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Long-term storminess and sea level variations on the Estonian coast of the Baltic Sea in relation to large-scale atmospheric circulation

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Abstract. Variations and trends in storminess (number of storm days), and mean and maximum sea levels were analysed along the Estonian coast during the last century. An increase in storminess was detected at the Vilsandi and Sõrve stations, although inhomogeneities in the wind data make the trends less reliable. Mean sea level trends depend on the post-glacial isostatic land uplift, which is different in different parts of Estonia. After eliminating the influence of the uplift, the estimated sea level rise was 2.2–3.2 mm yr^{-1} during 1950–2011, which was higher than the global mean (1.9 mm yr^{-1}). The majority of increases in storminess and sea level have been observed during the cold half-year (November–March). An increase in annual maximum sea level has been much higher than in mean values, which indicates a strong increase in the flooding risk. Atmospheric circulation is closely related to the frequencies of storms and high sea level events, especially during the cold season. Variables describing the intensity of zonal circulation (westerlies), such as the Arctic oscillation and North Atlantic oscillation indices, and the frequency of the circulation form W according to the Vangengeim–Girs classification are highly correlated with storminess and sea level on the Estonian coast during 1950–2011. Negative correlations appeared in case of the circulation form E and the SCAND index.

Key words: storm, sea level, acceleration, atmospheric circulation, climate change, Baltic Sea.

INTRODUCTION

Estonia is characterized by a long coastline up to 3800 km, with a large number of small islands and extensive low-lying coastal areas. The major part of its population is concentrated in the coastal area. Therefore, Estonian society is highly affected by such dangerous phenomena as severe storms and substantial sea level rises (Kont et al. 2007). Due to the fact that Estonia is located on the eastern coast of the practically tideless Baltic Sea, strong westerly and southwesterly winds related to deep cyclones cause heavy wind stress over the sea inducing a significant sea level pile-up near the coast.

The resort town of Pärnu is at the highest risk of flooding. It is located in southwestern Estonia on the northeastern coast of the Gulf of Riga at the end of a shallow bay. The maximum sea level rise in Pärnu, 275 cm above the Kronstadt zero bench mark, was observed on 9 January 2005. This storm and flooding, caused by the severe cyclone Gudrun, flooded 15 km^2 of the coastal area in the Pärnu region and damaged the coast in many places in western Estonia (Suursaar & Sooäär 2006; Suursaar et al. 2006a).

During the second half of the 20th century, storminess significantly increased in the Estonian coastal regions, gaining its maximum at the end of the 1980s and at the beginning of the 1990s (Orviku et al. 2003; Jaagus et al. 2008). It should be emphasized that the change was not observed during autumn months but only in winter, especially in February and March.

Increasing storminess has also been recorded in much wider regions in northern Europe (Alexandersson et al. 1998; Ulbrich & Christoph 1999; Gulev et al. 2002; Paciorek et al. 2002; Pryor & Barthelmie 2003; Bärring & von Storch 2004; Zhang et al. 2004; Matulla et al. 2008; Bärring & Fortuniak 2009; Donat et al. 2010; Vilibić & Šepić 2010). This change is considered as an important impact of global climate warming. Higher storminess is directly related to intense cyclonic activity, causing mild winters.

Analysis of much longer observation periods reveals a very high variability in cyclone activity and storminess. It was comparatively high in the late 19th and early 20th centuries, followed by a long period of decreasing storminess up to the 1960s (Alexandersson et al. 1998; Bärring & von Storch 2004; Bärring & Fortuniak 2009). Therefore, storminess has no clear long-term trends during the whole of the 20th century.

Many factors induce the intensification of coastal processes and enhance coastal damages in the Baltic Sea region. One of them is the global sea level rise related to global warming, but so far, it has been moderate. The main factor causing the increase in the frequency of extensive floodings on the Estonian coast is a change in the large-scale atmospheric circulation during the winter season.

The intensity of westerlies has significantly increased during the second half of the 20th century (Solomon et al. 2007). It means that low pressure and cyclonic weather conditions have become more frequent in the Arctic and sub-Arctic regions (Serreze et al. 2000; Gillett et al. 2003, 2005). The number of cyclones moving over northern Europe has increased in winter, suggesting a poleward shift of the storm track (Paciorek et al. 2002; Zhang et al. 2004; Wang et al. 2006). The number of cyclones moving from west to east between 60 and 65°N (i.e. over Finland) significantly increased in winter in 1948–2000 (Sepp et al. 2005). Sepp (2009) discusses an increase in cyclonic activity and the frequency of westerlies over the Baltic Sea basin during the 20th century along with a tendency of increased cyclogenesis. In recent years, the percentage of deep cyclones has risen, while the total number has not changed.

As a consequence, the percentage of anti-cyclonic conditions in winter described by low temperature, little precipitation, weak winds and clear sky has decreased in Estonia, and cyclonic weather with higher temperature, precipitation, cloudiness, wind speed and storminess has become much more typical (Jaagus 2006). Higher temperature prevents the formation of sea ice, which can protect the coast against coastal erosion. Coastal sediments that do not freeze in winter are easily affected by erosion (Orviku et al. 2003; Kont et al. 2007; Tõnisson et al. 2007, 2011). Severe westerly and southwesterly windstorms cause a marked sea level rise, which is an important prerequisite to severe coastal erosion events. A statistically significant increasing trend in the sea level around the Estonian coast has been detected only in winter (Suursaar et al. 2006b, 2007).

In many studies referred to above, storminess was estimated using the air pressure field. Calculation of wind speed is a bit too generalizing and does not take into account local conditions and wind obstacles. We have used the station data which can more exactly represent real wind conditions above the sea level and on the coast. This is just the wind that produces wind stress on sea surface, causing high water levels and coastal damages.

A catalogue of storms was compiled for studying the variability and changes in storminess at three coastal stations in Estonia during 1950–2001 (Orviku et al. 2003). A storm was defined using certain criteria. Results of this study indicated that during the study period, the mean annual number of storm days was 20 at Vilsandi, 14 at Sõrve and 13 at Kihnu. All three stations demonstrate large interannual variability and increasing trends in time series of storminess. The list of extremely stormy periods was compiled following the fixed criteria. Seventeen extremely stormy periods were detected during the 52 years of observations (Orviku et al. 2003).

It was demonstrated that an overwhelming majority of stormy winds on the western coast of Estonia blow from two directions – the southwest and the northwest, which are not shielded from the open sea at Vilsandi (Jaagus et al. 2008). A statistically significant correlation was detected between the atmospheric circulation indices and storminess at Vilsandi, while the characteristics of zonal circulation have a positive correlation and those of meridional circulation are related to no or a negative correlation (Jaagus et al. 2008).

Increasing trends in storminess are closely related to the increase in storm surge heights near the Estonian coast of the Baltic Sea (Suursaar et al. 2007). The results suggest that in addition to the effect of eustatic rise in mean sea level and its partial compensation by isostatic land uplift, the water level rose by up to 6 cm near the Estonian coast during 1950–2002, probably due to changes in wind climate. The sea level rise was concentrated in the cold season from November to March (Suursaar et al. 2006b). This result is in good correlation with the increasing trends in local storminess and in the higher intensity of westerlies. Very similar results were obtained for the western coastal region of Lithuania (Dailidiene et al. 2006).

The distribution of wind directions at 14 meteorological stations in Estonia decreased dramatically in the winter season during 1966–2008. The percentage of westerly and southwesterly winds increased significantly and the share of southeasterly, easterly and northeasterly winds decreased (Jaagus & Kull 2011).

Results of the previous investigations on storminess and sea level changes during the last half-century raised a need to analyse the frequency and strength of these phenomena for a much longer period back in time. A question arose whether these severe storm and flooding events, which were observed during the last decades, were unique among the long period of observations or whether such events have been recorded also in the first half of the 20th century and even earlier. The main assumption is that the frequency of severe storm and flooding events during the cold season has, due to global climate warming, today significantly increased in comparison with these earlier time intervals.

The objectives of this study are

- to collect and update all data of wind and sea level measurements in Estonia starting with the beginning of observations in the mid-19th century and focussing on severe storm and high sea level events;

- to estimate the quality and homogeneity of the old records;
- to analyse long-term fluctuations and trends in the frequency of severe storm and flooding events on the Estonian coast during the whole updated period of observations;
- to assess the relationships between severe storms, floodings and parameters of large-scale atmospheric circulation.

MATERIAL AND METHODS

Storm data

The wind and sea level observation data from coastal stations and the tide gauges of Estonia used in this study were obtained from the Estonian Meteorological and Hydrological Institute (EMHI). Catalogues of windstorms were compiled for two stations in Estonia, at Vilsandi and Sõrve, located in the westernmost coastal region of Saaremaa Island directly on the eastern coast of the Baltic Proper (Fig. 1). Meteorological observations at both stations, located at lighthouses, were started in 1865 and have been continued at the same place up to the present day.

The number of storm days is the main variable for describing storminess obtained from the catalogues of storms. Hereby, we use the same criterion for defining storm days as in the previous studies (Orviku et al. 2003; Kont et al. 2007; Jaagus et al. 2008). A storm is defined as an event when a 10-min mean wind speed ≥15 m s^{-1} is measured during at least one observation time a day. The catalogues of windstorms contain maximum mean wind speed, wind directions and storm durations.

Unfortunately, the wind speed data were totally inhomogeneous and incomparable before World War I. Wind speed was estimated visually and, therefore, the results obtained by different observers were different. These early data were used in this study only for checking whether a windstorm was also recorded in case of a particular high sea level event. The catalogues of storms were started only in 1920 at Vilsandi and in 1930 at Sõrve.

Gaps occur in the wind data for some years of World War II and later. At the Vilsandi station, the observation data are missing for September and October 1944, from 1946 to 1947 and from July to October 1991. At the Sõrve station, the wind data are missing from July 1940 to April 1941, from June 1941 to February 1942, from August 1944 to May 1945, from October 1945 to September 1947 and from May 1993 to December 1994. The gaps in time series of the number of storm days since 1950 were filled using data from the other station, i.e. either from Sõrve or Vilsandi.

Many factors have caused inhomogeneities in the long time series of windstorms. Different instruments have been used for measuring wind speed. Wind vanes with a heavy plate were installed in 1950. The heavy plates allowed more exact measuring of higher wind

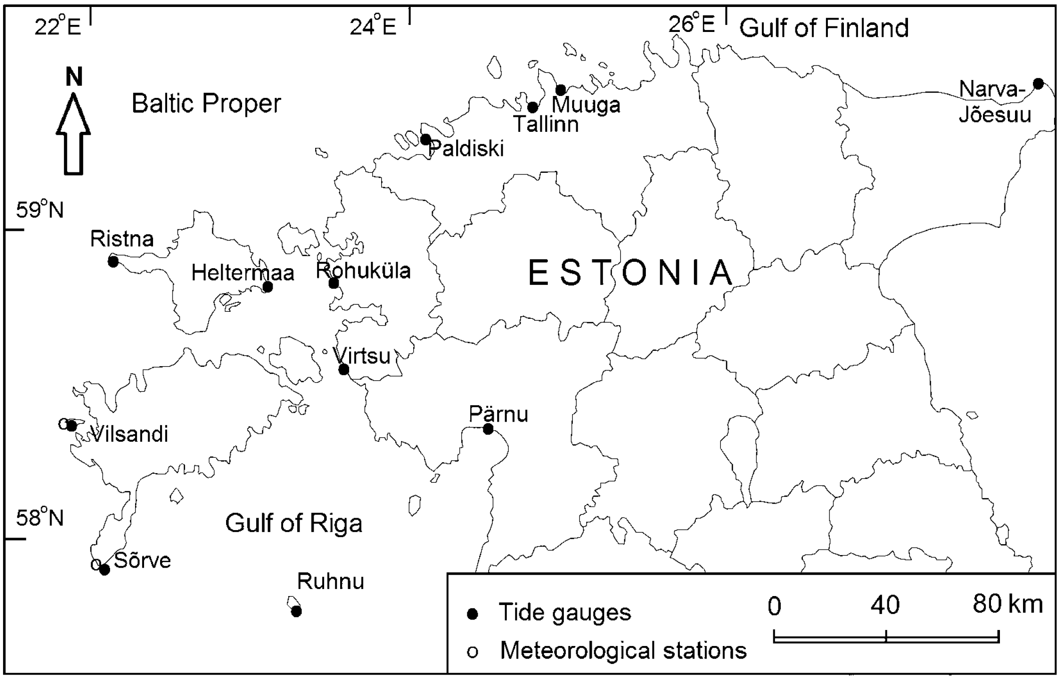

Fig. 1. Map of the study area with the observation sites.

speeds. The anemorhumbometers were installed at the Vilsandi and Sõrve stations in November 1976, and the automatic weather stations Milos 520 in September 2003.

Mean wind speed measured by a wind vane was higher than that measured by an anemorhumbometer. Mean differences between these two instruments were determined during a couple of years of parallel measurements. For example, the wind speed of 15 m s^{-1} measured by an anemorhumbometer is equal to 17 m s^{-1} measured by a wind vane. In the catalogues of storms, all measurements of wind speed that had been made by a wind vane during the earlier period have been recalculated to the records of the anemorhumbometer.

A different number of observation times per day during the long period is another source of data inhomogeneity. At first, measurements were made three times per day, at 7, 13 and 21 o'clock local time. Three observation times were used up to 1944. Then the fourth observation at midnight was added and the equal interval of six hours was used (at 1, 7, 13 and 19 o'clock local time). In 1966, eight observation times, every three hours, were introduced (3, 6, 9 and 12 a.m. and p.m. UTC). The automatic weather stations make wind records hourly but only each third record was taken into account in compiling the catalogue of storms. Consequently, the data set has been homogeneous in the sense of the number of observation times since 1966. The earlier period, however, has an artificial increasing trend in the number of storm days due to the increase in the number of observations per day. It is natural that the probability to detect a windstorm is higher in case of more frequent daily observations.

Changes in the openness of the measuring sites may significantly influence the homogeneity of wind data. Usually the openness decreases due to the growth of trees and the building of houses in the surroundings of a weather station. As a result, mean wind speed gradually decreases. In this case we consider this source on data inhomogeneity not important because both stations, Vilsandi and Sõrve, are located on the sea coast near lighthouses where the openness has not changed significantly during many decades.

Sea level data

Measurements of relative sea level variations by means of coastal tide gauges at the Baltic Sea have been conducted for more than two centuries. The longest continuous sea level record in Stockholm starts in 1774 (Ekman 1999). In St Petersburg, Russia, the storm surge record starts in 1703, and a more or less continuous sea level time series in 1806 (Lazarenko 1986; Bogdanov et al. 2000). In Tallinn, the capital of Estonia, regular sea level measurements started in 1809. The near-continuous data sets of mean sea level values are available since 1842. However, the older records do not include regular information on extreme sea level events. Monthly maximum sea level values are available since 1899 (Table 1). However, the measurements at the historically valuable location of the Tallinn Harbour were unfortunately discontinued and transferred to Muuga Bay in 1996 due to problems related to local land subsidence and construction work at the port. Merging the historical EMHI data with the new data by the Port of Tallinn has not yet been successful.

It is difficult to assess the total number of sea level measurements made in Estonia at different times. Jevrejeva et al. (2001) mentioned 29 stations. We found at least 34 stations, but the quality and extension of their data vary largely. Most of the time series cover less than 50 years and have many gaps, especially in 1944–1945.

Table 1. Monthly time series of the mean and extreme sea level available for the investigated tide gauges

Time series	Years covered (but may have missing months)
Tallinn (mean)	1842–1882, 1886–1917, 1923–1940, 1945, 1947–1996
Tallinn (max)	1899–1917, 1923–1940, 1945, 1947–1996
Narva-Jõesuu	1899–1915, 1923–1943, 1945–2011
Pärnu	1923–2011
Ristna	1950–2011
Virtsu	1889–1893, 1899–1912, 1947–2011
Rohuküla	1950–2011
Heltermaa	1950–2011
Paldiski	1950–2009
Sõrve	1894–1901, 1907–1914, 1922–1930, 1932–1939, 1950–2003
Ruhnu	1901–1913, 1947–1951, 1953–1988
Vilsandi	1884–1886, 1888–1913, 1924–1944, 1948–1980

Although there are 19 coastal marine stations operated by the EMHI, the sea level measurements are currently carried out at the Dirhami, Haapsalu, Heltermaa, Kunda, Loksa, Narva-Jõesuu, Pärnu, Ristna, Rohuküla, Rohuneeme, Roomassaare and Virtsu stations (however, the list can change from one year to another). Historically, most of the tide gauges operated by the EMHI were equipped with tide poles and had a sampling frequency of 2, 3 or 4 times a day. Such tide gauges also have many gaps in their time series, as well as uncertainties during extreme storms. Since 2009–2010, the measurements in the above-listed stations have been carried out by means of automatic measuring complexes. In addition, different ports and Tallinn University of Technology have carried out measurements at 6–12 port locations during the last decade (Lagemaa et al. 2011). These relatively short data sets have so far not been merged with those of the EMHI.

Table 1 presents a list of eleven most notable in our opinion sea level measurement locations, which are used in this study. Among them, the first four are the most valuable ones, since they include a considerable amount of hourly data (also before 2010). Automatic tide gauges (mareographs), which provided hourly data, are traditionally located at Pärnu, Narva-Jõesuu, Tallinn and Ristna (Fig. 1).

In the present study, we have used the digitized EMHI database, which includes both monthly mean and extreme sea levels, as well as hourly data from selected tide gauges. While the monthly and annual data are good for long-term analyses, the hourly data offer detailed information on short-term variability, especially during severe storms.

The height system used in Estonia and in other Baltic states of the former Soviet Union is called the Baltic Height System 1977 with its reference zero-benchmark at Kronstadt near St Petersburg (Lazarenko 1986; Bogdanov et al. 2000). The work on merging the different reference systems around the Baltic Sea is still on-going. The Kronstadt zero was defined as the average sea level of that tide gauge in 1825–1840. As a result of the global sea level rise, the Kronstadt zero is not the present-time mean sea level of this tide gauge. According to Bogdanov et al. (2000), the mean was 5.9 cm in 1971–1993. Instead, the mean sea level of Estonian tide gauges is roughly around the Kronstadt zero now. There is a quasi-permanent sea level slope towards the Danish Straits (e.g. Lazarenko 1986; BACC 2008). The zeros of Estonian tide gauges are at least annually levelled in relation to local benchmarks. A less frequent levelling between local benchmarks and the base frame is performed by national geodetic organizations (Jevrejeva et al. 2001).

Due to non-uniform land uplift in the study area, the use of fixed land level benchmarks poses specific problems for the comparison of the results from different tide gauges. Data on land uplift for the studied stations varied between 0.5 and 2.5 mm yr^{-1} and they were determined by using a map composed of the precise levelling data (Vallner et al. 1988). In 1977–1985, Vallner together with his colleagues carried out an extensive study of repeated precise levellings, taking into account data from previous levelling campaigns (1933–1943 and 1956–1970). The accuracy of uplift rates was then considered to be ± 0.2 mm yr^{-1}. Later, using precise gravity measurements (Sildvee 1998) and GPS technology, regional geoid models were worked out in cooperation with the Danish Institute of Geodesy (Forsberg et al. 1996) and the vertical motion rates were more or less verified. The actual accuracy and constancy of uplift rate estimates is yet unknown. The GPS altimetry time series are relatively short so far, but the estimates of land movements are gradually improving as series get longer and the equipment is being further developed.

A catalogue of extremely high sea level events for the Estonian coast was created and clearly fixed criteria – the monthly maximum sea levels – were used for determining such an event. A month is considered as an extremely high sea level event when the maximum sea level exceeds the 90th percentile at least at one of the five gauge stations (Pärnu, Narva-Jõesuu, Tallinn, Vilsandi, Ristna).

Atmospheric circulation data

Atmospheric circulation is an important factor determining the sea level as well as storminess (Jaagus et al. 2008). A large number of circulation variables are used in this study to detect these relationships. Circulation can be characterized by two types of variables – circulation indices and the frequency of circulation types according to different classifications. Hereby, we used both of these options. Monthly values of the circulation variables were used during the study period 1950–2011.

The Vangengeim–Girs classification is found to be the most appropriate for describing circulation conditions in Estonia (Sepp & Jaagus 2002). Monthly frequencies of the circulation macroforms W, E and C according to this classification were applied. The type W represents westerly airflow over Europe; E produces easterly and southerly winds in Estonia and C northerlies (Hoy et al. 2013).

The Arctic oscillation (AO) as well as the North Atlantic oscillation (NAO) indices was also used. The AO is the dominant pattern of sea level pressure variations north of 20°N latitude, characterized by pressure anomalies of one sign in the Arctic with the opposite anomalies centred about 37–45°N (Thompson & Wallace 1998). Positive AO anomalies correspond to a high pressure gradient and intense westerlies over mid-latitudes. Negative AO represents a weakening of zonal circulation.

The NAO is considered as the AO representation over the Atlantic/European sector. The NAO index is calculated as a difference between the standardized sea level pressure anomalies at the Azores high and Icelandic low (Hurrell 1995). There are numerous different NAO indices. We used two station-based NAO indices: the NAO-PD obtained from the pressure data in Ponta Delgada (Azores) and Stykkisholmur/Reykjavik (Iceland) (Hurrell & van Loon 1997), and the NAO-G using data from Gibraltar instead of Azores (Jones et al. 1997). As correlation coefficients for the NAO-PD were significantly lower than for the NAO-G, the first index was left out of further analysis.

We also used the NAO indices calculated by using mean pressure data for latitudinal belts 35°N and 65°N between 80°W and 30°E (NAO-C) (Li & Wang 2003), and the principal component analysis (NAO-P) (Hurrell & Deser 2010). In case of every NAO index, positive anomalies indicate a strong westerly airflow over the North Atlantic and negative anomalies correspond to a weakening of westerlies.

Additionally, we used some teleconnection patterns for the Northern hemisphere defined by Barnston & Livezey (1987) based on the PCA of pressure data. Five teleconnection patterns that may have a significant influence on climate variability in Estonia were used: the North Atlantic oscillation (NAO-T), the East Atlantic (EA), Polar/Eurasia (POL), East Atlantic/West Russian (EAWR) and Scandinavian (SCAND) patterns. The three first patterns describe the zonal circulation and the two last ones the meridional circulation. These data are available on the web site of the NOAA Climate Prediction Centre.

Methods of data analysis

Tendencies in the storminess (number of storm days) and the sea level (monthly mean and maximum sea levels) time series were analysed using the linear regression analysis and the Mann–Kendall test. Trends were considered statistically significant on the $p < 0.05$ level. Annual, seasonal and monthly time series were analysed. There was no autocorrelation in the time series of storminess and sea level.

The long time series of storminess (number of storm days) at Vilsandi during 1920–2011 was divided into two equal parts of 44 years, while years of the missing data were excluded. Comparing the summary monthly numbers of storm days during these two periods, it was possible to clearly demonstrate seasonal differences in the increase in storminess.

All cases of extremely high sea level in the catalogue were compared to the data in the catalogue of storms. The storm parameters were analysed together with the data of extreme water level. Analyses of relationships between the storms, high sea level events and different variables of atmospheric circulation were realized using correlation analysis. Thereby, the mean sea level and maximum sea level for Estonia were calculated as the mean for four stations (Pärnu, Narva-Jõesuu, Rohuküla, Ristna) during 1950–2011. The use of mean values of sea level observations is justified because it eliminates local influences on sea level variations. All four stations are located in different parts of the Estonian coastal zone (Fig. 1).

The correlations were found for two periods: 1950–2011 and 1966–2011. The longer period includes inhomogeneous data of storminess, while the second period consists of only homogeneous parts of the time series. All correlation coefficients were considered significant on the $p < 0.05$ level.

RESULTS AND DISCUSSION

Variations and trends in storminess

Storms can be observed as random and catastrophic events, which have different statistical properties in comparison with other meteorological variables. Storms are very irregular in time. They are frequent during some periods (months, years, decades) but rare or even absent during some periods. Extremely stormy periods occur when cyclonic activity has been very high during a number of weeks and months (Orviku et al. 2003).

Seasonality of storminess is clearly represented in Estonia (Jaagus et al. 2008). The majority of all storms take place during the storm season (September–March). Its proportion in the annual number of storm days was 86.3% at Vilsandi during 1920–2011 and 87.5% at Sõrve in 1930–2011. The highest number of storm days is recorded equally in November, December and January when the share of storms has been 16–17% of the annual value for each month. This period is known for the highest cyclonic activity in the Atlantic/European sector.

It is natural that the number of storm days is highest in coastal areas where the influence of wind obstacles is the lowest. The Estonian western coast is much stormier than the northern coast. Therefore, the data of the two westernmost stations in Estonia are analysed in this study. Time series of the number of storm days demonstrate a large interannual variability (Fig. 2). A clear storminess

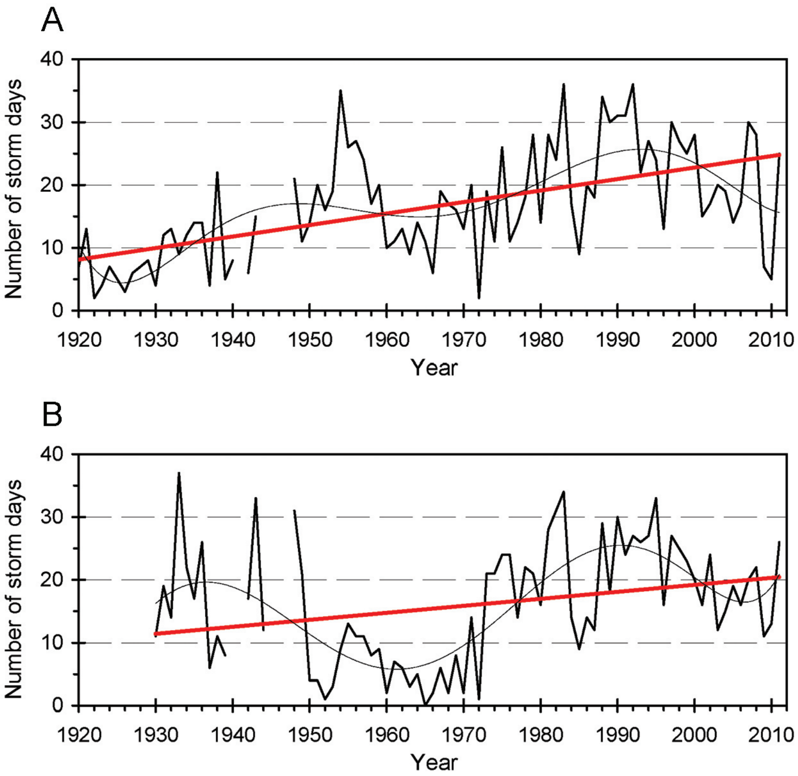

Fig. 2. Time series of the annual number of storm days recorded at Vilsandi (**A**) and Sõrve (**B**) with the linear trend and 5-order polynomial line to illustrate possible cycles and long-term tendencies (with some gaps in the 1940s).

maximum was observed in the 1980s and 1990s. A minimum occurred in the 1960s. These variations are similar on a much wider territory (Alexandersson et al. 1998).

Variations in the number of storm days at Vilsandi and Sõrve are well correlated during the second half of the time series ($r = 0.73$ in 1971–2011), but not correlated during the first half ($r = 0.07$ in 1930–1970). It means that the quality of the earlier data is much lower. Storminess at Vilsandi was notably higher than at Sõrve in the 1950s and much lower in the 1930s. Differences in wind measurements at these two stations can be explained by the influence of local obstacles around the measuring sites. This also means that the two stations are somewhat differently exposed to the possible storm winds and their temporal variations.

Both trends in Fig. 2 are statistically significant. The number of storm days has increased faster at Vilsandi than at Sõrve. The increasing trend is partly induced by the inhomogeneous time series due to different numbers of observation times per day, which was discussed in the section of storm data. Nevertheless, this trend contradicts the results of Alexandersson et al. (1998) showing decreasing storminess in northwestern Europe in the 20th century up to the 1960s. The decreasing trend could be found for Sõrve (Fig. 2B) but not for Vilsandi (Fig. 2A). Indirectly, the enhancing of coastal erosion and coastal damages caused by sea surges in Harilaid, the northwestern point of Saaremaa Island (Orviku et al. 2003; Tõnisson et al. 2007, 2011), support the suggestion of increasing storminess on the western coast of Estonia during the last century.

The increase in storminess has been different throughout a year (Fig. 3). Comparison of the monthly numbers of storm days at Vilsandi in two equal 44-year periods 1920–1967 (years with gaps are omitted) and 1968–2011 shows that the main increase in storminess takes place in the cold half-year, i.e. from November till March. In August, the number of storm days was even lower during the second period.

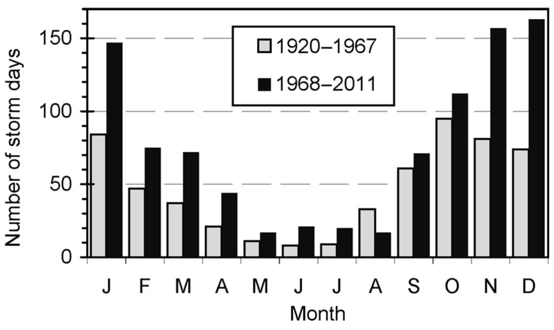

Fig. 3. Seasonal distribution of storm days at Vilsandi in two periods (considering gaps, both include data from 44 years).

Variations and trends in mean sea level

It is often noted that the sea level trends obtained from the less than 50–60-year-long tide gauge records are significantly ‘corrupted’ by decadal variations (e.g. Houston & Dean 2011). Estonian records include eight continuous series that are at least 60 years long (Fig. 4). As a result of the Fennoscandian postglacial isostatic land uplift, which may reach up to 8–9 mm yr^{-1}, the Baltic Sea level records from Finland and a large part of Sweden exhibit decreasing trends (Emery & Aubrey 1991; Ekman 1999; Johansson et al. 2001; Hünicke 2010). Land uplift is considerably smaller in Estonia. Thus, the time series representing annual mean sea levels show quite different

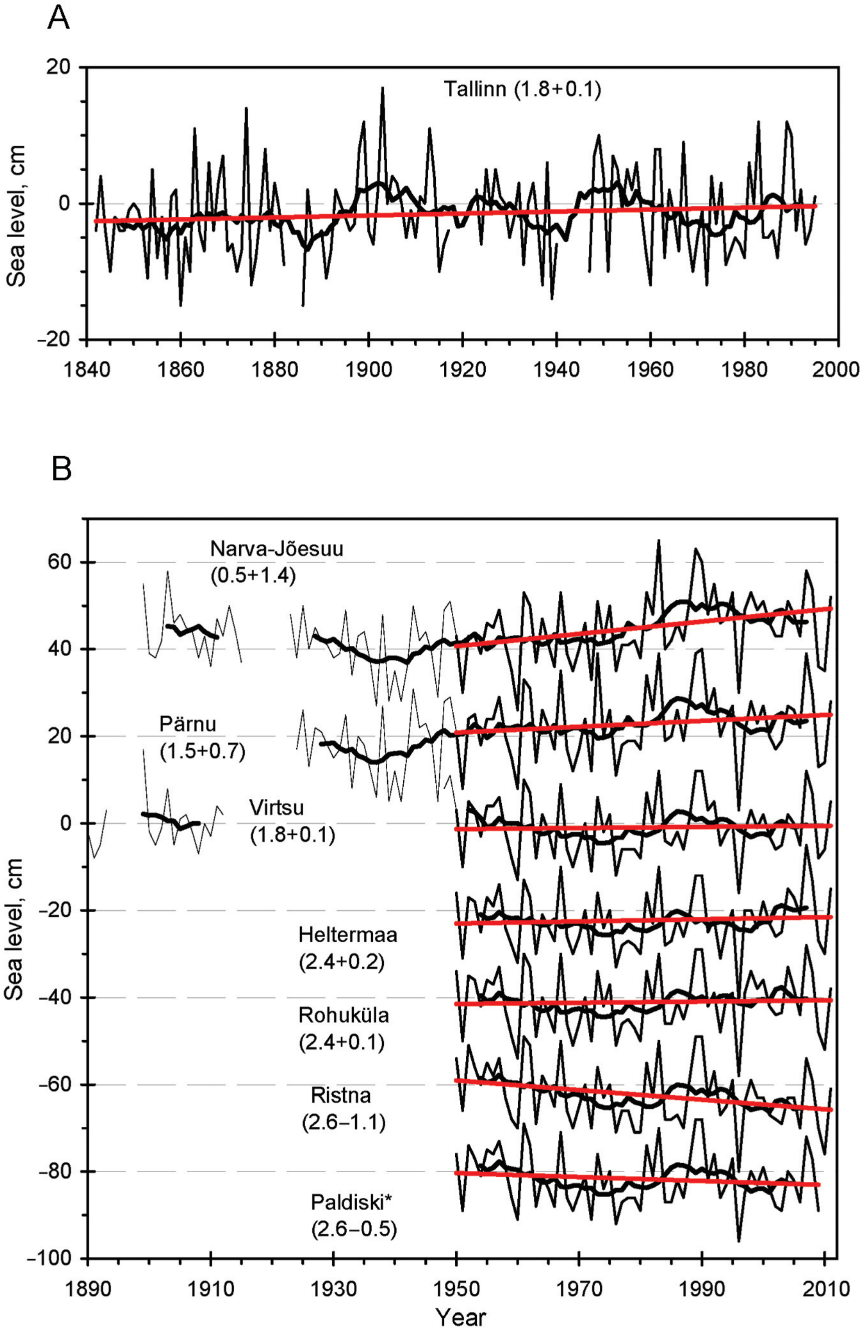

Fig. 4. Variations in annual mean relative sea levels, 11-year moving averages and linear trend lines calculated for the period 1950–2011 (*Paldiski 1950–2009). The values of land uplift according to Vallner et al. (1988) and the linear trend slopes of sea level data (in mm yr^{-1}) are respectively given in parentheses. For better viewing, the data of different tide gauges are shifted by 20 cm regarding each other.

but still increasing tendencies at six selected tide gauges, and yet decreasing trends on the northwestern coast at Ristna and Paldiski (Fig. 4B). The trend for the Tallinn station was calculated for the whole period 1842–1995 (Fig. 4A) while a similar period 1950–2011 was equally used for the other stations (Fig. 4B).

The land uplift rates given in the legends of Fig. 4 were taken from Vallner et al. (1988) and they are marginally higher than the values, which can be drawn from a less detailed Scandinavian isobase map by Eronen et al. (2001). The sum (e.g. 0.5 + 1.4 = 1.9 mm yr^{-1}) gives a sea level rise estimate corrected with land uplift, which could serve as a proxy for an omnipresent signal of climate change-induced sea level rise. However, it is difficult to properly isolate this 'global' component from the Baltic Sea level records, since a number of regional and local meteorological and hydrological influences are involved (Raudsepp et al. 1999; Hünicke & Zorita 2006; Suursaar & Kullas 2006). For example, meteorologically induced seasonality is one of the most important sea level variability features in the tideless Baltic Sea. It does not only appear as a seasonal signal in means and extremes (Fig. 5), but also in trends (Fig. 6). The (mostly) positive sea level trends in annual time series definitely appear due to the significantly steeper trends in winter, since during summer, such trends are negligible or even negative. The higher sea level rise in winter correlates with increased local storminess during the same months and with the greater intensity of westerlies in winter (e.g. Suursaar et al. 2006a).

Moving averages of annual mean sea level series show some quasi-periodic 30–50-year cycles, which roughly coincide with similar decadal variations at the Lithuanian (Dailidiene et al. 2006) or Finnish (Johansson et al. 2001) coasts. However, these cycles with the amplitude of about 5 cm can influence linear trend estimates. For example, the series of mean sea level at Narva-Jõesuu for 1899–2011 started with a period of high sea level and ended with a period of low sea level (Fig. 4B), and over the chosen period, the linear trend estimate probably underestimates the dominant tendency.

Figure 7 illustrates how the trend slope estimates depend on the chosen terminal points of time series. Using the 'running slope' estimates over the subseries of 41 years, the influence of the quasi-periodicity can be diminished at least starting from the 1950s. A similar method for obtaining the 'best' trend estimates for Narva-Jõesuu, Tallinn and Pärnu tide gauges until 2005 was also used by Suursaar & Sooäär (2007). The updated results of the 'running' sea level trend slopes (Fig. 7) yield mean values between 2.2 and 3.2 mm yr^{-1} over the period 1950–2011, which should be preferred over the inflicted from quasi-periodicity estimates in Fig. 4. Corrected with local uplift rates, the mean sea level rise rates in Estonia (Figs 4, 7) seem to be roughly equal to or insignificantly higher than the global tide-gauge-based estimates for the second half of the 20th century: 1.9 ± 0.4 mm yr^{-1} can be read from Church & White (2011) for both 1950–2009 and 1960–2009. Over the 20th century, the sea level rise rate was about 1.7 mm yr^{-1} according to, e.g., Church & White (2006) and Solomon et al. (2007). Recent estimates based on satellite altimetry tend to yield systematically higher values, e.g., up to 3.2 mm yr^{-1} for a shorter period 1993–2009 according to Church & White (2011).

The results of modelling experiments (Suursaar & Kullas 2006; Suursaar et al. 2006a) explained a hydrodynamic mechanism of how the sea level change rates of a semi-enclosed basin may deviate from the global estimates. A positive trend in wind speed and storminess should result in a steeper than average sea level trend on the windward side and a less steep one on the leeward side. Indeed, a clear increase in the westerly wind component occurred between 1950 and 2000 (Alexandersson et al. 1998; Keevallik & Rajasalu 2001; Jaagus et al. 2008). Statistically significant increasing trends in the percentage of westerly and southwesterly winds, and negative trends in easterly and southeasterly winds in Estonia in the winter seasons were reported by Jaagus & Kull (2011) and an increase in storminess can be seen in fig. 2 of this study. As the influence of small changes in mean wind speed on sea level is very small (Suursaar et al. 2006a), the most crucial impact on both the maxima and mean sea level regimes mainly originate from the increase in storminess, and particularly from winter storminess.

There is no common agreement, whether the sea level is globally accelerating or not (Jevrejeva et al. 2008; Houston & Dean 2011; Watson 2011). The values, either for acceleration or decelaration are rather small. From 1900 to 2009, the acceleration was 0.009 mm yr^{-2} according to Church & White (2011). Contributing to the acceleration, the sea level rise was relatively faster in 1930–1950 and again since the 1990s.

We cannot contribute much to the discussion since the Estonian sea level is heavily influenced by regional and local factors. The positive tendencies in trend slopes (e.g. Fig. 7B) describe the local sea level acceleration which was between 0.015 and 0.088 mm yr^{-2} in 1950–2011. While the sea level trend estimates are influenced by magnitudes and uncertainties in the magnitudes of land surface movement estimates, accelerations are not. However, much as the sea level itself, acceleration may change in time or it can even turn into deceleration. Also, in addition to the global climatological component, there may appear other climatological or geological

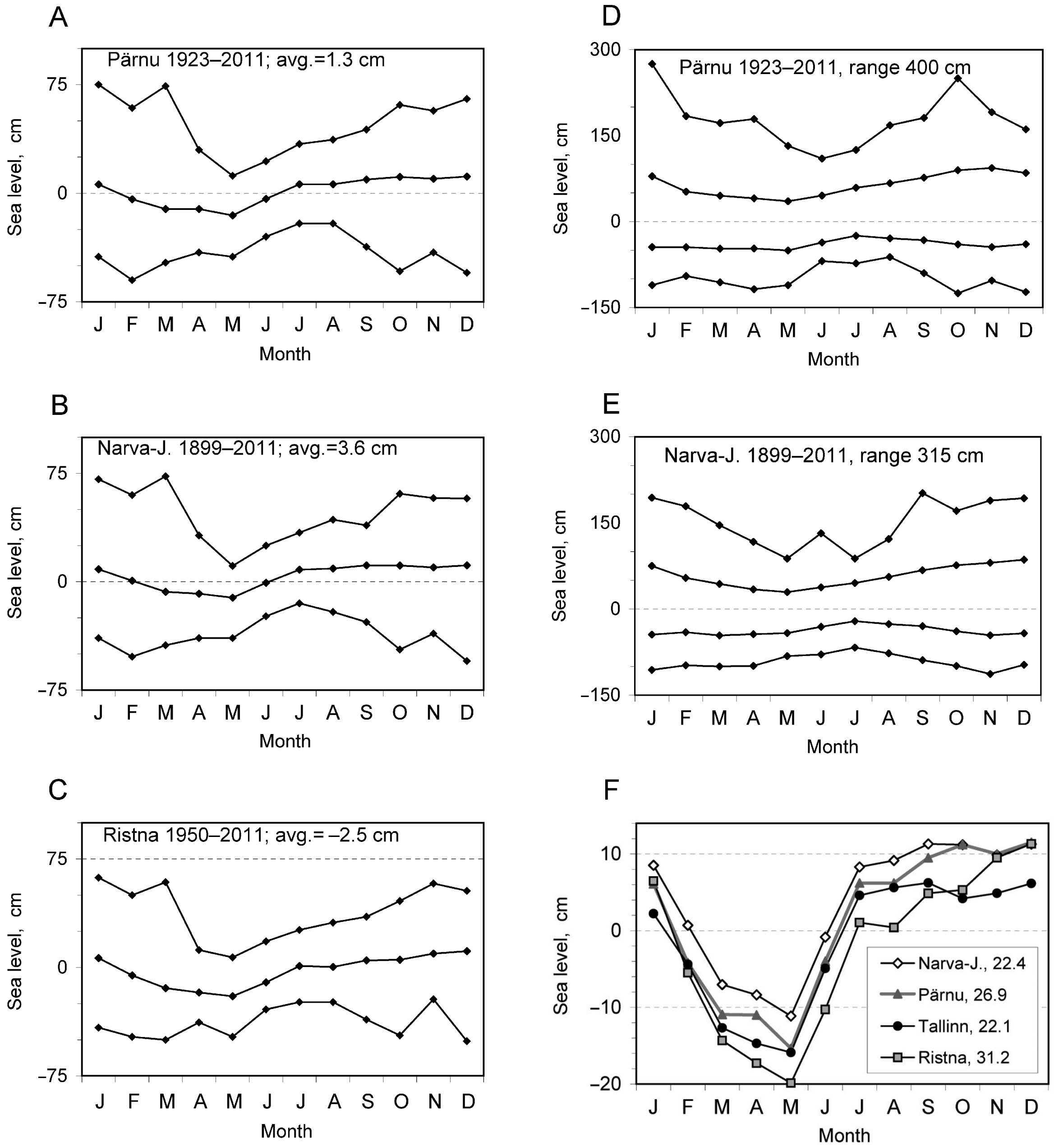

Fig. 5. Seasonal variations in monthly sea level statistics: (**A**–**C**) from the top: maximum averages, averages and minimum averages; (**D**, **E**) absolute maximum, average maximum, average minimum and absolute minimum; (**F**) averages in four tide gauges (variation ranges of monthly averages are given in the legend).

variability sources in local series. For instance, in some tide gauges (Venice, St Petersburg, probably also Tallinn) it can sometimes be influenced by temporal changes in land movements caused, e.g., by anthropogenic land subsidence.

Differently from the other stations (Fig. 7), only the Pärnu data show deceleration (–0.080 mm yr^{-2} in 1950–2011 or –0.025 mm yr^{-2} in 1924–2011). In general, the Pärnu sea level rise values used to be the highest among the Estonian tide gauges, ranging between 1.5 and 3.8 mm yr^{-1}. It seems that the Pärnu sea level experienced a notable rise already in the 1920s–1950s and somewhat lower rates in recent decades manifest as a deceleration. Although the sea level acceleration on the global scale probably occurred in the 1920s and 1930s as well (Jevrejeva et al. 2008; Houston & Dean 2011), the series at Pärnu are particularly influenced by meteorologically and hydrodynamically driven local factors. Among

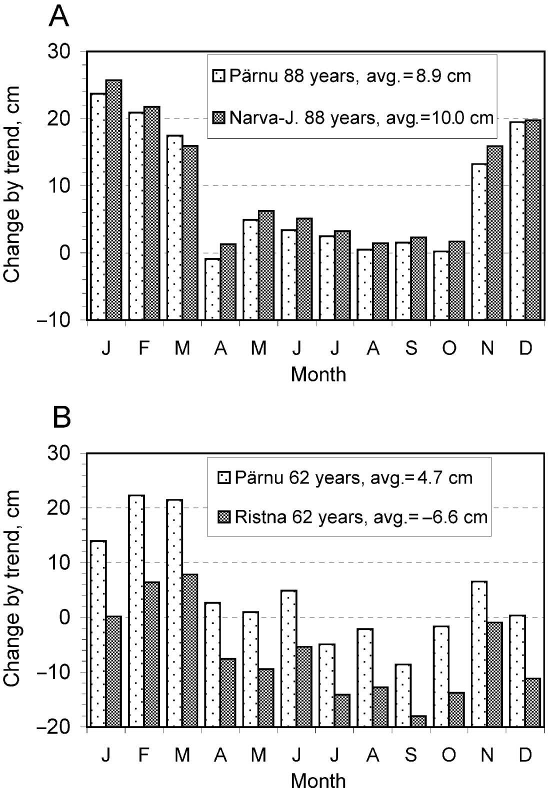

Fig. 6. Seasonal structure of mean sea level changes by linear trend at Pärnu and Narva-Jõesuu for 1924–2011 (**A**), and at Pärnu and Ristna for 1950–2011 (**B**). The trend slopes are multiplied with the number of years, 88 in (**A**) and 62 in (**B**). The change values partially reflect the influence of land uplift, which is fastest at Ristna.

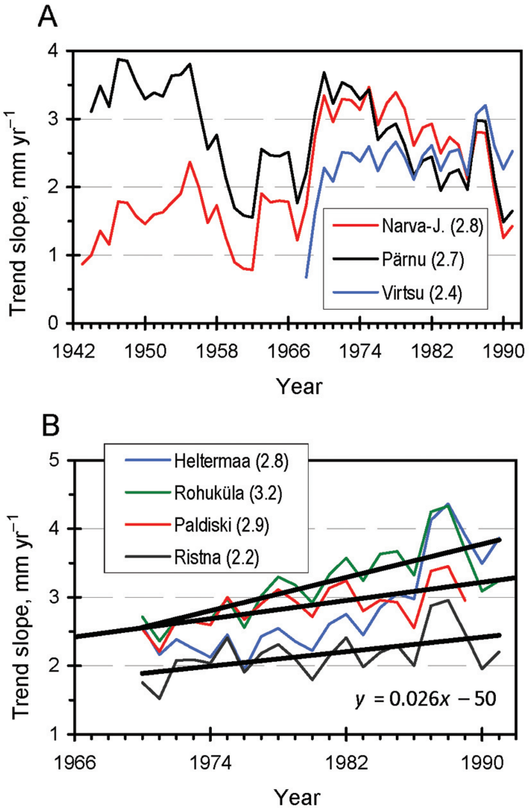

Fig. 7. Time series of slopes of trend lines corrected with land uplift rates for 41-year periods, where the value is assigned to the middle year of the running window; for example, 1970 for 1950–1990 and 1991 for 1971–2011. The numbers in parentheses mark average slope values in mm yr^{-1} for the period covered by the graphs, e.g. 1943–1991 for Narva-Jõesuu (**A**), representing 1923–2011 and 1970–1991 in (**B**), representing 1950–2011. The increasing trend in sea level trend slopes describes sea level acceleration, as shown, e.g., for Ristna in (**B**); roughly similar accelerations could be calculated by fitting quadratic to the sea level time series.

others, a recent turn in wind directions from SW towards W (Jaagus & Kull 2011) may decelerate sea level values at Pärnu, while the increase in westerlies is still favourable for general acceleration in the western Estonian coastal sea.

Variations and trends in maximum sea level

Much intriguingly, the trends in annual maximum sea levels are positive and steeply increasing in all Estonian tide gauges (Fig. 8). When considering also the land uplift rates, the increase rates range between 3.2 and about 9 mm yr^{-1}. The only possible forcing for that can be the increase in local storminess (Figs 2, 3) and the westerly wind component.

Because of the elongated shape of the Baltic Sea, its semi-enclosed configuration and the presence of shallow bays exposed to the direction of possible strong winds, considerable short-term sea level variations or storm surges can occur. Such extreme sea level variations are mainly due to wind setup. Smaller contributors may be the inversed barometric effect, the wave setup and the propagation or amplification of a remotely generated long wave (e.g. Suursaar et al. 2006a; Averkiev & Klevannyy 2010). The wind affects the Baltic Sea level in two principal ways. Firstly, a storm may build up a short-term sea level slope within the sea, resulting in the strongest deviations at the ‘ends’ of the Baltic (including the Gulf of Finland and the bays of Narva and Pärnu). Secondly, when a strong persistent wind from the southwest or the northeast is blowing over the Baltic Sea and its entrance, water is transported into or out of the Baltic, thereby raising or lowering the Baltic Sea level as a whole. Although the amplitude of such events alone is normally less than approximately 80 cm

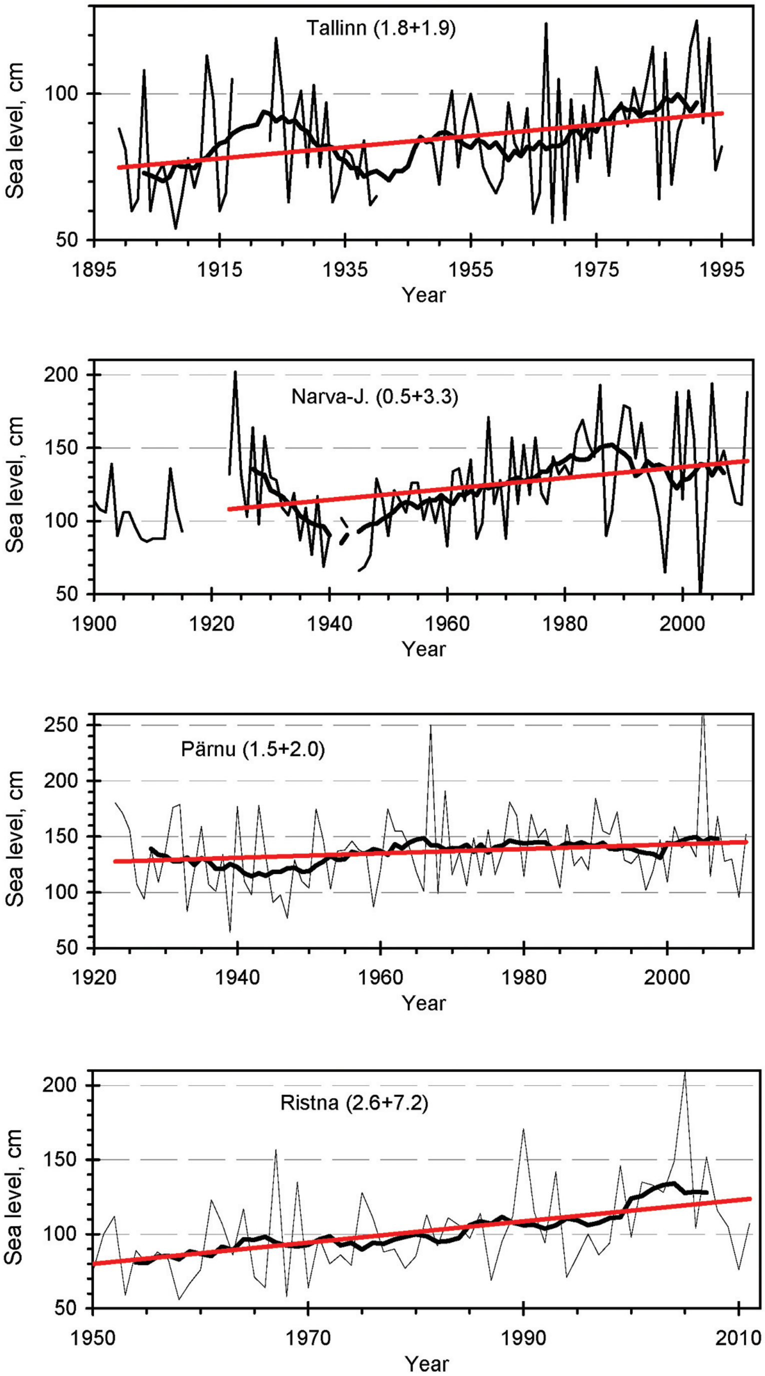

Fig. 8. Time series, 11-year moving averages and linear trend line in the annual maximum sea level data. The sums in parentheses represent the values of land uplift and the linear trend slopes of the sea level data (in mm yr^{-1}).

(Fig. 5A–C), they can provide preconditions for much larger local-scale storm surges, when combined with short-term windstorms during cyclones (e.g. Fig. 5D, E).

The catalogue of extremely high sea level events consists of 36 cases when the monthly maximum sea level exceeded the 90th percentile at least at one of the five stations having long series of measurements (Table 2). These critical values were 170 cm at Pärnu, 160 cm at Narva-Jõesuu, 105 cm at Tallinn, 90 cm at Vilsandi and 140 cm at Ristna. The first high sea level event was detected in February 1903 and the last one in December 2011.

Table 2. Catalogue of extremely high sea level events in Estonia: the year and the month of the event and the corresponding maximum sea levels measured at five stations. The sea level heights exceeding the 90th percentile are typed in bold

Year	Month	Pärnu	Narva-Jõesuu	Tallinn	Vilsandi	Ristna
1903	February	–	113	**108**	61	–
1913	December	–	136	**113**	79	–
1917	November	–	–	**105**	–	–
1923	November	**183**	109	84	–	–
1924	September	**174**	**202**	**119**	**94**	–
1927	November	81	**164**	74	52	–
1931	October	**179**	128	75	56	–
1932	April	**179**	35	17	16	–
1951	April	**175**	63	27	27	28
1952	January	147	114	101	**91**	112
1961	March	**175**	134	90	74	95
1962	January	142	95	82	**107**	107
1962	February	155	84	70	**107**	95
1963	November	155	114	65	**92**	86
1967	October	**250**	**171**	**124**	**206**	**157**
1969	November	**191**	128	**105**	**177**	135
1975	January	156	157	**109**	**97**	128
1975	December	129	154	**105**	74	109
1978	September	**181**	91	75	63	77
1981	November	**170**	130	102	–	113
1982	December	149	**160**	93	–	81
1983	January	133	**163**	100	–	109
1983	November	146	**169**	104	–	106
1984	January	132	153	**116**	–	106
1986	December	161	**193**	**114**	–	114
1990	January	140	157	**116**	–	**171**
1990	February	**184**	**179**	98	–	**166**
1990	March	154	146	**116**	–	112
1991	January	155	**177**	**125**	–	115
1993	January	**172**	**167**	**119**	–	**142**
1999	November	100	**188**	–	–	76
2001	November	159	**189**	–	–	**146**
2005	January	**275**	**194**	–	–	**209**
2007	January	168	148	–	–	**152**
2011	December	152	**188**	–	–	107

– Not measured.

Using all available sea level data, we can state that the absolute highest sea level record in Estonia during the period of observations was measured on 9 January 2005. The maximum record was measured at Pärnu (275 cm) as well as in other tide gauges operating at that time. The only exception was Narva-Jõesuu with the absolute maximum of 202 cm on 23 September 1924. The second in height maximum sea level during the period of observations occurred on 18 October 1967. These three flooding events were significantly stronger than the other extremely high sea level events (Table 2). Because of different exposition of the storm surge prone bays (Pärnu and Ristna to SW, Tallinn and Narva-Jõesuu to N–NW), but also due to a considerable geographical distance (up to 400 km) between these regions, the high sea level events do not simultaneously manifest in equal strength both in western Estonia and along the southern coast of the Gulf of Finland.

Out of 36 events, 32 occurred in the cold half-year (between October and March) and only four occurred between April and September. Also, the catalogue of extremely high sea level events indicates that more than 70% of all these events have occurred during the second half of the observation period since the 1960s. It means that the flooding risk of coastal areas has increased significantly (Fig. 3). It is an important outcome of this study, demonstrating an impact of climate change. We assume that the increase in air temperature in northern

Europe during the cold half-year is closely related to higher cyclonic activity, higher intensity of westerlies and higher storminess, less sea ice and higher sea level along the Estonian coast due to the higher wind stress.

Relationships between severe storms and high sea level events

Generally, correlation coefficients between the numbers of storm days and sea levels are significantly positive, especially in winter and autumn, gaining their maximum value 0.80 at Vilsandi in January (Table 3). This result was expected because both phenomena, the storms and high sea level events, are caused by the same factor, intense cyclonic activity. It is the highest during the storm season from September to March when the correlation is in its maximum (Table 3). The mean sea level and maximum sea level data for Estonia were obtained by averaging the measured values at four stations: Pärnu, Narva-Jõesuu, Rohuküla and Ristna during 1950–2011.

Mostly, the correlations with storminess at Vilsandi were higher than at Sõrve but, in March and April, the number of storm days at Sõrve was more closely related to sea level variations in comparison with Vilsandi. Correlation coefficients between the number of storm days and sea level are more or less similar at the four gauge stations because these records are highly correlated between themselves.

The correlations in case of maximum sea levels are somewhat higher than for mean sea levels. It is better expressed for spring, summer and autumn but not for the coldest period in January and February. Local storms act directly on the local incidental sea level, while the mean sea level largely follows the general Baltic Sea level variations with pronounced minima in summer (Fig. 5).

Comparing correlation coefficients calculated for two periods, 1950–2011 and 1966–2011, it can be concluded that the results are generally similar but the shorter period gives mostly higher correlations. It is logical because the use of inhomogeneous data in case of 1950–2011 decreases relationships.

The extreme sea level events largely coincide with extreme storms. However, some deviations still exist where strong storms did not produce remarkable storm surges and some storm surges appeared during a relatively non-remarkable wind event.

For instance, severe windstorms on 6–7 August 1967 (sustained wind speed up to 29 m s^{-1}) and on 13 March 1992 (up to 28 m s^{-1}) did not yield remarkable high sea level events. The storm track that crossed Estonia created strong northerly winds. Such winds do not have enough span of water (fetch) for northerly exposed bays, neither are they favourable for south-westerly exposed bays.

On the other hand, the background sea level of the Baltic Sea may affect local storm surge heights for up to approximately 80 cm (Fig. 5). The highest sea level events in October 1967 and January 2005 occurred on the basis of the initial 50–70 cm Baltic Proper Sea level. According to the mean seasonal sea level curve, storm surge in spring and summer has to begin on a relatively low background and no such remarkable events could be found from the catalogue. Due to a relatively small cross section of the Danish Straits, filling up the Baltic Sea with additional surplus of water takes some time and a sequence of gradually increasing storm surges can frequently be observed. For instance, a series of cyclones with local sustained wind speeds up to 21 m s^{-1} in November 2011–January 2012 yielded storm surges up to 110 cm at Pärnu at the beginning of the storm period. However, two months later, on 4 January 2012, an equally strong storm yielded already a surge of 160 cm.

For extreme surges in the coastal waters of Estonia, the centre of a powerful cyclone should bypass Estonia to the north over the Scandinavian Peninsula and the Bothnian Sea to make the local wind direction to turn from SW to NW (Suursaar et al. 2006b; Averkiev & Klevannyy 2010). As the strongest winds occur a few

Table 3. Correlation coefficients between the monthly numbers of storm days at Vilsandi and Sõrve, and monthly mean sea levels (upper values), and monthly maximum sea levels (lower values) for Estonia in 1966–2011. Statistically significant correlations on the $p < 0.05$ level are typed in bold

	January	February	March	April	May	June	July	August	September	October	November	December
Vilsandi												
Mean	**0.80**	**0.75**	**0.54**	**0.35**	0.14	**0.32**	0.15	0.20	**0.48**	**0.55**	**0.64**	**0.67**
Max	**0.69**	**0.70**	**0.55**	**0.40**	0.25	**0.45**	**0.40**	0.22	**0.53**	**0.65**	**0.64**	**0.74**
Sõrve												
Mean	**0.72**	**0.66**	**0.66**	**0.49**	0.01	0.13	0.11	0.23	**0.40**	0.20	**0.54**	**0.58**
Max	**0.72**	**0.67**	**0.72**	**0.51**	0.27	0.21	**0.46**	0.26	**0.62**	0.39	**0.62**	**0.69**

hundred kilometres to the right of the cyclone track, the reduced friction above the sea surface and the elongated shape of the Baltic Sea together with Pärnu Bay (in case of the Pärnu tide gauge) or the Gulf of Finland (for Narva-Jõesuu and St Petersburg) provide a span for a surge wave to increase towards the east, as the depth also diminishes and the gulf width converges.

Due to the specific configuration of the Gulf of Riga and Pärnu Bay, the sea level is proportional to wind speed in the power of 2.4 (Suursaar et al. 2002, 2006a), and at the upper range of wind speeds, a slight incremental increase in wind speed yields an exponentially higher incremental increase in storm surge level. Probability for an outstanding Pärnu storm surge therefore appears as a product of the probabilities of these three events: a suitable wind speed and direction, and a high boundary sea level. Using hydrodynamic modelling, Suursaar et al. (2006b) found that considering the 30 m s^{-1} sustained wind speed, the direction of SW and the Baltic mean sea level of 70 cm, the maximum sea level may reach 310 cm at Pärnu.

Influence of atmospheric circulation on severe storm and high sea level events

Correlation coefficients between the variables of large-scale atmospheric circulation and the numbers of storm days at the Vilsandi and Sõrve stations calculated for the period 1966–2011 are presented in Table 4. Correlations for the longer period 1950–2011 are similar but their maximum values are lower. It is clear that the maximum relationship is observed during the cold season from December until March. But the coefficients are different in case of different circulation variables. The most important regularity shown in Table 4 is that the characteristics of the intensity of westerlies (W, AO, NAO indices) have a highly positive correlation with storminess during the cold season. The maximum correlation above 0.7 was observed for the frequency of the circulation form W according to the Vangengeim–Girs classification. At the same time, a negative correlation appears between the frequency of the circulation form E and the number of storm days. It means that easterly and southeasterly winds do not bring storms to the coast of Estonia. The northerly circulation form C is not related to the occurrence of storms. This result lies well in line with the results of Jaagus et al. (2008).

Highly negative correlation with storminess appeared in case of the Scandinavian teleconnection pattern (SCAND) during the period from September till April (Table 4). This pattern could be interpreted with the prevailing of a large anticyclone over the Scandinavian and Baltic Sea regions in case of its positive phase. It is natural that there are no storms in anticyclonic conditions and many storms under cyclonic conditions, i.e. at negative SCAND values.

Table 4. Correlation coefficients between the monthly variables of atmospheric circulation (frequencies of circulation macroforms W, E and C according to the Vangengeim–Girs classification, Arctic oscillation (AO) index, North Atlantic oscillation (NAO) indices and Scandinavian (SCAND) teleconnection pattern) and monthly numbers of storm days at Vilsandi (upper values in the boxes) and Sõrve (lower values) in 1966–2011. Statistically significant correlations on the $p < 0.05$ level are typed in bold

	January	February	March	April	May	June	July	August	September	October	November	December
W	**0.51**	**0.74**	**0.35**	0.04	0.25	−0.08	−0.01	0.17	0.23	**0.44**	**0.39**	**0.52**
	0.51	**0.71**	**0.42**	0.21	**0.45**	0.23	−0.08	0.19	0.27	0.19	**0.49**	**0.40**
E	**−0.45**	**−0.60**	**−0.33**	−0.16	−0.22	0.18	0.13	−0.04	−0.14	**−0.52**	**−0.44**	**−0.39**
	−0.42	**−0.52**	**−0.34**	**−0.47**	−0.21	−0.15	0.15	−0.03	−0.04	−0.02	**−0.44**	−0.26
C	0.05	−0.17	0.09	0.13	0.09	**−0.32**	−0.17	−0.12	−0.10	0.16	0.19	−0.10
	−0.01	−0.25	0.02	**0.38**	−0.11	−0.03	−0.13	−0.19	−0.24	−0.25	0.08	−0.14
AO	**0.63**	**0.62**	**0.46**	0.24	0.13	−0.02	−0.14	0.01	0.27	0.27	**0.38**	**0.63**
	0.68	**0.56**	**0.46**	0.24	−0.23	−0.24	−0.09	0.02	0.27	0.01	**0.36**	**0.52**
NAO-G	**0.51**	**0.67**	**0.41**	0.14	−0.14	0.12	0.02	0.12	**0.31**	−0.22	**0.28**	**0.49**
	0.56	**0.57**	**0.38**	−0.11	−0.21	−0.19	−0.04	−0.23	**0.36**	0.09	0.19	**0.36**
NAO-C	**0.57**	**0.64**	**0.44**	0.10	−0.02	0.08	0.10	−0.03	0.24	0.14	**0.31**	**0.61**
	0.53	**0.54**	**0.43**	−0.01	−0.21	−0.17	−0.07	−0.04	0.16	0.14	**0.41**	**0.50**
NAO-P	**0.62**	**0.63**	**0.44**	0.21	0.08	0.00	−0.13	0.03	0.19	0.12	**0.41**	**0.63**
	0.61	**0.56**	**0.44**	0.01	**−0.32**	−0.21	−0.09	−0.11	0.20	0.15	**0.36**	**0.53**
NAO-T	**0.45**	**0.52**	**0.34**	0.04	−0.02	−0.23	−0.15	0.02	0.05	−0.11	0.22	**0.64**
	0.50	**0.47**	**0.43**	−0.12	−0.22	**−0.32**	−0.10	−0.15	0.15	−0.09	0.17	**0.55**
SCAND	**−0.64**	**−0.68**	**−0.58**	**−0.43**	−0.17	**−0.34**	−0.18	−0.25	**−0.44**	**−0.58**	**−0.63**	**−0.35**
	−0.63	**−0.61**	**−0.44**	**−0.58**	−0.07	**−0.28**	−0.11	**−0.34**	**−0.42**	**−0.16**	**−0.51**	**−0.36**

The influence of atmospheric circulation on storminess is negligible in summer. Storms are very few and random at that time, and the intensity of atmospheric circulation is much lower than in other seasons. Generally, the correlations are similar for the Vilsandi and Sõrve stations but mostly, Vilsandi has the higher ones.

Correlation coefficients between the variables of atmospheric circulation and sea level (Table 5) are, mostly, even higher than that for storminess. A storm is an irregular phenomenon, while the sea level height is a regular variable that could be measured every time. It is also very much affected by the intensity of westerlies. Strong westerly winds carry higher water to the Estonian coast. This relationship is the highest also in winter and autumn when the correlation coefficients are mostly between 0.4 and 0.7. The highest correlation was revealed in case of NAO indices in January.

Only two variables have statistically significant correlations throughout a year – W with a positive correlation and SCAND with a negative correlation. SCAND revealed the highest values at all, even above –0.70 in case of mean sea level records (Table 5). It demonstrates the impact of air pressure on water level in the Baltic Sea. High pressure induces low water level and low pressure high water level. The NAO teleconnection pattern (NAO-T) shows highly positive correlation only during December–March. The other teleconnection patterns (EA, EAWR, POL) did not give any statistically significant correlations with storminess and sea level. Therefore, they were omitted from Tables 4 and 5.

It is interesting that the NAO indices have no correlation with water level in November while having a significant correlation in December as well as in September and October. At the same time, sea level is highly correlated with the frequencies of the circulation macroforms W and E according to the Vangengeim–Girs classification. When considering the seasonal structure of the NAO trends, November is a kind of a transitional month between the increasing trends in winter and decreasing trends in summer, when no long-term changes have occurred. However, as a sea level increase has actually occurred also in November (Fig. 6), it must be related to local storminess (Fig. 3), and not to the NAO. A slight mismatch between November storminess and circulation indices can also be seen in Table 4.

Monthly maximum sea levels have generally lower correlations with the variables of atmospheric circulation than the mean sea level data in Table 5. It can be easily explained by the fact that the maximum values are measured only during a short time, while the mean

Table 5. Correlation coefficients between the monthly variables of atmospheric circulation (frequencies of circulation macroforms W, E and C according to the Vangengeim–Girs classification, Arctic oscillation (AO) index, North Atlantic oscillation (NAO) indices and Scandinavian (SCAND) teleconnection pattern) and monthly mean sea levels (upper values in the boxes), and monthly maximum sea levels (lower values) in 1950–2011. Statistically significant correlations on the $p < 0.05$ level are typed in bold

	January	February	March	April	May	June	July	August	September	October	November	December
W	**0.58** **0.51**	**0.62** **0.53**	**0.52** **0.53**	**0.37** **0.33**	**0.44** **0.47**	**0.49** **0.47**	**0.35** 0.20	**0.47** **0.29**	**0.52** **0.44**	**0.50** **0.44**	**0.62** **0.51**	**0.57** **0.45**
E	**–0.45** **–0.36**	**–0.59** **–0.49**	**–0.40** **–0.38**	–0.20 –0.15	–0.26 **–0.28**	**–0.38** –0.23	–0.15 –0.15	–0.27 –0.15	–0.24 –0.09	**–0.43** **–0.37**	**–0.64** **–0.46**	**–0.45** **–0.34**
C	–0.10 –0.12	0.04 0.04	–0.10 –0.13	–0.13 –0.13	–0.05 –0.06	0.00 –0.18	–0.11 0.02	–0.25 –0.14	**–0.33** **–0.39**	–0.11 –0.12	0.25 0.10	–0.04 –0.06
AO	**0.66** **0.61**	**0.54** **0.52**	**0.55** **0.52**	0.22 0.17	**0.31** 0.12	0.22 0.10	0.03 –0.10	0.12 –0.03	**0.42** **0.41**	**0.50** **0.38**	**0.29** **0.30**	**0.56** **0.49**
NAO-G	**0.70** **0.65**	**0.57** **0.55**	**0.52** **0.50**	–0.08 –0.08	**0.32** 0.17	**0.42** **0.28**	0.16 0.05	**0.37** 0.16	**0.44** **0.39**	**0.36** 0.25	0.06 0.05	**0.41** **0.35**
NAO-C	**0.69** **0.64**	**0.56** **0.53**	**0.55** **0.54**	–0.02 –0.01	0.27 0.11	**0.31** 0.15	0.15 –0.03	**0.37** 0.20	**0.45** **0.42**	**0.43** **0.35**	0.16 0.17	**0.54** **0.49**
NAO-P	**0.69** **0.65**	**0.56** **0.53**	**0.52** **0.53**	0.06 0.03	0.25 0.06	0.25 0.08	0.06 –0.09	0.25 0.13	**0.39** **0.37**	**0.45** **0.30**	0.20 0.17	**0.54** **0.49**
NAO-T	**0.55** **0.53**	**0.44** **0.42**	**0.51** **0.54**	–0.12 –0.11	–0.03 –0.08	0.06 –0.10	–0.18 –0.23	–0.09 –0.06	0.13 0.15	0.21 0.07	0.04 –0.04	**0.54** **0.50**
SCAND	**–0.70** **–0.60**	**–0.70** **–0.60**	**–0.66** **–0.57**	**–0.65** **–0.55**	**–0.53** **–0.36**	**–0.58** **–0.39**	**–0.45** **–0.31**	**–0.61** **–0.34**	**–0.70** **–0.57**	**–0.66** **–0.55**	**–0.72** **–0.60**	**–0.39** **–0.36**

sea level values as well as mean circulation variables describe the conditions during a whole month.

Storms act more directly on sea level than the circulation indices and therefore yield a slightly higher correlation. While mean sea level closely correlates with both atmospheric circulation indices (Table 5) and storminess (Table 3), the high sea level events have particularly close relationships with storminess (Table 3). The NAO and other atmospheric circulation indices involve a considerable amount of averaging and therefore are more suitable for describing mean sea level variations. However, high sea level events are stochastic events in their nature, which appear as a result of the combination of several factors.

Close relationships between the Baltic Sea level and indices describing atmospheric circulation above the North Atlantic are well known (Johansson et al. 2001; Andersson 2002), but the sea level regime in the windward western Estonian coastal sea seems to be even more sensitive to changes in wind climate and storminess (Suursaar & Kullas 2006). Water exchange processes in both the semi-enclosed Gulf of Riga and the Danish Straits largely depend on similar wind conditions. Intense westerlies and windstorms cause some mean volume surplus within the Baltic Sea and sea level inclination in the form of quarter-wave length oscillations in the fjord-like Baltic Sea. The effect is duplicated on a smaller scale within the Gulf of Riga and in the westerly or southwesterly exposed bays.

CONCLUSIONS

The study provided significant results on the variability and trends in time series of storminess and sea level along the Estonian coast, and on the relationships between storminess, sea level and large-scale atmospheric circulation.

1. Despite the inhomogeneity of the time series, it is very likely that the number of storm days has significantly increased on the western coast of Saaremaa Island since the 1920s. The main increase has occurred during the cold half-year (November–March). Comparatively lower quality of wind measurements during the first half of the 20th century and inhomogeneities due to the increase in the number of observation times partly lessen the reliability of the increasing trends.
2. Long-term trends in sea level records depend largely on post-glacial isostatic land uplift, which varies at different locations on the Estonian coast. The stations with a higher land uplift in northwesternmost Estonia (Ristna, Paldiski) have negative trends in mean sea level, while the stations with a lower land uplift have no trends or even have positive trends (Narva-Jõesuu, Pärnu).
3. Without the influence of land uplift the sea level rise at the Estonian coast (2.2–3.2 mm yr^{-1}) was slightly higher than the global mean (1.9 mm yr^{-1}) during 1950–2011. The highest sea level rise has been observed during the cold half-year (from November till March). The local sea level rise accelerated in 1950–2011. Since 1900 the periods of deceleration and acceleration have alternated, probably as a result of changes in regional wind climate, which adds to the global pattern.
4. Annual maximum sea level had steeply increasing trends at the Estonian tide gauges during the study period. This increase was much higher than the increase in mean sea level. It can be explained by the increase in local storminess and in the frequency of westerly winds.
5. The catalogue of extremely high sea levels contains 36 events. Thirty-two of them were observed during the period from October to March and 26 events have taken place since the 1960s. Three most severe flooding events were recorded on 23 September 1924, 18 October 1967 and 9 January 2005.
6. Correlation between storminess and sea level is highly positive, especially in winter and autumn, exceeding 0.6. Mostly, the correlation is higher for maximum sea levels than the mean values, but not in winter. Atmospheric circulation has significant correlations with storminess and sea level during the cold period from November to March. The number of storm days is positively correlated with the characteristics of the intensity of the westerly circulation (AO, NAOs, W). Negative correlations revealed in case of the southerly and easterly circulation E and the prevailing of an anticyclone (SCAND).
7. Similar and even higher correlations describe the relationships between atmospheric circulation and sea level records. Correlations with some variables (W, SCAND) are significant in all months while all correlations are the highest in winter. Correlation coefficients are slightly higher for mean sea levels in comparison with maximum sea levels.

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Tormisuse ja meretaseme muutused Läänemere Eesti rannikul seoses atmosfääri suuremõõtmelise tsirkulatsiooniga

Jaak Jaagus ja Ülo Suursaar

On uuritud tormipäevade arvu, keskmise ja maksimaalse meretaseme kõikumisi ning trende Eesti rannikul viimase sajandi jooksul. On kindlaks tehtud tormisuse suurenemine, kuigi tuule mõõteandmestiku mittehomogeensus muudab trendi vähem usaldusväärseks. Keskmine meretase sõltub oluliselt jääajajärgsest isostaatilisest maakerkest, mis on Eesti üksikutes osades erinev. Kui kõrvaldada maakerke mõju, siis hinnati keskmiseks meretaseme tõusuks perioodil 1950–2011 2,2–3,2 mm aasta kohta, mis oli suurem kui globaalne meretaseme tõus 1,9 mm aastas sama perioodi kohta. Põhiline osa tormisuse ja veetaseme kerkimisest on toimunud külmal poolaastal novembrist märtsini. Aasta maksimaalse meretaseme tõus on olnud oluliselt suurem kui keskmise veetaseme tõus, mis näitab üleujutuse riski tugevat suurenemist. Atmosfääri tsirkulatsioon on tihedalt seotud tormide ja kõrgete veeseisude esinemissagedusega, seda eriti külmal aastaajal. Tsonaalset tsirkulatsiooni ehk läänevoolu intensiivsust kirjeldavate muutujate, nagu Arktika ostsillatsiooni ja Põhja-Atlandi ostsillatsiooni indeksite ning tsirkulatsioonivormi W esinemissageduse väärtused korreleeruvad tugevalt tormisuse ja meretasemega perioodil 1950–2011. Olulised negatiivsed korrelatsioonid saadi tsirkulatsioonivormi E ja SCAND-indeksi korral.