

Possible changes in hydrodynamic regime in the Estonian coastal waters (the Baltic Sea) as a result of changes in wind climate

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ABSTRACT

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The objective of the paper is to investigate the effects of changes in wind climate on sea level and current regime in a nearly tideless, semi-enclosed sub-basin of the Baltic Sea. The paper presents a statistical analysis of sea level data obtained from the Estonian tide gauges over the period 1842–2005 and a hydrodynamic modeling study as a way to explain past sea level developments and to project probable future changes in sea level and current regime. After adjusting the historical sea level time series to take into account land uplift rates, the series display an upward trend of between 1.5 and 2.7 mm/yr, which in some windward tide gauges exceeds the global sea level rise estimate. The excessive rise in mean sea level, and particularly in maxima, can be explained by the local response to the changing regional wind climate and increasing storminess. The relevant hydrodynamic mechanisms are studied on the basis of sensitivity and scenario runs which are performed with a 2D model. The simulations prove that a relatively modest (2 m/s) mean wind speed increase can yield a mean sea level increase of up to 2–5 cm in the study area. It can also lead to increased water exchange through the straits, which in turn can lead to a strengthening of the basin scale circulation, greater vertical mixing, and an up to twofold increase in bottom stresses near coasts.

ADDITIONAL INDEX WORDS: *Climate change, Sea level, Currents, Hydrodynamic models, Trends*

INTRODUCTION

Estonia lies in the northern hemispheres zone of moderate latitudes (58°–60° N, Figure 1). As such, the predominant meteorological conditions in the area are characterized by the movement of humid air masses from the North Atlantic in the belt of the westerlies. The prevalence of south-westerly winds is expressed both on traditional wind roses (Figure 1) and in the directional distribution of extreme wind speeds. At Vilsandi station maximum mean wind speed over a 6 hour period can measure up to 27 m/s in the SW and NW directions, but only 12–15 m/s in the E, NE and SE directions (SOOMERE, 2001).

The coast of western Estonian is heavily indented and shallow. It includes two semi-enclosed sub-basins, connected to each other and to the Baltic Proper through four major straits (Figure 1). With amplitudes of M_2 and K_1 waves measuring less than 5 cm, the study area is nearly tideless. Given these characteristics, both currents and sea level variations are predominantly meteorologically forced in the study area. The frequent occurrence of cyclones passing from west to east, and their corresponding changes in wind direction and speed, create considerable sea level fluctuations there. While more than 95% of the sea level data fall within the range of –50 and +60 cm in relation to the Kronstadt zero benchmark (which is nearly equal to the long-term mean sea level for the Estonian coast), there are a few exceptional (up to 275 cm) storm surges on record.

During the last half-century, significant changes in the regional wind regime are evident. Increases have been reported in both the

winter westerly wind speed component and in the winter North Atlantic Oscillation (NAO) index (EKMAN, 1998; KEEVALLIK and RAJASALU, 2001; LOWE *et al.*, 2001). Also, cyclonic activity has risen and vitalization of coastal processes have been observed in recent decades in Estonia (ORVIKU *et al.*, 2003). Simulation results of climatological models predict further climate warming, as well as an increase of up to 2–3 m/s in the mean westerly wind component in winter and spring (e.g. RÄISÄNEN *et al.*, 2004).

This paper looks at the consequences of the wind changes observed in the past and anticipated in the future. In doing so, we ask whether a relative modest change in the wind climate can affect the mean sea level and current regime and whether there are any indications of the effects of such wind changes in the past sea level data series. The main objective of the study is to investigate how changes in wind speed and direction affect sea level and current regime using trend analysis of past sea level data and hydrodynamic modeling of sea level and currents.

MATERIAL AND METHODS

Sea level data sets and trend analysis

The Estonian Meteorological and Hydrological Institute (EMHI) currently operates 12 tide gauges. Most of these are equipped with tide poles and have a sampling frequency of 2 or 3 times a day. Automatic tide gauges of the EMHI, which provide hourly data, are located at Pärnu, Narva-Jõesuu and Ristna (Figure 1). In Tallinn, the capital city of Estonia, regular sea level

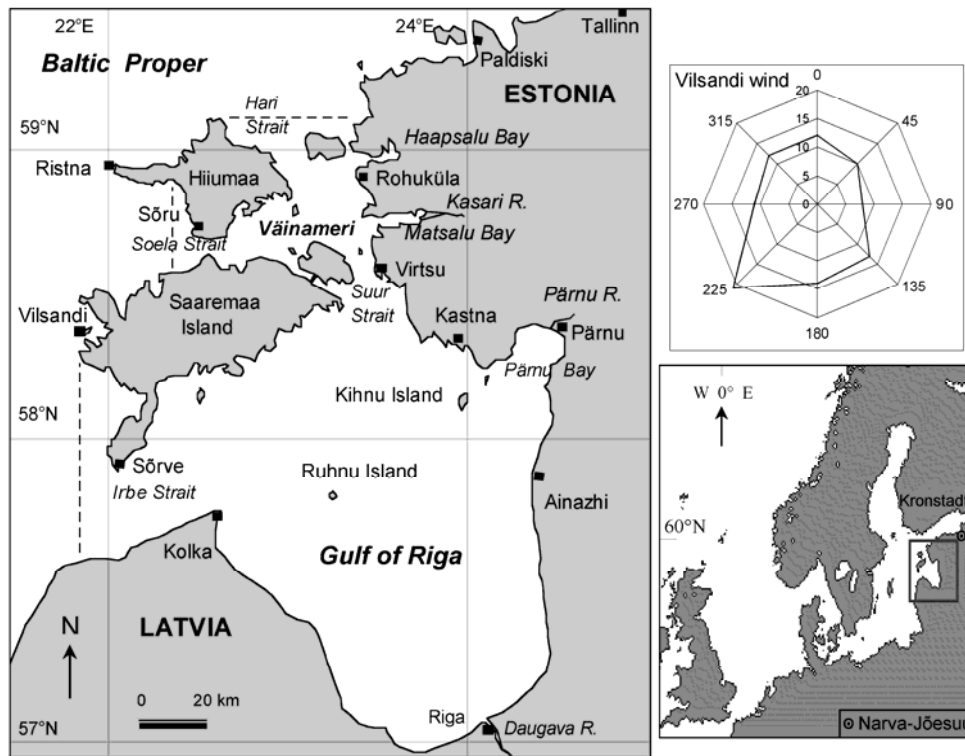


Figure 1. Map of the study area with model boundaries shown by dashed lines; the wind rose at Vilsandi weather station illustrates regional long-term mean wind conditions.

measurements started in 1809. The near continuous data sets are available from 1842, but the measurements were discontinued in 1996 due to construction work at the Tallinn Port.

We used the database of monthly mean and extreme sea levels by the EMHI. They represent relative sea level values in regard to the Kronstadt datum and are based, since 1951, on hourly measurements. The monthly values for earlier periods were obtained on the basis of daily data. Data about land uplift for the studied stations were taken from the map compiled on the basis of the precise levellings in 1933–1943, 1956–1970 and 1977–1985 (VALLNER *et al.*, 1988). The radial crustal movements in Estonia are mainly influenced by regional Fennoscandian postglacial rebound and the uplift rates vary between 0.5 and 2.8 mm/yr.

Tendencies in sea level time series were analysed using linear regression analysis, and trend slopes were calculated in respect of the rates of sea level rise. A slope indicates a mean change per year. The change by trend line is calculated by multiplying the slope by the number of years. Extreme value analysis was performed by calculating empirical return periods and fitting theoretical distributions to the samples of annual maximum values. Taking into account the gaps, the series included 83 values at Pärnu (in 1923–2005) and 85 values in Tallinn (in 1899–1995).

Hydrodynamic modeling

The two-dimensional (2D) hydrodynamic model used in the study simulates both sea level and current values depending on local wind stress and open boundary sea level forcing. It is a 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 definition at the sea-surface is taken from literature (e.g. SMITH and BANKE, 1975). The domain includes both the Gulf of Riga and the Vainameri sub-basins with the horizontal resolution of the Arakawa C grid of 1 km, yielding in total 18,964 marine grid-points. Wetting and drying, in response to the variations in the sea level, are not included. The model has relatively short, open boundaries, which are shifted by 5–20 km outside the narrowest parts of the straits. The model permits flux through its boundaries. The model equations were numerically solved using the finite difference method with an integration time step of 30 seconds. The model is more thoroughly described by SUURSAAR *et al.* (2002). Its performance was previously studied in comparison with flow measurements in the straits from 1993–1995 (KULLAS *et al.*, 2000). Several hindcast simulations proved the model's viability in simulating sea levels (SUURSAAR *et al.*, 2002).

For model input, we used hourly measured sea level time series obtained from Sõru tide gauge, which is located just outside the Soela Strait (Figure 1). The Sõru data were identically applied at the four cuts of the open boundaries for all of the control and scenario runs. The wind stress was calculated from the wind data measured at the Vilsandi station. Spatially homogeneous wind was applied on the grid-points. The data had a 1 m/s value interval, 10° angular resolution and a 6 h time step subsequently interpolated into hourly interval.

The rest of the factors (i.e., tides, precipitation-evaporation, river inflow, inverse-barometer response, and thermohaline effects) are less important. Moreover, since in the present study we are focused on the investigation of wind driven circulation and sea level regime, we focus primarily on the differences between control and scenario runs and reduce the other, potentially less relevant factors in the procedure (see also SUURSAAR *et al.*, 2006).

To begin, we identified maximum sea level heights for each grid point at a wind speed of 20 m/s. Next, we identified the specific wind directions yielding these values for the same points. These simulations indicate the most sensitive locations to changes in wind speed and direction, as well as the areas threatened by storm surges. Finally, we performed scenario runs using the realistic year 1999 forcing data as the control run, and several semi-realistic scenario runs with slightly modified wind forcing. For sea level, we emphasized SW winds by adding 2 m/s to both the southerly and westerly component (yielding a 2.8 m/s increase in the SW wind component). For currents, we emphasized westerlies (at 2 m/s) in one simulation and southerlies (at 2 m/s) in another, and calculated differences between the realistic control run and semi-realistic scenario runs for each grid point. In order to study possible influence on coastal geomorphology, we also produced time series for current speeds (8760 hourly values) at selected grid points near the coast.

RESULTS AND DISCUSSION

Decadal variations in mean sea level

With regard to mean relative sea level of a location, the main factors influencing its variations are: global sea level change, the land uplift or subsidence and changes in the water balance of the particular sub-basin. Time series of annual mean sea levels show slightly increasing tendencies (Figure 2) with rise rates between 0.1 and 1.0 mm/yr in Estonia. After adjusting these rates to account for land uplift rates, we calculated sea level rise rates of 1.9 mm/yr in Tallinn (1842–1995), 1.0 mm/yr in Narva-Jõesuu (1899–2005) and 2.6 mm/yr in Pärnu (1924–2005). The trend estimates for annual maximum sea levels vary between 3 and 10 mm/yr for different tide gauges and study periods.

Moving averages of annual mean sea level series show 30–40 year cycles (Figure 2), which coincide with similar sea level cycles in Finland (JOHANSSON *et al.*, 2004). These cycles, with an amplitude of about 5 cm, can influence linear trend estimates. For example, the Narva-Jõesuu sea level series for the period between 1899–2005 starts high and ends low, and the linear trend estimate of 1.0 mm/yr probably underestimates the real tendency. Due to the shortness of the series and the irregular nature of the cycles, it is difficult to eliminate fully the cycles' influence, but an analysis of several alternative sub-periods yielded our "best" trend slope estimates of 1.5–1.7 mm/yr in Tallinn, 1.7–2.1 mm/yr at Narva-Jõesuu and 2.3–2.7 mm/yr at Pärnu for the last 50–60 years.

Thus, except in Pärnu, the mean sea level rise rates are roughly equal to or insignificantly higher than the most recent global sea level rise estimates, which are around 1.7 mm/yr according to CHURCH and WHITE (2006). The excessive Pärnu sea level rise rate over the global estimates can be explained by hydrodynamic mechanisms, and will be discussed further below.

Pärnu's positive sea level trends in annual time series appear due to the significantly more positive trends in winter (December to March) sea level, since during the summer such trends are less steep or even negative. The significantly higher mean sea level rise in winter correlates with increased local storminess during the same months and with the greater intensity of westerlies in winter, as described by the NAO-index (ORVIKU *et al.*, 2003; SUURSAAR *et al.*, 2006). The existence of this type of time variable relationship between sea level and atmospheric circulation is common for other Baltic sea level data sets as well (EKMAN, 1998; WAKELIN *et al.*, 2003; JOHANSSON *et al.*, 2004).

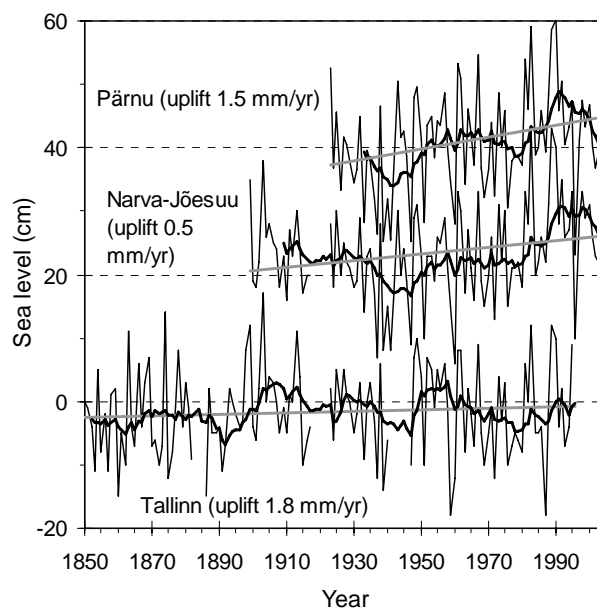


Figure 2. Decadal variations in annual mean relative sea levels together with 11-year moving averages and linear trendlines at three tide gauges. (The series are not corrected with land uplift rates, which are set forth in parentheses). The data of Narva-Jõesuu is shifted by 20 cm, and the data of Pärnu by 40 cm.

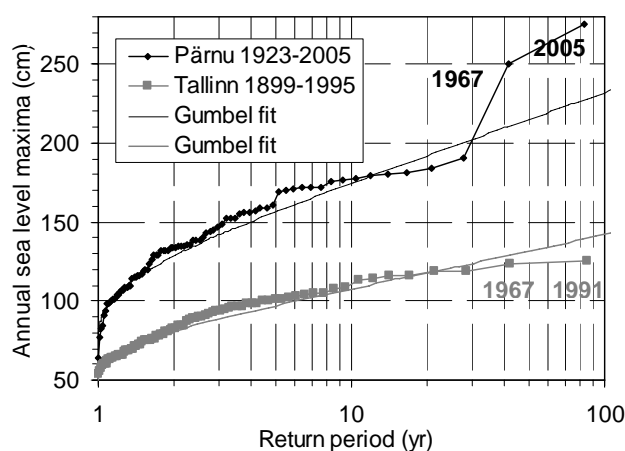


Figure 3. Return periods based on annual maximum sea level data at Pärnu and Tallinn tide gauges (corresponding theoretical Gumbel distributions were calculated using least squares method). The two highest values are separately marked for both stations.

Storm surges

Because of the semi-enclosed configuration of the study area and the presence of shallow bays exposed to the direction of the strongest possible winds, some of the highest Baltic storm surges are registered there. However, considering the shallow sea, low-lying coast, and virtual absence of tides, the local residents are not always sufficiently prepared for such, nevertheless rare, events. Trend analyses have shown that storm surges are becoming higher both in Estonia (SUURSAAR *et al.*, 2006), as well as in Western Europe (e.g. LOWE *et al.*, 2001).

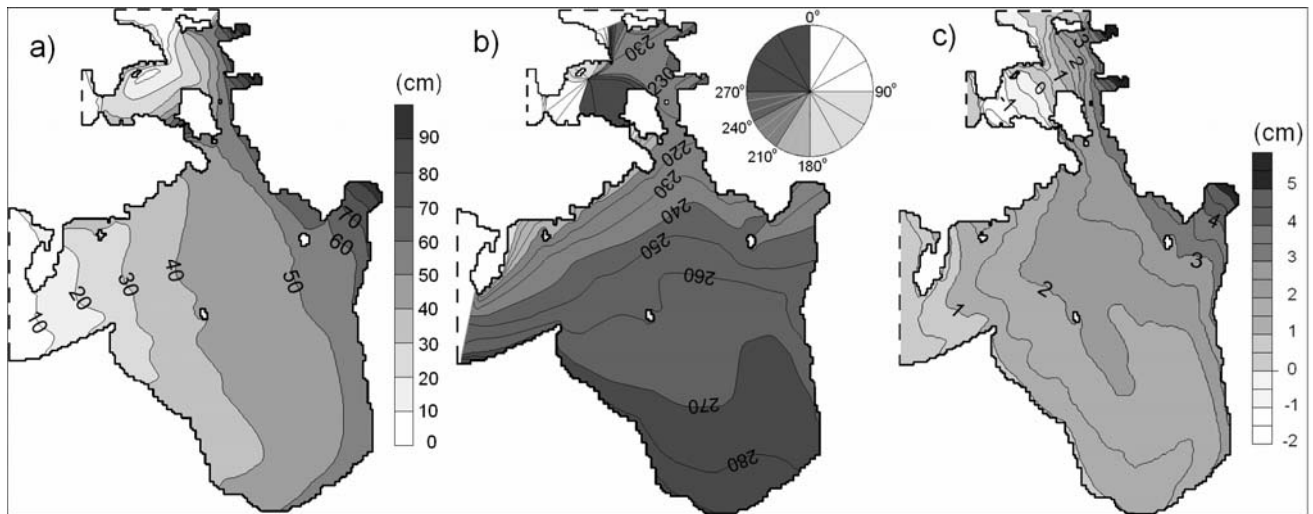


Figure 4. Horizontal distribution of the highest possible local sea levels (above the Baltic background sea level) modeled with 20 m/s stationary wind (a); the corresponding wind directions that produce the highest sea level of a location (b); horizontal distribution of the study period mean sea level differences calculated between the scenario run with increased (for 2.8 m/s) SW wind component and realistic control simulation for year 1999 (c).

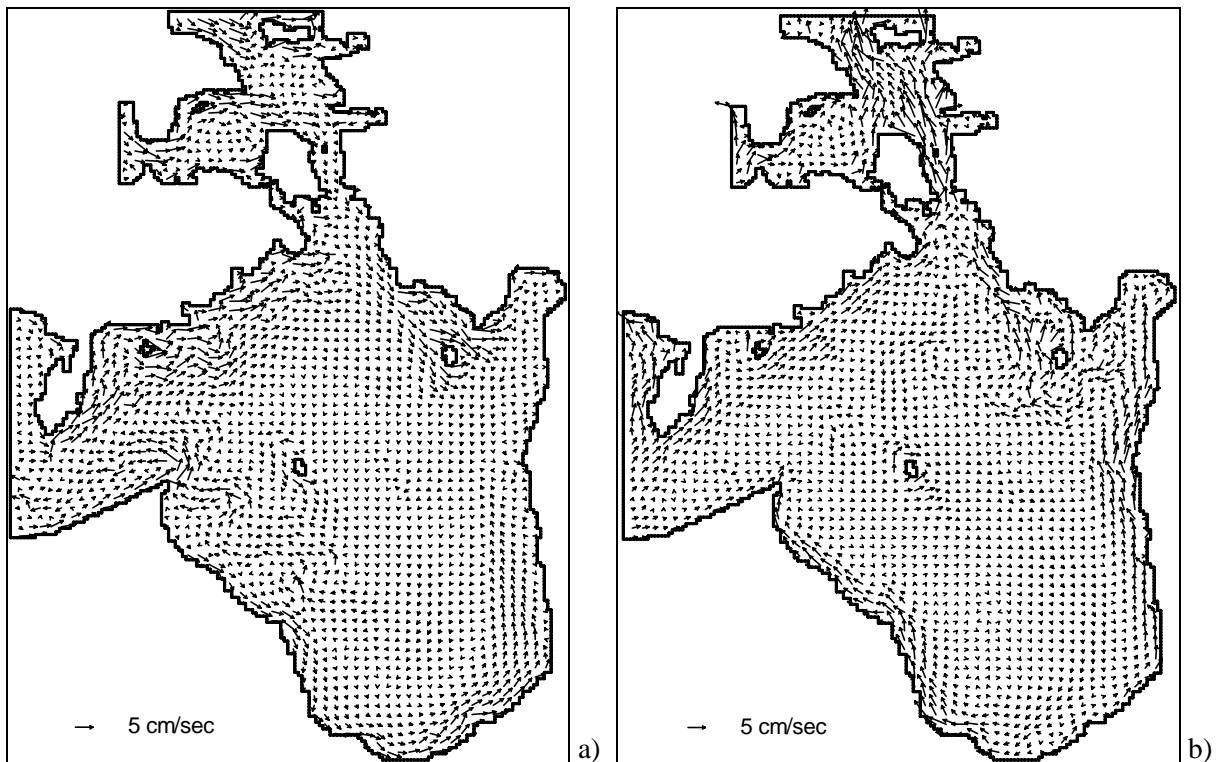


Figure 5. Horizontal distributions of depth integrated flow vectors showing the influence of a 2 m/s enhanced westerly wind component (a) and an enhanced southerly wind component (b), in each case as compared against the control run of realistic 1999 year. Every third arrow is drawn only, yielding 3 km grid-spacing.

Pärnu sea level record identify 29 individual events higher than the critical value of 150 cm, 23 of which occurred between the months of October–March and 6 between the months of April–September. The two highest sea level events off the Estonian coast (since 1923) were both registered at Pärnu: 253 cm on 19 October 1967 and 275 cm on 9 January 2005 (Figure 3).

The event on 9 January 2005 was produced by the cyclone Gudrun, which reached the power of a hurricane according to mean wind speed measurements (up to 34 m/s) in Denmark. As Gudrun's eye passed 300 km north of Estonia, heading from SW to NE, it created very strong SW winds (and later W–NW winds once it passed) reaching an average of 28 m/s over a one hour

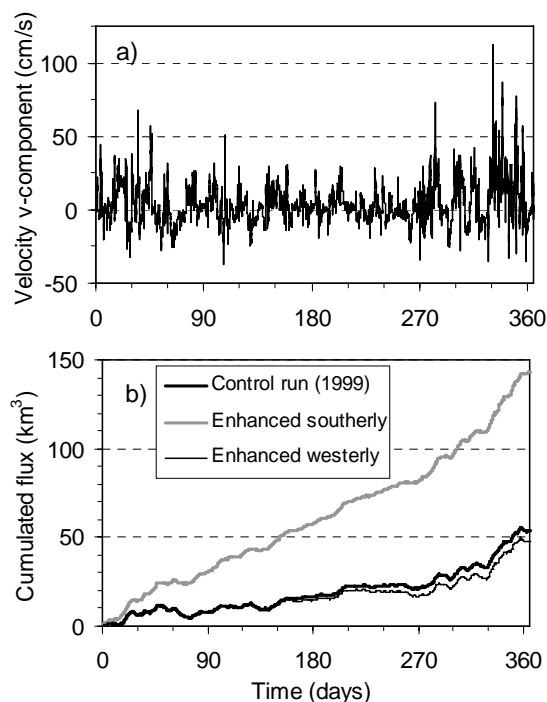


Figure 6. Time series of modeled currents in the Suur Strait near Virtsu in 1999, with v-component, and where the positive direction is northwards (a); modeled cumulative flows through the cross-section of the Suur Strait near Virtsu obtained with the year 1999 wind data, enhanced southerly and enhanced westerly forcing scenarios (b, see also Figure 5).

period. SW is the wind direction that is most effective in producing a storm surge in Pärnu Bay (Figure 4b). Another factor contributing to Gudrun's storm surge was the relatively high background sea level in the Baltic (70 cm) at the time. The higher background sea level was the result of strong cyclonic activity during the preceding month, which had the effect of pushing additional water through the Danish Straits into the Baltic Sea.

Empirical return periods show a more or less satisfactory fit with the theoretical (e.g. Gumbel-) distribution in the case of all the tide gauges (including Tallinn), other than at Pärnu (Figure 3). Probably no extreme value distribution could predict the two extreme sea level events of 253 cm and of 275 cm, which fall outside the outlier limits. Even before 2005, 253 cm was considered as a value significantly outside of such limits with a theoretical recurrence period of some 300–1000 years, but it was repeated and surpassed just 38 years later. The graph (Figure 3) is similar to a graph for gust wind speed records that is contaminated by occasional tornados (e.g. CHENG and YEUNG, 2002), or sea level data that includes abnormal tsunami events. These two anomalous and outlying values at Pärnu were nevertheless caused by normal storms. Due to the specific configuration of the Gulf of Riga and Pärnu Bay, the sea level is proportional to the wind speed in the power of 2.4 (SUURSAAR *et al.*, 2002; 2006). At the upper range of wind speeds, a slight incremental increase in wind speed yields an exponentially higher incremental increase in storm surge level. The existence of a relatively higher background sea level in the Baltic Sea can further enhance the strength of the storm surge event.

Wind regime changes and implications on sea level

Model simulations demonstrate that the most sensitive areas for wind forcing are the shallow windward bays of Haapsalu, Matsalu and Pärnu (Figure 4a). The most effective wind direction for these bays is 220°–240° (SW). The patterns of wind directions resemble co-phase lines of tidal charts (Figure 4b), particularly in the northern sub-basin of the Väinameri, where the phase (wind direction) rotates clockwise around an amphidromic point with zero-amplitude.

According to scenario runs, if the southwesterly wind component were to strengthen by 2.8 m/s, the mean sea level would rise up to 4–5 cm in the above-mentioned windward locations (Figure 4c). The average rise in the Gulf of Riga would be around 2 cm. We note that throughout the simulated year 1999, the mean wind speed increased only 18% in comparison with the control run. Changes of a similar magnitude probably occurred already between 1950 and 1990. Although further increase in westerly winds is anticipated, it is also possible that the increase in westerlies and winter NAO in 1950–90 could be followed by a relative increase in easterlies (e.g. HAGEN and FEISTEL, 2005). For other scenarios see also SUURSAAR *et al.* (2006).

The local wind-driven sea level change component we have analysed applies within our semi-enclosed study area, with straits lying in the SW, W and NW directions. An additional analogous change in the Baltic mean sea level probably exists. According to the study by MEIER *et al.* (2004), the latter component could be up to 3–4 cm in the central Baltic under similar circumstances, yielding up to 8 cm summary sea level rise at Pärnu.

These 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 result in a steeper than average sea level trend on the windward side and one that is less steep on the leeward side.

Wind regime changes and flow patterns

Every change in wind speed and direction also affects wind-driven currents and water exchange through the straits. Because of the shallowness and small density differences, the currents in the study area are determined mainly by the wind and modified by coastline and bottom topography. In the narrow straits, the flow velocity and direction are determined mainly by the projection of the wind vector on to the direction of the straits' axis. For both Pärnu Bay and the Gulf of Riga, our simulations revealed two well-defined basin scale flow regimes with cyclonic and anticyclonic circulation cells (SUURSAAR *et al.*, 2002). The pattern includes downwind flows near the shallower coastal areas and compensatory flows against the wind along the deeper middle section of the bay.

The increase in wind speed generally leads to enhanced water exchange through the straits, as well as to a strengthening of the basin-scale circulation. Water exchange in the eutrophied study area increases the most if the wind speed along the axes of straits increases (Figures 5,6). The current speed increases along the straight coastline parallel to the wind direction, and the counter-wind current speed somewhat increases in the middle of the sub-basin. Increased southerlies yield the highest current speed increments in the meridional Suur and Hari straits (Figure 5b). Westerly winds enhance flows in the Soela and Irbe Straits (Figure 5a). The absolute increase in current speeds is 1–3 cm/s near the straight coasts and 3–6 cm/s in the straits, which makes up roughly 15–20% of the corresponding mean current speeds.

Changes in the wind-driven hydrodynamic regime affect the aquatic environment via changes in water and matter exchange through the straits and intensification of mixing processes within the sub-basins. Near coasts, the relatively small (up to 20%) wind speed increase we have considered presumably enhances upwelling and downwelling events, and produces an up to two- to threefold increase in bottom stresses in cases where the direction of the particular coastline section coincides with that of the wind speed change (SUURSAAR and KULLAS, 2006). As bottom stress is proportional to the square of the flow speed (Figure 6), and wave energy density is proportional to the square of the wave amplitude, the changes are the most pronounced during the stormy winter months, whereas the relatively calm summer months are geomorphically inactive.

CONCLUSIONS

At Estonian tide gauges, the mean sea level rise rates (adjusted to take into account the land uplift rates) are generally 1.5–2.1 mm/yr over the last century. The trend at Pärnu (2.3–2.7 mm/yr) is steeper than the mean global sea level rise estimate and two storm surge events (in 1967 and 2005) are inconsistent with the theoretical distributions, which indicates that, at this location, the most extreme sea level events are not predictable by means of return statistics.

The excessive rise both in mean sea level and in maxima can be explained by the local sea level response to the changing regional wind climate and intensification of cyclones. Semi-realistic simulations using a 2D hydrodynamic model have demonstrated that a relatively modest increase in wind speed can be responsible for a mean sea level increase of up to 2–5 cm within the study area. Changes of a similar magnitude probably occurred already between 1950 and 1990, and several climate modeling studies anticipate further changes in wind climate. The increase in wind speed leads to enhanced water exchange through the straits, as well as to a strengthening of the basin-scale circulation. Near coasts, the relatively small wind speed increase we have considered presumably enhances both longshore currents and vertical fluxes, and produces an up to twofold increase in bottom stresses.

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