Journal of Coastal Research	SI 56	pg - pg	ICS2009 (Proceedings)	Portugal	ISSN

Coastal changes in Saaremaa Island, Estonia, caused by winter storms in 1999, 2001, 2005 and 2007

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ABSTRACT

ORVIKU, K., SUURSAAR, Ü., TÕNISSON, H., KULLAS, T., RIVIS, R. and KONT, A., 2009. Coastal changes in Saaremaa Island, Estonia, caused by winter storms in 1999, 2001, 2005 and 2007 Journal of Coastal Research, SI 56 (Proceedings of the 10th International Coastal Symposium), pg – pg. Lisbon, Portugal, ISBN

As a result of an increase in cyclonic activity above NW Europe, trends toward higher storm surge levels and intensification of coastal processes has been reported along the Eastern section of the Baltic Sea. Four extreme storms in 1999-2007 caused significant changes to the depositional shores in the West Estonian Archipelago. The main objective of the current paper is to present a comparative meteorological and hydrodynamic analysis of those four storms, and to analyse the specific influence of the extreme storms against the background of gradual decadal variations. Wind conditions, and sea level variations were studied. The wave and current regime was studied either on the basis of field data or hindcast simulations. Coastal changes were studied on the basis of annual geomorphic surveys. The precondition for the profound coastal changes was a combination of the absence of protecting ice cover on the sea, relatively high sea-level before the storms and intensive storm surges combined with strong wave activity. Our study reveals that almost all erosion on sandy beaches is caused by rare extreme storms. Four extreme storms in ten years caused 95% of erosion of the sandy scarp on Cape Kiipsaare.

ADDITIONAL INDEX WORDS: *Sea level, Coastal erosion, Accumulation, Gravel-pebble shore.*

INTRODUCTION

Saaremaa Island (2,671 km^2 in area) is the largest island in the west Estonian archipelago (Figure 1a, b). Its NW coast is exposed to strongest winds for that location and greatest wave activity. Also, the nearby coastal sea has the roughest wave climate along the Estonian coast (SOOMERE *et al*., 2008). Tidal motions are negligible and the major hydrodynamic agents acting on seashores are waves, and relatively infrequent storm surges, whereas the role of wind-driven currents is less important (SUURSAAR *et al*., 2008). It is an active region of both geomorphic and hydrodynamic processes, where historical changes in shoreline position and contours reflect past changes in wind and wave climate. The coastal processes in the past were largely dominated by isostatic land uplift (2-3 mm/yr), which is nearly compensated by sea level rise now (SUURSAAR and SOOÄÄR, 2007). Anticipated warmer winters, higher mean and extreme sea levels, more frequent strong storms, decreasing sea ice extent and duration are expected to intensify the shore processes in the future (e.g. ORVIKU *et al*., 2003; RIVIS, 2004).

As wave energy is roughly proportional to the wave height squared, the energy of extremely strong storms and their impact on the coastal zone are many times higher than that of ordinary storms. The imprint of changes in coastal areas generated by such kind of extreme events may endure for decades. Consequently, it should be possible to relate such changes to particular extreme meteorological events and hydrodynamic forcing.

The objectives of this study are: (1) To present meteorological and hydrodynamic analysis of four extreme storms in the last decade by comparing meteorological and hydrodynamic conditions before, during and after the storm surges and wavestorms; (2) To describe coastal changes in two study sites on the Harilaid Peninsula caused by the extreme storms; (3) To discuss the role of extreme storms and stormy periods on coastal processes with respect to gradual (i.e., "evolutional") long-term changes.

Study area

Two study sites on Harilaid, NW Saaremaa, were examined in the current study. Harilaid is a small (4.3 km^2) peninsula connected to the larger Tagamõisa Peninsula by a tombolo (Figure 1c). The primary landform of the peninsula is a glaciofluvial ridge. Sandy shores prevail on Harilaid. Gravel-pebble shores exist in its southern part.

Kelba study site is situated in the southern part of Harilaid (Figure 1d). It forms a series of beach ridges forming a ~1-km long spit. The spit consists mainly of well-rounded granite gravel, pebble, cobble and even some boulders and the beach ridges within it form distinct increments of different age. The heights of the crests of the beach ridges attain 2.5 m. There are lagoons and small lakes behind the spit. Deeper waters lie west of the study site. The near-shore bottom is strongly inclined, and the 2-m isobath is only a few meters from the shoreline. The study site is exposed to the Baltic Sea winds from the SW, W and NW. The general trend of development of the Kelba Spit over about the last century has been continuous accumulation of new beach ridges elongating the spit.

The Kiipsaare study site is situated in the north-westernmost tip of Harilaid (Figure 1e). A coastal scarp borders the 50 m wide beach from inland. The scarp is highest (3 m a.s.l.) in the NW part where shore processes are strongest. The study site is most influenced by waves from the SW, W, NW and N. The sea bottom is particularly flat and shallow northwest of Kiipsaare. The 5 m isobath is 4 km from the shoreline. The steepest underwater shore

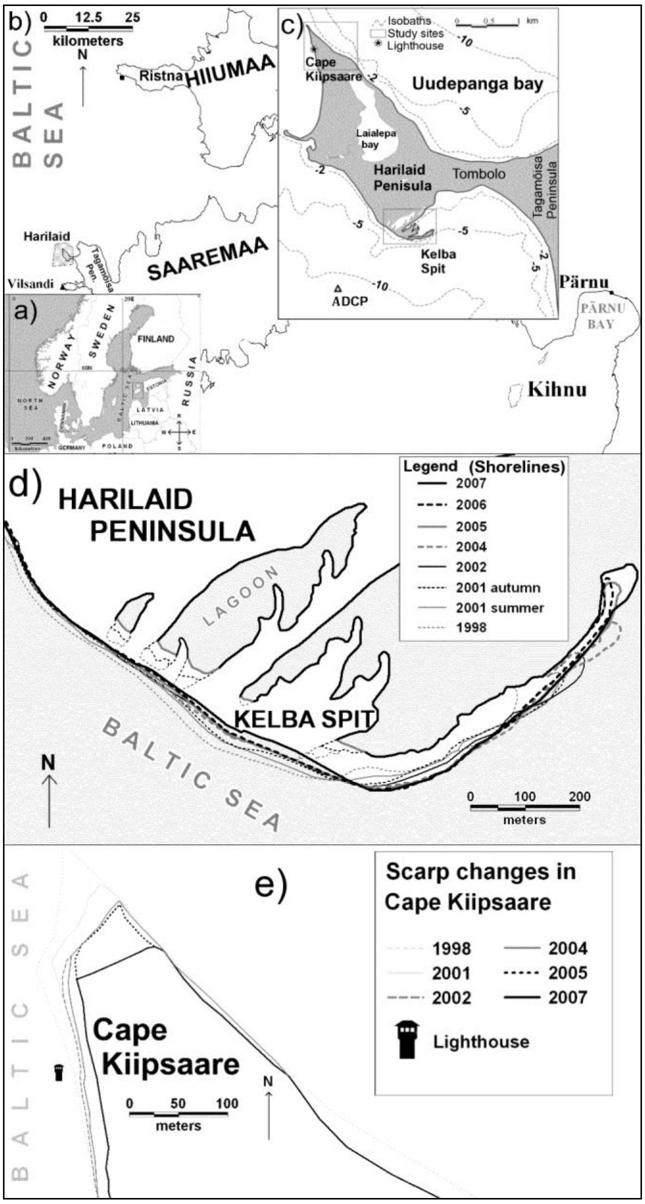

Figure 1. a) location of Estonia; b) west Estonian archipelago; c) Harilaid Peninsula and location of ADCP; d) shoreline changes on Kelba Spit; e) scarp changes on Cape Kiipsaare.

slope occurs northeast of the peninsula where the 5 m isobath is 350 m offshore. The earlier accumulative shoreline positions on Cape Kiipsaare are well-marked by a series of parallel beach ridges, which cross the current shoreline at a 30-350 angle. Shore processes during the last century have caused the north-westernmost point of the cape to migrate to the northeast (Orviku et al., 2003).

METHODS

Wind and sea-level data

For meteorological description and wave model forcing, we used data from Vilsandi and Kihnu stations operated by the Estonian Meteorological and Hydrological Institute (EMHI). The Vilsandi station is the most open to the marine winds among Estonian stations and is the closest to our measurement site (Figure 1b). However, the station occasionally malfunctions during strong storms. Therefore data from the Kihnu station were included. From 1976 to 2003 the stations were equipped with automatic anemometers, (8 daily measurements with 1 m/s value step for wind speed and 10º angular resolution for wind direction). Since September 2003, the stations are equipped with MILOS-520 automatic weather stations, which provide hourly average wind speed and gust wind speed with the value step of 0.1 m/s, and hourly prevailing wind direction with a resolution of 1º.

The sea-level data from Ristna and Pärnu tide gauges (Figure 1b) were used. The Ristna station is the closest to the study area, located on Hiiumaa Island, ~50 km from Harilaid. The tide gauge is an old Rohrdanz-type, which tends to malfunction during storm surges, whereas Pärnu station provides higher quality data.

Waves

The calculation of wave parameters for the period 1999 – 2007 was based on the fetch-limited equations of Sverdrup, Munk, and Bretschneider (SMB). The model has been used for local wave forecasts and engineering purposes (e.g. SEYMOUR, 1977). In shallow near-shore areas, using long-term hindcast simulations with more up-to-date wave models may be time-consuming. As we were interested in wave forcing conditions near the Kelba Spit, some 1-1.5 km off the coast, a simple fetch-limited point model may offer a simple alternative. The inputs for the SMB equations are wind speed, effective fetch and water depth and they provide significant wave height, wave period and wave length. For detecting the fetch lengths, we used a weighted average process over a wind sector ±40º from the wind direction. As a result, the calculated fetches varied between 2 km (30º-50º) and 250 km (270º-290º).

For calibration of the wave model, an ADCP was deployed (in a depth of 14 m) at the same location where the wave calculations were made. The instrument recorded between 20. December 2006 and 23. May 2007. The measuring interval was set at 1 h and the instrument provided 3691 h of data on multi-layer current regime, water temperature, turbidity and salinity (see also SUURSAAR *et al*., 2008). It is also equipped with a high-accuracy quartz-based pressure sensor, which enables it to measure the relative sea level variations and a set of wave parameters. During the 5-month calibration period, the significant wave height attained 3.2 m and the recorded maximum wave height reached 4.6 m. Based on the Vilsandi wind data and the corresponding fetch data, we firstly calculated the significant wave parameters for the same period and location. It appeared that the model slightly underestimated the measured waves. Therefore, the model output was slightly corrected using a fourth-order polynomial, which produced both high correlation coefficient (0.880), low RMSE (0.233) and nearly equal with the ADCP average and maximum values. The same settings were further used in the full 1999-2007 wave hindcast.

Wave energy was calculated at the RDCP location for the whole study period. The share of the extreme storms to the cumulative wave energy was calculated by taking into account 15 days before and 15 days after the peak of the storm. The parameter used to compare with coastal changes was showing how many times more wave energy appeared during those four months in respect to the mean value of wave energy.

Coastal changes

Orthophotos of the study sites from 1998 and 2005 were used to map shoreline position in Kelba and scarp position in Kiipsaare. Manual GPS measurements were carried out in the study sites at

Table 1. Major storms (1999-2007). Sustained wind speeds, sea levels, and computed significant wave heights are given as maximums (Max) and averages (Av.6d) for a 6 day period (3 days before and after the maximum).*- possible equipment malfunction.

Date	Name	Vilsandi wind, m/s (Max/Av.6d)	Kihnu wind, m/s (Max)	Ristna sea level, cm (Max/Av.6d)	Pärnu sea level, cm (Max/Av.6d)	Wave height (Max/Av.6d)
29/30.11.1999		22/12.6	19	70/23	100/44	4.0/1.4
6.12.1999	Anatol	24/9.6	19	133/48	134/58	2.8/1.0
17/18.12.1999		**25/11.6**	**24**	**140/59**	**146/73**	**3.1/1.1**
23.12.1999		18/11.5	17	91/42	99/47	2.8/1.0
1.11.2001	Pyry	25/11.8	20	77/29	144/51	3.6/1.4
11.11.2001		18/10.7	18	108/54	146/65	3.4/1.3
15.11.2001	**Janika**	**19/11.4**	**24**	**133/53**	**158/58**	**3.6/1.4**
9/10.01.2005	**Gudrun**	**23*/8.6***	**25***	**207*/102***	**275/92**	**4.2/1.5**
14/15.01.2007		**23/9.4**	**19**	**171*/88***	**176/87**	**3.2/1.2**

least once a year since summer 2001. Garmin GPS was used for GPS-measurements, which is accurate to within 3 m. By connecting the GPS-marked points and averaging 3 measurements in mapping the shoreline or contour line of the scarp we reduced the margin of error to 1 m. Shoreline position is not the best indicator to describe short time changes on sandy beaches (too much dependence on sea level fluctuations). Therefore, the measurements were focused on changes in area covered by gravel-pebble beach ridges in Kelba and recession of the scarp in Kiipsaare. The cumulative changes in area were calculated in Kelba (accretion and erosion) for each year. For more homogenous results only measurements taken during each spring/early summer were used (similarly low sea level and minimal effect of waves). To compare annual changes during 1998-2007, an increase in the total length of the Kelba Spit and recession of the scarp at Kiipsaare were also considered.

RESULTS AND DISCUSSION

Meteorological and hydrodynamic description

During the last decade, the major storm periods in the west-Estonian archipelago occurred in 1999, 2001, 2005 and 2007. There were a few other storms with some parameters approaching the major storms (e.g. in 25. January 2002), but with less total impact. All storms took place in late autumn or early winter.

In 1999 and 2001 a succession of storms struck Estonia. Sustained wind speed attained 25 m/s in both years (Table 1). Sea level gradually increased during the stormy period, resulting in the highest localized storm surges during the last storm events (see also SUURSAAR *et al*., 2003). Some of the storms affected all of northern Europe. Some storms, designated “storms of the century” in Denmark and Sweden (e.g. Anatol and “Danish storm” on 3rd December 1999, see NIELSEN and SASS, 2003), were in the phase of seclusion and disintegration upon reaching Estonia.

Hurricane “Gudrun/Erwin” of 8-10 January 2005 was equally renowned both in the Nordic countries as well as in Estonia (RØSTING and KRISTJANSSON, 2008; TÕNISSON *et al*., 2008). The hurricane had the maximum sustained wind speed of 28 m/s in Estonia. It produced the highest ever recorded sea level in Estonia (275 cm in Pärnu, Figure 2h) and probably the highest waves in the Northern Baltic Proper (SOOMERE *et al*., 2008, Table 1).

Observed coastal changes related to the storms

1999 strom. By comparing the orthophoto from 1998 with the measurements from 2001 and considering the average changes in 1998/1999 and 2000/2001 winters, we estimate that the cumulative area changes caused in Kelba were nearly 8,500 m^2. The share of erosion was about 5,500 m^2 while accumulation approached 3000 m^2 (the amount of relocated sediments was approximately 10 000 m^3). The proximal part of the Kelba Spit receded by 15 to 20 m. The distal part extended by over 50 meters. All the accumulation occurred in the distal part while most of the erosion affected the proximal part of the spit. The highest beach ridge measured in the distal part of the spit was 1.8 m a.s.l. The recession of the scarp in Cape Kiipsaare ranged from 15 m on the western side of the cape to 30 meters on the north-western side. The eroded area of the beach formations totalled ~5,000 m^2.

2001 storm. The cumulative changes in the area of the Kelba Spit in winter 2001/2002 were 16,000 m^2. The greatest changes occurred in the proximal part of the spit. The shoreline retreated by 10-15 m and the overall loss in area was 6,100 m^2. The total area of the spit increased by about 9,000 m^2, one third of which was from filling of the backing lagoons and lakes by sediments (the landward side of the spit got wider by 45 m). The spit extended by 55 m. The highest beach ridge in the distal part of the spit was 1.5 m a.s.l. Significant changes at Cape Kiipsaare took place only on the north-western shore. The sandy scarp receded by 12-23 meters. The overall area of erosion is estimated at nearly 2,000 m^2. As the mean height of the scarp is about 1.5 m, the amount of eroded sediments was estimated at 3,000 m^3.

2005 storm. The area of the Kelba Spit increased by about 4,300 m^2. Most of this increase consisted of filling the back lagoons and small lakes by sediments. Erosion on the seaward proximal slope of the spit and the cast of eroded deposits over the crest of the spit into the lagoons leveled the older beach ridges and widened the proximal part of the spit toward the lagoons. The distal part of the spit shifted north by 15-30 m. The rate of erosion was about 15 m^3 of deposits per meter of shoreline resulting in an elongation of the spit by 75 m. 2.8 m high ridge arose as a result of the storm in the distal part of the spit. Some of the older beach ridges on the seaward side were completely destroyed, but the submarine base of the spit remained stable. The most significant changes took place on the western shore of the Kiipsaare study site. The sandy scarp receded by 10-20 m. As the mean height of the scarp is about 1 m, the approximate amount of the eroded sediments is 5,000 m^3. The ridge of foredunes was destroyed and the area flattened. The sand from the beach was transported up to 50 m inland from the edge of the dunes by swash (TÕNISSON *et al*., 2008). Most of the eroded material was deposited directly on the beach, flattening and elevating it by 0.5 m, and obscuring the distinct boundary between the former beach and the scarp. Some of the sand has been transported around the cape and deposited on the eastern shore.

2007 storm. The distal part of the Kelba Spit shifted from north to northeast. The distal top of the spit has advanced about 50 m, and its area has increased by about 5,000 m^2. In the proximal part of the spit, the shoreline has receded by up to 15 m along a 400 m stretch accounting for approximately 3,500 m^2 of land loss. The eroded volume in the proximal part of the Kelba Spit is relatively small, as the near-shore sea is only 2 m deep and beach face is covered by cobble and boulder sized sediments. Such large sized sediments act as wave breakers and most of the energy generated by the swash does not reach the higher elevations of the spit. We estimate that the erosion in the proximal part was 4,000-5,000 m^3, whereas accumulation in the distal and eastern part was nearly 13 000 m^3. The highest beach ridge measured in the distal part of the spit was 2.0 m a.s.l. Recent measurements at the Kiipsaare study site show a retreat of the sandy scarp in the western part, while the scarp in the north-eastern part of Cape Kiipsaare remained stable. The sandy scarp on the northern and north-western shore receded by 35-50 m. As the mean height of the scarp is over 2 meters, the estimated amount of eroded sediment is about 5,000 m^3.

The impact of different forcing factors and storms

All four extreme storms displayed variable characteristics and impact (Tables 1 and 2). The strongest storm was Gudrun, both in terms of meteorological and hydrodynamic parameters (Figure 2g, h, i). The sea level and wave height were by far the highest compared to the other storms, but coastal changes (in area) in Kelba were much smaller than in 2001 and comparable to the changes in 1999. The cumulative wave energy during the storm month was actually the lowest. Moreover, that scarp changes on Cape Kiipsaare were nearly two times greater than those in 1999. The period of high sea-level was short. Sea-level was over 100 cm for less than 24 h and just after the peak of the storm the wind turned to the NW (Figure 2g). Therefore, the Kelba study site was no longer directly exposed to the storm, whereas the Kiipsaare site was exposed to the strongest storm wind and waves throughout the event. Most of the changes took place some distance away from the shoreline (filling the lagoons and erosion of the sandy scarp) due to the extremely high sea level. The storm caused few shoreline changes, rather reshaped older beach ridges and eroded sandy scarps on higher elevations and off the mean shoreline.

The next strongest storm was Janika (2001), although we need to consider three separate storms that hit the study sites in two weeks. It is remarkable that during this period the sea level approached 150 cm three times. The wind speed and wave characteristics were comparable with Gudrun but the sea level among the lowest of the four events (Figure 2d, e, f). High waves caused great changes at the Kelba study site. Also, the wind direction was more conductive at the Kelba location, blowing perpendicularly to the proximal part of the spit during the peak of the storm and causing sediments to be cast across the older beach formations. The highest measured beach ridges were only 1.5 m a.s.l. Low sea level did not allow the waves to erode the sandy scarp, while all the cumulative wave energy released in sediment transport and modifying the shoreline on Kelba Spit.

Table 2. Relative wave energy over the mean (15 days before and after the storm) calculated for the ADCP location. Area changes (times over the mean winter without extreme storm) /percent of total changes accounting for specific winter. Percent of total area changes in Kiipsaare accounting for specific winter.

Winter	Wave energy	Kelba area changes	Kiipsaare area changes %
1999/2000	4.3	2.5x /15%	26%
2001/2002	4.2	4.2x /25%	11%
2004/2005	2.7	2.8x /17%	41%
2006/2007	3.7	2x /12%	17%

The next period actually consists of four different storm events (Nov.-Dec. 1999). During each event the sea level attained 1 m. Wind blew directly from the south leaving the Kelba study site protected by Vilsandi Island when the highest waves occurred. During this event the sea-level remained above 100 cm nearly 48 h, but the maximum sea-level was the lowest of the four events (Table 1, Figure 2a, b, c). Wave energy was the highest compared to the other storms, and caused the second greatest changes in the Kiipsaare study site, while the changes in Kelba were moderate. Such changes seem to be related to wind direction. Recession (~40 m) of the scarp on the western side of Cape Kiipsaare supports our assumption. Such a high rate of erosion is probably caused by the uncharacteristically long period of high sea-level.

The January 2007 storm was atypical among storms striking the West-Estonia. The wind originally blew from the north, turning to the north-west by the peak of the storm and finally to the south (Figure 2j, k, l). The second highest ever sea-level was measured in Ristna. It was the shortest of the four studied storms. The sea level remained above 100 cm for ~12 h and the mean wind speed over 15 m/s lasted only 6 h. This storm resulted in the smallest changes in the area of the Kelba Spit while it had much greater impact on the Kiipsaare study site (Figure 1e). Clearly, the high rate of erosion on Cape Kiipsaare resulted from a short but high sea level and conductive north western winds during the peak of the storm. The foot of the scarp is 120-130 cm a.s.l. (TÕNISSON *et al*., 2008), therefore we can assume that during the peak of the storm the waves reached nearly half of the height of this scarp. The sea level rose much higher than during the 2001 storm but the changes were the smallest in Kelba. There was no overflow of sediments across the proximal part of the spit. The storm caused the formation of a 2 m a.s.l beach ridge near the distal part of the spit. Nearly 40 cm lower wave height might be another contributing factor for much smaller impact compared to the 2001 storm. This suggests that higher sea levels must be accompanied by winds from a particular direction to cause major changes on gravel-pebble shores. Even a small deviation from this favourable wind direction might result in far less change.

The importance of single storm events versus long-term evolution of the coasts

Due to global warming and related sea level rise, the northern part of the Baltic Sea has experienced a significant increase in cyclonic activity, which also affects Estonia. We suggest that dominating erosion on sandy beaches and increased erosion rate on gravel- pebble shores (normally accumulative shores) is caused by increased cyclonic activity (ORVIKU *et al*., 2003; etc.).

Rates of cumulative changes were similar (difference less than 5%) in winters without extreme storms (2002/2003, 2003/2004, 2005/2006). The total length of the Kelba Spit increased by 28% during 1998-2007 and the recession of the scarp in Kiipsaare comprised 14% of change in area over the same period. The winters of 1998/1999 and 2000/2001 were similar to the three winters without extreme storms. Therefore, we could calculate the approximate cumulative area changes for these two winters by considering the total length of the spit and total cumulative area changes from 1998 to 2001. Our study reveals that almost all erosion on sandy beaches is caused by rare extreme storms. Four extreme storms in ten years caused 95% of erosion of the sandy scarp on Cape Kiipsaare.

The relationship is more complicated on gravel pebble-shores. It was impossible to estimate the impact of single storms. However,

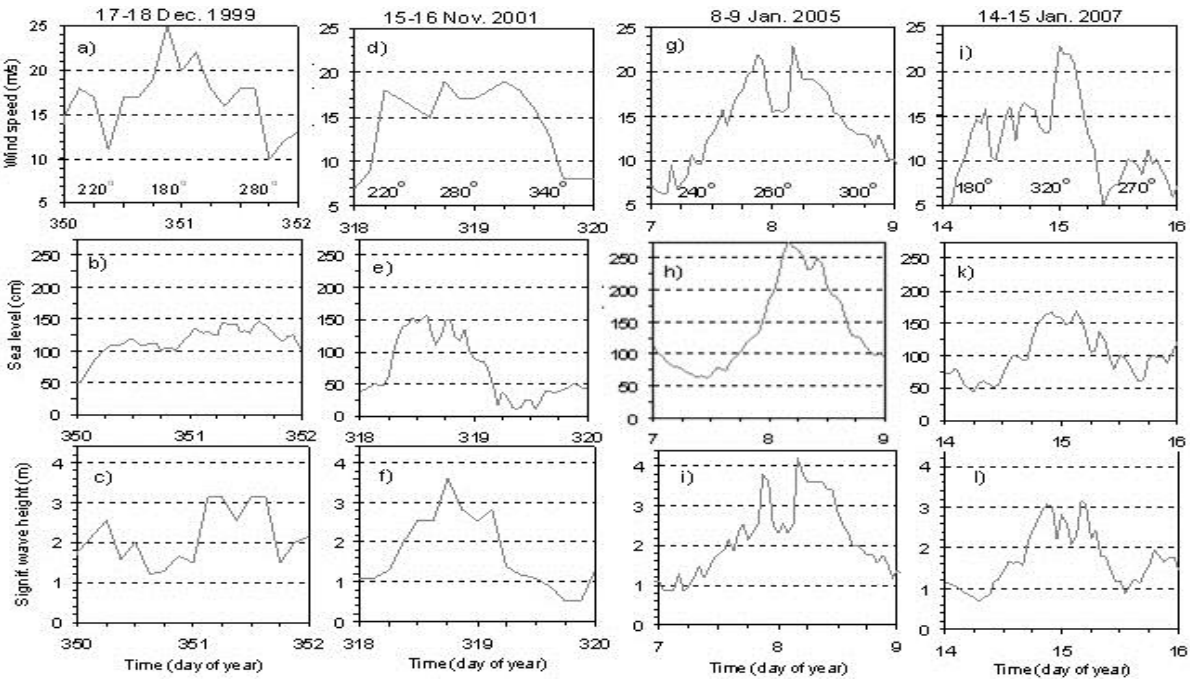

Figure 2. Wind speed, wind direction, sea level and significant wave height during the four studied storms.

we could estimate the impact of winters with extreme storms. We have shown that nearly half of the area change in ten years took place during these four winters. We estimate that at least 30% of the total change was caused by the four extreme storms, assuming that about 6% of area change is constant for each year. The rate of change during the extreme storms is 2-5 times higher than in normal winters. It seems that about 12% of wave energy is causing 30% of changes on gravel beaches and 95% of changes on sandy scarps. But the rate of changes is also dependent on sea-level and wind direction during a storm event.

CONCLUSIONS

All the extreme storms occurred in late autumn or early winter. When a series of successive storms struck the area (as in 1999 and 2001), the sea-level gradually increased due to inflow of water through the Danish Straits, allowing the highest localized storm surges to occur during the last storm events. Therefore, these storm events should be considered stormy periods. Storms in 2005 and 2007 were deemed separate events.

The storms with very high sea-levels and conductive wind direction caused the greatest changes on gravel-pebble shores, which might remain evident for many years. The biggest changes in area on gravel-shores appear after long lasting storms with high sea-level. Gravel and pebble are transported only in a narrow swash zone near the shoreline. Therefore, in extremely high sea level conditions (as those during Gudrun) the wave energy relocates sediments further inland across the beach and has much less influence on shoreline changes. A few extremely strong storms with accompanying high sea-level has resulted in recent turnaround in terms of prevailing processes (from accumulation to erosion) on sandy shores exposed to the storm winds.

ACKNOWLEDGEMENT

This work was supported by ESF Grants No. 7609, 7564, 6998 and target financed theme No SF0280009s07. The authors express their gratitude to Dr. Robert Szava-Kovats for some valuable suggestions in preparing the manuscript.

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