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Long-term changes in the sea ice regime in the Baltic Sea near the Estonian coast

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Abstract. Long-term changes in the parameters of the sea ice regime (the date of appearance of the first sea ice in the beginning of winter, the date of the formation of fast ice, the date of the formation of young ice, the date of the break-up of fast ice, the date of the final disappearance of sea ice and the total number of days with sea ice) in the Baltic Sea near the Estonian coast are analysed for the period 1950/1951–2004/2005. Data were obtained from 8 stations at different coastal regions. Medians, quartile ranges and extremes were calculated. Spatial differences in the sea ice regime between different coastal regions of Estonia were determined. A statistically significant decrease in sea ice was detected that lies in a good correlation with the general warming trend in winter and spring during the same period. Large differences in the magnitude of the trends can be found between different coastal regions of Estonia. On the southern coast of the Gulf of Finland, long-term changes in sea ice parameters are small and mostly insignificant. The highest decrease in sea ice has been observed on the islands of the West-Estonian Archipelago, where the period with ice has decreased by 1.5–2.5 months. Possible causes for the spatial differences are discussed.

Key words: sea ice, climate change, trend analysis, atmospheric circulation.

1. INTRODUCTION

Climatic conditions in the Baltic Sea region are formed under the influence of many factors. High latitude is a reason for the rather cold climate of the temperate zone with significant seasonal fluctuations in solar radiation and temperature. At the same time, the influence of the mild polar maritime air mass, formed over the Northern Atlantic and transported to the Baltic area, is strongly evident. Intensity of westerlies in winter determines weather conditions during the whole winter season and also in the following spring [1]. In case of strong Atlantic influence, mild winters with little ice cover and early spring are observed. Weakening of westerlies is accompanied by cold winters, thick long-lasting ice cover and late spring.

Ice cover is an important factor, influencing weather formation in the Baltic Sea region. During mild winters, little sea ice is observed. The ice-free sea surface heats the air above it. The mild air, moving from the sea to coastal regions, keeps air temperature above zero. In case of mild winters, significant thermal contrasts can be found between the mild coastal zone and the cooled continental part of Estonia.

In cold winters, the weather situation is different. Sea ice forms near the coast rather early, mostly in December. The thermal contrasts gradually decrease and even disappear. The heating influence of the sea cannot be sensed. Thick ice cover causes low temperatures above the ice even in spring. After a cold winter, warming of the sea surface takes a lot of time and the summer season starts later than usual.

On the other hand, the sea-ice regime is determined by weather conditions. It depends directly on the air temperature and indirectly on the atmospheric circulation, first of all on the intensity of westerlies in winter. The advection of mild air from the North Atlantic determines air temperature in the Baltic Sea region. Cyclones, moving eastward from the ocean, usually bring mild air, strong winds and precipitation. In addition to meteorological conditions there are many other hydrological and hydrographical factors influencing the sea ice formation on the Baltic Sea: big extension of the sea in the meridional direction, isolation from the ocean, comparatively shallow sea, complex coastline, low salinity of water, and the absence of tides and large currents.

Sea ice has a substantial influence on human activities in Estonia. It is the main obstacle for winter navigation. Increasing sea traffic has raised an urgent need for the year-round navigation, but using ice breakers is very expensive for the state. On the other hand, thick sea ice permits to establish ice roads, which significantly enlarge transport possibilities between the islands and the mainland [2].

Sea ice conditions near the Estonian coast have been studied in many papers. Using long-term proxy data on the sea ice break-up dates at the Tallinn port, the mean winter air temperature has been reconstructed back to the year 1500 [3]. Relationships between the mean winter air temperature and the extent of sea ice has been analysed [4,5]. The sum of negative daily mean temperatures has the highest correlation with the number of days with sea ice. The duration of snow cover in Estonia is also largely influenced by sea ice [6].

The most significant contribution to the studies of the sea ice regime in Estonia has been provided by Jevrejeva. She has analysed time series of ice days and winter air temperatures during 1900–1990 and their relationships. The number of days with sea ice has decreased by 5–7 days in a century in the Gulf of Finland and by 5–10 days in the Gulf of Riga. Most of the trends during that period were statistically insignificant [7].

Fluctuations in the severity of the winter season in the Baltic region during 1529–1990 were analysed using proxy data (dates of ice break-up at the port of Riga). The only statistically significant trend that was detected indicated a shift of the ice break-up to an earlier date in severe winters [8]. At some stations in Estonia, the date of the ice break-up has shifted earlier by 8–15 days during 1890–1990 [9]. Based on the results of more detailed data, a number of statistically significant trends were revealed concerning the same 100-year period [10]. However, this period did not include the last decade of the 20th century, which has been characterized by a high frequency of mild winters.

Relationships between sea ice parameters and atmospheric circulation are analysed using singular spectrum analysis, coherent fluctuations in sea ice parameters and the North Atlantic oscillation and the Arctic oscillation [11]. A remarkable negative correlation between the number of days with sea ice and the NAO index was detected (r varies between –0.37 and –0.66). Dates of the ice break-up depend on the NAO index in winter [12,13]. High intensity of westerlies and the prevalence of cyclonic weather are related to a smaller number of days with sea ice and to an earlier ice break-up while the northerly and easterly circulation with governing anti-cyclones in northern Europe is observed in case of maximum sea ice.

The main objective of this article is to analyse changes in the characteristics of sea ice near the Estonian coast during the second half of the 20th century. Climate warming has been most remarkable in Estonia during the same period [1]. An increase in the surface air temperature has been observed, first of all, in winter and spring, i.e. in the sea ice season. In previous studies [14,15], only three parameters of the sea ice regime (dates of the first appearance and disappearance of sea ice, number of days with ice) have been analysed. A general decreasing trend in sea ice duration has been detected in Estonia. It was the highest in the West-Estonian Archipelago while the trend was insignificant on the southern coast of the Gulf of Finland. The date of disappearance of sea ice has moved significantly earlier at practically all stations. The date of the first sea ice has largely varied. Mostly, it has not changed, but it has shifted later at some stations [15]. In this paper, a much larger number of variables, describing the sea ice regime, are analysed. We included data on fast ice and the years lacking fast ice and sea ice at all. These variables can describe changes on the coast of the Baltic Proper where sea ice is much less common than at sheltered locations.

2. MATERIAL AND METHODS

Sea ice regime in the Baltic Sea near the Estonian coast is described by a number of variables:

- date of appearance of the first sea ice in the beginning of winter;
- date of formation of fast ice;
- date of formation of young ice;
- date of break-up of fast ice (sea ice starts moving);
- date of final disappearance of sea ice;
- total number of days with sea ice.

The date of the first appearance of sea ice is registered when ice of any type is first observed. Fast ice is recorded when ice is fixed to the coast or a shallow in the sea. Young ice (thickness 10–30 cm) is recorded when all the visible sea surface is covered by ice, i.e. pieces of sea ice have frozen and joined into the general ice cover. All these data have been observed at eight coastal hydrometeorological stations of Estonia (Fig. 1) during 55 winters (1950/1951–2004/2005).

It is essential to notice that, in some parts of the Estonian coast, extremely mild years without any sea ice have been observed. At stations located on the coast of the Baltic Proper (Pakri, Ristna and Sõrve), fast ice and young ice usually do not form at all. The number of years without fast ice and any sea ice at all are grouped into five 11-year periods. These variables are appropriate to reflect changes in the sea ice regime in the regions of little sea ice. The data on sea ice are stored in the archive of the Estonian Meteorological and Hydrological Institute. Single gaps in time series were filled using data from neighbouring stations.

Statistical analysis of the sea ice variables is complicated due to the specificity of the data. At first, normality of the data distribution was checked using the Lilliefors test for normality and the Shapiro–Wilk W test. If one of these tests showed normality, the data were considered as normally distributed.

Ordinary statistics, such as average and standard deviations, are not appropriate to use in case of data where some measurements are missing due to the lack of sea ice. Median values are used for describing mean sea ice conditions and quartile ranges are used for describing temporal variability. In addition, minimum and maximum values are presented.

Fig. 1. Location of the stations the sea ice data of which are used in this study.

Usually, trends are estimated using the linear regression analysis. A change by trend is calculated by multiplying the slope with the number of years. In cases of non-normal distribution, the Mann–Kendall test was used for trend analysis. Trends are considered significant at the $p < 0.05$ level. The statistics of the sea ice regime are calculated using observation data only from the years with existing sea ice. Trends are not calculated for the time series that have interruptions due to the lack of sea ice.

3. RESULTS

3.1. Average sea ice regime

The sea ice regime along the Estonian coast is characterized by a significant temporal and spatial variability. Table 1 presents the medians of the sea ice regime at eight stations during 1950/1951–2004/2005. Remarkable spatial differences appear between different coastal parts of Estonia. First, near the coasts of shallow and closed bays, sea ice is usually observed already in November. On most parts of Estonian coastline, the first sea ice forms in December and only on the open coast of the Baltic Proper it appears in January. It must also be taken into account that at three stations (Pakri, Ristna and Sõrve), lack of sea ice is observed during some extremely mild winters. When averaging the dates of appearance and disappearance of sea ice, these years were not taken into account. Therefore, the median dates are not fully comparable between the stations.

Fast ice forms approximately one month after the appearance of the first ice, i.e. at the end of December and beginning of January. First, it appears in the shallow Pärnu Bay. At the westernmost stations, fast ice and young ice usually do not form at all. Formation of young ice is usually observed only in closed bays, first of all in the Pärnu Bay and in the Väinameri. The years lacking of different types of sea ice are excluded from the calculation of median dates.

Table 1. Medians of the sea ice regime during 1950/1951–2004/2005

	Narva-Jõesuu	Kunda	Helter-maa	Kihnu	Pärnu	Sõrve	Pakri	Ristna
First ice	6 Dec	17 Nov	28 Nov	26 Nov	26 Nov	15 Dec	5 Jan	25 Dec
Fast ice	5 Jan	13 Dec	18 Dec	12 Jan	10 Dec	28 Dec	–	–
Young ice	26 Jan	1 Feb	31 Dec	–	15 Dec	31 Jan	–	–
Break-up of fast ice	12 Apr	12 Apr	11 Apr	12 Apr	18 Apr	30 Mar	–	–
Final disappearance	20 Apr	18 Apr	16 Apr	24 Apr	23 Apr	7 Apr	10 Apr	5 Apr
Days with sea ice	119	128	125	127	142	90	50	63
Years without sea ice	0	0	0	0	0	1	6	4
Years without fast ice	5	1	4	18	0	8	–	–
Years without young ice	8	9	9	–	0	19	–	–

In the middle of March, the break-up of fast ice begins on the western coast of Saaremaa and Hiiumaa islands, where the ice is much thinner in comparison with other coastal regions. Generally, the break-up of fast ice occurs during the first half of April. Final disappearance of sea ice is observed approximately one week after the break-up of fast ice. For the longest period, sea ice remains over Pärnu Bay.

The number of days with sea ice largely varies in the coastal regions of Estonia, depending on local geographical conditions. Sea ice is the rarest on the open coast of the Baltic Proper. The duration of sea ice is much longer on the southern coast of the Gulf of Finland, in the Gulf of Riga and in Väinameri, 120–125 days on the average. In Pärnu Bay, sea ice exists for a much longer time. Table 1 presents also the numbers of the years with no fast ice, young ice and sea ice during the observed 55-year period. If the number of lacking data exceeds half of the length of the time series, the corresponding median values are not presented in Table 1.

3.2. Temporal variability of sea ice characteristics

Sea ice conditions near the Estonian coast are very variable. In case of severe winters, the whole sea surface is covered by ice for 4–6 months. In mild winters, ice cover forms only on shallow and closed bays while the rest of the sea is ice-free. Such a high variability allows to assume that sea ice could be a sensitive indicator of local climate change.

Quartile ranges of the parameters of the sea ice regime are presented in Table 2. They indicate a high temporal variability. They are calculated using only the data from the years when the corresponding type of sea ice existed. It is typical that the lowest temporal variability corresponds to the maximum duration of sea ice. The sea ice regime in the Pärnu Bay is the most stable, whereas the maximum variability is observed at the islands. At the stations on the coast of the Gulf of Finland (Narva-Jõesuu and Kunda), higher variability can be found at the time of the formation of fast ice but on the coasts of the Gulf of Riga and Väinameri (Heltermaa and Kihnu) it can be found at the time of the young ice and in the days with sea ice. The highest temporal variability of a number of days with sea ice is observed near to the open coast of the Baltic Proper.

Table 2. Quartile ranges of the sea ice regime during 1950/1951–2004/2005

	Narva-Jõesuu	Kunda	Heltermaa	Kihnu	Pärnu	Sõrve*	Pakri*	Ristna*
First ice	23.0	18.0	23.5	25.0	18.0	22.3	27.0	31.0
Fast ice	34.3	41.5	28.5	31.0	21.0	40.0	–	–
Young ice	32.5	30.8	33.3	–	18.5	32.0	–	–
Break-up of fast ice	19.3	19.5	16.0	17.5	15.0	29.3	–	–
Final disappearance	18.5	20.0	18.0	26.0	14.5	31.5	28.0	25.5
Number of days with sea ice	31.0	43.0	51.0	49.5	31.0	69.3	56.5	81.5

* Ice-free winters have been observed.

Table 3. Extreme values of the parameters of the sea ice regime during 1950/1951–2004/2005

	Narva-Jõesuu	Kunda	Helter-maa	Kihnu	Pärnu	Sõrve*	Pakri*	Ristna*
Earliest first ice	2 Nov 1960	15 Oct 1976	24 Oct 1959	29 Oct 1956	16 Oct 1976	8 Nov 1956	3 Dec 1980	11 Nov 1951
Latest first ice	27 Jan 2005	28 Dec 2005	20 Feb 1992	22 Feb 1992	19 Jan 1983	–	–	–
Earliest fast ice	26 Nov 1965	25 Oct 1992	8 Nov 1964	14 Nov 1965	21 Oct 1976	18 Nov 1965	10 Feb 1953	29 Dec 1978
Earliest young ice	2 Dec 1973	25 Dec 1995	25 Nov 1965	5 Jan 1951, 1952	16 Nov 1993	21 Dec 1969	–	–
Latest break-up of fast ice	12 May 1956	5 May 1956	8 May 1956	13 May 1972	5 May 1956	22 Apr 1963	30 Apr 1956	18 Apr 1963
Earliest disap-pearing	21 Feb 1990	15 Feb 1990	27 Jan 1990	17 Jan 1989	15 Mar 1990	–	–	–
Latest disap-pearing	12 May 1956	11 May 1960, 1987	10 May 1956	19 May 1956	19 May 1955	17 May 1969	5 May 1966	20 Apr 1956
Minimum days with sea ice	52 1992	42 1961	5 1992	8 1992	68 2000	0 1992	0 6 years	0 4 years
Maximum days with sea ice	161 1966	167 1966	171 1966	169 1966	180 1955	167 1966	115 1996	135 1960

Extreme values of the studied parameters of the sea-ice regime and the corresponding years are presented in Table 3. Extremely cold winters were mostly concentrated around the 1950s and 1960s and mild winters on the second half of the study period. Mentioning the extremes, first of all, the spring of 1956 with a very late disappearance of sea ice should be picked out. The winter of 1965/1966 had the longest duration of sea ice at most of the stations. At the same time, mild winters with little sea ice (1960/1961, 1982/1983, 1988/1989, 1989/1990, 1991/1992, 1999/2000, 2004/2005) are clearly presented in Table 3.

3.3. Long-term trends in sea ice regime

The 55-year period under observation is described by increasing trends in mean air temperature in Estonia, especially in the winter and spring seasons [[13]]. These trends cause general decreasing tendencies in the time series of sea ice. Table 4 presents the results of the trend analysis of variables of the sea ice regime during the period 1950/1951–2004/2005 in a very concentrated form. There are changes by trend (days) during the 55 years. Statistically significant trends are typed in bold. In most cases, when data were normally distributed, the significance was found by means of linear regression analysis using Student's t-test. In case of non-normal distribution (for example, in Heltermaa, Kihnu and partly in Sõrve, Pärnu, Pakri and Ristna) the Mann–Kendall test was used. All sea ice parameters were normally distributed only in Narva-Jõesuu and Kunda.

Table 4. Changes by the trend of variables of the sea ice regime during 1950/1951–2004/2005. Statistically significant trends on $p < 0.05$ level are typed in bold

	Narva-Jõesuu	Kunda	Helter-maa	Kihnu	Pärnu	Sõrve	Pakri	Ristna
First ice	5.9	9.8	**36.7**	**49.2**	**20.3**	–	–	–
Fast ice	–	–	–	–	9.3	–	–	–
Young ice	–	–	–	–	12.4	–	–	–
Break-up of fast ice	–	–	–	–	**–15.5**	–	–	–
Final disappearance	**–20.4**	–8.8	**–32.5**	**–48.0**	**–21.8**	–	–	–
Number of days with sea ice	–19.1	–14.0	**–54.7**	**–73.7**	**–36.8**	**–46.0**	**–35.0**	**–60.9**

Trends are not similar over the coastal regions of Estonia. Less change has occurred on the southern coast of the Gulf of Finland (Kunda and Narva-Jõesuu). The date of the first appearance of sea ice has shifted to slightly later, the date of the final disappearance of sea ice has shifted earlier and the number of days with sea ice has decreased by about two weeks. Mostly, these changes are not statistically significant on $p < 0.05$ level.

Decreasing trends in sea ice parameters are much stronger on the western coast of continental Estonia (Pärnu and Pakri). The duration of sea ice has shortened by more than one month. These changes are statistically significant. Full time series for the dates of fast ice formation and break-up and of young ice formation are available only for Pärnu. The duration of fast ice and young ice in Pärnu has shortened. The break-up date of fast ice has moved significantly earlier. The dates of formation of fast and young ices have shifted later by 1–2 weeks, but the trends are insignificant.

The most dramatic changes in the time series of sea ice variables have occurred on the islands of the West-Estonian archipelago. The date of the first appearance of sea ice has shifted later by more than one month, the date of the final disappearance of sea ice has shifted earlier by approximately the same period, and the number of days with sea ice has decreased by 1.5–2.5 months. These changes are really tremendous and of high statistical significance.

Time series and trend lines for the dates at the two different regions in Estonia are presented in Fig. 2 and the time series of the number of days with sea ice at the same stations in Fig. 3. It can be resumed that the strong trends at Kihnu are caused by a dramatic decrease in sea ice in case of mild winters, the frequency of which has risen during the last two decades. Long-term changes in sea ice on the coast of the Gulf of Finland, at Narva-Jõesuu and Kunda stations are not very substantial. Therefore, we can conclude that the spatial differences in sea ice in Estonia are high in case of mild winters and low in case of cold ones.

It is rather difficult to estimate changes in time series where some values are missing. Changes in the frequency of ice-free winters serve as an important indicator of climate change. Years without sea ice are concentrated into the last third of the time series. The numbers of years without fast ice, grouped by

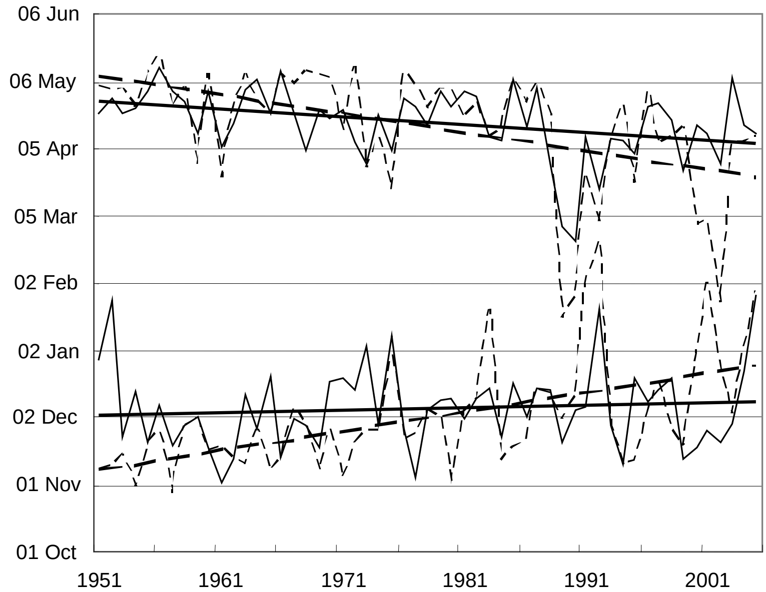

Fig. 2. Time series of the dates of the first appearance of sea ice and the final disappearance of sea ice in Kihnu (dashed line) and Narva-Jõesuu (solid line), and their linear trends.

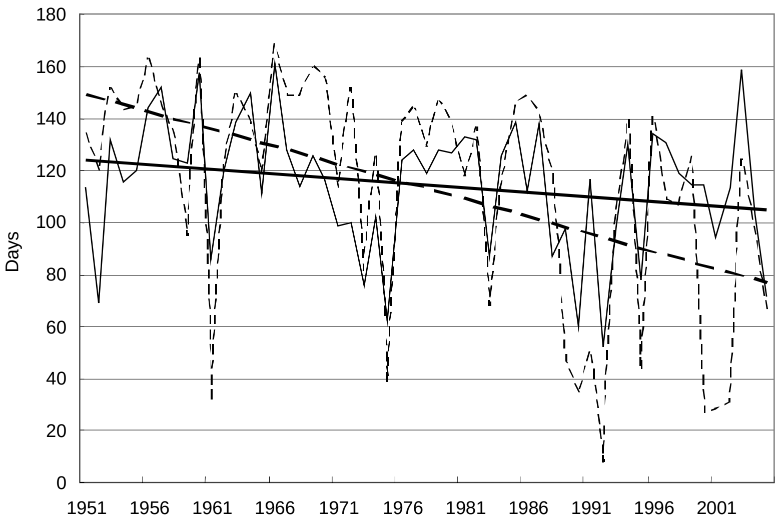

Fig. 3. Time series of the number of days with sea ice in Kihnu (dashed line) and Narva-Jõesuu (solid line), and their linear trends.

11-year periods, are presented in Table 5. It is evident that years without fast ice have also occurred mostly during the last two 11-year periods (1984–1994, 1995–2005). Fast ice is rare at the Pakri station because it is located on the coast that is open to winds and where the sea is deep near to the coast.

Table 5. Number of years without fast ice during 1950/1951–2004/2005 in the five 11-year periods

Period	Narva-Jõesuu	Kunda	Helter-maa	Kihnu	Pärnu	Sõrve	Pakri	Ristna
1951–1961	0	1	0	1	0	1	3	6
1962–1972	0	0	0	0	0	0	4	3
1973–1983	0	0	0	2	0	0	9	5
1984–1994	1	0	3	6	0	5	11	6
1995–2005	4	0	1	9	0	2	10	9

4. DISCUSSION AND CONCLUSIONS

Analysis of the time series of sea ice parameters in the Baltic Sea along the Estonian coast revealed a remarkably high temporal and spatial variability as well as significant trends indicating a decrease in sea ice during 1950/1951–2004/2005. The changes have been in correlation with the general warming during the same period. These results approve and adjust the results of the previous studies on sea ice variations along the Estonian coast. If the earlier study [15] analysed only three parameters of sea ice using mean values and standard deviations, this paper gives more appropriate results, based on a greater number of variables describing different types of sea ice and using medians and quartile ranges as better statistics.

The dates of the formation of the first sea ice, of fast ice and of young ice have shifted to a later time during the 55-year period. At the same time, the dates of the break-up of fast ice and of the final disappearance of sea ice have moved earlier even more rapidly. As a conclusion, the number of days with sea ice in the winter season has decreased significantly.

The most interesting aspect is that changes in the sea ice regime in different coastal regions of Estonia have been of different magnitude. On the southern coast of the Gulf of Finland (Narva-Jõesuu and Kunda), long-term changes in sea ice parameters are small and mostly insignificant. A decrease in the number of days with sea ice by more than two weeks is statistically insignificant on the $p < 0.05$ level due to a very high temporal variability of these variables. The most dramatic decrease in sea ice parameters has been observed on the islands of the West-Estonian Archipelago (Kihnu, Sõrve, Ristna and Heltermaa) where the number of days with sea ice has decreased by 1.5–2.5 months.

Such large spatial differences over the coastal regions of Estonia can be explained by the following hypotheses. Estonia is located in the transition zone between maritime climate in the west and continental climate in the east. Air temperature gradient in winter is high. For example, mean surface temperature in January varies from –1.6 °C on the western coast of Saaremaa Island up to –6.9 °C in Narva on the north-eastern border. The western coast is located at the critical temperature limit between freezing and melting. The same temperature increase will induce a dramatic decrease in sea ice on the western coast but a moderate decrease in the east. On the coast of the Gulf of Finland, mean air temperature is much lower and the critical temperature limit is farther off.

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Läänemere jäärežiimi pikaajalised muutused Eesti ranniku lähedal

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On vaadeldud Eesti rannikumere jäärežiimi pikaajalisi muutusi perioodil 1950/1951–2004/2005. On uuritud esimese jäätekke, kinnisjää ning noore jää

tekke kuupäevade, kinnisjää lagunemise ja jää lõpliku kadumise kuupäevade ning jääpäevade arvu aegridu. Kasutatud on kaheksa rannikujaama andmeid. Erilist tähelepanu on osutatud jäärežiimi kohalikele isaärasustele Eesti erinevatel rannikualadel. On kindlaks tehtud statistiliselt oluline jää vähenemistrend, mis on heas kooskõlas talvise ja kevadise õhutemperatuuri tõusutendentsiga. On selgunud ka suured erinevused jäärežiimi muutustes erinevatel rannaaladel. Soome lahe lõunarannikul on jääkatte vähenemine olnud kõige väiksem ja trendid on põhiliselt ebausaldusväärsed. Jääpäevade arvu vähenemine enam kui kaks nädalat pole statistiliselt oluline. Suurimad muutused jääkatte parameetrites on toimunud Lääne-Eesti saarestikus, kus jääpäevade arv on vähenenud 6 kuni 10 nädalat. Jää on hakanud tekkima hiljem ja kaduma palju varem.