BOREAL ENVIRONMENT RESEARCH 11: 143–159
Helsinki 24 April 2006 ISSN 1239-6095

Cyclone Gudrun in January 2005 and modelling its hydrodynamic consequences in the Estonian coastal waters

Ülo Suursaar[1)]*, Tiit Kullas[1)], Mikk Otsmann[1)], Ivo Saaremäe[2)], Juta Kuik[2)] and Merike Merilain[2)]

[1)] *Estonian Marine Institute, University of Tartu, Mäealuse 10a, 12618 Tallinn, Estonia (*corresponding author's e-mail: ulo.suursaar@ut.ee)*
[2)] *Estonian Meteorological and Hydrological Institute, Rävala 8, 10143 Tallinn, Estonia*

Received 30 Mar. 2005, accepted 25 July 2005 (Editor in charge of this article: Timo Huttula)

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.

Meteorological parameters of windstorm Gudrun on 8–9 January 2005 and its hydrodynamic and environmental consequences are analysed on the basis of observational data and hydrodynamic modelling. The study focuses mainly on describing events and reception in Estonia. We estimate that in meteorological terms, the cyclone was among the five most powerful ones in recorded history. Considering also the new highest storm surge record (275 cm in Pärnu), extensive property damage and massive media coverage, it became the most influential natural disaster in Estonia. Using a shallow sea 2D hydrodynamic model with a 1-km grid step, a hindcast modelling study of the sea level was carried out. Hydrodynamic simulations suggest that an inflow of 24 km^3 (5.4% of the Gulf's average volume) occurred in the Gulf of Riga. The sub-basin of the Väinameri was nearly entirely flushed through by more saline and nutrient-poorer water from the Baltic Proper. The simulated current velocities, sea levels and wave parameters indicate that prominent coastline changes and replacement of sediments could have occurred within a single day.

Introduction

An extratropical cyclone reaching the power of a hurricane, according to the Saffir-Simpson hurricane scale, developed above the North Atlantic and travelled over Ireland, Scotland, Scandinavia and Finland on 7–9 January 2005. The hurricane was known as Gudrun in the Nordic Countries and Erwin in the British Isles and central Europe. The storm was one of the worst in Denmark, Scandinavia and Estonia for at least 40 years, causing massive forest damage, and disruption of power and phone lines. The storm killed at least 17 people, including one in Estonia. The main property damage was a result of strong winds and flooding of the coastal areas. The highest storm surge in known history occurred in Pärnu (275 cm) and probably in most locations along the west Estonian coast as well.

The previous surge with nearly comparable height (253 cm) took place 38 years ago and was empirically considered as an extremely rare event (e.g. Suursaar *et al*. 2003). However, an increase in storminess in the NE Atlantic, intensification of westerlies and trends towards higher storm surge levels is recently reported both in the British Isles (Lowe *et al*. 2001), German and Danish coasts (Langenberg *et al*. 1999), Finland

(Johansson *et al*. 2003, 2004, Jylhä *et al*. 2004), Sweden (Meier *et al*. 2004, Räisänen *et al*. 2004) and Estonia (Jaagus *et al*. 2004). Such developments pose increasing risks for coastal communities. In addition to hazards for man-made infrastructure, vitalization of coastal geomorphic processes is foreseen as a result of anticipated sea level rise and increasing storminess (e.g. Kont *et al*. 2003, Suursaar *et al*. 2004). Study of the processes related to the evolution and consequences of both cyclones and storm surges are therefore of high importance.

Gudrun and its immediate impacts were swiftly and widely covered by the media. However, the parameters and consequences of the cyclone require more detailed scientific analysis. The objectives of this study are (1) to document the cyclone and its consequences in Estonia, (2) to provide meteorological and hydrodynamical analysis of the event, (3) to present hydrodynamic simulation results of sea levels, currents and water exchange before and during the surge, (4) to discuss the influence of the event on the marine environment of Estonia; we also (5) discuss the prognostic and risk management aspects that arose in Estonia during and after the storm.

Material and methods

Meteorological and sea level data

The network of weather stations (Fig. 1) maintained by the Estonian Meteorological and Hydrological Institute (EMHI) includes 12 meteorological stations and 9 meteorological-hydrological stations. Between 2001 and 2004, all the mentioned 21 stations were equipped with MILOS-520 or MAWS-type automatic weather stations by Väisälä OY. The data are collected and transmitted to the head office at Tallinn, where data processing and prognoses are done.

The description and analysis of the storm parameters was done on the basis of all the meteorological stations, though, those located in west Estonia became the most important. For hydrodynamic modelling purposes, wind data from Vilsandi and Ruhnu stations were used. The Vilsandi station (58°22´59´´N, 21°48´55´´E) has the most open location for wind measurements among all Estonian stations. Ruhnu station (57°46´48´´N, 23°16´12´´E) has relatively good unspoiled conditions for wind measurements as well. The advantage of this station is its location in the middle of the hydrodynamic model domain. The data sets include hourly 10 min average wind speeds, hourly 1 h average wind speeds, prevailing wind directions for the same integration periods, and hourly maximum wind speeds (gusts) both on the 10 min and 1 h basis.

EMHI currently runs three automatic tide gauge stations (mareographs) with locations at Ristna, Pärnu and Narva-Jõesuu (Fig. 1). Additional mareographs are maintained by ports in Muuga Bay and at Pärnu. The stations equipped only with bench-sticks are located at Heltermaa, Rohuküla, Virtsu and Vilsandi along the western coast of Estonia, and at Dirhami, Kunda, Loksa, Toila and Narva-Jõesuu along the northern coast. Sea level observations at these stations are carried out two or three times a day. Marine stations currently not equipped with mareographs or bench-sticks are at Sõrve, Ruhnu, Kihnu and Pakri. The height system used in Estonia and in the other Baltic states of the former Soviet Union is called the Baltic Height System (1977) with reference to Kronstadt "zero" bench mark (*see* e.g. Lazarenko 1961).

For hydrodynamic modelling, sea level data only from the stations at Pärnu and Ristna could be used, providing hourly data. The mareograph used in Pärnu is by SEBA Hydrometrie GmbH, equipped with digital pressure sensor DS-30. It is allocated into a moat (Vallikraav) in the Pärnu River mouth, about a kilometre upstream. The mareograph called Rohrdanz used at Ristna is of Czartist-Russian construction. Vertical movements of the float are mechanically transmitted to an ink-pen recording unit in this Litke-Lenz principle mareograph (*see* e.g. Snezhinsky 1951). It is located on a designated well in shallow Kalana Bay. The Pärnu sea level values are transmitted through telecommunication lines, whereas from Ristna station paper charts are periodically removed and transported to Tallinn, where visual readings are taken. Both hourly data from these two stations, as well as average daily values from all the sea level stations are stored in the database.

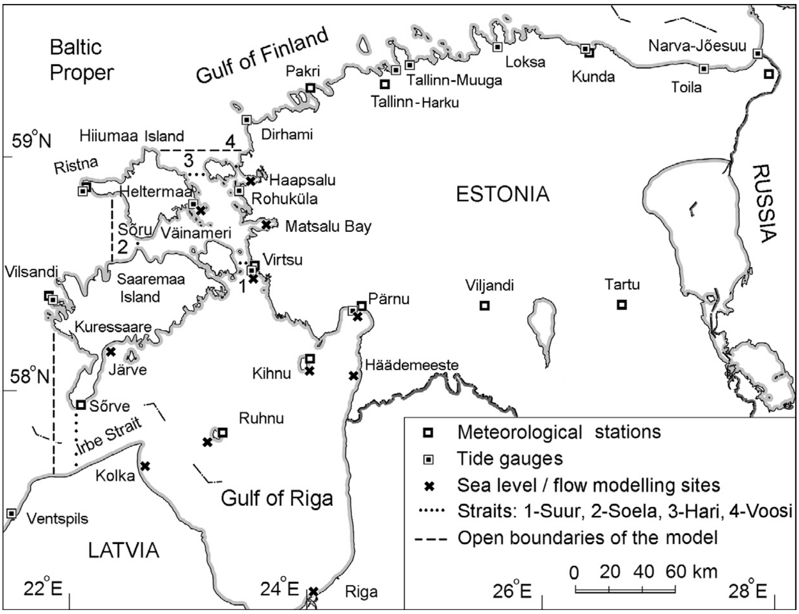

Fig. 1. Map of the study area, showing the locations of the selected meteorological and sea level stations, sea level and flow modelling sites, and straits of water transport calculations.

Hydrodynamic modelling

The hindcast simulations presented and discussed in the paper were performed using a simple two-dimensional shallow sea hydrodynamic model. The model is more thoroughly described in some previous papers (e.g. Suursaar *et al*. 2002a, 2003), and only a brief overview is given here.

The model is a shallow sea depth-averaged free-surface model composed of momentum balance and volume conservation equations. The model equations were numerically solved using the finite difference method. The horizontal resolution of the model grid is 1 km and the model domain includes in total 18 964 marine points. Arakawa C-grids with position of sea level heights in the centre of the grid box and velocities at the interfaces were used. At coastal boundaries the normal component of the depth mean current is considered as zero. Data for bottom topography and coastline were taken from the Latvian bathymetric database (Berzinsh *et al*. 1994) and Estonian nautical maps. The bottom topography is presented with the accuracy of 0.1 m. Nautical maps with the scale of 1:100 000 used for bathymetry digitalisation in the coastal sea provided roughly one depth reading for each 1-km^2 grid-cell.

The model is forced by the wind and open boundary sea level data. Due to the microtidal regime of the Baltic Sea (the amplitudes of M_2 and K_1 waves smaller than 2 cm near the Estonian coast), no tidal forcing was applied. Other minor factors, such as local thermal expansion, precipitation–evaporation, salinity differences, and change in the sea surface area were entirely neglected. The absence of flooding and drying feature has a negligible influence on model performance, as the ratio of flooded (or dried up) area to the average sea surface area is very small. A few 1-km^2 grid-cells might appear or disappear only in Matsalu Bay, Haapsalu Bay and near the SE coast of Hiiumaa Island (Fig. 1). The model, naturally, takes into account the changes in grid-box depths and straits cross-section areas along with sea level variations, as well as the Coriolis force. The influence of atmospheric pressure (also called inverted barometer effect) is imported through the open boundary sea level, and its local differences are small within the relatively small study area. Also possible near-shore sea level increase due to wave break and Stokes drift cannot be resolved with our 1-km grid-size. Wind stress can be calculated either from some single-point measured data or from HIRLAM output. Both the wind drag description with the formula by Smith and Banke (1975), and the quadratic bottom friction parametrization (with bottom stress coefficient k = 0.0025) is common

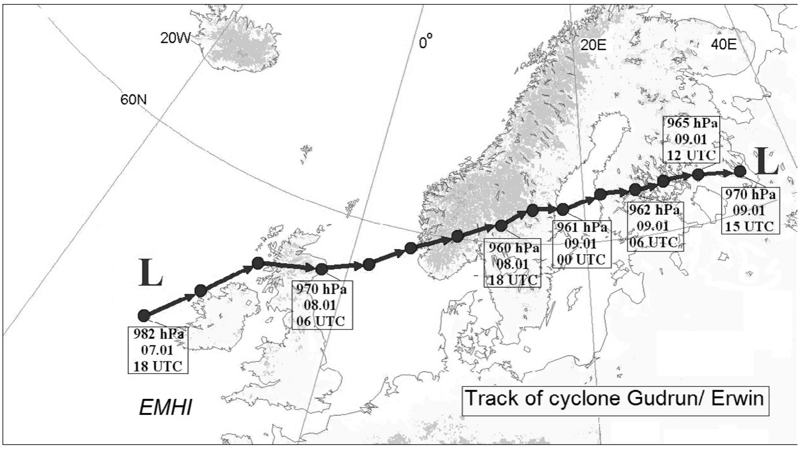

Fig. 2. The trajectory of the cyclone's eye on 7–9 January 2005.

for such models (e.g. Jones and Davies 2001). The 2D model results were previously compared with the currents from the Helmholtz model (Otsmann *et al*. 2001) and field measurements in the straits from 1993–1995 (Kullas *et al*. 2000).

In this study the hourly sea-level time series obtained from Ristna tide gauge for the period between 1 and 9 January 2005 were used as boundary conditions. The data were applied identically at the three cuts of the open boundaries near the Irbe, Soela and Hari Straits. The relatively short open boundaries of the model are shifted 5–20 km outside the narrowest parts of the straits. The wind stress as the second main forcing factor was calculated from the wind data measured either at the Vilsandi or Ruhnu meteorological station. Both stations are located on islands and the data are relatively unspoiled by the direct influence of land. Spatially homogeneous hourly one hour average wind data was applied over the whole modelled area. As our study area is relatively compact and not very large (140 × 220 km^2) in comparison with the wide coverage of strong wind area of Gudrun, the use of single-point wind data is justified. In general, wind data from Sõrve, Kihnu, Ruhnu and Vilsandi show high coherence. Other stations do not properly reflect marine wind conditions. Unfortunately, the least disturbed, Vilsandi station, suffered from equipment malfunction during the storm peak.

Hourly time series of the sea level and current velocities were computed in different hindcast runs for the selected gridpoints. Also, cross-section average water transport time series were calculated in the straits of Irbe, Suur, Soela, Hari and Voosi (Fig. 1). The hourly output of current velocities were used for estimating current-induced bottom stresses and work. Also preliminary rough estmations of wave action were calculated at a selected point in Pärnu Bay using a simple first generation wave model based on the SMB method (*see* e.g. Huttula 1994).

Results and discussion

Evolution and parameters of the hurricane

Cyclone Gudrun was born in the afternoon of 7 January 2005, as a perturbation on the polar front in a region west of Ireland (Fig. 2). Sea surface air pressure was around 995–1000 hPa in this region then and the cyclone was barely visible as a low pressure area of about 990 hPa. The further evolution of the cyclone was fed by large temperature contrast between the cold air mass in the north and warm and moist air mass to the south from the front. The characteristic deformation of the polar front rapidly grew and the cyclone continued to deepen by the evening of 8 January, when the cyclone's centre was travelling across the Scandinavian Peninsula. A decrease in air pressure by 30 hPa during one day indicated its energy and intensity. The nadir point of 960 hPa was reached northeast of Oslo at 20:00 GMT (Carpenter 2005). Since then, the travelling speed of the baric system somewhat decreased, but air pressure in the centre remained relatively stable for twelve more hours. It started to increase very slowly, reaching 962 hPa above Finland and 970 hPa above Lake Onega, Russia (Fig. 2).

Large energy content of the vortex, fast travelling speed and development of so called "sting jet" within the cyclone yielded in damaging winds at the surface. A sting jet occurs when a stream of very strong upper-level winds descends to the ground at the centre of a low pressure area (e.g. Chromow 1940, Carpenter 2005). According to Danish Meteorological Institute (DMI) and Swedish Meteorological and Hydrological Institute (SMHI) the highest wind speeds reached 34 m s^{-1} in mean values both on the western coast of Denmark and southern Skåne in Sweden. Wind gusts up to 46 m s^{-1} were recorded in Denmark and 42 m s^{-1} in Sweden. According to the Saffir-Simpson classification, the hurricane starts with 1 min average wind speeds from 32.7 m s^{-1} (12 on the Beaufort scale, 64 knots, 74 mph, 119 km h^{-1}). Thus, the cyclone clearly reached the power of a hurricane on the basis of the maximum mean wind speed in Denmark.

Estonian territory was about 300–500 km south (i.e. righthand) of the centre trajectory of the cyclone, thus falling into the zone of strongest wind speeds. Although the wind speeds had already slightly decreased by the evening of 8 January, SW and W winds with maximum average speeds of up to 28 m s^{-1} battered west Estonian coastal areas. The actual maximum wind speed could have been even stronger, as gaps appeared in the wind speed records (Table 1). Gust wind speed reached 38 m s^{-1} in Kihnu, 33–34 m s^{-1} gusts were registered at Ruhnu, Sõrve and Vilsandi (Table 1 and Fig. 3). Minimum registered air pressure was 972 hPa at Pärnu and 968 hPa at Ristna, still some 30 hPa lower than during the periods between the previous (on 2, 5 and 7 January) and the next (10–11 January) cyclones.

Another storm, Gero, followed Gudrun on 10–11 January 2005. Though air pressure was as low as 948 hPa at the nadir point north of Scotland, the cyclone started to fill up quickly. The storm track was about 300 km north as compared with that of Gudrun and its consequences were relatively mild in Estonia. Average wind speeds reached 15 m s^{-1} at Vilsandi and Ruhnu (Fig. 3) and Pärnu sea level height reached only 125 cm (Fig. 5).

The main financial losses during Gudrun probably occurred as the result of flooding of urban areas of Pärnu, Haapsalu and Kuressaare. Wind damage of power lines, transport infrastructure, buildings, and forests rank close behind. According to estimates by Estonian Energy about 32% of households lost power in Estonia, including 100% in Hiiumaa, 78% in Saaremaa and 64% in the Pärnu county. Preliminary cost estimations yielded about 50 million euros, which comprise about 0.7% of the country's annual GDP according to preliminary estimates of authorities published in current press. The Pärnu county suffered the most with about 30 million euros. Forest damage needs further assessment. Nearly one million m^3 of timber was toppled by the storm in Estonia.

The hurricane was among the strongest in recorded history in the areas below the cyclone's trajectory, though its position in record-lists differs by countries. In Sweden, Gudrun was probably the most serious storm in 35 years and probably the costliest in history, exceeding the costs of 1999's Anatol by at least two times. According to the DMI, Gudrun was among the ten largest

Table 1. Maximum observed average wind velocities (10 min averages, m s^{-1}) and wind gusts on 9 January 2005 together with times of the events (GMT) at the selected Estonian meteorological stations. The stations are arranged by longitude increase, the last five stations are inland or sheltered by land from SW. * missing values due to equipment malfunction near maximum readings; the majority of maximum wind directions was between WSW and WNW.

Station	Wind speed	Gusts
Vilsandi	22.9 (04:00)*	33.4 (05:00)
Sõrve	28.0 (09:00)*	35.0 (08:00)
Ristna	18.5 (04:00)	28.9 (05:00)
Ruhnu	26.0 (06:00)*	34.2 (05:00)
Virtsu	14.7 (04:00)	27.1 (09:00)
Kihnu	25.2 (03:00)*	37.5 (03:00)
Pakri	20.5 (12:00)	30.3 (11:00)
Pärnu	18.4 (03:00)	30.8 (02:00)
Tallinn-Harku	12.3 (11:00)	21.8 (05:00)
Viljandi	11.4 (05:00)	28.9 (06:00)
Kunda	11.0 (20:00)	21.9 (20:00)
Tartu	10.3 (10:00)	22.5 (07:00)
Narva	10.8 (21:00)	24.2 (19:00)

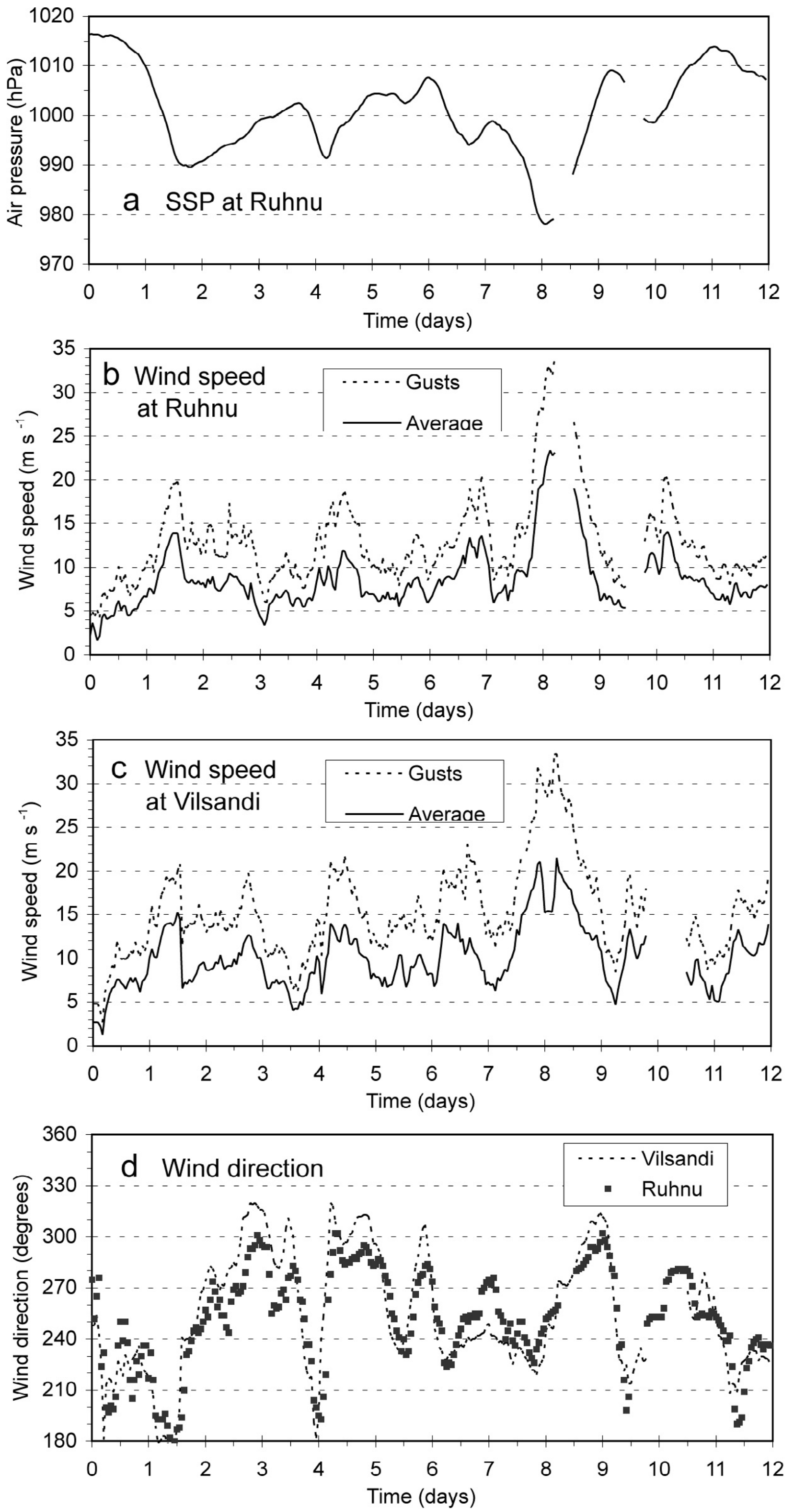

Fig. 3. Meteorological conditions, including hourly average wind speeds on 1–12 January 2005 at Ruhnu and Vilsandi stations. Time axis here and below starts at 00:00 GMT on 1 January 2005.

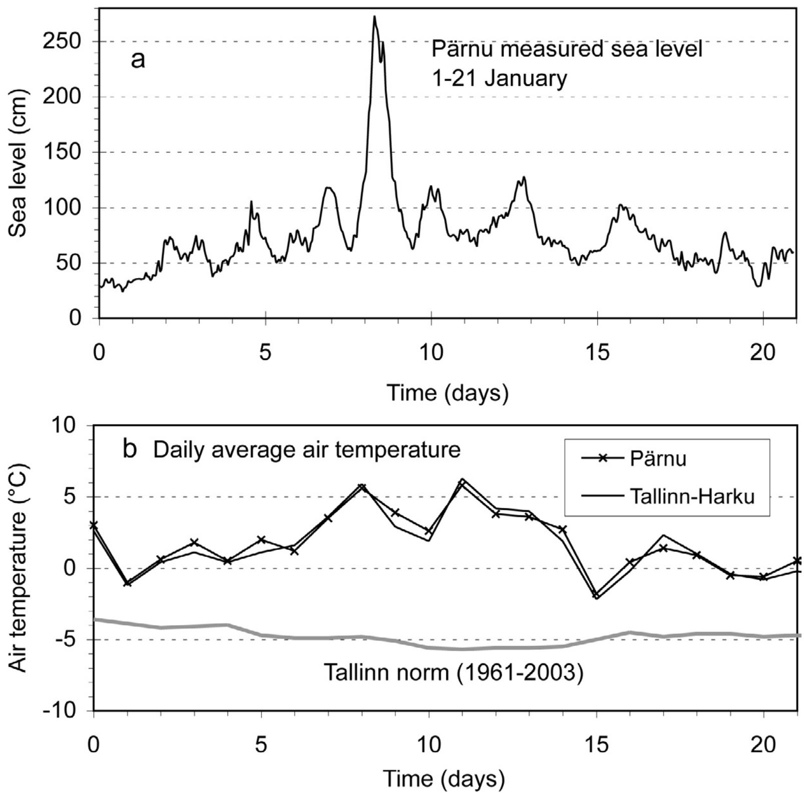

Fig. 4. — **a**: Observed sea level variations in Pärnu; — **b**: Measured air temperatures in Pärnu and Tallinn compared with meteorological norm.

storms ever experienced in this region, but both by wind speed values and estimated losses it was not as serious as hurricane Anatol on 3–4 December 1999. In Estonia, by wind speed Gudrun falls into the same rank with 23 January 1995 storm, which damages were, however, smaller. It also ranks close to 6–7 August 1967 and 18 October 1967 storms. The first one, called then as "the storm of the century" featured extensive forest damages in NW Estonia, and the second one set a new prominent sea level height record at Pärnu of +253 cm. The strongest wind speed, gust wind of 48 m s^{-1} was recorded during 27 October–2 November 1969 storm at Ruhnu. However, no reliable average wind speed data are available on that event. The highest recorded average wind speed reached 35 m s^{-1} both at the Dirhami and Tallinn stations during the 6–7 August 1967 storm. These two storms are probably the only recorded storms reaching the strength of a hurricane in Estonia.

It is difficult to assess and juxtapose the different aspects of a storm, but according to our opinion, Gudrun was the storm with the highest overall impact for Estonia. It was among the five strongest, if considering both the maximum wind speed and the area affected by high wind speeds. It produced the most severe coastal area flooding and a new sea level height record. It was the worst in terms of property damage due to stormwind and flooding.

Observed storm surge parameters

Air temperatures were well above the norm since December 2004 (Fig. 4b). As a result of strong cyclonic activity the Baltic sea level was already exceptionally high as well. The background sea level before the storm was about 70 cm in Estonian coastal waters (Fig. 4a) and roughly similar values were recorded over the whole Baltic Proper as well. At that point, any cyclone with mean wind speeds over 20 m s^{-1} and track over central Scandinavia would elevate sea level over the critical value, which was 170 cm at Pärnu, and 140 cm at Haapsalu. Over 20 m s^{-1} storm surge risk spirals fast up, as tangential wind

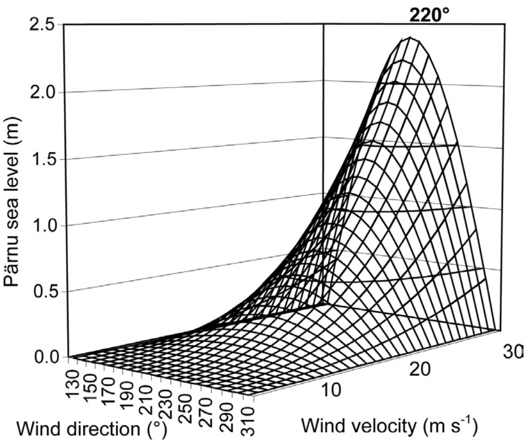

Fig. 5. Modelled sea level in Pärnu as the dependence from the direction and velocity of the stationary wind above the 2D model domain. Open boundary background sea level should be added to obtain the actual sea level height in Pärnu, inflow through the open boundary enabled. (After Suursaar *et al*. 2003).

stress is proportional to wind speed squared. This could be predicted also from the nomogram for Pärnu Bay (Fig. 5), prior versions of which were published both in scientific papers (Suursaar *et al*. 2002a, 2003) and in some Estonian scientific-popular journals.

Table 2. The maximum sea levels (cm) measured at Estonian tide gauge stations during and prior to Gudrun. In Haapsalu and Virtsu, estimations based on subsequent levelling of water markings were performed; at some stations measurements were impossible due to waves or fouling. * station with episodic past measurements.

Station	Highest prior to 2005	Maxima on 09.01.2005
Narva-Jõesuu	202 (23.09.1924)	194 (08:00 GMT)
Haapsalu*	150 (26.12.1951)	197 (estimated)
Loksa	140 (18.10.1967)	
Dirhami	148 (18.10.1967)	134 (06:00 GMT)
Rohuküla	160 (18.10.1967)	
Virtsu	150 (18.10.1967)	200 (estimated)
Heltermaa	148 (18.10.1967)	146 (00:00 GMT)
Pärnu	253 (18.10.1967)	275 (05:00 GMT)
Ruhnu*	145 (18.10.1967)	
Vilsandi*	206 (18.10.1967)	
Kihnu*	152 (02.11.1969)	
Kunda	157 (06.01.1975)	139 (12:00 GMT)
Ristna	170 (26.01.1990)	207 (04:00 GMT)
Toila	155 (11.01.1991)	160 (06:00 GMT)
Port of Tallinn	135 (15.11.2001)	152 (06:00 GMT)

Warning of the approach of a cyclone with wind speeds up to 30 m s^{-1} was uploaded to EMHI's web-site about 1.5 days prior to its onset to Estonia. Official storm-wind warnings were repeated via several channels (newspapers, radio and TV) throughout 8 January. Finnish Institute of Marine Research (FIMR) gave a forecast of a 150 cm flood in Helsinki, which later turned out to be correct. As EMHI carried no responsibility for marine prognoses, information about flood risk presented by DMI on their web-site was intermediated by individuals, such as Dr. Tarmo Soomere (*see* e.g. Soomere 2005). The event revealed some deficiencies in flood risk forecasting abilities in Estonia. In general, the scientific knowledge about the sea level forecasting possibilities and needs existed (e.g. Suursaar *et al.* 2002a, 2002b). However, during the hurricane, there were no operative forecast models working in Estonia, though there were several models in scientific or pre-operational mode: 2DM and FinEst in the Estonian Marine Institute, Bryan-Cox-Killworth type models in the Marine Systems Institute (MSI) and MIKE 21 in the Institute of Mechanics, Tallinn Technical University. A Cmod hindcast simulation of Pärnu sea level was presented on the websites of DMI and MSI shortly after the event.

It also appeared that people did not realise and acknowledge the meaning of a 2.4 m storm surge warning. At least during its onset, the scale and consequences of the flooding were quite unexpected both for the population and authorities.

According to the mareograph data from EMHI, the highest sea level reached 275 cm (272 cm according to the Port of Pärnu tide gauge) at 07 LT (05 GMT) on 9 January 2005 (Fig. 5). The maximum coastline recession reached about 1 km in Pärnu, flooding densely populated urban areas and large SPAs like "Tervis", "Estonia" and "Sõprus". The previous remarkably high sea levels for the period of 1923–2005 were in Pärnu on 18 October 1967 (253 cm), 2 November 1969 (193 cm), 12 September 1978 (184 cm), 27 February 1990 (184 cm), 17 December 1923 (183 cm) and 20 October 1924 (possibly around 190 cm).

New highest maximum sea levels were registered also in Virtsu, Vilsandi, Ristna, Rohuküla, Heltermaa, Dirhami and Tallinn (Table 2).

However, 2–3 measurements a day and difficult wave conditions did not allow the proper documentation of the surge event in most of the stations. Congestion with ice and fouling with trash aggravated the observations in some stations. The actual sea level height at important resorts like Haapsalu and Kuressaare remained unknown, as no sea level measurements were carried out. It is possible only to estimate the sea level developments in such places by the means of hindcast hydrodynamic simulations, presented below in this paper.

Among neighbouring countries, new sea level records were established in four stations in Finland: Helsinki (151 cm), Hamina (197 cm), Hanko (132 cm) and Turku (130 cm), according to the data presented on the web-site of FIMR. Previous maxima were retained both in the Bothnian Bay (up to 201 cm in Kemi since 1982), St. Petersburg (423 cm since 1824, *see* e.g Lazarenko 1961), Riga and Ventspils (148 cm from 1967). Sea level height reached a relatively modest 230 cm in St. Petersubrg on 9 January 2005. Along the Swedish (i.e. leeward) coast of the Baltic Sea, Gudrun produced negative surges with relative sea level drop up to 150 cm in Skanör and Simrishamn, according to SMHI. Gudrun also caused prominent positive surges along the Danish west coast (up to +402 cm in Ribe) and German NW coast with the North Sea, according to DMI.

Hindcast simulation of the sea levels

Hindcast simulations firstly included model "training" simulations with different combinations of inputs, bearing especially in mind the correct reproduction of the Pärnu surge peak. Then the most successful sets of forcings were used to simulate sea levels in other points of interest, as well as currents and water exchange.

In a previous, year 1999 hindcast simulation (Suursaar *et al.* 2002a), we successfully used input data from Vilsandi meteorological station and Sõru tide gauge station. In 2004 and 2005, the only sea-level recorder near the open boundaries of our model domain was located at Ristna. Sõru and Ristna, 40 km apart from each other, should have roughly similar sea level statistics.

The initial sets of year 2004 hindcast simulations showed acceptable results for both Ruhnu wind–Ristna level and Vilsandi wind–Ristna level forcing combinations. Correlation coefficient between Pärnu measured and modelled time series (n = 8800) was slightly better (r = 0.92) with Ruhnu wind. However, both simulations nearly systematically showed about 10 cm underestimation in the case of low sea level and 10–40 cm overestimation during high sea level events. The effect was missing in 1999 simulations with Sõru data and we conclude that Ristna sea level data is less appropriate for applying as open boundary conditions. Differently from Sõru station, a remarkable local wind-driven sea level pile-up or declension may occur at Ristna. Possibly, additional sea level rises due to storm waves affect the sea level readings in the gently sloping Kalana Bay, where the horizontal pipe feeding the mareograph's well ends just some 10 metres from the shoreline.

For model "training" we considered, in addition to hourly Vilsandi and Ruhnu wind data, sea levels at Ristna (data available up to 10 January) and Ventspils (5 to 12 January, provided by the Latvian Hydrometeorological Agency), as well as Ristna–Ventspils average sea levels, Ventspils level plus a constant, and some other modifications.

It appeared that, though in moderate meteorological conditions, Ristna–Ruhnu forcing combination yielded good model performance, in extreme storm-wind conditions the Ristna measured sea level apparently deviated from the expected open boundary sea level conditions, producing erroneously high sea levels around the whole model domain (Fig. 6). In addition, after the storm surge recession the sea level remained unrealistically high on 10 January — possibly the channel feeding the mareograph was congested with ice or sediments.

The results created with Ventspils sea level data, which were available for the period between 5 and 12 January 2005 and supplemented with Ristna data for the less critical period (1–4 January) of simulations, showed poor reproduction of the surge peak (220 cm *vs*. 275 cm, Fig. 6b). Ventspils is located 50 km SW from the nearest point of the open boundary and 200 km from the furthest point. Though the long-term mean qua-

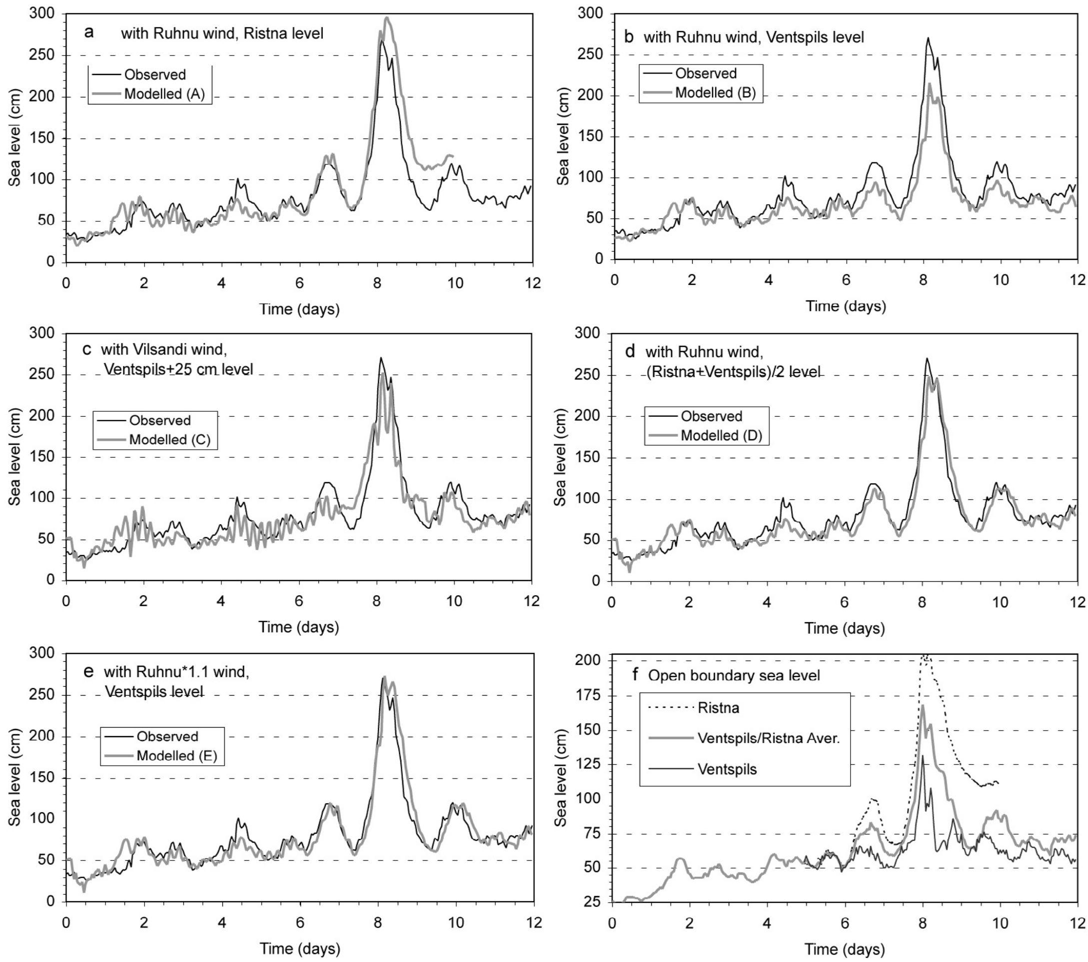

Fig. 6. — **a**–**e**: Comparison of observed Pärnu sea level with simulated series for establishing applicable combinations of forcing data; — **f**: open boundary sea level series.

sistationary Baltic sea-level slope explains only a 1–3 cm difference (Lazarenko 1986), Ventspils level is apparently too low for our boundary conditions. Further, the simulations with arbitrary addition to the Ventspils level (e.g. 25 cm in Fig. 6c) improved the peak reproduction; the replacement of Ruhnu wind with Vilsandi wind always worsened the output quality due to strong residual oscillations after remarkable changes in wind conditions (*see* e.g. Fig. 6c). The 5-h oscillation period is the main seiche period for the Gulf of Riga, which frequently appears both in model outputs and sea-level measurement records at Pärnu (e.g. Suursaar *et al*. 2003). However, by far too strong oscillations in Fig. 5c indicate poor quality of Vilsandi wind data, which includes unrealistically rapid changes in wind speed on days 2 (14.5 to 6.6 m s^{-1}), 5 and 8.

The scenario with the Ruhnu wind and Ventspils–Ristna combined sea level was one of the best simulations (Fig. 6d). It yielded acceptable reproduction of the surge peak (249 *vs*. 275 cm) and good reproduction of other events. The best reproduction of the Pärnu peak (273 *vs*. 275 cm) was obtained with the Ventspils-based sea level input (similar to that in Fig. 6b) and Ruhnu wind speed multiplied by the constant of 1.1 (Fig. 6e). We choose the simulations “D” and “E” for further study. Both of these two scenarios had small advantages in certain aspects, yielding better results according to least-squares fitting criteria in comparison with the rest.

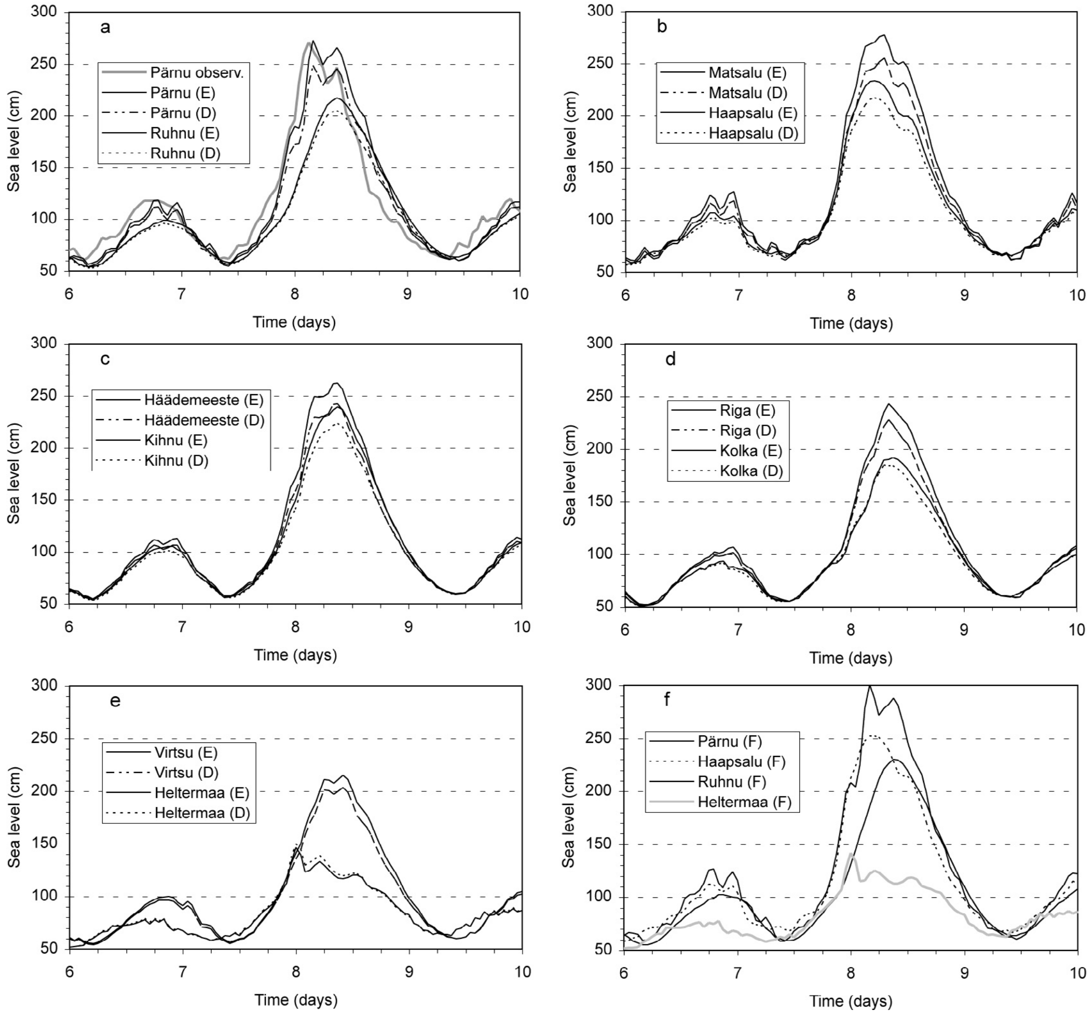

Fig. 7. — **a**–**e**: Hindcast simulations of sea level in selected locations along the west Estonian coast using the selected model forcing combinations D and E (*see* Fig. 6); — **f**: modelled sea levels calculated with 20° subtracted from wind directions in days 7.5–8.5.

It is important to stress that we did not apply too sophisticated manipulations with inputs. Average sea level of Ristna and Ventspils seem justified, as the longest section of the open boundaries near the Irbe Strait indeed is located between these two ports. On the other hand, the wind input at the height of 10 m in open landscapes required by the model may indeed differ from the measurement-based values, which are averaged over an hour and possibly somewhat screened by land and vegetation.

Figure 7 shows the hindcast reproductions of sea levels in the selected points and Table 3 shows the surge peak values according to the two selected input setups. The difference is maximal in the case of Pärnu (24 cm), for other locations it remains between 2 and 20 cm. We expect that the "real" value will be between these two estimates. The only place where the surge height could exceed the Pärnu value was in the head of Matsalu Bay. The bay is extremely shallow and not as voluminous as Pärnu Bay. However, in the case of short-period surges the real sea level height could not be as high as shown by the model. Due to the gently sloping coast the seawater can spread and inundate the coastal areas. It is known that the floods of the Kasari River delta region can cover an area up to 110 km^2 (Mardiste and Kaasik 1985).

The peak sea-level values for some other vulnerable locations (according to surge-time emergency calls) were 242–262 cm near Häädemeeste, 217–234 cm in Haapsalu Bay and 205–217 cm close to Kihnu Island. The Ruhnu sea level, roughly representing the average sea level of the Gulf of Riga sub-basin, was extraordinarily high (205–217 cm) as well. The sea level in the southern part of the Gulf of Riga remained between 227 and 243 cm, and between 146 and 192 cm along the leeward coast.

Influence of cyclone trajectories

The highest surge events at the west Estonian coasts are associated with deep cyclones producing strong SW or W storm-winds above Estonia. Such winds create an initial sea level surplus in the Baltic Sea, especially if there were series of consecutive cyclones. Additional water volume may be pressed into the semi-enclosed Gulf of Riga sub-basin, functioning as a smaller replica of the Baltic Sea itself. Within the gulf, a basin-wide sea-level slope will be created and the final effect is localised in the narrow and shallow bays with remarkable width convergence and the depth vanishing. So-called long-wave amplification phenomenon, when the sea level disturbance travels ahead of the baric system and resonating with the immediate cyclone impact, is possible within each individual sub-basin (e.g. Baltic Proper–Gulf of Finland system or Gulf of Riga sub-basin) separately. However, the long-wave travelling speed (10–15 m s^{-1}) in the relatively shallow Gulf of Riga is quite close to the cyclone's travelling speed.

However, due to the indented coastline, reaction of coastline morphomertry on wind stress is the main factor for sea-level variations in the study area. As the tangential wind stress is proportional to wind velocity squared, the sea level remarkably grows at the wind speed over about 20 m s^{-1} (Fig. 5). According to statistics, such strong winds can blow only from the western directions (i.e. between 180° and 360°) in west Estonia, and never from E, SE or NE (e.g. Soomere and Keevallik 2001). Though on the north coast of Estonia east winds blowing along the axis of the Gulf of Finland yield secondary peak in directional distribution of maximum wind speeds (e.g. Soomere and Keevallik 2003), they are irrelevant for storm surges.

Characteristic directions of strongest winds and possible storm surges related to them in Pärnu Bay were studied considering different cyclone trajectories. The zone with highest winds usually remains righthand from the cyclone eye's track, when looking along the cyclone's trajectory. It can be explained by the vectorial presentation of Fig. 8, which summarizes some main possibilities.

Local wind speed can be looked upon as a vector sum of two components: winds of a baric system itself due to pressure gradient, and travelling velocity of the baric system relative to land. For example, assuming that maximum baric wind speed within a cyclone is 20 m s^{-1} and the cyclone travels with a velocity of 10 m s^{-1}, then a maximum wind speed of 30 m s^{-1} could be obtained during the periods when these components are unidirectional (e.g. W1 in Fig. 8a and b); similarly strong northerlies may appear above Estonia with track N and southerlies with track S1 (Fig. 8c). Focussing on flood risk in west Estonia, major threats are associated with trajectories around W1 and SW1 (Fig. 8a) when the centre of the powerful and fast moving cyclone passes Estonia from the north over the Scandinavian Peninsula and Bothnian Sea. The following factors combine then: initial sea level

Table 3. Modelled maximum sea levels (cm), maximum and average current velocities (cm s^{-1}) obtained with simulations D and E at the selected locations on 1–12 January 2005.

Location	Max. level D/E	Max. velocity D/E/Direction	Average modulus D/E
Pärnu	249/273	94/111/E	18.7/21.5
Häädemeeste	242/262	35/40/NW	8.8/10.1
Kihnu	224/240	72/85/SE	13.0/14.9
Ruhnu	205/217	56/65/SE	15.3/17.5
Virtsu	203/215	30/31/SE	6.2/6.7
Haapsalu	217/234	42/49/NE	7.8/8.9
Heltermaa	150/146	95/103/SE	20.7/22.9
Matsalu	255/278	18/20/SW	3.8/4.4
Järve	161/163	85/94/E	19.0/21.2
Kolka	185/192	48/56/SE	11.8/13.5
Riga	227/243	71/82/NE	16.8/19.2

rise of the Baltic Sea due to inflow through the Danish Straits, relatively small decrease in wind speed due to smaller friction along the sea-surface before reaching the Estonian coast. The wind speed decrease due to friction on land surface is especially apparent for period averages, the decrease is relatively smaller in wind gusts (e.g. Table 1).

Hence, the crucial factor is the coincidence of the strongest possible SW–W winds with the axis directions of Pärnu, Haapsalu and Matsalu Bays. After passing the Estonian longitude, the wind direction changes from SW and W to NW and N, and the wind speed decreases, as the two mentioned components come to partially eliminate each other. Therefore the storm surge can not last long in Pärnu or Haapsalu (*see* Fig. 5). Even if it is theoretically possible that cyclones retard for a while due to confronting an anticyclone, then the local wind loses the travelling component of the baric system.

According to statistics, in addition to western cyclones (about 80%), cyclones may also approach the Baltic Sea from the north (5%–10%) or the south (10%–15%), but never from the east (Chromow 1940, Põiklik 1964). Although both northerlies and southerlies may be very strong in respective cases, they do not produce extreme surge events. As for northerlies, they regionally lower both the west Estonian and central Baltic sea level, and the relatively narrow Gulf of Finland does not allow large sea level inclinations towards the northern coast of Estonia. As for S-cyclones, east winds of an approaching cyclone lower the sea level in the west Estonian coast before the potential surge, and friction above land surface diminshes wind speeds.

The strongest eastwinds are possible during anticyclonic blockage above Russia, as happened in December 1959, when –123 cm at Pärnu was recorded. Such events develop slowly, during weeks or even months (Suursaar *et al.* 2003). Maximum winds do not exceed 15–20 m s^{-1}, as such large and stable in character systems lack the westward travelling component.

Nevertheless, the 8–9 January cyclone may have had even more potential for the Pärnu Bay sea level, if during the wind speed peak the wind direction was closer to 220° instead of actual 260°–280° (Fig. 3d) meaning a bit steeper

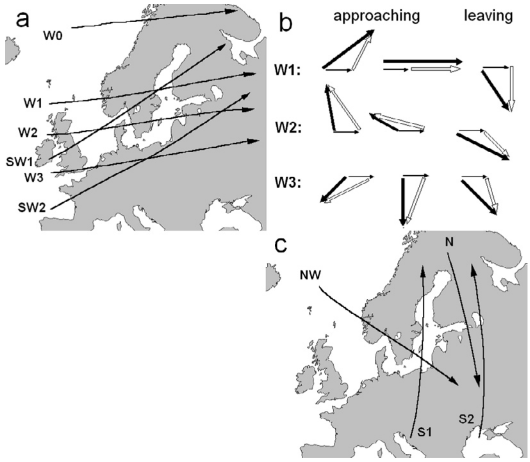

Fig. 8. Selection of (**a**) western, and (**c**) northern and southern cyclone tracks. A simplified sketch explaining the combination of (**b**) wind speed components when the cyclone's centre passes the given location lefthand (W1), across (W2), or righthand (W3). Thin arrows = travelling velocity of the cyclone, thick empty arrows = air movements within the baric system, thick black arrows = resulted wind on surface.

(SSW–NNE) trajectory of the cyclone. We performed a simulation by subtracting 20 degrees from the actual wind direction during one day (day 7.5–8.5, Fig. 7f) which yielded a 300 cm sea level at Pärnu. The sea level was higher by 10 to 30 cm also at Haapsalu and Matsalu, but lower at Heltermaa. It is important to stress, that even higher storm surges can be expected, considering that the average sea level will probably rise both globally and locally (e.g. IPPC 2001, Johansson *et al.* 2001, Kont *et al.* 2003, Suursaar *et al.* 2004). Also, trajectories of western cyclones have generally shifted to the higher latitudes and stronger storms could appear due to the atmosphere's increasing energetic level (e.g. Schmidt *et al.* 1998, J. Jaagus pers. comm.). According to our analysis 1 m s^{-1} wind speed increment yields about a 20 cm surge height increment in Pärnu in the range of wind speeds around 27–30 m s^{-1}.

Simulated currents and water exchange

In order to estimate the influence of the hurricane on the magnitude of currents and water exchange, we performed flow simulations together with sea level hindcast simulations using D and E forcing

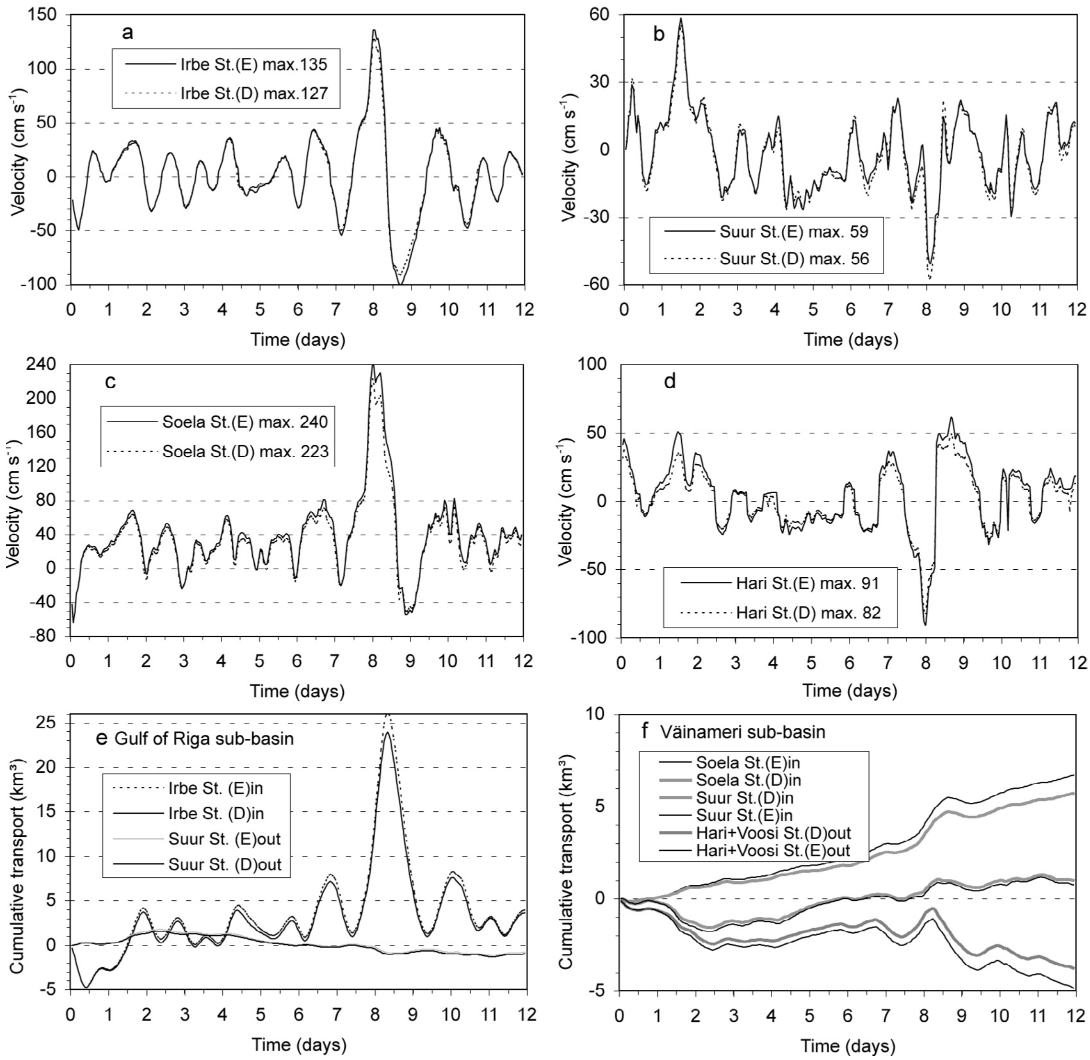

Fig. 9. — **a**–**d**: Modelled cross-section mean current velocities in the four major straits (*see* also Fig. 1) with maximum current speeds marked in the legend boxes (two different runs, *see* also Fig. 6); cumulative water flows in (**e**) the Gulf of Riga and (**f**) Väinameri. Legends in **e** and **f** follow lines order.

scenarios. Unfortunately, since there are no *in situ* flow measurements available for comparison for neither 2005 nor 2004, the calculated flow properties should be taken as approximate ones. Also, as current velocities may vary spatially, the calculated flows mainly describe the chosen locations in case of nearshore sea-level points (Table 3).

As the strongest winds of the event were westerlies (Table 1), also the maximum values of the cross-section average current velocities were the most prominent in W–E directed straits, such as the Soela and Irbe Straits (Fig. 9c and a). In the meridionally directed Suur and Hari Straits the maximum velocities did not exceed 1 m s^{-1} (Fig. 9b and d). Velocities nearly reached 2 m s^{-1} also in the NW–SE directed Voosi Strait. In water exchange calculations the flows of this narrow and shallow strait were combined with the parallel Hari Strait.

It appeared that during the hurricane alone the Irbe Strait probably contributed to the Gulf of Riga nearly 24 km^3 of Baltic Proper water with higher salinity for about 1–1.5 psu, according to studies by Lips and Lilover (1995). The inflowing volume comprises 5.4% of the average water volume of the Gulf. However, as one day later the same volume left through the same strait due to change in the wind direction, the hydrological influence of the inflow was restricted mainly to the region of the Irbe Strait and marine area south of Saaremaa. In the long-term course, the flows in the Suur Strait respond to the Irbe Strait as a mirror (Otsmann *et al.* 2001). However, during such rapid events, the Suur Strait with a cross-section area nearly 10 times smaller, was able to pass only 2 km^3 of the water northwards during the whole 12-day period under study. Also the westerly wind direction was not favourable for large flows through the Suur Strait. Thus, nearly the whole surplus of the 24 – 2 = 22 km^3 was stored in the elevated by 2 m sea level of the Gulf in days 8–9.

The most important strait for the Väinameri sub-basin was the shallow and narrow Soela Strait with a W–E direction and the funnel-like mouth. During the twelve days the Strait supplied the Väinameri with 6 km^3 of new water, while the almost 5 times larger Suur Strait contributed only 1 km^3. The cross-section area of the Soela Strait (which is on average 2 m deep) markedly increased due to sea level rise, enabling extraordinary large flows through the strait. The actual cross-section area could have been 30% larger during the 12-day period as an average. About 4 km^3 outflowed through the Hari and Voosi Straits (Fig. 9), leaving 3 km^3 to be stored in the sea level difference between 1 and 12 January (Fig. 4).

Possible consequences for the marine environment and seacoasts

The hurricane influenced the Estonian coastal zone by (1) water and matter exchange through the straits, (2) intensification of vertical mixing processes within the sub-basins, (3) intensification of coastal geomorphic processes as a result of strong currents, wave action and high sea level.

Inflow of 24 km^3 through the Irbe Strait during the 1–2 days is a remarkable event, bearing in mind that our simulations yielded 50 km^3 cumulative inflows for the entire year 2004. However, while in the case of seasonal water exchange processes, we can assume that actual replacement of water takes place, the effect of the inflow of 8–9 January is probably not so influential. Though some mixing of different water masses might have happened during one–two days, the inflow did not much affect the central and southern parts of the Gulf. Exchange processes were still somewhat intensified due to larger wind-driven currents within the sub-basins.

For the Väinameri, however, the 6-km^3 inflow from the Soela Strait and 1 km^3 from the Suur Strait comprises about 70% of the sub-basins water volume. Nearly 4 km^3 departed via the Hari and Voosi Straits during the same 12 days and the surplus of nearly 3 km^3 stored in the higher sea level departed later northwards as well. The western section of the Väinameri (also called Kassari Bay), which according to hydrodynamical properties could be taken as a separate sub-basin with the water volume of 5 km^3 (Suursaar *et al.* 2001), was entirely flushed through. Shallow bays like Haapsalu and Matsalu, were entirely flushed with possible resuspension events. Water entirely renewed also in the northern part of the Väinameri. Substitution was not complete only in the SE section of the Väinameri.

The extraordinary event contributed to the Väinameri more saline, but less nutrient-rich water from the Baltic Proper, decreasing therefore trophic status of that eutrophied area. On the other hand, the strong hydrodynamic processes could have also affected the deeper layers, and some secondary pollution due to resuspension of bottom sediments probably occurred. In the short span of time, the water column of the relatively shallow sub-basin was homogenized as the result of action of strong winds and horizontal advective fluxes.

The strong impact of the hurricane on coastal geomorphic processes as a result of strong currents, wave action and high sea level was evident already from the first days of the event. Damage to harbours and beach facilities was reported by Estonian media. Changes in coastline, beach profiles, etc. are already being studied and will be studied by researchers within different projects, including the national coastal monitoring programme. According to some preliminary very qualitative estimates, the amount of work by waves and currents was perhaps comparable to the total activity within many preceding years or even decades (A. Kont and K. Orviku pers. comm.). Though the processes should be examined profoundly in the future, it could be explained in a way that the work done by near-bottom currents is proportional to velocity cubed whereas the wave energy is proportional to amplitude squared. Due to remarkable sea level increase, much higher waves were allowed near the coast.

Conclusions

The extratropical cyclone reached the power of a hurricane according to maximum wind speeds measured in Denmark (34 m s^{-1}, gusts of up to 46 m s^{-1}). On 8–9 January 2005 the cyclone's eye passed Estonia 300 km to the north, affecting coastal areas with average wind speeds up to 28 m s^{-1} (at Sõrve) and wind gusts up to 38 m s^{-1} (at Kihnu). As a result of high (+70 cm) initial values of the Baltic Sea level, the fast travelling cyclone with a favourable trajectory and strong SW–W winds, the new highest recorded storm surge occurred in Pärnu (+275 cm), as well as in many other locations along the west Estonian coast. Preliminary estimated losses due to flooding of urban areas of Pärnu and Haapsalu and wind damage of forests and infrastructure reached about 50 million Euros (0.7% GDP).

Hindcast simulation study of sea levels showed that in case of an extremely strong storm the use of open boundary sea level data from the tide gauge stations could produce biases, as in the case of shallow and narrow bays the sea level may be affected by the coastal morphometry. Either model "training" with available forcing data should be carried out, or application of Baltic Sea–local area nested model configuration should be used.

Sea level modelling showed that, apart from Pärnu, the sea level probably reached 205–217 cm near Häädemeeste, 217–234 in Haapsalu and 205–217 cm near Kihnu Island. The sea level maximum could have even reached 300 cm in Pärnu, if the cyclone had had a slightly steeper trajectory into the north, causing maximum wind speeds around SW direction instead of WSW–W.

The hurricane also influenced the Estonian coastal zone by increasing water and matter exchange through the straits, intensifying vertical mixing processes within the sub-basins, and accelerating coastal geomorphic processes as a result of strong currents, wave action and high sea level. Only during the hurricane, the Irbe Strait contributed to the Gulf of Riga nearly 24 km^3 of fresh water; for the Väinameri sub-basin 6 km^3 inflow from the Soela Strait and 1 km^3 through the Suur Strait equals about 70% of the sub-basins water volume. The western section of the Väinameri, also called Kassari Bay, was entirely flushed through.

Acknowledgements: The study was supported by the Estonian Science Foundation through the grants No. 5929 and 5763. We are thankful to Mrs. Pille Allik and Jekaterina Sooäär from the Estonian Meteorological and Hydrological Institute, and to three anonymous referees for their valuable comments and suggestions.

References

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.

Carpenter G. 2005. Windstorm Erwin/Gudrun — January 2005. *Specialty Practice Briefing* 2: 1–14. (Also available on the web at http://www.guycarp.com/portal/extranet/pdf/Speciality_Briefing_170105.pdf?vid=2).

Chromow S.P. [Хромов С.П.] 1940. [*Synoptical meteorology*], Gidrometeoizdat, Moscow. [In Russian].

Huttula T. 1994. Suspended sediment transport in Lake Säkylän Pyhäjärvi. *Aqua Fennica* 24(2): 171–185.

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

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.

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(1–2): 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.

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

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.

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(4): 284–294.

Langenberg H., Pfizenmayer A., von Storch H. & Suendermann J. 1999. Storm-related sea level variations along the North Sea coast: natural variability and anthropogenic change. *Cont. Shelf Res*. 19: 821–842.

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. *Baltic Sea Environm. Proc*. 16: 64–80.

Lips U. & Lilover M.-J. (eds.) 1995. *IRBEX-95 data report*. EMI Report Series 2, Estonian Marine Institute, Tallinn.

Lowe J.A., Gregory J.M. & Flather R.A. 2001. Changes in the occurrence of storm surges around the United Kingdom under a future climate scenario using dynamic storm surge model driven by the Hadley Centre climate models. *Climate Dynamics* 18: 179–188.

Mardiste H. & Kaasik T. 1985. Matsalu lahe ja Kasari jõe hüdroloogiline reziim [Hydrological regime of the Matsalu Bay and Kasari River]. In: Kumari E. (ed.), *Matsalu — rahvusvahelise tähtsusega märgala [Matsalu — a wetland of international importance]*, Valgus, Tallinn, pp. 15–25. [In Estonian with English summary].

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 Res*. 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.

Põiklik K. (ed.) 1964. *Üld- ja agrometeoroloogia*, Eesti Raamat, Tallinn.

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.

Schmidt T., Kaas E. & Li T.S. 1998. Northeast Atlantic winter storminess 1875–1995 re-analysed. *Climate Dynamics* 14: 529–536.

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.

Snezhinsky V.A. [Снежинский В.А.] 1951. [*Practical oceanography*]. Gidrometeoizdat, Leningrad. [In Russian].

Soomere T. 2005. Estonia got storm warning from newspapers. *The Scandinavian Shipping Gazette* 4: 26–29.

Soomere T. & Keevallik S. 2001. Anisotropy of moderate and strong winds in the Baltic Proper. *Proc. Estonian Acad. Sci. Eng*. 7: 35–49.

Soomere T. & Keevallik S. 2003. Directional and extreme wind properties in the Gulf of Finland. *Proc. Estonian Acad. Sci. Eng*. 9: 73–90.

Suursaar Ü., Kullas T. & Otsmann M. 2001. The influence of currents and waves on ecological conditions of the Väinameri. *Proc. Estonian Acad. Sci., Biol. Ecol*. 50: 231–247.

Suursaar Ü., Kullas T. & Otsmann M. 2002a. 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. 2002b. A model for storm surge forecasts in the Eastern Baltic Sea. In: Brebbia C.A. (ed.), *Risk analysis III*, WIT Press, Southampton, Boston, pp. 509–519.

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., Kont A., Jaagus J., Orviku K., Ratas U., Rivis R. & Kullas T. 2004. Sea level rise scenarios induced by climate change, and their consequences for the Estonian seacoast. In: Brebbia C.A. (ed.), *Risk analysis IV*, WIT Press, Southampton, Boston, pp. 333–343.