Tellus (2007), 59A, 249–260

TELLUS

Decadal variations in mean and extreme sea level values along the Estonian coast of the Baltic Sea

By ÜLO SUURSAAR[1]* and JEKATERINA SOOÄÄR[2], [1]*Estonian Marine Institute, University of Tartu, Mäealuse 10a, Tallinn 12618, Estonia;* [2]*Estonian Meteorological and Hydrological Institute, Tallinn, Estonia*

(Manuscript received 29 April 2006; in final form 14 November 2006)

ABSTRACT

This study presents an overview of the Estonian sea level data set obtained from the coastal tide gauges over the period 1842–2005. Variations in the time-series of annual mean sea level, maxima and minima, as well as standard deviations are investigated and their relationships with variations in the North Atlantic Oscillation index are studied. After correcting the sea level series to spatially varying land uplift rates the series display increasing (1.5–2.7 mm yr^{-1}) trends, which in case of Pärnu tide gauge evidently exceed the global sea level rise rate. The increase is larger in winter, which is in accordance with similar seasonal structures of the NAO index trends. The rise in mean sea level, standard deviations and particularly in maxima (3.5–11.2 mm yr^{-1}) could be explained by the local response to the changing regional wind climate. Due to its windward location the sea level variations in the semi-enclosed study area are sensitive to the ongoing intensification of cyclones and prevailing westwinds. In case of the Pärnu Bay, the statistical fit of both the frequency distributions of hourly data and the maximum values distributions for 1923–2005 are inconsistent with the two highest storm surge values of 253 and 275 cm.

1. Introduction

Measurements of relative sea level variations by means of coastal tide gauges have more than two centuries of history in the Baltic Sea. Most notably, the world's longest continuous sea level record compiled from disparate historical measurements in Stockholm starts in 1774 (Ekman, 1999). Records from Swinoujscie and Kolobrzeg, both from Poland, start from 1811. 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). A number of investigations are up to now available, focusing on one or several of such problems as derivation of land uplift or subsidence rates from tide gauge data, investigation of temporal variations in relation to varying meteorological and oceanographic forcing, estimation of global sea level rise rates (e.g. Lisitzin, 1964; Vermeer et al., 1988; Ekman, 1999; Samuelsson and Stigebrandt, 1996; Johansson et al., 2001; Andersson, 2002). So far the vast majority of such work in the Baltic Sea has been based on Swedish, Finnish, German or Danish tide gauge data. In addition to some earlier papers, mostly in Russian (e.g. by Lazarenko, Mikhailov and Chernysheva), some information on Estonian sea level measurements has been presented by Raudsepp et al. (1999), Jevrejeva et al. (2001, 2005) and Suursaar et al. (2006a). However, the Estonian tide gauge data in general have not been thoroughly investigated and published yet.

In Tallinn, the capital city of Estonia, regular sea level measurements started in 1809. The near-continuous data sets are available from 1842 (Table 1, Fig. 1). Estonian historical tide gauge data are certainly a valuable source for investigating various aspects of decadal sea level tendencies, as the regional conditions affecting the sea level (land uplift rate, meteorological and oceanographic conditions, configuration of coastline) are rather different along the west and east coasts of the Baltic Sea. Other studies of the Baltic sea level are therefore not representative for the Estonian coastal sea.

'Sea level' is understood as relative sea level throughout this paper, if not otherwise specified. With regard to mean relative sea level of a location, there are three main factors influencing its variations: global sea level change, the land uplift or subsidence and changes in the water balance of the particular sea. According to numerous studies (Gornitz et al., 1982; Vermeer et al., 1988; Woodworth, 1990; Ekman, 1999; IPCC, 2001; Church and White, 2006) the global sea level rose by 1–2 mm yr^{-1} during the 20th century. The overall reason for that rise is climate warming with the main mechanism acting via the thermal seawater expansion and the gradual melting of glaciers. As it mainly occurs due to the thermal expansion of the whole ocean, it should evidently be manifested within the Baltic Sea as well, with or without temperature rise in the Baltic Sea.

*Corresponding author.
e-mail: ulo.suursaar@ut.ee
DOI: 10.1111/j.1600-0870.2006.00220.x

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

Time-series	Years covered	Years with gaps (number of missing months in brackets)
Tallinn mean	1842–1882, 1886–1917, 1923–1940, 1945, 1947–1996	1996 (9)
Tallinn extremes	1899–1917, 1923–1940, 1945, 1947-19-96	1924 (3), 1928 (1), 1929 (1), 1945 (2), 1947 (4), 1996 (9)
Narva mean	1899–1915, 1923–1943, 1945–2005	
Narva exteremes	1899–1915, 1923–1943, 1945–2005	1899 (4), 1900 (4), 1905 (1), 1907 (1), 1913 (1), 1915 (4), 1922 (3), 1941 (3), 1947 (3)
Pärnu mean	1923–2005	1923 (6)
Pärnu extremes	1923–2005	1923 (6), 1941 (1), 1944 (4), 1945(2), 1948 (5)
Ristna (all)	1950–2005	

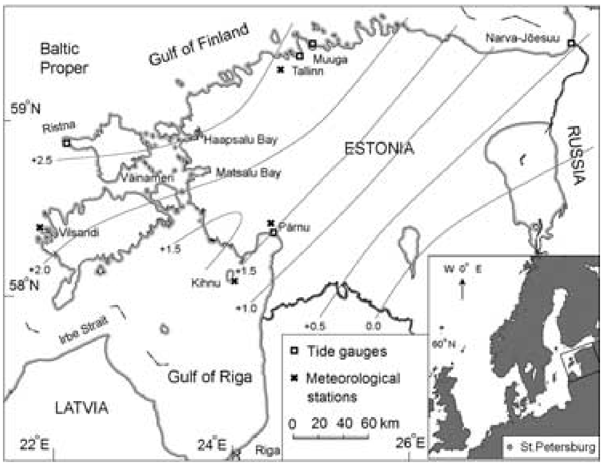

Fig. 1. Locations of selected meteorological and tide gauge stations, together with vertical crustal movement rates (Vallner et al., 1988; isobase contour interval 0.5 mm yr^{-1}).

The second main factor, the radial crustal movements, which are mainly influenced by postglacial rebound (glacial isosatic adjustment) in Estonia, is of regional origin and varies locally. The uplift rate varies among the Finnish tide gauges between 8.9 at Vaasa and 3.1 mm yr^{-1} at Hamina (Lisitzin, 1964; Vermeer et al., 1988). In the coastal areas of Estonia it varies between 0.5 and 2.8 mm yr^{-1} (Vallner et al., 1988). Another regional sea level component appears as a result of variations in the water balance of the Baltic Sea as a whole. These variations are mainly caused by water exchange processes through the Danish Straits, and by river runoff. Both are largely controlled by atmospheric pressure patterns over the North Atlantic, the North Atlantic Oscillation (NAO) (Ekman and Stigebrandt, 1990; Heyen et al., 1996; Lehmann et al., 2002; Johansson et al., 2004). Minor factors for decadal Baltic Sea level changes are variations in salinity, temperature, precipitation and evaporation regime (e.g. Ekman and Stigebrandt, 1990; Meier et al., 2004). According to Hünicke and Zorita (2006), temperature and precipitation account for up to 15% of the total sea level variability in winter and up to 35% in summer. However, this statement applies to a few, more southern stations, and the statistical inferences may be correlated with other factors.

Although most studies of past sea level changes have concentrated on changes in mean sea level instead of extremes, it is actually the latter that has the most substantial impact for the coast (Lowe et al., 2001; Orviku et al., 2003; Woodworth and Blackman, 2004). Systematic changes in extreme high waters are reported, for example, by Langenberg et al. (1999) and Johansson et al. (2001). Factors related to cyclone frequency, intensity, and their tracks are the most crucial ones for the issue. Besides the well-known St. Petersburg area, the Pärnu Bay (Fig. 1) is an area where some of the largest Baltic storm surges can occur. Since 1703 the St. Petersburg storm surge record includes just five surges larger than 280 cm above the Kronstadt zero, that is, the surges that are larger than the 275 cm surge at Pärnu on 9 January 2005 (Suursaar et al., 2006b). Due to site-specific features, the West Estonian bays are subject to storm surge hazard. Besides, it is supposed that due to the low-lying land, the gently sloping coasts and indented coastline, the flooding generated both by local storm surges and climatologically induced global sea level rise will increasingly affect the nearly tideless Estonian coastal zone (Kont et al., 2003; Orviku et al., 2003; Suursaar et al., 2006b).

The objectives of this study are (1) to investigate long-term changes both in mean water level and in extreme sea level events in the Baltic Sea along the Estonian coast; (2) to analyse relationships between sea level and atmospheric circulation indices; (3) to study changes in sea level variability and to discuss past and possible future changes in sea level regime due to changes in global and regional climate and (4) to discuss the possibility of estimating maximum expected future surge heights in Estonian coastal waters.

2. Data sets and statistical methods

Sea level observations on the territory of Estonia have been carried out at different times at 29 locations (see Jevrejeva et al., 2001; Suursaar et al., 2006a for additional overviews). However, most of the time-series are not long term and have a lot of gaps. The number of tide gauges currently operated by the Estonian Meteorological and Hydrological Institute (EMHI) is 12, in addition a few tide gauges are operated by ports. Most of the tide gauges are equipped with tide poles and have a sampling frequency of two or three times a day. Automatic tide gauges, currently operated by the EMHI, which provide hourly data, are located at Pärnu, at Narva-Jõesuu (denoted as 'Narva' in figures and tables) and at Ristna (Fig. 1). Measurements at the historically valuable location of the Tallinn Port were unfortunately discontinued and transferred to the Muuga Bay in 1996 due to the problems related to local land subsidence and construction work at the port. In the present study, data from four tide gauge stations, offering a most extensive and reliable data, were considered. We have used the database of monthly mean and extreme sea levels by the EMHI (Table 1). They represent relative sea level values in regard to the Kronstadt datum and are based on hourly measurements since 1951. The monthly values for earlier periods were obtained on the basis of daily data. Thereby the minor gaps (e.g. single months in case of mean sea level) were filled by the measured values at neighbouring stations by the EMHI according to their routines. Larger gaps were left blank (see Table 1). Annual values were calculated provided at least 9 monthly values were available. In case of monthly extreme sea levels a missing value in winter could rule out an annual value. Gaps in extreme values were not as a rule interpolated. In addition to this base of monthly and annual data hourly data from the period 1961–2005 were used to calculate the probability distributions and descriptive statistics at Pärnu.

The height system used in Estonia and in other Baltic states of the former Soviet Union differs from the Finnish and Scandinavian tide gauging standards (e.g. Lisitzin, 1966; Johansson et al., 2001). It is called the Baltic Height System 1977 with its reference zero-benchmark at Kronstadt near St. Petersburg (Lazarenko, 1986; Bogdanov et al., 2000). The Kronstadt zero was defined as the average sea level of 1825–1840. Naturally, the Kronstadt zero is not the present-time mean sea level of this tide gauge. According to the data published by 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. The zeroes of Estonian tide gauges are at least annually levelled in relation to local benchmarks. A less frequent levelling between local benchmarks and base frame is performed by national geodetic organizations (see also 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 time-series analysis as well as comparison of the results from different tide gauges. Data about the land uplift (Table 2, Fig. 1) for the studied stations were determined by using the map composed of the precise levelling data (Vallner et al., 1988). These rates should be taken as estimates for 'absolute vertical motions', not 'apparent land uplift' rates (e.g. Ekman, 1996), nor exactly as glacial isosatic adjustments (GIA). In 1977–1985 Vallner together with his colleagues from the Institute of Astrophysics and Atmospheric Physics carried out an extensive study of repeated precise levellings, taking into account data from previous precise levelling campaigns (1933–1943 and 1956–1970). The preciseness of uplift rates was considered ±0.2 mm yr^{-1} then. Later, using precise gravity measurements (e.g. Sildvee 1998) and GPS technology, regional geoid models were worked out in cooperation with the Danish Institute of Geodesy (e.g. Forsberg et al., 1996; Milne et al., 2001) and the vertical motion rates verified. The actual accuracy and constancy of uplift rate estimates is yet unknown. In comparison with some other sources (Vermeer et al., 1988; Ekman, 1996; Kakkuri, 1997; Johansson et al., 2004) we assume that this might be up to ±0.5 mm yr^{-1}. In addition, there may be local disturbances, such as neotectonic and anthropogenic components. This may introduce a small error in long-term trend estimates for mean sea level, but it less affects the results on seasonal variability, extremes and correlations with forcing factors.

As a deviation from Fig.1, an uplift rate of 1.8 mm yr^{-1} was used for Tallinn (Table 2). Due to local subsidence anomaly the uplift rate in the city-location is lower than in the adjacent areas (Vallner et al., 1988). The uplift rate near St. Petersburg and

Table 2. Changes by trend of relative sea level time-series (mm); linear trend slopes S, local uplift rates U, and their combinations S + U (mm yr^{-1}). Trends of relative sea level (S) on the $p < 0.05$ significance level are marked with an asterisk

Time-series	Period	Years	Change	S	U	S+U
Tallinn mean	1842–1995	154	18	0.12	1.8	**1.9**
Tallinn mean	1923–1995	73	−6	−0.08	1.8	**1.7**
Tallinn mean	1947–1995	49	−15	−0.31	1.8	**1.5**
Narva mean	1899–2005	107	55	0.51*	0.5	**1.0**
Narva mean	1923–2005	83	98	1.18*	0.5	**1.7**
Narva mean	1946-2005	60	97	1.61*	0.5	**2.1**
Pärnu mean	1924–2005	82	87	1.06*	1.5	**2.6**
Pärnu mean	1946–2005	60	48	0.80*	1.5	**2.3**
Ristna mean	1950-2005	56	−66	−1.12*	2.6	**1.5**
Tallinn max	1899–1995	97	186	1.92*	1.8	**3.7**
Tallinn max	1948–1995	48	189	3.93*	1.8	**5.7**
Narva max	1899–2005	107	475	4.44*	0.5	**4.9**
Narva max	1946–2005	60	479	7.98*	0.5	**8.5**
Pärnu max	1924–2004	81	164	2.02	1.5	**3.5**
Pärnu max	1946–2005	60	299	4.99*	1.5	**6.5**
Ristna max	1950–2002	53	322	6.08*	2.6	**8.7**
Ristna max	1950–2005	56	484	8.64*	2.6	**11.2**
Tallinn min	1899–1995	97	11	0.11	1.8	**1.9**
Tallinn min	1947–1995	49	−49	−1.00	1.8	**0.8**
Narva min	1899–2005	107	27	0.25	0.5	**0.8**
Narva min	1946–2005	60	40	0.66	0.5	**1.2**
Pärnu min	1924–2005	82	120	1.46	1.5	**3.0**
Pärnu min	1946–2005	60	98	1.63	1.5	**3.1**
Ristna min	1950–2005	56	–9	−0.17	2.6	**2.4**

Kronstadt is practically zero (Lazarenko 1986; Vallner et al., 1988).

Tendencies in sea level time-series were analysed using linear regression analysis. For sea level rise rates linear trend slopes (mm yr^{-1}) were calculated. Multiplying a slope by a number of years, 'change by trend' for a period was obtained (Table 2). The trends were considered to be statistically significant on the $p <$ 0.05 level, evaluated by the Student's t-test. The obtained trend estimates were further adjusted to take into account land uplift rates.

Relationships between relative sea level and intensity of westerly (i.e. the NAO index) or local storminess were studied by correlating the time-series. Atmospheric circulation features were described by the NAO index which is downloadable from the NOAA Climate Prediction Centre website (http://www.cpc.noaa.gov/data/teledoc/telecontents.shtml). The NAO is usually described as a difference between the standardized sea level pressure anomalies between Icelandic low and Azores high and can be calculated using either data from Ponta Delgada, Lisbon (Hurrell, 1995) or Gibraltar (Jones et al., 1997). The data of Gibraltar were used, as the NAO Gibraltar index offers slightly better results for the changes in Estonian climate (Jaagus, 2006a). The number of storm days per year at the Vilsandi meteorological station was used to measure local storminess. A 'storm day' has at least one observation with mean wind speed 15 m s^{-1} or higher (Orviku et al., 2003).

Applying a running correlation method, the temporal development of the correlation between the winter (January–March, abbreviated as JFM) sea level and winter NAO index was investigated. Similarly to Andersson (2002), and Hünicke and Zorita (2006) a 21-yr window was used. The correlation coefficient was calculated between the series with a length of 21 yr, the values assigned to the middle year of the window. The window was slid along the series with a 1-yr time step, yielding time-series of correlation coefficients.

Extreme value analysis was performed by fitting Gumbel distribution to samples of annual maximum and minimum values. Taking into account the gaps (see also Table 1), the series for this analysis included 83 yr (1923–2005) at Pärnu, 96 yr (1899–2005) at Narva Jõesuu (Narva), 56 yr (1950–2005) at Ristna and 85 yr (1899–1995) in Tallinn.

3. Results and discussion

3.1. Decadal sea level variations

Time-series representing annual means and selected seasonal mean sea levels show quite different, but still mostly increasing tendencies (Figs. 2, 3). Statistical significance is not a particularly important issue in this case, as both the sign and significance of a trend-line depend on whether we consider sea level changes relative to benchmarks (i.e. relative sea level), or we take land uplift into account (Table 2). Furthermore, moving averages of annual mean sea level series show 30–40 yr cycles (Fig. 3) which coincide with the similar cycles, for example, in Lithuanian (Dailidiene et al., 2006) or Finnish (Johansson et al.,

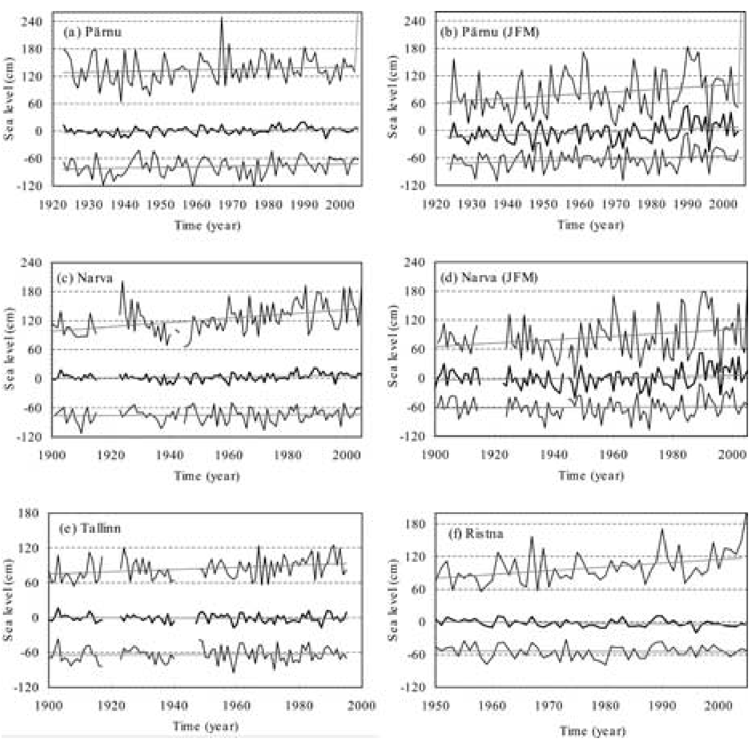

Fig. 2. Decadal variations in maximum, mean and minimum sea levels for the whole year (a, c, e and f), and winter months (b and d). The data of Tallinn are shown since 1900. Note that January 2005 maxima at Pärnu (a and b, 275 cm) and Ristna (f, 209 cm) are not considered in the trend analysis.

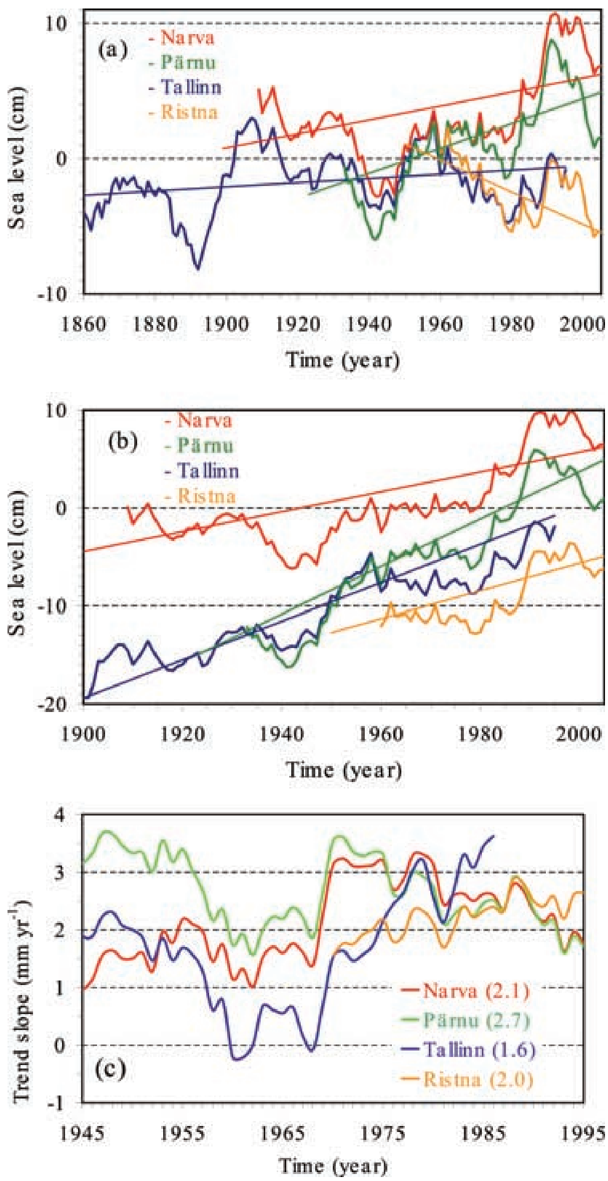

Fig. 3. Time-series of 11-yr moving averages and linear trendlines of relative mean sea level data (a, original annual data are not shown); moving averages and trendlines after correcting the sea level series with land uplift rates (b); slopes of trendlines for 41 yr periods (c), the value is assigned to the middle year of the running window, for example, 1945 for 1925–1965 and 1985 for 1965–2005; trendlines are shorter after 1985, that is, 1975–2005 for 1995. The numbers in brackets (c) mark average slope values for the period 1945–1985 (representing 1925–2005).

2004) sea level data. These cycles, with the amplitude of about 5 cm (Fig. 3b), can influence linear trend estimates. For example, the series of Narva mean sea level for 1899–2005 starts 'high' and ends 'low' (Fig. 3a,b) and the linear trend estimate (S + U = 1.0 mm yr^{-1}, Table 2) probably underestimates the real tendency. Due to the irregular nature of these cycles and shortness of the series, it is difficult to properly eliminate the cycles' influence, but some alternative (shorter) periods are considered in Table 2, bearing also in mind the gaps. Besides, as trend slope estimates depend on chosen terminal points (and length) of a time-series, we calculated 'running slope' estimates, which display rather large time-dependent variability of (corrected with land uplift) trend slopes (Fig. 3c). It is interesting to point out that while all the possible 41-yr periods yielded trend slopes between 1.5 and 2.8 mm yr^{-1} for Ristna (Fig. 3c), the full 56-yr period just yielded 1.5 mm yr^{-1} (Table 2). We consider the latter value as infected from periodicity and non-representative, though the series is longer. The best trend slope (S + U) estimate for the period of about 1925–2005 might be 1.5–1.7 mm yr^{-1} in Tallinn, 1.5–2 mm yr^{-1} at Ristna, 1.7–2.1 mm yr^{-1} at Narva-Jõesuu and 2.3–2.7 mm yr^{-1} at Pärnu (Table 2, Fig. 3c).

Thus, the mean sea level rise rates for Tallinn, Narva and Ristna are roughly equal to or insignificantly higher than the most recent global estimates, about 1.7 mm yr^{-1} according to, for example, Church and White (2006) or about 1.5 mm yr^{-1} as the central value for 1–2 mm yr^{-1} estimate of 20th century sea level rise by IPCC (2001). However, even considering possible uncertainties in data quality and land uplift rates, the trend estimates for Pärnu tide gauge seem to be significantly higher (2.3–2.7 mm yr^{-1}) than the global one (Table 2, Fig. 3).

The excess over the proposed global rate of 1.5 or 1.7 mm yr^{-1} could be explained by the local influence of the changing regional wind climate, as discussed in a hydrodynamic modelling study (Suursaar et al., 2006b; Suursaar and Kullas, 2006). The increase in the westerly wind component above North Europe over the last 50 yr is quite evident (Siegismund and Schrum, 2001; Keevallik and Rajasalu, 2001; Räisänen et al., 2004). Our results on Pärnu show, that the effect of increasing southwesterly winds and storminess over the Baltic Sea can be larger than considered earlier. The Pärnu tide gauge is both regionally and locally windward, and therefore sensitive to wind climate changes. The effect is localised at the bays exposed to SW or W (Suursaar et al., 2006a). In the West-Estonian coastal sea there are three such bays, Haapsalu, Matsalu and Pärnu (Fig. 1), the latter being the only one to have a tide gauge. The crucial role of changes in wind climate could be confirmed by astonishingly large change rates in maximum sea levels (Table 2), ranging between 3.5 and 11.2 mm yr^{-1}, while the rates in minima are only 0.8–3.1 mm yr^{-1}. No other meteorological or hydrological forcing could yield such sea level developments (see also Langenberg et al., 1999). It can be argued that perhaps the sparse measurements of the first half of the 20th century did not determine the peak values too precisely. But latter hourly data, available from the 1950s, demonstrate similar very steep trends. Additional discussion on sea level relationships with zonal circulation and storminess is presented in the following chapter.

The positive trends in annual time-series definitely appear due to the positive trends in winter (JFM) (Figs. 2a–d, 6). Seasonality is an important sea level variability feature. It does not only

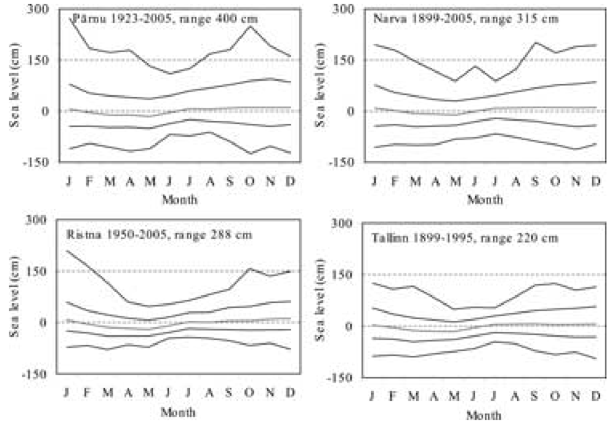

Fig. 4. Seasonal variations in monthly sea level statistics. Lines from top: absolute maximum, average maximum, mean, average minimum and absolute minimum.

appear as a seasonal signal in means (with amplitude 10–20 cm), but also in magnitudes (Fig. 4) and temporal tendencies of extremes (Fig. 6). Furthermore, significant seasonal structure of the trends should lead to enhancement of seasonal signal in sea level records. The tendency has already been reported for various parts of the Baltic Sea (Ekman and Stigebrandt, 1990; Ekman, 1998; Plag and Tsimplis, 1999; Suursaar et al., 2006a) and it has increased over the last decades (Fig. 6e and f).

Annual fluctuations of minima and averages show significant correlations (e.g. $r = 0.57$ at Pärnu), whereas maxima and averages are not so well connected to each other ($r = 0.40$). While high sea level events usually appear as short individual peaks with low impact on annual statistics, the low sea level events develop slowly during more stable anticyclonic weather patterns due to continuous east or north winds (Suursaar et al., 2002).

Pärnu sea level record has the largest variability in the study area (Figs. 4, 5). It includes 29 individual events higher than 150 cm, 23 of which occurred in October-March and six in April–September. The period 1923–1963 includes 13 such events *vs.* 16 events in 1964–2004. Substantial increase in wintertime maxima

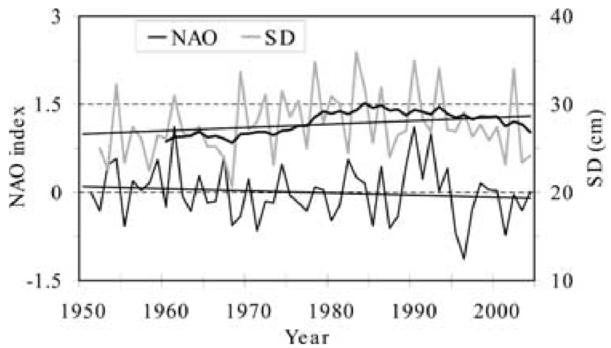

Fig. 5. Variations in annual mean NAO-indices and Pärnu sea level standard deviations (*SD*, calculated from hourly data) together with linear trendlines and 11-yr moving averages for the *SD*.

(Fig. 2b) could be explained both by increased storminess and by more mild ice conditions. These factors are correlated both mutually and with the NAO in Estonia (Jaagus, 2006a,b). Storm surge cannot develop in Pärnu Bay, if the Gulf of Riga is covered with ice. Indeed, the date of appearance of sea ice has shifted to mid-winter and the number of ice days has decreased by 70 in Kihnu over the last 54 yr (Jaagus, 2006b).

The sea level variability expressed as annual standard deviations, calculated on the basis of hourly data, show a statistically significant rise by 2 cm in 1952–2004 (Fig. 5). Standard deviations have increased by 1–3 cm over a period of 50 yr also at Finnish tide gauges (Johansson et al., 2001). Both in Finnish and Estonian stations the sea level variability was somewhat lower in 1950s, and higher in 1980s. The average standard deviation was 27.7 with variability range 20.6–35.9 cm at Pärnu. This is close to the estimates at Kemi and St. Petersburg, where average standard deviations are approximately between 25 and 30 cm (e.g. Lazarenko, 1986; Johansson et al., 2001).

3.2. Correlations with the NAO index

Close relationships between the Baltic sea level and various indices describing atmospheric circulation above North Atlantic (NAO, AO) or, more specifically, above the Baltic Sea (BAC, BSI and Wibix) are well known (Andersson, 2002; Lehmann et al., 2002; Hagen and Feistel, 2005). The NAO index is not a single forcing for sea level, it rather manifests through a complex of forcing factors such as stronger westerly airflow, higher winter temperature, higher precipitation rate, lower ice extent, etc. All these manifestations are mutually correlated, but their specific impacts on sea level are hardly distinguishable. The main hydrodynamic mechanism for the Baltic sea level applies through the more intensive water inflow through the Danish Straits as a result of sea level differences in the transition area between the North and Baltic Seas, which in turn appears due to stronger westerlies and more frequent storms (Stigebrandt, 1984; Heyen et al., 1996; Samuelsson and Stigebrandt, 1996).

Estonian sea level data show low-frequency correlations with the NAO index and the Baltic Sea level. According to a hydrodynamic modelling study (Suursaar et al., 2006a), the share of locally generated sea level variability is up to 40% in a few windward bays and below 20% virtually elsewhere in the study area. Water exchange processes both in the semi-enclosed Gulf of Riga and in the Danish Straits are sensitive to similar wind conditions. Intense westerly and windstorms cause mean volume surplus within the Baltic Sea and sea level inclination as quarter-wave length oscillations in the fjord-like Baltic Sea. The effect is duplicated on a smaller scale within the Gulf of Riga. Model runs also showed that every change in long-term wind regime (change in average wind speed, variability, or directional distribution) has an effect on the established sea level equilibrium (Suursaar et al., 2006a). The reaction depends on coastline configuration and bottom topography, and it is strongest in the far

Table 3. Regression between winter (January to March) NAO index (WNAO) and winter mean sea level (WSL, cm)

Tide gauge	Period	Regression result	R^2
Pärnu	1924–2005	WSL = 12.07 WNAO – 8.67	0.54
Narva	1923–2005	WSL = 11.59 WNAO – 5.56	0.53
Tallinn	1900–1996	WSL = 8.68 WNAO – 10.13	0.44
Ristna	1950–2005	WSL = 11.42 WNAO – 9.46	0.55

ends of windward bays, like Pärnu Bay. Increase in western wind component by magnitude of 2–3 m s^{-1} reported for the last 50 yr (Alexandersson et al., 1998; Siegismund and Schrum, 2001; Keevallik and Rajasalu, 2001) may account for up to a 5 cm rise in annual mean sea level at Pärnu (Suursaar et al., 2006a). This wind-induced local change component appears in addition to a possible analogous change outside our study domain, which, under similar circumstances, could be up to 3–4 cm in the Central Baltic according to the study by Meier at al. (2004).

The correlations between NAO and Estonian sea level series are both the highest and statistically most significant in winter (JFM), the local storminess additionally showing strong relationships for October–December (Fig. 7). Storms act more directly on sea level than the NAO index does and therefore yield a slightly higher correlation. On the basis of the winter NAO index it is possible to present some diagnostic relationships (Table 3), which allows the reconstruction of JFM mean sea level on the basis of the NAO index. The seeming disagreement between gently decreasing NAO trend for the chosen period (Fig. 5), and positive mean sea level and sea level variability trends, could be explained by the seasonal structure of the NAO index trends (Fig. 6f). The positive NAO trend in winter is likely to affect sea level more strongly than the negative NAO trend in summer does. The seasonal curves of the NAO index trend slopes are quite similar to the curves of mean sea level trend slopes. Moreover, seasonality has increased for both cases over the last 150 yr (Fig. 6).

The results of running correlation analysis show variations in correlations between 0.25 and 0.75 at Pärnu (Fig. 8). Correlations with winter data show values between 0.41 and a remarkably high 0.94 at Pärnu and 0.93 at Narva–Jõesuu. The long-term cycles (Fig. 8) are coherent with the results acquired with the similar 21-yr running window for the other parts of the Baltic Sea (Andersson, 2002; Hünicke and Zorita, 2006). This time-variable nature of the relationships between sea level and the NAO mainly appear due to the changes in the locations of the Azores high- and Icelandic low-pressure centres that define the NAO index (Ulbrich and Christoph, 1999; Wakelin et al., 2003; Hu and Wu, 2004).

3.3. Frequency distributions and return periods

The sea level variability range at Pärnu is rather large (400 cm, Figs. 2a and 4) for a nearly tideless location. While empirical

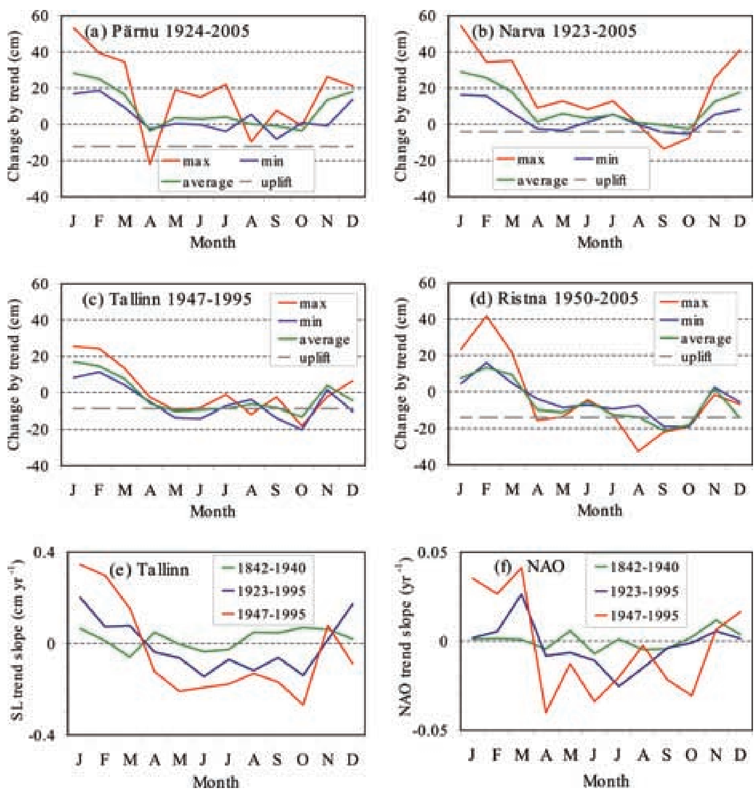

Fig. 6. Seasonal structure of changes by trend and trend slopes in sea level (SL) data and NAO. ‘Uplift’ can be viewed as zero-correction, any change above the line means climatological (global, regional and local) sea level rise.

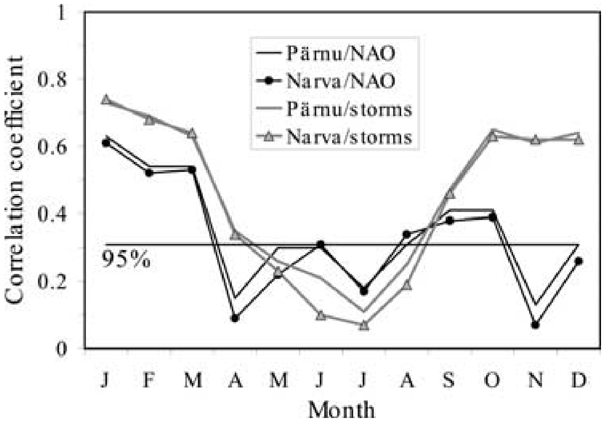

Fig. 7. Seasonal variations in correlations of sea level at Pärnu and Narva with NAO index and frequency of storm days at Vilsandi. The calculations were based on data from 1950 to 2002 (see: Suursaar et al., 2006a) and are shown with the 95% significance level.

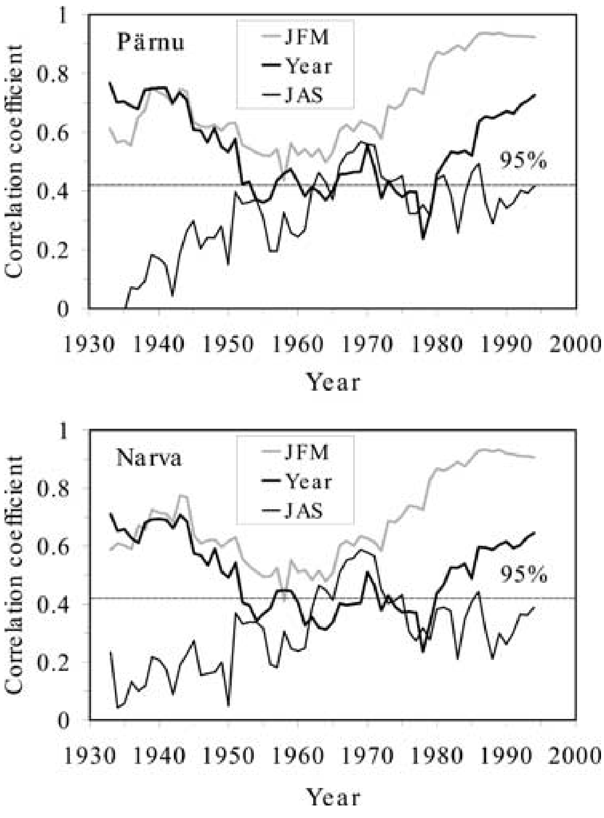

Fig. 8. Running correlations with 21-yr window between sea level and NAO for winter months (JFM), July to September (JAS), and the whole year, shown together with the 95% significance level.

probability distributions for individual years show some interannual variability, the distributions of 20-yr periods become smoother and more stable (Fig. 9). The curve of 1981–2000 has shifted towards higher values, when compared with the period 1961–1980 (Fig. 9a). As the postglacial rebound and global

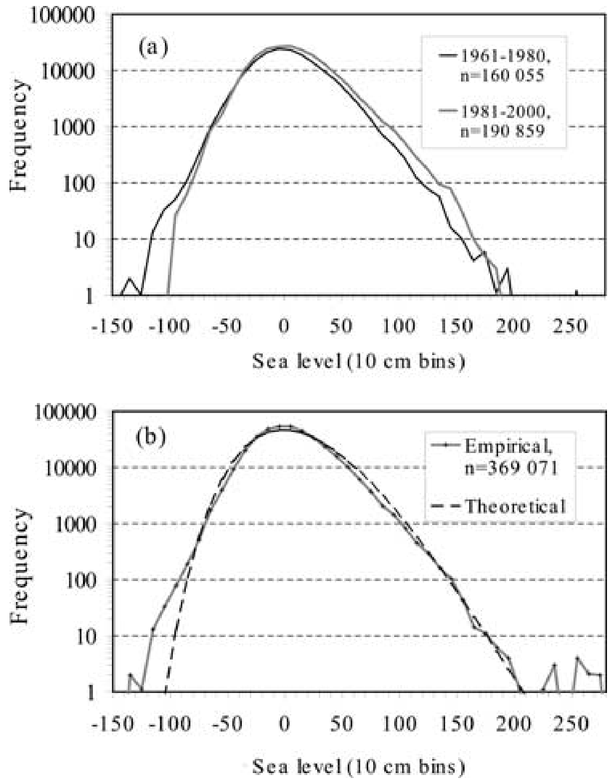

Fig. 9. Empirical frequency distributions of Pärnu hourly sea level data for the two sub-periods (a), and for the whole period of 1961–2005 together with a theoretical distribution version (b). Note that logarithmic *y*-axis visually emphasizes tail areas. There appear to be at least 12 outliers (values above 200 cm in b) which do not fit theoretical distributions.

sea level rise roughly compensate each other at Pärnu, the shift appears due to the changes in wind climate (NAO, storminess, etc.). According to Johansson et al. (2001) the distribution curves of Finnish tide gauge data has also become somewhat broader, and the probability for high sea level values has increased.

Sea level data from a tide gauge can nearly always be fitted by some theoretical distribution. However, in case of Pärnu the empirical distribution function for the period from 1961 to the end of January 2005 (Fig. 9b) cannot be fitted by any single reasonable theoretical distribution, so that both, the main bulk of the data and the tail areas were successfully described. In statistical terms the distribution is contaminated. It probably consists of several distributions due to mixed populations, for example, as the result of interannual variations in the Baltic mean sea level. Furthermore, about 12 values (describing two short storm events on 18 October 1967 and on 9 January 2005) from the sample of 369 071 elements, remain 'outliers' or 'errors' in any case (Fig. 9b).

We shall further discuss the annual maxima and minima, and their distributions. It is usually believed, that out of Fisher-Tippet function family (Type I Gumbel, Type II Frechet or Type III reverse Weibull) both for extreme wind speeds and return periods of extreme sea level the best fit is offered by the Gumbel distribution (Gumbel, 1958; Onforio et al., 1999; Lowe et al., 2001; Wroblewski, 2001). To find empirical return periods the observation period was divided by the (ranking) number of events. Using least-squares method, mode and scale parametres for theoretical Gumbel distributions were calculated for the tide gauges under study. The plots against the empirical data (Fig. 10a and b) show a more or less satisfactory fit in case of three tide gauges, but failure in case of Pärnu maxima. It should be stressed here that our idea was not to find the ideal fit by checking a large number of distribution parametres, and some other distribution would possibly have offered a slightly better fit (i.e. less steep slope) in the region of higher values. The main idea was to show that no extreme value distributions could probably describe or predict the two extreme sea level events of 253 cm (in 1967) and of 275 cm (in 2005).

Outlier is sometimes defined using the difference between the first and third quartile of the sample. The difference multiplied by 1.5 and added to the third quartile would give an inner fence for 'mild outlier'. Both 253 and 275 cm values fall far behind this limit. 209 cm at Ristna (in 2005) is also an outlying, but not very representative value (see Suursaar et al., 2006b). According to the distribution based on 82 yr of data valid until the end of 2004, the value 253 cm should be considered as a very outlying value (Fig. 10c). It has the recurrence period of some 300 yr, according to Gumbel fit and possibly around 1000 yr according to some 'better' fit. If there were a gap in measurements in 1967, the 81-yr empirical data set (Fig. 10c) would not project that event even within 1000 yr. The event of 1967 was actually repeated and surpassed just 38 yr later.

A misbelief probably exists, that as soon as we discover the 'right' theoretical distribution function, we can extrapolate the return period outside the length of the empirical series. Evidently, an estimation of certain extreme events in dependence on long return periods can be valid for certain established climatological equilibrium and changes in meteorology will lead to future changes in the return periods of extreme events. However, the changes in empirical response data cannot follow the ongoing climatological changes fast enough, as extreme events are rare anyhow. Thus, the existing bulk of the data does not carry sufficient statistical information about possible extreme sea level values at Pärnu, as the most extreme values seem to appear 'outside' the system. The situation is comparable with the gust wind speed record that includes both 'normal' winds and data from occasional tornados (e.g. Cheng and Yeung, 2002), or sea level data, including tsunami events, due to earthquake or asteroid impact.

The final question is, how to explain these two extremely high sea level values at Pärnu, which statistically appear as unpredictable outliers, but are nevertheless caused by 'normal' storms (though, with catastrophic consequences for West Estonia; Suursaar et al., 2006b)? The main reason lies in the southwesterly exposition and the specific configuration of the Gulf of Riga, and the Pärnu Bay in particular. Suursaar et al. (2002, 2006a) modelled the dependence of Pärnu local sea level constituents from wind speed and direction, and found that it is proportional to the wind speed in the power of 2.4. This dependence introduces a large uncertainty component at the upper range of wind speeds: a slightly higher wind speed and a 'suitable' direction (closer to

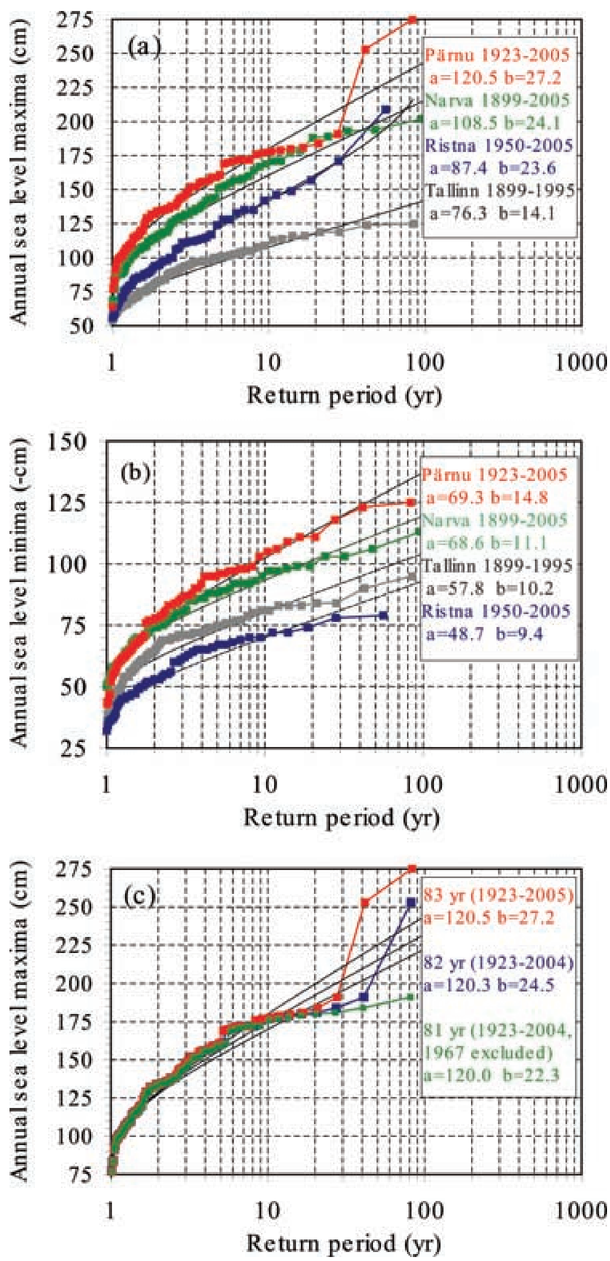

Fig. 10. Return periods based on annual maximum (a and c) and minimum (b) sea level data for the four tide gauges (a and b), and for Pärnu (c) together with theoretical Gumbel distribution curves. Distribution parameters shown in legend boxes (a-mode, b-scale) were calculated using least-squares method.

220° for the Pärnu Bay) lead to remarkable differences in Pärnu surge heights. One metre per second wind speed increment yields a 20 cm higher surge near the 30 m s^{-1} mean wind speed value. On the other hand, a deviation of wind direction by about 20° has an opposite effect with the same magnitude. The third crucial factor for the two highest Pärnu surges was the high (60–90 cm) Baltic background sea level. Probability for an outstanding Pärnu storm surge therefore appears as a product of probabilities of these three events: a suitable wind speed and direction, and a high boundary sea level.

According to sensitivity runs of the hydrodynamic model (Suursaar et al., 2002, 2006a) and considering the 30 m s^{-1} mean wind speed (which has occurred at least two to three times in the last 50 yr), the direction of SW (which is quite usual, if the cyclone passes Estonia from the north, heading from SW to NE), and the Baltic mean sea level of 70 cm for at least a few days (which happens once or twice almost every autumn or winter), the maximum sea level may easily reach 310 cm at Pärnu. Considering the further rise of the global sea level (IPCC, 2001) and an anticipated intensification of storms (Räisänen et al., 2004), a surge up to 350 cm is hydrodynamically and meteorologically possible. Coincidence of these three nearly independent events is just needed. This probability should be further estimated on the basis of meteorological data, rather than on sea level data.

4. Conclusions

(1) Trend analysis of the Estonian sea level data from the period 1842–2005 showed that, at Tallinn, Ristna and Narva–Jõesuu tide gauges the mean sea level rise rates (corrected with land uplift rates) were about 1.5–2.1 mm yr^{-1}. Besides, trend slope estimates considerably depended on the chosen terminal points of the series. Nevertheless, the trend at Pärnu (2.3–2.7 mm yr^{-1}) was significantly steeper than the mean global sea level rise estimate (1.5–1.7 mm yr^{-1}; IPCC, 2001; Church and White, 2006).

(2) The sea level increase mainly occurs in winter, which is in good accordance with similar seasonal structures of the NAO trends, and local storminess data. In the Estonian coastal waters the excessive rise in mean sea level and particularly in maxima (3.5–11.2 mm yr^{-1}) could be explained by the local sea level response to the changing regional wind climate. Sea level variations in the semi-enclosed study area with windward location are sensitive to the current increase in the westerly and intensification of cyclones. The results indicate that in case of an obvious decadal trend in wind conditions 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 yield steeper than average sea level trend in windward side, and less steep in leeward side (and vice versa in case of a negative wind speed trend).

(3) Increase in wind speed and storminess lead to the sea level variability increase in the windward section of the Baltic Sea. Annual standard deviations calculated on the basis of hourly sea level data at Pärnu show a rise from 26.5 to 28.5 cm for the period 1951–2004. Results from the running correlation analysis between NAO index and the Estonian sea level data showed temporal variations with maximum correlations in 1940s and 1980s. Wintertime correlations reached 0.94 at Pärnu and 0.93 at Narva-Jõesuu.

(4) In the Pärnu Bay the statistical fit of both frequency distributions of hourly data from the period 1961–2005 and maximum values distributions for 1923–2005 are inconsistent with the data from the two highest storm surges of 253 cm (in 1967) and 275 cm (in 2005). In statistical terms they appear as outliers, or elements of some other population. The parametres of maximum expected storm surges could be estimated on the basis of hydrodynamic modelling study.

5. Acknowledgments

The study was supported by the Estonian Science Foundation (through the grants No. 5929, and 5763).

References

Alexandersson, H., Schmidt, T., Iden, K. and Tuomenvirta, H. 1998. Long-term variations of the storm climate over NW Europe. *Global Atmos. Ocean. Syst* **6**, 97–120.

Andersson, H. C. 2002. Influence of long-term regional and large-scale atmospheric circulation on the Baltic Sea level. *Tellus* **54A**, 76–88.

Bogdanov, V. I., Medvedev, M. Yu., Solodov, V. A., Trapeznikov, Yu. A., Troshkov, G. A. and co-authors. Mean monthly series of sea level observations (1777-1993) at the Kronstadt gauge. *Reports of the Finnish Geodetic Institute* **2000:1**, Kirkkonummi, Finland.

Cheng, E. and Yeung, C. 2002. Generalized extreme gust wind speeds distributions. *J Wind Eng. Ind. Aerodyn.* **90**, 1657–1669.

Church, J. A. and White, N. J. 2006. A 20th century acceleration in global sea-level rise. *Geophys. Res. Lett.* **33**, L01602.

Dailidiene, I., Davuliene, L., Tilickis, B., Stankevičius, A. and Myrberg, K. 2006. Sea level variability at the Lithuanian coast of the Baltic Sea. *Boreal Env. Res.* **11**, 109–121.

D'Onofrio, E. E., Fiore, M. M.E. and Romero, S. I. 1999. Return periods of extreme water levels estimated for some vulnerable areas of Buenos Aires. *Cont. Shelf Res.*. **19**, 1681–1693.

Ekman, M. 1996. A consistent map of the postglacial uplift of Fennoscandia. *Terra Nova* **8**, 158–165.

Ekman, M. 1998. Secular change of the seasonal sea level variation in the Baltic Sea and secular change of the winter climate. *Geophysica* **34**, 131–140.

Ekman, M. 1999. Climate changes detected through the world's longest sea level series. *Global Planet. Change* **21**, 215–224.

Ekman, M. and Stigebrandt, A. 1990. Secular change of the seasonal-variation in sea-level and the pole tide in the Baltic Sea. *J. Geophys. Res. - Oceans* **95**, 5379–5385.

Forsberg, R., Solheim, D. and Kaminskis, J. 1996. Geoid of the Nordic and Baltic area from gravimetry and satellite altimetry. *Proc. Int. Symposium on Gravity, Geoid and Marine Geodesy, Tokyo*, 540–548.

Gornitz, V., Lebedeff, S. and Hansen, J. 1982. Global sea level trend in the past century. *Science* **215,** 1611–1614.

Gumbel, E.J. 1958. *Statistics of Extremes*. Columbia University Press, New York.

Hagen, E. and Feistel, R. 2005. Climatic turning points and regime shifts in the Baltic Sea region: the Baltic winter index (WIBIX) 1659-2002. *Boreal Env. Res* **10**, 211–224.

Heyen, H., Zorita, E. and von Storch, H. 1996. Statistical downscaling of monthly mean North Atlantic air-pressure to sea level anomalies in the Baltic Sea. *Tellus* **48A**, 312–323.

Hu, Z.-Z. and Wu, Z. 2004. The intensification and shift of the annual North Atlantic Oscillation in aglobal warming scenario simulation. *Tellus* **56A**, 112–124.

Hurrell, J.W. 1995. Decadal trends in the North Atlantic Oscillation: regional temperatures and precipitation. *Science* **269**, 676–679.

Hünicke, B. and Zorita, E. 2006. Influence of temperature and precipitation on decadal Baltic Sea level variations in the 20th century. *Tellus* **58A**, 141, 153.

IPCC 2001. *Climate change 2001: Synthesis Report*. Cambridge University Press, Cambridge, UK, 408 pp.

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 in the Baltic Sea near the Estonian coast during the period 1949/50-2003/04 and their relationships to large-scale atmospheric circulation. *Boreal Env. Res*. **11,** 169–183.

Jevrejeva, S., Rüdja, A. and Mäkinen, J. 2001. Postglacial rebound in Fennoscandia: new results from Estonian tide gauges. In: *Gravity, geoid and geodynamics* (ed. M. Sideris), IAG Symposia **123**, Springer-verlag, Berlin-Heidelberg-New York, 193–198.

Jevrejeva, S., Moore, J. C., Woodworth, P.L. and Grinsted, A. 2005. Influence of large-scale atmospheric circulation on European sea level: results based on the wavelet transform method. *Tellus* **57A**, 183–193.

Johansson, M., Boman, H., Kahma, K. K. and Launiainen, J. 2001. Trends in sea level variability in the Baltic Sea. *Boreal Env. Res.* **6**, 159–179.

Johansson, M., Kahma, K. K. and Boman, H. 2004. Scenarios for sea level on the Finnish coast. *Boreal Env. Res.* **9**, 153–166.

Jones, P. D., Jónsson, T. and 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.

Kakkuri, J. 1997. Postglacial deformation of the Fennoscandian crust. *Geophysica* **33**, 99–109.

Keevallik, S. and Rajasalu, R. 2001. Winds on the 500 hPa isobaric level over Estonia (1953-1998). *Phys. Chem Earth (B)* **26**, 425–429.

Kont, A., Jaagus, J. and Aunap, R. 2003. Climate change scenarios and the effect of sea-level rise for Estonia. *Global Planet Change* **36**, 1–15.

Langenberg, H., Pfizenmayer, A., von Storch, H. and Sündermann, J. 1999. Storm-related sea level variations along the North Sea coast: natural variability and anthropogenic change. *Cont. Shelf Res*. **19**, 821–842.

Lazarenko, N. N. 1986. Variations of mean level and water volume of the Baltic Sea. In: Water Balance of the Baltic Sea. *Baltic Sea Environm. Proc.* No. 16, pp. 64–80.

Lehmann, A., Krauss, W. and Hinrichesen, H.-H. 2002. Effects of remote and local atmospheric forcing on circulation and upwelling in the Baltic Sea. *Tellus* **54A**, 299–316.

Lisitzin, E. 1964. Contribution to the knowledge of land uplift along the Finnish coast. *Fennia* **89**, 22 pp.

Lisitzin, E. 1966. Mean sea level heights and elevation systems in Finland. *Societas scientiarum Fennica, Commentationes physico-mathematicae*, Vol. 32, N. 4. 14 pp.

Lowe, J. A., Gregory, J. M. and Flather, R. A. 2001. Changes in the occurrence of storm surges around the United Kingdom under a future climate scenarion using a dynamic storm surge model driven by the Hadley Centre climate models. *Clim. Dyn.* **18**, 179–188.

Milne, G. A., Davis, J. L., Mitrovica, J. X., Scherneck, H.-G., Johansson, J. M. and co-author. 2001. Space-geodetic constraints on glacial isostatic adjustment in Fennoscandia. *Science* **291**, 2381–2385.

Meier, H. E. M., Broman, B. and Kjellström, E. 2004. Simulated sea level in past and future climates of the Baltic Sea. *Clim. Res.* **27**, 59–75.

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

Plag, H. P. and Tsimplis, M. N. 1999. Temporal variability of the seasonal se-level cycle in the North Sea and Baltic Sea in relation to climate variability. *Global Planet.Change* **20**, 173–203.

Raudsepp, U., Toompuu, A. and Kouts, T. 1999. A stochastic model for the sea level in the Estonian coastal area. *J. Mar.Sys.* **22**, 69–87.

Räisänen, J., Hansson, U., Ullerstig, A., Döscher, R., Graham, L. P. and co-authors. 2004. European climate in the late twenty-first century: regional simulations with two driving global models and two forcing scenarios. *Clim. Dyn.* **22**, 13–31.

Siegismund, F. and Schrum, C. 2001. Decadal changes in the wind forcing over the North Sea. *Clim. Res*. **18**, 39–45.

Samuelsson, M. and Stigebrandt, A. 1996. Main characteristics of the long-term sea level variability in the Baltic Sea. *Tellus* **48A**, 672–683.

Sildvee, H. 1998. Gravity measurements of Estonia. *Reports of the Finnish Geodetic Institute* **98:3**, Masala, Finland.

Stigebrandt, A. 1984. Analysis of an 89-year-long sea level record from the Kattegat with special reference to the barotropically driven water exchange between the Baltic and the sea. *Tellus* **36A**, 401–408.

Suursaar, Ü., Kullas, T. and Otsmann, M. 2002. A model study of sea level variations in the Gulf of Riga and the Väinameri Sea. *Cont. Shelf Res.* **22**, 2001–2019.

Suursaar, Ü., Jaagus, J. and Kullas, T. 2006a. Past and future changes in sea level near the Estonian coast in relation to changes in wind climate. *Boreal Env. Res.* **11**, 123–142.

Suursaar, Ü., Kullas, T., Otsmann, M., Saaremäe, I., Kuik, J. and co-authors. 2006b. Cyclone Gudrun in January 2005 and modelling its hydrodynamic consequences in the Estonian coastal waters. *Boreal Env. Res.* **11,** 143–159.

Suursaar, Ü. and Kullas, T. 2006. Influence of wind climate changes on the mean sea level and current regime in the coastal waters of west Estonia, Baltic Sea. *Oceanologia* **48**, 361–383.

Ulbrich, U. and 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.

Vallner, L., Sildvee, H. and Torim, A. 1988. Recent crustal movements in Estonia. *J. Geodyn.* **9**, 215–223.

Vermeer, M., Kakkuri, J., Mälkki, P., Boman, H., Kahma, K. K. and co-authors. 1988. Land uplift and sea level variability spectrum using fully measured monthly means of tide gauge readings. *Finnish Ma. Res.* **256**, 3–75.

Wakelin, S. L., Woodworth, P. L., Flather, R. A. and Williams, J. A. 2003. Sea-level dependence on the NAO over the NW European Continental Shelf. *Geophys. Res. Lett*. **30**: Art. No. 1403.

Woodworth, P. L. 1990. A search for accelerations in records of European mean sea level. *Int. J. Climatol.* **10**, 129–143.

Woodworth, P. and Blackman, D. 2004. Evidence for systematic changes in Extreme high waters since the mid-1970s. *J. Clim.* **17**, 1190–1197.

Wroblewski, A. 2001. A probabilistic approach to sea level rise up to the year 2100 at Kolobrzeg, Poland. *Clim. Res*. **18**, 25–30.