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Changes in coastal processes in relation to changes in large-scale atmospheric circulation, wave parameters and sea levels in Estonia

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ABSTRACT

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Estonia is sensitive to climate change manifestations such as an increase in cyclonic activity, westerly circulation and a northward shift of the Atlantic storm track over the last decades. Changes in meteorological conditions have changed wave climate and sea-level conditions as well the rate at which shore processes occur. The current study analyzed how the consequences of changes in large-scale atmospheric circulation have influenced the coastal sea and shore processes in various locations having varying exposure to the sea. Sea ice conditions, wind speed, and wind direction were taken from observational data from meteorological stations. Data from tide gauge stations were used to ascertain sea level changes. Hydrodynamic conditions were taken from field studies using RDCP. To study long-term changes in wave conditions a simple fetch-based SMB wave model was used. We used topographic maps, aerial photographs, orthophotos and GPS to analyze shoreline changes. The relationships between meteorological and hydrodynamic parameters and the speed of shoreline changes were analyzed. The decreasing rate at which shore processes are occurring on the northern coast of Estonia and the increasing rate at which such processes are occurring in western Estonia were documented. Such changes are probably caused by a northward shift of the cyclone trajectories in recent decades resulting in a reduction of northerlies and an increase in westerlies. Thus, we can conclude that a shift in the path of passing cyclones, as well as an overall increase in cyclonic activity, will impact shore processes differently depending on their exposure to the prevailing winds.

ADITIONAL INDEX WORDS: *Erosion, Accumulation, Storminess, Hindcast, Storm surge, RDCP.*

INTRODUCTION

Large-scale atmospheric circulation is one of the main factors influencing climate in every region. During the second half of the 20th century, significant changes have occurred in circulation. An increase in mean sea-level pressure gradient in the Northern Hemisphere mid-latitudes and associated intensification of westerly circulation in winter has been the most important change (IPCC, 2007). Such change has shifted the North Atlantic storm track about 180 km northward (Wang *et al*., 2006).

Stronger westerlies and cyclones moving along the northern tracks have brought more maritime air into northern and central Europe causing higher winter temperature. Close relationships between the increasing trends in westerly circulation and air temperature (Jaagus, 2006a), and decreasing of sea-ice (Jaagus, 2006b) have been detected in Estonia

Estonia is a small country (45,227 km^2) on the eastern coast of the Baltic Sea with a wide variety of different coast and shore types. This is due to a relatively long coastline (3,800 km) and its location in a transitional area between major geological structures. In addition, Estonia lies in a transitional zone between regions with a maritime climate (in the west) and a continental climate (in the east). Accordingly, Estonia is sensitive to such climate change manifestations. Climatic changes affect wave climate and sea-level conditions as well the rate at which shore processes occur, which have accelerated over the last 50 years at many locations in Estonia (Orviku *et al*., 2003).

The current study analyzed how the consequences of changes in large-scale atmospheric circulation have influenced the coastal sea and the shore processes in various locations in Estonia with different exposure to the sea. The main objectives of this paper were: (1) To analyse sea level changes and changes in wave parameters in the sea near the coastal study sites; (2) To measure changes in the rate of shore processes in the study sites on the southern coast of the Gulf of Finland and on the eastern coast of the Baltic Sea Proper; (3) To discuss the relationships between climatic changes, exposure of the shores, sea level changes, changes in wave parameters, and the rate of coastal changes.

Study area

Four sites with different exposure to the open sea were studied. Two of them - Küdema and Kelba – are located in the western part of Saaremaa Island, western Estonia. The other two - Kunda and Sillamäe – are located in northern Estonia.

The Küdema study site is situated on the eastern coast of Küdema Bay (Figure 1). A complex accumulative coastal formation with a spit nearly 3 km long, 0.5 km wide and up to 3.5 meters high is the principal evolving relief structure of this study site. The formation and development of the spit depends on the erosion of Panga cliff that lies to the north of it. Deeper waters occur north-west of the study site, reaching 22 m in depth about 1 km form the shoreline. About 100 m from the shoreline of the study site, the basin becomes abruptly shallower forming a 2–3 m

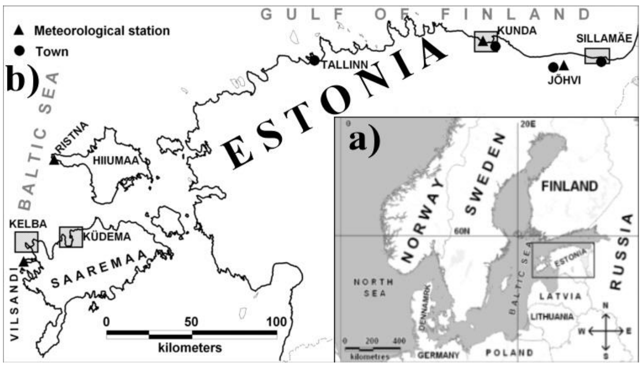

Figure 1. a) Location of Estonia; b) the study sites and meteorological stations.

deep erosion surface in the Silurian limestone. The study site is exposed to the Baltic Sea Proper to the NW and N. The general trend of development of Küdema Spit has been a continuous accumulation of gravel-pebble on the distal part thereby elongating the spit to the southern direction.

The Kelba study site is situated in the southern part of Harilaid Peninsula (Figure 1). It consists of a series of beach ridges forming an approximately 1-km long spit. The spit is mainly made up of well-rounded crystalline 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 are 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 Proper to the SW, W and NW. The general trend of development of the Kelba Spit over about the last century has been a continuous accumulation of new beach ridges thereby elongating the spit.

The Kunda study site is situated on the north-eastern coast of Estonia in the head of Kunda Bay (Figure 1). Kunda Bay is bordered by Cape Toolse in the west and Cape Letipea in the east. The coastal sea is relatively shallow and the coastal slope is very gentle. The 2 m isobath is located over 200 meters from the shoreline. The sediments are eroded from the sides of the peninsulas bordering the bay, transported towards the head of the bay and accumulated there. Therefore, the shoreline is moving slowly towards the sea at the head of the bay. Due to the land uplift the erosion is dominating only in a few locations along the sides of the bordering peninsulas. However, one of the few erosion areas was chosen to estimate the rate at which the shore is retreating. Both the shores at the head of the bay and in the studied section contain fine grained sediments (sand and silt).

The Sillamäe study site is situated on the north-eastern coast of Estonia in the south-eastern part of the Gulf of Finland. It is located between Cape Päite and Cape Kannuka (Figure 1) in a narrow ancient river valley which has eroded into the Baltic Klint. The ancient valley is filled with loose Pleistocene sediments and Holocene marine deposits which is easily eroded and transported by waves. Most of the shores are made up of gravel and pebble, but sand and silt occur along the whole coastal slope of the study site. Sandy shores prevail in the middle part of the study site covering approximately 1 km of the shoreline. The coastal slope is quite gentle. The 2 m isobath is located between 50 and 100 meters from the shoreline. The main direction of sediment transport is from west to east.

DATA AND METHODS

Meteorological data and wave parameters. Sea ice conditions, wind speed, and wind direction were taken from the observation data of Vilsandi, Ristna, Kunda and Narva-Jõesuu stations operated by the Estonian Meteorological and Hydrological Institute. The data from tide gauge stations located near the western (Ristna) and northern (Narva-Jõesuu) coasts of Estonia were used to ascertain sea level changes. The sea level heights are based on the Baltic System 1977 with its reference zero-benchmark at Kronstadt, near St. Petersburg. To study changes in wind climate and to force the wave model, we used the data from Kunda. This study is limited to the digitized data of 10 minutes mean wind speed and direction since 1966. The number of storm days – i.e., days when 10-minute mean wind speed was measured at 15 m/s or higher – was used as a measure of storminess.

The hydrodynamic conditions were taken from the field studies carried out near Letipea Peninsula and Harilaid Peninsula using an oceanographic measuring complex RDCP-600 by AADI Aanderaa. The instrument was used to measure hourly data on currents, wave parameters, sea level variations and water column properties, such as water temperature, salinity and turbidity. The wave data included significant wave height (Hs) as the most commonly used wave parameter as well as maximum wave heights and different versions of wave periods. Four moorings in 2006-2009 with total duration of 293 days were performed at the Letipea site (59º34’N 26º 40’E). 154 days of measurements were carried out at the Harilaid-Vilsandi mooring site (58º28’N 21º49’E) in 20 December 2006–23 May 2007. Both sites were 1.5 km off the shore and 11–12 m deep.

In order to assess long-term variations in forcing conditions for the coasts a wave hindcast was performed using a semi-empirical SMB-type wave model. The SMB-model, also called the significant wave method, is based on the fetch-dependent shallow-water equations of Sverdrup, Munk, and Bretschneider (Seymour, 1977). Based on wind data, it calculates the significant wave height (Hs), wave period and wavelength for a chosen location. As remotely generated waves (swell) play a small role in the Baltic Sea, this relatively simple method can deliver quick and reasonably reliable results about the selected study areas. The study near Saaremaa Island was based on Vilsandi wind data in 1966–2006 and RDCP calibration data of waves near Harilaid Peninsula in winter 2006–2007 (Suursaar and Kullas, 2009). The wind data from Kunda was used to run the wave model for the North Estonian coastal section of the Gulf of Finland. The data obtained between 16 October and 24 November 2008 were used for calibration (Suursaar, 2010).

The model parameters were calibrated to achieve the best possible fit between the data collected and the hindcast for each applicable area. The calibration was done mainly by prescribing fetch distances for different wind directions. For the hourly-based 39 day calibration period, we obtained nearly the same wave heights for the Kunda - Letipea calibration] with a correlation coefficient of 0.92. A roughly similar value (r=0.88) was also obtained for the Vilsandi - Harilaid calibration. The site-dependent calibrated model was then used in multi-year (1966–2009) wave hindcast at a 3h interval. Both the Harilaid-Vilsandi and Kunda-Letipea hindcasts cover the 1966–2009 period.

Coastal studies. The dynamics of the seashores was assessed by comparison of areal changes of the shore formations and changes in shoreline positions in space and time. A comparison of topographic maps in 1:25,000 scale from 1948, 1961 and 1981, as well as orthophotos from 1996, 1998, 2005, 2008 and 2009, were conducted to analyze the geomorphology, changes in shoreline

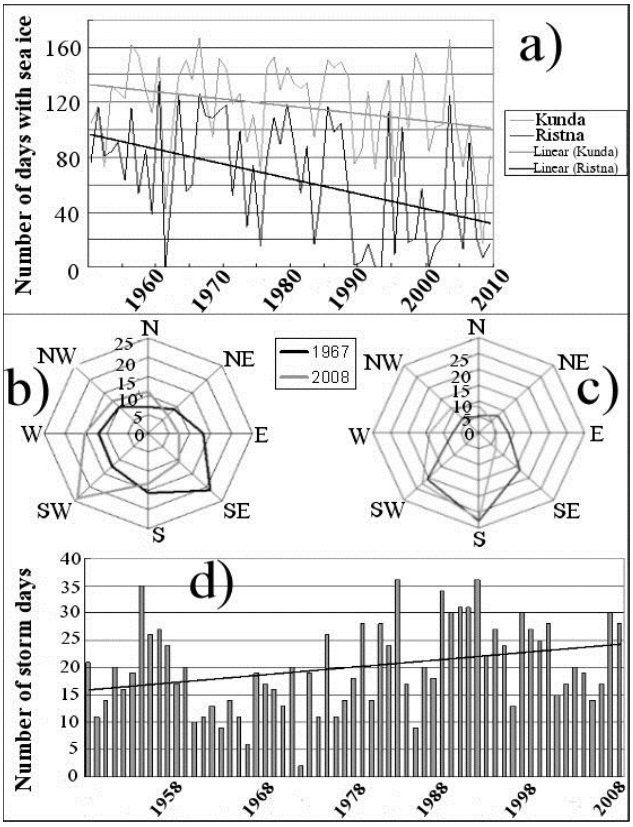

Figure 2. Number of ice days in Kunda and Ristna during the period 1949/50–2008/09 and their linear trend (a); changes in winter (DJF) wind directions in Jõhvi (b) and Vilsandi (c); number of storm days in Vilsandi (d).

position and character of shore processes in the study sites. Old topographic maps from 1900 (1:42,000), 1935 and 1939 (1:50, 000) were used to analyze the general tendencies in the shore developments.

In 2000–2009, we annually took GPS-measurements to ascertain short-term changes in shoreline positions and contours of beach ridges. Garmin 12 and Garmin 60CS GPS devices were used for GPS-measurements, both of which are accurate to within a 3 m diameter circle. By connecting the GPS-marked points in mapping the shoreline or contour line of the scarp we reduced the margin of error to 1 m. The collected data were processed using MapInfo software, which was also used for calculating reductions in the erosion areas and increments in accumulative areas. The mean changes were calculated over sub-periods each of which was slightly different according to the available datasets.

We conducted a topographic survey to assess beach profiles at the study sites. The survey was taken on the profiles in the Küdema, Kelba and Sillamäe study sites. The profiles enabled us to estimate short- and long-term elevation changes in the study sites. To eliminate sea level differences, all the profiles were related to the Kronstadt benchmark.

RESULTS AND DISCUSSION

Climate warming during the second half of the 20th century has been significant in Estonia. The temperature increase has taken place during winter and spring seasons. Milder winters are caused by intense westerly airflow from the Atlantic and by high cyclonic activity (Jaagus, 2006a). The mean storm track has shifted northwards, which enables warm maritime air to move into the Baltic Sea region. The intense cyclonic activity has induced greater storminess in winter. Higher temperatures and greater storminess have reduced the formation of sea ice along the Estonian coast (Figure 2a), and less sea ice and higher storminess has in turn led to an intensification of coastal processes. The decrease in sea ice has been lesser in the Gulf of Finland and significantly greater on the open coast of the West Estonian Archipelago.

Variations in mean and extreme sea level. Owing to rapid land uplift, 2.8 mm/yr (Vallner *et al*., 1988), the local mean sea level at Ristna has decreased over the measurement period (since the 1950s). As the uplift rate is only about 0.5 mm/yr at Narva-Jõesuu, the mean sea level has actually slightly risen. The mean sea level rise rates for Narva-Jõesuu and Ristna, adjusted for local land uplift rates, are roughly equal to the global estimates for the 20th century, which are about 1.5–2 mm/yr (IPCC, 2007). However, there are large change rates in maximum sea levels, ranging between 3.7 and 13 mm/year in the Estonian coastal waters (Suursaar and Sooäär, 2007), including Ristna (Figure 3). The main reasons for that could be statistically significant changes in wind climate, particularly an increase in storminess and in the westerly wind component (Figure 2b,c,d).

The rise in sea levels with quasi-periodic cycles has not been constant over time. A high phase both in average and maximum sea level occurred in the 1910–1920 s, and again in the 1980–1990s. A less variable period occurred in the 1930–1950s and may possibly be occurring now. The high sea level events in the Estonian coastal waters are mainly associated with north European cyclonic storms, which coincide also with high Baltic background sea level. The centre of a powerful and fast moving cyclone should bypass Estonia to the north over the Scandinavian Peninsula and Bothnian Sea and make the local wind direction turn from SW to W and NW. Eastern winds lower the sea level, and western winds raise it.

The significantly higher mean sea level rise in winter correlates with increased local storminess during the same months and with the positive phases of the NAO-index (Suursaar and Sooäär, 2007). Thus, in the windward Estonian coastal waters the rise in winter sea level and particularly in maxima (3.5–11.2 mm year^{-1}) could likely be explained by the local sea level response to the changing regional wind climate (Figure 2c,d; 4d).

Variations in wave climate. Wave action is the main hydrodynamic agent for Estonian coastal geomorphic changes. According to the wave hindcasts in the two areas of the Estonian coastal sea, the mean properties of wave heights showed roughly similar quasi-periodic cycles with the last high stage in 1980–1995 (Suursaar, 2010). However, while at Harilaid the trend in mean wave heights was slightly decreasing, the trend was steeply decreasing near Letipea (-0.005 m/year in 1966–2008). On the

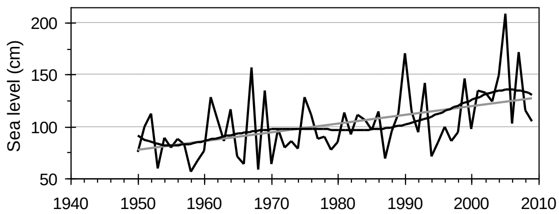

Figure 3. Decadal variations in annual maximum sea levels at Ristna.

basis of annual maxima, the trends were clearly increasing near Harilaid, but still decreasing near Letipea (Figure 4a,b).

At Kunda, we also took into account the influence of seasonal sea ice conditions on annual wave statistics. The mean duration of fast ice at Narva-Jõesuu was about 70 days, but it varies, depending on winter, between about 0 and 150 days. As a result, the trend adjusted for seasonal ice conditions was not as steep as that calculated in the original series. But it is still decreasing by 40 cm over the 43-year period. In addition to a general decreasing trend, there were periods with relatively higher wave activity in the 1960s and the 1990s. Particularly high wave events took place in 1975, 1983, 1989 and 2001. Relatively calm conditions prevailed in late 1970s and also in recent years.

Over the last decades, although the average wind speed has probably decreased at the Vilsandi (Figure 4c) meteorological station, the frequency and strength of storm events have increased at Vilsandi (Figure 2d), but decreased at Kunda. Although slightly increasing (Figure 4d), the westerly winds have relatively small fetches for the Letipea area, and this impedes wave height, while the northerly wind component has been decreasing. The increasing storminess at Vilsandi and decreasing strong winds at Kunda are probably connected to the changes in atmospheric pressure patterns above North Europe and the northward shift of cyclonic trajectories over the last decades (Jaagus *et al*., 2008). Essentially, there are more cyclones bypassing Estonia from the north, and those are the kind that produce strong westerly winds. And, there are fewer cyclones crossing over Estonia itself, and those are the kind that produce strong northerly winds in the course. Thus, probably as a result of the northward shift in cyclone trajectories, high waves have increased along the western coast (W Estonia) and decreased on the northern coast (N Estonia).

Coastal changes. In general, the results of the current research confirm the conclusions of many earlier studies (Orviku *et al*., 2009; Tõnisson *et al*., 2007 etc.) showing the increasing trend of storminess and vitalization of shore processes, particularly on accumulative shores at western Estonian study sites. Although the time intervals for the study sites analyzed in this paper do not coincide precisely with each other, a clear increasing trend over the last half-century is evident in Kelba and Küdema study sites

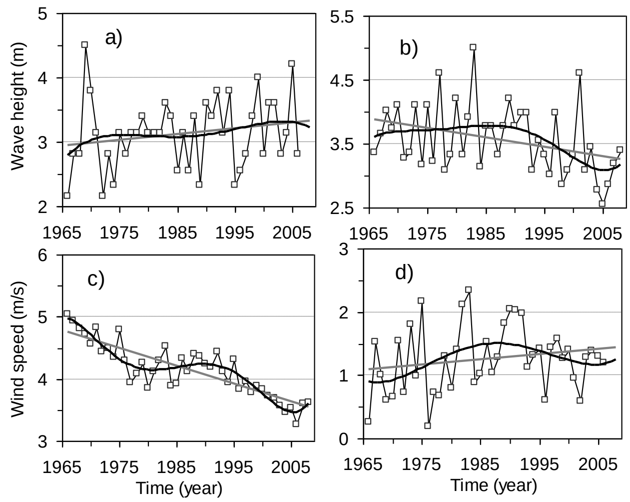

Figure 4. Variations in hindcast annual average maximum wave heights (a,b) at Vilsandi-Harilaid (a) and Kunda-Letipea (b, adjusted for seasonal ice conditions); measured average wind speed at Vilsandi (c), and corresponding u-component wind velocity (d).

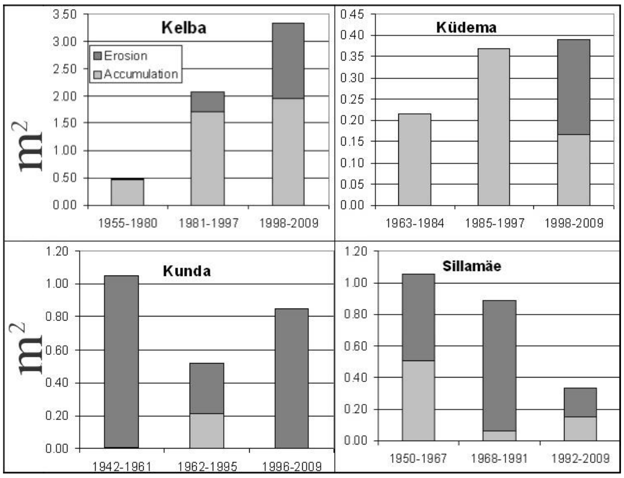

Figure 5. Area changes in m^2 per one meter of shoreline in different sub-periods in different study sites.

(Figure 5). The Kelba study site has seen the largest changes in area. There, the mean speed of annual changes of its gravel-pebble beach ridges has increased from $0.5m^2$/yr per 1 m of shoreline to nearly 3.5 m^2/yr. As a result of such change the spit has become elongated by nearly 1050 m in 55 years (19 m per year on average). The erosion at the proximal portion of the spit over the same time period has shifted the shoreline of the southwestern portion of the spit by 100 m to the north-east (Figure 6), and caused the sediments to roll over the spit into the lagoons situated behind it as far back as 50 m.

Much slower changes, but still with increasing velocity can be observed in the second west Estonian study site, Küdema. Here the rate of change has increased from 0.2 m^2/yr per 1 m of shoreline to 0.4 m^2/yr. Similarly to the Kelba study site, accumulation in the distal part of the spit and erosion in the proximal part (during the last period) can be observed here (Tõnisson *et al*., 2007).

Those changes correlate well with the rapidly increasing annual maximum sea levels at Ristna (Figure 3), the increasing annual average maximum wave heights (Figure 4a) and with the increasing linear trend of increasing number of storm days in the same location (Figure 2d). The increasingly frequent absence of sea-ice in winter and shift of the prevailing winds to the direction with the longest possible fetch are also speeding up the pace of coastal processes.

However, we do not find the same clear trend in the northern Estonian study sites (Kunda and Sillamäe). The coastal sea in Kunda Bay is very shallow and estimating shoreline changes using maps is very difficult. Therefore, we chose an erosion dominated section in the western part of the bay. There we found that erosion processes were the most intensive during the first period from 1942–1961 reaching to 1.1 m^2/yr per 1 m of shoreline. From 1962–1996 the rate of erosion decreased by nearly half The next increase (up to 0.8 m^2/yr) is characteristic of the last period. The tendencies in Sillamäe are more straightforward. There, we observed the greatest decrease in erosion, from 1.1 m^2/yr per 1 m of shoreline to 0.3 m^2/yr.

There is a strong correlation between the decreasing pace of shore processes and the decreasing annual average maximum wave heights in Sillamäe (Figure 4b). The shift of prevailing wind direction (away from the direction with the longest fetch for northern Estonian study sites) and, to a lesser degree, the decrease

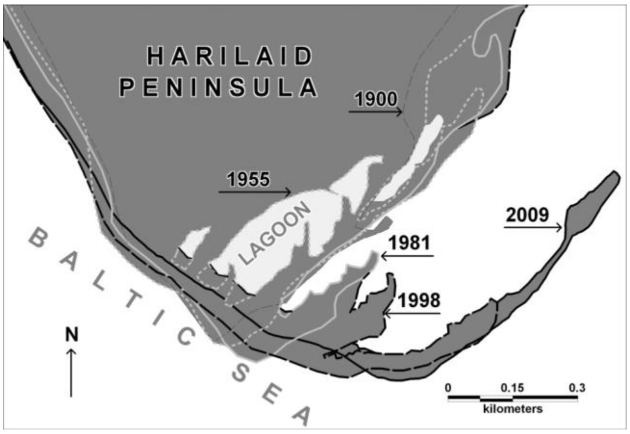

Figure 6. Shoreline changes at Kelba study site on Harilaid Peninsula.

in the number of days with sea ice are also favorable for natural stabilization of the seashores. During the second sub-period of the investigation, the accumulation rate in the study site had decreased nearly ten times compared to the first sub-period. This could be caused by a new mole constructed at Päite which may be inhibiting alongshore sediment movement in the eastern direction. The increasing activity of shore processes in Kunda during the last sub-period can be explained by two reasons: first, an increase in annual maximum sea levels (Figure 3); and, second, prevailing finer-grained shore sediments (sand and silt), which are more vulnerable and easily erodible in high sea level conditions and less sensitive to waves.

CONCLUSIONS

The annual maximum sea-level on the west coast of Estonia has increased during the last decade. All in all, fewer storms are hitting the Estonian coast but in western Estonia they are significantly more intense. As such, we are seeing an intensification of shore processes. The measurements in the study sites of western Estonia show that the current rate of coastal change is up to 10 times higher than in the 1950s. We conclude that a possible reason for the acceleration in the rate by which such coastal processes are occurring is because the increased number of strong storms, coupled with higher sea levels, does not leave enough time during the calm periods for the restoration of the shores. Therefore, each subsequent storm reaches an already vulnerable beach profile. In addition, higher sea levels during the storms have also caused the erosion area to move further inland with each subsequent storm.

Unlike in western Estonia, due to a decrease in storm days and lower wave parameters, the intensity of shore processes in northern Estonia has significantly decreased, and the shores there have stabilized during the last decade. The longest fetch for the northern coast of Estonia is for the waves coming from the north and north-east. As a result of changes in wind climate, such as an increase in westerly winds and slight decrease in northerly winds, the wave activity has decreased over the last decade.

Slower changes in the shores at the study sites on the northern coast of Estonia and increasing velocity of shore processes at the study sites of western Estonia are probably caused by the northward shift of the cyclone trajectories in recent decades resulting in a reduction of northerlies and an increase in westerlies. Thus, we can conclude that a shift in the path of passing cyclones, as well as an overall increase in cyclonic activity, can have a completely different impact on the seashores that are separated by only a few hundred kilometers but are exposed to different directions.

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