Vol. 36: 29–40, 2008
doi: 10.3354/cr00725

CLIMATE RESEARCH
Clim Res

Published March 13

Changes in storminess on the western coast of Estonia in relation to large-scale atmospheric circulation

Jaak Jaagus[1,*], Piia Post[2], Oliver Tomingas[1]

[1]Department of Geography, University of Tartu, Vanemuise 46, 51014 Tartu, Estonia
[2]Department of Environmental Physics, University of Tartu, Tähe 4, 51014 Tartu, Estonia

ABSTRACT: Intensification of coastal erosion caused by windstorms is an important problem in the coastal regions of Estonia. The objective of this study was to analyse relationships between storms observed at Vilsandi, the westernmost station in Estonia, and large-scale atmospheric circulation. Statistical analyses reveal close correlation between parameters of atmospheric circulation and the number of storms. Windstorms are related to intense zonal circulation, i.e. westerlies, while reduced storminess is associated with meridional circulation. The Arctic Oscillation (AO) index has the highest correlation (0.68) with the frequency of storms during the winter season (December to February). Even the correlation coefficients for the local zonal circulation index for Estonia do not exceed this value. These results show that large-scale circulation patterns determine circulation on the local scale. Results of the conditional Mann-Kendall test confirm that the increasing trend in winter storminess is induced by a positive trend in the intensity of westerlies, as seen in time series of the AO index and in the frequency of the circulation form W of Vangengeim and Girs. These changes were most substantial in February.

KEY WORDS: Windstorm · Atmospheric circulation · Baltic Sea · Mann-Kendall test

1. INTRODUCTION

Windstorms are important atmospheric phenomena that significantly influence human activity in the Baltic Sea area. They affect sea transport as well as coastal management. Coastal erosion caused by severe storms leads to destruction of harbours and sandy beaches.

The relationship between climate change and changes in storm activity is the subject of much debate. Some studies indicate no significant trends in cyclone activity and storminess over the Atlantic/European sector (WASA Group 1998, Bijl et al. 1999, Gulev et al. 2001, Houghton et al. 2001). Other studies demonstrate increasing winter storminess in northern Europe since the 1960s (Alexandersson et al. 1998, Ulbrich & Christoph 1999, Gulev et al. 2002, Paciorek et al. 2002, Pryor & Barthelmie 2003, Zhang et al. 2004). A northward shift of the winter storm track has been observed during recent decades (Orlanski 1998, Sickmöller et al. 2000, McCabe et al. 2001). Consistent with these studies, the number of cyclones passing the Baltic Sea region in winter has increased during the second half of the 20th century (Sepp et al. 2005).

Changes in other atmospheric parameters have been detected in Estonia during the same period (Jaagus 2006a). Air temperature has increased for January through May. Increasing precipitation has been observed during the cold half of the year, from October until March, and also in June. Snow cover duration has decreased in Estonia by 17 to 20 d for inland regions and by 21 to 36 d on the coast between 1951 and 2000. These changes are significantly related to changes in large-scale atmospheric circulation, first of all, to an increase in the intensity of zonal circulation (westerlies) in winter (Jaagus 2006a). Winter warming is manifested in a significant decrease in the number of days

*Email: jaak.jaagus@ut.ee

with sea ice and an earlier ice break-up along the Estonian coast (Jaagus 2006b).

As a result of these changes, coastal erosion has become much more intense (Orviku et al. 2003). The number of storm days has significantly increased (>50%) at all 3 coastal stations under investigation (Vilsandi, Kihnu, Sõrve) during the second half of the 20th century.

The most severe events of coastal erosion occur from a combination of high wind speed, high sea level, and the lack of sea ice. Climate warming in the Baltic Sea region in winter is directly related to a greater influence of warm air from the North Atlantic, lower pressure, and greater cyclonic activity, less snow cover and sea ice (Omstedt et al. 2003, Jaagus 2006a). It leads to increased storminess and coastal damages.

The latest extreme storm seriously affected the Estonian coast on 9 January 2005 (Suursaar et al. 2006). The cyclone was known as Gudrun in the Nordic countries and Erwin on the British Isles and in Central Europe. In Denmark, Scandinavia, Latvia and Estonia, the storm was one of the strongest in the last 40 yr, causing massive forest damage, and disruption of power and phone service. The storm killed at least 17 people, including 1 in Estonia. The main property damage was a result of strong winds and flooding of the coastal areas. The highest storm surge in known history occurred in Pärnu (275 cm above mean sea level), and probably in most locations along the West Estonian coast as well. Substantial parts of the coastal towns Pärnu and Haapsalu were flooded.

Windstorms are closely related to cyclones and to atmospheric circulation in general. Strong pressure gradients and storm winds are usually observed in association with deep lows, which are most frequent in northern Europe during the period of maximum cyclonic activity in late autumn and early winter. When anticyclonic conditions prevail, storms are rare.

The objective of the present study was to analyse relationships between windstorms, observed at the Vilsandi Station, and the large-scale atmospheric circulation. The most important characteristics influencing storminess in Estonia were selected. To give a better understanding of the variables of atmospheric circulation, their correlation maps with sea-level pressure were presented. Changes in storminess were estimated in relation to changes in atmospheric circulation.

2. WINDSTORM DATA

Windstorm data were obtained from a catalogue of storms over the Island of Vilsandi (Orviku et al. 2003). A storm is defined as an event when a 10 min mean wind speed ≥15 m s^{-1} is measured during at least 1 observation time a day. The windstorm catalogue contains maximum mean wind speed, wind direction and the duration of storms during the period from 1948 to 2004.

Vilsandi is a small island located close to the central part of the Baltic Sea (Fig. 1), near the western coast of the island of Saaremaa. It is the westernmost inhabited place in Estonia. The highest mean wind speed and the maximum frequency of windstorm days for Estonia are recorded at this meteorological station (58° 23′ N, 21° 49′ E). The site is partly protected by a low forest on the eastern side and by a lighthouse on the western side. The windrose compiled using storm events on Vilsandi (Fig. 2) demonstrates 2 main directions of storm winds: the southwest and northwest, in line with the results of other studies on wind climate (Soomere 2001, Soomere & Keevallik 2001).

A total of 1133 storm days was recorded during 57 yr, giving 19.9 storm days per year on average. The maximum number of storm days at Vilsandi (36) was observed in 1992, while the minimum (2 storm days)

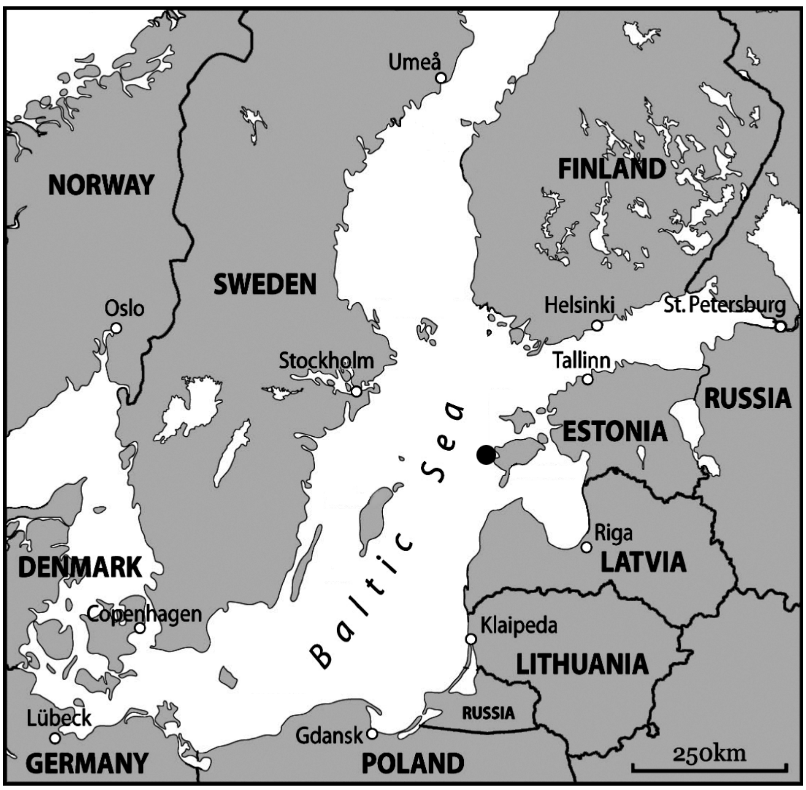

Fig. 1. Location map of the Vilsandi station (●)

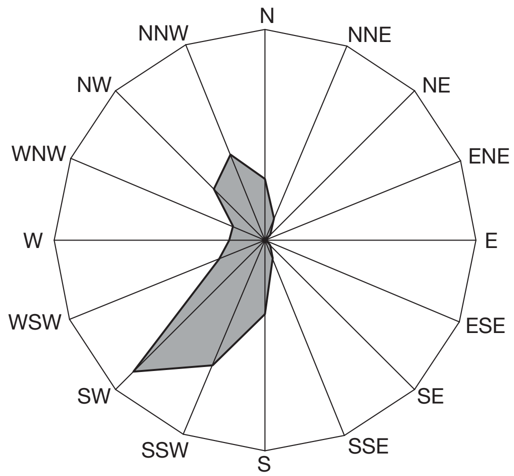

Fig. 2. Windrose of storms at Vilsandi station

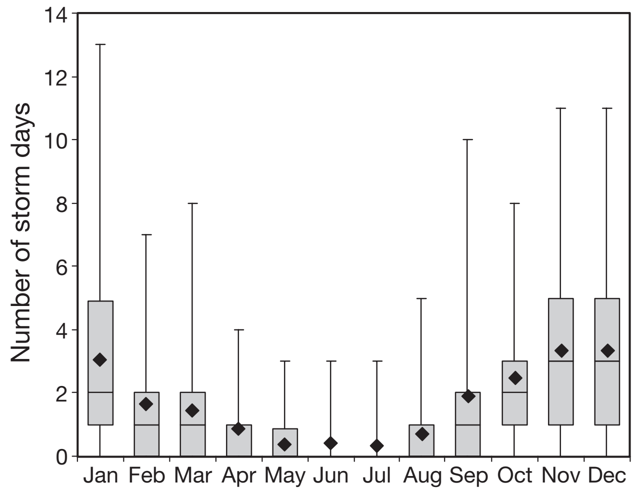

Fig. 3. Seasonal cycle of storm days on Vilsandi from 1948 to 2004. Boxes show medians, upper and lower quartiles of the data; whiskers indicate maximum values, black squares show mean values of storm days during the month

occurred in 1972. Temporal variability of the number of storm days is very high—the standard deviation is 7.9 d. The majority of storms are in autumn and winter (Fig. 3). Therefore, we define the storm season in Estonia to last from September until March, which includes 86% of all storm days. The highest frequency of windstorms is observed in November, December and January.

A higher threshold maximum wind speed of 18 m s^{-1} was used in part of this study to distinguish heavy storms. A total of 289 d with such heavy storms was recorded. Special attention was paid to extremely stormy periods of long duration, some of which lasted for several months. The most severe coastal damages occur during these periods. They were defined as those with a duration of at least 15 d (with windstorm days constituting at least 20% of all days during the period), and a maximum wind velocity ≥20 m s^{-1} during at least 3 d (Orviku et al. 2003); 18 extremely stormy periods were determined in Estonia, containing a total of 409 storm days.

The number of storm days in Estonia has significantly increased during the second half of the 20th century (Orviku et al. 2003). On Vilsandi, the annual number of storm days has grown by 8.6 d (44%) during the 57 yr period under study (Fig. 4). The strongest positive trend is found in winter, especially in February (Table 1). August has a significant decrease in storminess. The last August storm on Vilsandi occurred in 1995. A weak negative trend appears for September, October and for autumn as a whole (SON).

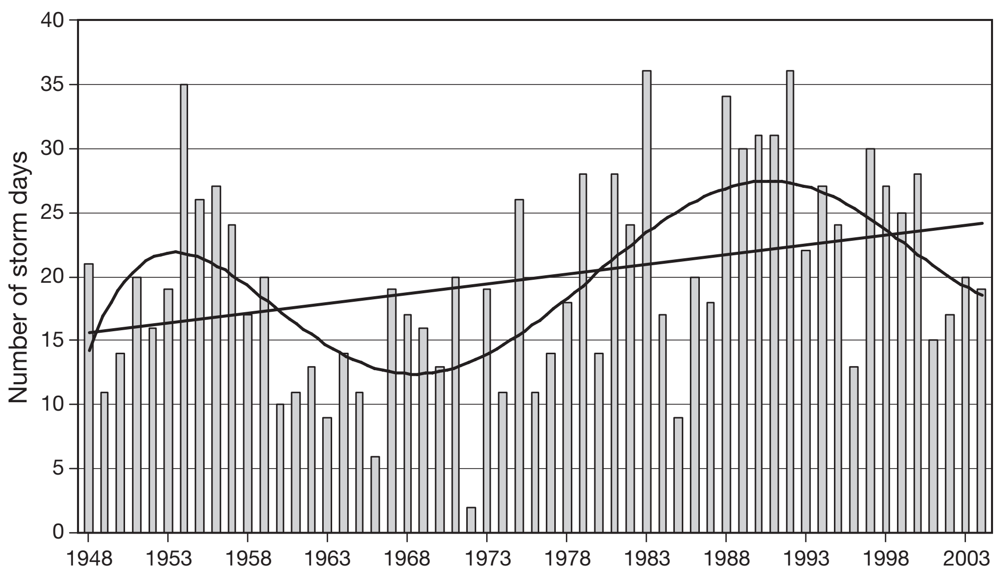

Fig. 4. Annual number of storm days on Vilsandi (1948 to 2004), its linear trend and the fifth-order polynomial line

Table 1. Changes in the number of storm days from 1948 to 2004 on Vilsandi. Percent change is calculated by dividing change by trend in days with the mean number of storms. Statistically significant trends on the $p < 0.05$ level are marked in bold. SON: overal autumn values; DJF: overall winter values

Period	Change by trend (no. of days)	Change by trend (%)
Aug	**−1.2**	**−170**
Sep	−1.0	−53
Oct	−0.4	−17
Nov	+0.8	+25
Dec	+2.1	+73
Jan	+2.6	+84
Feb	**+2.3**	**+140**
Mar	**+1.8**	**+102**
SON	−0.6	−8
DJF	**+6.4**	**+78**
Year	**+8.6**	**+44**

3. ATMOSPHERIC CIRCULATION DATA

A number of circulation classifications and indices representing atmospheric flow over northern Europe at a monthly time resolution are used in this study. The physical essence of these variables will be discussed in Section 5. Monthly frequencies of circulation forms from 2 manual classifications were used.

(1) Vangengeim-Girs classification (Vangengeim 1952, Girs 1971), considered to be the most appropriate for this region (Sepp & Jaagus 2002). There are 3 circulation forms (W, E and C) (see Table 2). W represents northerly, E southerly and easterly, and C northerly airflow.

(2) 'Grosswetterlagen' by Hess and Brezowsky (Gerstengarbe et al. 1999). The classification consists of 29 weather types, subjectively determined using daily synoptic maps. The prevailing airflow is analysed with respect to Central Europe. The weather types are drawn together into 3 groups. The zonal circulation group Z expresses only westerly patterns, the half-meridional group ZM represents the south-westerly and north-westerly flow, and the meridional group M includes all other directions, i.e. between the north, east and south.

Several circulation indices were used in this study, the best known of which is the North Atlantic Oscillation (NAO) index that measures the intensity and location of westerlies in the Atlantic-European sector. The NAO index is calculated as a difference between the standardised sea-level pressure anomalies at the Azores high and Icelandic low. Two NAO indices were used: (1) NAOPD, obtained from pressure data in Ponta Delgada (Azores) and Stykkisholmur/Reykjavik (Iceland) (Hurrell & van Loon 1997); (2) NAOG, which uses data from Gibraltar and Stykkisholmur/Reykjavik (Jones et al. 1997). The Arctic Oscillation (AO) index was obtained through the principal components analysis (PCA) of the Northern Hemisphere sea-level pressure fields and describes the strength of the circumpolar vortex (Thompson & Wallace 1998).

Use was also made of large-scale teleconnection indices for the Northern Hemisphere, defined by Barnston & Livezey (1987) and based on PCA. Monthly indices were obtained from the NOAA Climate Prediction Centre (CPC; www.cpc.noaa.gov/data/teledoc/telecontents.shtml); 5 teleconnection patterns that may have a significant influence on climate variability and change in Estonia were used: the North Atlantic Oscillation (NAOT), East Atlantic (EA) and Polar/Eurasia (POL) patterns mostly describe the zonal circulation, while the East Atlantic/West Russia (EAWR) and Scandinavia (SCA) patterns describe the meridional circulation.

Monthly values for all above-mentioned variables were used. They represent the large-scale circulation conditions in northern Europe, especially in the Baltic region. The following 2 datasets characterise regional and local circulation conditions over Estonia at daily resolution; circulation indices by Tomingas (2002) were calculated using the daily $5 \times 5°$ gridded sea-level pressure data for the years 1881 to 1997. (1) Zonal circulation index (ZonEst), a difference between the standardised pressure anomalies at 3 grid cells south (52.5° N) and north (62.5° N) of Estonia (Fig. 5). Positive values of ZonEst represent a stronger than normal westerly circulation, and negative values indicate weaker than normal westerlies or an easterly airflow. (2) Meridional circulation index (MerEst), a difference between the standardised average pressure anomalies

Table 2. List of abbreviations

Acronym	Definition
AO	Arctic Oscillation
NAO	North Atlantic Oscillation
NAOPD	NAO (Azores–Iceland)
NAOG	NAO (Gibraltar–Iceland)
NAOT	NAO teleconnection
POL	Polar/Eurasia teleconnection
EAWR	East Atlantic/West Russia teleconnection
SCA	Scandinavia teleconnection
ZonEst	Zonal circulation index for Estonia
MerEst	Meridional circulation index for Estonia
SE–NW	SW–NW circulation index for Estonia
SW–NE	SW–NE circulation index for Estonia
Z	Zonal circulation group
ZM	Half-meridional circulation group
M	Meridional circulation group
C, E, W	Circulation forms according to Vangeheim-Girs

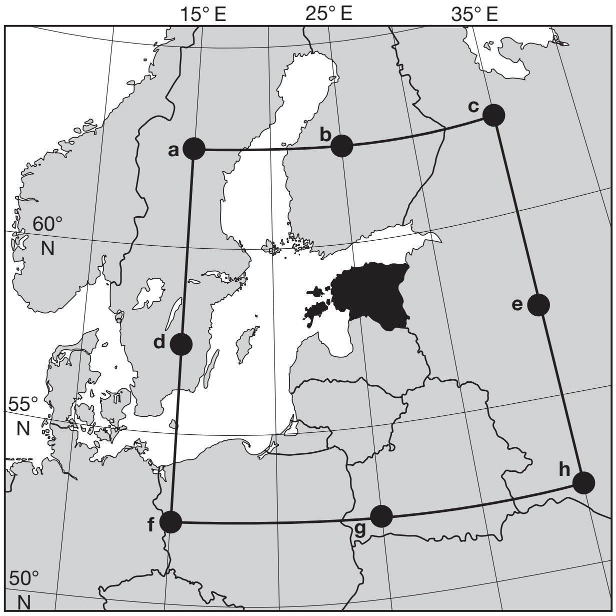

Fig. 5. Location of grid points used for determining circulation indices for Estonia (Tomingas 2002)

at 3 grid cells east (35° E) and west (15° E) of Estonia. The positive values of MerEst correspond to the southerly circulation and the negative values to northerlies. Additional circulation indices for intermediate directions are used. The SW–NE and SE–NW circulation indices express the intensity of airflow from the southwest and southeast (positive values), and from the northeast and northwest (negative values), respectively (Tomingas 2002). Monthly values of the circulation indices for Estonia were also analysed.

In addition, we used the circulation weather types for Estonia, elaborated using the methodology by Jenkinson & Collison (1977). This is an automated version of the Lamb classification initially used for the description of atmospheric circulation over the British Isles. The daily circulation pattern is described using the location of the centres of high and low pressure and determined from geostrophic flow. Daily gridded sea-level pressure in the surroundings of Estonia (with the centre at 60° N, 22.5° E) was used as the initial dataset (Post et al. 2002).

Comparing the magnitudes of the geostrophic resultant flow F and vorticity Z, 27 weather types were distinguished: cyclonic (C), anticyclonic (A), types according to the direction of the airflow (N, NE, E, SE, S, SW, W, NW), and hybrid types according to the vorticity and the direction of the airflow, i.e. types of cyclonic (CN, CNE, CE, CSE, CS, CSW, CW, CNW) and anticyclonic relative vorticity (AN, ANE, AE, ASE, AS, ASW, AW, ANW). An unclassified type was also used (Post et al. 2002).

4. METHODS

Correlation analysis was used for examining relationships between monthly circulation variables and storminess (e.g. number of windstorm days). The significance level $p < 0.05$ was used. Only the months of the storm season (September to March) were used. Mean values for winter (December to February) and for the whole storm season (September to March) were also correlated.

Mutual correlation between some characteristics of atmospheric circulation allowed us to reduce their number and to concentrate on the analysis of the closest relationships. In cases when the correlation coefficient exceeded 0.7, the circulation variable was omitted. Correlation maps between selected circulation variables and sea-level pressure were drawn to better explain circulation conditions described by the corresponding circulation characteristic.

The circulation indices and circulation weather types for Estonia were determined for every storm day in the catalogue of storms over Vilsandi. Weather types corresponding to windstorm days were summed up by months, and the stormiest types were determined. Mean circulation indices for Estonia (Tomingas 2002) for the storm days were calculated.

The Mann-Kendall (MK) test was applied for trend analysis. This is a non-parametric test that enables analysis of time series without a normal distribution. The main idea of the MK test for the trends is to determine the signs 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 & Grimvall 2002, Salmi et al. 2002).

The conditional (or partial) MK test was applied when a trend in 1 time series (dependent variable) was analysed in relation with trends in 1 or several covariates (independent variables) (El-Shaarawi 1993, Libiseller & Grimvall 2002). It is assumed that the trends in all these variables are statistically significant. The main objective of the conditional MK test was to verify whether the trend in the time series of a dependent variable is statistically determined by the trend in the time series of the covariate.

In the present study, the conditional MK test was applied to explore relationships between the number of storm days (the dependent variable) and the parameters of large-scale atmospheric circulation, which were used as covariates. A trend in the time series of the dependent variable was considered to be determined by the trend in the time series of a covariate in the case when the significance of the conditional MK statistic was $p > 0.05$. Consequently, a trend in the time series of the covariate describes the entire significant change in the time series of the dependent variable studied.

The conditional MK test was applied in the cases where there were statistically significant trends in both the time series of circulation and storminess, and there was a significant correlation between them.

5. CORRELATION BETWEEN THE CIRCULATION VARIABLES AND SEA LEVEL PRESSURE

Many circulation variables are correlated, especially in the case of characteristics of zonal circulation. The AO index is the most general indicator of the intensity of westerlies in the Northern Hemisphere. The monthly and seasonal AO indices have the highest correlation also with the number of stormy days on Vilsandi (Section 6).

Regional circulation indices (NAOs, POL) and local indices (ZonEst) could be observed as subsets of the AO. They were highly correlated among themselves (Table 3). The highest correlation was for winter months and for the whole storm season. The relationships between the AO index and the other indices were lower in autumn. Nevertheless, the AO index describes more than half of the variance of the NAO indices and ZonEst. The NAO indices and POL were excluded from the analysis of relationships between circulation and storminess. Only ZonEst was analysed together with the AO index to compare how the global and local indices are related to local storms.

Correlation between the AO index and frequency of W and Z was much lower (Table 3). EA seems to be orthogonal to AO.

The 5 × 5 degree gridded sea level pressure values from the Global Climatological Dataset (Climate Research Unit, University of East Anglia, UK, available at www.cru.uea.ac.uk/cru/data) were compiled for a sector between 35 and 75° N, and 30° W and 60° E.

The maps show the linear correlation coefficients between the characteristics of atmospheric circulation and sea level pressure. The analysis was carried out only for 2 seasons—autumn and winter—that belong to the storm season. Areas of high positive correlation correspond to the location of high pressure regions in case of a high positive value of a circulation variable. Areas of high negative correlation indicate the location of low pressure.

A number of circulation indices express the intensity of zonal circulation, i.e. westerlies. The AO index as well as different NAO indices have a high positive correlation in southern Europe and a negative correlation in northern Europe. Westerlies prevail between these pressure centres. In the case of high positive values of the AO and NAO indices, the meridional pressure gradient over Europe is strong and westerly airflow is intense. When the indices are negative, the pressure gradient is small and zonal circulation weakens or even stops.

Correlation maps for the AO and NAO indices in winter are very similar (Fig. 6a,b). More or less the same pattern is presented also on the correlation map for POL (Fig. 6c). Similarity of the correlation maps justifies the use of only 1 index (AO) instead of a larger number of indices for the analysis of the relationships with storminess. Correlation maps for autumn have more or less similar patterns to those for winter. Isolines in the Baltic Sea region are orientated in a west–east direction.

The correlation (i.e. pressure) centres for EA are shifted to the south. They reflect the intensity of westerly circulation only in western Europe at southern latitudes. There is no correlation in the Baltic Sea region (Fig. 6d).

SCA and EAWR patterns describe meridional circulation: the first one in the North Sea and the South Baltic region and the second one in the Central and North Baltic and the East European Plain (Fig. 6e,f). Positive values of the SCA index correspond to the NW airflow and negative values to the SE one. For the EAWR index, the correlation centres and main directions of airflow are of the opposite sign.

Circulation forms according to the classifications by Vangengeim-Girs and Hess-Brezowsky represent conditions over Europe quite well. W and Z express westerlies (Fig. 7a,b). E corresponds to a high over northern Russia and a low over France and Italy (Fig. 7c), associated with easterly, southeasterly and southerly winds in Estonia. C defined by Vangengeim and Girs is characterized by airflow from northern directions (Fig. 7d). The mean correlation map for the frequency of M,

Table 3. Correlation coefficients between the AO indices and other variables describing the intensity of westerlies. See Section 3 for explanation of circulation abbreviations. Bold: significant; SON: overall autumn values; DJF: overall winter values

	NAOPD	NAOG	W	Z	NAOT	EA	POL	ZonEst
Sep	**0.46**	**0.59**	0.28	0.20	**0.51**	**0.38**		**0.58**
Oct	**0.52**	**0.64**	**0.35**	0.29	**0.59**	−0.13		**0.67**
Nov	**0.55**	**0.56**	**0.34**	**0.31**	**0.65**	−0.10		**0.53**
Dec	**0.67**	**0.68**	**0.42**	0.27	**0.65**	−0.05	**0.49**	**0.63**
Jan	**0.76**	**0.81**	**0.54**	**0.48**	**0.74**	0.24	**0.59**	**0.71**
Feb	**0.87**	**0.85**	**0.59**	**0.45**	**0.80**	0.17	**0.58**	**0.79**
Mar	**0.84**	**0.81**	**0.42**	**0.49**	**0.74**	0.24		**0.76**
SON	**0.43**	**0.45**	**0.34**	0.12	**0.64**	−0.19		**0.61**
DJF	**0.78**	**0.82**	**0.62**	**0.42**	**0.76**	0.08	**0.61**	**0.86**
Sep–Mar	**0.73**	**0.74**	**0.45**	**0.45**	**0.77**	0.05		**0.75**

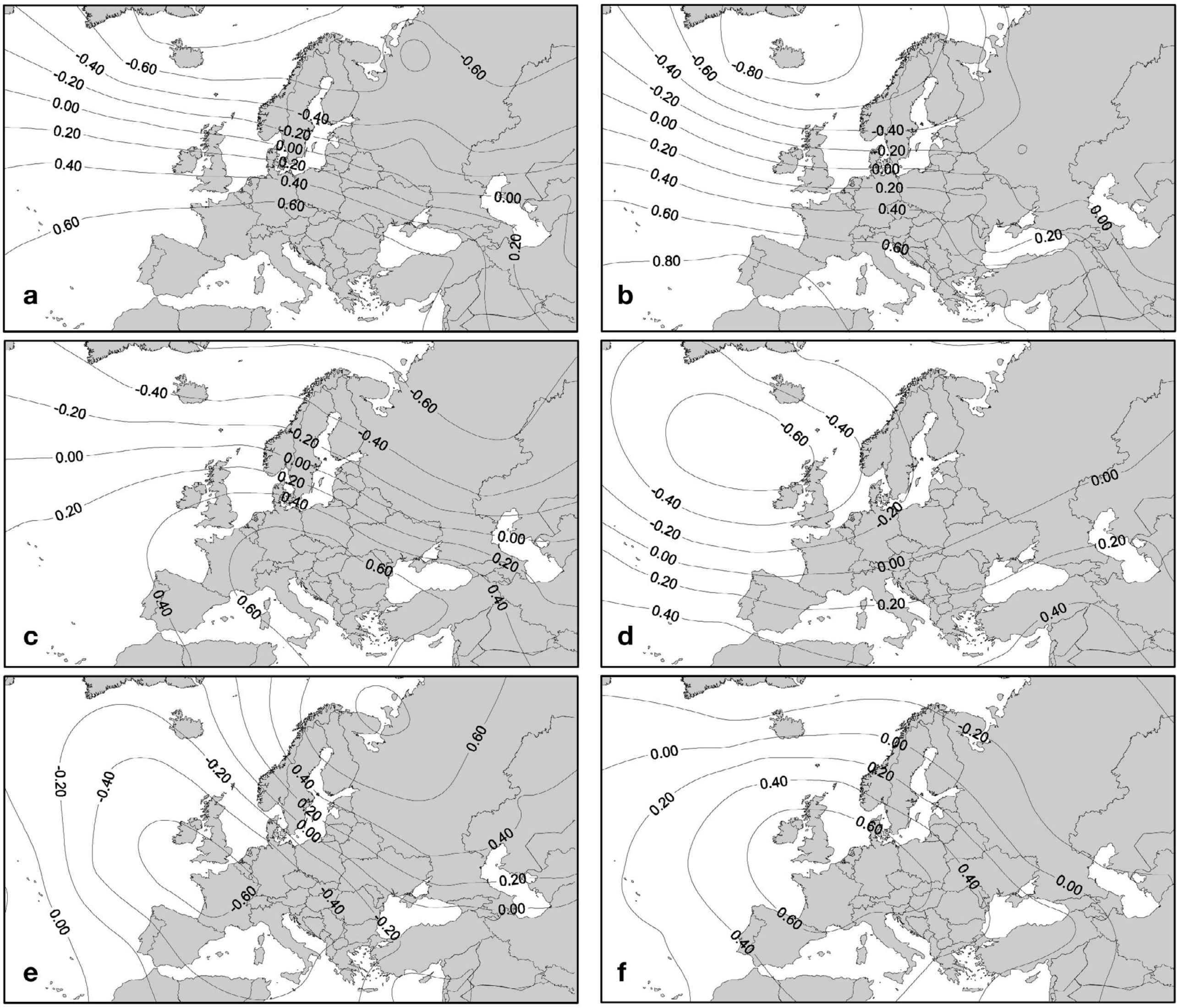

Fig. 6. Isolines of correlation coefficients between the monthly circulation indices and sea level pressure in Europe: (a) AO in winter, (b) NAOG in winter, (c) POL in winter, (d) EA in winter, (e) SCA in autumn and (f) EAWR in winter. See Table 2 for abbreviations

according to the Hess-Brezowsky classification, shows an anticyclone located centred over northern Scandinavia and low pressure in the Mediterranean region (Fig. 7e). In the case of ZM, the correlation is lower and northwesterly airflow is indicated (Fig. 7f).

6. RELATIONSHIPS BETWEEN WINDSTORMS AND ATMOSPHERIC CIRCULATION

Results from correlation analysis between the number of storm days and the parameters of large-scale atmospheric circulation are presented in Table 4. Zonal circulation corresponds to greater storminess. Four variables characterising the intensity of westerlies—AO, ZonEst, W and Z—have a significant positive correlation with the number of storm days.

The highest correlations are with AO and W. These are significant in all months during the storm season. The relationship is strongest for winter and for the storm season (September to March) as a whole (Fig. 8). Correlation coefficients in the case of single months are lower. Z is not a good characteristic of westerlies for Estonia, having lower correlations in winter. It describes the intensity of westerlies directed to Central Europe.

ZonEst does not have higher correlation with local storminess than AO. The large-scale atmospheric circulation determines the intensity of westerlies in the Baltic Sea region.

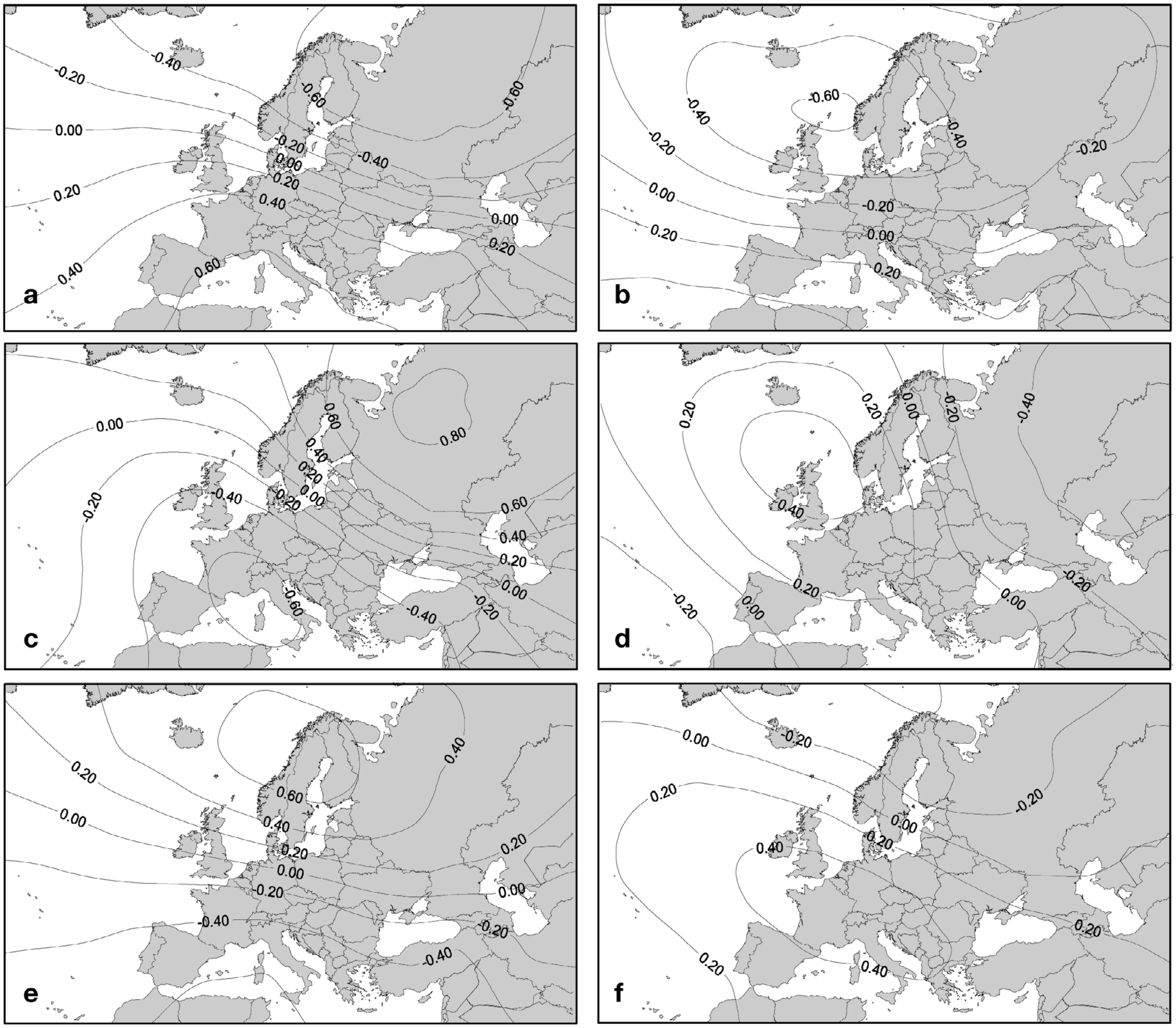

Fig. 7. Isolines of correlation coefficients between the monthly frequencies of the main circulation forms (according to the Vangengeim-Girs and Hess-Brezowsky classifications) and sea level pressure in winter: (a) W, (b) Z, (c) E, (d) C, (e) M and (f) ZM. See Table 2 for abbreviations

Table 4. Correlation coefficients between the number of storm days and monthly and seasonal circulation variables. Statistically significant values are shown in bold. See Table 2 for explanation of circulation abbreviations

	AO	ZonEst	W	Z	E	M	SCA	SE–NW
Sep	**0.30**	0.27	**0.53**	**0.41**	–0.29	**–0.33**	**–0.45**	–0.21
Oct	**0.38**	**0.47**	**0.55**	**0.53**	**–0.54**	**–0.48**	**–0.62**	**–0.46**
Nov	**0.45**	**0.60**	**0.52**	0.15	**–0.52**	**–0.42**	**–0.66**	**–0.54**
Dec	**0.53**	**0.41**	**0.44**	0.18	**–0.30**	**–0.49**	**–0.32**	**–0.37**
Jan	**0.53**	**0.55**	**0.43**	0.28	–0.29	**–0.40**	**–0.50**	**–0.49**
Feb	**0.59**	**0.51**	**0.59**	**0.31**	**–0.57**	**–0.41**	**–0.51**	**–0.43**
Mar	**0.51**	**0.57**	**0.45**	**0.44**	**–0.42**	**–0.50**	**–0.55**	**–0.53**
Sep–Mar	**0.60**	**0.59**	**0.57**	**0.46**	**–0.49**	**–0.53**	**–0.74**	**–0.58**
Dec–Feb	**0.68**	**0.60**	**0.59**	**0.37**	**–0.48**	**–0.52**	**–0.57**	**–0.56**

Meridional circulation is usually associated with few storms. E has a strong negative correlation with storminess. A similar and even stronger negative relationship is observed for SCA, which is most outstanding in November and October. This pattern reflects southeasterly (positive index values) and northwesterly (negative values) airflows over the Baltic Sea (Fig. 8). The highly negative correlation means that storms on Vilsandi are closely related to northwesterly circulation.

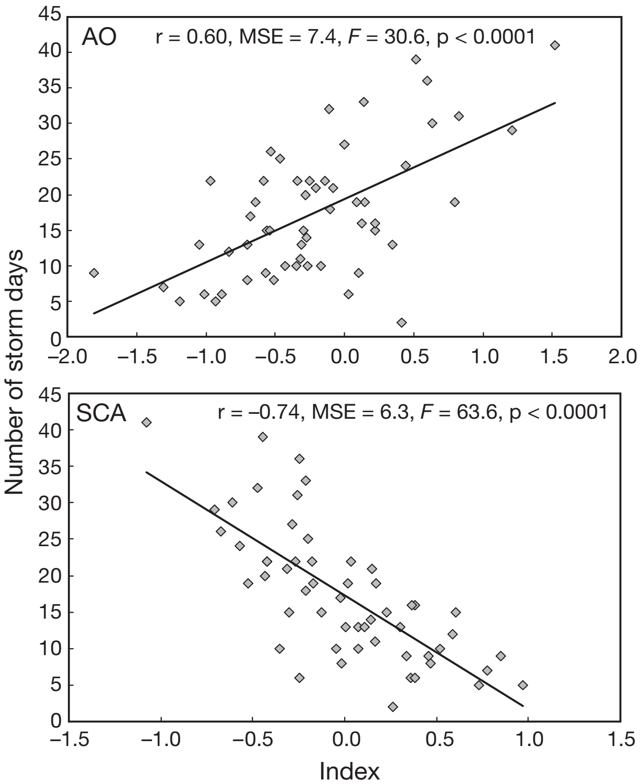

Fig. 8. Number of storm days at Vilsandi against the Arctic Oscillation (AO) and Scandinavia teleconnection (SCA) indices during the period September to March

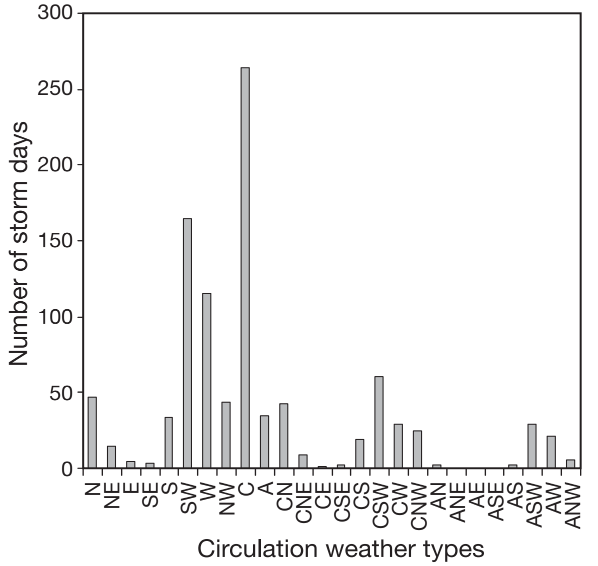

Fig. 9. Frequency of synoptic weather types in Estonia corresponding to windstorms at Vilsandi (1968 to 1997)

The frequency of M has a significant negative correlation for all months of the storm season. Mostly it corresponds to high pressure conditions. Among the circulation indices developed for Estonia, the highest negative correlation with storminess is with the SE–NW index. The relationship is similar to that of SCA. Some circulation characteristics (C, ZM, EA, EAWR, SW–NE) show no correlation with the number of storm days.

Analysis of monthly values provides only a broad description of the relationship between circulation and storminess. To provide more detail, the daily circulation types and circulation indices for Estonia were analysed for storm days. The distribution of the synoptic weather types in Estonia corresponding to storm days is presented in Fig. 9. Storms on Vilsandi occur mostly in the case of the 3 main weather types (Post et al. 2002)—cyclonic (27 %), southwesterly (17 %) and westerly (12 %). Taken together, they account for 56 % of storms. For comparison, annual mean cyclonic, southwesterly and westerly types make up 14.6, 8.7 and 7.9 %, respectively, and altogether 31.2 %. Among the heavy storms, with maximum mean wind speed ≥18 m s^{-1}, the frequency of the cyclonic type was even higher at 29 %. The monthly distribution of storms with the 3 main types (Fig. 10) reveals that storms with the cyclonic type are the most frequent throughout a year. This shows that not only the direction or the intensity of flow is important, but also the vorticity of the pressure field, as the day is classified into the cyclonic weather type if the ratio of the vorticity Z to the resultant geostrophic flow F is >2.

The daily mean circulation indices for Estonia (Tomingas 2002) for storm days are presented in Table 5. Positive values of ZonEst indicate that storms at Vilsandi occur mostly under the conditions of westerly circulation. Negative values of meridional circulation mean a more frequent northerly and a less frequent southerly

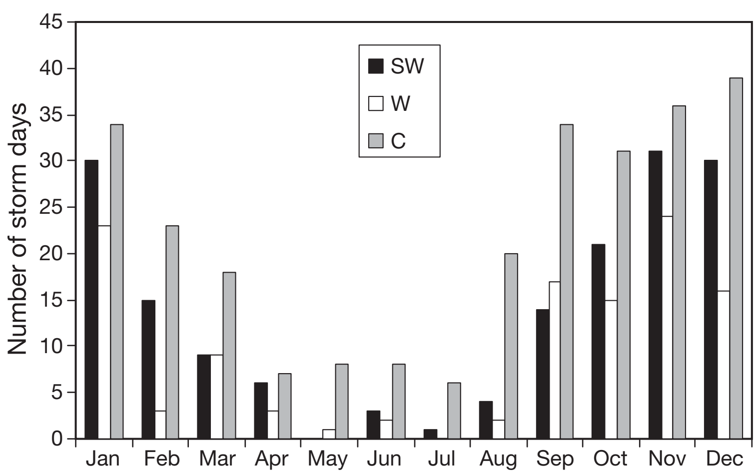

Fig. 10. Monthly distribution of windstorms during the 3 weather types—W: westerly flow; SW: southwesterly flow; C: cyclonic

Table 5. Mean circulation indices for Estonia on storm days. See Table 2 for abbreviations

	ZonEst	MerEst	SW–NE	SE–NW
All storms	0.46	–0.26	0.08	–0.36
Heavy storms (≥18 m s^{-1})	0.55	–0.24	0.13	–0.39
Extremely stormy periods	0.69	–0.31	0.17	–0.50

Table 6. Parameters of atmospheric circulation, the trends of which are significantly related to storminess at Vilsandi according to the conditional Mann-Kendall test. Dash: negative relationship. See Table 2 for abbreviations

Period	Circulation variables
January	AO, W, E–, POL
February	NAOPD, NAOG, AO, W, E–, NAOT, EA, POL
Winter	NAOPD, NAOG, AO, W, E–, POL

circulation. The northwesterly circulation is more closely related to storms than the southeasterly airflow. In the windrose of measured windstorms at Vilsandi the most frequent direction was SW (Fig. 2).

To further clarify the relationships between circulation and heavy storms, correlations between the circulation indices and heavy storms, and storms during the extremely stormy periods were calculated. As a rule, these correlation coefficients are higher than in the case when all storms are taken into account.

7. TRENDS IN STORMINESS INDUCED BY CIRCULATION CHANGES

A general increase in storminess in Estonia was documented in Orviku et al. 2003. Statistically significant increase in the number of storm days was detected in annual values ($p < 0.05$). The univariate MK test also revealed significant trends in monthly and seasonal values—a positive trend in January, February, March, May, July and winter (December to February), and a negative trend in August. The largest change in storminess during the period from 1948 to 2004 occurred in February ($p < 0.01$).

Table 6 presents the circulation variables with trends which are significantly related to trends in storminess. Parameters of atmospheric circulation having a linear trend (Jaagus 2006a) were used as covariates. It can be concluded that the positive trend in storminess is related to a positive trend in the intensity of zonal circulation. The conditional MK test demonstrated that using the positive trends in AO, POL and W entirely eliminates trends in the number of storm days in January, February and in winter. While the frequency of W increased, E decreased during the observation period; this has an opposite relationship with storminess. Corresponding trends in the intensity of westerlies and in the number of storm days are depicted in Fig. 11.

8. DISCUSSION AND CONCLUSIONS

If one climate variable changes, it tends to cause changes in other climate elements. The increase in surface air temperature in Estonia during winter is closely related to negative trends in snow cover and sea ice. Warmer weather is usually induced by mild maritime air coming from the northern Atlantic.

Relationships between large-scale atmospheric circulation and storminess at Vilsandi are typical for the coastal regions of Estonia and for the whole eastern central part of the Baltic Sea. However, the Vilsandi meteorological station is somewhat protected on the eastern side (forest) and on the western side (lighthouse), which diminishes wind speed and the number of storm days.

Correlation analysis between circulation variables and the number of storm days during the storm season (September to March) show coherent relationships. Storminess is positively correlated with the characteristics of westerlies and negatively correlated with some variables of the meridional circulation. In addition, the most common indices describing the intensity of westerlies in the Atlantic-European sector (those of the NAO) have a remarkably lower correlation with storminess than AO, POL and W. Also, ZonEst does not have a closer relationship with the number of storms

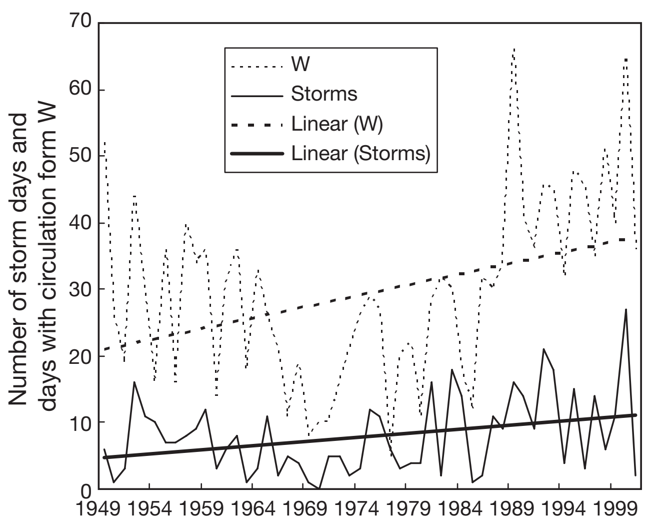

Fig. 11. Time series of the frequency of the zonal circulation form W and of the number of storm days in winter ($r = 0.59$, $MSE = 4.9$, $F = 27.8$, $p < 0.0001$)

days than AO. Large-scale atmospheric circulation determines the regional and local circulation in the Baltic Sea area.

Among different months, the highest correlations with these circulation types are usually observed in February. Correlation coefficients calculated for longer periods, for winter (December to February) or for the whole storm season (September to March), are even higher — up to 0.68 for the AO index.

Using 5 yr running average time series of the number of storm days at Vilsandi and of the AO index, the correlation coefficient between them increases significantly. For example, in the case of winter values, it was initially 0.68, and after using the filtered series it increased to 0.78. These data show that decadal variability in storminess is well explained by long-term, low-frequency variability of the AO index.

Similar results were obtained when the daily circulation variables designed specifically for the Baltic Sea region and for Estonia were used. More than half of all storm days occurred in conjunction with 3 circulation weather types — cyclonic, western and southwestern. The daily mean zonal circulation index for Estonia, calculated only for storm days, shows that the stronger the storms, the higher the intensity of the zonal circulation.

In cases of zonal circulation, cyclonic weather conditions prevail in Estonia. Indices of zonal circulation describe the linear airflow. Circulation weather types used in the present study are valuable, because they also describe the vorticity of airflow in cases of cyclonic or anti-cyclonic flows. We have demonstrated that a large proportion of the windstorms occur along with cyclonic weather types.

A negative correlation exists between storminess and the frequency of some meridional circulation types (E, M, SCA). When these patterns are established, there are few storms. In such cases, Estonia tends to be influenced by anti-cyclonic conditions.

Results of the conditional MK test confirm that the positive trend in winter storminess is associated with a positive trend in the intensity of westerlies, i.e. in time series of the AO and in the frequency of W. These changes have been most substantial in February. The increased frequency of W is related to a decrease in E.

Acknowledgements. The study is sponsored by the Estonian Science Foundation (Grants No. 5786 and 5763).

LITERATURE CITED

Alexandersson H, Schmith T, Iden K, Tuomenvirta H (1998) Long-term variations of the storm climate over NW Europe. Glob Atmos Ocean Syst 6:97–120

Barnston AG, Livezey RE (1987) Classification, seasonality and persistence of low-frequency atmospheric circulation patterns. Mon Weather Rev 115:1083–1126

Bijl W, Flather R, de Ronde JG, Schmith T (1999) Changing storminess? An analysis of long-term sea level data sets. Clim Res 11:161–172

El-Shaarawi AH (1993) Environmental monitoring, assessment and prediction of change. Environmetrics 4:381–398

Gerstengarbe FW, Werner PC, Rüge U (1999) Katalog der Grosswetterlagen Europas (1881–1998) nach Paul Hess und Helmuth Brezowsky, 5. Auflage. Institut für Klimafolgenforschung, Potsdam

Girs AA (1971) Mnogoletnije kolebanija atmosfernoj cirkuljacii i dolgosročnyje gidrometeorologičeskije prognozy (Interannual fluctuations of atmospheric circulation and long-term hydrometeorological forecasts). Gidrometeoizdat, Leningrad (in Russian)

Gulev SK, Zolina O, Grigoriev S (2001) Extratropical cyclone variability in the Northern Hemisphere winter from the NCEP/NCAR reanalysis data. Clim Dyn 17:795–809

Gulev SK, Jung T, Ruprecht E (2002) Climatology and interannual variability in the intensity of synoptic-scale processes in the North Atlantic from the NCEP-NCAR reanalysis data. J Clim 15:809–828

Houghton JT, Ding Y, Griggs DJ, Noguer M (eds) (2001) Climate change 2001: the scientific basis. Third Assessment Report, IPCC, Cambridge University Press, Cambridge

Hurrell JW, van Loon H (1997) Decadal variations in climate associated with the North Atlantic Oscillation. Clim Change 36:301–326

Jaagus J (2006a) Climatic changes in Estonia during the second half of the 20th century in relationship with changes in large-scale atmospheric circulation. Theor Appl Climatol 83:77–88

Jaagus J (2006b) Trends in sea ice conditions on the Baltic Sea near the Estonian coast during the period 1949/50–2003/04 and their relationships to large-scale atmospheric circulation. Boreal Environ Res 11:169–183

Jenkinson AF, Collison FP (1977) An initial climatology of gales over the North Sea. Synoptic Climatology Branch Memo 62, Meteorological Office, Bracknell

Jones PD, Jónsson T, Wheeler D (1997) Extension to the North Atlantic Oscillation using early instrumental pressure observations from Gibraltar and South-West Iceland. Int J Climatol 17:1433–1450

Libiseller C, Grimvall A (2002) Performance of partial Mann-Kendall test for trend detection in the presence of covariates. Environmetrics 13:71–84

McCabe GJ, Clark MP, Serreze MC (2001) Trends in Northern Hemisphere surface cyclone frequency and intensity. J Clim 14:2763–2768

Omstedt A, Pettersen C, Rodhe J, Winsor P (2003) Baltic Sea climate: 200 yr of data on air temperature, sea level variation, ice cover, and atmospheric circulation. Clim Res 25:205–216

Orlanski I (1998) Poleward deflection of storm tracks. J Atmos Sci 55:2577–2602

Orviku K, Jaagus J, Kont A, Ratas U, Rivis R (2003) Increasing activity of coastal processes associated with climate change in Estonia. J Coast Res 19:364–375

Paciorek CJ, Risbey JS, Ventura V, Rosen RD (2002) Multiple indices of Northern Hemisphere cyclone activity, winters 1949–1999. J Clim 15:1573–1590

Post P, Truija V, Tuulik J (2002) Circulation weather types and their influence on temperature and precipitation in Estonia. Boreal Environ Res 7:281–289

Pryor SC, Barthelmie RJ (2003) Long-term trends in near-surface flow over the Baltic. Int J Climatol 23:271–289

Salmi T, Määttä A, Anttila P, Ruoho-Airola T, Amnell T (2002) Detecting trends of annual values of atmospheric pollutants by the Mann-Kendall test and Sen's slope estimates—the EXCEL template application MAKESENS. Publications on air quality 31, Finnish Meteorological Institute, Helsinki

Sepp M, Jaagus J (2002) Frequency of circulation patterns and air temperature variations in Europe. Boreal Environ Res 7:273–279

Sepp M, Post P, Jaagus J (2005) Long-term changes in the frequency of cyclones and their trajectories in Central and Northern Europe. Nord Hydrol 36:297–309

Sickmöller M, Blender R, Fraedrich K (2000) Observed winter cyclone tracks in the Northern Hemisphere in re-analysed ECMWF data. QJR Meteorol Soc 126:591–620

Soomere T (2001) Extreme wind speeds and spatially uniform wind events in the Baltic Proper. Proc Estonian Acad Sci Eng 7:195–211

Soomere T, Keevallik S (2001) Anisotropy of moderate and strong winds in the Baltic Proper. Proc Estonian Acad Sci Eng 7:35–49

Suursaar Ü, Kullas T, Otsmann M, Saaremäe I, Kuik J, Merilain M (2006) Cyclone Gudrun in January 2005 and modelling its hydrodynamic consequences in the Estonian coastal waters. Boreal Environ Res 11:143–159

Thompson DW, Wallace JM (1998) The Arctic Oscillation signature in the wintertime geopotential height and temperature fields. Geophys Res Lett 25:1297–1300

Tomingas O (2002) Relationship between atmospheric circulation indices and climate variability in Estonia. Boreal Environ Res 7:463–469

Ulbrich U, Christoph M (1999) A shift of the NAO and increasing storm track activity over Europe due to anthropogenic greenhouse gas forcing. Clim Dyn 15:551–559

Vangengeim GJ (1952) Osnovy makrocirkuljacionnogo metoda dolgosročnyh meteorologičeskih prognozov dlja Arktiki (Principles of macro-circulational method of long-term meteorological forecasts for the Arctics). Trudy AANII 34:11–66 (in Russian)

WASA Group (1998) Changing waves and storms in the Northeast Atlantic? Bull Am Meteorol Soc 79:741–760

Zhang X, Walsh JE, Zhang J, Bhatt US, Ikeda M (2004) Climatology and interannual variability of Arctic cyclone activity: 1948–2002. J Clim 17:2300–2317

Editorial responsibility: Robert Davis, Charlottesville, Virginia, USA

Submitted: March 27, 2006; Accepted: November 16, 2007
Proofs received from author(s): February 21, 2008