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HYDRODYNAMIC MODELLING OF SEA LEVELS IN THE VÄINAMERI AND PÄRNU BAY

Ülo SUURSAAR, Tiit KULLAS, and Mikk OTSMANN

Estonian Marine Institute, Paldiski mnt. 1, 10137 Tallinn, Estonia; ys@sea.ee

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Abstract. Using a 2D hydrodynamic model, water level in the Väinameri and in the northern part of the Gulf of Riga is investigated on the basis of data from 1999. Comparison of the modelling results with measurement data shows that the model can be applied in describing and predicting both the high water levels (storm surges) in the Pärnu Bay and the low levels (which often disturb navigation) in the Väinameri.

Key words: Baltic Sea, sea level, hydrodynamical modelling, 2D models, storm surges.

1. INTRODUCTION

Sea level measurements in the Estonian coastal waters have been carried out with small gaps since 1805. The network of sea level measurement stations has been revised several times during the history. At the time of writing of this paper there were mareographs (tide gauges) at Pärnu, Ristna, Rohuküla, Paldiski, Tallinn, and Narva Jõesuu. Some additional bench sticks are located at Virtsu, Heltermaa, Põõsaspea, Paldiski, and Tallinn. Statistical properties of the historical sea level data along the Estonian coast are discussed in [1–4] where long term trends, seasonal components, spatial correlations and fluctuations spectra have been described. However, from the practical point of view it is important to model the sea levels dynamically, bearing in mind the possibility of giving forecasts. Such operational models already function in Denmark, Germany, and Sweden. In the Baltic States the sea level prognoses are given on empirical basis.

Operational prognosis of very high sea levels (storm surge warnings) is important in the Pärnu Bay. The highest ever sea level on the Estonian coast was registered namely in Pärnu (+253 cm during a storm on October 18, 1967). The role of low sea levels is important, for example, along the Rohuküla–Heltermaa and Rohuküla–Sviby ferry routes. Operation of ferries has been often cancelled when the sea level has lowered for about –50 cm relative to the 5–5.2 m normal depth of the Rohuküla–Heltermaa fairway.

The aim of this study is to present some sea level simulations, to analyse the mechanisms of formation of extreme sea levels and to discuss the possibility of making prognostic calculations.

2. MODELLING METHODS

2.1. The models

As the two hydrodynamic models used in the study are already described in our previous papers [5–7], only a brief explanation will be given below. The forced oscillations model (FOM) is based on the motion and volume conservation equations and describes along with average flows in the straits also the sea level changes averaged over the Gulf of Riga and the Väinameri (Moonsund), the two relatively small and semi-enclosed sub-basins of the Baltic Sea. The model has been previously used for the calculation of currents in the straits connecting the above-mentioned sub-basins with the Baltic Proper and also themselves. As the highest sea levels are usually local and the sea surface is considerably inclined during storm surges, horizontal 2D or 3D models with reasonable spatial resolution are needed, especially in the case of bays (Pärnu, Matsalu, and Haapsalu). Though the average levels of the Väinameri, calculated with the FOM, are applicable for the central part of the sub-basin, here the main role of FOM is to provide time series for the verification of the 2D model.

The hydrodynamic numerical 2D model for the Gulf of Riga and the Väinameri is based on hydrodynamic equations for shallow sea and is presented in [6]. The model has grid step of 1 km and includes a total of 18 964 marine points. Due to their suitable configuration, the Gulf of Riga and the Väinameri can be modelled with relatively short open boundaries. In this case they are slightly shifted outside the narrowest parts of the Irbe, Soela, and Hari straits. The 2D model has been calibrated and verified with the FOM [6], while the FOM has been calibrated and verified using field measurement data from 1993–1998 [5]. Some of the flow simulations obtained with the 2D model are presented in [6,7] and a case study, including a preliminary sea level simulation, is presented in [7].

In addition, a version of the 2D hydrodynamic model for the Baltic Sea has about 4.5 km grid step and includes 18 246 points. The model provided boundary conditions for the Gulf of Riga model if no data about the sea level was available.

2.2. Input and verification data

The above-mentioned models need similar input data – the wind data above the sea and the sea level data on the open boundaries. We assume that these two factors are most important by modelling a relatively small and semi-enclosed marine area. Some minor factors (for example, inversed barometer effect and local thermal expansion) are not taken into account here. In addition, average monthly river inflow data are used for keeping the long-term water budget of the sub-basins, but the influence of that input on the water levels or currents is very small.

Wind stress may be calculated either using the High Resolution Limited Area Model (HIRLAM), or from single-point measurements. For the present study the data from Vilsandi meteorological station from 1999 were used with 6-h time step and 10° angular resolution. As the station is located in an island on the western border of Estonia, the data are not contaminated by the influence of land. Homogeneous wind was applied over the whole modelled area.

Open sea level data were obtained from the Sõru marine station, providing mareograph data with a 1-h time step in 1999. The height system used in Estonia and in other Baltic states is the so-called Baltic geodetic system, its predecessor with "zero" sea level at Kronstadt was introduced by Lazarenko [1]. The input sea levels were applied identically at three sections of the open boundaries near the Irbe, Soela, and Hari straits. Missing data were linearly interpolated. For comparing the simulated sea level time series, hourly mareograph data from Rohuküla and Pärnu marine stations were used. All the above marine stations and the Vilsandi meteorological station are operated by the Estonian Meteorological and Hydrological Institute.

2.3. The simulations

The simulations were carried out using the above described Vilsandi wind and Sõru sea level input data from the entire year 1999. This year was chosen due to stormy conditions in November and December, offering presumably interesting sea level behaviour. According to observations, several successive storm surges occurred in the Pärnu Bay (+114 cm on December 1, +134 cm on December 6/7, +146 cm on December 18). Strong coastal erosion both on the Pärnu beach and on the nearby coastal sections of Audru and Uulu were observed by the Geological Survey of Estonia [8].

Time series of sea levels were modelled at Rohuküla and Heltermaa (located at the ends of the Väinameri ferry route) and in the Pärnu Bay (Fig. 1). In addition, horizontal distributions of sea levels and flow patterns during some periods were calculated.

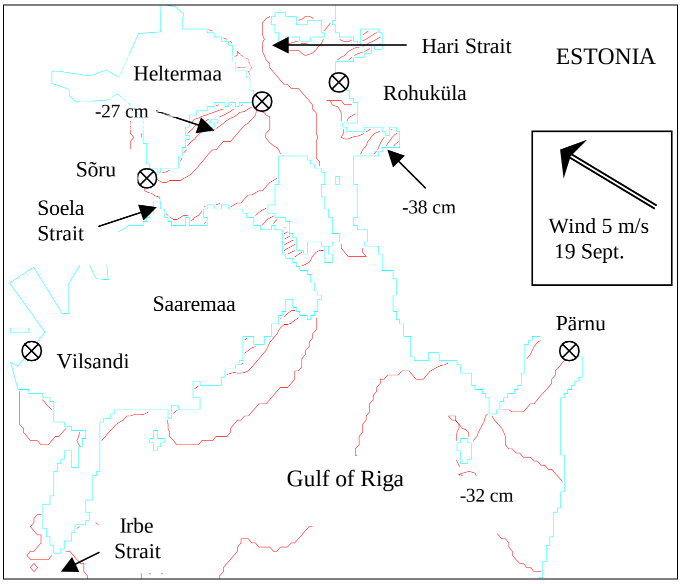

Fig. 1. The study area: the background presents a snapshot (on September 19, 1999 at 1100) of the sea level isolines in the case of a low sea level situation calculated using the 2D hydrodynamic model (minimum level –38 cm, maximum –27 cm).

3. RESULTS AND DISCUSSION

3.1. Low sea levels in the Väinameri

Comparison of the hourly measured and modelled time series at Rohuküla (Fig. 2a) shows that the series are in good agreement. The correlation coefficient is very high ($r = 0.93$, 8760 data pairs). Both the output series and their difference (Fig. 2a,b) display smaller variability in summer months and larger deviations in meteorologically restless winter months.

The lowest water levels measured at Rohuküla were –42 cm (May 11, 131st day) and –49 cm (September 20, 263rd day). The situation during the September low is depicted in detail in Fig. 3. It is evident that in general terms the minimum was determined at Sõru –43 cm (Fig. 3c). However, such a low sea level in the Baltic Proper near Estonian coast was produced by northern and eastern winds (2–8 m s^{-1}), blowing continuously from these directions for about 10 days (Fig. 3a,b). To that regional flee a local wind effect was added. At Rohuküla the minimum measured sea level was –49 cm (calculations gave –44 cm). At Heltermaa the lowest calculated sea level was –40 cm.

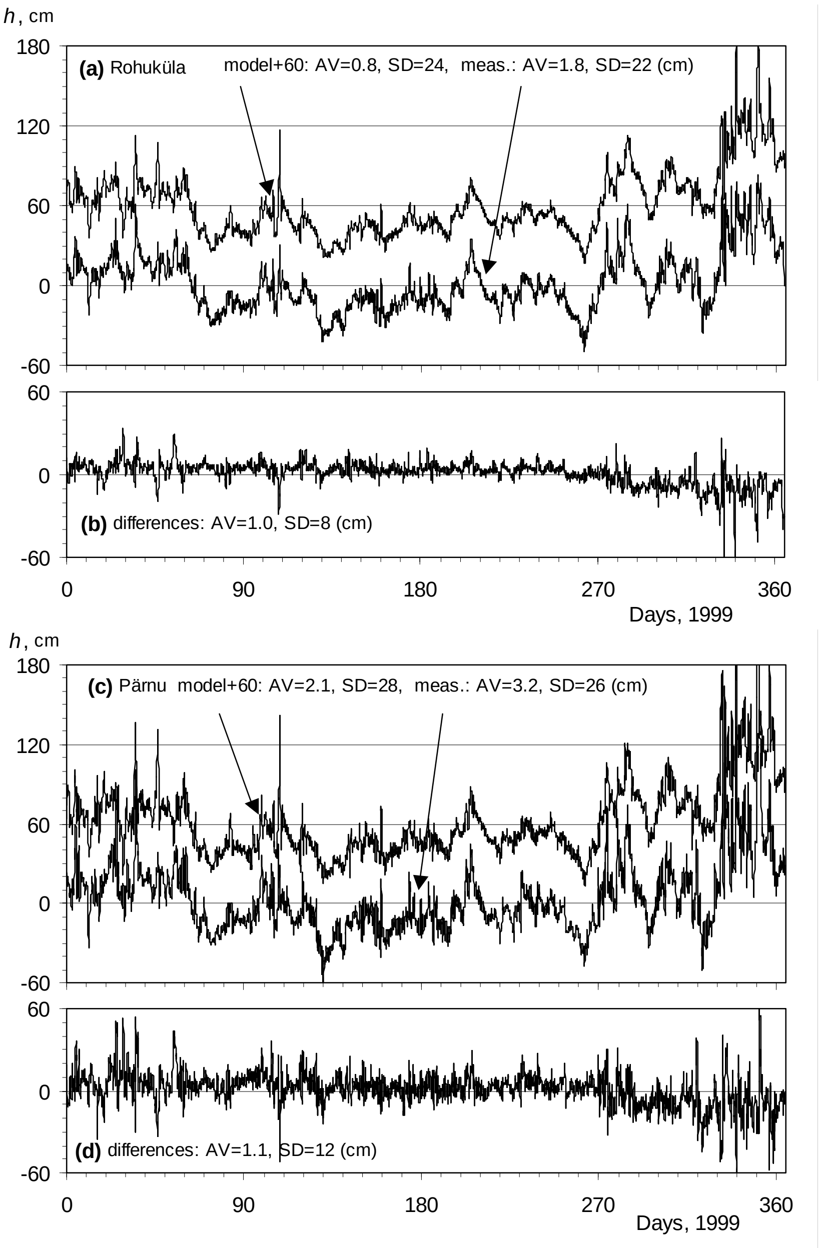

Fig. 2. Comparison of the hourly measured and modelled sea level time series at Rohuküla (a) and Pärnu (c) during 1999 (60 cm are added to the modelled values for better distinguishing of the series); b, d – time series of the difference between the measured and modelled values; AV – average, SD – standard deviation.

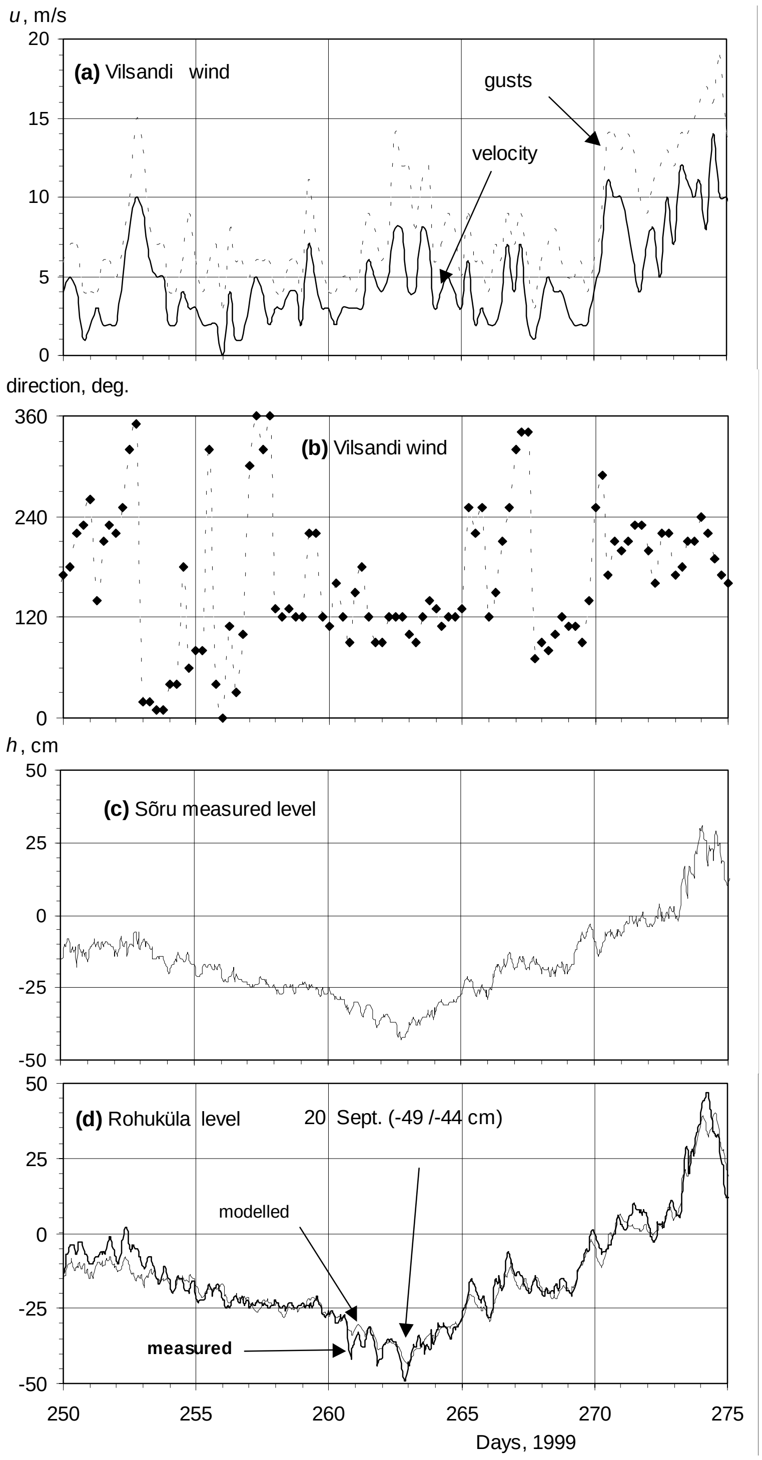

Fig. 3. Model input data (a)–(c) and comparison of the calculated and measured sea levels at Rohuküla (d) during the low sea level between September 8 and October 2, 1999.

The lowest sea level of that year was not extreme because of the relatively low wind velocity. Indeed, at the end of the month wind velocity increased up to 10–15 m s^{-1}, but then it was from the “wrong” direction, from south and SE. As a result the water level was raised up to +45 cm at Rohuküla (only +25 cm at Sõru) on the 274th day (Fig. 3c,d). According to FOM analysis [5,7] and observations [2], winds from 200°–270° evoke high sea level in the Väinameri and the lowest levels are produced by the winds between 20° and 90°. However, due to considerable anisotropy of wind conditions above the Baltic Proper, strong winds between these directions are rare, maximum winds at Vilsandi did not exceed 11 m s^{-1} (in the case of eastern winds) or 14 m s^{-1} (NE winds) during 1977–1991 [9]. However, the lowest historical sea level in the study area was measured in December 9, 1959 (–130 cm in the southern part of the Gulf of Riga, –120 cm at Pärnu, and –113 cm in the Väinameri, at Virtsu). It was associated with strong (20–25 m s^{-1}) eastern winds during rare and long-lived pattern of atmospheric high and low pressure systems [10]. Though not so critical from the navigational point of view, the lowest sea levels in the study area occur not in the Väinameri, but in the Pärnu Bay. Also in 1999, the annual lowest level was measured at Pärnu (–62 cm on May 11 as compared to –49 cm in September 20 or –42 cm on May 11 in Rohuküla).

According to the modelled time series for 1999, the water level at Rohuküla was on average 2.4 cm higher than at Heltermaa. It is evidently an expression of statistically prevailing western winds. During the warm half-year (from April to September), the dominance of such winds is not so evident, thus the average difference of the levels was only 0.9 cm. Between October and March the difference was 3.9 cm. During the stormy December 1999, Rohuküla had on average 9 cm higher sea level, while in September (including the above described low level situation) the level was for 0.6 cm lower.

3.2. High levels in the Pärnu Bay

The correlation coefficient between the measured and modelled series in the Pärnu Bay (Fig. 2c) is slightly lower ($r = 0.90$) than in the Väinameri and the time series of differences (Fig. 2d) has a higher standard deviation (12 cm against 8 cm at Rohuküla). However, relatively high variability of absolute differences should not be overestimated, as they are calculated from the hourly output and in general the model seems to describe the sea levels satisfactorily. On the basis of Fig. 4d we can analyse the possible sources of modelling errors.

First, a time lag (phase shift) tends to appear between the measured and simulated values, especially during the fast and dramatic changes of the situation; in the case of slow and smooth changes of the input forces, the model describes the real situation better. For example, in the case of the second large surge event in Fig. 4d, the model reproduces the rise of the sea level 7–8 h before the actual rise. In the case of the low level situation in the Väinameri (Fig. 3d), the modelled minimum appeared 2–3 h after the proper time. This feature can be explained by

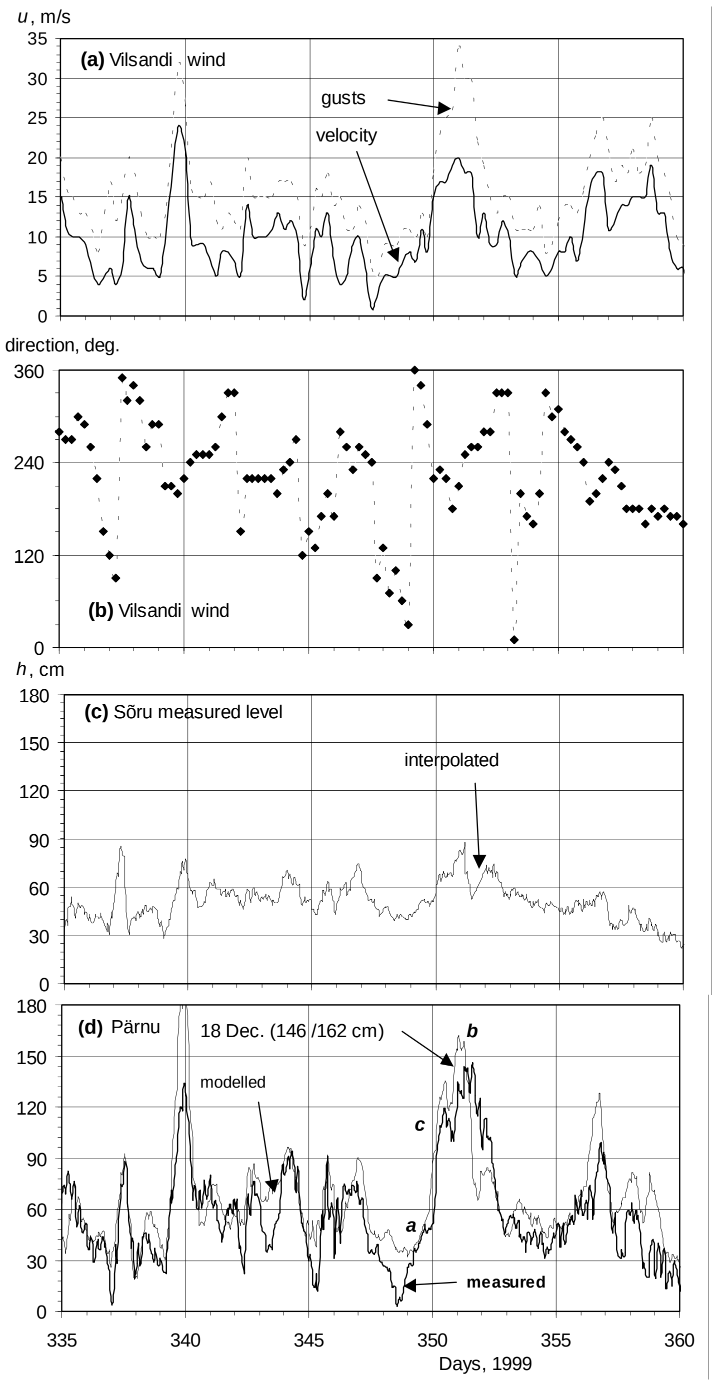

Fig. 4. Model input data (a)–(c) and comparison of the calculated and measured sea levels (d) in the Pärnu Bay during the storm surges between 2 and 27 December, 1999. Moments for snapshots presented in Fig. 5 are marked in (d) with “a”, “b”, and “c”.

the properties of the model wind input: Vilsandi winds with a 6-h time step were applied homogeneously over the whole model domain. It also means that in case of the increase of the west wind velocity it happens simultaneously both at Vilsandi and Pärnu. Actually, the approach of the wind front along that distance (130 km) may take several hours, but depending on the atmospheric baric systems it can happen also simultaneously. In the case of the Rohuküla low-level event the situation is opposite, as east winds act ahead of the model simulation.

The model seems to be somewhat too sprightly. The standard deviations of the modelled series exceed the corresponding values of the measured series by about 10% and the modelled maxima are in several cases too high. The model may be "tuned" in the future. One may improve the quality (both temporal and horizontal resolution) of the wind input by using either realistic wind data from several measurement stations or applying HIRLAM winds (with temporal resolution of 15–55 km in different versions).

While the measured maxima in the Pärnu Bay in 1999 were +134 cm (on December 7) and +146 cm (on December 18), the model produced +191 and +162 cm, respectively. The first of these two surges (Fig. 4d) was extremely rapid, it took only 18 h to rise the sea level from 100 to 191 cm and lower it again to 100 cm. The model evidently overreacted in this case, though the timing and the phenomenon itself was modelled successfully. In the case of the second surge, a large error appeared in the abatement phase. In addition to the above phase shift effect, the reason for that big error could be a 13 h gap in the original Sõru input series (probably the storm had spoiled the mareograph). The gap was interpolated for the calculations, but in reality the level at Sõru could be somewhat higher.

The third justification of the model results is the location of the Pärnu mareograph itself. It is not located in the sea but about 3 km upstrem from the mouth of the river moles. It has been assumed that in the case of rapid surges actual marine sea level could be higher than the mareograph shows, because the Pärnu River then starts to flow in the opposite direction [8].

Figure 5a,b shows the sea level isolines just before the highest surge close to its peak. Horizontal sea level gradients are smaller in the case of low level situations (Figs. 1 and 5a), level patterns in such cases are smooth and carry more regional character, while high level zones during high sea level events are distinctly local. Level difference within the boundaries of 50 km (Fig. 5b) exceeds 35 cm. This difference is caused by the length and tapering shape of the Pärnu Bay. Similar high gradients could appear also in the Matsalu and Haapsalu bays. The flow pattern during the onset of the surge (Fig. 5c) shows quite dynamic and curious behaviour: flow enters the bay along the coasts and leaves it along the central part of the bay forming several cyclonic and anticyclonic gyres with short life-time.

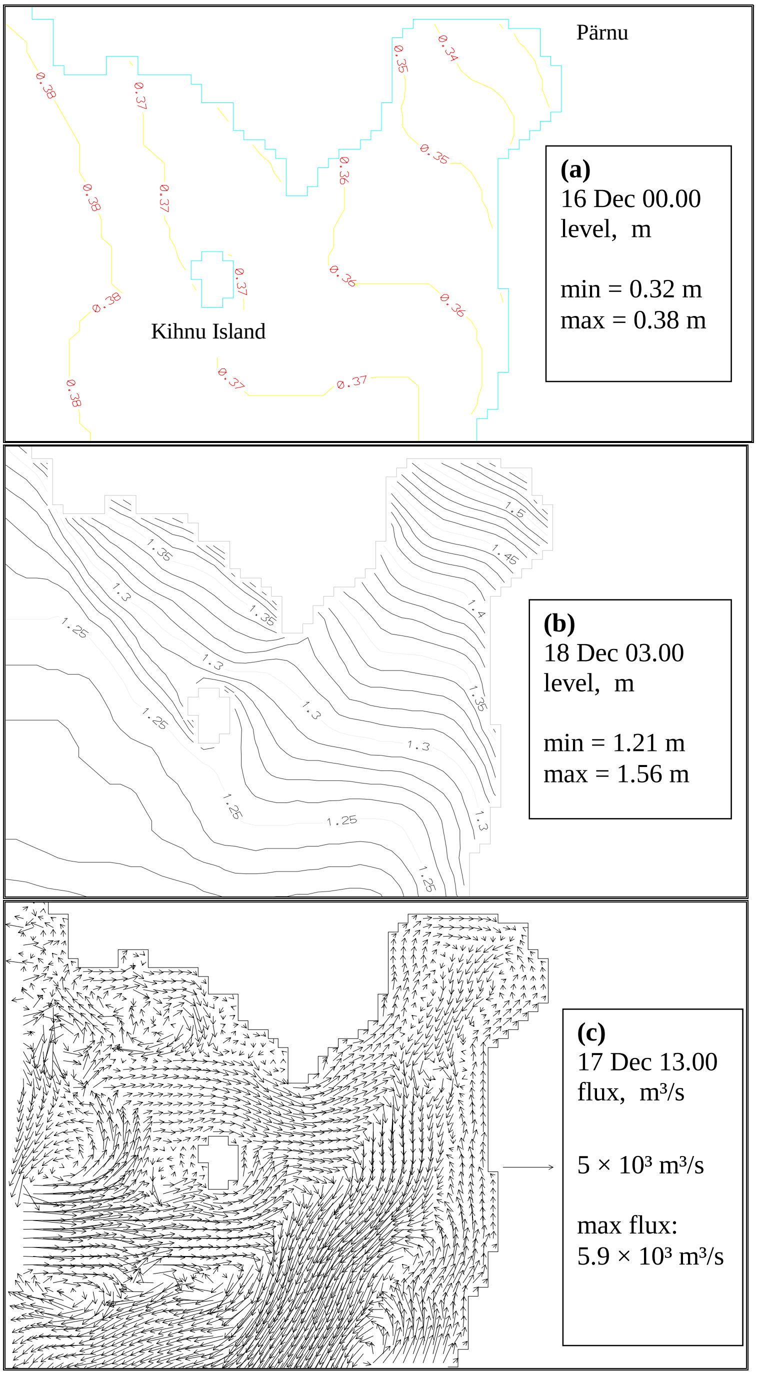

Fig. 5. Snapshots of calculated sea levels in the Pärnu Bay and NE corner of the Gulf of Riga before the storm surge (a) and during the maximum sea level (b); (c) snapshot of currents (water fluxes) during onset of the surge. See also Fig. 4d for the exact moments of the snapshots.

When analysing the input forces (Fig. 4a–c) together with the level response (Fig. 4d) it appears that the role of the outer sea level was small. The crucial factor was strong wind (15–20 m s^{-1}, gusts up to 34 m s^{-1}) blowing continuously from the suitable direction (200°–240°) during two days. The common mechanism is that strong storms from suitable (SW) direction firstly pump water through the Danish Straits into the Baltic Sea, then press into the Gulf of Riga and finally create inclination of the sea level. The bearing of the Pärnu Bay fairway is 204°. This direction coincides with the direction of the strongest possible local winds: 25 m s^{-1} for 225° and 22 m s^{-1} for 203°, while for the opposite direction the maximum winds were only 14–17 m s^{-1} during 1977–1991 [9]. This also explains the asymmetry between the highest (+253 cm) and the lowest (–120 cm) ever recorded sea levels in the Pärnu Bay.

Detailed analysis of the December 18 events revealed also that the first sub-peak was evoked by SW winds (17 m s^{-1}). Then the wind velocity increased up to 20 m s^{-1}, but its direction (W) was not so favourable and the level began to lower slightly. After half a day the second (and the highest) maximum was provoked by south and SW winds, though the velocity started to decrease from 20 to 18 and 14 m s^{-1}. Thus in the case of the Pärnu Bay the highest surges can probably appear during continuous storms when the wind direction changes from 230°–270° to 190°–210°. It means that the centre of the cyclone passes Estonia from the south. If it passes from the north, the wind direction changes from west to north, creating more favourable surge conditions for the southern part of the Gulf of Riga [11]. The role of a possible resonance situation due to a series of cyclones combined with long waves has been discussed in case of the Neva surges [1,12]. We have found from our model simulations that the Helmholtz period is about 24 h and the barotrophic seiche period is about 5 h for the Gulf of Riga. Their role should be analysed in the future. Such resonance effects will be immanently reflected in the model output.

4. CONCLUDING REMARKS AND FUTURE PROSPECTS

The preliminary simulations based on data from 1999 has shown that it is possible to reproduce sea levels in the study area and to develop an operational system for predicting extreme sea levels both in the Väinameri and in the Pärnu Bay. The modelling errors can be probably reduced in the future by improving the quality of the wind input data. Taking into account that in this study homogeneous winds were applied over the modelled area on the basis of the single-point wind data given with 6-h time step, the preliminary results presented in this paper are actually rather good.

For providing sea level prognoses it is necessary to apply real-time wind and sea level data and prognoses for a couple of days ahead. Such wind prognoses are delivered by meteorological services or calculated by HIRLAM centres. The sea level prognoses in the eastern section of the Baltic Proper can be either obtained from an existing operational sea level prognostic system of Swedish or Danish institutions, or calculated on the basis of HIRLAM wind prognoses and sea level data, measured at Göteborg, using our version of the 2D Baltic Sea hydrodynamic model.

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VÄINAMERE JA PÄRNU LAHE VEETASEME HÜDRODÜNAAMILINE MODELLEERIMINE

Ülo SUURSAAR, Tiit KULLAS ja Mikk OTSMANN

Kasutades kahemõõtmelist hüdrodünaamilist mudelit on 1999. aasta andmete põhjal simuleeritud veetaset Väinameres ning Liivi lahe põhjaosas. Tulemuste analüüs näitab, et kasutatud mudel suudab adekvaatselt kirjeldada ja prognoosida nii tormidega kaasnevaid kõrgeid veeseise Pärnu lahel kui ka laevanduse seisukohast olulisi madalaid veeseise Väinamerel. Mudeli järgi oli Rohuküla madalaimaks veetasemeks 1999. aastal −44 cm (tegelikult −49 cm) ning Pärnu lahe kõrgeimaks veetasemeks 18. detsembri tormi ajal +162 cm (tegelikult +146 cm).