Sea level rise scenarios induced by climate change, and their consequences for the Estonian seacoast

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Abstract

Due to the low-lying land, the gently sloping coasts and the virtual absence of tides, the flooding generated both by local storm surges and the climatologically induced global sea level rise will increasingly affect the Estonian coastal zone. Both the static as well as the dynamic aspects of the sea level rise are studied and their consequences are discussed. Recession of the shoreline due to different global sea level rise estimates is investigated, taking into account the isostatic land uplift of the Baltic Sea region. Meteorological forcing time series (NAO-indices, local wind and storminess data etc.) are analysed and the sea levels are dynamically modelled in the Estonian coastal sea using a 2D hydrodynamic model with 1 km grid-step. Increased storminess, in addition to the sea level surge events, will favour the destruction of the shores and harbour facilities.
Keywords: floods, storm surges, climate change, hydrodynamic models.

1 Introduction

Climate change – global warming, changes in precipitation and increasing storminess – is expected to have a significant impact on natural environment and human activity in high latitudes [1,2]. The warming due to enhanced greenhouse effect is supposed to have some positive influences on Estonia, but there are some major threats as well. They are connected with the sea-level rise and the

Risk Analysis IV, C. A. Brebbia (Editor)

flooding of coastal areas, the erosion of seashores, and the destruction of harbour infrastructure. Sea-level rise may strongly affect Estonia because it has a relatively long and indented shoreline (3794 km; Fig. 1). The highest point of Estonia is 318 m and the country has extensive low-lying coastal areas. In addition, occasional storm surges can pose serious risks for near-shore inhabitants. Much more frequent and energetic storms are expected; therefore bearing in mind the shallow sea, the gently sloping coasts and the virtual absence of tides, people are not well enough prepared for such events.

The paper deals with the analysis of the influence of climate change on the Estonian coastal zone. (1) The extent of shoreline recession due to the "static" sea level rise induced by global warming is described, (2) additional local sea level changes due to the changes in the regional wind regime are studied, and (3) influence of the sea level rise combined with increased storminess on the coastal zone is discussed.

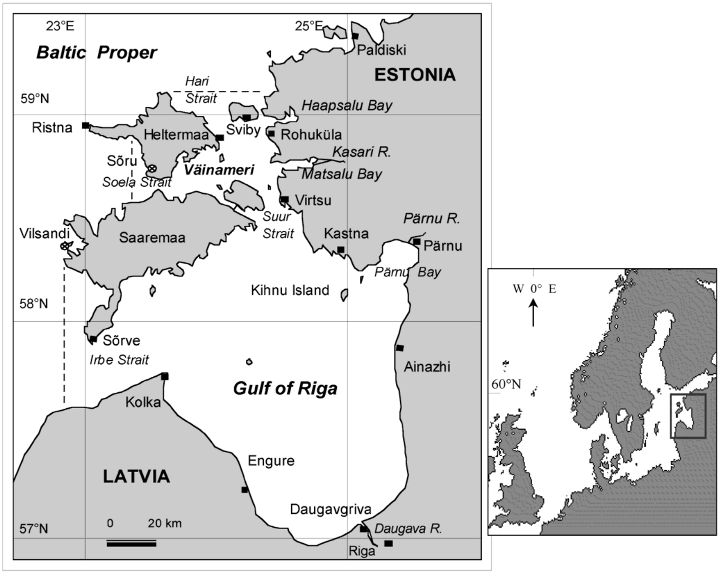


Figure 1: The map of the study area (-- open boundaries of the 2D model).

2 Material and methods; meteorological forcing

For obtaining sea level rise estimates, climate change scenarios for Estonia were generated using a simple climate model called the Model for the Assessment of Greenhouse-gas Induced Climate Change (MAGICC) and a regional climate change database SCENario GENerator (SCENGEN) [3]. MAGICC version 2.3 combines a coupled gas-cycle and climate, as well as ice-melt models that allow the user to find the global mean temperature and sea-level consequences of a user-specified greenhouse gas and sulphur dioxide emissions. The corresponding recession of the Estonian coastline, as well as the coastal geomorphology was analyzed using topographic maps and commercial GIS software packages, taking also into account the isostatic land uplift [4].

The Estonian seacoast has been emerging during the whole Holocene period and at present the annual uplift rate ranges from 1.0 to 3.5 mm (Fig. 2). However, while a possible sea level rise would be partly mitigated by land uplift, there are some meteorologically induced hydrodynamic processes, that could considerably change the “static” scenario.

Sea level variations and wind-driven currents are modelled using a high-resolution (1 km grid step) shallow sea 2D hydrodynamic model, which is forced by the wind and open boundary sea level data. The model itself as well as the simulation conditions are more thoroughly described in [5,6]. The simulations based both on idealistic (i.e., certain stationary wind schemes from different directions) and realistic (1999 year) conditions were carried out. The extensive output data (sea level and flow time series in up to 18964 gridpoints) were statistically analysed. The studied relationships between the meteorological (wind-)conditions and both the sea level and flow regime variations could be extrapolated into a climatological scale. Therefore some recent trends in the meteorological situation above Estonia were analysed.

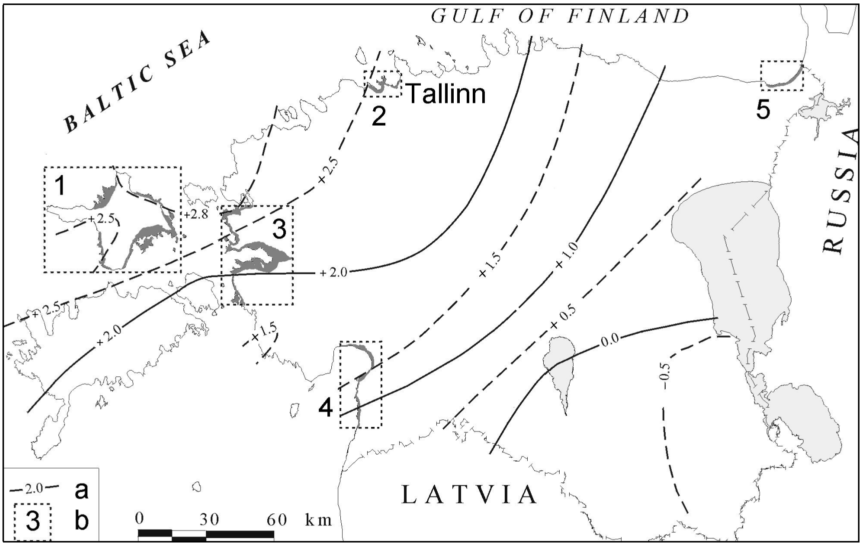


Figure 2: Isobases of vertical land movements (mm/year [4]; a). Areas under the risk of inundation (grey shade within the study sites; b): 1-Hiiumaa Island, 2-Tallinn, 3-Matsalu Bay, 4-Pärnu Bay, 5-Sillamäe-Narva.

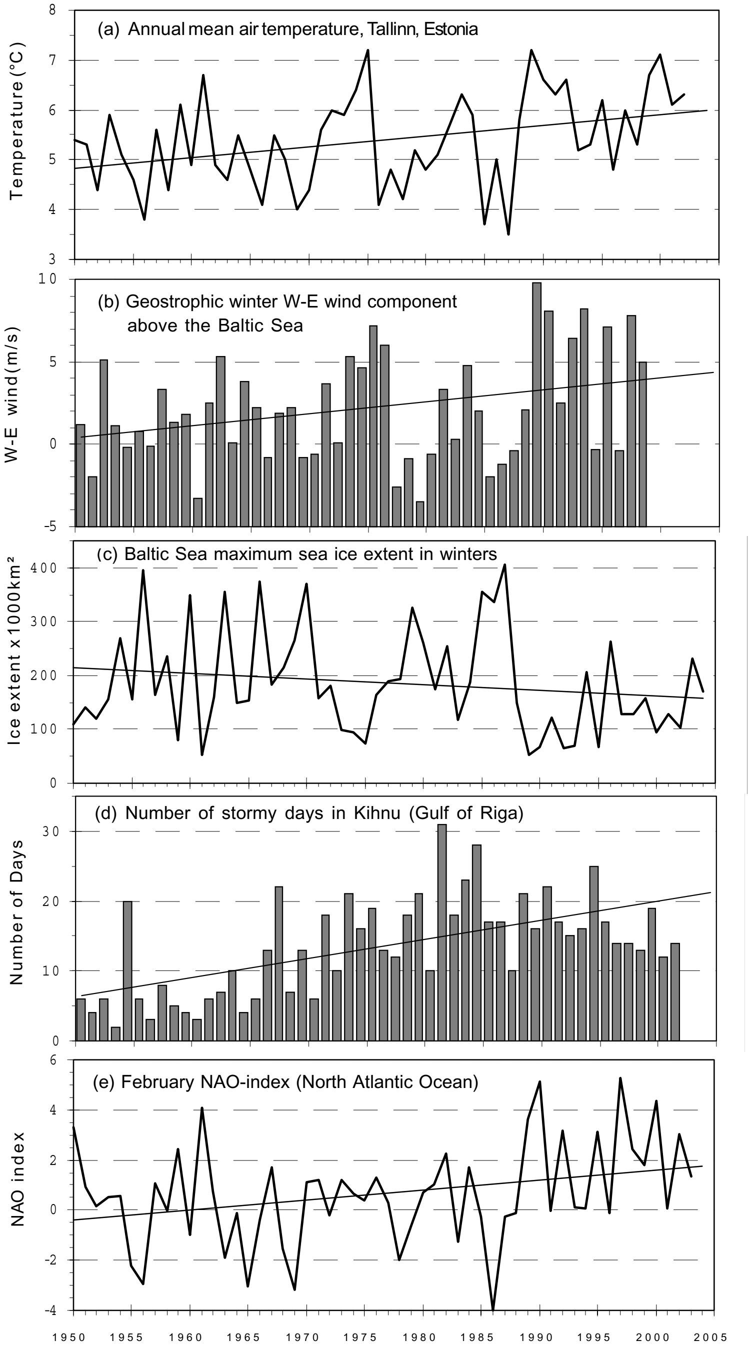


Figure 3: Time series of meteorological forcing factors in 1950-2003.

Firstly, a clear positive temperature trend (+1.2ºC/53 years) is visible (Fig. 3a)[7]. Change by trend of monthly mean air temperature during 1950–2000 is most prominent (2–3.5ºC) from January to April according to the time series of the Vilsandi station [8]. Secondly, the Baltic marine area is located within the westwind zone, where cyclones coming from W or SW dominate the weather. In addition to the increased number of stormy days (days with wind speed >15 m/s) and an increased average wind speed evident in many meteorological stations, the directional distribution of winds is about to change as well.

Geostrophic W-E wind component shows prevalence of westerly flow over meridional (southerly) air flow. The intensification of westerlies [9] during the cold half-year is evident (Fig. 3b). A decrease in the Baltic Sea ice extent (Fig. 3c) is a result of the rise both in temperature as well as in storminess (Fig. 3d)[10]. The above mentioned local and regional trends are closely related to the global trends in atmospheric circulation patterns above the North Atlantic. They could be described using a multitude of variables, NAO-indices [11] among others, showing positive trends especially in February and March (Fig. 3e).

3 Results and discussion

3.1 Consequences of the global sea level rise: static scenario

Using three alternative greenhouse gas emission scenarios, an increase of mean annual air temperature by 2.3–4.5ºC is expected for the year 2100. The highest warming is supposed to take place in winter and the lowest one in summer. The climate of Estonia is becoming less continental and more maritime with an increase in annual precipitation between 5% and 30%. The sea level rise as another output of the MAGICC model shows an increase by 38–55 cm for the year 2100 [2]. Unfortunately, the sea level rise error margins for the year 2100 are very wide, yielding 1 m as the maximum sea level rise value. The projection of the sea-level rise by 1 m during a century seems to be a reliable scenario for Estonia and is recommended e.g. by the US Country Studies Program, Intergovernmental Panel on Climate Change (IPCC) [1] etc. Due to the compensating effect of isostatic land uplift (see Fig. 2), the actual sea-level rise would vary from 72 to 80 cm in the case of 1 m sea-level rise scenario.

As the Estonian coastal zone is very low-lying and flat, the dominant processes would be inundation and temporal flooding by storm surges. Considering the “static” 72–80 cm sea level rise only, the maximum shoreline recession is up to 6.4 km near the Matsalu Bay. In total 76 km^2 of the Matsalu Study area territory would be inundated (Fig. 2). Coastline recession would be up to 1.4 km on the coasts of Hiiumaa Island, 1 km near the capital city Tallinn, 0.7 km near Rohuküla, 0.6 km near Pärnu, etc. In general, the sea level rise would restore approximately the same shoreline position as in the 1700s.

3.2 Local sea level rise: influence of the changes in the wind regime

An aspect usually not considered in the sea level rise scenarios is the influence of the local sea level changes due to the changes in meteorological conditions. These features could only be studied using hydrodynamic models. It appeared that in each given location the sea level actually reflects the existing equilibrium in the wind regime in reaction with the configuration of the shoreline (Figs. 4–6). We are used to the existing sea level regime, but we must not take it for granted. In heavily indented and semi-enclosed coastal areas the conditions vary considerably between straight coasts and long tapering bays, leeward and windward sides of the sub-basins, etc.

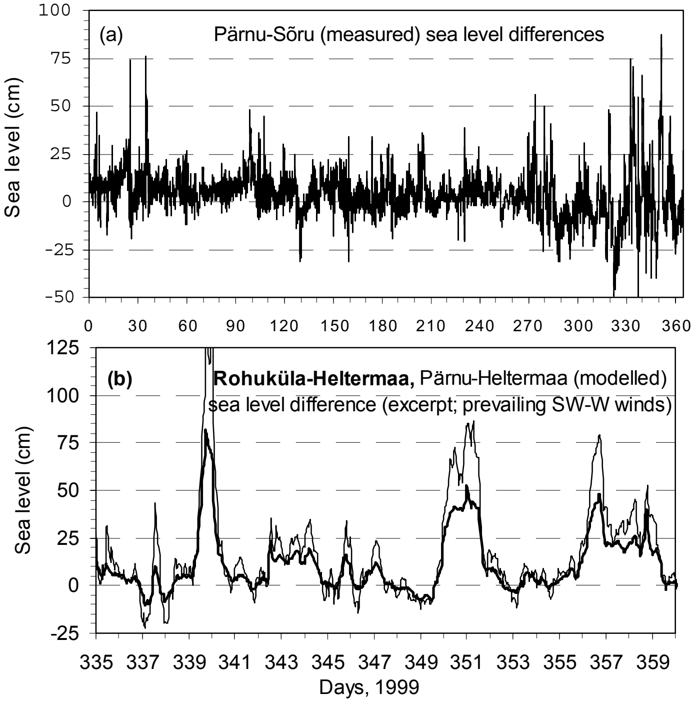


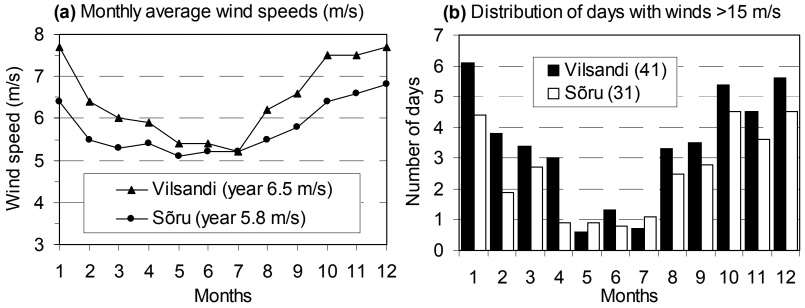
Figure 4: Local sea level differences as measured (a) or modelled (b) in 1999.

Fig. 4a shows the variations in local sea level differences, which were up to 1 m between Pärnu and Sõru, some 110 km apart from each other. Rohuküla and Heltermaa, locating on different sides of the Hari strait only 20 km from each other, had short-term sea level differences up to 80 cm in 1999 (Fig. 4b).

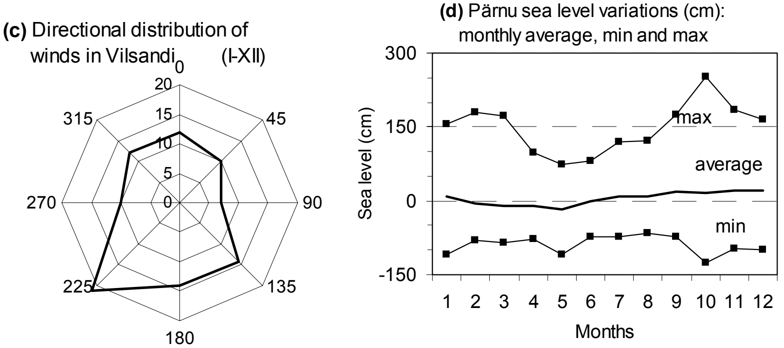
The hydrodynamic reason for that feature could be explained by the dependence of the sea levels on the direction of wind in the semi-enclosed sub-basin of the Gulf of Riga and its different locations (Fig. 6a). It also shows that

Risk Analysis IV, C. A. Brebbia (Editor)

the possible change in the long-term average (resulted) wind direction has a measurable effect on the sea level. SW winds prevail above the Baltic Sea (Fig. 5c) with the previously discussed increase in westerlies (Fig. 3b) due to the climate change in the years 1950–2003. The increase in the wind speed from specific directions, i.e. 220° for the Pärnu Bay and 260° for the Matsalu Bay, elevates the sea level in the correspondingly oriented bays (Fig. 6b). The effect is very small in the case of small wind speed values. For example, the increase in stationary 220°-projected wind speed from 7 to 9 m/s yields the persistent sea level change of only about 7 cm at Pärnu (Fig. 6b). However, in statistical sense the average sea level is strongly affected by infrequent high values during storms. Two days with the wind speed 5 m/s in one day and 15 m/s in the other have a higher average sea level than two days with 10 m/s wind. The 2 m/s wind speed increment between 28 and 30 m/s yields a 50 cm higher surge (240 cm vs. 290 cm; background Baltic sea level value from the open boundary of our study area should be added to obtain the final sea level height at Pärnu). In other words, only a slightly higher wind speed during a storm can produce a significantly higher storm surge. Up to now +253 cm is the highest measured sea level (Pärnu, October 18, 1967) in Estonia. This comprised 1.6 m local surge and 0.9 m background value near Sõru. However, we should expect new sea level extremes in the epoch of increasing storminess.


(a) Monthly average wind speeds (m/s)

(b) Distribution of days with winds >15 m/s


(c) Directional distribution of winds in Vilsandi (I-XII)

(d) Pärnu sea level variations (cm): monthly average, min and max

Figure 5: Directional distribution of winds (c), seasonal variations of meteorological (a,b) and sea level (d) conditions in Estonia.

The changes in the shoreline (wetting and drying) in response to the variations in the water level are not included in our 2D model. However, a 2–3 m sea level rise will temporarily “elongate” the Matsalu Bay for at least 10 km and the Pärnu Bay up to 5 km. As the storm surge height also depends on the length of the bay, this will additionally elevate the sea level for about 50 cm (Fig. 6b). Changes in the wind climate, e.g. increase in westerlies, firstly raise the average level of the Baltic Sea due to its fjord-like SW-NE-orientated shape. This sea level rise in the NE part of the sea is likely to be relatively small (below 5 cm), but it is more pronounced in its semi-enclosed small sub-basins, like the Gulf of Riga. On the basis of Fig. 5, Fig. 6 and Table 1 we can speculate: if the wind climate would change from the conditions like “June-July” (with 5.5 m/s average wind) into “October-December” (7.5 m/s; more frequent storms; Fig. 5a,b), the average sea level in Pärnu would rise for about 30 cm and the heights would grow from 100 cm to 250 cm (Fig. 5d).

Wind speed increase 2 m/s per 100 years (e.g. from 6.5 to 8.5 m/s) seems quite a reasonable scenario. Actually, either a change in average wind speed or just a change in directional distribution is needed (see Figs. 3b, 5a,c). However, in the leeward side of the Gulf of Riga or the Väinameri Sea, the average sea levels could decrease in some locations, but less than about 10 cm. It is because the 30 cm rise at Pärnu essentially includes also the variations (rise) in the Baltic background sea level and an increase in the Gulf of Riga average sea level.

3.3 Influence of the sea level rise and storm events on the coasts

Extensive erosion and alteration of depositional coasts, e.g. sandy beaches, have been observed during the last decades in Estonia. For instance, at Harilaid (near Vilsandi) the shoreline has receded on average 1.5 m/year in the last 20 years [12]. Severe coastal damage usually results from a combination of strong storms, high sea-level and absence of protective ice cover in winter: most storms occur during the cold half-year (see Fig. 5b). As Estonia lies close to the average Baltic Sea winter freezing line, the ice conditions near the Estonian coast are relatively sensitive to the decreasing Baltic ice extent trends (Fig. 3c).

It could be concluded from Table 1, that while the period from October to December had average wind speeds about 2 times higher than June-August, the average sea level is higher for 30–40 cm, current velocities are about 2–4 times higher, but bottom stresses are about 5–10 times higher. The tendency is even more pronounced when comparing shorter periods, e.g. July vs. December, a stormy period vs. calm period. It was found that roughly half of the currents and waves work attacking the coast is done during the 2–3 stormy days of the year in the Pärnu Bay and the high velocities operate 1–2 m above the average waterline height, while the geomorphologically insignificant small velocities act around the average waterline [13].

Both the sea level rise and storm surges need additional risk analyses and hazard mitigation efforts. On the West Estonian coast the main hazard lies in the changes of coastal ecosystems and land use. A number of valuable natural ecosystems, such as reed beds and coastal meadows, including rare plant

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communities and suitable breeding grounds for birds, would be in danger. Most sandy beaches of high recreational value would disappear. However, possible economic losses in Tallinn, the city of 400 000 inhabitants, would be the greatest. The other site of great risk is Sillamäe, an important industrial centre and a former uranium enrichment plant. The dumping site containing ^{238}U, ^{232}Th, and ^{226}Ra is separated from the sea by a narrow dam. (Fortunately, an extensive depository rehabilitaton and dam fortification project is in process now). To prevent coastal land loss, the construction of seawalls and dikes could be applied. Sandy beaches of Estonia need to be protected by beach nourishment. Most of the harbours need upgrading. An operational system for providing sea level prognoses and storm surge warnings should be developed.

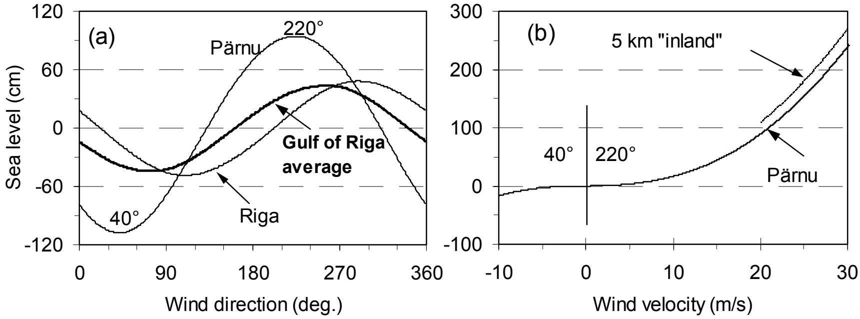

Figure 6: Modelled dependence of the sea levels on the stationary and uniform wind (with 20 m/s modulus) from different directions (a). Sea levels at Pärnu and at a hypothetical “inland” point (after flooding the coastal plains near Pärnu for 5 km) depending on wind velocity (b).

Table 1: Seasonal variations in monthly average measured Vilsandi wind speed (m/s), Pärnu modelled sea level (cm), Pärnu modelled wind-driven coastal current modulus (cm/s), current generated bottom stresses, and bottom stresses generated by wave orbital velocities (dyn/cm²) in 1999.

	Months of 1999											
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Wind speed	7.0	6.5	4.9	5.6	5.0	4.5	4.4	4.1	4.1	7.2	6.9	9.6
Sea level	8.1	12.9	-16.0	-8.7	-23.8	-15.3	-6.7	-9.6	-16.6	17.5	13.6	30.8
Current speed	9.3	9.3	5.7	7.1	5.4	5.4	4.6	4.8	4.9	11.1	8.7	18.3
Current stress	0.32	0.35	0.12	0.26	0.11	0.12	0.08	0.09	0.09	0.45	0.27	1.57
Wave stress	2.2	1.8	1.3	1.6	0.8	0.8	0.4	0.6	1.3	2.3	2.6	3.6

4 Conclusions

Climate warming due to the enhanced greenhouse effect is expected to produce up to 1.0 m sea level rise by 2100 in the Baltic Sea, which in some places will be partly (up to 0.3 m) compensated by land uplift. The maximum recession of the shoreline would comprise 6.4 km in West-Estonia. The time series analysis shows a significant increase in the wind speed and the frequency of storm days over the last half-century. As a result, the changes in the wind climate will supplement the "static" sea level rise induced by global warming. An additional local sea level rise occurs in certain bays exposed towards the most expected directions of storms (SW-W), both in terms of average (up to 0.3 m) and short-term surge events. A slightly higher wind speed during storm may result in a significantly higher storm surge and a much more destructive shore erosion. As SW-W storms are associated with the sea level rise off West Estonia, the high flow velocities and strong wave action, decisive factors in erosion events, act 1–3 m higher than the ordinary coastline. Increased storminess in combination with warmer winters will favour the destruction of the shores and harbour facilities due to the unfrozen sediments and the absence of protective ice cover.

Acknowledgements

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