Extreme sea level events in the coastal waters of western Estonia

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Abstract

Extraordinarily low and high sea level events are analysed on the basis of historical data and their mechanisms of occurrence are studied with the 1 km grid size 2D hydrodynamic model in the two almost tideless semi-enclosed sub-basins of the Baltic Sea, the Gulf of Riga and the Väinameri. The sea level is modelled with realistic meteorological forcing and comparison data from 1999 and 2001. Resonance properties of the sub-basins are studied and their possible role in the formation of extraordinary sea level events is discussed. While the extremely low levels (−1.23 m below the mean sea level) in the Estonian coastal waters do not generally originate locally, the high levels (up to 2.53 m above the mean as measured in the Pärnu Bay) are short-term and local. They occur in combination with several forcing and morphometrical factors and are localised in the shallow and narrow bays exposed to the direction of the strongest possible storm winds, SW and W. Model simulations show that extremely high and low sea levels in some small bays of western Estonia can exceed the corresponding values in the Pärnu Bay.

Keywords: Sea level; 2D models; Storm surges; Oscillations; Resonance; Baltic Sea

1. Introduction

Frequent passages of atmospheric pressure systems generate considerable water level fluctuations in the nearly tideless Baltic Sea (amplitudes of $M_2$ and $K_1$ waves 0.01–0.02 m in the Baltic Proper according to e.g. Magaard and Krauss, 1966). The historical range of maximum sea level fluctuations at both ends of the elongated Baltic Sea is up to 5.7–5.8 m, while in the central part of the sea the range is between 2 and 3 m. 27.4 h is the well-known seiche period for the Baltic Proper–Gulf of Finland system and about 39 h for the Baltic Proper–Gulf of Bothnia system (e.g. Wübben and Krauss, 1979; Metzner et al., 2000). Estonia is located in the central part of the Baltic Proper near the nodal line of the Baltic quasistationary sea level slope (0.18 m towards SW according to Lazarenko, 1986) and the largest (about 27 h) seiche, but due to the complex configuration of its coastal waters and the existence of some semienclosed sub-basins (Fig. 1a) the variability is high and the mechanisms forming the sea level regime are rather intricate. The highest sea level registered near the Estonian coast (2.53 m above the Baltic Mean Level or Kronstadt ‘zero’ in...
Pärnu on 18 October 1967) is probably the highest Baltic sea level measured outside the two well-known specific areas: the Neva Bay near St. Petersburg, Russia, in the north-east, and the coastal region near Schleswig, Germany, in the south-west.

Storm surges above the 1.6 m critical value cause flooding both in St. Petersburg and in Pärnu. Extremely negative surges may affect optimal ship loading in ports. When the sea level falls to about \(-0.5\) m below the mean in the Väinameri, the operation of ferries is cancelled along the Rohuküla–Heltermaa and Rohuküla–Sviby ferry routes. Operational sea level forecast is therefore of considerable importance. So far such forecasts in the Baltic States of the former Soviet Union have been given on an empirical basis; however, hydrodynamic models have also been used for predicting St. Petersburg surges (e.g. Klevanny et al., 1994).

The present study presents sea level and flow simulations. It describes and analyses the hydrodynamic mechanisms forming extraordinary sea level events on the basis of historical records and simulation results. Discussion of resonance effects on the sea level fluctuations in the study area is of major interest as well.

2. The study area and an overview of the historical data

The Estonian northern coast is relatively straight along the Gulf of Finland, while the western coast is heavily indented. The two semi-enclosed sub-basins are located there. The Gulf of Riga covers an area of 140 km from west to east and of 150 km from south to north with a sea surface area of 17 913 km\(^2\). The Väinameri (also the Moonsund) has a surface area of 2243 km\(^2\). The average depth of the Gulf is 23 m, and the average depth of the Väinameri is merely 4.7 m. These sub-basins are connected with each other and with the Baltic Proper by four narrow straits (Fig. 1a), 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 are subject to the
prevailing westerly winds and the passage of cyclones.

Sea level measurements in the Estonian coastal waters have been carried out with small gaps since 1842 (in Tallinn). According to the statistics of historical data, the possibility of both high and low sea levels is highest in the meteorologically variable winter months (Fig. 1b–d). The standard deviations of the sea level time series given on a monthly basis are usually much higher from October to February (Fig. 2c), correlating well with the corresponding standard deviations of wind velocity modules (Fig. 2d). According to Latvian data, 79% of the surges near Daugavgriva in the southernmost part of the Gulf of Riga occurred in the September to February half-year in 1947–1967 (Pastors and Iljina, 1976). The historical range of sea levels is highest near Pärnu (Fig. 1d). The top five storm surges of Pärnu include: 2.53 m (October, 1967), 1.84 m (February, 1990), 1.81 m (September, 1978), 1.80 m (November, 1923) and 1.79 m (April, 1932) for the period of 1923–2001. Due to its smallness, the Väinameri (Rohuküla) has a smaller sea level range (Fig. 1c), whereas the Ristna station more or less represents the Central NE Baltic situation with a narrow historical sea level range and minor local wind effect (Fig. 1b).

3. Material and methods

3.1. The models

The main tool used in the study is the 2D hydrodynamic model for the Gulf of Riga and Väinameri, supplemented by a simple Helmholtz model for the same sub-basins and a Baltic 2D model. The supplementary Baltic 2D model for the whole Baltic Sea region from Göteborg to St. Petersburg as well as to Kemi receives input sea levels from Skagen or Göteborg in the Kattegat. The modified Hansen (1956) model uses a 4.5 km (2.5° lat × 5° lon) grid-size and includes 18246 marine points (see also Otsmann et al., 2001). It could provide boundary conditions for the Gulf of Riga models if there are no measured sea level data available near the boundaries of the Gulf. It is also used in the investigation of certain resonance situations in the study area with idealistic wind and sea level forcings. The Helmholtz model is built up as a combination of 5 Helmholtz oscillators, two for the Gulf of Riga and three for the Väinameri (Otsmann et al., 2001). It includes 2 marine points for sea levels and simulates currents in the four straits. The only role of the model in this study is to provide calibration and comparison data for the main 2D model.

The Gulf of Riga–Väinameri 2D model is a shallow sea depth-averaged free-surface model with quadratic bottom friction using 1 km grid size. The model is more thoroughly described in Kullas et al. (2000).
and Suursaar et al. (2002). It is composed of momentum and continuity equations:

\[
\frac{DU}{Dt} - fV = -g(H + \xi) \frac{\partial \xi}{\partial x} + \frac{\tau_x}{\rho_w} - \frac{kU}{H^2} (U^2 + V^2)^{1/2},
\]

\[
\frac{DV}{Dt} + fU = -g(H + \xi) \frac{\partial \xi}{\partial y} + \frac{\tau_y}{\rho_w} - \frac{kV}{H^2} (U^2 + V^2)^{1/2},
\]

\[
\frac{\partial \xi}{\partial t} + \frac{\partial U}{\partial x} + \frac{\partial V}{\partial y} = 0,
\]

\[
\frac{D}{Dt} = \frac{\partial}{\partial t} + \frac{1}{H} \left( U \frac{\partial}{\partial x} + V \frac{\partial}{\partial y} \right),
\]

where \( U \) and \( V \) are vertically integrated volume flows in \( x \) and \( y \) directions respectively, \( \xi \) is the sea surface elevation (from the equilibrium depth, \( H \)), \( f \) is Coriolis parameter, \( \rho_w \) is water density, \( k \) is the bottom stress coefficient \( (k = 0.0025 \) see e.g. Jones and Davies, 2001), \( \tau_x \) and \( \tau_y \) are wind stress components of \( \tau \) along \( x \) and \( y \) axis. Wind stress \( (\tau) \) was computed using the formula by Smith and Banke (1975), which includes a non-dimensional empirical function of the wind velocity: \( C_D = (0.63 + 0.066 |W_{10}|) \times 10^{-3}, \) where \( |W_{10}| \) is the wind velocity vector modulus (with dimension \( \text{m s}^{-1} \)) at 10 m height above the sea level.

3.2. Input data and simulations

Wind above the sub-basins and open boundary sea levels are the major forcings for sea level changes in such a relatively small and semi-enclosed marine area. Factors such as local thermal expansion, precipitation-evaporation and change in the sea surface area have not been taken into account here. The inverted barometer effect is also imported through the open boundary sea level, but its local differences are small within the study area. Average monthly river runoff (in total 34 km\(^3\) y\(^{-1}\) for the Gulf of Riga, e.g. Berzinsh et al., 1994) applied for keeping the long-term water budget enters the sea via three rivers: the Daugava (near Riga), Pärnu (near Pärnu) and Kasari (in the Matsalu Bay). However, the rivers do not significantly affect the dynamic aspects of the sea level. According to our estimates their influence remains below 0.01 m even near their entering points.

The year (1999) chosen for the simulations offered some interesting sea level situations; some coastal erosion events on the beaches of the Pärnu Bay were observed by the Geological Survey of Estonia. The wind data from the Vilsandi meteorological station used in the present study had a 6 h time step, 1 m s\(^{-1}\) value interval and a 10° angular resolution. The station is located on an island west of the Estonian mainland (Fig. 1a), the data are not contaminated by the direct influence of land to the east. Homogeneous wind was applied over the whole modelled area. Open sea level input originated from the Sõru marine station, providing mareograph data with a 1 h time step. The Sõru measurement history covers only a few years, but it should have statistics similar to those of the nearby Ristna station (Fig. 1b). The input sea levels were applied identically at the three cuts of the open boundaries near the straits. For comparing the simulated sea level time series, hourly mareograph data from the Rohuküla and Pärnu marine stations were used. Using the Helmholtz model, hourly sea level time series were calculated in the Väinameri and the Gulf of Riga for 1999. Corresponding horizontal average time series were also calculated with 2DM, as well as sea level time series in special gridpoints for Rohuküla, Heltermaa, and the bays of Haapsalu, Matsalu and Pärnu (Fig. 1). We also calculated horizontal distributions of the sea levels and flow pat-
tems, but no flow observations were available for the comparison that year.

4. Results and discussion

4.1. Description of the simulation results

Comparison between the hourly modelled and the measured sea level time series of the Rohuküla and Pärnu stations showed rather high correlation coefficients ($r = 0.94$ in Rohuküla and $r = 0.90$ in Pärnu; $n = 8760$ pairs). Both the output series and the series of errors (Fig. 2a,b) display larger deviations in meteorologically more variable winter months (Fig. 2d). The relatively high variability of differences (Fig. 2b) calculated from hourly unfiltered output should not be overestimated. The differences appear mainly due to a time lag. In the case of the surge events in Pärnu (Fig. 3d) the model frequently reproduced the level rise 4–8 h before the actual rise, in the case of low sea level in the Väinameri (Fig. 3b) the modelled minimum appeared 2–3 h after the correct time. The explanation is that during the rapid increase in the west wind the velocity reacts simultaneously both in Vilsandi and Pärnu, while the actual approach of the wind front along the distance of 130 km could take some hours. In the low-level events the east wind acts ahead of the model. A considerable difference in day 352 (Fig. 3d) appeared due to a 13 h gap in the original Sõru input series: the storm had spoiled the mareograph. The linear interpolation of the gap probably underestimated the actual contribution of the Sõru sea level. The Pärnu tide gauge due to its location in the river, some 3 km upstream from the sea, might not provide correct data during extremely rapid storm surge events, such as in day 340 (Fig. 3d). Reversed flow in the lower reach of the Pärnu River could be observed during such events. In addition, the Vilsandi wind is probably a little too strong for the Pärnu Bay area, especially during storms. As the most important information for the sea level is captured in the wind data (see e.g. Figs. 2 and 3), it is advisable to improve the output quality mainly by improving the temporal and horizontal resolution of the wind input. Using either interpolation of in situ wind measurements from several points to regular grid or applying HIRLAM (High Resolution Limited Area Model, a climate model with the resolution of 15–55 km in different versions) winds, the operational system of sea level forecasts could be improved in the future.

The lowest water level in 1999 was measured in Rohuküla as $-0.49$ m (September 20, day 263), whereas the model yielded $-0.44$ m (Fig. 3b). The highest level in Pärnu was measured as 1.46 and modelled as 1.62 m on 18 December 1999 (Fig. 3d). Some prognostic sea level calculations made during the 15 November 2001 surge event in Pärnu predicted 1.6 m as the maximum sea level value for the concurrent meteorological conditions of that storm,

![Fig. 3. Open boundary sea level input (a) and comparison of sea level output at Rohuküla with measured sea level data (b) during the low level situation between 8 September and 1 October 1999. Wind input (c) and comparison of sea level output at Pärnu with measured sea level data (d) during the storm surges between 2 and 26 December 1999.](image-url)
which appeared to be quite correct (1.59 m, see Fig. 4a).

4.2. The mechanisms of extreme sea level events

Near the open boundaries of the study area, the range between historically extreme sea levels is only around 2 m (Fig. 1b) against 5.76 m in St. Petersburg. Thus, probably no big storm surges could be expected in the coastal waters of Estonia or Latvia outside the Gulf of Riga. However, inside the Gulf the direct local meteorological forcing and some local hydrographical features become highly important.

The analysis of the input forces together with the response reveals that the high and low sea level events have different mechanisms in the study area. The September low level event at Rohuküla was largely determined by the outer sea level (Sõru minimum — 0.43 m, Fig. 3a,b). According to the tide gauge data from Stockholm (Dr. K. Döös, pers. comm., 2001) the lowest sea level of 1999 (— 0.31 m below the years average) was also registered near the Swedish coast during the same event. The regional lowering in the central Baltic was produced by continuous northern and eastern winds. Such events are connected with the simultaneous low sea levels in the Kattegat. Due to the limited flow capacity of the Danish straits, the co-oscillations of the Baltic and North Sea levels are strongly damped for periods of less than about a month, resulting a time delay between the winds above the North Sea and the Baltic Sea level response (Svansson, 1980; Stigebrandt, 2001). A sufficiently stable meteorological situation with prevailing east winds can only appear during anticyclonic blockage above the Baltic Sea and Russia. Large-scale and relatively small local differences of the historically lowest sea level event can be seen in Fig. 5b. Sea levels as low as — 1.3 m near Daugavgriva (Pastors, 1961), — 1.23 m near Pärnu, and — 1.13 cm in the Väinameri developed on 9 December 1959 after a month with strong (20 m s⁻¹) east winds during an uncommonly long blockage pattern of atmospheric pressure systems with 1050 mb above Russia and 980 mb above the British Isles.

High sea level events appear in the background of the initial volume increase in the Baltic Sea, which are
associated with W cyclones, pressing water through the Danish Straits (e.g. Lass and Matthäus, 1996; Stigebrandt, 2001). Although the Baltic Sea level can increase by about 1 m during stormy autumns and winters (e.g. Lazarenko, 1986), the extreme high-level events are fairly brief and local (Figs. 3d, 5a). Additional water volume is pressed into the semi-enclosed Gulf of Riga sub-basin, functioning in relation to west winds as a smaller replica of the Baltic Sea itself. The final effect driven by strong wind (Fig. 3c) is localised in the narrow bays exposed to the direction of a storm. The role of the outer sea level was relatively minor during the December 1999 storm surge in Pärnu (Fig. 3d). During the October 1967 storm surge the local sea level height in the Pärnu Bay exceeded the open boundary value by about 1.5 m (Fig. 5a).

For the Pärnu Bay, the most efficient wind direction for high sea levels is around 220° (Fig. 6). Although the low sea levels of roughly equal magnitude could be produced by equal stationary winds from the opposite direction (40°), such winds are statistically not expected. The bearing of the Pärnu Bay fairway coincides well with the direction of the strongest possible local wind: according to statistics from 1977–1991 the maximum values are 25 m s\(^{-1}\) for 225° and 22 m s\(^{-1}\) for 203°, whereas for the opposite direction the maximum expected wind speed is only 14–17 m s\(^{-1}\) (Soomere and Keevallik, 2001). Local east winds above the bays are additionally shaded by land from the east.

According to our model simulations quite large sea level fluctuations can also appear in some shallow west Estonian bays, which have no tide gauges. In 1999 the modelled maximum sea level values for the Haapsalu inner bay exceeded the values of Pärnu by 0.14 m and those of the Matsalu Bay by 0.06 m (Fig. 7a). However, these differences fall within the modelling error margin and cannot be proved by measurements. The search for the lowest modelled values of the year gave 0.86 m in the Haapsalu Bay and 0.77 m in the Matsalu Bay on 29 January 1999 (Fig. 7b). Both, the Pärnu Bay and the southern part of the Gulf of Riga had simultaneous, but much smaller lowering. The event was produced by NE winds (in days 26–29) with a velocity of up to 15 m s\(^{-1}\). Though in reality this particular sea level event could not be so extreme due to the ice-cover in the bays, the lowest sea levels possible are not likely to occur in the Pärnu Bay, as assumed on the basis of direct measure-
ments, but in the much smaller and shallower Haapsalu and Matsalu Bays. Due to the smaller water volume, the remarkable lowering could only take 3–5 days there. The shallow bays are prone to short-term extraordinary sea levels, because it is easier to blow a thin water film up (or down) the coastal slope than to create a similar free surface slope of the deep water by the wind stress.

The records of the surge events near Pärnu in 1967 and 2001 (Figs. 4a, 5a) show some periodical components. Resonance should appear immanently in the model output of realistic simulations, but the conditions and limits of such events could be studied using idealistic forcing schemes. Connected with the periodical changes of the sub-basins water volume, the Helmholtz oscillations of the Gulf could not produce remarkably high levels, as the flow is restricted in the straits. However, we can consider an amplification due to the series of cyclones or fronts combined with the seiche periods, including the 5 h barotropic seiche for the Gulf of Riga sub-basin. The 1967 surge (Fig. 5a) seems to have had interactions with the sea level events created by previous storms, appearing successively after 27–40 h (i.e., close to the period of largest Baltic Sea seiche). The simulation with the constant 20 m s$^{-1}$ wind blowing along the Pärnu Bay fairway with impulsive start produced the damped oscillations with a 5 h period and the level increase by 1.2 m near Pärnu (Fig. 8a). Again, the direction of 220° was the most efficient one. The initial effect of the impulsive start (maximum sea level 1.2 m) is somewhat higher than the steady state (0.9 m) with the equal wind speed (compare Figs. 6 and 8a).

To create the resonance, the wind with a periodically changing velocity between 0 and 20 m s$^{-1}$ was applied (Fig. 8b,c) in the Gulf of Riga–Väinameri 2D model. The most favourable wind direction for the Pärnu Bay created the gradually increasing double-amplitudes of the sea level oscillations (1.1, 2.1, and 2.3 m, converging near 2.4 m, Fig. 8b). The most favourable wind direction for the southern part of the Gulf of Riga (350°) had an even stronger impact on the Pärnu Bay sea level than on the southern Gulf (Fig. 8c). Evidently, due to the relatively large Green’s factor (which depends on the width convergence and the depth vanish, see e.g. LeBlond and Mysak, 1978), the Pärnu Bay has the most favourable conditions for sea level amplification. Though in stationary wind conditions the sea levels of the Haapsalu and Matsalu Bays could possibly exceed the corresponding maxima in Pärnu, the Pärnu Bay has an advantage for amplification of sea level oscillations. Such oscillations are effectively damped by friction in the small and extremely shallow Väinameri sub-basin, as the Gulf of Riga 5 h seiche hardly penetrates the narrow Suur Strait.

Thus, with proper timing of external factors, the second or the third wave could easily add another 1 m double-amplitude to the initial 1 m seiche near Pärnu. A similar additional impulse with perfect timing and the right period appeared in Pärnu during the 2001 surge (Fig. 4b). Despite the relatively low wind
velocity of the impulse, the sea level almost regained its first maximum (Fig. 4a). However, the wind direction was changing to a less favourable direction (W–SW) and the sea level steadily decreased, displaying residual 5 h oscillations.

5. Conclusions

High and low sea level events have different mechanisms and unequal magnitudes in the study area. Extremely low (up to –1.3 m) sea levels are caused by continuous east and north winds during the anticyclonic blockage above the Baltic Sea. Such sea level events are smooth and regional in character. Extremely high (up to 2.53 m) sea level events are short and local. They appear during heavy SW and W storms in the suitably orientated bays, such as the Pärnu Bay, where the local storm surge height can exceed the regional (open boundary) Baltic Sea level by 1.5 m.

Although the historically highest and lowest sea level values were found in the Pärnu Bay, the model simulations show that at least the minimum sea levels could be lower in the Matsalu and Haapsalu Bays. These bays could also have higher sea level values in stationary west wind conditions, but the Pärnu Bay still has an advantage due to better conditions for amplification of the sea level oscillations during the most extreme surges.

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References


