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Trends in sea ice conditions in the Baltic Sea near the Estonian coast during the period 1949/1950–2003/2004 and their relationships to large-scale atmospheric circulation

Jaak Jaagus

Department of Geography, University of Tartu, Vanemuise 46, 51014 Tartu, Estonia

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In this paper, I study changes in the sea ice regime near the Estonian coast in 1949/1950–2003/2004. The trends in the dates of the first appearance of sea ice and final disappearance of sea ice, as well as in the number of days with sea ice, were analysed and related to the trends in air temperature and atmospheric circulation characteristics. The dependence of sea ice trends on circulation changes was estimated with the conditional Mann-Kendall test. The results revealed no similar trends in sea ice parameters in different areas of Estonia. I found a significant shift towards a later date in the first appearance of sea ice on the western Estonian coast of the inland sea, but not on the coasts of the Gulf of Finland and the Baltic Proper. This trend could not be explained by the trends in the circulation parameters. The date of the final disappearance of sea ice has shifted earlier by more than a month. The largest change has occurred at the westernmost stations and the smallest change was typical for the Gulf of Finland. This variable had a close correlation with the intensity of westerlies during the whole winter. The correlation coefficient between the date of the final disappearance of sea ice, NAO and AO indices and the frequency of the zonal circulation type W during the winter season (December–March) lay between –0.56 and –0.73. Concerning single months, the circulation in February plays a key role. The number of days with sea ice, as the main characteristic of the iciness, has decreased significantly in all the stations, except in Kunda and Narva-Jõesuu located on the southern coast of the Gulf of Finland. The most substantial decrease was observed at the westernmost stations located on the open coast of the Baltic Proper. This change was also induced by an increase in the intensity of winter westerlies.

Introduction

The Baltic Sea is characterised by a very high temporal and spatial variability of sea ice in winter. The Bothnian Bay, the eastern part of the Gulf of Finland and the sea at the western coast of the continental part of Estonia are covered by ice every year, whereas the southern part of the Baltic Sea has an ice cover only in 10% of winters (Climatological ice atlas for the Baltic Sea, Kattegat, Skagerrak and Lake Vänern (1963–1979) 1982). Naturally, sea ice is more frequent near the coast than on the open sea.

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

Temporal variations and trends in the time series of sea ice in the Baltic Sea have been thoroughly investigated (Betin and Preobraženskij 1962, Alenius and Makkonen 1981, Dubra 1993, Seinä 1993, Koslowski and Löwe 1994, Haapala and Leppäranta 1997, Koslowski and Glaser 1999, Sztobryn and Krzyminski 1999, Jevrejeva *et al.* 2004). Sea ice conditions near the Estonian coast have been studied with respect to long-time series of proxy data (Tarand 1993, Tarand and Nordli 2001), ice roads to islands of the West Estonian archipelago (Mardiste 1999), air temperature fluctuations (Vahter 1994, Jaagus 1999) and snow cover variations (Tooming and Keevallik 2001). The first day of ice break-up in Tallinn port served as a proxy for the mean winter (December–March) air temperature, which has made it possible to reconstruct the temperature time series back to 1500 (Tarand and Nordli 2001). Vahter (1994) described the mean sea ice regime (the starting dates of sea ice phases, ice thickness and maximum extent of sea ice in the Baltic) in the Gulf of Finland near Tallinn. She classified the winters during 1920/1921–1984/1985 as mild, moderate or severe. There was a close correlation between the sum of negative daily-mean temperatures during a winter and extent of sea ice (Vahter 1994, Jaagus 1999). Inter-annual sea ice fluctuations in the Baltic Sea are relatively coherent with snow cover fluctuations in Estonia (Jaagus 1999, Tooming and Keevallik 2001).

Jevrejeva and co-workers (Jevrejeva 2000, 2001, 2002a, Jevrejeva and Leppäranta 2002) made the most detailed studies on sea ice in Estonia by analysing the time series of ice days and winter air temperatures during 1900–1990 and their relationships. Some trends were determined in these studies, but the majority of the trends were insignificant. The number of days with sea ice has decreased by 5–10 days during the observation period (Jevrejeva 2000). At some Estonian stations, the date of ice break-up had been shifted earlier by 8–15 days in 1890–1990 (Jevrejeva 2002a).

Sea ice conditions in the Baltic Sea depend directly on the winter air temperature, so these two quantities are usually analysed together. Temperature, in turn, is related to the large-scale atmospheric circulation. Many investigators demonstrated that the extent of sea ice in the Baltic is governed by circulation, especially by the intensity of the westerlies, being correlated negatively with the sea ice extension, while the northerly and easterly circulations are correlated positively with each other (Koslowski and Löwe 1994, Girjatowicz 2001, Jevrejeva and Moore 2001, Omstedt and Chen 2001, Jevrejeva 2002b, Jevrejeva *et al.* 2003, Launiainen *et al.* 2003, Omstedt *et al.* 2004). Mild winters and a reduced ice cover are related to the prevalence of cyclones, whereas severe winters with an extended ice cover take place together with governing anti-cyclones in northern Europe.

The atmospheric circulation has a deep influence on the variations in sea ice. Different types of circulation cause different sea ice anomalies. The circulation affects sea ice indirectly via the air temperature. In the case of strong westerlies and under the direct influence of the Atlantic air masses, sea ice appears late. Airflows from the eastern directions favour the early formation of sea ice. A persistence of sea ice in early spring depends on atmospheric circulation during the whole winter. A prevalence of westerlies leads to an intense cyclonic activity, higher temperatures, frequent melting periods, high cloudiness, precipitation, storms and rapid weather changes, which prevent the formation of sea ice. A prevailing meridional circulation and anti-cyclones correspond to cold winters with extensive sea ice.

Unfortunately, the earlier studies analysed sea ice data only in general terms, paying no special attention to the physio-geographical conditions of an observation site. The observed data indicate that in Estonia, both the formation and persistence of sea ice depend very much on local conditions. The ice regime differs much between the closed bays, open coasts of the Gulfs of Riga and Finland and the open coast of the Baltic Proper.

Sea ice forms at first in closed and shallow bays near the coastline. A weak water exchange in the sea favours the cooling of water and ice formation. The Pärnu Bay, for example, extends

Fig. 1. Location of the stations in Estonia used in this study.

far into the continent, which induces the early formation of sea ice. At an open coast with a straight coastline and in deep waters near the coast, freezing is hindered and sea ice forms only during severe winters. Strong winds and high waves do not favour the formation of sea ice. Usually, ice forms during a cold and calm night.

The salinity of seawater influences the ice formation, with higher salinities corresponding to lower freezing temperatures. The salinity of the Baltic Sea near the Estonian coast varies between 4‰ and 7‰. This variability is negligible in the sense that it does not cause significant spatial differences in the sea ice formation.

I propose here a hypothesis that at different geographical locations, climate change and changes in atmospheric circulation have different effects on sea ice.

I investigated only the second half of the 20th century, since the most significant climatic changes have occurred during this very period (IPCC 2001), and since the methods of observing sea ice in Estonia have not changed during that time.

The objectives of this study are (1) to estimate changes in the sea ice regime in the Baltic Sea near the Estonian coast during 1949/1950–2003/2004, (2) to estimate changes in air temperature parameters that are closely related to the formation of sea ice, and (3) to analyse the influence of large-scale atmospheric circulation on the sea ice parameters at different coastal regions in Estonia.

Material and methods

Material

I describe sea ice conditions in winter by using the dates of the first appearance and final disappearance of sea ice, as well as the number of days with sea ice, including all types of sea ice. The observation data were obtained from the archive of the Estonian Meteorological and Hydrological Institute for nine coastal stations in Estonia (Fig. 1) during the period 1949/1950–2003/2004. The stations are located in different geographical conditions: on the coasts of the Gulf of Finland (Narva-Jõesuu, Kunda), the Gulf of Riga (Pärnu, Kihnu), Väinameri (a shallow inland sea between the mainland and larger Estonian islands; Virtsu, Heltermaa) and on the coasts of the open part of the Baltic Sea — the Baltic Proper (Pakri, Ristna, Sõrve). The sea ice in these stations has been observed daily during the mornings.

The time series of the observations were generally continuous. Single gaps in the data were filled using the data from the neighbouring stations. A problem appeared in the statistical analysis of the data from the three westernmost stations. During some extremely mild winters, no sea ice formed there. For example, four such winters were recorded in Ristna: 1960/1961, 1991/1992, 1992/1993 and 1999/2000. In this case, trends in the first and last date of sea ice could not be analysed correctly.

Air temperature conditions related to sea ice were considered using the following variables: (1) the start of the cold period, i.e. the date of a permanent drop in daily-mean temperature below 0 °C in the beginning of the winter, (2) the end of the cold period, i.e. the date of the permanent rise of the daily-mean temperature above 0 °C in the end of the winter, (3) the duration of the cold period, i.e. the interval between the two dates mentioned above, and (4) the sum of negative degree-days during the whole winter.

The dates of the permanent temperature drop below 0 °C or rise above 0 °C were determined using the following procedure applied by meteorological services. Sometimes, the daily-mean temperature crosses 0 °C several times before the final temperature rise or drop. During this intermediate period, positive and negative temperature deviations from 0 °C are summed up separately. In late winter, the first crossover of the 0 °C is considered as the permanent temperature rise if the sum of positive temperature deviations exceeds that of negative ones. If, however, the sum of negative temperature deviations exceeds that of positive ones, the end of the intermediate period is defined as the permanent temperature rise above 0 °C. In the beginning of winter the permanent drop of daily-mean temperature below 0 °C is calculated in the same way but with opposite signs.

The sum of negative degree-days is probably the most important indicator of the severity of a winter. It is calculated by summing up all negative daily-mean air temperatures during the cold period while positive daily-mean temperatures are omitted. The sum of negative degree-days characterises the total amount of coldness that was observed during the whole winter. This parameter has a very large temporal and spatial variation, differing from < 100 up to 1000 degree-days between the mild and severe winters.

The temperature characteristics were calculated for seven stations. Continuous air temperature measurements were not made in Heltermaa and Narva-Jõesuu.

The homogeneity of initial data is a key problem in a time series analysis. Results are reliable only when homogeneous time series are used. The temperature time series could be considered as homogeneous. The locations of the observation sites did not change substantially during the observation period. The Alexandersson's homogeneity test did not indicate significant breaks in the time series of air temperatures during the study period.

Estimating the homogeneity of a sea ice time series is much more complicated. Ice properties and observations depend very much on the site. For example, sea ice observations in Vilsandi were made at many locations without proper recordings of distinctions between them. Therefore, the results of sea ice variations in Vilsandi were not reliable and they were not analysed in this paper.

In this study, I characterised the atmospheric circulation in northern Europe using a large number of variables. The circulation forms W, E and C, according to the Vangengeim-Girs classification (Vangengeim 1952, Girs 1971), are the most appropriate for this region (Sepp and Jaagus 2002). This classification was developed in the 1930s and has been used since then in the Arctic and Antarctic Research Institute, St. Petersburg, for the description of the large-scale atmospheric circulation over the Atlantic–European sector. It is a so-called manual or subjective classification based on daily synoptic maps. According to the location of lows and highs, up to thirty elementary synoptic types are distinguished, which are grouped into the three main circulation forms. The frequency of these circulation forms has the highest correlation with climate variations in northern and eastern Europe (Kożuchowski and Marciniak 1988). The form W represents the westerly circulation, E represents the southerly and easterly circulation and C represents the northerly airflow. I used the monthly frequencies of the circulation forms and, in addition, calculated the winter-mean values (December–March).

The North Atlantic oscillation (NAO) index is a measure of the intensity of the westerlies in the Atlantic–European sector. It is calculated as the difference between the standardised sea-level pressure anomalies between the Azores maximum and Icelandic minimum. I used three NAO indices in this study. Of these, NAOPD is calculated on the basis of the pressure data in Ponta Delgada (Azores) and Stykkisholmur/Reykjavik

(Iceland) (Hurrell and van Loon 1997). NAOL uses data from Lisbon (Hurrell 1995) and NAOG from Gibraltar (Jones *et al*. 1997) instead of the Azores. The Arctic oscillation index (AO) describes the strength of circumpolar vortex (Thompson and Wallace 1998).

As an additional source of data on the large-scale atmospheric circulation, I applied the teleconnection indices for the northern hemisphere (Barnston and Livezey 1987) using a principal component analysis. The monthly values of these indices are presented and updated by the NOAA Climate Prediction Centre. Seven teleconnection patterns may have a significant influence on climate variability and change in Estonia. Of these, the North Atlantic Oscillation (NAOT), East Atlantic (EA), East Atlantic Jet (EAJ) and Polar/Eurasia (POL) patterns described mainly the zonal circulation, whereas the East Atlantic/West Russia (EAWR) and the Scandinavia (SCA) patterns describe the meridional circulation. Trends in the parameters of the large-scale atmospheric circulation were examined in the previous paper (Jaagus 2006).

Methods

The trend analysis was performed using a linear regression analysis and Mann-Kendall test. The former method requires a normal distribution of data while the latter does not. Due to the fact that sea ice data may not be normally distributed, the use of the Mann-Kendall test is preferred. The main statistic drawn from the regression analysis — the slope — indicates the mean trend as a change per year of the studied variable. The total change based on the mean trend during the observation period is obtained by multiplying the slope with the number of years (55 years in this study). The trends are considered to be statistically significant on the $P < 0.05$ level.

The Mann-Kendall test is a non-parametric tool that enables one to analyse a time series without a normal distribution. The main idea of the Mann-Kendall test for trends is to determine the sign of all pair-wise differences between the consecutive elements of a time series, while each of them is compared with all previous values of the time series (Libiseller and Grimvall 2002, Salmi *et al*. 2002).

An increasing trend exists when the MK (Mann-Kendall) statistic for a monotone trend is positive, i.e. the number of positive differences is significantly higher than the number of negative differences, and vice versa. The statistic is near zero when the number of positive and negative differences is more or less equal.

I estimated the influence of the atmospheric circulation parameters on sea ice by using a correlation analysis and conditional Mann-Kendall test. A correlation coefficient allows one to estimate the strength of relationship. The conditional MK test statistics explains to how large an extent the trends in the circulation parameters determine the trends in sea ice parameters.

The conditional (or partial) Mann-Kendall test is designed for a multivariate trend analysis. It is applied when a trend in one time series (dependent variable) is analysed in relation with trends in one or several covariates (independent variables) (El-Shaarawi 1993, Libiseller and Grimvall 2002). It is assumed that all the trends are statistically significant. The main objective of the conditional MK test is to verify whether a trend in the time series of a dependent variable is statistically determined by the trend in the time series of the covariate.

In this study, the conditional MK test was applied to climatic variables (air temperature and precipitation) in dependence on the large-scale atmospheric circulation parameters that were used as covariates. A trend in the time series of a dependent variable is considered to be determined by the trend in the time series of the covariate when the significance of the conditional MK statistics is higher than 0.05. Consequently, the trend in the time series of the covariate describes the entire significant change in the time series of the studied dependent variable.

Generally, the trends in climatic variables are analysed in relation with the parameters of the atmospheric circulation of the same time interval. In addition to that, circulation data from the previous months and seasons are also used. For example, sea ice in spring months is very much influenced by temperature and atmospheric circulation during the preceding winter.

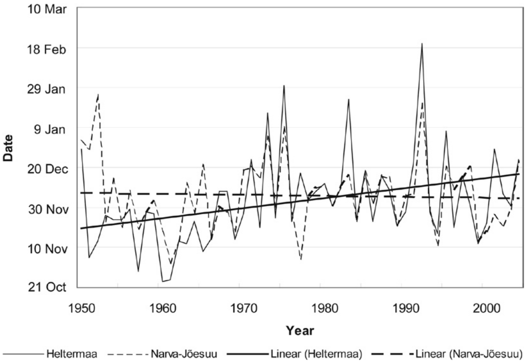

Fig. 2. The dates of the first appearance of sea ice in Heltermaa and Narva-Jõesuu, and their linear trends.

Results

Trends in sea ice parameters

It is well known that the general sea ice extent in the Baltic Sea has decreased during the last two decades as a consequence of climate warming (Omstedt *et al*. 2004). The observation data from the Estonian coast confirm this statement. The mean values and changes as shown by the trends of the studied sea ice parameters in 1949/1950–2003/2004 revealed quite remarkable spatial differences (Table 1). Mostly, the differences were caused by different locations and geographical conditions. At some stations sea ice appeared for the first time at a later date, while at other stations no change took place (Fig. 2). The former group includes stations located on the western coast of the continental part of Estonia and on the islands on the coast of the inland sea (Väinameri, Gulf of Riga). No change was detected on the coast of the Gulf of Finland (Kunda, Narva-Jõesuu). The only exception here is Virtsu, located on the coast of Väinameri, where no statistically significant trend in the date of the first appearance of sea ice was detected.

Generally, inter-annual fluctuations of the date of the first appearance of sea ice are coherent (Fig. 2). In some years, however, substantial spatial differences between the different stations were registered. The date of the first appearance of sea ice was not a good parameter for describing sea ice conditions during the whole winter. Only a weak negative correlation existed between this date and the number of days with sea ice.

At all the stations final disappearence of sea ice was registered at an earlier date. This trend was most significant on the islands where the change was larger than one month. A weaker trend was typical for closed and shallow bays (Pärnu) and for the coast of northern Estonia. The trend was insignificant only in Kunda. The large spatial differences in the disappearance of sea ice have taken place in extremely mild winters (Fig. 3). In three such winters (1989, 1990,

Table 1. Average dates of first appearance of ice, final disappearance of ice and average number of days with ice for the period 1949/1950–2003/2004. Change (number of days) is the difference between the 2004 value and the 1949 value indicated by the trends calculated for each of the above. Significant trends ($P < 0.05$) are set in boldface. The asterisk (*) indicates the stations where ice-free winters were observed.

Station	First appearance of ice[1]		Disappearance of ice[2]		Number of days with ice[3]	
	Average date	Change	Average date	Change	Average value	Change
Heltermaa	3 Dec	**27.6**	11 Apr	**–32.9**	116.2	**–49.7**
Kihnu	1 Dec	**39.5**	15 Apr	**–49.9**	114.3	**–70.1**
Kunda	17 Nov	4.1	17 Apr	–7.5	121.9	–7.4
Narva-Jõesuu	6 Dec	–2.6	17 Apr	**–19.2**	115.3	–12.3
Pärnu	24 Nov	**19.5**	22 Apr	**–22.9**	137.8	**–32.1**
Virtsu	9 Dec	–2.8	18 Apr	**–24.7**	124.7	**–27.9**
Pakri*	–	–	–	–	47.7	**–47.3**
Ristna*	–	–	–	–	67.4	**–56.8**
Sõrve*	–	–	–	–	82.9	**–43.8**

[1] cf. Fig. 2 for Heltermaa and Narva-Jõesuu.

[2] cf. Fig. 3 for Kihnu and Kunda.

[3] cf. Fig. 4 for Ristna and Narva-Jõesuu.

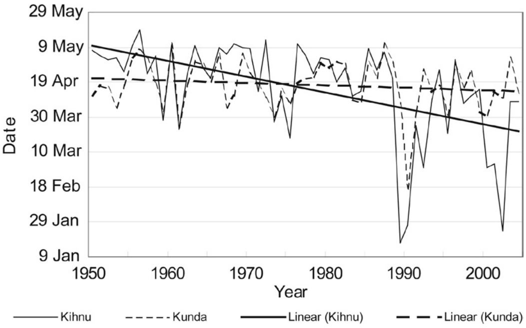

Fig. 3. The dates of the final disappearance of sea ice in Kihnu and Kunda, and their linear trends.

2002), sea ice disappeared in Kihnu already in January. This is the main reason for the steepness of the trend. At the same time, sea ice remained for a much longer time in Kunda.

It is not correct to analyse changes in the dates of the first and last appearance of sea ice on the coast of the Baltic Proper, since a few ice-free winters occurred there. Therefore, no data from that area are presented in Table 1. The existing observation data showed, however, a substantial shift of the final disappearance of sea ice to earlier dates at these stations.

The number of days with sea ice is a parameter that can be used for estimating changes in sea ice conditions during the whole winter. The results of the trend analysis were rather similar to those concerning the dates of the final disappearance of sea ice (Table 1). The most substantial change has occurred at the westernmost stations, whereas only weak and insignificant decreasing trends described the two stations on the coast of the Gulf of Finland (Fig. 4). Consequently, spatial contrasts in the iciness on the Estonian coast have increased with time. Mild winters caused a significant decrease in the number of days with sea ice on the western coast, while at the same time on the northern coast of Estonia the air temperature remained lower and affected less sea ice.

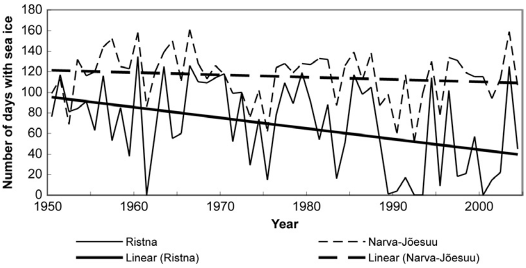

Fig. 4. The numbers of days with sea ice in Ristna and Narva-Jõesuu, and their linear trends.

Trends in winter air temperatures

Low winter temperatures are the main cause of sea ice formation. Therefore, it is important to analyse trends in temperatures (Tables 2 and 3). The remarkable difference, as compared with that

Table 2. Average dates of the start and end of the cold period in 1949/1950–2003/2004. Change (number of days) is the difference between the 2004 value and the 1949 value indicated by the trends calculated for the above. Significant trends on the $P < 0.05$ level are in bold.

Station	Start date of the cold period		End date of the cold period	
	Average date	Change	Average date	Change
Kunda	30 Nov	–5.1	20 Mar	**–18.9**
Pakri	7 Dec	–1.3	17 Mar	**–30.1**
Virtsu	12 Dec	–0.4	20 Mar	**–26.3**
Pärnu	3 Dec	1.9	20 Mar	**–30.8**
Kihnu	17 Dec	6.3	19 Mar	**–23.1**
Ristna	27 Dec	1.9	9 Mar	**–38.3**
Sõrve	24 Dec	1.3	10 Mar	**–38.6**

Table 3. Average duration of the cold period (days) and the sum of negative degree-days in 1949/1950–2003/2004. Change (number of days) is the difference between the 2004 value and the 1949 value indicated by the trends calculated for the above. Significant trends on the $P < 0.05$ level are in bold.

Station	Duration of the cold period		Sum of negative degree-days	
	Average value	Change	Average value	Change
Kunda	109	–13.8	–536	**282**
Pakri	100	–28.8	–401	**244**
Virtsu	98	–25.8	–394	**447**
Pärnu	106	**–32.7**	–486	**322**
Kihnu	92	–29.4	–376	**285**
Ristna	73	**–40.2**	–249	**179**
Sõrve	76	**–39.9**	–258	**209**

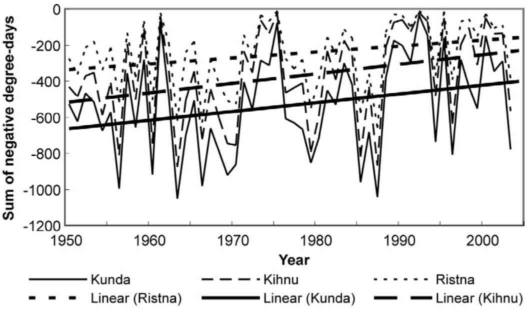

Fig. 5. The sums of negative degree-days in Kunda, Kihnu and Ristna during the winters 1949/1950–2003/2004, and their linear trends.

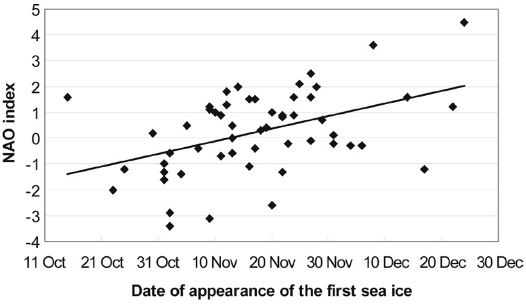

Fig. 6. Relationship between the NAOPD index in October and the date of the appearance of the first sea ice in Kunda (correlation coefficient $R = 0.449$).

shown by the trends presented in Table 1, is that the temperatures were much more similar between the stations, i.e. spatial differences were not very large. The air temperature is under the influence of the large-scale atmospheric circulation, whereas sea ice is very much dependent on local geographical conditions near the observation site. All the trends in the parameters of air temperature can be considered as manifestations of climate warming.

The initial date of the cold period (i.e., the mean date when the daily mean air temperature drops permanently below zero) did not change during the past 55 years. Its change, as shown by the trend, varied around zero (between –5 and +6 days) at the stations (Table 2).

The cold period ended earlier at all the stations. The greatest changes (by more than one month) correspond to the westernmost stations located on the coast of the Baltic Proper, the smallest changes being typical for the coast of the Gulf of Finland (Kunda) (Table 2). The duration of the cold period has decreased by 2–6 weeks. This trend is significant only at some westernmost stations (Table 3).

The sum of negative degree-days was the most important parameter of the winter severity. It was highly correlated with sea ice and its interannual variability was extremely high. In mild winters the sum of negative degree-days could be below 100 while in severe winters it could exceed 1000. The sum of negative degree-days at the Estonian coastal stations has decreased approximately by a factor of two during the study period, being statistically significant at all stations (Table 3, Fig. 5). According to the trend line, the value has decreased from –673 to –408 at Kunda, from –527 to –236 at Kihnu and from –344 to –161 at Ristna. These numbers also demonstrate a more substantial change at the western coast and weaker change at the northern coast.

Correlation between the large-scale atmospheric circulation and sea ice

As a rule, the circulation parameters did not correlate significantly with the date of the first appearance of sea ice at the beginning of winter. The mean correlation coefficients for Estonia were calculated using the data from the nine stations (Table 4). A remarkable positive correlation between the NAO and AO indices in October and the date of the first sea ice could be found at few stations only (Fig. 6), which means that sea ice forms later when the intensity of the westerlies is higher. The same relationship existed also for the frequency of the zonal circulation form W.

The meridional circulation parameters had also some important relationships with the date of the first appearance of sea ice. The frequency of the circulation form E and the SCA teleconnection index in October had a positive correlation, but the frequency of the form C and EAWR teleconnection index had a negative correlation (Fig. 7). This can be explained by the fact that the southerly and south-easterly airflows are related to the later formation of sea ice, whereas the northerly and north-westerly circulations cause an earlier appearance of sea ice.

Due to the fact that all these correlation coefficients were rather low (mostly < 0.4), and that statistically significant correlations were revealed not in all but only some stations, we can conclude that the influence of atmospheric circulation on the formation of sea ice is weak.

A different picture appears when we analyse the relationship between the atmospheric circulation and the date of the final disappearance of sea ice. The melting of ice was related closely to circulation (Table 4). The date of the final disappearance of sea ice had a high negative correlation with the characteristics of the intensity of the zonal circulation. This means that sea ice disappears earlier when the intensity of westerlies is higher. The highest correlation was found for the AO index during total winter period (Decem-

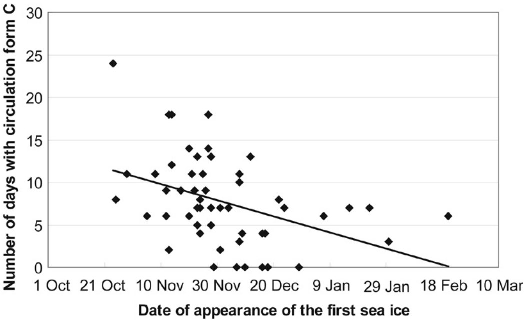

Fig. 7. Relationship between the frequency of the circulation form C in October and the date of the appearance of the first sea ice in Heltermaa ($R = 0.423$).

Table 4. Correlation coefficients between the date of the first appearance of ice, date of disappearance, number of days with ice in Estonia and large-scale atmospheric circulation indices/forms over northern Europe in 1949/1950–2003/2004 averaged over the stations. Statistically significant values ($P < 0.05$) are set in boldface. The Roman numbers indicate month(s) for which the circulation indexes/forms were averaged.

	Date of the first appearance of ice	Date of disappearance of ice	Number of days with ice
NAOL XII–III	0.161	**–0.638**	**–0.572**
NAOPD I	0.062	**–0.423**	**–0.386**
NAOPD II	0.142	**–0.567**	**–0.474**
NAOPD III	0.056	**–0.345**	–0.181
NAOPD XII–III	0.118	**–0.565**	**–0.491**
NAOG I	0.111	**–0.533**	**–0.488**
NAOG II	0.112	**–0.614**	**–0.521**
NAOG III	–0.007	**–0.309**	–0.157
NAOG XII–III	0.129	**–0.649**	**–0.567**
AO XII	0.127	–0.245	**–0.324**
AO I	0.227	**–0.498**	**–0.517**
AO II	0.157	**–0.662**	**–0.534**
AO III	0.063	**–0.427**	–0.253
AO XII–III	0.258	**–0.731**	**–0.658**
NAOT I	0.063	**–0.371**	**–0.321**
NAOT II	0.127	**–0.446**	**–0.407**
NAOT III	0.027	**–0.370**	–0.176
NAOT XII–III	0.098	**–0.558**	**–0.458**
EA I	0.086	**–0.366**	–0.301
EA XII–III	0.051	**–0.330**	–0.246
POL I	0.218	**–0.373**	**–0.437**
POL II	0.082	**–0.394**	–0.272
POL XII–II	0.195	**–0.384**	**–0.393**
EAWR X	–0.240	0.274	**0.342**
W II	0.151	**–0.544**	**–0.457**
W III	0.019	**–0.375**	–0.253
W XII–III	0.146	**–0.594**	**–0.523**
E I	–0.237	0.285	**0.330**
E II	–0.212	**0.477**	**0.460**
E XII–III	–0.245	**0.478**	**0.483**

For abbreviations *see* Material.

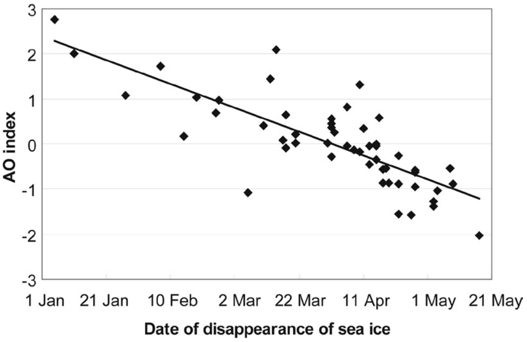

Fig. 8. Relationship between the mean AO in December–March and the date of the final disappearance of sea ice in Sõrve ($R = -0.790$).

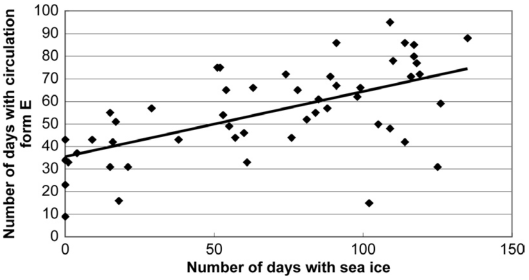

Fig. 9. Relationship between the frequency of the circulation form E in December–March and the number of days with sea ice in Ristna ($R = 0.602$).

ber–March) (Fig. 8). A remarkable correlation could also be found between the end date of sea ice and circulation parameters of single winter months (January, February and March). The key month seems to be February, the coldest month on the Estonian coast. Sea ice characteristics (the date of disappearance of sea ice and number of days with sea ice) had the highest correlation with circulation parameters in February (in comparison with the other months). The frequency of the meridional circulation form E in winter was positively correlated with the date of the disappearance of sea ice (Fig. 9), i.e. airflow from east, southeast and south was related to later melting of sea ice.

The number of days with sea ice was rather similarly correlated with circulation as was the date of the final disappearance of ice, but the correlation coefficients were lower. We can conclude that sea ice conditions in spring are very much determined by the intensity of the zonal circulation in winter. The thermal inertia of sea ice plays a key role here. In cold winters an extended and thick sea ice is formed. The ice persists until the second half of April and even until the beginning of May, having a significant cooling effect throughout the whole spring. In mild winters caused by strong westerlies sea ice is less extended, so that the ice melts fast and its cooling effect is weak.

The analysis of single correlation coefficients at different stations allows one to conclude that high correlations between sea ice and circulation are typical for stations that are exposed to the open sea (Ristna, Sõrve, Pakri, Kihnu). The influence of the other local factors on the formation of sea ice is less remarkable. Lower correlation is obtained for stations on the coast of the inland sea or the Gulf of Finland (Pärnu, Virtsu, Narva-Jõesuu, Kunda), in which the local influence on sea ice formation is much more important.

Influence of the circulation on sea ice changes

Results of the conditional Mann-Kendall test allow us to estimate to how large an extent the trends in the parameters of the atmospheric circulation determine the trends in sea ice. The trends found in the time series of the date of the first appearance of sea ice were not related to circulation changes, e.g., no significant trends could be found in the parameters of atmospheric circulation during the period of sea ice formation (November, December). On the contrary, the trends in the date of the final disappearance of sea ice and in the number of days with sea ice were strongly related to the trends in circulation changes. Based on the conditional Mann-Kendall test, a list of such circulation parameters is presented that had trends related significantly to those in sea ice (Table 5).

A general regularity is evident. If the trend in sea ice parameters is less significant, i.e. the *P* value lies between 0.01 and 0.05, the trends in circulation fully describe the trend in sea ice. This was typically the situation for the trends in the number of days with sea ice (Fig. 10). If the trend in a sea ice parameter has a high significance, such as in the dates of the final disappearance of sea ice, the trends in circulation describe

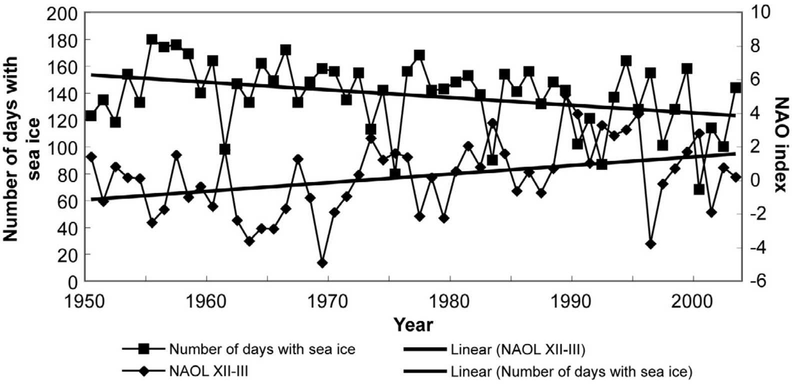

Fig. 10. The numbers of days with sea ice in Pärnu and of the NAOL index in December–March (R = –0.463), and their linear trends.

the trend in sea ice only partly (Fig. 11). This means that if we use the circulation series as a covariate in the conditional Mann-Kendall test, the trend in sea ice remains but is at a lower significance level. There must still be other factors causing the trend in sea ice.

Table 5. A list of atmospheric circulation indexes/forms having trends related significantly to the date of disappearance of sea ice and/or the number of days with sea ice. Negative relationships are in italics. The asterisk (*) indicates the stations where ice-free winters were observed. The Roman numbers indicate month(s) for which the circulation indexes/forms were averaged.

Station	Circulation indexes/forms associated with the date of disappearance of sea ice	Circulation indexes/forms associated with the number of days with sea ice
Heltermaa	*NAOL XII–III, NAOPD II, XII–III, NAOG II, III, XII–III, AO I, II, XII–III, NAOT II, III, XII–III, EA I, II, XII–II, POL I, II, XII–II*, EAWR X, *W I, II, III, XII–III*, E I, II, XII–III	*NAOL XII–III, NAOPD II, XII–III, NAOG II, XII–III, AO I, II, III, XII–III, NAOT II, XII–III, POL I, II, XII–II*, EAWR X, *W II, XII–III*, E I, II, XII–III
Kihnu	*AO XII–III, NAOT XII–III, EA I, XII–III, W II, XII–III*, E II, XII–III	*NAOL XII–III, NAOPD II, XII–III, NAOG II, XII–III, AO I, II, XII–III, NAOT II, XII–III, POL I, XII–II*, EAWR X, *W II, XII–III*, E I, II, XII–III
Narva–Jõesuu	*NAOL XII–III, NAOPD II, XII–III, NAOG II, XII–III, AO II, XII–III, NAOT II, III, XII–III, EA I, W XII–III*, E II	
Pärnu	*NAOL XII–III, NAOPD II, NAOG II, XII–III, AO II, XII–III, NAOT III, XII–III, EA I, W II, XII–III*, E II, XII–III	*NAOL XII–III, NAOPD II, NAOG II, XII–III, AO II, XII–III, NAOT XII–III, W XII–III*, E I, II, XII–III
Pakri*	*NAOL XII–III, NAOPD II, XII–III, NAOG II, XII–III, AO II, XII–III, NAOT II, III, XII–III, EA I, XII–III, W II, XII–III*, E XII–III	*NAOL XII–III, NAOPD II, XII–III, NAOG II, XII–III, AO II, XII–III, NAOT II, XII–III, EA I, XII–III, W II, XII–III*, E II, XII–III
Ristna*	*NAOL XII–III, NAOPD II, XII–III, NAOG II, III, XII–III, AO I, II, XII–III, NAOT II, III, XII–III, EA I, XII–II, POL I, II, XII–II*, EAWR X, *W I, II, III, XII–III*, E I, II, XII–III	*NAOL XII–III, NAOPD* ***II***, *XII–III, NAOG II, XII–III, AO I, II, XII–III, NAOT II, XII–III, EA* ***I***, *XII–III, POL I, II, XII–II*, EAWR X, *W I, II, XII–III*, E I, II, XII–III
Sõrve*	*NAOL XII–III, NAOPD II, III, XII–III, NAOG II, XII–III, AO II, XII–III, NAOT II, III, XII–III, EA I, XII–II, W II, III, XII–III*, E I, II, XII–III	*NAOL XII–III, NAOPD II, XII–III, NAOG II, XII–III, AO I, II, XII–III, NAOT II, XII–III, POL I, XII–II*, EAWR X, *W I, II, XII–III*, E I, II, XII–III
Virtsu	*NAOL XII–III, NAOPD II, III, XII–III, NAOG II, III, XII–III, AO I, II, III, XII–III, NAOT II, III, XII–III, EA I, II, XII–II, POL I, II, XII–II, W II, III, XII–III*, E I, II, XII–III	*NAOL XII–III, NAOPD II, XII–III, NAOG II, XII–III, AO I, II, XII–III, NAOT II, XII–III, POL I, II, XII–II*, EAWR X, *W II, XII–III*, E I, II, XII–III

For abbreviations *see* Material.

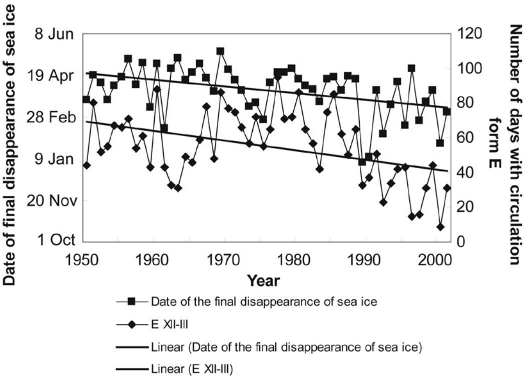

Fig. 11. Time series of the date of the final disappearance of sea ice in Sõrve and of the frequency of the meridional circulation form E in December–March (R = 0.570), and their linear trends.

All the characteristics of zonal circulation — the NAO indices, AO, EA and W — were listed (Table 5). Mostly, trends in their mean winter value (December–March) were the main factors causing a decrease in sea ice in spring. A maximum change in the intensity of westerlies occurred in February. Only some trends in circulation parameters, being significant in January (AO, EA, POL) and in March (NAOG, NAOT, AO), were related to the decreasing trends in sea ice. An increase in the frequency of the zonal circulation form W in March had an influence on the date of the final appearance of sea ice but not on the number of days with sea ice.

While the prevalence of the zonal circulation in winter induces higher temperatures and a lower sea ice extent, the meridional circulation is followed by lower temperatures and higher values of sea ice. The frequency of the meridional circulation form E according to the Vangengeim-Girs classification had a negative trend in winter (Fig. 11), corresponding to the trends in sea ice.

The East Atlantic/West Russia pattern (EAWR) describes the SE–NW circulation in Estonia. It had a significant negative trend in October that was related to the later formation of sea ice and lower number of days with sea ice during winter.

Discussion and conclusions

In general terms, the results of this study are in good concordance with those of the previous studies on the sea ice trends in the Baltic Sea region (Omstedt and Chen 2001, Launiainen *et al*. 2003, Omstedt *et al*. 2004). All the previous studies show warming that has caused a decrease in sea ice during the second half of the 20th century. Similar trends have also been observed on the coast of Estonia. The trends in sea ice during 1949/1950–2003/2004 analysed in this study are much more significant than the trends detected for a longer period (1900–1990) by Jevrejeva (2002a). At the same time, changes in sea ice conditions are not similar. They depend very much on the local geographical conditions.

The beginning of the ice season depends strongly on the heat content of seawater accumulated during the whole previous summer. The end of the sea ice period depends very much on the previous winter. Weather conditions in summer are related weakly to circulation, whereas the winter weather is practically entirely determined by circulation.

It is reasonable to discuss the results of this paper separately for the three variables of sea ice regime.

Date of the first appearance of sea ice

On average, the first sea ice appears near the Estonian coast in November and December. The ice is observed earliest in closed and shallow bays on the coast of the inland sea and latest at the open coast of the Baltic Proper. During the second half of the 20th century, the sea ice appeared at a later date at three stations (Kihnu, Heltermaa, Pärnu) located on the western coast of the continental part of Estonia and on the islands of the inland sea (Gulf of Riga, Väinameri). This date has not changed on the coast of the Gulf of Finland.

It is difficult to explain the observed spatial differences. No significant change in the air temperature regime has been observed in Estonia during the second half of a year, including the summer, autumn and the beginning of winter (Jaagus 2006). The start of the cold period has not changed during the study period. The influence of the large-scale atmospheric circulation on the date of the first appearance of sea ice is weak.

The formation of sea ice is a very complex process influenced not only by the air temperature in the beginning of winter. The temperatures of the preceding summer and autumn determine the heat content of the seawater. The prevalence of cyclones or anticyclones in autumn influences the wind regime. A high frequency of storms is related to an intense water exchange in the sea, which prevents the formation of sea ice. An increase in storminess near the Estonian coast has been documented for the same time interval that is used in this study (Orviku *et al*. 2003).

In conclusion, I cannot point out any substantial change in the date of the first formation of sea ice.

Date of the final appearance of sea ice

The most important changes in the sea ice regime near the Estonian coast during the second half of the 20th century took place at the end of winter and in spring. The final disappearance of sea ice — which was observed from the end of March (on the coast of the Baltic Proper) to the middle of April — happened at an earlier date at all stations except Kunda. The most remarkable change, more than one month during the study period, has occurred at the westernmost stations. On the coast of the inland seas, this change is slightly smaller and on the coast of the Gulf of Finland it has been the smallest. During mild winters, the Baltic Proper is not covered by ice at all. On the coast of the Baltic Proper, sea ice disappears quickly or does not form at all.

The trend in the date of the final disappearance of sea ice is related directly to the statistically significant changes in the large-scale atmospheric circulation over northern Europe and to the increase in air temperature in winter and spring. During the second half of the 20th century, the monthly mean air temperature in Estonia increased significantly in January (by 2.2–3.7 °C), February (by 3.2–3.9 °C), March (by 3–5 °C) and April (by 1.7–3.0 °C) (Jaagus 2006).

This study revealed a significant shift to earlier end dates of the cold period at all the stations. The mean dates at which the daily-mean air temperature permanently rises above 0 °C are between 9 and 20 March, i.e. nearly one month earlier than the dates of the final disappearance of sea ice. At present, the daily-mean air temperature rises above 0 °C approximately one month earlier than a half century ago. This is one of the main reasons causing the earlier disappearance of sea ice. The change as revealed by the trend was 19–38 days, with smaller values being typical for the coast of the Gulf of Finland and the largest values corresponding to the coast of the Baltic Proper. These spatial differences are similar to those for sea ice trends.

The earlier date of the final disappearance of sea ice near the Estonian coast is related closely to changes in the circulation. The intensity of the westerlies in the Atlantic/European sector has increased significantly during the cold half of the year, particularly in February and March. This is reflected in the trends of the NAO and AO indices as well as the East Atlantic (EA) and Polar/Eurasia (POL) teleconnection indices, in the frequency of the zonal circulation form W, and in the decrease of the meridional circulation form E according to the circulation classification elaborated by Vangengeim and Girs (Jaagus 2006).

February seems to be a key month for sea ice conditions in the end of the cold season. The atmospheric circulation during February determines the date of the final disappearance of sea ice. In case of a weak zonal circulation, prevalence of anticyclones and meridional airflow, the resulting cold weather conditions cause a thick and long-lasting ice cover on the sea. In the opposite case when the intense westerlies in February bring mild Atlantic air to northern Europe, sea ice breaks up early.

Number of days with sea ice

The total number of days with sea ice has decreased remarkably during the study period. The highest decrease is evident on the coast of the Western Estonian Archipelago, being most substantial (70 days) in Kihnu. The decrease is not statistically significant at the coast of the Gulf of Finland. The total number of days with sea ice describes best the general sea ice regime and the influence of climate change on sea ice.

To date, climate warming has influenced sea ice most in the westernmost part of the Estonian coast. The eastern part of the Estonian coast in the Gulf of Finland remains outside the zone where the warming has substantially shortened the duration of sea ice. In this area, winter temperatures are lower than in western Estonia.

The decrease in the number of days with sea ice is coherent with trends in the winter air temperature. The cold period has shortened significantly only at the westernmost stations located on the coast of the Baltic Proper. This peculiarity is reflected in an earlier disappearance of sea ice at those stations. The sum of negative degree-days has decreased dramatically at all the stations. According to the linear trend, this sum has decreased nearly by a factor of two during 1949/1950–2003/2004. Thereby, the change is stronger on the westernmost coast than on the coast of the Gulf of Finland.

The observed spatial differences in the sea ice trends near the Estonian coast can be explained as follows. The relation between the winter air temperature and sea ice is not linear but exists only in a certain temperature interval. At lower temperatures, sea ice forms and persists anyway, whereas at higher temperatures it does not form at all. The winter mean air temperature in western Estonia is remarkably higher than in eastern Estonia. The warming trend has caused a significant decrease in sea ice in the western part while only a slight decrease in the eastern part, on the southern coast of the Gulf of Finland.

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