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Long–Term Variability of Sea Ice and Air Temperature Conditions Along the Estonian Coast

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Abstract

The results of the analysis of long-term time series regarding ice conditions along the Estonian coast are presented in this paper. This work was focused on the analysis of air temperature, onset of freezing and melting air temperatures, the sums of negative degree-days and the number of ice days. Most of the data were not yet published. Statistical analysis was carried out on the data. Mean air temperatures for November–April indicate that during winter seasons almost all parts of Estonia experienced an overall warming of 0.5–1.0 ºC for the period 1900–1990. The date of stabilised transition of the air temperature to sub-zero values was observed about 8–14 days later at the end of the study period than in the beginning, while the date of melting air temperature onset was observed 10–15 days earlier. Correlation coefficients between time series of sum of negative degree-days and number of ice days were from 0.61 to 0.76.

Key words: Baltic Sea, trends, winter air temperature conditions, number of days with ice

1. Introduction

Estonia is situated on the Baltic Sea and its coastal areas are covered by ice during the winter season. Sea ice coverage information has a large economic importance as the main factor restricting winter navigation.

The Gulf of Finland was a subject for intensive investigation during previous decades. In Finland ice time series analysis have been done by *Jurva* (1937), *Palosuo* (1953), *Makkonen et al.* (1984), *Seinä* (1993), *Leppäranta* (1989), *Haapala and Leppäranta* (1996).

For the western Baltic Sea the analysis of ice conditions has been done in terms of a mass-related severity index by *Koslowski and Loewe* (1996), *Koslowski and Glaser* (1995). Several studies were done by *Girjatowicz* (1995), *Sztobryn* (1994) in Poland.

There is a lack of publications about ice conditions along the Estonian coast and the necessity for such analysis has increased recently due to intensive navigation activity and climatological investigations.

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Earlier some publications appeared in Estonia, but these are very dated (1939). Long term continuous time series of ice break-up at the port of Tallinn based on historical information has been re-constructed by *Tarand* (1993). Some internal reports and investigations for different periods and different places were compiled in Estonian Meteorological and Hydrological Institute (EMHI).

The results from analysis of the basic climatological characteristics of ice seasons – severity of winter seasons, air temperature, the sum of negative degree-days and number of ice days- are given in this paper. Those results will be used in the larger study aimed to investigate the temporal variability of sea ice conditions including time series of date of the first freezing and formation of permanent ice cover, date of the end of permanent ice cover, the final disappearance of ice and thickness of ice on the Baltic Sea along the Estonian coast during the period 1900–1990.

2. Available data

The relevant data sets from EMHI archives were converted into computerised form, screened and checked. The main criteria were quality and regularity on the data in time. The data from three stations Narva, Tallinn, Naissaar located in the Gulf of Finland and five stations Virtsu, Pärnu, Sõrve, Ruhnu, Kihnu situated in the Gulf of Riga were selected for the analysis. These sites are shown in Figure 1.

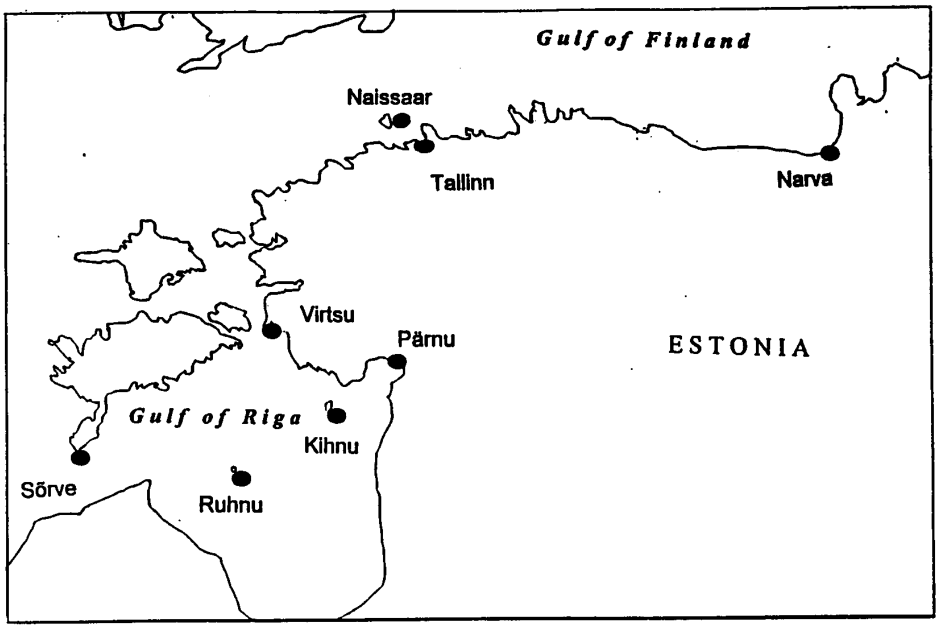

Fig. 1. The locations of the observation stations.

The data sets included information about the date of the first freezing and date of ice break-up. During the ice period air temperature measurements were also made, those data being used to construct time series. Time series of mean air temperature were calculated from mean monthly air temperature for the available period (see Table 1).

The time series of onset of freezing air temperatures and onset of melting air temperatures were collected from the mean daily air temperature. Sums of negative degree-days were calculated from the mean daily air temperature values. Number of ice days was defined as a number of days with sea ice occurrence. Most of the time series covered the period 1900–1990 (Table 1), although there were some gaps during the periods of First and Second World Wars.

Table 1. Description of time series.

Stations	**Periods of time series**				
	Mean air temperature (November–April)	Onset of freezing air temperatures	Onset of melting air temperatures	Sum of negative degree-days	Number of ice days
Narva	1904–1990	1908–1990	1907–1990	1904–1990	1904–1990
Tallinn	1900–1990	1923–1990	1923–1990	1900–1990	1903–1990
Naissaar		1949–1990	1949–1990		1908–1990
Sõrve	1866–1990	1903–1990	1903–1990	1900–1990	1903–1990
Ruhnu		1930–1990	1930–1990		1903–1990
Kihnu		1950–1990	1950–1990		1903–1990
Virtsu		1911–1990	1910–1990	1942–1990	1904–1990
Pärnu	1878–1990	1920–1990	1920–1990		1921–1990

3. Results

Time series were analysed by descriptive statistics such as average, standard deviation, maximum, minimum and frequency histograms. Results of regression analysis, correlation coefficients, number of samples and the significance level were expressed.

3.1 Fluctuation of mean air temperature for the period November–April

Time series of mean air temperature for the period from November to April between 1900–1990 were analysed (see Table 2). Mean air temperature for this period falls between -2.8 °C at the station Narva and -0.1 °C at the station Sõrve; the standard deviation maximum value is 1.9 °C at station Narva. In general, during the winter seasons a warming was observed at the Estonian coast. The variation of mean air temperature over the period 1900 to 1990 shows the increasing of 0.5–1.0 °C per 100 years for given stations. However, only the data from station Sõrve, situated on the island Saaremaa, reveal the statistically significant (99.9% level) linear warming of 0.1 °C per 100 years, confirmed by t-test; for the rest stations the increase is significant at the less than 95% level.

Table 2. Statistics of time series of mean air temperature (November–April) Tallinn, Narva, Sõrve, Pärnu.

	Narva	**Tallinn**	**Sõrve**	**Pärnu**
Average	–2.8	–1.6	–0.1	–1.8
St. dev.	1.9	1.7	1.7	1.8
Max	0.6	2.0	3.2	2.0
Min	–9.4	–8.1	–6.1	–7.7

An agreement was found between the obtained results and the results published by *Jaagus* (1996) and *Tarand* (1998), indicating the warming in spring and winter over Estonian territory. Similar findings can be found from many other analyses of European temperature time series published by *Balling et al.* (1998) and *Jones* (1994). On the other hand, the cooling during the winter seasons over the whole Finland was published by *Heino* (1994) and *Tuomenvirta and Heino* (1996).

The time series of mean air temperature for the period from November to April at station Tallinn is given in Figure 2. There are the same shapes for the graphs of other time series. Correlation coefficients between time series of mean air temperature are given in Table 3.

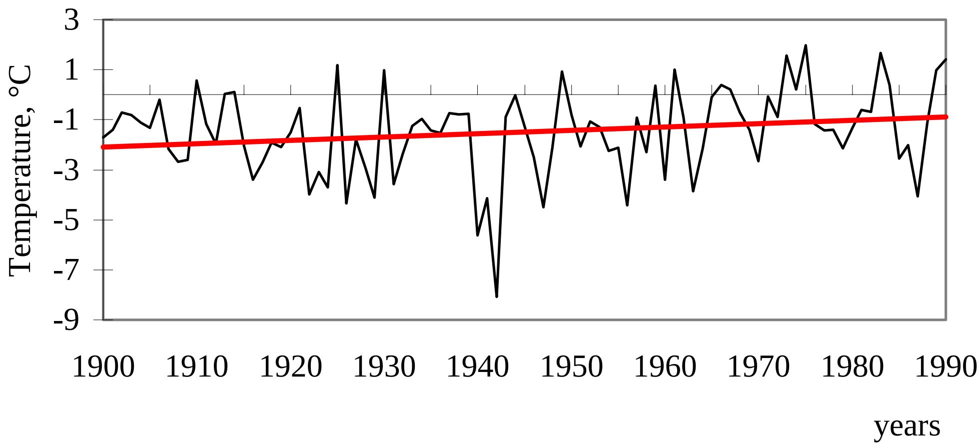

Fig. 2. The time series of mean air temperature for the period from November to April at station Tallinn (1900–1990).

Table 3. Correlation coefficients between time series of mean air temperature during November–April along the Estonian coast.

	Narva	**Pärnu**	**Sõrve**
Tallinn	0.96	0.86	0.87
Sõrve	0.87	0.96	
Pärnu	0.90		

Relation between time series of mean air temperature for the period November–April and number of ice days was examined. The time series of number of days with ice were treated as the dependent variable and the time series of the mean air temperature for the periods November–April were treated as independent variable in a regression analysis. Correlation coefficients were – from 0.57 (Narva) to 0.82 (Sõrve).

3.2 Onset of freezing air temperatures

In order to obtain more information about freezing the specific date for the zero crossing of air temperature was defined by the method given in "*Guideline for the construction of climatological time series*" (1969). Time series of the dates of decreasing air temperature passing through 0 °C was constructed from the data. The statistical characteristics of time series are given in the Table 4.

Table 4. Statistics of time series of freezing air temperatures onset, time series of melting air temperatures onset and time series of number of ice days.

	Narva	**Tallinn**	**Naissaar**	**Sõrve**	**Ruhnu**	**Kihnu**	**Virtsu**	**Parnu**
Statistics of time series of freezing air temperatures onset								
Mean	24. Nov.	4. Dec.	14. Dec.	24. Dec.	23. Dec.	13. Dec.	11. Dec.	2. Dec.
St. dev.	16	21	19	22	21	19	18	21
Early	30. Oct.	1. Nov.	14. Nov.	11. Nov.	25. Nov.	4. Nov.	12. Nov.	4. Nov.
Latest	16. Jan.	9. Feb.	30. Jan.	18. Feb.	19. Feb.	31. Jan.	30. Jan.	18. Jan.
Statistics of time series of melting air temperatures onset								
Mean	27. Mar.	23. Mar.	29. Mar.	19. Mar.	24. Mar.	25. Mar.	26. Mar.	26. Mar.
St. dev.	16	26	17	23	14	22	20	19
Early	26. Jan.	15. Jan.	30. Jan.	30. Dec.	5. Feb.	3. Jan.	3. Jan.	13. Jan.
Latest	21. Apr.	25. Apr.	21. Apr.	20. Apr.	16. Apr.	19. Apr.	20. Apr.	25. Apr.
Statistics of time series of number of ice days								
Mean	115	71	69	85	82	127	126	141
St. dev.	31	41	39	38	37	35	26	23
Max	177	150	149	167	139	174	173	180
Min	11	1	5	3	7	31	53	80

Decreasing linear trends were found for the time series of all stations. In general, at the end of the period 1900–1990 the onset of freezing air temperatures occurred about 8–14 days later than at the beginning of the century (see example in Figure 4). However, those trends are below the significance level. Only for times series of station Narva the decrease is significant at the 95% level (Fig. 4).

Time series of onset of freezing air temperatures were grouped into three different time series according the severity of winter seasons (Chapter 3.4, Table 5). Obtained time series are characterised by high random variability. Statistical analysis of four time series (Narva, Tallinn, Virtsu and Sõrve- severity of those stations were defined in the chapter 3.4) was done separately for the severe, average and mild winter seasons. Results are shown in Figure 3.

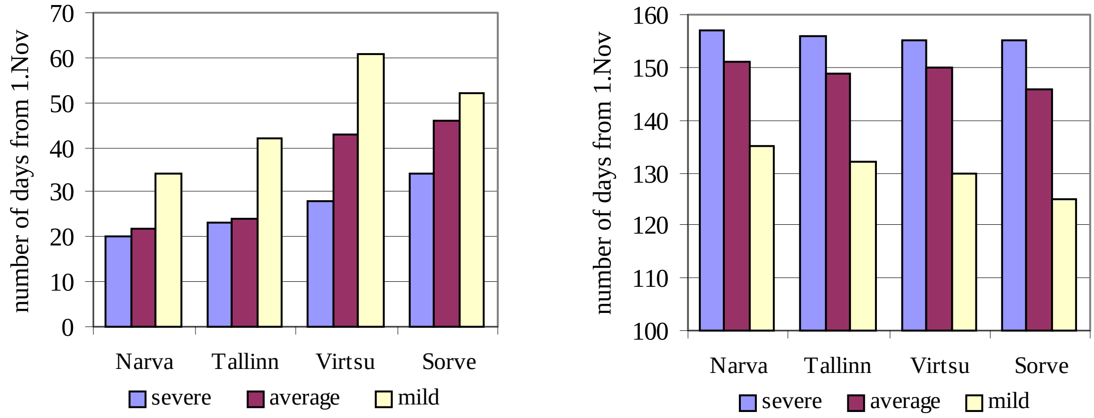

Fig. 3. Mean onset of freezing and melting air temperatures for the severe, average and mild winter seasons along the Estonian coast (1920–1990).

The mean onset of freezing air temperatures during the severe winter seasons occurred from the 20th of November (Narva) to the 4th of December (Sõrve); during the average winter seasons from the 22nd of November (Narva) to the 16th of December (Sõrve); during the mild winter seasons from the 4th of December (Narva) to the 30th of December (Virtsu).

Those results will be used in order to investigate the relation between time series of onset of freezing temperatures and date of freezing in the following study.

3.3 Onset of melting air temperatures

Time series of onset of melting air temperatures were constructed from the data in order to analyse the break-up of ice. The dates of increasing air temperatures passing through 0 °C was defined according the method given in "*Guideline for the construction of climatological time series*" (1969). Results of statistical analysis of time series are shown in Table 4.

In the time period evaluated, the onset of melting air temperatures was found to occur earlier. In general, at the end of the study period the onset of melting air tempera tures was observed 10–15 days earlier than at the beginning. Statistically significant trends were detected for time series of Narva ($p<0.03$), Tallinn ($p<0.03$), Pärnu ($p<0.04$). For the rest stations obtained trends were below the significance level. As an example the time series of freezing air temperature onset and melting air temperature onset at station Narva are given in Figure 4.

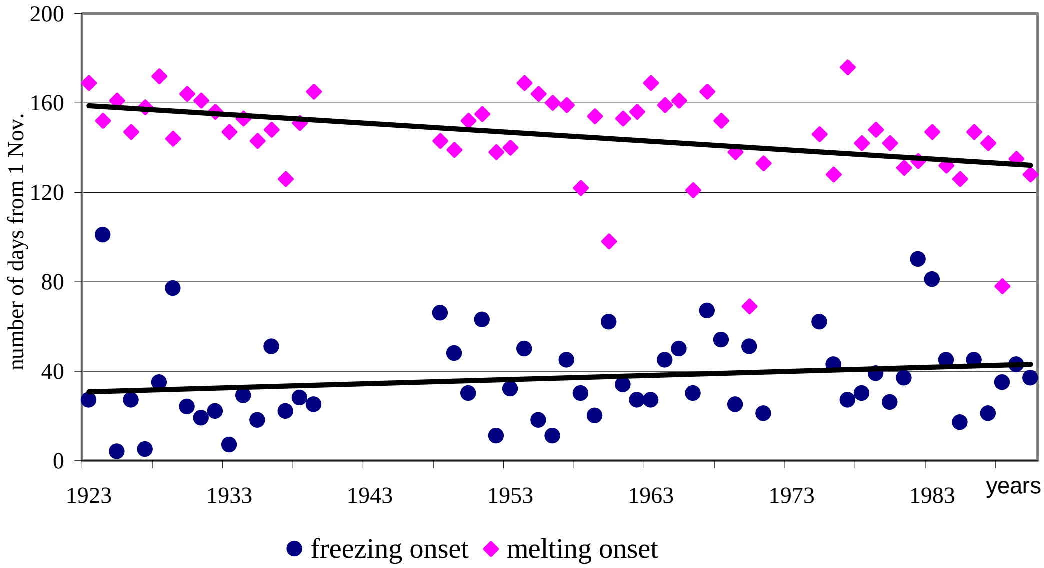

Fig. 4. Time series of freezing air temperature onset and melting air temperature onset at station Narva (1923–1990).

Time series of onset of melting air temperatures were arranged according to the severity of winter seasons (chapter 3.4; Table 5). The random variability of those time series was lower than in case of onset of freezing air temperatures. Mean onset of melting air temperatures during the severe winters occurred on the 4–6th of April; during the average – from the 26th of March (Sõrve) to the 31st of March (Narva) and during the mild winter seasons from the 5th of April (Sõrve) to the 15th of April (Narva).

The obtained results will be used in order to analyse the relation between time series of onset of melting air temperatures and date of ice break-up.

3.4 Sum of negative degree-days

The sums of negative degree-days were calculated for four stations, Narva and Tallinn situated in the Gulf of Finland; Virtsu and Sõrve located in the Gulf of Riga. Correlation coefficients between all stations were quite high, ranging from 0.93 to 0.99. A time series of the sums of negative degree-days at Tallinn is shown in Figure 5.

A tendency of decreasing numbers of negative degree-days was observed over the study period. This was similar at all stations. The fifth-degree polynomial fit for the time series is shown in Figure 5. This indicates a warming from the end of the 19th century until around 1940, then a cooling until 1960 and then again a slight warming.

The sums of negative degree-days have been used to define the severity of winter seasons. Classification of the winter seasons has been done according to the calculated sums of negative degree-days for each observing station. The rates of sum of negative degree-days for severe, average and mild winter seasons are given in Table 5.

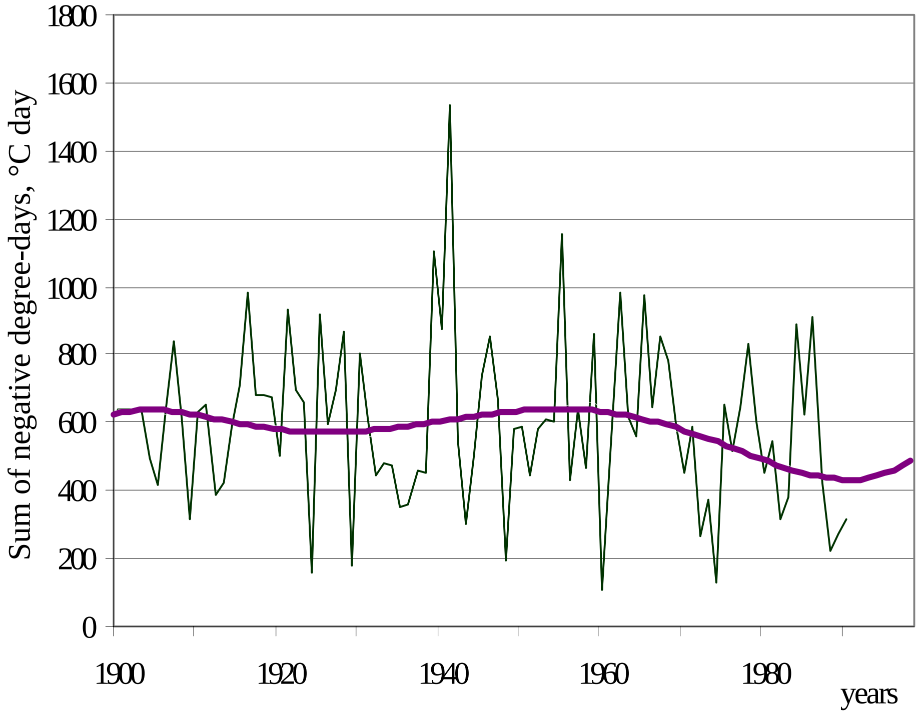

Fig. 5. Time series of sums of negative degree-days at station Tallinn (1923–1990). The thick line represents the fifth degree polynomial fit.

Table 5. The rates of sum of negative degree-days for mild, average and severe winter seasons.

	Sums of negative degree-days for mild, average and severe winters		
	Mild	Average	Severe
Narva	<550	550–830	> 830
Tallinn	<470	470–710	>710
Virtsu	<380	380–570	>570
Sõrve	<270	270–520	>520

The histograms of sums of negative degree-days for Tallinn, Narva, Virtsu and Sõrve are presented in Figure. 6. The shape of histograms is positively skewed; the mild and average winter seasons dominated during this century.

Mean sums of negative degree-days for the severe, average and mild winters were calculated for each of stations. There is quite significant difference between the values of sums of negative degree-days for the stations situated in the Gulf of Finland and sums of negative degree-days for the stations situated in the Gulf of Riga. The results for the station Narva (Gulf of Finland) and station Sõrve (Gulf of Riga) are shown in Figure 7.

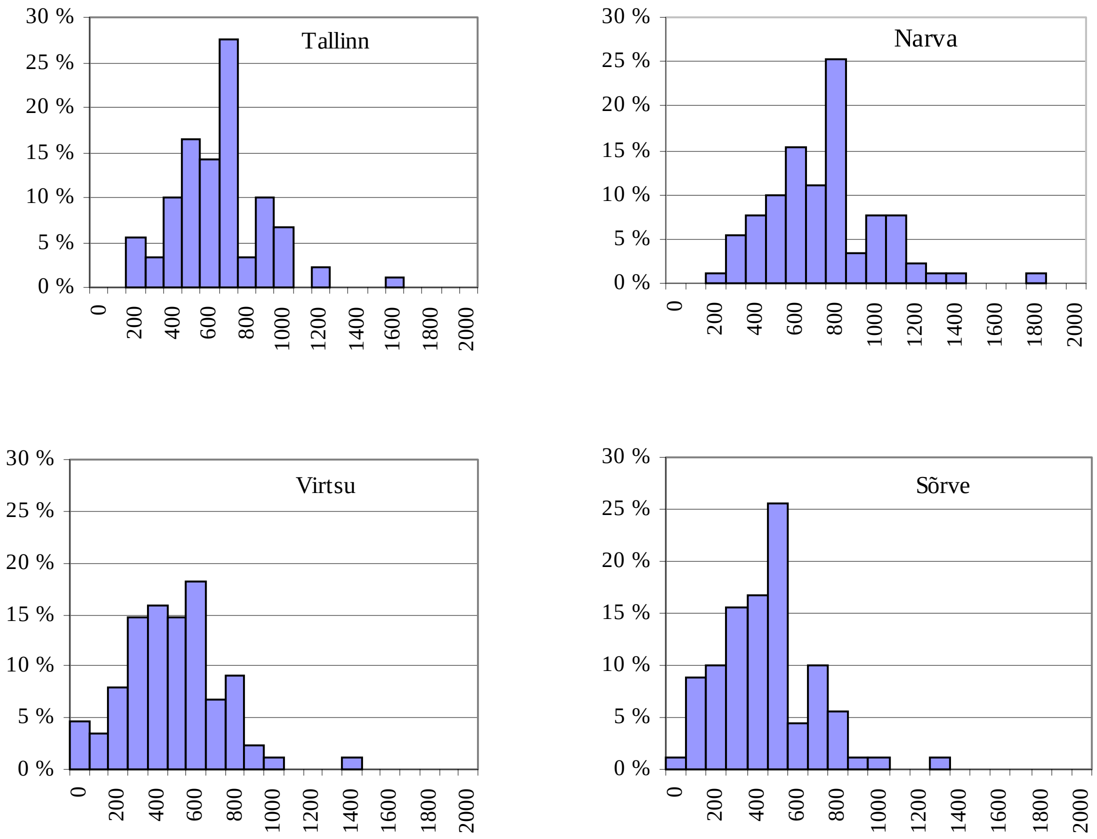

Fig. 6. Histograms of sums of negative degree-days at stations Tallinn, Narva, Virtsu and Sõrve (1900–1990).

3.5 Number of ice days

The results of statistical analysis of time series of number of ice days are given in Table 4. Observations of duration of ice seasons along the Estonian coast indicate a large interannual variability between ice seasons. The range of variation of the number of ice days is several months; maximum value of standard deviation is 41 days. The most significant variations (166 days, more than 5 months) in the number of ice days were found for the eastern part of the Gulf of Finland (station Narva). It is more than was found for the Finnish stations by *Leppäranta* (1985). In general, the duration of ice seasons in Gulf of Finland along the Estonian coast is less if compared with duration of ice seasons along the Finnish coast.

Histograms of the number of days with ice at eight stations situated along the Estonian coast are given in Figure 8. There is significant difference in the shapes of histograms. There are positive kurtoses of Narva, Pärnu, Kihnu time series and shape is with clearly indicated peak; for the rest stations the shape of histograms is rather flat. Most of histograms are negatively skewed; only for station Naissaar the value of skew-ness is 0.

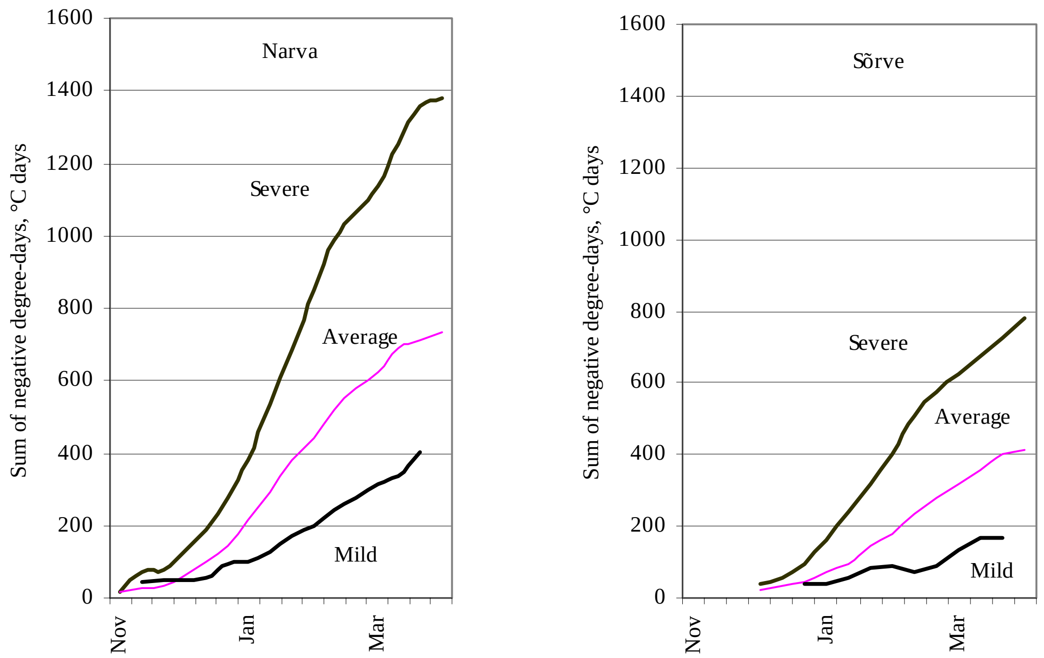

Fig. 7. Mean sums of negative degree-days for the severe, average and mild winters calculated for Narva (Gulf of Finland) and Sorve (Gulf of Riga).

The number of days with ice decreases for each station during investigated period. The rate of decreasing is 5–7 days in a century in the Gulf of Finland and 5–10 days in a century in the Gulf of Riga. The decreasing about 20–30 days in a century for the time series of Finnish stations situated in the Gulf of Finland was found by *Leppäranta* (1989).

Relation between the time series of sum of negative degree-days and number of ice days was investigated. Time series of number of ice days was treated as the dependent variable and the time series of sum of negative degree-days was treated as the independent variable in a regression analysis, where the R-values were 0.61 (Narva), 0.69 (Tallinn) and 0.76 (Sõrve). As an example the regression line between time series of sum of negative degree-days and number of ice days at station Sõrve is shown in Figure 9. Nevertheless, for station Virtsu regression analysis resulted into the R-value 0.12. It can be explained by the location of station on the strait.

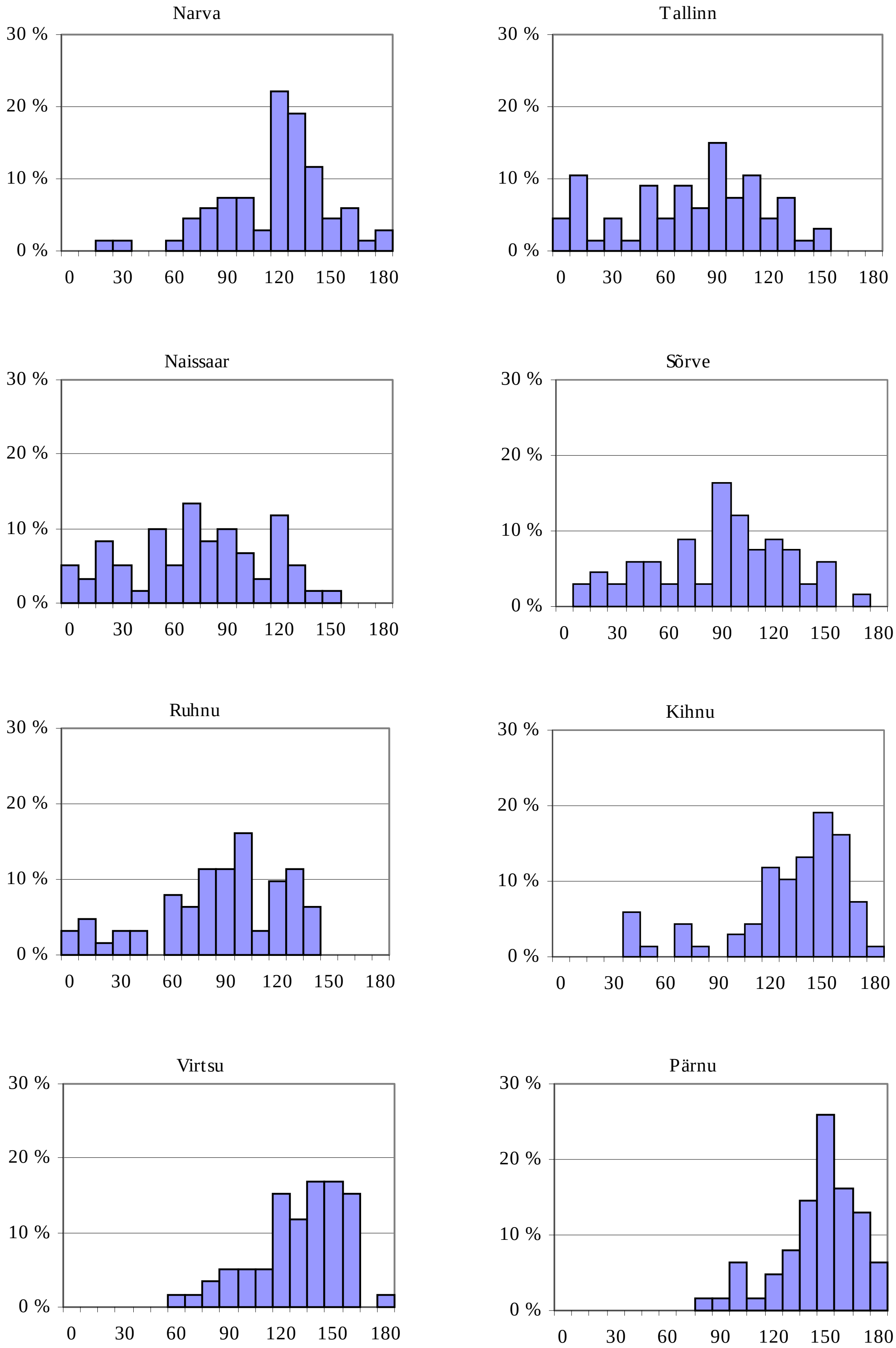

Fig. 8. Histograms of number of days with ice.

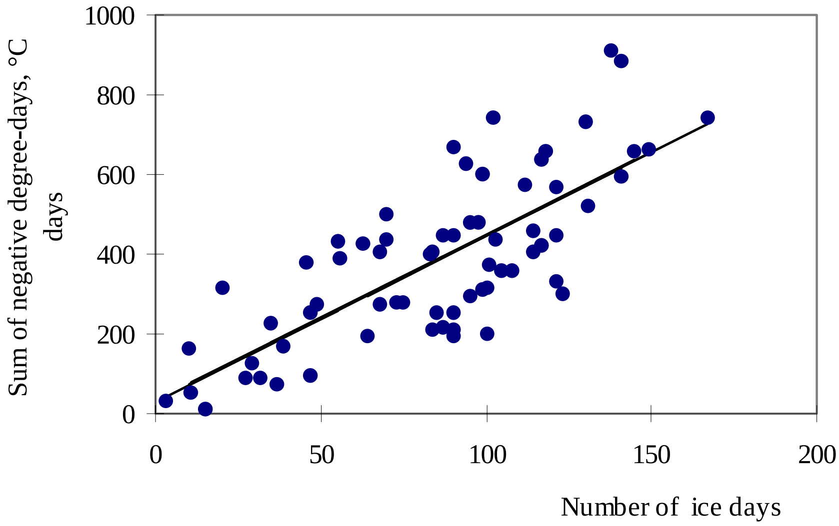

Fig. 9. Regression between sum of negative degree-days and number of ice days at station Sõrve.

4. *Conclusion*

Based on the analysis of air temperature, onset of freezing and melting air temperatures, the sum of negative degree-days and the number of ice days the following conclusions can be drawn:

- The results of analysis of mean air temperatures for November–April indicate during the winter seasons almost all parts of Estonia experienced an overall warming of 0.5–1.0 °C for the period 1900–1990, however the increase is statistically significant only for station Sõrve, for the rest time series the increase is significant on the less than 95% level.
- The early decades of the 20th century were cooler than the period from 1920 to 1936.
- It was cooler again until 1960, when temperatures start to rise again.
- The date of stabilised transition of the air temperature to sub-zero values was observed about 8–14 days later at the end of study period than in the beginning, while the date of melt air temperature onset was observed 10–15 days earlier during the spring seasons.
- Significant variations were found in time series of onset of freezing air temperatures; variations of time series of melt air temperature onset were lower.
- High correlation coefficients (0.93–0.99) were found between the time series of sums of negative degree-days for the stations situated along the Estonian coast.
- Correlation coefficients (0.86–0.96) were found between the time series of mean air temperature during November–April for the stations situated along the Estonian coast.

- The number of days with ice decreases about 5–7 days in a century in the Gulf of Finland and 5–10 days in the Gulf of Riga.
- Correlation coefficients between time series of mean air temperature during November–April and number of ice days were from 0.57 to 0.82.
- Correlation coefficients between time series of sum of negative degree-days and number of ice days were from 0.61 to 0.76.

Further investigations of freezing, break-up and ice thickness will be performed on the basis of the results of this study.

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