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Impact of climate change on Estonian coastal and inland wetlands — a summary with new results

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The natural environment of Estonia is sensitive to climate change due to its location in a transitional zone between areas with different bioclimatic conditions. We studied the NAO index and data on temperature, moisture, wind, and sea level regimes in Estonia and the Baltic Sea region. We also looked at the relationships between meteorological forcing time series and changes in wetlands. The effects of changing climatic conditions are clearly reflected in the data from the station at Tooma mire, where we identified shorter snow-cover duration, decreased soil-frost depth and changed groundwater levels in the bog. In comparing various types of Estonian wetlands under such changing climatic conditions, we also identified greater instability in the character of coastal wetlands compared to that of the inland bogs. We found that the most marked coastal changes in Estonia result from a combination of strong storms, high sea levels induced by storm surge, ice free seas and unfrozen sediments. Finally, we also found that a significant trend in the development of seashore grasslands is the replacement of former meadows by reed beds, shrubberies or woodland.

Introduction

Although Estonia is a relatively small country (45 227 km^2, Fig. 1), it is rich in different types of landscapes and ecosystems. This is due to its geographical location in moderate latitudes in a transitional area between major geological structures (Fennoscandian Shield and East European Platform) and climatic (maritime and continental) and biogeographical regions (Atlantic and Boreal) of northern Europe. Estonia has a comparatively long coastline (nearly 3800 km) due to numerous peninsulas, bays and islands. Flat and low-lying topography combined with positive water balance has resulted in a considerable amount and extent (about 25% of the territory)

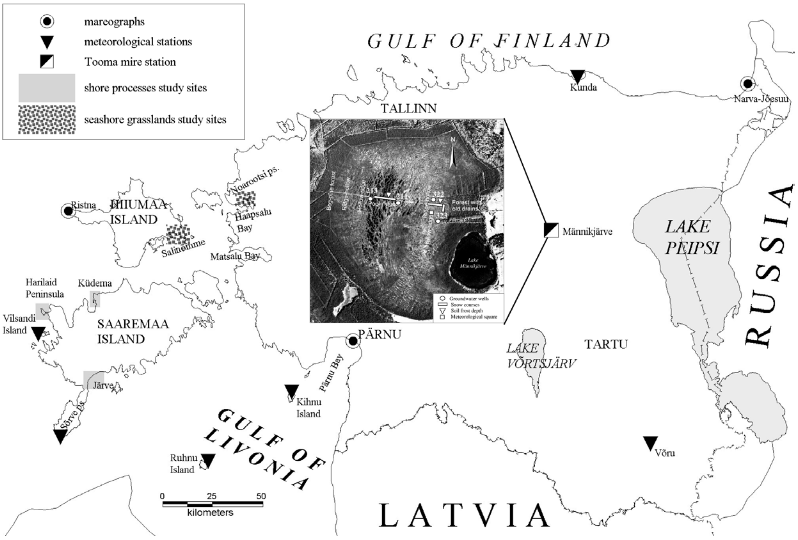

Fig. 1. Location of coastal and inland wetland study sites and EMHI monitoring sites.

of both coastal and inland (terrestrial) wetlands.

Coastal areas, mires and floodplains are valuable ecosystems and important resources for socio-economic development. The Estonian coast is geologically rather diverse and used by its population in a variety of different ways. Most depositional shores are very dynamic and quickly changing under the impact of changing climatic conditions. About 70% of the Estonian mires have been drained for different purposes during the last 100 years (Paal *et al.* 1998), making them more sensitive to changes in climatic conditions today (Vasander *et al.* 2003). There is a widespread understanding of the dominant role of hydrological changes in wetlands due to the increased intensity of snow melt, evaporation rates, droughts, storms and floods (Poff *et al.* 2002). Because of extremely high dependency on climate and changes in the atmosphere, both the inland and coastal wetlands are very vulnerable ecosystems.

Global temperatures increased an average of 0.6 ± 0.2 °C since the beginning of the 20th century (Folland *et al.* 2001). Over the past century, the Baltic Sea region saw a statistically significant increase in mean air temperature from 0.5 to 0.9 °C (Heino 1994, Moberg and Alexandersson 1997, Balling *et al.* 1998, Jaagus 1998). The decrease in the duration of snow cover in Estonia and ice cover in the Baltic Sea (Haapala and Leppäranta 1997, Jaagus 2006b) is also a clear consequence of the higher mean air temperature.

In the regions of central and eastern Europe where snow traditionally contributes significantly to the annual precipitation amount the share of rainfall has steadily increased due to warmer winters in recent decades and has resulted in increased runoff and more frequent inundations.

Seasonal changes — i.e. the formation, duration and disappearance of snow and ice cover — have a strong influence on nutrient supply and fluxes and associated biological processes (including peat production) in wetlands (Wider and Vitt 2006). Recent studies suggest that nutrient-poor peatlands may be able to accumulate more carbon in warmer climatic conditions, and nutrient-rich peatlands may become potential additional sources of atmospheric carbon. We might also see boreal peatlands expand northwards but degrade at their southern limits even faster.

An increase in storminess in the NE Atlantic in the last few decades and a recent trend towards higher storm surge levels on the German and Danish coasts (Langenberg *et al.* 1999) is consistent with natural variability evident over the last 150 years. Many papers have identified an increase in storminess in the NE and NW Atlantic during the last 10–20 years (Carter and Draper 1988, Van Hooff 1994, Schmith *et al.* 1998, Alexandersson *et al.* 2000). Other papers indicated important changes in wind regime in the Baltic Sea area (Ekman 1999, Pryor and Barthelmie 2003, Orviku *et al.* 2003). Warmer winters, increased cyclonic activity and frequent

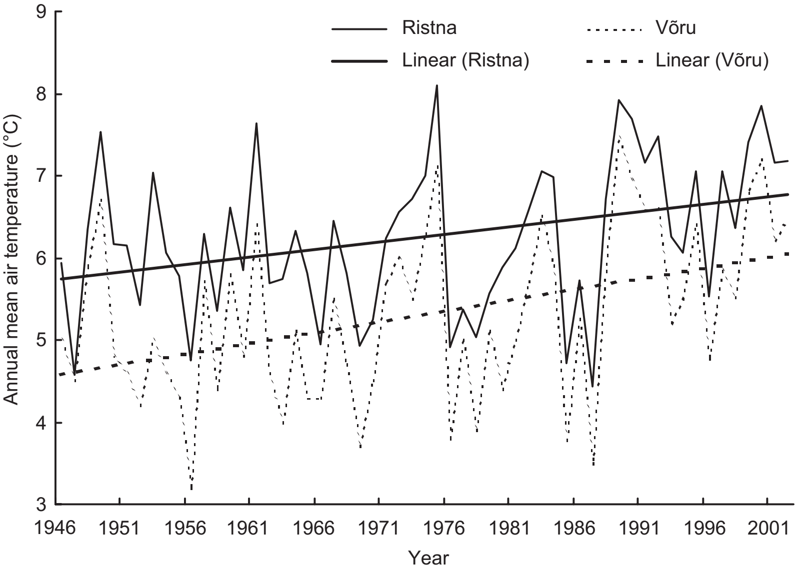

Fig. 2. Time series of annual mean air temperature in Võru and Ristna, and their linear trends during 1946–2002.

occurrence of extremely strong storms in northern Europe seem to be closely related phenomena caused by climate change.

The current paper focuses on the observed changes in the structure and development of coastal and inland wetlands as a result of changed climatic conditions over the last half-century in Estonia. The main objectives of this paper are:

- To present evidence of observed climatic changes in Estonia and to analyze their specific impacts both on terrestrial and coastal wetlands in Estonia.
- To characterize the long-term (i.e. averaged over 50 years) hydro-meteorological seasons in an inland raised bog and to analyze the impact of climate changes on bog hydrology over the last fifty years.
- To describe the relationships between changed meteorological and hydrological parameters and the principal geomorphic processes on Estonian coasts.

Background for the current study

Observed climate changes in Estonia.

The territory of Estonia lies within the region where the most significant increase in air temperature has been observed over the last decades (IPCC 2001). The annual mean air temperature in Estonia increased by 1.0–1.7 °C during the second half of the 20th century (Jaagus 2006a, Fig. 2). That said, seasonality plays an important part in climate warming in Estonia. A statistically significant increase in monthly mean temperature is present only during the period from January to May, with the greatest increase in March. During the rest of the year, practically no change in annual mean air temperature has been identified (Jaagus 2006a).

The duration of snow cover (Jaagus 1997, Tooming and Kadaja 1999) and sea ice (Jaagus 2006b) decreased significantly during the second half of the 20th century. Over this period, the date by which sea ice appears has been very consistent, but the date by which it disappears at the end of each winter has gotten earlier (Fig. 3). The maximum extent of sea ice in the Baltic Sea has decreased approximately by 50 000 km^2 according to linear trend during the second half of the 20th century. In general, the end of winter and start of spring occurs much earlier than before.

Earlier melting of snow cover causes changes in the hydrological regime. For instance, modeling results demonstrate the rivers reach their point of maximum runoff earlier and that the magnitude of such runoff is generally smaller (Jaagus *et al*. 1998). The water content of the soil is comparatively smaller and drought conditions appear earlier. Drier climatic conditions in spring

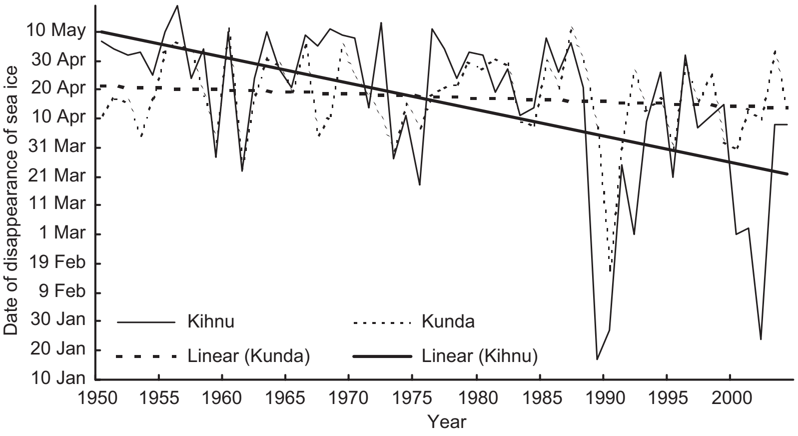

Fig. 3. Time series of the date of the final disappearance of sea ice in Kihnu and Kunda, and their linear trends during 1949/1950–2003/2004.

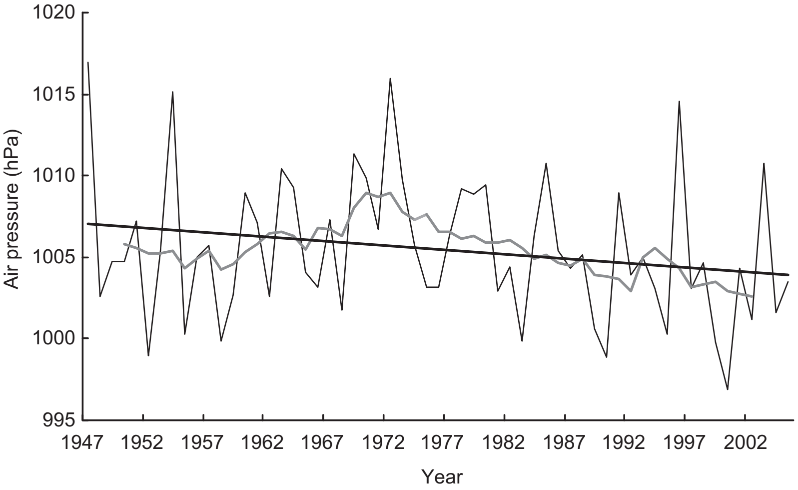

Fig. 4. Time series on winter mean (DJF — December, January, February) station level air pressure in Tartu during 1946/1947–2004/2005, its 7-year moving mean values and linear trend.

and in the first half of summer are projected for Estonia in the future (Kont *et al*. 2002, 2003). It is very likely that precipitation in Estonia has increased, especially in winter. Since 1966 precipitation series are homogeneous. They indicate an increase during the cold half-year and also in June (Jaagus 2006a).

Changes in atmospheric circulation over Estonia have taken place during the last decades (Rajasalu and Keevallik 2001, Tomingas 2002, Jaagus 2006a). The most important trend detected is a significant increase in the intensity of zonal circulation, i.e. westerlies in winter, especially in February and March. Parameters of meridional circulation show an increase in southerly airflow and decrease in northerly airflow in March and in October.

Climatic changes in Estonia can be also explained by increased frequency of cyclonic weather conditions. This is illustrated by the decreasing trend in winter mean air pressure (Fig. 4). The number of storm days in Vilsandi, the westernmost station in Estonia located on the coast of the Baltic Sea proper, has increased dramatically in winter (Orviku *et al*. 2003) (Fig. 5).

Climate changes in mires

Earlier studies of climate impact on Männikjärve bog, a bog located in central Estonia, showed an increase in the perimeter of the bog's pools and a decrease in the shorelines of islets within the bog (Mets 1982). One study assumed that an increased growth of bog pines on the ridges between the pools was the result of climate change rather than a change in the groundwater regime (Läänelaid 1982).

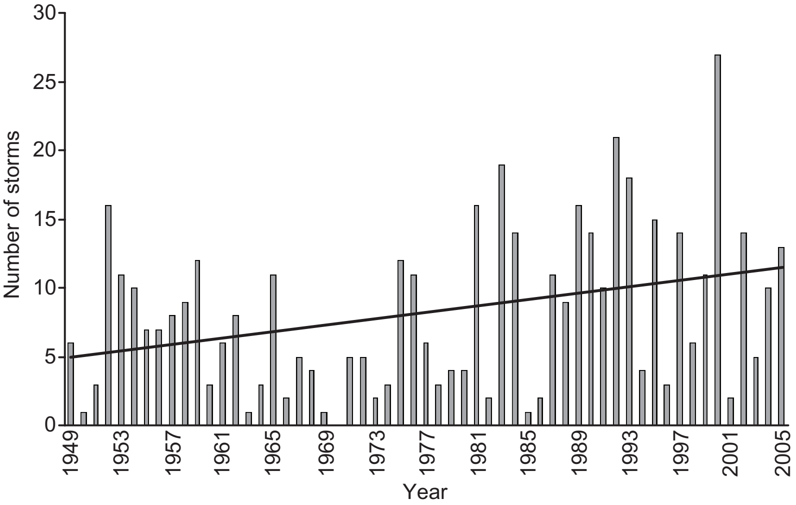

Fig. 5. Time series of number of storm days in winter (DJF) at Vilsandi during 1948/1949–2004/2005.

Although the systematic mire studies in Estonia started just after establishment of the Tooma Experimental Moor Station in 1910 and were intensified after the Tooma Hydrometeorological Mire Station was founded on Männikjärve and Linnusaare bogs in 1950 (Kimmel 1998, Soovik and Tomson 2001, Lode *et al*. 2003b), the analysis of the contemporary climate change impact on bog eco-hydrology is still insufficient. The most comprehensive analysis of hydrological variables monitored at the Männikjärve bog cover the period between 1951–1969, for which the averages and extremes, together with probability and variability curves of different variables, were calculated (Anon. 1972). Studies that were intended to reflect the effects of climate change on the bog landscape were either fragmented or not fully completed due to limited access to the monitoring data sets (Valgma 1998, Lode 2001, Lode *et al*. 2003a).

However, a detailed microclimatic study by Viigimäe (1957) on the Männikjärve bog showed that the air temperature at five cm above the bog surface (i.e. 22.5 °C) was 5.5 °C higher than the temperature at 1.5 m height on a summer day. There was a shift towards cooler weather at the beginning of the vegetation period in the bogs than on mineral soils. As a rule, the air temperature in pine-forest microtope was 0.2–2.5 °C lower than in the ridge-hollow microtope. The relatively high surface water temperature during summer months contributes to a faster drainage flow in surface layer (Franzén 1987). Analysis of the bog catchment seasonal behavior in different water year conditions (i.e. wet, normal, dry year) indicates a more fluctuating groundwater levels for the 'warm' periods, i.e. higher standard deviations, compared with the 'cold' periods. The average groundwater levels in the bog microtopes differed more in normal than in wet and dry water years (Lode 2001).

Climate change impact on coastal sea and seashores

The effects of climate change on seacoasts can be seen in the changes in sea level (both mean sea level changes and sea level changes during aperiodic events, such as storm surges), in changes in coastal hydrodynamics (both in wave climate and current regime), and in ice conditions.

The changes in sea level regime include global, regional and local mechanisms. Firstly, the induced global sea level rise rate is estimated to be 1.5 ± 0.5 mm yr^{-1} (e.g. Church *et al*. 2001, IPCC 2001). The latest studies suggest a sea level rise of about 10–50 cm during the next century (e.g. Church *et al*. 2001, Dawson 2004).

Regional sea level trends usually deviate from the global mean sea level tendencies, primarily due to isostatic vertical movements of the earth's crust. The postglacial land uplift rate varies in the coastal areas of Estonia between

0.5 and 3.5 mm yr^{-1} (Vallner *et al.* 1988). Thus, while in Finland clear decreasing sea level trends are still evident (Johansson *et al.* 2004), the present-day global sea level rise is roughly compensated by uplift in Estonia.

There is, however, an additional local sea level change component, i.e. variations in the water balance of semi-enclosed marine areas as a result of regional changes in wind climate, that should be consider (Suursaar *et al.* 2006a). Our previous studies analyzed this local hydrodynamically-driven sea level change component using sensitivity and scenario runs from a two dimensional hydrodynamic model (Suursaar *et al.* 2003a, 2006a). Consistent with the observed tendencies for an increase in atmospheric westerlies, the hydrodynamic model simulations identified a mean sea level rise in some windward bays of the Gulf of Riga of between 5–6 cm under a simulated mean wind speed increase of just 1–2 m s^{-1}. The rise could be as high as between 9–11 cm under conditions of greater variability.

Increased storminess together with increased frequency of mild winters and higher sea level has an indisputable impact on the intensification of shore processes and the dynamics of coastal geomorphology. The presence of sea ice tends to retard the surface movement of water and also to protect the shoreline from the water's erosive effects. Conversely, the decrease in sea ice duration (Figs. 3 and 4) or the absence of ice cover altogether enables water essentially to "pile up" as a result of storm wind stress and, exposes the shores to wave action.

It has been shown that in any given year the greatest amount of erosive damage to Estonia's coasts usually occurs during just a couple of stormy days. In case of the Pärnu Bay, large hydrodynamic stresses operate one to three meters above the mean waterline height, while the geomorphically insignificant small stresses operate around the mean shoreline (Suursaar *et al.* 2003b).

One example of this dynamic is Gudrun, a powerful storm that moved through the Baltic Sea on 9 January 2005. That storm was of short duration, but, due to the way in which large storms can operate above the shoreline, the storm's wave energy was released much further inland than usual and, in some places, even outside the landward boundary of the coastal zone.

According to preliminary simulation results, the erosive effects associated with currents and wave induced bottom stresses caused by Grudrun exceeded the combined erosive effects of all of the storms over the prior few years. An increase in mean wind speed by only 2 m s^{-1} above the present day mean (6.5 m s^{-1}) roughly doubles the annual amount of hydrodynamically induced bottom stresses in Estonia's coastal zone (Suursaar *et al.* 2006b).

Extensive erosion and alteration of depositional coasts, such as sandy beaches, was observed during the last decades. The lack of evidence for a substantial mean sea level rise during this period suggests that beach erosion is largely due to recent increased storminess in the eastern Baltic Sea (Orviku 1992, Orviku *et al.* 2003). The greatest alteration potential in the coastal zone in Estonia occurs on depositional coasts that are well exposed to waves and is probably associated with stormy periods when storm surges elevate sea level. Increasing growth rates of accumulative gravel spits in Saaremaa and many other places were observed during the last decades (Orviku 1974, 1992, Rivis 2004).

Seashore grasslands

Coasts that develop as a result of geological activity usually lack well-defined shore vegetation. Therefore, coastal wetland vegetation, including seashore meadows, is mostly located in shallow regressive coastal areas with wide and flat nearshore (wave brake is far from the shoreline) where wave activity is negligible even during strong storms. Periodic inundation with seawater plays a decisive role in the development of seashore vegetation, determining their specific moisture regime as well as the content and distribution of chemical elements in the soil. Seashore meadow communities usually form distinct belts reflecting differences in seawater influence. In lower and middle geolittoral zones (Du Rietz 1950), well-developed seashore communities with halophilous plant species are widespread. In places where the shore is flat and wide, *Carex*-rich seashore meadows have developed away from the shoreline.

Above the mean surge level, the seashore meadows on Salic Fluvisols are gradually replaced by paludified meadows on Gleysols. During extremely high water levels, when the typical seashore meadows are submerged by seawater, the storm waves carry drifting litter and mineral sediment further inland and on higher elevations. The layer of such material can be very thick, destroying the existing plant cover and hampering the development of soils in the epilittoral zone, as clearly shown by the January 2005 storm.

The soil-vegetation complexes of the Estonian seashore meadows have undergone a series of stages in their development from hydrolittoral to epilittoral as a result of land uplift. A constant replacement of one plant community by another in a certain site over a certain time interval supports this general process (Puurmann and Ratas 1998). In some places a number of lagoons, which are temporarily connected to the sea enhance the invasion of seashore plant communities far inland enriching the landscape variety at a distance from the sea today (Ratas and Rivis 2003). The seashore grasslands can survive only where regular flooding occurs. In case of sea level rise, the new situation would favor reedbeds, which would expand their growth area and replace the former seashore grasslands.

Study areas, material and methods

Study areas and data sets

This study is based on both routine climatic, hydrological and oceanographic data, as well as on *in situ* research data from different terrestrial and coastal study sites. Trends in annual and seasonal mean air temperature and precipitation over the last 50 years shown in the current paper are based on the analysis of observation data of meteorological stations maintained by the Estonian Meteorological and Hydrological Institute (EMHI).

The sea level data are also collected by EMHI. Currently there are eight stations equipped with tide poles and three automatic tide gauge stations (mareographs) at Ristna, Pärnu and Narva-Jõesuu (Fig. 1), which provide hourly sea level measurements. Sea level time series start from 1899 in Narva-Jõesuu, 1923 in Pärnu and 1950 in Ristna. Time series from Tallinn tide gauge, the observations from which began in 1842 but contain gaps in the data, were discontinued in 1996. The study used wind data from the meteorological stations of Vilsandi, Sõrve and Kihnu (Fig. 1) to describe the impact of increased storm activity on coastal processes and recent shoreline displacement.

The analysis of the response of the inland wetlands to today's changing climatic conditions is based primarily on detailed studies of Männikjärve raised bog (208 ha) (Fig. 1). Data on long-term hydro-meteorological conditions of the Männikjärve bog were collected from the annual Mire Yearbooks of Tooma mire station compiled by EMHI since 1951. The data on monthly air temperature and precipitation were collected from two different meteorological observation squares — one on the dome of the bog massif and the other on a neighboring mineral about one km south-east from the bog square. The data on groundwater level (GWL) monitored in stationary groundwater wells, snow cover thickness and depth of frozen soil were also collected from the bog massif observation sites (Fig. 1).

Due to reorganization of the monitoring program at Tooma in 1960, the parallel daily recordings of air temperature and precipitation in the bog massif and neighboring mineral land observation sites were interrupted. After the 1960s, the recording of air temperature and precipitation in the bog was continued only during the warm half of the year between 1 May and 31 October. Therefore, linear interpolations were used to fill in the gaps in the data sets (Lode and Endjärv 2003). Complete meteorological data sets of the Männikjärve bog were divided into four main eco-hydrological seasons. The criteria for defining spring and autumn seasons were the months when mean daily temperatures rose above 0 °C in spring, and *vice versa* in autumn. The defined eco-hydrological seasons are as follows: winter (December to March), spring (April to May), summer (June to September), and autumn (October to November).

Recent changes in the activity of shore processes and the results of shoreline changes are discussed based on the field measurements carried out in three study sites — Harilaid, Küdema and Järve — on Saaremaa (2671 km^2 in area, Fig. 1), the largest island of the west Estonian archipelago. These sites represent different geomorphic shore types each with differing exposure to the open sea. The study sites of seashore grasslands represented in the current study are located in Salinõmme on the Hiiumaa island and Noarootsi on the northern coast of the Haapsalu Bay (Fig. 1).

Methodology

This study uses usual statistics, such as mean values, maximum and minimum values and standard deviation, to describe the variability of the parameters. Trend analysis of long-term climatic and hydrological time series is carried out by means of the linear regression analysis. Slope, i.e. change of trend over one year, is the most important trend characteristic. Also, the total change by trend (range change) is calculated by multiplying the slope by the number of years in the time series. Changes are considered significant at the $P < 0.05$ level.

The results and discussion in the current study concerning the impact of climate change on inland wetlands are based on the analysis of hydrological and meteorological data recorded at the Tooma mire station mostly in 1951–2002.

As major part of lagg areas of Estonian mires has been drained for forestry, this study focused on the central part of the bog massifs in order to minimize the possible effects of changes induced by humans. Therefore, for purposes of our analysis, we averaged the long-term monthly groundwater records of two ridge-pool and two ridge-hollow microtopes of the Männikjärve bog dome. We also divided the monthly GWL data into the same eco-hydrological periods as we did for the meteorological data.

Records of soil-frost depth and thickness of snow cover were analyzed at the same ridge-pool and ridge-hollow microtopes as the groundwater levels. Each microtope was represented with data averaged from two microforms — hummock and the depression between the hummocks. The long-term averaged soil-frost depths were calculated for the recorded winter periods of snow cover, i.e. from previous autumn until next spring.

Sea level variations and shallow sea processes were studied on the basis of historical sea level data and hydrodynamic investigations. Estonian tide gauge data, briefly analyzed in this paper, include monthly and annual mean data from eight tide-gauge stations (Fig. 1) where data with sufficient scope and quality from a relatively uninterrupted period (i.e. 1950–2005) are available. Pärnu tide-gauge data (1923–2005) were studied in more detail. The height system currently used in Estonia and in other Baltic states of the former Soviet Union is different from the Finnish and Scandinavian tide gauging standards. It is referred to as the Baltic Height System and has its “zero-benchmark” reference point at Kronstadt near St. Petersburg (e.g. Lazarenko 1986). Though land uplift is slower in the study area than in Fennoscandia, non-uniform shift of fixed references pose some specific problems for time series analysis and comparison of results from different tide gauges. Therefore data about the isostatic land uplift (Vallner *et al.* 1988) were used. Using linear regression analysis, trends in time series of relative sea level were estimated. After combining the results with land uplift rates, the actual “climatological” sea level change component was obtained.

The study also analyzed sea level variability range, long-term trends, seasonality and correlations with the North Atlantic Oscillation (NAO) index and storminess. The NAO index is often defined as the difference between standardized sea-level pressures at two centers of action, one over the Azores and the other in Iceland (Hurrell 1995, Hurrell and Van Loon 1997). It reflects the intensity of westerlies over the North Atlantic and Europe.

Topographic, geomorphic, land use maps and aerial photographs from different times (from the beginning of the 1900s to the end of the 1990s) were used to identify changes in shoreline contours and position. Maps and aerial photographs were entered into MapInfo using certain control points and their Cartesian co-ordinates. Shoreline contours and the nearest scarps were digitized and analyzed using MapInfo (Orviku *et al.* 2003, Rivis 2004).

Field measurements in relation to local benchmarks and a topographic survey of coastal formations were carried out to determine changes in shoreline position. The measurements and survey were repeated at the same study areas at irregular time intervals depending on specific tasks in the frameworks of different studies. GPS measurements were carried out to determine short-term changes in shoreline position, contours of beach ridges and the location of their crests during the last six years (i.e. 2000–2005). Data from 2004 and 2005, just before and after Gudrun swept through the region, were used for purposes of analyzing the storm's impact in January 2005. Sea level fluctuations (15–20 cm above or below the Kronstadt 0) during the aerial photography and GPS measurements were unimportant due to the relatively steep nearshore slopes.

Many large-scale transects (i.e. 1:2000) along and across the coastal formations were compiled and were later extrapolated over the whole study area. Changes in the morphological features of coastal formations were modeled on the basis of these transects. The volumes of coastal formations and the overall amounts of sediment were calculated to determine changes over particular time intervals. The relationships between storm data and shoreline changes from 1957 (the earliest date from which aerial photographs were available) to 2005 were examined using a simple visual comparison.

With respect to investigating changes in landscape ecology and land cover on very low and flat coasts, we used the following methods. First, we compared maps from different periods with visually analyzed changes in the landscape. (The land cover units are based on the *Corine* system (Meiner 1999)). Second, we classified each study site's landscape units following either their mesoscale landforms or the character of their sediments (litho-genetic type and granulometric composition in case of plains and prevailing plant communities), and based on that, we compiled large-scale maps (i.e. 1:10 000). Third, for some study sites, we compiled landscape transects of the vertical cross-section of the basic components of the landscape units (i.e. topography, rocks and sediments, soil, vegetation, and land use) in order to conduct a detailed analysis of the mutual relationships and processes between different components in certain sampling points along the transects.

Results and discussion

Climate change impact on inland wetlands

The main statistics for seasonal mean air temperature and precipitation at Männikjärve bog during the eco-hydrological years of 1951–2002 are presented in Table 1. Linear trends for the 52-year time series of air temperature indicate statistically significant warming by 3.3 °C in winter and by 2.0 °C in spring, and no changes in summer and autumn (Fig. 6). These changes are consistent with temperature trends in other regions of Estonia.

This study identified a significant increase

Table 1. Main statistics for the long-term seasonal air temperature (T, °C) and precipitation (P, mm) compiled for the Männikjärve bog eco-hydrological years of 1951–2002, where * = statistically significant changes at the $P <$ 0.05 level, CV = coefficient variation of the data set.

Variable	Winter		Spring		Summer		Autumn	
	T	P	T	P	T	P	T	P
Mean	–4.7	156	7.0	86	14.0	294	2.6	121
Max.	–0.3	276	9.9	165	15.8	474	5.8	198
Min.	–9.2	62	2.9	17	11.9	164	–1.4	47
SD	2.5	45.0	1.3	35.3	0.9	88.2	1.6	38.2
SE	0.3	5.6	0.2	4.6	0.1	11.7	0.2	5.0
CV	0.53	0.29	0.19	0.41	0.06	0.30	0.62	0.32
Slope step	0.063	1.160	0.039	–0.220	0.008	0.020	–0.005	0.60
Range change	3.3*	60*	2.0*	–11	0.4	1	–0.2	31

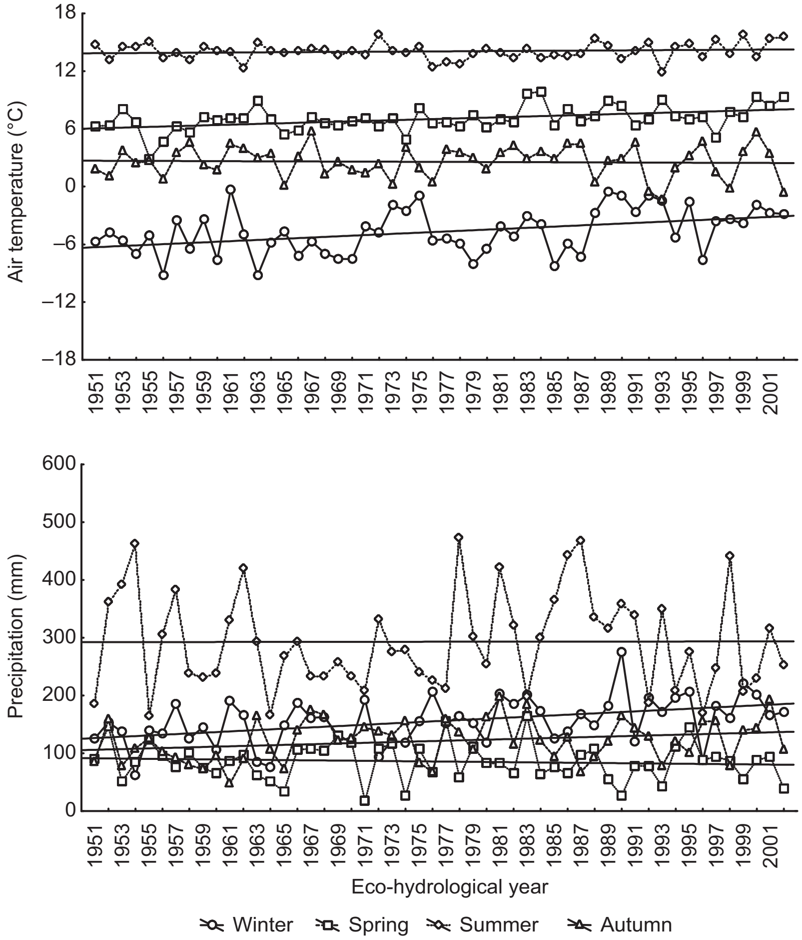

Fig. 6. Long-term seasonal changes in air temperature and precipitation in Männikjärve bog for eco-hydrological years of 1951–2002.

in seasonal precipitation (by 60 mm) at Männikjärve bog only during winter. While autumn precipitation also increased, the rise of autumn precipitation by 31 mm is slightly less significant ($P < 0.05$). A weak and insignificant negative trend is typical for spring precipitation during the study period (Fig. 6).

Based on the statistical values (Table 1), this study found that summers were the most stable in relation to long-term air temperature and winters were the most stable in relation to precipitation of the analyzed eco-hydrological seasons.

Although we expected to find a solidly inverse proportional relationship between mean snow depth and soil-frost depth in the bog (Fig. 7), it was not statistically significant. This probably resulted from different methods of measurements. The snow cover depths were measured on transects and the results were averaged, while soil-frost depths were measured only at the sites (Fig. 1). During 1959–2002, the mean soil-frost depth at the sites was 16 cm with an mean snow cover of 14 cm in the surrounding areas. During that period, the mean thickness of snow cover decreased by 5 cm, while the mean soil-frost depth decreased by only on mean 0.3 cm. However, 5-cm decrease in annual maximum depth of soil frost reveals existance of warming trend. The latter has a reasonably strong correlation with the mean soil-frost depth in case of snow cover, whereas the correlations between mean and maximum soil-frost depths showed a higher dependency at the sites where the ridge-pool microtope was measured ($r = 0.91$ for hummocks; $r = 0.79$ for depressions) than at the sites where the ridge-hollow microtope was measured ($r = 0.88$ for both hummocks and depressions).

Soil frost usually started at the end of the

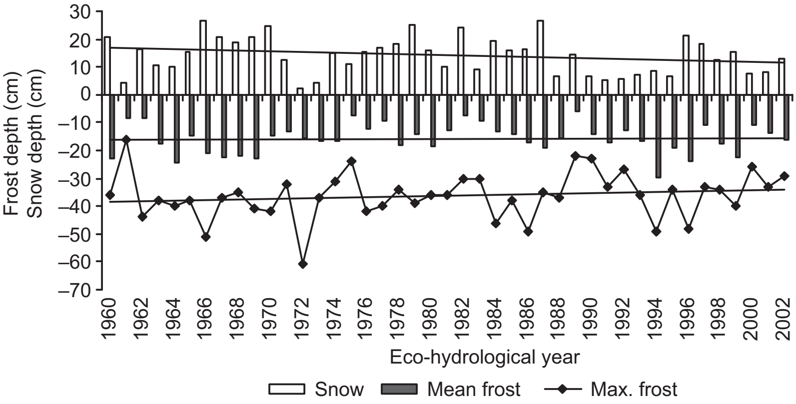

Fig. 7. Integrated graphs of long-term changes in mean snow and soil-frost depths, and maximum soil-frost depth in Männikjärve bog for eco-hydrological years of 1960–2002.

first 10-day period in November and formation of snow cover followed about 20 days later. This pattern was fairly stable during the 43 years of recording. That said, considerable changes have taken place in terms of when snow cover disappears and frozen soil melt-up. The current dates of these events in Männikjärve bog are now on average three to four weeks earlier as compared with the situation 43 years ago. Today, the snow cover disappears at least three weeks before the soil melts.

We also found that different microforms of the bog surface have a significant impact on that process. For instance, the melting in depressions between hummocks at the ridge-pool microtope occurs about three weeks earlier than on the hummocks themselves.

Analyzed long-term GWLs in the Männikjärve bog showed water level changes for eco-hydrological seasons that were microtope site specific. Generally, there are no large seasonal differences in the mean GWLs of the ridge-pool and ridge-hollow microtopes. An exception is the summer when the GWL in the ridge-hollow microtope is four cm lower than in the ridge-pool microtope (Table 2). The mean GWL of both microtopes lies 23–25 cm below the bog surface during the rest of a year. However, very significant differences can be observed in 47-year trends between different microtopes. GWL of the ridge-pool microtope has risen by 11–12 cm in winter, summer and autumn and by 6 cm in spring. In the ridge-hollow microtope, the linear trend in GWL was negative for most of the year; the lowering in spring was on average 7 cm, and on average 3 cm in summer and autumn (Table 2 and Fig. 8).

The changes in GWL at the center of the Männikjärve bog seem to be unexpected in terms of identifying a clearly rising trend in the ridge-pool microtope and a clearly lowering trend in the ridge-hollow microtope. Moreover, no particular change in summer mean air temperature and precipitation over the last 50 years could be observed there. One explanation for such a phenomenon is probably related to the bog dome morphology and the heights of the microtope locations on the bog surface. In our case, the ridge-hollow microtope we analyzed is located about 1.0–1.5 m higher than the ridge-pool microtope (Van der Schaaf *et al*. 2004).

Even though during dry summer periods the hydrological functioning of the different microtopes on the dome of the Männikjärve bog is relatively isolated, the ridge-pool zone may act as a surface water collector during cloudburst events in the summer. This idea is supported by the low surface water holding capacity of the acrotelm layer associated with the topographical location of the comparable microtopes (Lode *et al*. 2003). Differences in the surface heights of the studied microtopes may also explain the long-term GWL rise in the ridge-pool microtope in winter as a reaction to the long-term increased air temperature and precipitation in winter. In spring, the ridge pool microtope with its lower elevations may be more thoroughly saturated with water and have relatively higher GWL, which could lead to earlier snow and soil melting times as compared with those in the ridge-hollow microtope with its relatively lower GWL.

The most significant changes in the ridge-

Table 2. Main statistics for seasonal groundwater levels (GWL, cm) on the ridge-pool and ridge-hollow microtopes compiled for the Männikjärve bog eco-hydrological years of 1956–2002, where CV = coefficient variation of the data set.

GWL	Winter		Spring		Summer		Autumn	
	Ridge-pool	Ridge-hollow	Ridge-pool	Ridge-hollow	Ridge-pool	Ridge-hollow	Ridge-pool	Ridge-hollow
Mean	−23	−24	−23	−25	−31	−35	−25	−25
Maximum depth	−38	−35	−31	−35	−48	−51	−42	−41
Minimum depth	−13	−17	−16	−19	−17	−20	−15	−18
SD	5	4	4	4	7	8	6	5
SE	0.8	0.6	0.6	0.6	1.0	1.1	0.9	0.7
CV	0.22	0.17	0.17	0.16	0.23	0.23	0.24	0.25
Slope step	0.251	0.001	0.132	−0.144	0.240	−0.072	0.225	−0.070
Range change	12	0	6	−7	11	−3	11	−3

hollow microtope have taken place in spring where we observed the largest decrease in long-term GWL (Table 2). This can probably be explained by the different dates of the soil melt on the current topographic profile and also by the start of evapotranspiration processes. Extending the trends of climate change in the Männikjärve bog, one can draw a scenario for further development where the dryer ridge-hollow microtopes may get dryer and the ridge-pool microtopes may get wetter. As dryer areas of the bog may enhance the tree growth, we might expect to see higher rates of evapotranspiration. If such were the case, a higher rate of evapotranspiration, together with a concurrent increase in the water deficit in the acrotelm layer, could result in a lowering GWL.

An increased amount of surface water in the ridge-pool zone must either be stored — either in the expanded lower parts of the bog surface or in the open water areas — or discharged out of the bog via its flow paths. The alternating freezing and melting periods in winter, the increased air temperature in spring and the intensive cloudburst events in summer would definitely support the theory of the mire's massif eroding from the inside. Such a scenario could also cause substantial changes in the bog surface topography where the ridge-hollow microtope may subside and where the formerly driest areas of the bog may become the storage areas for excessive amounts of surface water, thereby also prolonging the dystrophic stage of the mire landscape development. Although the rates and speed of dystrophic development are hard to predict, there is no doubt that climate warming trends even only in winter will increase the deterioration of Estonia's bog landscapes.

Climate change impact on coastal sea

The Pärnu tide gauge data were re-analysed especially in relation to high sea level events (Fig. 9). As was shown by Suursaar *et al*. (2006a), the rising trends of mean sea level appear mainly due to significantly higher sea levels between November and March (Fig. 10a). This seasonal pattern is well correlated with storminess and the NAO indices (Fig. 10b).

However, the trend's increase is particu-

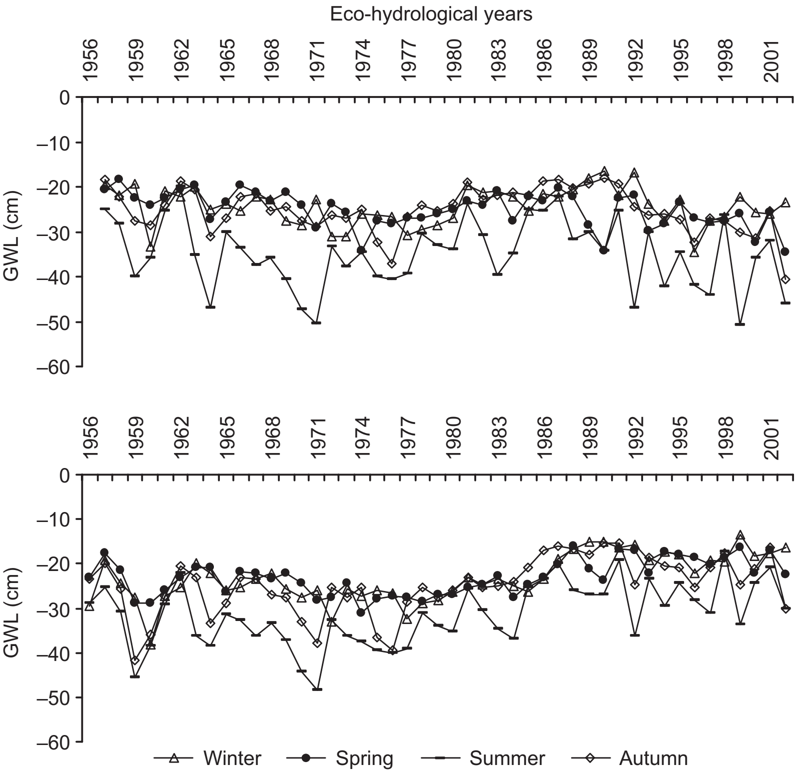

Fig. 8. Long-term seasonal groundwater level (GWL) changes in microtopes of Männikjärve bog for eco-hydrological years of 1956–2002.

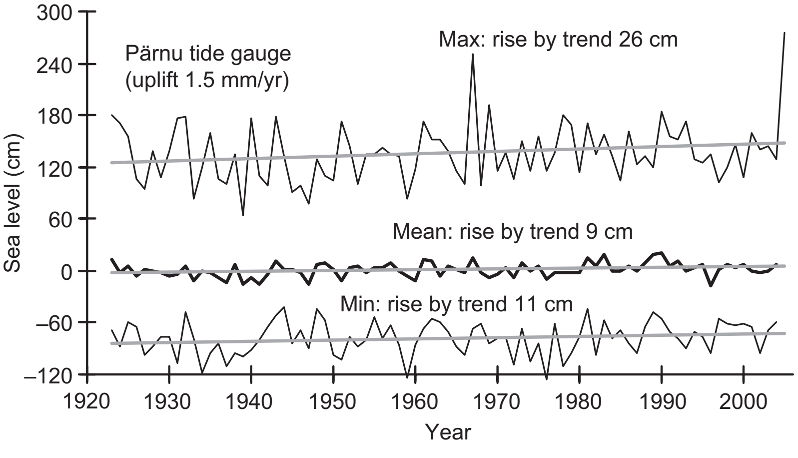

Fig. 9. Variations in annual maximum, mean and minimum sea levels at Pärnu together with trend lines.

larly large in time series of annual maximum sea levels, which vary between 1.9 and 6.1 mm yr^{-1} (Fig. 9). This could be explained as a local response to changing regional wind climate, as sea level variations in the semi-enclosed study area (the windward locations of which are in relation to prevailing south-westerlies) are sensitive to increase in the westerly wind speed component and to the intensification of cyclones which has been observed over the last half century (Alexandersson *et al.* 2000, Orviku *et al.* 2003, Sepp *et al.* 2005). If the frequency of westerlies and intensity of storms continues to increase, we may anticipate a further rise in sea level of up to ten cm along the windward locations of the heavily serrated Estonian coast.

While long-terms trends may be subtle and not readily noticeable to people, aperiodic events,

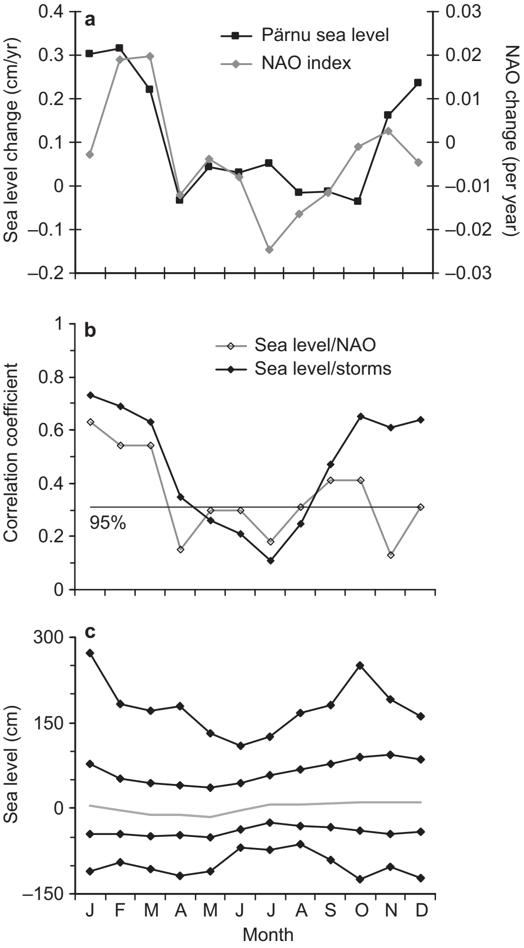

Fig. 10. (**a**) Seasonal structure of sea level change rates in Pärnu and NAO indexes for the period of 1923–2004, (**b**) seasonal variations in correlation coefficients between Pärnu sea level, the NAO index, and the number of storm days at Vilsandi, and (**c**) seasonality in maximum, mean maximum, mean, mean minimum, and minimum sea levels at Pärnu.

such as storm surges, offer a sharp reminder of the ways in which changing climatic conditions can affect us all. In Estonia, the most vulnerable areas to storm surges are the shallow and narrow bays of Pärnu, Matsalu and Haapsalu, which are exposed to the strongest storm winds in the Baltic Sea region, the south-westerlies and westerlies.

Pärnu is also the place with the highest historical sea level variability (400 cm), which is fairly large for a nearly tideless semi-enclosed sea. That means that large areas of coastal wetlands near Pärnu and Matsalu Bays are flooded almost regularly by brackish seawater during autumn and winter storms. The most recent storm surge was produced by the extratropical cyclone Gudrun on 9 January 2005, which caused a 275 cm sea level in Pärnu (Fig. 11) and up to a 220 cm sea level in many other bays of western Estonia. It also caused a temporary recession of the coastline of nearly five km and an extensive inundation of wetlands near Matsalu Bay.

The most efficient wind direction for storm surge is around 225° from the north (Fig. 11) for the Pärnu Bay and around 240° for the Matsalu and Haapsalu Bays. The pile-up effect is very small where wind speed values are low but very large during storm events. However, the 2 m s^{-1} wind speed increment between 28 and 30 m s^{-1} yields a 50-cm higher surge. Consequently, a relatively small incremental increase in wind speed during a storm can produce a disproportionate and significantly higher storm surge.

Shore processes and coastal geomorphology

A comparison of maps from different periods and the field measurement results in test areas clearly reveal increased activity in both the erosion and accumulation processes. For instance, shore processes during the last century have caused the north-westernmost point of the Harilaid Peninsula on Saaremaa to migrate to the north-east and to change its shape (Fig. 12). The intersects of beach ridges of different ages, the formation of new scarps and the recession of old ones are a clear consequence of erosion on the western coast of the peninsula. Erosion of the western coast of Harilaid is also revealed by the position of the lighthouse that was initially erected at the centre of the cape (about 100 m from the shoreline) and which currently stands in the sea and is tilted about 10°. Although erosion has dominated on the western coast of Harilaid since at least the beginning of the 20th century, the correlation between shoreline changes and certain extremely stormy periods remains unclear.

The relationships between storm parameters and coastal processes in southeastern Harilaid (Fig. 13) are much clearer. Elongation of a spit consisting of beach ridges is well delineated by

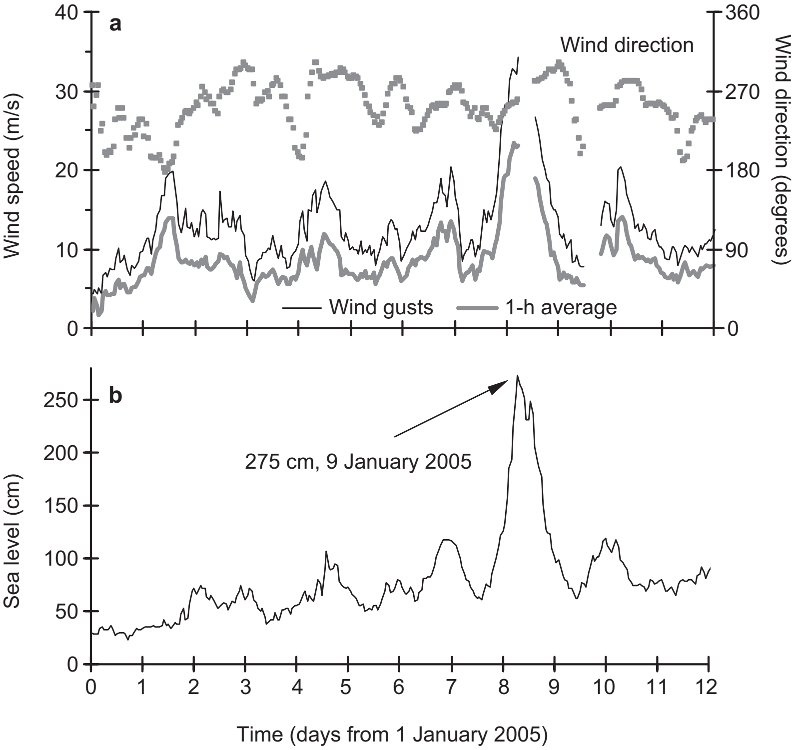

Fig. 11. The highest sea level event in recorded history at Pärnu in 2005 (b); corresponding local wind forcing (wind direction, wind gusts and hourly mean wind speeds at Ruhnu station).

the newly formed ridges and their positions, and these changes coincide with the storm data. The gravel and pebble accumulated on new ridges is probably eroded and transported by westerly and north-westerly storm surges from the submarine shoals south-west of Harilaid.

A comparison of topographic surveys at the Järve study site on the southern coast of Saaremaa made just before and after the stormy period in winter 1990 (contained eight days of a storm where maximum wind speed reached 25 m s^{-1}, S, sea level rised up to +171 cm) shows that the 4-km-long scarp had receded by four to five m. Over 6500 m^3 of sand was eroded from the scarp. This coastal destruction was the result of the cumulative effect of strong storms with high sea level and the absence of ice cover. During the following period from 1990 to 1999, which saw no severe storms, beaches in the west Estonian archipelago were more stable. However, a new vitalization of shore processes has started since 1999.

At the Küdema study site along the coast of Saaremaa, Gudrun caused unusual changes to the position and morphology of the beach. The seaward slopes of the beach ridges became steeper and the youngest ridges, consisting of pebble and gravel, became higher by approximately one m (Fig. 14). Pebble, which typically can be eroded and removed only by very strong waves,

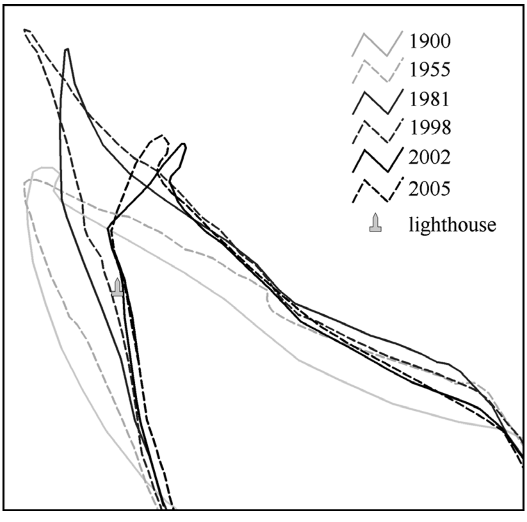

Fig. 12. Shoreline changes of Cape Kiipsaare (1900–2005), NW Saaremaa (location shown in Fig. 1).

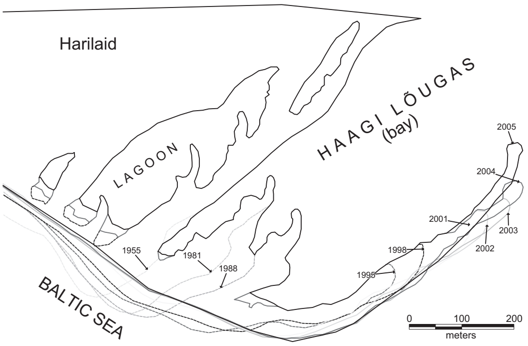

Fig. 13. Increment of gravel spit at Cape Kelba (1955–2005), NW Saaremaa (location shown in Fig. 1).

has been deposited on older vegetated ridges in many places at Küdema. A clear consequence of the January storm is a freshly formed beach ridge at the distal part of the spit, which is much higher than the older ones behind it. The gravel-pebble beach ridges that were formed during Gudrun — positioned as they are so far inland from the mean shoreline and located at such higher elevations due to the storm's high sea levels — are likely to remain there unchanged for a long time, as the unique confluence of factors that produced Gudrun and its resulting shoreline processes are unlikely to be recreated anytime soon.

Seashore grasslands

As seashore grasslands in Estonia are semi-natural plant communities their development is dependent on both natural conditions and human impact. The economic significance of inundated grasslands has decreased and the areas remained unmanaged during the last decades. After cessation of traditional management activities, more species poor communities have replaced the former plant communities thereby eliminating the habitats of several species including rare and protected ones (Puurmann and Ratas 1998). Frequently they are characterized by low biodiversity or are dominated by a single species, mainly by *Phragmites australis*, forming thick littoral reed-beds.

Land maintenance subsidies are being paid for the maintenance of the semi-natural communities in protected areas and, since 2001, in areas beyond the protected areas, such as in potential Natura 2000 areas. Several Estonian non-governmental organisations and the WWF Sweden have initiated a Väinameri project with the aim of restoration and conservation of semi-natural coastal landscapes in the regions of our study sites (Kokovkin 2005).

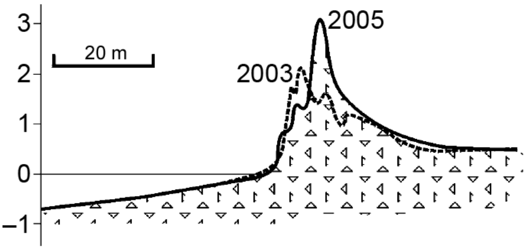

Fig. 14. Beach profiles on Küdema spit in 2003 and after the storm Gudrun.

In general, comparative analysis of land cover maps of coastal areas from different periods shows that the share of land that is used for agriculture steadily decreased during the last 60 years. Reed beds, shrubberies or woodlands and overgrowth have replaced the former grasslands (Fig. 15). For instance, large areas of reed beds and seashore grasslands were prevailing at both the Salinõmme and Noarootsi study sites in the middle of the last century. As a result of land uplift and sediment accumulation, the share of the terrestrial area considerably increased over the last 50 years: by 3% in Salinõmme and 10% in Noarootsi. These newly formed areas have been influenced by human activity since the very beginning of their development

Conclusions

The trend of climate warming, particularly in winter and spring, over the last half-century was evident in Estonia. Warmer winters, together with increased cyclonic activity in the atmosphere, had a noticeable impact on the natural environment in moderate and high latitudes, such as the coastal and inland wetlands of Estonia.

Extensive erosion and alteration of depositional coasts, and frequent floods on flat and low silty shores were observed during the recent decades. The most marked coastal changes in Estonia resulted from a combination of strong

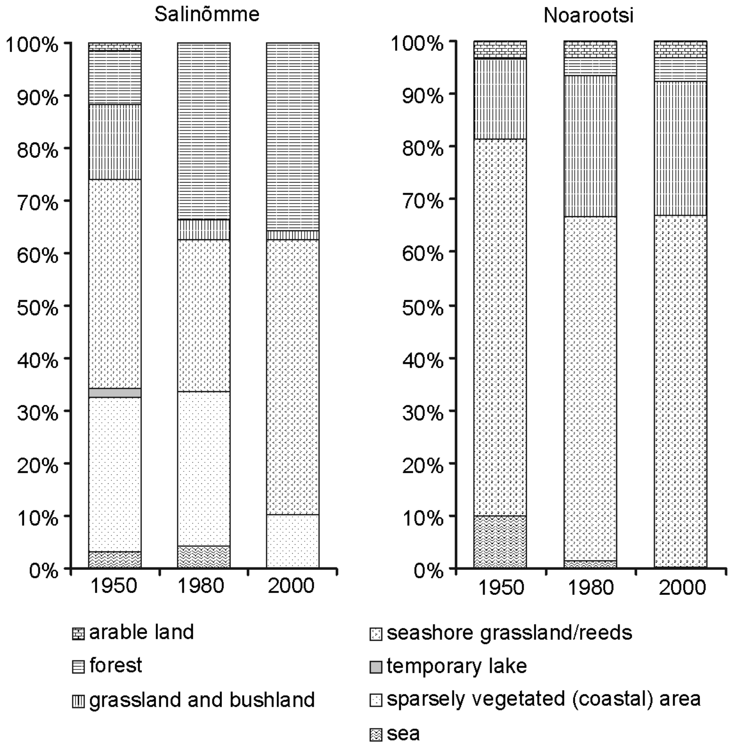

Fig. 15. Land cover changes in 1956–1996 in Salinõmme and Noarootsi.

storms, high sea-levels induced by storm surge, ice free seas and unfrozen sediments, all of which enhance erosion and transport of sediments inland of the mean shoreline. It can be concluded that an extremely strong storm event like Gudrun in January 2005 may cause substantially larger changes to the depositional shores in west Estonia than all of the storms over the entire preceding 10–15 years.

The winter–spring seasonal warming trend in the Männikjärve bog in central Estonia fits well into the observed general climatic changes in Estonia. Changes in the atmosphere that are presented in this study are clearly reflected in the shorter duration of snow cover, decreased soil-frost depths and changed groundwater levels in the bog. Comparative study of the Estonian coastal and inland wetlands under changing climatic conditions clearly shows the more unstable character of coastal wetlands compared to the inland bogs, particularly in relation to landscape morphological changes. Relatively small changes in the hydrological regime of bogs on one hand indicate for a rather stable and adaptive ecological system in the bogs to a negligibly short period climate changes. On the other hand, it also indicates an extremely high importance of usually non-recognizable small GWL changes in the bog landscapes, which in longer time span may lead to irreversible disturbances in the bog landscapes.

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