BOREAL ENVIRONMENT RESEARCH 11: 123–142
Helsinki 24 April 2006
ISSN 1239-6095

Past and future changes in sea level near the Estonian coast in relation to changes in wind climate

Ülo Suursaar[1)]*, Jaak Jaagus[2)] and Tiit Kullas[1)]

[1)] *Estonian Marine Institute, University of Tartu, Mäealuse 10a, 12618 Tallinn, Estonia (*corresponding author's e-mail: ulo.suursaar@ut.ee)*
[2)] *Institute of Geography, University of Tartu, Vanemuise 46, 51014 Tartu, Estonia*

Received 10 Dec. 2004, accepted 23 Nov. 2005 (Editor in charge of this article: Timo Huttula)

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

The dependence of sea level on past and future climatological conditions is investigated in nearly tideless semi-enclosed sub-basins of the Baltic Sea using trend analysis of the tide gauge data for the period of 1924–2003 and hydrodynamic modelling. 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 has risen by up to 6 cm near the Estonian coast during the last fifty years, probably due to changes in wind climate. The sea-level increase was concentrated in the period from November to March. It is in good correlation with increasing trends in local storminess and in higher intensity of westerlies, as described by AO and NAO indices. For the future sea level, a set of sensitivity and scenario runs considering possible future changes in wind climate was performed using a 2D hydrodynamic model with a 1-km grid-step. The scenario runs show that if the intensity of westerlies continues to grow (with less than 20% annual mean wind speed increase) the local annual mean sea level rise up to 5–6 cm can occur in some windward bays of the Gulf of Riga. The rise can be up to 9–11 cm in winter months, while in summer the sea level rise is unlikely. Also, increase in variability and extremes can be expected.

Introduction

Climate change is believed to have some positive influences on Estonia, mainly due to the diminishing of energy consumption for heating and more favourable conditions for agriculture and for sea transport in winter (e.g. Kont *et al.* 2002). However, 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 Estonian coastal zone (Kont *et al.* 2003, Orviku *et al.* 2003, Suursaar *et al.* 2006). The major threats, in addition to the sea-level rise and the flooding of coastal areas, are the erosion of seashores and the destruction of harbour infrastructure. Study of sea-level changes is therefore both theoretically and practically of high importance.

There are three main factors influencing long-term sea-level variations: global sea level change, earth's crust isostatic uplift or subsidence and changes in the water balance of the particular sea. Numerous studies of the long-term sea level variations both in the global scale (Gornitz *et al.* 1982, Woodworth 1987, 1990, IPCC 2001, Wakelin *et al.* 2003), as well as in the Baltic Sea (Ekman 1988, 1996, 1999, Vermeer *et al.* 1988, Samuelsson and Stigebrandt 1996, Johansson *et al.* 2001) were carried out. It appears from these studies that the global sea level has already risen by 1–2 mm per year during the 20th century due to climate warming. The main reasons are the thermal seawater expansion and the gradual melting of glaciers. The latest scenarios (IPCC 2001) predict global temperature rise of between 2 and 4 degrees by the 2080s and eustatic increase in the global mean sea level of 0.1–0.9 m by 2100. The range of different sea level rise projections appears due to different global greenhouse gas emission projections (A1: rapid growth and rapid introduction of new technologies, A2: heterogeneous world scenario, B1: convergent world, B2: sustainable world, etc.) as well as different models involved in prediction (HadCM3, ECHAM4/OPYC3, GFDL-R30, MAGICC, etc.). The gridded model results of climate and sea level variables are downloadable from the IPCC Data Distribution Centre (http://ipcc-ddc.cru.uea.ac.uk/). A comprehensive overview of different possible future climate change tendencies in the region of Fennoscandia was recently presented e.g. by Jylhä *et al.* (2004) and Räisänen *et al.* (2004).

The second main factor, the isostatic movements of the earth's crust, is of regional origin and varies locally. According to the analysis of Finnish sea level time series for the period 1887–2002, the post-glacial land uplift rate among the Finnish tide gauges is between 8.9 mm yr^{-1} at Vaasa and 3.1 mm yr^{-1} at Hamina (Johansson *et al.* 2004). These absolute land uplift rates were obtained by adding the global mean sea level rise rate estimate of 1.5 ± 0.5 mm yr^{-1} to the relative land uplift, displayed by the sea level time series. At the Stockholm tide gauge time series, the uplift contributes to the sea level lowering of 4.5 mm yr^{-1} on average (Ekman 1988). Land uplift varies in the coastal areas of Estonia between 0.5 and 2.8 mm per year, as detected by crustal movement observation (Vallner *et al.* 1988, Sildvee 1998). The land uplift rate ranges between 2 and 3 mm yr^{-1} in the region of Hiiumaa Island, the lowest values apply for NE Estonia. Zero-isobase runs across the southern Baltic Sea and also through the southern part of the Gulf of Riga (Vallner *et al.* 1988, Ekman 1996).

Another main 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 inflow and outflow of water through the Danish Straits and by river runoff. Both are essentially controlled by atmospheric pressure patterns over the North Atlantic, the North Atlantic Oscillation (NAO) (e.g. Ekman and Stigebrandt 1990, Heyen *et al.* 1996, Andersson 2002, Lehmann *et al.* 2002, Johansson *et al.* 2003, Wakelin *et al.* 2003, Jevrejeva *et al.* 2005). While the connections between Baltic Sea level and changes in wind climate and NAO are thoroughly studied, similar publications on Estonian sea level are virtually non-existent. However, general studies on Baltic Sea level can only be partly representative for Estonian sea level regime. The West-Estonian coast is heavily indented including two relatively shallow (maximum depth 50 m) semi-enclosed sub-basins — Gulf of Riga and Väinameri Sea (Fig. 1). Sea level variations include a considerable local component here and, besides the St. Petersburg area, some of the highest Baltic storm surges are registered including the +275 cm surge in Pärnu on 9 January 2005 (Suursaar *et al.* 2006). In the present study we mainly focus on these sub-basins.

The Gulf of Riga covers an area of 140 km from west to east and 150 km from south to north with a sea surface area of 17 913 km^2. The Väinameri (also called Moonsund) has a surface area of 2243 km^2. These sub-basins are connected with each other and with the Baltic Proper by four straits directed to the S (Suur Strait), SW (Irbe Strait), W (Soela Strait), and NW (Hari Strait). Therefore the sea level variations in the study area, being a kind of a smaller replica of the Baltic Sea itself, are subject to the prevailing westerly winds and the passage of cyclones. While the low-pass filtered by the Danish Straits' external forcing dominates on time scales of one month or longer in the Baltic Sea (Stigebrandt 1984, Samuelsson and Stigebrandt 1996), the much smaller Gulf of Riga is mainly externally forced on time scales over about 1–2 days (Otsmann *et al.* 2001). The sea level variations in such semi-enclosed basins occur then as quarter-wave oscillations with a node at the entrance and larger variability in the far end of the bay. Shorter period sea level variations are mainly internally forced by the local wind, and appear as

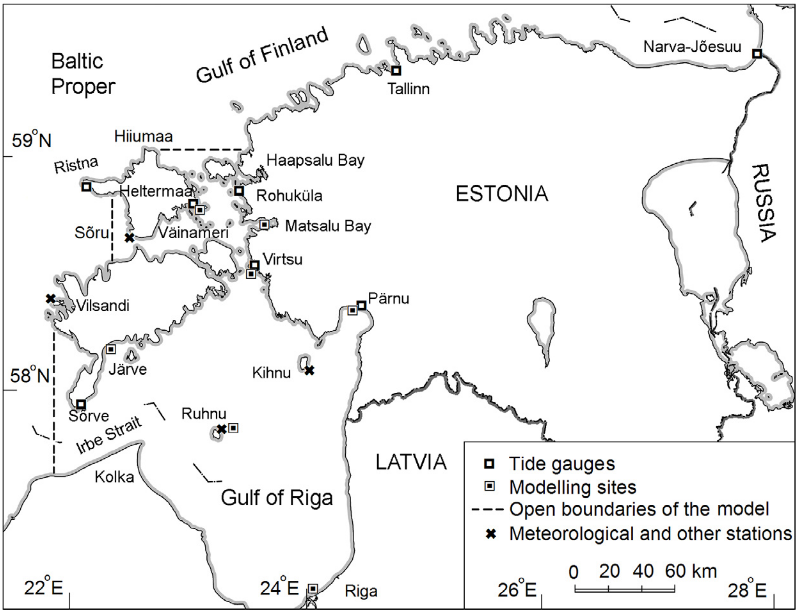

Fig. 1. Study area with the tide gauge stations and modelling locations.

wind setup and internal seiches with a period of about 5 h (Suursaar *et al*. 2003).

The assumption of increase in mean wind speed or increase in westerlies is usually made when considering possible future changes in wind regime. In fact, increase in mean zonal (west-east) component of the geostrophic airflow is reported for the 20th century (e.g. Ekman 1998, Matthäus *et al*. 2003). Zonal component of wintertime upper-air winds has increased for 3 m s^{-1} above Estonia in 1954–1998 (Keevallik and Rajasalu 2001). In addition, mean meridional component has changed its sign in March due to increased southflow and decreased northflow. According to overviews presented by e.g. Jylhä *et al*. (2004) and Räisänen *et al*. (2003) some of the climate models predict the following increase in the mean westerly component by the 2080s: in winter up to 2.3 and 1.7 m s^{-1} (ECHAM4 climate scenarios A2 and B2, respectively); in spring up to 2.8 and 2.0 m s^{-1} (ECHAM4 A2 and CGCM2 A2); in autumn up to 1.9 and 1.3 m s^{-1} (ECHAM4 A2 and B2); in summer up to 1 m s^{-1} (ECHAM4 A2). It would be important to know how large the magnitude of local sea level response to such changes in wind climate is. This local response component should be detectable in sea level time series of the past after subtracting global and regional sea level and crustal movement components. A similar component should also appear in hydrodynamic modelling runs, where wind speed change component is applied to realistic wind forcing time series. In the present study we, bearing in mind the abovementioned global and regional developments, mainly focus on these specific wind driven local sea level change components, which appear extra to those of the Baltic Sea.

The objectives of this study are (1) to investigate long-term changes in mean water level in the Baltic Sea near the Estonian coast; (2) to analyse relationships between mean sea level and atmospheric circulation indices such as different teleconnection patterns and storminess; (3) to illustrate regional and local hydrodynamic mechanisms responsible for the sea level changes forced by changes in wind climate; (4) to present and discuss future sea level scenarios for the coastal waters of Estonia.

Material and methods

Time series of sea level and atmospheric circulation indices

Sea level observations in the territory of Estonia began in Tallinn in 1842. They have been carried out at different times at 29 locations (*see* also Jevrejeva *et al.* 2001). The majority of them are not long-term and have a lot of gaps. The gaps mostly occur in 1944–1945. In this study, monthly and annual mean data from 8 tide gauge stations (Fig. 1) from the relatively uninterrupted period of 1950–2002 were considered. The most reliable data, which are based on hourly measurements and have only minor gaps in time series, come from Pärnu, Narva-Jõesuu and Ristna. Longer data series obtained in 1924–2003, which were analysed additionally, are available from two stations only — Pärnu and Narva-Jõesuu. Gaps in these time series were filled by measured values at neighbouring stations by the Estonian Meteorological and Hydrological Institute that operates the tide gauges. It was justified because correlation coefficients between analysed monthly time series of adjacent tide gauges was 0.92–0.99.

The height system still used in Estonia and in other Baltic states of the former Soviet Union is different from the Finnish and Scandinavian tide gauging standards (most recently the Nordic height system 1960, NH60). It is called the Baltic Height System with its reference zero-benchmark at Kronstadt near St. Petersburg (*see* e.g. Lazarenko 1961, 1986). Though land uplift is slower in the study area than in Fennoscandia, non-uniform shift of fixed references poses some specific problems for time series analysis and comparison of results from different tide gauges. Data about the isostatic land uplift for the studied stations were determined using the map (Vallner *et al.* 1988) composed from the precise levelling data. The figures for the tide gauge stations fit the isolines presented in some other available sources (Lazarenko 1961, Ekman 1996, Sildvee 1998) with up to ±0.4 mm yr^{-1} accuracy.

Using linear regression analysis, trends in time series of sea level were estimated. The trends were considered to be statistically significant at $p < 0.05$. Multiplying the slope by a number of years, total change given by the trend was calculated as a main parameter of change for different months and for the whole year. After the change due to land uplift was added, the actual sea level rise component was obtained.

Further, water level data was correlated with storminess and atmospheric circulation data, which, rather than direct local wind data, were used as wind climate change parameters. Changes in local wind speed and directions deserve special analysis, but in our case there were some considerations in favour of more general indices. Local long-term wind time series are very sensitive, firstly, for building activity and changes in vegetation near the stations, and secondly, to inhomogeneity caused by instrument changes (e.g. from weathercocks to automatic anemorhumbometers).

Monthly and annual numbers of storm days in Vilsandi, Sõrve and Kihnu stations during 1950–2002 were used in this study. A storm was defined when the mean wind speed during a single observation (10 minutes) was 15 m s^{-1} or higher. The frequency of storms (number of storm days per year) was used to measure storminess. A storm day was defined when storms were recorded during at least one observation. The datasets additionally include information about storm intensity, such as the highest mean wind speed, wind directions and duration. Long-term changes in storminess were analysed using the Mann-Kendall test, which does not require normal data distribution and accommodates gaps in time series (e.g. Libiseller and Grimvall 2002, Salmi *et al.* 2002). Time series analysis was presented in more detail by Orviku *et al.* (2003).

Atmospheric circulation features were described by North Atlantic Oscillation (NAO) and Arctic Oscillation (AO) indices (which are downloadable e.g. from NOAA Climate Prediction Centre (http://www.cpc.noaa.gov/data/teledoc/telecontents.shtml)), and by frequency of circulation forms W, E and C according to the Vangengeim and Girs classification (Girs and Kondratovich 1978). The latter classification belongs to the so-called subjective manual classifications (Yarnal 1993) that was worked out more than half a century ago. Based on daily synoptic maps up to thirty circulation types are distinguished. They are grouped into three main circulation forms. The form W means westerly airflow, E represents easterly and southerly flow in Estonia, and C — northerly flow. The data were obtained from the Arctic and Antarctic Research Institute in St. Petersburg. The AO index is usually defined as the first empirical orthogonal function of the northern hemisphere sea level pressure anomalies northwards of 20°N (Thompson and Wallace 1998). The NAO, influencing climate over the North Atlantic and Europe, may be viewed as a regional manifestation of the AO (e.g. Wallace 2000). It is described as a difference between the standardized sea level pressure anomalies between Icelandic low and Azores high and could be calculated using either data from Ponta Delgada, Lisbon (Hurrell 1995) or Gibraltar (Jones *et al*. 1997). They all are mutually correlated, but the NAO Gibraltar index offers slightly better results for the changes in Estonian climate (Jaagus 2006), and was therefore used in this study.

Hydrodynamic modelling

For investigating possible future sea level developments in the study area, a Gulf of Riga–Väinameri two-dimensional (2D) shallow sea hydrodynamic model was used (*see* also Suursaar *et al*. 2002). It is a type of shallow sea depth-averaged free-surface model, which is composed of momentum balance and volume conservation equations. Both the quadratic bottom friction parameterization (with bottom stress coefficient $k = 0.0025$) and wind drag parameterization at the sea-surface is taken from literature (Jones and Davies 2001, Smith and Banke 1975, respectively).

The horizontal resolution of the model grid is 1 km and the model domain includes in total 18 964 marine points. For bottom topography and coastline we used the Latvian bathymetric database (*see* Berzinsh *et al*. 1994) and Estonian nautical maps with the scale of 1:100 000. Wetting and drying in response to the variations in the sea level were not included, however, the model takes into account the changes in grid-box depths, as well as the Coriolis force. The model equations were numerically solved using the finite difference method with an integration time step of 30 seconds on a staggered Arakawa C grid. The 2D model performance was previously studied in comparison with Helmholtz model (Otsmann *et al*. 2001) and flow measurements in the straits from 1993–1995 (Kullas *et al*. 2000). Hindcast simulations for 1999 and January 2005 proved the model's ability in a successful simulation of the sea levels (Suursaar *et al*. 2002, 2006).

The 2D model was forced by the local wind and open boundary sea level data. The primary forcing factor for the semi-enclosed study area is the Baltic Sea level (border sea level), which, according to our hindcast study with year 1999 data, yields correlation coefficients between 0.88 and 0.94 at different locations within the study area (Suursaar *et al*. 2002). The role of this forcing component is important for the time-scale longer than one–two days (Fig. 2a and c). The secondary forcing, the local wind (i.e. wind modulus, W–E or SW–NE component, Fig. 2b) yields correlation with Pärnu sea level of 0.53–0.59. This factor is important in periods less than one day and especially in case of storm surges. It is also responsible for the specific difference from the Baltic Proper sea level (Fig. 2b and d). The rest of the factors (tides, seiches, precipitation-evaporation, river inflow, inverse-barometer response, thermohaline effects, etc.) are unimportant for this study for several reasons. Firstly, their influence on local sea level is considerably smaller than that of the listed two primary factors. Secondly, as in the present modelling study we investigated the specific wind driven local sea level change component appearing extra to those of the Baltic Sea, we looked at differences between control and scenario runs. Doing so, all the actual and potential factors cancel each other on both sides except the wind forcing, which is different in different scenario runs (Table 1). What we actually sought was the specific reaction of the local sea level on differences between different wind scenarios (*see* Fig. 2e). It is worth mentioning that we even got rid of some modelling errors, e.g. systematic error components, which otherwise require some model tuning. We used raw output data and the model was not "tuned" for a certain location or event. On the other hand, we could not omit the Baltic Sea level variations on the borders, although they nearly entirely disappear as well. Despite the sub-basins sea level rapidly adjusts to the relatively slow Baltic Sea level variations, small time lags can exist yielding a small influence on sea level scenario differences within the study area.

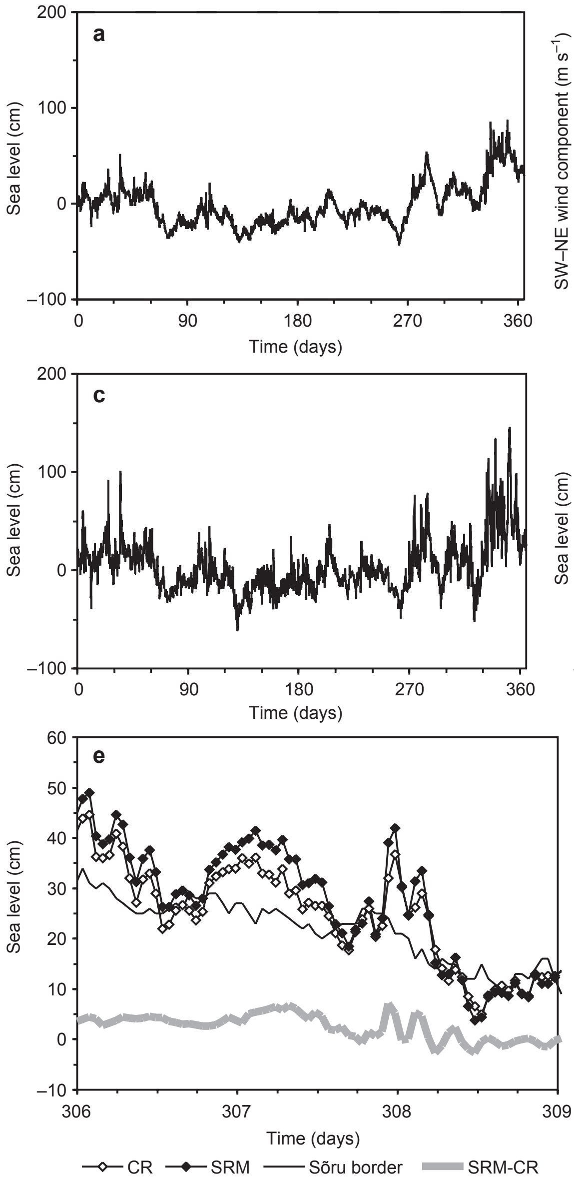

Fig. 2. Measured sea level variations at (**a**) Sõru and (**c**) Pärnu in 1999. (**b**) Vilsandi wind speed projected to SW (positive)–NE (negative) direction. (**d**) Modelled sea level variations at Pärnu, and (**e**) an excerpt explaining calculation of scenario differences (*see* also Table 1). Time axes start with zero on 1 January 1999 00:00 GMT.

Table 1. Explanation and statistics of wind forcing time series used in the sea level modelling: average wind speeds (AV), maxima (Max.) and standard deviations (S.D.) in m s^{-1}, increase in average wind speed compared to CR (AV. Inc.).

Scenario	Explanation for wind forcing scenario	Wind forcing statistics			
		AV	AV.Inc. (%)	S.D.	Max.
CR	Measured Vilsandi wind 1999	5.85	0	3.42	24.0
SRM	2 m s^{-1} added to modula (except 0)	7.83	33	3.42	26.0
SRS	2 m s^{-1} added to S–N component	6.43	10	3.63	25.9
SRW	2 m s^{-1} added to W–E component	6.36	9	3.79	24.8
SRSW	2 m s^{-1} added to S and W components	6.91	18	3.98	26.6
SRE	–2 m s^{-1} added to W–E component	5.88	1	3.20	23.4

The question of boundary conditions is important yet quite complex in hydrodynamic modelling (e.g. Andrejev *et al*. 2004, Blayo and Debreu 2005). In addition to concentrating on scenario differences we also relied on a relatively well-defined semi-enclosed shape of our study area and on using relatively short open boundaries, which were shifted 5–20 km outside the narrowest parts of the straits. The simulation results were taken within the sub-basins well "behind" the straits. We used hourly measured sea level time series obtained from Sõru tide gauge located just outside the Soela Strait. The Sõru data (Fig. 2a), applied at the three cuts of the open boundaries near the Irbe, Soela and Hari Straits, were identically used as sea level boundary conditions for all the control and scenario runs for the year 1999. Sõru sea level height varied between –43 and +87 cm in 1999, while near Pärnu the sea level ranged between –62 cm and +146 cm (*see* Fig. 2c and Table 2).

The wind stress as the second main forcing factor was calculated from the wind data measured at the Vilsandi meteorological station (58°22´59´´N, 21°48´55´´E). As the station is located on an island west of the Estonian mainland (Fig. 1), the data is not contaminated by the direct influence of land to the east. The data had a 1 m s^{-1} value interval, 10° angular resolution and a 6-hour time step subsequently interpolated into an hourly interval. Spatially homogeneous wind was applied over all the grid-points of the modelled area. It is justified, as West-Estonian meteorological stations at our relatively compact and not very large study area generally show rather coherent wind data (Soomere 2001, Suursaar *et al*. 2006).

The wind scenarios used in the study (Table 1) were based on the year 1999 data and included a realistic simulation considered as the "control run" (CR), and several semi-realistic "scenario runs" (SRM, SRS, SRW, SRSW, SRE) with slightly modified wind forcing. The directional distributions of winds were identical for the CR and the SRM scenarios, as 2 m s^{-1} was added to wind speed regardless of its direction. The four other modified 1999 scenarios emphasized S, W, SW and E directions and reduced occurrence of N, E, NE and W winds, respectively. The actual wind speed increment was nearly 2 m s^{-1} in the case of SRM scenario. (It was not exactly 2 m s^{-1}, as this addition was not applied to still conditions, which have no wind direction). The increase in average wind speed was only 0.5–0.6 m s^{-1} for the next two scenarios, as 2 m s^{-1} was added to western or southern wind component, which diminished the eastern and northern wind speeds, respectively. The addition of 2 m s^{-1} to both southerly and westerly wind components actually yielded a maximum 2.83 m s^{-1} increment to SW winds. The resulted increase in annual average wind speed was roughly similar or a bit smaller than in the modelling scenarios used by Meier and Krauker (2002) and Meier *et al*. (2004), which included 34% increased freshwater inflow or 30% increased wind speed. We stress here that the wind speed increase magnitude considered by us is rather realistic, but we do not unconditionally expect such changes in the future. We studied what is the local sea level response if such changes in wind climate would occur.

Time series of sea level were calculated for

Table 2. Monthly wind speed (m s^{-1}) and sea level (cm) averages (AV) and standard deviations (S.D.) in 1999 and 1961–1990.

	Months												Year
	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	
Vilsandi wind speed statistics													
AV 1999	7.0	6.3	5.0	5.5	5.0	4.4	4.4	4.2	4.4	7.2	7.5	9.1	5.9
S.D. 1999	3.1	3.4	2.3	3.2	2.2	2.3	2.3	2.1	2.2	3.3	3.8	4.8	3.4
AV 1961–1990	7.5	6.6	6.5	6.2	5.5	5.5	5.5	5.8	6.9	7.4	7.9	7.8	6.6
Measured sea level statistics in 1999													
Pärnu AV	15.1	19.5	–11.1	–2.3	–20.4	–13.8	–2.7	–5.1	–12.6	13.9	7.1	52.6	3.2
Pärnu S.D.	16.1	14.9	14.7	13.0	14.4	10.4	15.5	9.8	13.7	22.3	22.7	29.3	25.9
Sõru AV	4.9	11.0	–16.7	–11.6	–23.8	–16.9	–7.5	–9.7	–16.6	16.1	11.9	48.0	–0.9
Sõru S.D.	8.7	9.0	13.3	8.8	9.1	6.6	10.2	5.7	10.2	14.8	9.6	12.6	22.1

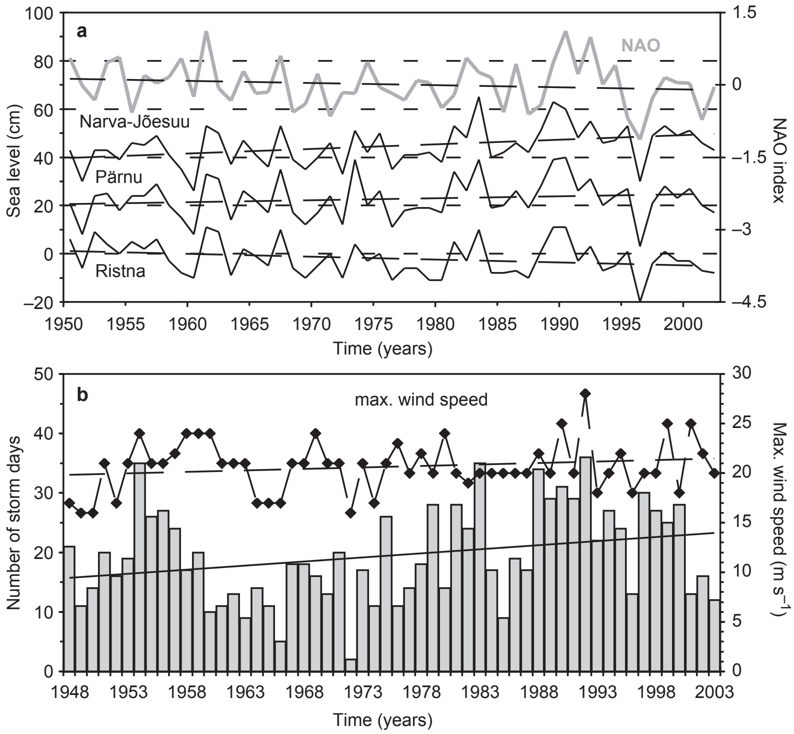

Fig. 3. (**a**) Time series and linear trendlines of annual mean sea level data at Narva-Jõesuu, Pärnu and Ristna in 1950–2002 together with annual variations in NAO index; the left-hand side vertical scale is for Ristna, the data of Pärnu is shifted by 20 cm and the data of Narva-Jõesuu by 40 cm. (**b**) Frequency of storm days (grey bars) and maximum storm winds together with trendlines at Vilsandi in 1948–2003.

each forcing scenario in the selected grid points representing the bays of Pärnu and Matsalu, and locations of Virtsu, Heltermaa, Ruhnu, Järve and Riga (Fig. 1). Ruhnu is located roughly in the middle of the Gulf of Riga and represents the average sea level of the study area. While the Pärnu and Matsalu Bays are in the windward side of the study area, the Heltermaa's location represents the leeward side in relation to prevailing winds. The sea level output included therefore 42 time series, of 8760 hourly readings each.

Results and discussion

Observed changes in sea level, storminess and atmospheric circulation in 1924–2003

Regression analysis of sea level time series revealed some important changes in tide gauges of Estonia. Variations in annual mean sea levels for the three selected tide gauges (Fig. 3), and changes by trend in annual mean sea level at 8

Table 3. Annual mean sea level and standard deviations of monthly values in tide gauge stations of Estonia, changes by trend in sea level records, total land uplift and summary sea level rise during 1950–2002. * = time series with small gaps filled with observation data from neighbouring stations.

Station	Annual mean (cm)	S.D. (cm)	Change as estimated from the trend (cm)	Annual land uplift rate (mm yr^{-1})	Total land uplift (cm)	Total sea level rise (cm)
Narva-Jõesuu	4.7	8.0	10.2	0.5	2.7	12.9
Pärnu	2.7	8.1	4.3	1.5	8.0	12.3
Ristna	–2.0	7.1	–6.3	2.6	13.8	7.5
Rohuküla*	–1.3	6.9	–0.2	2.6	13.8	13.6
Heltermaa*	–2.9	6.4	–2.2	2.6	13.8	11.6
Virtsu*	–1.2	6.8	–0.8	1.8	9.5	8.7
Tallinn*	0.0	7.3	5.8	1.8	9.5	15.3
Sõrve*	–1.5	6.9	6.0	1.5	8.0	14.0

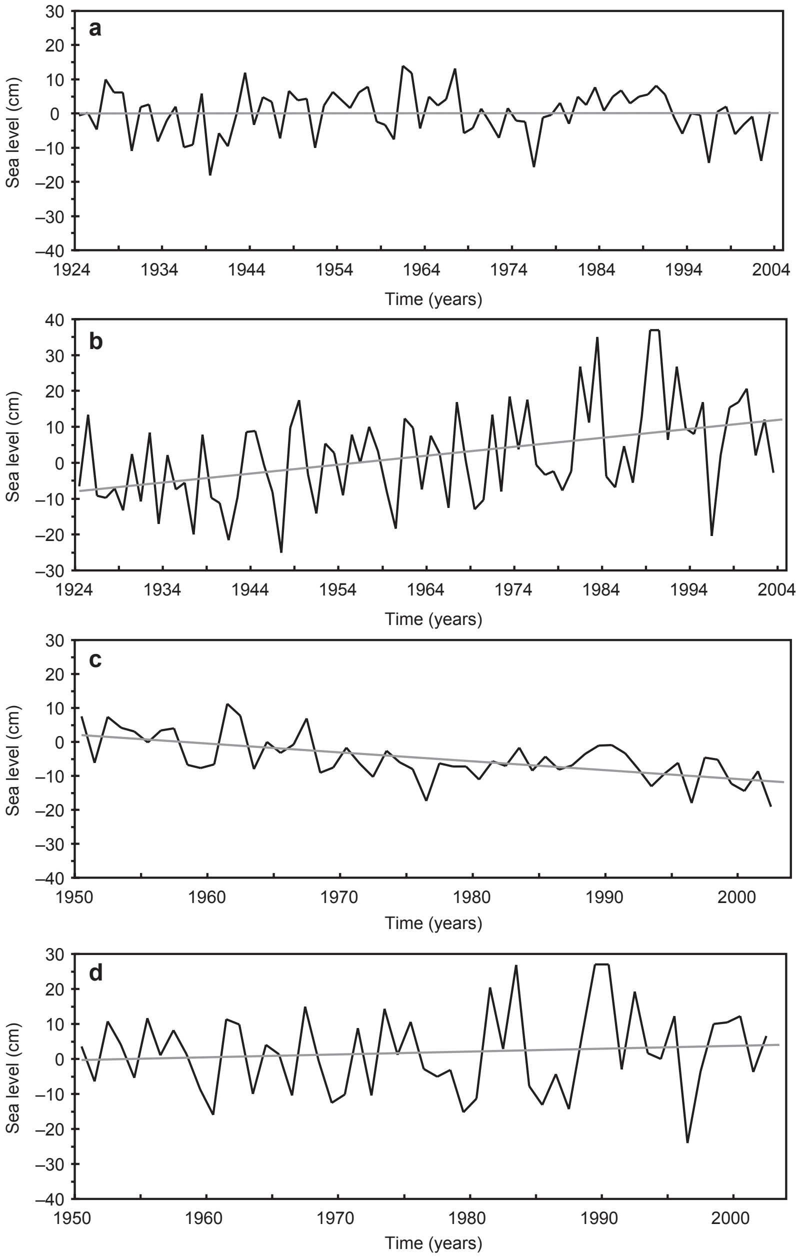

Fig. 4. Sea level variations together with linear trendlines at Pärnu in 1924–2003 (**a**: April–October, **b**: November–March) and at Ristna in 1950–2002 (**c**: April–October, **d**: November–March) for the two different seasons.

tide gauge stations during 1950–2002 (Table 3) suggest that the changes are negative on the Hiiumaa Island, close to zero in the Väinameri region and positive in the other stations. Results from the five last stations are slightly less reliable due to gaps filled with measured results at a neighbouring station and slightly different periods considered. Besides, land uplift has been the highest in Ristna and the lowest in Narva-Jõesuu. During the period of 1924–2003, annual mean sea level has increased by 8.4 cm in Pärnu and by 10.4 cm in Narva-Jõesuu. Both trends were statistically significant. The entire increase has occurred during the cold half-year (Figs. 4b and 5a). Remarkable changes were evident in monthly sea level record from November to March. Almost no changes have been observed during the rest of the months (Figs. 4a and 5a).

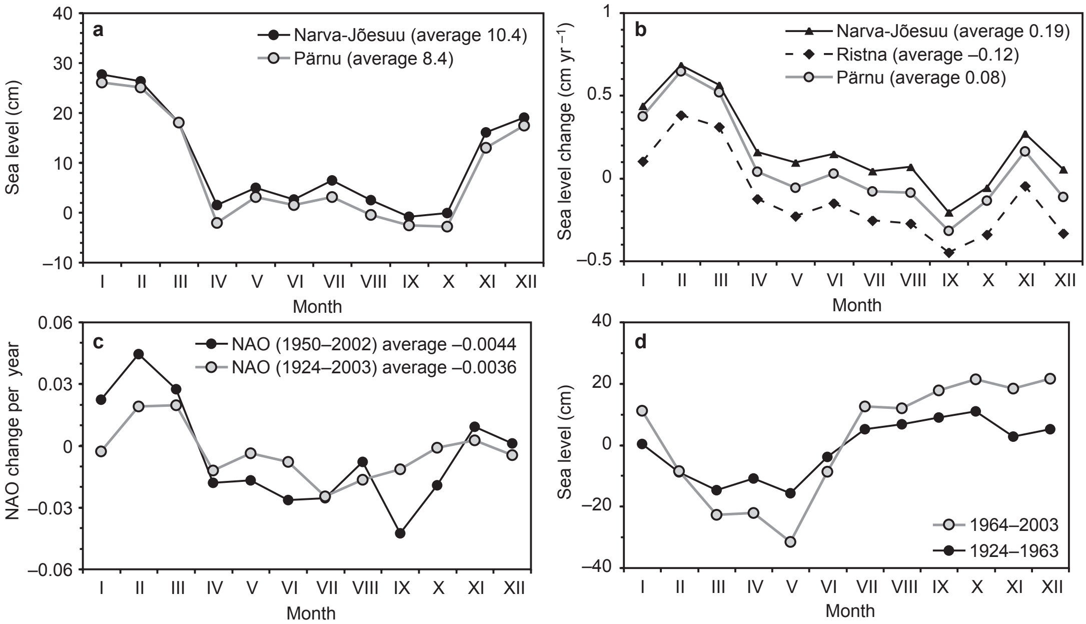

Fig. 5. (**a**) Seasonality in total sea level changes at Pärnu and Narva-Jõesuu in 1924–2003, (**b**) sea level change rates (cm yr^{-1}) in 1950–2002, (**c**) slopes of NAO index trends calculated for two periods, and (**d**) changes in sea level seasonality at Pärnu.

Data from Ristna should normally show negative sea level trend (Fig. 4c), but reveals a positive trend in the cold half-year (Fig. 4d).

Combining total land uplift and change in sea level records, a summarised sea level rise between 7.5 and 15.3 cm was obtained (Table 3). According to the estimates of the global sea level rise (e.g. IPCC 2001), about 7–8 cm could be explained by that global component. When considering only the three most reliable time series, still an up to 6 cm rise should be explained regionally or locally. The rise seems to be smaller

Table 4. Correlation coefficients between mean sea level at tide gauge stations (Pärnu, Narva-Jõesuu, Ristna) and number of storm days measured in Kihnu, Vilsandi and Sõrve in 1950–2002. Significant coefficients on $p < 0.05$ level are set in boldface.

Month	Pärnu			Narva-Jõesuu			Ristna		
	Kihnu	Vilsandi	Sõrve	Kihnu	Vilsandi	Sõrve	Kihnu	Vilsandi	Sõrve
January	**0.53**	**0.73**	**0.58**	**0.55**	**0.74**	**0.60**	**0.48**	**0.70**	**0.50**
February	**0.60**	**0.69**	**0.51**	**0.58**	**0.68**	**0.52**	**0.58**	**0.67**	**0.48**
March	**0.56**	**0.63**	**0.69**	**0.57**	**0.64**	**0.69**	**0.53**	**0.57**	**0.63**
April	–0.13	**0.35**	**0.31**	–0.07	**0.34**	**0.40**	–0.17	0.25	0.21
May	0.05	0.26	0.14	0.03	0.23	0.15	0.08	0.12	0.11
June	0.09	0.21	0.03	0.08	0.10	0.02	–0.05	0.01	–0.07
July	0.02	0.11	–0.05	0.05	0.07	–0.02	–0.09	0.03	–0.13
August	**0.33**	0.25	0.28	0.26	0.19	0.25	0.27	0.31	0.22
September	**0.43**	**0.47**	**0.34**	**0.41**	**0.46**	**0.37**	**0.34**	**0.49**	0.28
October	**0.52**	**0.65**	**0.43**	**0.49**	**0.63**	**0.38**	**0.42**	**0.59**	**0.33**
November	**0.64**	**0.61**	**0.59**	**0.60**	**0.62**	**0.59**	**0.58**	**0.56**	**0.51**
December	**0.55**	**0.64**	**0.30**	**0.53**	**0.62**	**0.33**	**0.48**	**0.59**	0.26
Nov–Mar	**0.59**	**0.79**	**0.60**	**0.62**	**0.79**	**0.65**	**0.47**	**0.73**	**0.47**
Year	**0.37**	**0.54**	**0.43**	**0.43**	**0.64**	**0.61**	0.05	**0.39**	0.13

at Ristna near the nodal area of external sea level variations of the study area (being also near the node of internal Baltic Sea level variations) and higher in the bays (Pärnu, Narva-Jõesuu). We should bear in mind, however, that the summary error margin is up to a few centimetres for the Estonian tide gauge time series processing, land uplift estimate and global sea level rise estimate during the period of fifty years.

Mean sea level in Estonia has a significant positive correlation with storminess (Table 4) and atmospheric circulation indices (Table 5 and Fig. 3a). Atmospheric circulation is obviously a very important factor influencing the sea level in the Baltic Sea via different mechanisms (Ekman and Stigebrandt 1990, Heyen *et al*. 1996, Plag and Tsimplis 1999, Andersson 2002, Lehmann *et al*. 2002, Johansson *et al*. 2004). Considerable time variable relationship between sea level and NAO and change in the locations of the Azores high- and Icelandic low-pressure centres has been found (e.g. Ulbrich and Christoph 1999, Hu and Wu 2004). Therefore some regional indices such as Baltic Sea Index (BSI) defined by sea level pressure differences between Oslo and Szczecin (Lehmann *et al*. 2002) or the Baltic Atmospheric Circulation (BAC) index (Andersson 2002) has been described, offering better correlations with sea level. Whereas maximum winter correlations with AO index reach 0.73 and 0.65 with NAO index in Estonia (Table 5), winter correlation coefficients as high as 0.79 appear between the number of storm days in Vilsandi and sea level (Table 4). The winter NAO index and the number of storms in Vilsandi yield statistically significant mutual correlation of 0.43. The number of stormy days during 50 years (1948–1997) in Vilsandi was 973, resulting in 19.5 as the annual mean value. The highest occurrence of storms is between September and February. Annual storminess series have statistically significant increasing trends in Estonia (Fig. 3b), but the number of storms has increased mainly in winter, especially in February. Also the wind speed maxima show a slight increase, which is statistically insignificant. The change from visual readings from weathercocks into electric anemorhumbometers may introduce inhomogeneties into the data sets. For example, the highest reported average wind speed in Estonia, 35 m s^{-1} registered in August 1967, should be nowadays considered as about 30 m s^{-1} according to conversion tables.

The seasonal curves of NAO trends (Fig. 5c) are quite similar to curves of sea level trends in different months (Fig. 5a and b) with correlation coefficient equal to 0.92 for Pärnu (1950–2002). Trends in both AO and NAO indices were significant and positive for the period from November to March, but insignificantly negative for the annual data set (Fig. 3c). It is interesting to mention that the frequency of the zonal circula-

Table 5. Correlation coefficients between mean sea level and parameters of atmospheric circulation in 1950–2002. Significant coefficients on $p < 0.05$ value are set in boldface.

Month	Pärnu			Narva-Jõesuu			Ristna		
	NAO	AO	W	NAO	AO	W	NAO	AO	W
January	**0.63**	**0.61**	**0.60**	**0.61**	**0.63**	**0.62**	**0.72**	**0.67**	**0.52**
February	**0.54**	**0.60**	**0.61**	**0.52**	**0.60**	**0.61**	**0.56**	**0.48**	**0.58**
March	**0.54**	**0.55**	**0.46**	**0.53**	**0.53**	**0.45**	**0.50**	**0.50**	**0.48**
April	0.15	**0.38**	**0.40**	0.09	**0.37**	**0.41**	–0.02	0.19	**0.36**
May	**0.30**	**0.35**	**0.40**	0.22	**0.35**	**0.40**	**0.33**	0.22	**0.38**
June	**0.30**	0.15	**0.56**	**0.31**	0.13	**0.59**	**0.50**	0.19	**0.57**
July	0.18	0.03	**0.37**	0.17	0.12	**0.46**	0.28	–0.02	0.29
August	**0.31**	–0.06	**0.43**	**0.34**	0.04	**0.49**	**0.36**	–0.04	**0.46**
September	**0.41**	**0.38**	**0.45**	**0.38**	**0.37**	**0.42**	**0.46**	**0.37**	**0.56**
October	**0.41**	**0.46**	**0.54**	**0.39**	**0.49**	**0.53**	**0.40**	**0.48**	**0.49**
November	0.13	0.27	**0.55**	0.07	0.28	**0.57**	0.07	0.20	**0.67**
December	**0.31**	**0.49**	**0.60**	0.26	**0.53**	**0.62**	**0.35**	**0.42**	**0.50**
Nov–Mar	**0.65**	**0.72**	**0.58**	**0.62**	**0.73**	**0.63**	**0.59**	**0.64**	**0.51**
Year	**0.47**	**0.60**	0.20	**0.42**	**0.62**	**0.31**	**0.49**	**0.43**	0.17

tion form W has a significant positive correlation with sea level throughout the year while the indices have a remarkable correlation during the winter months only. It can be concluded that the NAO and AO indices are not good variables to describe the intensity of westerlies during the warm half-year. It is known that NAO is mainly a winter phenomenon (e.g. Rogers 1985, Hurrel and van Loon 1997, Andersson 2002). The circulation form E is related to lower sea level in Estonia and it is negatively correlated with sea level fluctuations, whereas the form C has no significant correlation with sea level fluctuations.

In addition to trends in the time series, the seasonal component in sea level time series is undergoing change as well (Fig. 5d). When comparing the two halves of the period of 1924–2003, the amplitude of the seasonal signal has increased by about 5 cm in Pärnu and Narva-Jõesuu, and the phase has shifted for about 30°. It means that the newer seasonal curve lags for approximately one month. Enhancement of the seasonal signal is observed in other places in the Baltic Sea as well (e.g. Ekman and Stigebrandt 1990, Ekman 1998, Plag and Tsimplis 1999).

Evidently, a set of climatological changes combines in Estonia (and similarly above Fennoscandia): warmer winters occur together with increase in storminess and precipitation, higher westerlies and decrease in sea ice extent (Hagen and Feistel 2005, Jaagus 2006). This set is well explained by positive trends of NAO index in winter (Fig. 5c), which serves as a measure of intensity of westerlies. Intense zonal circulation is followed by strong cyclonic activity and frequent storms; also the higher cold half-year temperature is induced by higher intensity of westerlies. Precipitation has also increased in Estonia by about 10%. According to the change as given by a linear trend, the annual mean air temperature has increased by 1.0–1.7 °C in Estonia during 1950–2000. It has appeared mainly due to warming in the cold half-year. No temperature trends were detected in summer and autumn. While the warming is both remarkable and statistically significant in spring, the warming in winter is nearly as large, but mostly insignificant due to high variation in winter temperature.

Sensitivity runs: wind-driven sea level change mechanisms in the study area

The results from sensitivity runs show that response of the sea levels to the direction and velocity (Fig. 6a and b) of stationary (or slowly changing) wind conditions is rather different within the study area. The shape of the curves is determined by the morphometric features of the straits (directions, water exchange capacities), measures of the sub-basins, and particularly by the morphometry of the bays within the sub-basins, such as the distance of the head of the bay from the nodal point of the sub-basin, the breadth convergence and depth vanish. In general, southerlies-westerlies raise sea level almost in every location of the study area due to major straits directed to SW (Irbe Strait), W (Soela Strait) and NNW (Hari Strait). The sea level variations were smaller near the open boundaries (Irbe Strait, Fig. 6a), and larger in the furthermost bays of Pärnu and Matsalu.

For the Pärnu Bay, the most efficient wind direction for sea level rise is around 220° and the opposite direction 40° lowers the level the most. The direction of 220° nearly corresponds to the axis of the Bay (205°), the slight deviation appears as a result of combination of the local most favoured direction with the most favoured direction for the Gulf of Riga average sea level (250°). Pärnu sea level (PL, cm) response on Baltic Sea level near the boundaries of the Gulf of Riga (BL, cm) and measured or expected wind conditions could be expressed as:

$$PL = BL + 0.068WS^{2.4} \times \cos(WD\text{-}220°),$$

where WS is the maximum 1-hour average wind speed (m s^{-1}) above the open part of the Gulf and WD is wind direction (degrees). The semi-empirical formula is fitted on the basis of hydrodynamic model runs for 0–30 m s^{-1} wind speed span (*see* also Fig. 5a and c) and can be used for rough estimation of Pärnu storm surge heights. The very shallow and narrow Matsalu Bay seems to have the potential for even larger sea level variations than the Pärnu Bay (Fig. 6a), but this is not confirmed due to the absence of a tide gauge. Modelling results on the Matsalu Bay are not very reliable in extreme cases. The

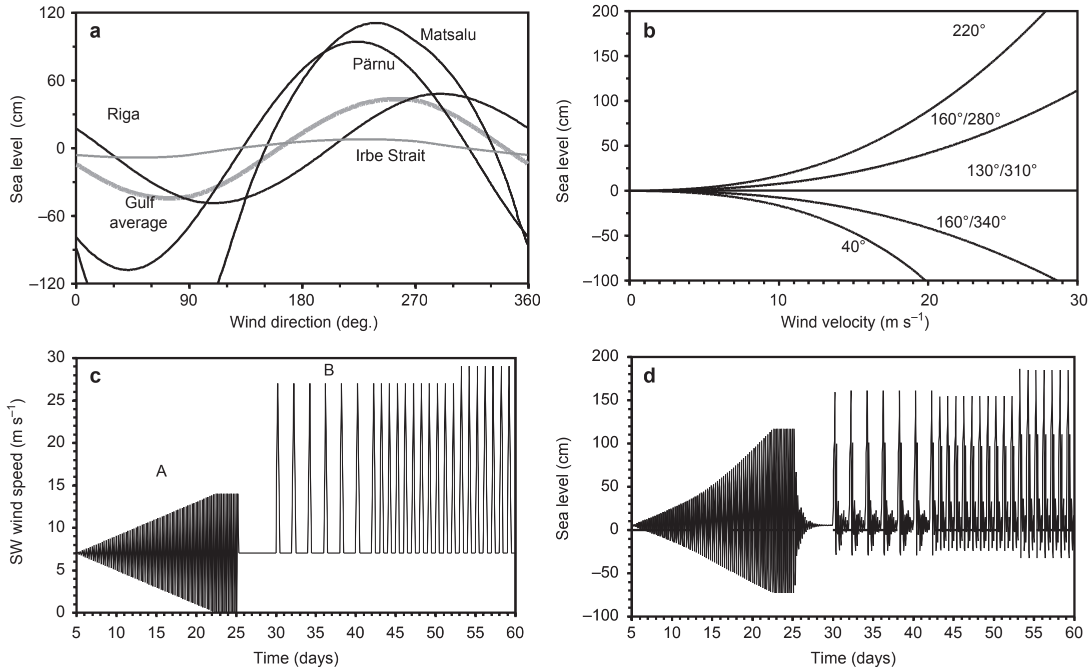

Fig. 6. (**a**) Dependence of the sea levels on stationary and uniform wind (with 20 m s^{-1} modulus) from different directions modelled at different locations of the study area. (**b**) Sea levels at Pärnu depending on wind velocity for some selected wind directions. (**c**) Wind speed of constructed forcing scheme, and (**d**) corresponding sea level reaction at Pärnu.

sea level lowering for more than 1 m causes drying at the end of the bay, which cannot be considered by the model. On the other hand, the sea level rise of 2 m causes extensive inundation of the flat wetland areas in the region of Matsalu Bay, which is not considered by the model either. The actual sea level rise could therefore be somewhat lower. Hence we consider the Pärnu Bay as the location with the largest proved sea level variability in the study area, which, differently from the Matsalu Bay, also displays possible magnification of 5 h seiches of the Gulf of Riga due to resonance, while the 1.5 h Väinameri seiches are effectively damped by large topographically induced friction (Suursaar *et al*. 2003).

Sensitivity runs with wind direction SW included the constructed events of wind variability increase, while the average wind speed remains a constant 7 m s^{-1} (region "A" in Fig. 6c), as well as "stormwind" peaks with different magnitude and frequency ("B", Fig. 6c). Pärnu sea level response is shown in Fig. 6d as an example, but the reaction of the sea level was rather different at different locations. "Storms" evoked rapid sea level rise followed by subdued oscillations at the windward points and negative surges at leeward points (e.g. Heltermaa). The 29 m s^{-1} SW wind yielded a 185 cm relative surge at Pärnu (Fig. 5d), only up to 47 cm rise peaks at Ruhnu, oscillations between +50 and –50 cm near Kolka and 160 cm negative surges at Heltermaa. It appeared that virtually every change in long-term average wind speed, wind variability (even if the average remains the same), and directional distribution of the wind had a specific effect on the mean sea level regime of a location. In windward bays both the average sea level and sea level variability increased with wind speed variability increase, as well as with increased frequency and magnitude of storms. The sea level increment became larger with the wind speed increase *versus* small effect in the case of smaller wind speeds: the 2 m s^{-1} wind speed increment yielded additional 30–40 surge centimetres between 27 and 29 m s^{-1} in the Pärnu and Matsalu Bay, but only 3–5 cm sea level rise around 3–7 m s^{-1} wind speeds.

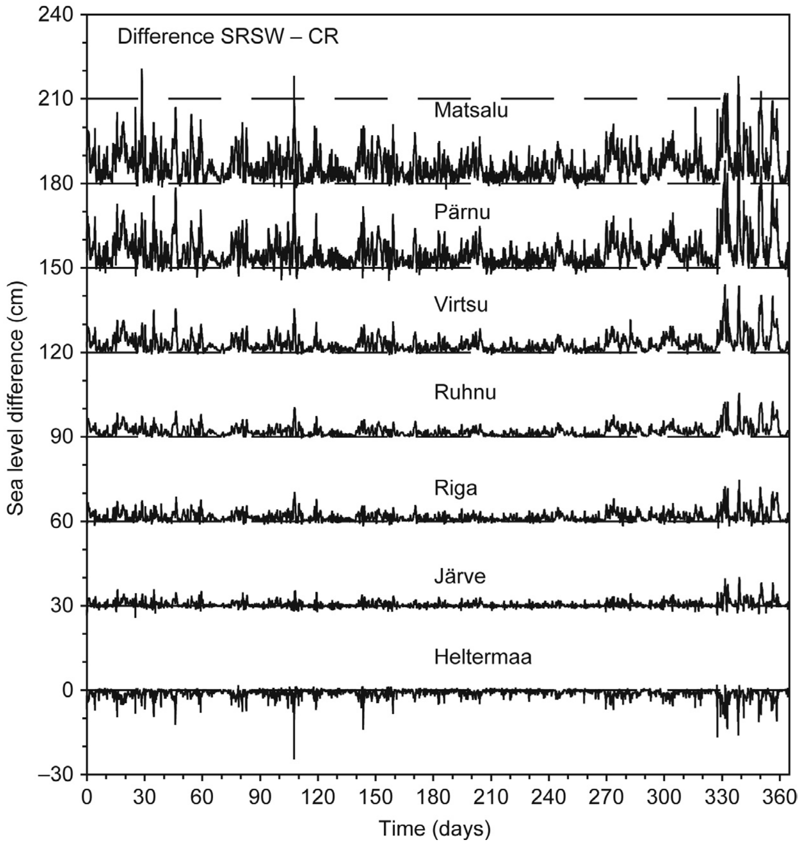

Fig. 7. Example of variations of sea level differences calculated between the simulations SRSW and CR at different locations (*see* also Table 6). Offset of 30 cm is applied between the different time series.

Scenario runs: estimation of sea level change component due to possible changes in wind regime

The difference between the open boundary (Fig. 2a) and Pärnu (Fig. 2c) sea level variations expressed influence of local wind forcing on the Pärnu sea level. Similarly, differences between control run (CR, Fig. 2d, which, as a hindcast run, should be close to the measured Pärnu sea level, *see* e.g. Suursaar *et al*. 2002) and scenario runs express the specific local sea level change components we sought for (Fig. 2e). Monthly average differences computed on the basis of hourly differences (*see* those exemplified in Fig. 7 for the SRSW scenario) for all the scenarios and locations are presented in Table 6.

The sea level changes in comparison with the control simulation were largest in the Bays of Pärnu and Matsalu, and smallest in the points close to the open boundaries (Järve, Ruhnu). At all the points except Riga, the SRSW has the highest impact on sea levels, which strongly stressed the most important wind directions for the system (Table 1). At Riga the sea level reaction was the most sensitive to increased westerlies and possibly also to northerlies. The intensification of westerlies (SRW) had the second powerful effect at Matsalu Bay and for the Gulf of Riga average sea level, while SRS had second effect among the scenarios at Pärnu and Järve. The annual mean sea level increase was largest at Pärnu and Matsalu, where scenarios predicted up to a 5.4 to 6.5 cm sea level rise (Table 6). Increase with the similar magnitude could also occur in the Haapsalu Bay, which, like the Matsalu Bay is very shallow and narrow. Though the sea level lowering at leeward Heltermaa was nearly invisible even in SRW and SRSW scenarios (change between –0.3 and –1.2 cm), the effect can be somewhat more pronounced in some other shallow leeward bays.

When looking at different months, the largest increase of 5–11 cm occurred in December (Table 6). Simply, change in wind speed has a larger effect in high wind speed (*see* also Fig. 6) and December was the stormiest month in 1999. We must bear in mind that it is not necessarily so every year. For example, November was the stormiest month in 2001, February in 2002, December in 2003 and 2004, and January in 2005. Occurrence of storm days in October–January is on average 10 times higher at Vilsandi than in May–June, and maximum stormwinds are higher in the cold half-year (e.g. Soomere 2001). Thus, we should not stick to the exact monthly values presented in Table 6, but consider evident tendencies instead. If the speed of westerlies and south-westerlies continue to increase (and this

Table 6. Monthly and annual sea level differences produced by scenario runs (SRM, SRW, SRS, SRSW, SRE) in comparison with the CR for the selected locations.

Scenario	Months												Year
	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	
Pärnu Bay (near Valgerand)													
SRM-CR	2.1	0.8	1.6	1.6	–0.1	1.2	1.5	–0.3	0.8	2.1	2.9	5.2	1.6
SRS-CR	3.6	2.9	2.1	2.5	2.0	1.9	2.2	1.3	1.6	3.0	3.6	4.6	2.6
SRW-CR	3.3	2.8	2.0	2.5	1.8	1.8	1.6	1.3	1.7	2.9	3.3	4.7	2.5
SRSW-CR	7.2	5.8	4.5	5.3	3.9	4.1	4.1	2.8	3.6	6.2	7.2	9.7	5.4
SRE-CR	–2.9	–2.7	–1.5	–2.2	–1.9	–1.6	–1.4	–1.5	–1.3	–2.5	–2.9	–4.0	–2.2
Matsalu Bay													
SRM-CR	1.7	0.1	2.9	1.6	–0.7	1.4	1.1	–0.7	1.6	1.5	2.6	4.8	1.5
SRS-CR	3.2	2.4	1.7	2.0	1.6	1.7	1.8	0.9	1.3	1.8	2.5	3.1	2.0
SRW-CR	5.2	4.5	3.8	4.2	3.4	3.2	2.7	2.6	3.2	5.1	5.4	6.5	4.1
SRSW-CR	8.6	7.1	5.8	6.5	5.1	5.2	4.9	3.7	4.7	7.3	8.2	10.0	6.4
SRE-CR	–2.9	–2.7	–1.5	–2.2	–1.9	–1.6	–1.4	–1.5	–1.3	–2.5	–2.9	–4.0	–2.2
Virtsu (Suur Strait)													
SRM-CR	1.2	0.5	0.9	0.9	–0.1	0.7	0.8	–0.2	0.4	1.2	1.6	3.1	0.9
SRS-CR	2.0	1.6	1.1	1.3	1.1	1.0	1.2	0.7	0.8	1.7	2.0	2.7	1.4
SRW-CR	1.8	1.5	1.1	1.4	1.0	1.0	0.9	0.7	0.9	1.6	1.8	2.6	1.4
SRSW-CR	4.0	3.2	2.3	2.8	2.1	2.2	2.2	1.4	1.9	3.5	4.1	5.7	2.9
SRE-CR	–1.5	–1.4	–0.8	–0.7	–1.0	–0.8	–0.8	–0.7	–0.8	–1.4	–1.5	–2.2	–1.2
Ruhnu (Central Gulf of Riga)													
SRM-CR	0.7	0.2	1.1	0.7	–0.2	0.4	0.2	–0.2	0.7	0.6	1.0	1.9	0.6
SRS-CR	0.6	0.4	0.2	0.3	0.2	0.2	0.2	0.0	0.1	0.2	0.4	0.6	0.3
SRW-CR	1.9	1.7	1.4	1.6	1.2	1.1	1.0	1.0	1.2	2.0	2.1	2.9	1.6
SRSW-CR	2.6	2.2	1.6	2.0	1.4	1.5	1.4	1.0	1.4	2.4	2.6	3.8	2.0
SRE-CR	–1.7	–1.6	–1.0	–1.4	–1.3	–1.0	–0.9	–1.1	–0.9	–1.9	–1.8	–2.6	–1.4
Järve (Suur Katel Bay)													
SRM-CR	0.3	0.2	0.1	0.2	0.0	0.1	0.2	0.0	0.0	0.4	0.3	0.8	0.2
SRS-CR	0.5	0.4	0.2	0.3	0.2	0.2	0.2	0.0	0.1	0.5	0.6	0.8	0.3
SRW-CR	0.2	0.1	0.0	0.1	0.0	0.0	0.0	0.1	0.1	0.0	0.1	0.4	0.1
SRSW-CR	0.8	0.5	0.2	0.4	0.2	0.2	0.3	0.0	0.1	0.6	0.8	1.4	0.4
SRE-CR	–0.1	–0.1	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.0	0.0	–0.3	0.0
Heltermaa (Väinameri Sea)													
SRM-CR	–0.5	–0.3	–0.3	–0.4	–0.1	–0.3	–0.5	0.0	–0.1	–0.5	–0.7	–1.2	–0.4
SRS-CR	–1.0	–0.8	–0.7	–0.8	–0.7	–0.6	–0.7	–0.5	–0.5	–0.9	–1.0	–1.1	–0.8
SRW-CR	–0.5	–0.4	–0.3	–0.4	–0.2	–0.2	–0.1	–0.2	–0.1	–0.4	–0.6	–0.8	–0.3
SRSW-CR	–1.6	–1.2	–0.9	–1.3	–1.0	–0.9	–0.8	–0.6	–0.8	–1.3	–1.7	–2.0	–1.2
SRE-CR	0.4	0.3	0.1	0.3	0.2	0.2	0.1	0.1	0.1	0.3	0.4	0.5	0.3
Riga													
SRM-CR	1.2	0.4	1.3	1.0	–0.2	0.8	0.7	–0.2	0.7	1.1	1.7	3.1	1.0
SRS-CR	–0.2	–0.3	0.3	–0.3	–0.3	–0.2	–0.3	–0.4	–0.3	–0.7	–0.6	–0.7	–0.4
SRW-CR	2.0	1.9	1.7	1.8	1.4	1.3	1.1	1.2	1.4	2.4	2.4	3.3	1.8
SRSW-CR	1.9	1.7	1.4	1.6	1.1	1.2	1.0	1.0	1.1	1.8	1.9	2.8	1.5
SRE-CR	–1.8	–1.9	–1.2	–1.6	–1.5	–1.2	–1.1	–1.3	–1.1	–2.3	–2.2	–3.0	–1.7

probably occurs in the cold half-year), then we can also expect local annual mean sea level rise for up to about 3–6 cm in a few locations (Pärnu, Matsalu and Haapsalu Bays). 0–3 cm rise is expected in the majority of other locations of the study area, and up to 1 cm decrease in a few leeward coastal areas. The change would be larger in winter months showing up to 7–10 cm higher values. Also further strengthening of the seasonal signal in sea level records can be expected.

Although such a climate scenario confirmed by numerous atmospheric scenarios (Kont *et al.* 2003, Räisänen and Alexandersson 2003, Jylhä *et al.* 2004) is highly expected, some other possibilities should also be considered. For example, considering that NAO is mainly a winter phenomenon, some climate scenarios predict future wind speed increase only in cold half-year. Some authors (e.g. Hagen and Feistel 2005) argue that winter NAO index, following certain natural long-term cycles, probably displayed maximum values in the 1990s and the tendency is about to change, so that even relative enhancement of easterlies can occur. According to our model runs, the SRE scenario yielded annual mean sea level change between –2.2 and –0.3 cm. When combining SRSW scenario in cold half-year with SRE scenario in warm half-year we obtain the annual mean sea level rise around 3 cm at Pärnu and Matsalu and about 1 cm in the Gulf of Riga as an average (Table 6). Then, our analysis predicted a specific sea level change inside our well-defined study area. But we should expect additional sea level rise with a roughly similar magnitude within the Baltic Proper as well, because the water exchange processes in the Danish Straits are sensitive to the same wind change scenarios. Intensified westerlies and storminess will cause both additional mean volume surplus within the Baltic Sea, and certain change in the mean sea level inclination due to the fjord-like shape of the Baltic Sea. This effect was recently modelled by Meier *et al.* (2004). Their simulations predicted average Baltic Sea level rise by about 3–4 cm in the average wind speed increase for 30%. Figure 3 of that work predicted an additional 2–3 cm increase towards Pärnu and St. Petersburg, which is quite close, but a bit less than our study showed, probably due to their relatively rough grid resolution of 6 nautical miles.

A possible increase in wind speed and storminess will in general also lead to the sea level variability increase. Positive trend of standard deviations among Finnish tide gauge data was recently reported by Johansson *et al.* (2001). Standard deviations of the Baltic Sea level vary roughly between 17–18 cm near the Swedish coast of the southern Baltic and 25–30 cm in the far heads of the Gulf of Finland and Gulf of Bothnia (e.g. Lazarenko 1961, Samuelsson and Stigebrandt 1996, Johansson *et al.* 2001). Within our study area the historical variability of sea level is not properly analysed yet, but the standard deviations ought to be around 20–21 cm near the boundary and 25–26 cm in Pärnu Bay (Lazarenko 1961, Tables 2 and 7). The standard deviations of the modelled sea level series (Table 7) possibly exceed the actual values by up to 1 cm, as model output data on their original form are analysed here. It means that no model "tuning" or data smoothing are carried out for better hindcast simulation. As far as we look at scenario differences and general tendencies, such manipulations are not necessary.

The share of locally generated variability is up to 40% only in a few windward bays and below 20% virtually elsewhere in the study area (Table 7). This locally driven variability is higher in winter and smaller in relatively calm summer months. It appeared that all the wind regime change scenario runs except SRE generally yielded increase both in sea level variability and in the percentage of local variability component in it. Somewhat exceptionally the sea level variance decreased at Heltermaa, representing the areas where regional windward reaction is partly deleted by local leeward response component.

The increase in maximum values is up to 40 cm in the Matsalu and Pärnu Bays in our scenarios. The actual possible magnitudes of sea level extremes can not be estimated on such scenario runs. It is nearly impossible to estimate them as statistical return values either, at least for Pärnu. Although the previous (since 1924) highest measured sea level event near the Estonian coast (253 cm in Pärnu on 18 October 1967) was empirically considered as an extremely rare event, the possibility of exceeding this value was reported on the basis of hydrodynamic model runs by Suursaar *et al.* (2003). Co-occurrence of some meteorological and hydrological factors, separately not even of extreme magnitude, are just required. The new highest storm surge of 275 cm, measured on 9 January 2005, was produced by an open boundary sea level of about 170 cm and local wind velocity between 25 and 28 m s^{-1} (Suursaar *et al.* 2006). Considering that the wind direction was not exactly the most effective (actual 260°–280° *vs.* 220°, Fig. 6a) and the stormwind speed increment as small as 2 m s^{-1} would yield about 40 cm higher surge, even a 350 cm surge is meteorologically and hydrodynamically possible at Pärnu. Projected global, regional and local mean (background) sea level rise components additionally favour such events in the future.

Summary and conclusions

1. Regression analysis of the most reliable Estonian tide gauge time series revealed an annual mean sea level increase of 8.4 cm in Pärnu and 10.4 cm in Narva-Jõesuu during the period of 1924–2003, an increase of 4.3 cm in Pärnu, 10.2 cm in Narva-Jõesuu, and a decrease of 6.3 cm in Ristna during 1950–2002. Taking into account the isostatic land uplift (which ranges between 0.5 and 2.8 mm yr^{-1} along the Estonian coasts), an actual water level rise between 7.5 and 15.3 cm was obtained for the last 53 years. As the global eustatic sea level rise due to climate warming with the present rate 1.5 ± 0.5 mm yr^{-1} explains the 7–8 cm, the rest up to 6 cm should be explained regionally and locally.
2. Remarkable sea level increase has concentrated in the period from November to March (about 0.3 cm yr^{-1} at Pärnu) with almost no changes during the other months. The amplitude of the seasonal signal has increased by about 5 cm at Pärnu. The mean sea level rise due to significant rise in cold half-year correlated well with increased local storminess time series during the same months, and with higher intensity of westerlies, as described by different semi-global circulation indices (NAO, AO, circulation form W). This sea level change component can be largely explained by mechanisms of hydrodynamic nature.

Table 7. Averages (AV, cm), standard deviations (S.D.), changes in minima (Min.Inc., cm) and maxima (Max.Inc., cm) in sea level scenario runs compared to CR, percentage of locally originated variance (cm^2) from total variance in annual course (LV%), and local variance in Nov–Mar (LV%W). Local Variance (LV) is calculated as difference between a scenario run series variance and Sõru measured sea level variance (488 cm^2 in 1999).

Scenario	AV	S.D.	Min.Inc.	Max.Inc	LV%	LV%W
Pärnu Bay (near Valgerand)						
CR	2.2	28			39	48
SRM	3.8	31	–22	30	51	59
SRS	4.8	30	4	15	45	53
SRW	4.7	30	5	26	45	53
SRSW	7.6	32	8	40	51	59
SRE	0.0	27	–7	–20	34	43
Matsalu Bay						
CR	2.3	29			41	50
SRM	3.8	32	–31	30	54	62
SRS	4.3	30	11	10	50	53
SRW	6.5	31	25	27	48	56
SRSW	8.7	32	34	38	52	59
SRE	–1.5	28	–28	–25	37	47
Virtsu (Suur Strait)						
CR	0.8	25			22	29
SRM	1.7	27	–1	18	31	38
SRS	2.2	26	0	10	27	34
SRW	2.1	26	0	14	27	34
SRSW	3.7	27	1	23	32	38
SRE	–0.4	25	–1	–11	18	25
Ruhnu (Central Gulf of Riga)						
CR	0.1	24			13	18
SRM	0.7	24	0	11	18	24
SRS	0.4	24	0	3	15	20
SRW	1.7	24	1	11	18	23
SRSW	2.1	25	1	15	20	26
SRE	–1.3	23	–1	–10	8	14
Järve (Suur Katel Bay)						
CR	–0.7	23			6	8
SRM	–0.5	23	0	8	9	12
SRS	–0.4	23	0	3	8	10
SRW	–0.7	23	0	7	7	10
SRSW	–0.3	23	0	10	9	12
SRE	–0.7	23	0	–5	5	7
Heltermaa (Väinameri Sea)						
CR	–1.7	22			7	6
SRM	–2.1	21	–14	0	8	7
SRS	–2.5	21	–6	0	8	7
SRW	–2.0	21	–7	0	7	7
SRSW	–2.9	21	–14	0	8	7
SRE	–1.4	21	5	0	6	6
Riga						
CR	–0.2	23			11	17
SRM	0.1	24	–3	10	15	22
SRS	–0.6	23	0	–1	10	16
SRW	1.6	24	1	12	17	23
SRSW	1.3	24	0	11	16	22
SRE	–1.9	23	–1	–11	6	11

3. The local hydrodynamically driven sea level change component in the semi-enclosed sub-basins of the Estonian coastal sea due to possible changes in wind climate was analysed on the basis of sensitivity and scenario runs of the 2D hydrodynamic model. It was demonstrated that every change in long-term wind regime (e.g. change in average wind speed, variability, or directional distribution) has an effect on the established sea level regime, the effect is different along the coastline and it depends on coastline configuration and bottom topography.
4. The scenario runs showed that if the intensity of westerlies continue to grow (as predicted by numerous atmospheric change scenarios), then the local annual mean sea level rise component up to 5–6 cm can occur in some windward bays of the Gulf of Riga. The rise is bigger (up to 9–11 cm) in more stormy winter months, while in summer the sea level rise is unlikely. Enhancement of southwesterly component with just less than 20% annual mean wind speed increase is needed for that. The local wind-driven sea level change component analysed by us applies within the semi-enclosed sub-basin of the Gulf of Riga and the Väinameri Sea, in addition to possible analogous sea level change of the Baltic mean sea level. The latter component could be up to 3–4 cm in the central Baltic according to the study by Meier *et al*. (2004). Considering both the regional and local sea level change components, a total 8–10 cm wind-induced average sea level rise can occur at Pärnu and Matsalu. In some leeward areas of the Gulf of Riga and the Väinameri, being still at regionally windward coast of the Baltic Sea, the sea level would remain almost unchanged.
5. Possible increase in wind speed and storminess will generally lead to sea level variability increase. More frequent and extreme storm surges can also be expected. "Successful" combination of forcing components allows up to 350 cm storm surges at Pärnu.

Acknowledgements: We are thankful to Mrs. Jekaterina Sooäär from the Estonian Meteorological and Hydrological Institute for providing the tide gauge data. The study was supported by the Estonian Science Foundation (grants No. 5929, 5786 and 5763).

References

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

Andrejev O., Myrberg K., Alenius P. & Lundberg A. 2004. Mean circulation and water exchange in the Gulf of Finland — a study based on three-dimensional modelling. *Boreal Env. Res*. 9: 1–16.

Berzinsh V., Bethers U. & Sennikovs J. 1994. Gulf of Riga: bathymetric, hydrological and meteorological databases, and calculation of the water exchange. *Proc. Latvian Acad. Sci. Section B* 7/8: 107–117.

Blayo E. & Debreu L. 2005. Revisiting open boundary conditions from the point of view of characteristic variables. *Ocean Modelling* 9: 231–252.

Ekman M. 1988. The world's longest continued series of sea level observation. *Pure Appl. Geophys*. 127: 73–77.

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 and Planetary Change* 21: 215–224.

Ekman M. & Stigebrandt A. 1990. Secular change of the seasonal-variation in sea-level and the pole tide in the Baltic Sea. *Journal of Geophysical Research — Oceans* 95: 5379–5385.

Girs A.A. & Kondratovich L.I. [Гирс А.А. & Кондратович Л.И.] 1978. [*Methods of long-term weather forecasts*], Leningrad, Gidrometeoizdat. [In Russian].

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

Hagen E. & 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. & 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. & Wu Z. 2004. The intensification and shift of the annual North Atlantic Oscillation in a global 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.

Hurrel J.W. & van Loon H. 1997. Decadal variations in climate associated with the North Atlantic Oscillation. *Climate Change* 36: 301–326.

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

Jaagus J. 2006. Climate change 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., Post P. & Toomingas O. 2004. Storminess on the western coast of Estonia in relation to large-scale atmospheric circulation. In: Isemer H.-J. (ed.), *Fourth Study Conference on BALTEX*, pp. 127–128.

Jevrejeva S., Rüdja A. & Mäkinen J. 2001. Postglacial rebound in Fennoscandia: new results from Estonian tide gauges. In: Siders M. (ed.), *Gravity, geoid and geodynamics,* IAG International Symposium, Banff, Alberta, Canada, July 31–August 5, 2000. IAG Symposia 123, Springer, pp. 193–198.

Jevrejeva S., Moore J.C., Woodworth P.L. & 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.M., Kahma K.K. & Boman H. 2003. An improved estimate for the long-term mean sea level on the Finnish coasts. *Geophysica* 39: 51–73.

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

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

Jones J.E. & Davies A.M. 2001. Influence of wave-current interaction, and high frequency forcing upon storm induced currents and elevations. *Estuarine, Coastal and Shelf Science* 53: 397–413.

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

Jylhä K., Tuomenvirta H. & Rusteenoja K. 2004. Climate change projections for Finland during the 21st century. *Boreal Env. Res*. 9: 127–152.

Keevallik S. & 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. & Aunap R. 2003. Climate change scenarios and the effect of sea-level rise for Estonia. *Global and Planetary Change* 36: 1–15.

Kont A., Jaagus J., Oja T., Järvet A. & Rivis R. 2002. Biophysical impacts of the climate change on some terrestrial ecosystems in Estonia. *GeoJournal* 57: 169–181.

Kullas T., Otsmann M. & Suursaar Ü. 2000. Comparative calculations of flows in the straits of the Gulf of Riga and the Väinameri. *Proc. Estonian. Acad. Sci. Eng*. 6: 284–294.

Lass H.U. & Matthäus W. 1996. On temporal wind variations forcing salt water inflows into the Baltic Sea. *Tellus* 48A: 663–671.

Lazarenko N.N. [Лазаренко Н.Н.] 1961. [Variability of sea level in the Baltic Sea]. *Trudy Gosudarstvennogo Okeanograficheskogo Instituta* (Leningrad) 65: 39–127. [In Russian].

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*. 16, pp. 64–80.

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

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

Matthäus W., Bergström S., Carlsson B., Graham L.P. & Andersson L. 2003. General meteorology, hydrology and hydrography. Environment of the Baltic Sea Area 1994–1998. *Balt. Sea Environ. Proc*. 82B: 21–28.

Meier H.E.M. & Krauker F. 2002. *Simulating Baltic Sea climate for the period 1902–1998 with the Rossby Centre coupled ice-ocean model*. Reports Oceanography No. 30, Swedish Meteorological and Hydrological Institute, Norrköping.

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

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

Otsmann M., Suursaar Ü. & Kullas T. 2001. The oscillatory nature of the flows in the system of straits and small semienclosed basins of the Baltic Sea. *Cont. Shelf Res*. 21: 1577–1603.

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

Räisänen J. & Alexandersson H. 2003. A probabilistic view on recent and near future climate change in Sweden. *Tellus* 55A: 113–125.

Räisänen J., Hansson U., Ullerstig A., Döscher R., Graham L.P., Jones C., Meier H.E.M., Samuelsson P. & Willen U. 2003. *GCM driven simulations of recent and future climate with the Rossby Centre coupled atmosphere — Baltic Sea regional climate model RCAO*. Reports Meteorology and Climatology No. 101, Swedish Meteorological and Hydrological Institute, Norrköping.

Räisänen J., Hansson U., Ullerstig A., Döscher R., Graham L.P., Jones C., Meier H.E.M., Samuelsson P. & Willen U. 2004. European climate in the late twenty-first century: regional simulations with two driving global models and two forcing scenarios. *Climate Dynamics* 22: 13–31.

Rogers C.J. 1984. The association between the North Atlantic Oscillation and the Southern Oscillation in the northern hemisphere. *Mon. Wea. Rev*. 112: 1999–2015.

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

Samuelsson M. & 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 3.

Smith S.D. & Banke E.G. 1975. Variation of the sea surface drag coefficient with wind speed. *Quarterly Journal of Royal Meteorological Society* 101: 665–673.

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

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.

Stigebrandt A. & Gustafsson B.G. 2003. Response of the Baltic Sea to climate change — theory and observations. *J. Sea Res.* 49: 243–256.

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

Suursaar Ü., Kullas T., Otsmann M. & Kõuts T. 2003. Extreme sea level events in the coastal waters of West Estonia. *J. Sea Res.* 49: 295–303.

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

Thompson D.W. & Wallace J.M. 1998. The Arctic Oscillation signature in the wintertime geopotential height and temperature fields. *Geophys. Res. Lett.* 25: 1297–1300.

Ulbrich U. & Christoph M. 1999. A shift of the NAO and increasing storm track activity over Europe due to anthropogenic greenhouse gas forcing. *Climate Dynamics* 15: 551–559.

Vallner L., Sildvee H. & Torim A. 1988. Recent crustal movements in Estonia. *Journal of Geodynamics* 9: 215–223.

Vermeer M., Kakkuri J., Mälkki P., Boman H., Kahma K.K. & Leppäranta M. 1988. Land uplift and sea level variability spectrum using fully measured monthly means of tide gauge readings. *Finnish Marine Research* 256: 3–75.

Wakelin S.L., Woodworth P.L., Flather R.A. & Williams J.A. 2003. Sea-level dependence on the NAO over the NW European Continental Shelf. *Geophys. Res. Lett.* 30, 1403, doi:10.1029/2003GL017041.

Wallace J.M. 2000. North Atlantic Oscillation/annular mode: Two paradigms — one phenomenon. *Quarterly Journal of Royal Meteorological Society* 126: 791–805.

Woodworth P.L. 1987. Trends in UK mean sea-level. *Marine Geodesy* 11: 57–87.

Woodworth P.L. 1990. A search for accelerations in records of European mean sea level. *International Journal of Climatology* 10: 129–143.

Yarnal B. 1993. *Synoptic climatology in environmental analysis*, Belhaven Press, London.