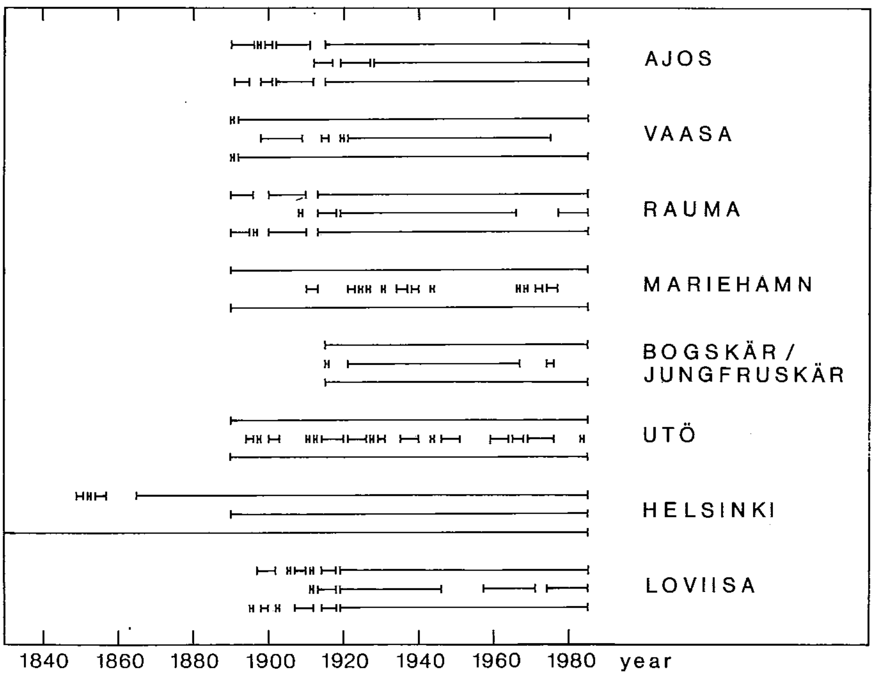

Fig. 2. The availability of data. For each station three lines are given describing, from the top down, the availability of the freezing date, ice thickness and breakup date data (empty regions stand for gaps).

harbour Ajos. For Vaasa harbour these years are 1889, 1890 and 1898, for Rauma harbour 1889, 1890 and 1908, and for Mariehamn Western Harbour 1889, 1890 and 1911. For Bogskär/Jungfruskär the data begin in 1914; freezing and breakup have been observed at Bogskär and maximum ice thickness at Jungfruskär, an island near Bogskär. For Utö the years are 1889, 1890 and 1895, for Helsinki 1849; 1830 and 1890 (the dates of freezing and breakup are given for the South Harbour and the maximum ice thickness for the North Harbour), and for Loviisa harbour 1896, 1895 and 1911.

The earliest material, from Helsinki 1830–1888, has been collected by LEVÄNEN (1889) from Helsinki newspapers, publications of the Finnish Society of Sciences (Bidrag till kännedom af Finlands natur och folk and Öfversigt af förhandlingarna) and notes of principal M. Brenner and professor S.G. Elmgren. According to Levänen ice information prior to 1830 is too vague to extend the time series further back.

For the next 24 years observations of all our stations have been published by the Finnish Geographical Society, Finnish Society of Sciences, Statistical Office of the City of Helsinki, Finnish Meteorological Institute and professor V.V. Korhonen (at his own expense). From the ice season 1913/14 onwards the Finnish Institute of Marine Research has published the ice data. Some of the gaps in the published data could be filled from archived material.

The time series of the maximum annual ice extent in the Baltic Sea was initiated by professor Jurva. The data is available for every ice season since 1719/20. Jurva published it from 1830/31 onwards in graphical form first in 1944 (JURVA, 1944) and again some years later (JURVA, 1952). The period 1719/20–1829/30 can be found only in PALOSUO (1953). This early part was considered uncertain by Jurva and is not included in the following calculations. To our knowledge the original numerical values prior to 1930 are no more available – they were burnt in the Second World War bombings – and we have estimated them from the graphical presentation in PALOSUO (1953). The period 1930/31–1954/55 is given in PALOSUO (1965) and from 1965 onwards the maximum ice extent has been published by the Finnish Institute of Marine Research in the data reports on ice winters. For 1955/56–1964/65 only archived material has been available. Now the whole data since 1719/20 is available in numerical form in LEPPÄRANTA & SEINÄ (1985).

3. *Statistical properties*

Random variability is very high in the present time series. Hence to gain a perspective on long-term characteristics the data have been smoothed by low pass filtering with a transition band of 4 to 10 cycles per 100 years (Fig. 3–6). *I.e.* all

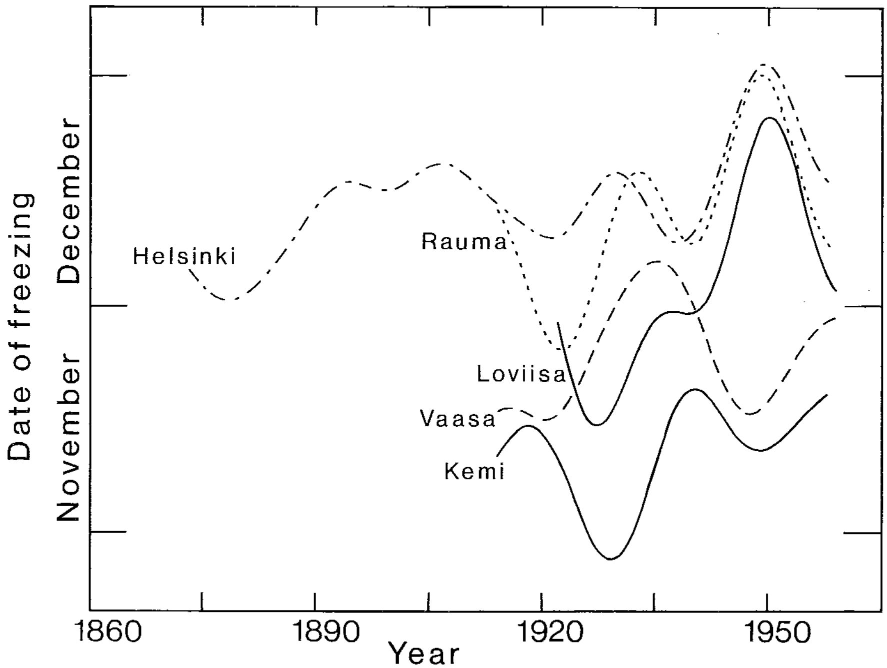

Fig. 3. Low pass filtered (transition band 4 to 10 cycles/100 years) records of the date of freezing along the Finnish coast.

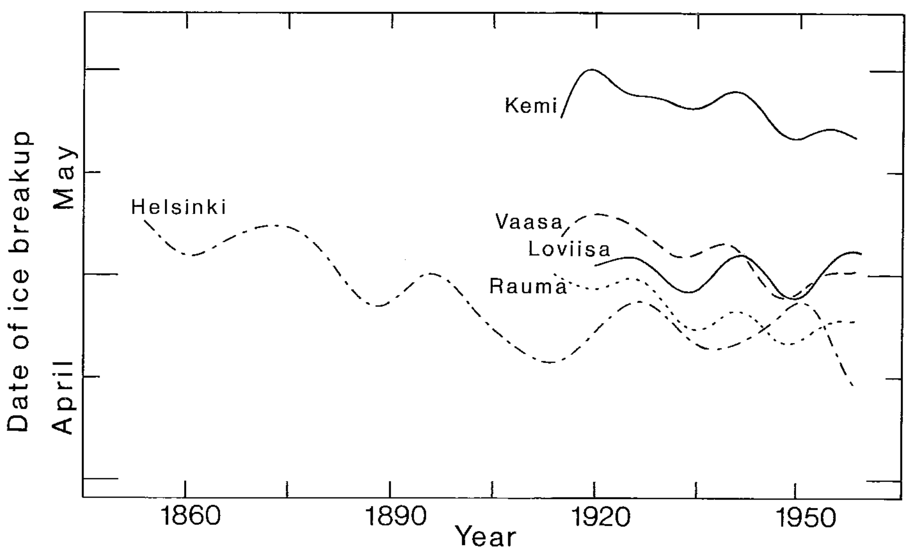

Fig. 4. Low pass filtered (transition band 4 to 10 cycles/100 years) records of the date of ice breakup along the Finnish coast.

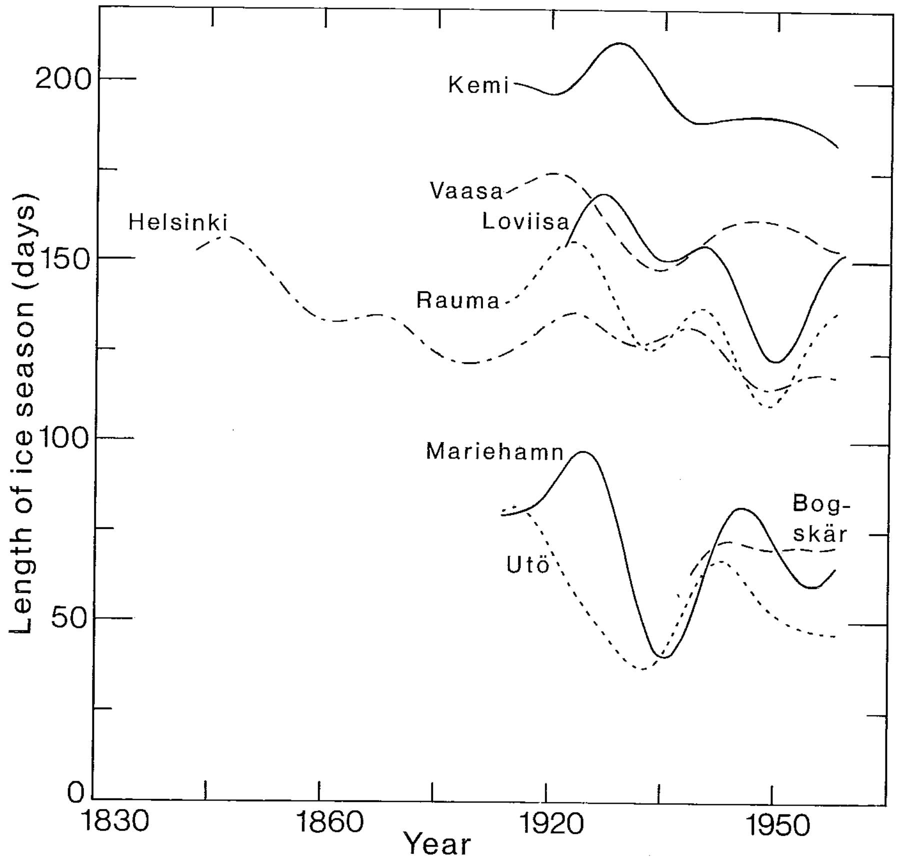

Fig. 5. Low pass filtered (transition band 4 to 10 cycles/100 years) records of the length of ice season along the Finnish coast.

variance with higher frequency than 10 cycles per 100 years is filtered and all variance with lower frequency than 4 cycles per 100 years is passed. The filtering technique given by HIBLER (1972) has been used, and that necessiated the loss of 25 years from both ends of the time series.

It is a general feature that the ice season has slowly become easier or milder during this century. Ice conditions get more difficult northward and eastward so that the coast of the Gulf of Finland is on the average similar to the coast of the Bothnian Sea. The stations of these basins (Vaasa, Rauma, Helsinki and Loviisa) seem to form together one group, whereas Mariehamn, Bogskär/Jungfruskär and Utö form one for the Archipelago Sea and Kemi alone one for the Bothnian Bay. Considering the last 30 years, the characteristic lengths of the ice season and ice

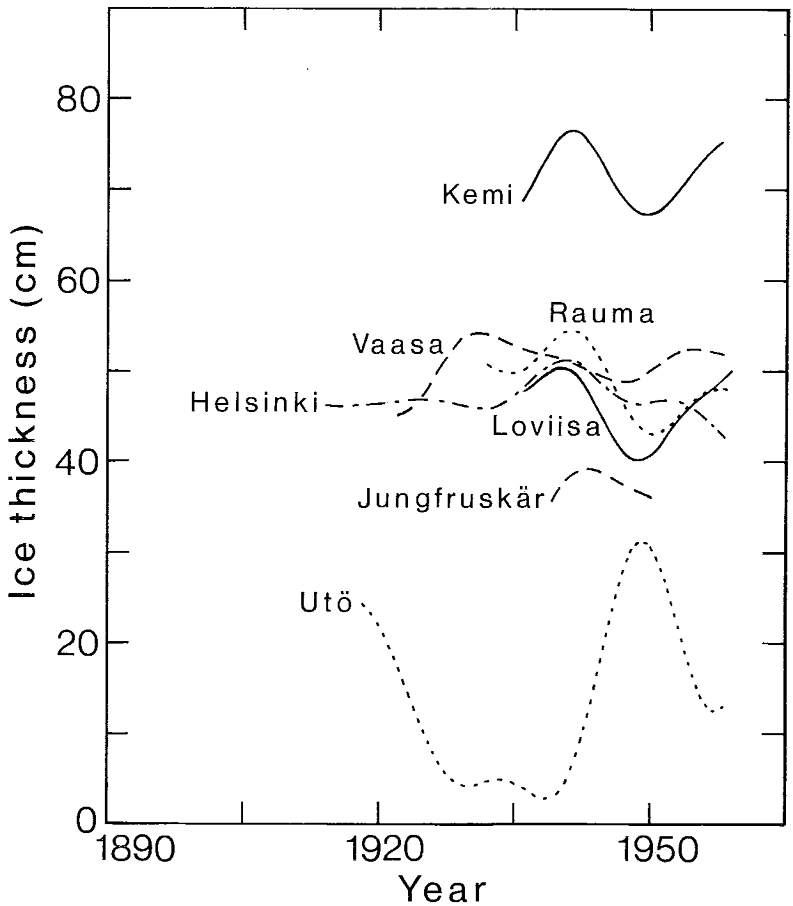

Fig. 6. Low pass filtered (transition band 4 to 10 cycles/100 years) records of the maximum annual ice thickness along the Finnish coast.

thickness are 6 1/2 months and 75 cm for Kemi, 4 1/2 months and 50 cm for the Gulf of Finland – Bothnian Sea, and 2 months and 25 cm for the Archipelago Sea. It is likely that urbanization has had a strong influence on the Helsinki records. During this century, *e.g.*, the population of Helsinki has grown from about one to five hundred thousand (Helsinki City, 1982).

A first order explanation to the decrease of the length of ice season (from its both ends) is the warming trend in the air temperature since the last century. PALOSUO (1979) has shown that for a certain area there is a more or less fixed value which the freezing-degree-days must exceed before freezing occurs. Thus, if the annual air temperature cycle rises by ΔT then the freezing date becomes delayed by $\Delta T/\dot{T}$ where $\dot{T}$ is the time rate of change of the air temperature in the autumn. *E.g.*, in Finland the air temperature drops typically by 5 °C in one month in autumn; thus one-degree rise in the annual cycle would delay the freezing date by 1/5 month. It is also likely that a similar kind of connection exists between the degree-days in spring and the ice breakup date. However, there one should note that the thicker the ice the more energy is needed to melt it.

The basic properties of the time series are given more exactly in Table 1. It is seen that the range of variation of the freezing date is very large, 2–3 months, whereas the standard deviation is 2–3 weeks. The trend shows that the freezing date has been delaying by 10–20 days in one century but only at Vaasa, Utö, Helsinki and Loviisa this trend is statistically significant. The highest time correlation is obtained for Vaasa, 0.37, which means that the trend can there explain 14 % of the total variance. The range of variation of ice breakup date is smaller than in the case of freezing date. It is 1–3 months and the standard deviation is 1–2 weeks. The trend shows that ice breakup has become 7–15 days earlier in one century and is significant for six sites. The time correlations are in absolute value about the same as in the case of the freezing date.

Naturally the combined effect of later freezing and earlier breakup is a strongly decreasing length of ice season. The rate of decrease is 20–30 days in a century and it is statistically significant for all sites except Bogskär/Jungfruskär. The range of variation of the length of ice season is several months. At Kemi the length is always at least 5 months whereas in the Archipelago Sea it is always less than that.

Of all our time series the thickness of ice seems to be the most purely random. It has been slightly decreasing in the Gulf of Finland and Archipelago Sea but slightly increasing in the Gulf of Bothnia. However, the trend is significant only at Kemi and Helsinki. These features in ice thickness may be due to that the ice growth in the Baltic Sea is highly influenced by the amount and timing of snowfall in addition to the air temperature (LEPPÄRANTA, 1983). In Helsinki the highly decreasing trend is probably due to the urbanization effects. The rate of change of the ice thickness has been of the order of 10 cm in a century.

Also shown in Table 1 are the present »normal values» predicted from the trend. They should be useful in considering the severity of ice seasons in the future. *E.g.*, on average the ice breakup has occurred on 26 April in Helsinki. When one takes into account the trend toward earlier ice breakup, the expected value is 14 April for the ice season 1984/85 and 12 April for the turn of the next century. This spring (1985) ice breakup occurred on 26 April; this is exactly the 156-year average but 12 days late from the trend value.

Table 1. Statistics of the date of freezing, date of ice breakup, length of ice season and maximum annual ice thickness on the Finnish coast. Underlined trends are statistically significant (5 % level). The parenthesis indicate values which are not (cannot be) based on all data because the probability of ice occurrence is less than one. Normal 1984/85 is the value predicted from the trend for the ice season 1984/85.

	Station / Quantity	Kemi	Vaasa	Rauma	Mariehamn	Bogskär/ Jungfru-skär	Utö	Helsinki	Loviisa
	Probability of occurrence of ice	1.00	1.00	1.00	0.89	0.90	0.84	1.00	1.00
Date of freezing	Number of data	87	95	89	86	64	81	127	81
	Mean	10 Nov	20 Nov	12 Dec	(16 Jan)	(27 Jan)	(28 Jan)	13 Dec	4 Dec
	St. dev. (days)	14	17	22	(26)	(19)	(22)	18	20
	Latest	22 Dec	25 Jan	16 Feb	(30 Mar)	(15 Mar)	(31 Mar)	1 Feb	28 Feb
	Earliest	7 Oct	10 Oct	1 Nov	19 Nov	24 Dec	5 Dec	21 Oct	8 Oct
	Trend (days/100 a)	8	24	12	15	8	21	15	19
	St. dev. of trend	5	6	9	10	12	9	4	9
	Time correlation	0.11	0.37	0.11	0.12	0.00	0.24	0.28	0.20
	Normal 1984/85	14 Nov	1 Dec	18 Dec	(24 Jan)	(30 Jan)	(7 Feb)	23 Dec	12 Dec
Date of breakup	Number of data	87	95	90	85	64	81	156	80
	Mean	23 May	2 May	23 Apr	(11 Apr)	(19 Apr)	(13 Apr)	26 Apr	29 Apr
	St. dev. (days)	9	11	14	(17)	(17)	(18)	15	9
	Latest	28 Jun	23 May	21 May	8 May	18 May	20 May	31 May	16 May
	Earliest	17 Apr	31 Mar	3 Mar	(30 Jan)	(13 Mar)	(28 Feb)	16 Feb	7 Apr
	Trend (days/100 a)	-7	-10	-14	-14	-13	-9	-15	-10
	St. dev. of trend	4	4	5	6	10	7	2	4
	Time correlation	-0.17	-0.22	-0.25	-0.21	-0.10	-0.10	-0.45	-0.24
	Normal 1984/85	20 May	26 Apr	17 Apr	(4 Apr)	(15 Apr)	(8 Apr)	14 Apr	25 Apr
Length of ice season	Number of data	84	95	89	85	64	81	127	77
	Mean (days)	194	163	132	84	82	75	132	145
	St. dev. (days)	17	22	30	35	31	32	27	24
	Longest (days)	237	208	189	150	137	140	193	210
	Shortest (days)	156	79	24	0	0	0	30	55
	Trend (days/100 a)	-18	-33	-27	-29	-21	-31	-33	-29
	St. dev. of trend	7	8	12	13	19	13	6	12
	Time correlation	-0.27	-0.40	-0.22	-0.21	-0.05	-0.24	-0.44	-0.25
	Normal 1984/85	186	146	120	70	74	60	111	133
Ice thickness	Number of data	71	68	60	20	48	50	96	59
	Mean (cm)	72	52	49	14	35	20	48	51
	St. dev. (cm)	11	10	17	18	20	17	14	14
	Maximum (cm)	105	78	95	58	78	60	85	76
	Minimum (cm)	48	20	18	0	0	0	15	16
	Trend (cm/100 a)	14	0	2	1	-23	-9	-23	-11
	St. dev. of trend	6	5	11	19	20	10	5	8
	Time correlation (with time)	0.23	0.00	0.00	0.00	-0.09	0.00	-0.45	-0.12
	Normal 1984/85	77	52	50	15	26	16	37	47

Table 2. Local cross-correlations (in per cent) between different ice characteristics on the Finnish coast.

Station / Quantity	Kemi	Vaasa	Rauma	Marie-hamn	Bogskär/ Jungfruskär	Utö	Helsinki	Loviisa
Date of freezing and date of breakup	–5	–19	–32	–27	–54	–32	–33	–16
Date of freezing and maximum thickness	–14	–24	–32	–8	–48	–29	–28	–40
Date of breakup and maximum thickness	24	49	36	49	67	54	51	57

Local cross correlations of the present ice season characteristics are nearly all significant and usually less than about 0.5 (Table 2). As one can expect, they are higher where ice season is shorter. The best correlations are obtained between maximum ice thickness and breakup, the highest value being 0.67 for Bogskär/ Jungfruskär. This is likely due to that it takes a longer time to melt thicker ice. The cross correlations between different locations are again nearly all significant and generally higher the closer the locations are to each other (Table 3). They are highest among the Archipelago Sea sites probably because the ice season is there shortest. The average value is there 0.67 for the date of freezing, 0.79 for date of breakup, 0.75 for length of ice season and 0.88 for maximum ice thickness.

Table 3. Spatial cross-correlations (in per cent) of ice season characteristics on the Finnish coast.

Date of freezing

Quantity / Stations	Va	Ra	Ma	BJ	Ut	He	Lo
Kemi	33	27	14	14	24	28	49
Vaasa		40	12	22	32	32	45
Rauma			49	45	39	60	56
Marie-hamn				69	60	29	20
Bogskär/ Jungfru-skär					72	36	15
Utö						28	10
Helsinki							54

Date of breakup

Quantity / Stations	Va	Ra	Ma	BJ	Ut	He	Lo
Kemi	55	38	27	42	25	23	24
Vaasa		78	47	69	13	49	60
Rauma			66	78	61	66	65
Marie-hamn				77	76	68	51
Bogskär/ Jungfru-skär					85	73	73
Utö						52	56
Helsinki							60

Length of ice season

Quantity / Stations	Va	Ra	Ma	BJ	Ut	He	Lo
Kemi	46	29	21	29	26	34	49
Vaasa		61	33	50	41	45	56
Rauma			61	65	55	65	63
Marie-hamn				75	67	48	27
Bogskär/ Jungfru-skär					82	57	39
Utö						39	24
Helsinki							52

Maximum annual ice thickness

Quantity / Stations	Va	Ra	Ma	BJ	Ut	He	Lo
Kemi	48	46	37	51	27	34	45
Vaasa		67	77	63	65	56	65
Rauma			71	72	60	66	66
Marie-hamn				85	96	56	58
Bogskär/ Jungfru-skär					84	77	67
Utö						77	58
Helsinki							70

In regards with the maximum annual ice extent (Fig. 7), the average value since 1830 has been 209 x 10^3 km^2 which is almost exactly one-half of the total area of the Baltic Sea and Kattegat to the line Skagen-Grimstad, 420 x 10^3 km^2, traditionally mapped by the Ice Service in Finland (Table 4). The ice extent has had a trend of -42 x 10^3 km^2 in one century which is just above the significance level. Comparing the ice extent with the ice conditions along the Finnish coast it is seen that the ice extent correlates best with the maximum annual ice thickness and worst with the date of freezing (Table 5). The correlation was best between the ice extent and ice thickness probably because they both depend strongly on freezing-degree-days during winter. Ice extent depends to some degree linearly on the sum of the freezing-degree-days (PALOSUO, 1953) whereas ice thickness is often taken proportional to the square root of this sum. The correlations are almost all significant and decrease eastward and northward as the ice season becomes longer.

Table 4. Statistics of the maximum annual ice extent (unit 10^3 km^2) of the Baltic Sea (underlined trend statistically significant). Normal 1984/85 is the value predicted from the trend for the ice season 1984/85.

Number of data	156
Mean (10^3 km^2)	209
Standard deviation	115
Maximum	420
Minimum	51
Trend (10^3 km^2/100 years)	<u>−42</u>
St. dev. of trend	20
Time correlation	0.14
Normal 1984/85	176

Table 5. Cross-correlations (in percent) of the Baltic Sea ice extent with local ice characteristics along the Finnish coast.

Quantity / Station	Date of freezing	Date of breakup	Length of ice season	Maximum thickness
Kemi	−11	44	30	59
Vaasa	−24	55	46	55
Rauma	−35	64	57	64
Mariehamn	−47	56	64	63
Bogs./Jungfrus.	−60	77	77	86
Utö	−34	60	56	74
Helsinki	−28	52	50	64
Loviisa	−17	54	35	55

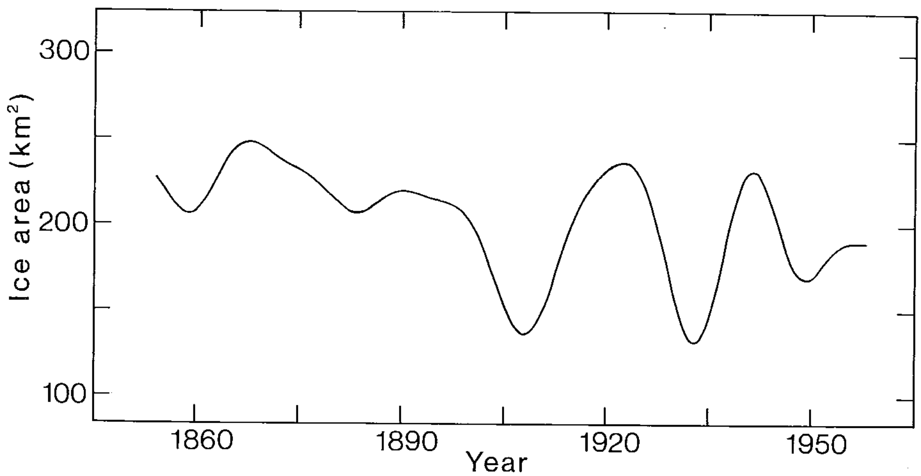

Fig. 7. Low pass filtered (transition band 4 to 10 cycles/100 years) record of the maximum annual ice extent in the Baltic Sea.

As the last point the spectra of the present ice season characteristics were taken into consideration. Trends were first removed from the data and gaps filled through linear interpolation before the calculations. The spectrum of the remaining deviations from the trend is even in almost all cases. Three sites, Kemi, Utö and Helsinki, are given as examples in Figs. 8–10. These spectra have been normalized by dividing with the total variance. It is seen that only the thickness of ice at Utö deviates significantly from the even shape. It has more variations in low frequencies. Finally, Fig. 11 shows that the spectrum of the maximum annual ice extent is even.

It is quite natural that even spectra result to the ice season characteristics. The memory of the thermal system of the Baltic Sea should be much less than a year. On the other hand the governing meteorological quantity, air temperature, has even spectrum (for periods longer than one year). Using easily available data (Keränen, 1928; Finnish Meteorological Institute, 1982) this was checked to be the case for the monthly mean air temperature in Helsinki.

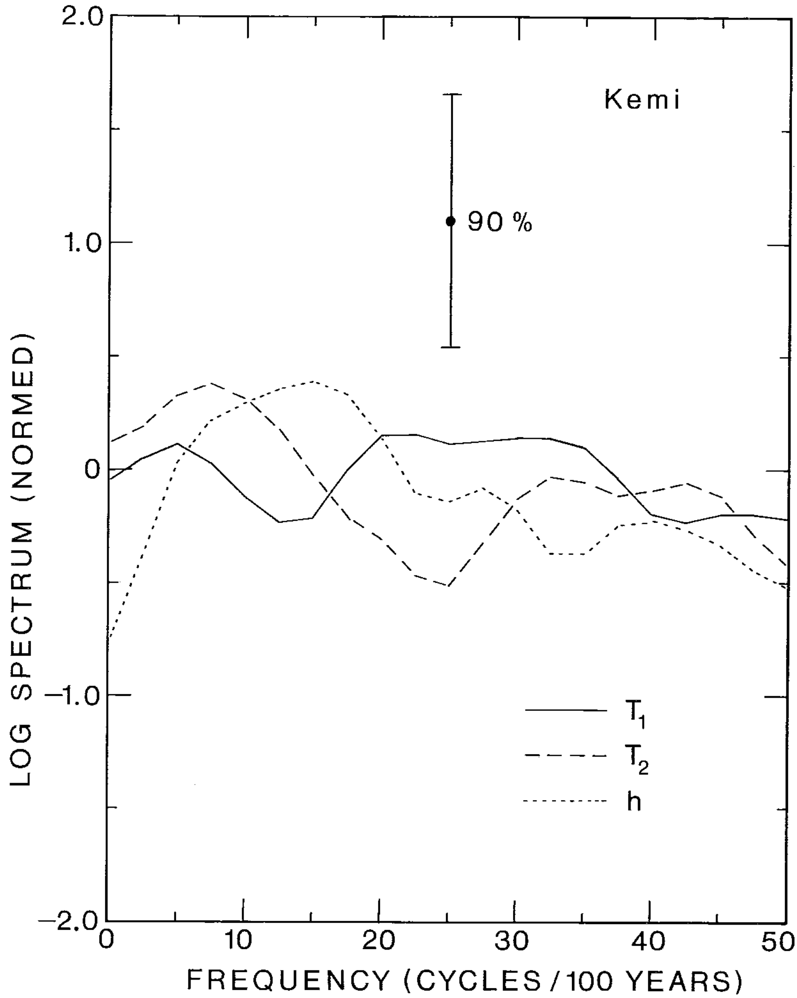

Fig. 8. The spectra of the date of freezing ($T1$), maximum annual ice thickness (h) and date of ice breakup ($T2$) at Kemi.

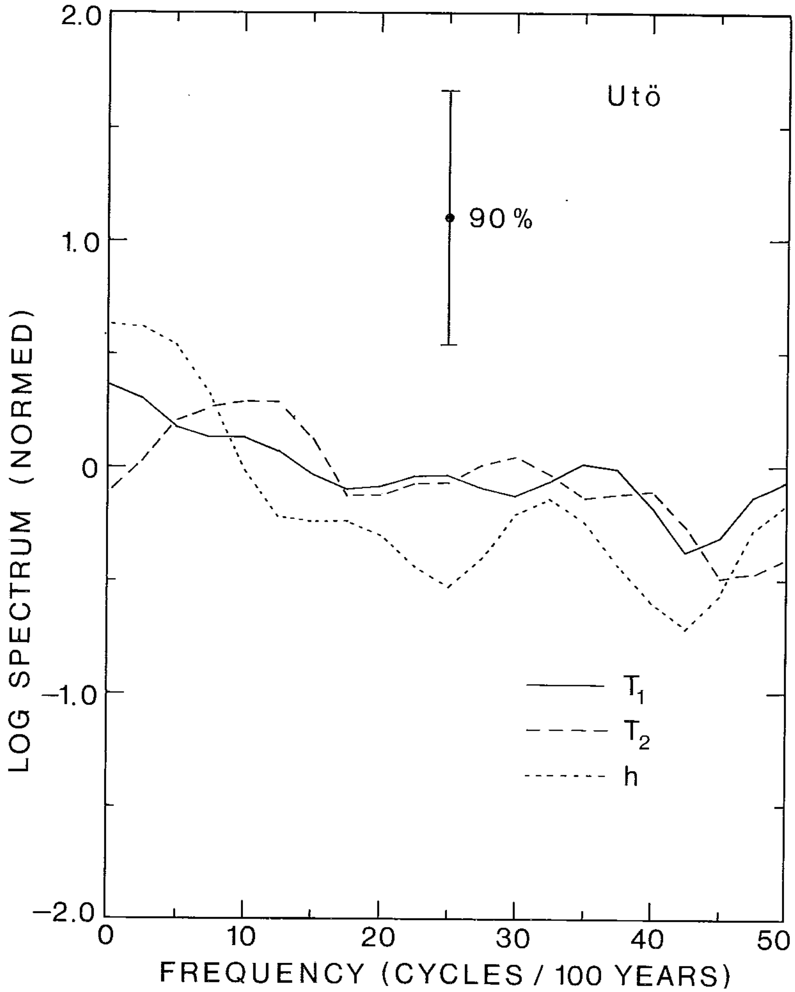

Fig. 9. The spectra of the date of freezing ($T1$), maximum annual ice thickness (h) and date of ice breakup ($T2$) at Utö.

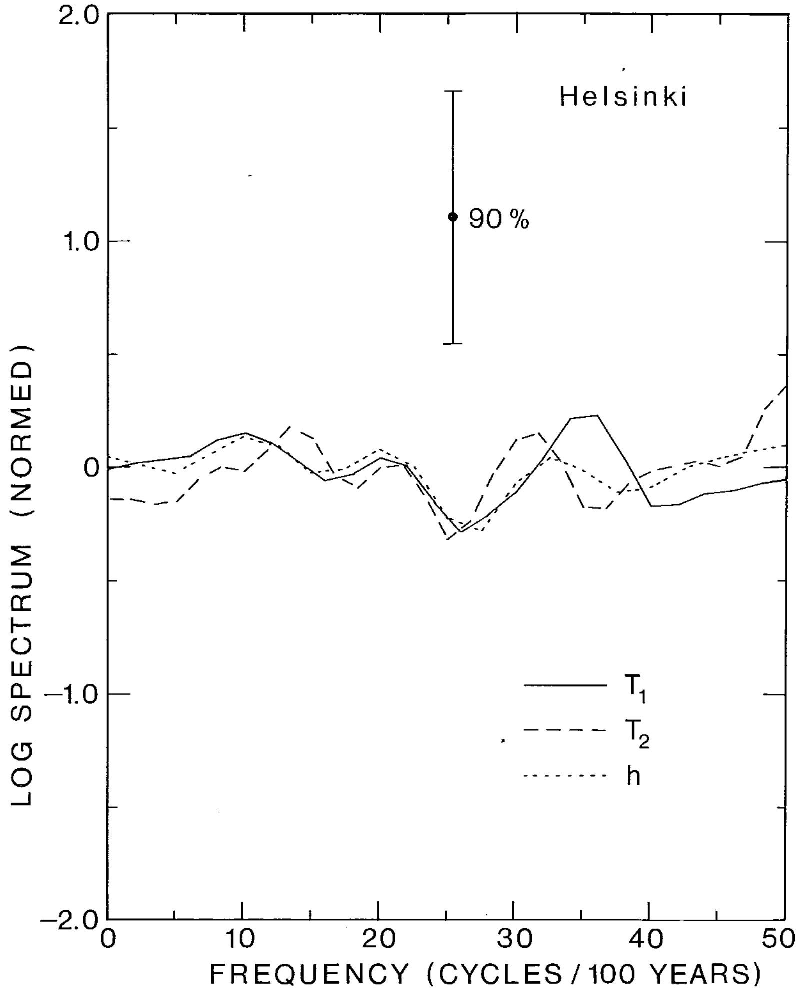

Fig. 10. The spectra of the date of freezing (*T*1), maximum annual ice thickness (*h*) and date of ice breakup (*T*2) at Helsinki.

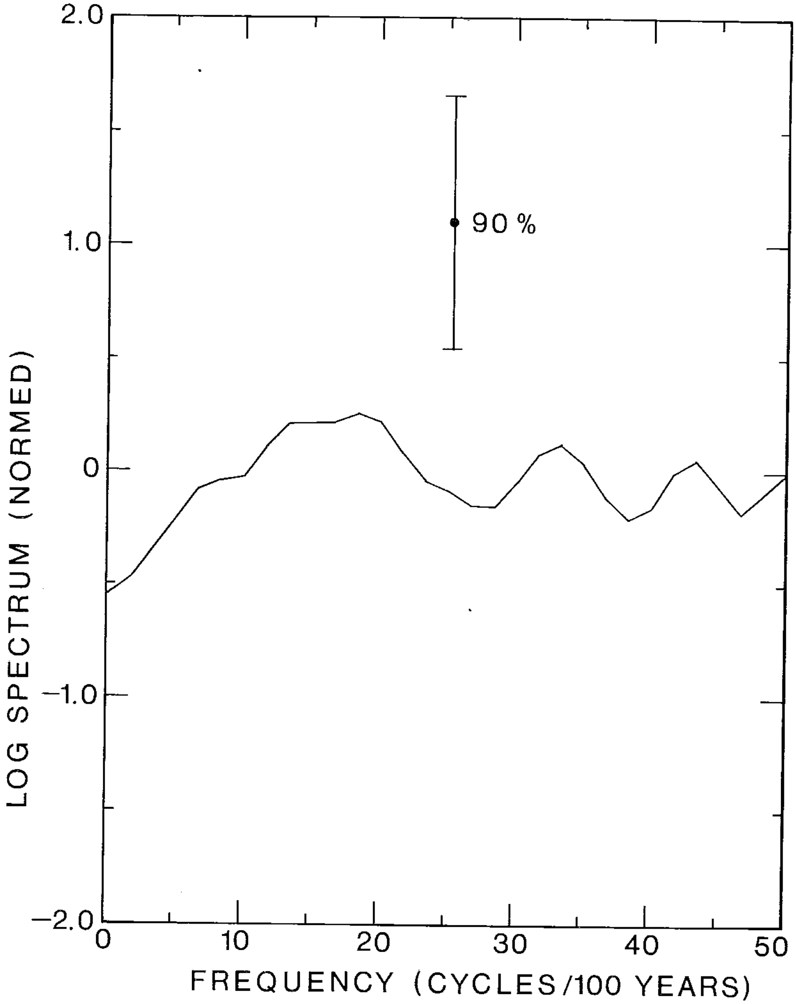

Fig. 11. The spectrum of the maximum annual ice extent of the Baltic Sea.

4. *Conclusions*

From 70 to 156 years long time series of ice conditions along the Finnish coast of the Baltic Sea have been analyzed. The data included the dates of freezing and breakup, the length of ice season and the maximum annual ice thickness at eight locations, and, in addition, the maximum annual ice extent of the Baltic Sea.

The results show a general trend toward easier ice conditions. This is best seen in the case of the length of ice season which has been decreasing by 20–30 days per century, whereas the maximum annual ice thickness seems to have been the most randomly varying. The ice extent has been decreasing by 10 % of the total area of the Baltic Sea in 100 years, but this trend is just above the significance level. The observations in Helsinki have likely been effected by urbanization.

Local correlations of different quantities are typically less than 0.5. The date of freezing is involved with the lowest correlations. Correlations for a given quantity between different stations are on average about 0.5. They are highest in the Archipelago Sea where the ice season is shortest. The date of freezing gives the lowest correlations. The ice extent in the Baltic Sea correlates best with the maximum annual ice thickness probably because they both depend strongly on the freezing-degree-days during the ice season.

The spectra of the ice season characteristics are almost all even. This seems to be due to the similar shape of the air temperature spectrum and due to the short memory of the thermal system of the Baltic Sea.

Considering future work the next step should be analyzing these ice time series together with meteorological and hydrographic data. In particular, two aspects are emphasized for such investigations. First, maybe the most poorly understood part is the role of the heat content of the water masses in the ice season climatology of the Baltic Sea. Secondly, the ice extent, or more generally the navigability conditions in winter, developes through coupled dynamic and thermodynamic processes. *E.g.*, as the ice moves and opens up, new ice will be very effectively formed in the new openings.

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