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Morphosedimentary evolution of Estonian coastline: role of climatic and hydrodynamic forcing over the past decades

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Decadal trends in regional climate are investigated for their possible influence on the shoreline changes at a number of Baltic Sea sites in Estonia. Between 1951 and 2020, the annual mean surface air temperature at coastal stations has increased by 2.2–2.6°C, with no clear trends detected in the number of storm days during 1966–2020. However, a period of increased storminess was observed in the 1980s and 1990s. Due to post-glacial land uplift, with geocentric values between 1.3–3.5 mm yr^{-1}, the mean relative sea level has been nearly stable or slightly falling during the study period, while the annual maxima have increased everywhere along the Estonian coast. Changes in wind regime and sea ice climate have caused temporal variations in sea level and wave conditions and, ultimately, manifested themselves in shoreline trends. Along the depositional segments, a relatively low activity of shore processes with slow erosion of the seabed and limited progradation of the beaches occurred before the 1980s. Following a clear shift in climatic conditions since the end of the 1980s and diminishing ice cover conditions along the coast, frequent storms accompanied with high sea levels resulted in increased activity of shore processes and substantial changes in alongshore morphology and beach profiles, and following an intense storm Gudrun (2005), minor events have not had substantial impact on the shore processes, with majority of the beaches attaining a new equilibrium morphodynamic state.

Introduction

Changes in coastal processes (inundation, erosion, accretion, sediment transport, etc.), as consequences of climatic forcings and perturbations, influence hydrodynamic processes along continental and insular margins. These have been systematically observed over the past half-century along many coastlines of the world, with extensive erosion of depositional coasts, including sandy beaches, taking place in many regions (e.g., Bird 1985, Clarke and Rendell

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2009, Eberhards *et al*. 2009, Jarmalavičius *et al.* 2016, Weisse *et al.* 2021). The anticipated sea-level rise (IPCC 2021) and increased storminess (Alexandersson *et al.* 2000, Orviku *et al.* 2003) result in intensification of coastal processes, which in turn may lead to considerable ecological changes and economic damage to coastal communities and infrastructure (Leatherman and Nicholls 1995, FitzGerald *et al*. 2008, Hallegate *et al.* 2013).

According to the latest IPCC report, global mean air temperature during the past decade (2011–2020) has been higher by 1.09°C than the mean for the period from 1850–1900 (IPCC 2021). In northern Europe, the increase in air temperature has been faster than the global mean (BACC 2015, Meier *et al.* 2022). Estonia is one of the northern European countries where long-term research of coastal morphodynamics can be correlated with hydroclimatic forcing and perturbations (storms) in the Baltic Sea. During the second half of the 20th century, the annual mean temperature at ten meteorological stations in Estonia has increased by 1.0–1.7°C (Jaagus 2006a). Even greater climate warming has taken place during the past decade. Using the Rodionov test, a regime shift was detected for mean annual and winter temperatures at the end of the 1980s. Since 1988/1989, the mean level of temperature fluctuation rose by ~2°C (Jaagus *et al.* 2017), which has introduced a cascade of changes in sea-ice conditions and in other oceanographic variables (Kotta *et al.* 2018).

Sea ice is an important product and indicator of winter weather conditions (Leppäranta and Myrberg 2009). The annual maximum extent of ice cover has decreased and the length of the ice season shortened during the past decades in the Baltic Sea (BACC 2015). According to the observational data from Estonian coastal stations (Jevrejeva *et al.* 2004, Jaagus 2006b), the formation of sea ice has been delayed and the date of its break-up occurs much earlier. Warmer winters, longer duration of ice-free sea, and unfrozen shore sediments are all favourable preconditions facilitating beach erosion in a regime of strong and lasting storms (Tõnisson *et al.* 2007, Vihma and Haapala 2009).

Along with an increase in mean air temperature, also changes in wind regime, storminess, and ultimately, in sea level have occurred (e.g., Johansson *et al.* 2001, Dailidiené *et al*. 2006, Kont *et al.* 2007, Johansson and Kahma 2016). The frequency of westerly, south-westerly, and north-westerly winds has significantly increased during the winter season in 1966–2008 at several stations in Estonia (Jaagus and Kull 2011). Warmer winters are caused by prevailing cyclonic weather conditions which, in turn, are often associated with storm surges.

In the semi-enclosed and functionally tideless Baltic Sea (e.g., Alenius *et al.* 1998), mean sea-level variations may deviate from the global sea-level rise (GSLR) component, which has been estimated at ~1.7 mm yr^{-1} during the 20th century (IPCC 2021), but it is also time-dependent (i.e., likely accelerating). Local deviations along the Estonian coastal waters occur due to postglacial rebound in the region of the Baltic Shield (Vestøl *et al.* 2019; Fig. 1 inset), local land movements (e.g., subsidence) at tide gauges (Suursaar and Kall 2018), decadal-scale (wind-driven or steric) variations in the water budget of the Baltic Sea (Leppäranta and Myrberg 2009, Hünicke *et al.* 2015), as well as local sea-level deviations generated by variations in wind climate changes in relation to a tide gauge with a particular exposure and hydrodynamic setting (Suursaar and Kullas 2006, Männikus *et al.* 2019, Wolski and Wiśniewski 2020). Although the GSLR is partly counteracted by land uplift and the relative mean sea level at Estonian tide gauges is more or less stable (or, at least, not increasing rapidly), the annual maximum sea level is clearly rising (Suursaar and Sooäär 2007, Weisse *et al.* 2021). The main reason for this is changes in atmospheric circulation and storminess (Jaagus and Suursaar 2013).

Strong storm waves combined with high sea level may cause substantial damage to coastal areas far inland from the mean shoreline, even outside the landward boundary of the coastal zone (Orviku *et al.* 2009, Soomere *et al.* 2020). Whereas the impact of more frequent moderate storms on the dynamics of depositional seashores is rather modest and the traces of minor beach erosion may disappear in a few years (Orviku *et al.* 2003), the energy of intense or extreme storms and their effect on the coastal zone are orders of magnitude higher. Morpho-

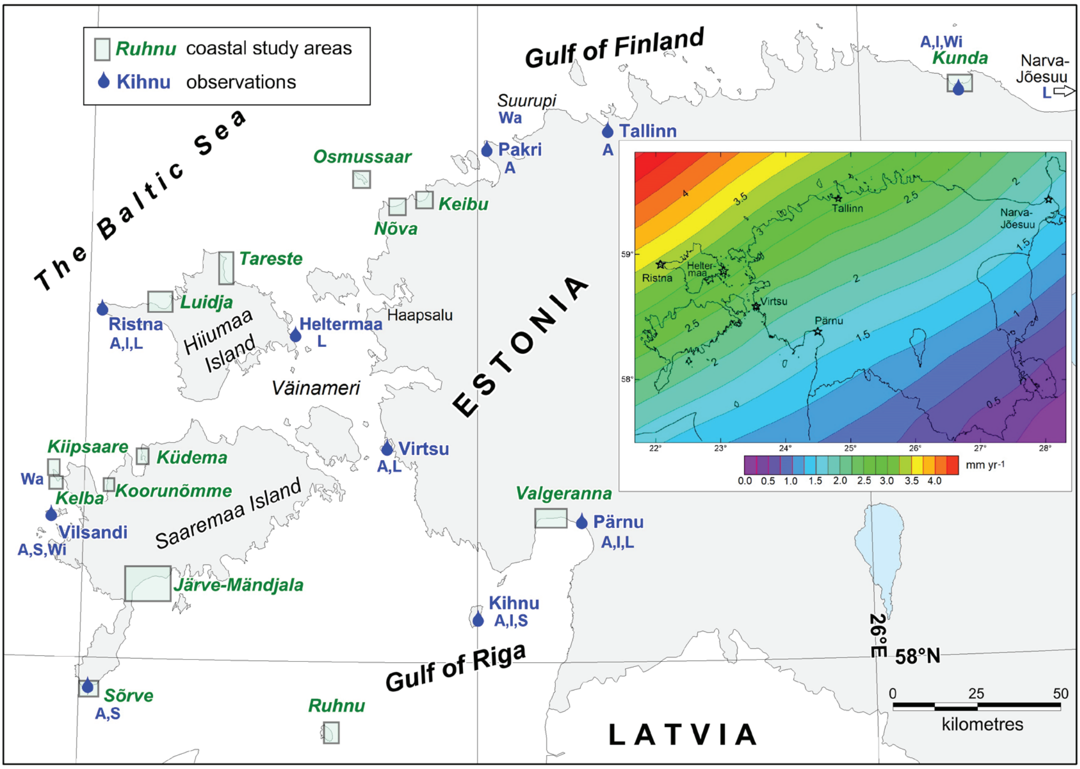

Fig. 1. Location of meteorological observation stations, coastal study areas and tide gauges (inset; with isobases of geocentric uplift according to the NKG2016LU_lev model (Vestøl *et al.* 2019); Estonian fragment modified from: Suursaar and Kall (2018)). The codes near stations refer to the following measurements: A – air temperature, I – sea ice, S – storms, Wi – wind, Wa – wave hindcast, L – sea level.

dynamic changes in coastal areas generated by these high-intensity events can persist for decades or more, and in some cases the previous state of a shoreline may be irreversible (Eberhards *et al*. 2009, Leszczyńska *et al.* 2022). For instance, the most extreme storm of the past decades, known as Gudrun in the Nordic countries, occurred on 7–9 January 2005. In addition to extensive inundation at Pärnu and Haapsalu, it induced clearly visible changes in shoreline trends and the dynamics of beach sediments along nearly all of Estonian coastline (Tõnisson *et al.* 2008). Intense storms have impacted this region after Gudrun as well, offering an opportunity to observe and quantify the results of their impact on shore processes, nearshore bathymetry, and beach profiles at our long-term study sites at different locations along the coast (Fig. 1; Tõnisson *et al.* 2013, 2016).

Yet, to date, there is no consensus in the scientific community concerning the recent trends and projections of future storminess patterns, nor their impact at least in northern Europe. Most studies indicate no significant trends, rather than high decadal variation (e.g., Bijl *et al.* 1999, Krueger *et al.* 2013, BACC 2015), whereas some authors (Alexandersson *et al.* 2000, Donat *et al.* 2010), suggest an increasing trend in storminess over the past decades. The projections for extreme storm parameters under modelled future climate scenarios are not sufficiently constrained for the Baltic Sea region either (Mäll *et al.* 2020, Meier *et al.* 2022). The latest general overviews of the development of the Estonian seashores (Orviku *et al.* 2003, 2009, Kont *et al.* 2007, 2011, Tõnisson *et al.* 2007, 2011) reflect the storminess and sea level situation as of ~10–15 years ago. But as recent climate warming and sea-level rise have been proceeding, their effects at least in part must be manifested as the changes in storminess, wave climate, and their cumulative impact on large-scale coastal morphodynamics.

That is why it is crucial to re-analyse and refine previous findings and combine them with new observations, as part of a growing dataset.

The aim of this paper is to synthesise a growing dataset of field and instrumental data on large-scale coastal behaviour as a function of hydrodynamic and climatic forcing. Building on the literature (e.g., Orviku *et al.* 2003, Rivis 2005, Kont *et al.* 2007, 2011, Suursaar *et al.* 2015, Tõnisson *et al.* 2019), it offers an updated overview of the changes in climatic forcing, associated hydrodynamics of coastal waters, and their cumulative impact on the development of Estonian depositional seashores over the past half-century with a special focus on the events in recent decades.

Site

Coastal morphology and processes in Estonia have been systematically examined on islands of Saaremaa (2671 km^2 in area) and Hiiumaa (1018 km^2), as well as several smaller islands and along the Estonian mainland. For additional information about specific study sites (Fig. 1), see e.g., Orviku *et al.* (2003), Tõnisson (2004), Rivis (2005), Kont *et al.* (2007), Suursaar *et al.* (2008, 2013), and Tõnisson *et al.* (2008, 2019).

All six study sites on Saaremaa Island (Fig. 1) investigated here are depositional landforms composed of sand and gravel, with varying exposure to the prevailing wind and waves. On the north-western part of Saaremaa, along the Harilaid Peninsula, the sandy Cape Kiipsaare (Fig. S1 in Supplementary Information) exhibits a wave-cut bench formed in a submarine glacial ridge that acts as the main sediment source. The west-facing Cape Kelba on the south-eastern coast of the peninsula is a 2-km-long-spit consisting of a series of beach ridges. The recurving pebble-cobble accumulation form is composed of well-rounded crystalline clasts. Shallow lagoons and small lakes lie behind the spit, whereas the west-facing nearshore gradient is rather steep.

The Koorunõmme study site on the northern coast of Saaremaa consists of 900-m-long gravelly beach ridges. These form an independent erosional-accretionary system where sediments are supplied from an underwater limestone bench. The nearby Küdema site includes a complex accumulative coastal landform with a 3-km-long distal spit, the formation and development of which depend strongly on erosion of the nearby 21-m-high Panga limestone cliff.

The Sõrve site in SW Saaremaa consists of beach ridges composed mostly of cobbles and pebbles. The ridges continue to the southwest in the form of islets of similar composition and origin, which change their shape because of storm wave activity from different directions, as the southern tip of the peninsula has an open exposure to both the Baltic Proper and the Gulf of Riga (see Fig. S2 in Supplementary Information).

The Järve-Mändjala site on the southern coast of Saaremaa is a typical sandy beach with up to 6-m-high dunes and an inland-shifting scarp in older coastal and marine sediments. The nearshore sea is shallow and the exposure to the Gulf of Riga is rather limited.

The Luidja study site on the western Hiiumaa Island is a sandy beach with foredunes and spit-like ridges, which are exposed to the northerly winds and waves from the Baltic Proper. The shoreline is retreating along its western section, whereas in the central and eastern parts of the study site the shoreline is slowly accreting seaward (prograding).

On the north-easterly exposed Tareste site in the northern part of Hiiumaa, there is a sediment deficit in the northern part of the study site because the Lehtma Harbour jetties hinder the longshore sediment transport from north to south. The shoreline is retreating, and storm waves erode the relict beach formations (see Fig. S3 in Supplementary Information). The sandy Tareste spit in the southern part is gradually elongating and a small bay behind it will likely turn into a lagoon in the near future.

Along the mainland coast of Estonia, the northerly exposed Nõva and Keibu study sites both include ~100-m-wide sandy beaches, which are backed by an extensive system of foredunes and older ridges. Alternation of erosion and accretion and predominant eastward sediment transport occurs in the western part of the Nõva site. At Keibu, erosion dominates both sides of the bay and accumulation occurs at the bay head shoreline.

Offshore, the Osmussaar Island study site consists of 2–3-metre-high gravel beach ridges, with brackish-water coastal lagoons formed behind the spits. The 7-m-high Ordovician limestone cliff in the northern part of the island is gradually eroded by storm waves, feeding the southward longshore sediment flux. Along with the Harilaid study sites, the wave climate near the Osmussaar is one of the roughest among our research locations.

To the east, the Kunda site in the Gulf of Finland is exposed to the storm winds and waves from the north. However, the prevailing direction of sediment transport is to the east, which is characteristic of the entire northern coast of Estonia. The shore types vary between sandy beaches with gravel, till exposures, and silty scarps.

The southerly exposed Valgeranna in the Pärnu Bay was formerly a very popular sandy beach with a pine forest covering the dunes. A seaside cafe is protected by a concrete wall and fitted revetment against waves and storm surges. However, this structure began to enhance erosion in Valgeranna and produced a serious sediment deficit during the past decades.

The Ruhnu study site is located on the dominantly sandy section of the eastern coast of a small Ruhnu Island in the middle of the Gulf of Riga. The island is exposed to winds and waves from all directions but currently the most active changes occur along the east coast.

Data and methods

Meteorological data

Changes in climatic variables along the Estonian shoreline have been analysed using data from coastal meteorological stations operated by the Estonian Environment Agency (EEA; Fig. 1). Three of them — Sõrve, Vilsandi, and Ristna — are located on the western coast of the west Estonian archipelago under the direct influence of the Baltic Proper where the waters are now typically ice-free in winter (Tarand *et al.* 2013). For detecting regional climatic patterns, we used a 70-year study period (1951–2020). The data on surface air temperature, wind speed and direction, storminess, and sea ice have been used as a means of establishing the links between the hydrodynamic forcing and morphosedimentary patterns along depositional coasts.

Long-term (1966–2021) variations in wind conditions were illustrated based on data from the Vilsandi station (western coast of Saaremaa Island), and from the northerly exposed Kunda station (Fig. 1). Wind velocity components (u, positive to the east; v, positive to the north) and average air flow parameters (direction) were calculated. Storminess was also analysed based on the database of wind metrics (see e.g., Orviku *et al.* 2003, Suursaar *et al*. 2015). A day was considered stormy if a 10-minute mean wind speed of 15 m s^{-1} or higher was measured at least once in the day. Catalogues of storms were created for three stations (Vilsandi, Sõrve, and Kihnu; Fig. 1). They include date(s) of storms, maximum mean wind speed during the event, storm duration, and observed wind directions. Based on the catalogues of hydroclimatic events, monthly and annual numbers of stormy days were found. Extremely stormy periods have been recognised using a specific set of criteria: the minimum duration of at least 15 days, maximum mean wind speed of $\geq$20 m s^{-1}, and at least 20% of days in the data series being stormy days (Orviku *et al.* 2003). Changes in storminess used in this study have been analysed since 1966. Before 1966, only up to four observations were performed a day. The number of storm days was analysed for autumn (September–November), winter (December–February) and for the entire stormy period (September–March).

Sea ice

Three variables of sea ice: 1) the number of days with sea ice; 2) the date of appearance; and 3) the date of disappearance of sea ice were used in this study (see also: Jaagus 2006b). Unfortunately, there are several gaps in the time series, therefore, we can use the data from only four stations. Pärnu site describes sea ice conditions in a shallow semi-enclosed Pärnu Bay, Kihnu represents the conditions in the Gulf of Riga, Kunda

— in the Gulf of Finland, and Ristna records sea ice cover near the coast of the Baltic Proper (Fig. 1). The period 1949/50–2020/21 was used for the analysis of sea ice data in Kihnu and Ristna, while for Pärnu the most recent winter when the data was available was 2016/17 and for Kunda it was 2014/15. There were some winters without sea ice — two at Kihnu (2014/15 and 2019/20) and six at Ristna (1960/61, 1991/92, 1992/93, 1999/2000, 2014/15, and 2019/20). For trend analysis we used the intermediate dates between the first appearance and disappearance of sea ice, which was 6 February at Kihnu and 10 February along Ristna. This method allows more reliable and accurate results during the monitoring period. Regional climatic changes have been investigated using the least square method and the Mann-Kendall test. A trend is considered statistically significant at the $p < 0.05$ level. Trend values are presented in days per decade, as well as in days for the entire observation period.

Sea level and wind waves

Among ~40 historic sea-level time series, just a few provide accurate long-term tide-gauge-based data (Suursaar and Kall 2018). The longest series are at Tallinn, where records of daily averages begin in 1842, and extremes since 1899. The series were discontinued due to port construction in 1995. Since 2011, measurements at Tallinn-Pirita station exist, but the locations are ~4 km apart and are exposed to different storm wind directions. The series span the intervals of 1899–2021 at Narva-Jõesuu, 1924–2021 at Pärnu, and 1950–2021 at Ristna, Virtsu, and Heltermaa (Fig. 1).

Before 2018, Estonian tide gauges were connected to the Baltic Height System 1977 (BHS77 or BK77), which was dependent on the so-called "Kronstadt Zero". Since 1 January 2018, Estonia changed its height benchmark to the European Vertical Reference System (EVRS), which is based on the level of the Normaal Amsterdams Peil (EH2000). The zeroes of these two systems differ from each other by 13–26 cm in Estonia (between 19–26 cm at the studied stations). The Kronstadt Zero was defined as the average sea level of that tide gauge during 1825–1840. However, due to sea-level rise, the present-time mean sea level of this gauge is higher, and instead the mean sea level at the Estonian tide gauges is currently near BK77 zero (Suursaar and Kall 2018). Therefore, sea levels are presented here in the BK77 system. The ~20 cm difference between Amsterdam and Kronstadt zeroes can be also interpreted, so that the Baltic Sea surface is tilted upward toward Kronstadt due to considerable freshwater input from the north and east, and prevailing westerlies causing the basinal water setup towards the northeast.

Waves have been routinely measured in the Baltic Sea in the recent decades. However, the network of wave buoys is still relatively sparse, with considerable measurement gaps (Hünicke *et al.* 2015). In the coastal sea of Estonia, we have episodically measured wave conditions close to our geomorphic case study locations using a Recording Doppler Current Profiler (RDCP600) since 2006 (Suursaar *et al*. 2008). The depths of RDCP sites were between 5.5 and 20.0 m. Altogether, 1624 days' worth of measurements (typically hourly) have been obtained between 2006 and 2014 at ten locations near the coastal study sites (Suursaar 2015).

The spatial and long-term variations in wave climate along an irregular shoreline is a subject of a separate study. Some of the latest research in the Gulf of Finland and in the Estonian coastal sea can be found in Tuomi *et al.* (2011, 2014), Björkqvist *et al*. (2018), Giudici *et al*. (2023), and Soomere (2023). The present study utilises simple wave models, which have proven to be a rather cost-effective method to analyse long-term variations at specific study sites (Männikus *et al.* 2023). It rather seems that the properties (quality) of the input wind data and mesh size of the model may have a crucial role in nearshore applications (e.g., Tuomi *et al*. 2014, Giudici *et al.* 2023). On the basis of the RDCP measurements and regular wind data, a SMB-type (fetch- and depth-based) wave model has been established and calibrated (Suursaar 2015). This allowed to extrapolate the wave conditions beyond the measurement time, so long as the wind data from the same station were available. For this paper, the previously existing time series were updated up to the end of 2021. The wave series for the westerly exposed Kelba study site used wind input from Vilsandi station (7 km off the wave measuring/modelling site). As an example for northerly exposed location, wave measurements off the Suurupi Peninsula were used. For wave model input, wind data from Pakri station were integrated over the strictly homogeneous period from 2004 to 2021 (for more details, see: Suursaar *et al*. 2015).

Shoreline changes

Aerial photographs of the study sites from 1955, 1981, 1985, and 1995 and orthophotos by the Estonian Land Board (ELB) from 1998, 2005, 2012, and 2021 were used to investigate shoreline changes through time. All the aerial and orthophotographs have been georeferenced by the ELB. Systematic (annual) field research at the study sites was initiated in 1999. Shorelines were recorded and georeferenced using a handheld GPS (~3-m accuracy) and later an RTK-GPS (~2-cm accuracy; see Tõnisson *et al*. 2008, 2013). The accuracy of integrating shorelines into GIS database varied in time and depended on the map and photograph scaling. In older sources the accuracy probably was 3–6 metres (e.g., Suursaar *et al*. 2013). Since the 1990s, only those photographs were chosen, which approximate average sea-level conditions (estimated from the daily sea-level data by the EEA). Older topographic surveys were correlated to local benchmarks to help improve accuracy and precision of changes in shoreline position. In addition, beach profiles measured over the past decades were used to assess the volumetric changes. The measurements and surveys were repeated along several profiles at the study sites at least once a year, which offered an opportunity to calculate the amount of sediment displaced on the coast over various time intervals (e.g., see Tõnisson *et al.* 2007, 2011, 2013). Based on changes in shoreline position and beach profiles, we calculate how much sediment per unit shoreline has been removed in areas of erosion and accumulated in areas of accretion. Finally, all the data were spatially overlain and analysed using *ArcGIS* and *Mapinfo* software.

Although the results from thirteen study sites (Fig. 1) are discussed in the article, the completeness and length of the data series was not sufficient for assessment of temporal changes at all sites. Therefore, a more detailed study of the Estonian depositional seashores over the past nearly half-century was performed using GIS-based cartographic analysis of shoreline at the nine study sites. All these, more or less embayed sites, represent (nearly closed) erosion — longshore transport — accumulation systems, the lengths of which were determined in the field and subsequent GIS-based analysis. The shoreline lengths of the study areas were: Kunda (2.9 km), Keibu (5.4 km), Nõva (6 km), Osmussaar (5 km), Tareste (5.1 km), Luidja (7.6 km), Kelba (2.4 km), Sõrve (6 km), and Valgeranna (4.2 km). Within these coastal sectors, segments of erosion and accretion were identified, with corresponding areal changes calculated for four sub-periods between 1947 and 2021. These intervals were not exactly the same at different study sites due to variable features at different localities and data availability. At each location and for every sub-period, the changes due to erosion and accumulation was expressed in square metres per linear metre of shoreline and a year (m^2 m^{-1} yr^{-1}). Comparison of the rates (change speeds) from nine study sites and four study periods illustrate spatio-temporal morphosedimentary trends.

Geological Database

To complement the instrumental data and to assess the direction and magnitude of sediment transport in the field, especially related to storms, different methods are employed at gravel vs. sand-dominated sections. Also, an analysis of painted sediments has been carried out to understand the local-scale sediment transport patterns at the study sites that have gravel beach ridges (Suursaar *et al.* 2013, Tõnisson *et al.* 2016).

On freshly eroded sandy beaches, dark areas of heavy-mineral concentration (HMC) can serve as indicators of reworking by waves and wind (Buynevich *et al*. 2007a). Whereas immediately following a storm, HMCs are visible on the beach surface, the older anomalies crop out in erosional scarps or trench walls dug into older sand horizons (see Fig. S3 in Supplementary Information). HMCs of variable thickness and intensity (fair-weather or storm-generated) contain varying ferromagnetic (e.g., magnetite) fractions. As an effective alternative to laborious mineralogical and granulometric analyses, bulk volume low-field magnetic susceptibility database from beach and dune sands can be used to quantify the degree of heavy-mineral enrichment (Buynevich *et al.* 2007b, Buynevich 2012, 2020).

High-resolution ground-penetrating radar (GPR) SIR-3000 and ImpulseRadar CO730 (e.g., Muru *et al.* 2018, Suursaar *et al*. 2022) were used to visualise subsurface sedimentary structures (interfaces and bounding surfaces) and anomalies (disconformities). GPR antennas included 70, 100, 270, and 300 MHz transceivers, with ranges up to 400 ns and trace spacing of 0.05 m. The post-processing and presentation of digital GPR data were performed using *Radan 7* and *GPR Slice* software. The electromagnetic georadar signal reflects variations in dielectric properties of sediment in beach and dune sequences, including electromagnetically strong response to HMCs as potential indicators of major events (intense storms, gales, and sea-ice scarping; Buynevich *et al*. 2007a, 2023a, Suursaar *et al*. 2022). Guided by GPR surveys, sediment cores were taken with an engine-driven hand auger (up to 9 m deep), a window sampler (~4 m deep), and a peat corer (up to 2 m deep), that provided accurate depths of key stratigraphic boundaries and helped to ground truth geophysical records.

Results and interpretation

Changes in climatic conditions

During 1951–2020, monthly mean air temperatures varied seasonally with minima in February (–5.3°C at Kunda; –2.6°C at Vilsandi) and maxima in July (17.7°C at Pärnu; 16.7°C at Sõrve and Ristna). The lowest annual mean temperature is typical for the coast of the Gulf of Finland (5.5–5.7°C at Kunda and Tallinn) and the warmest stations, especially in winter, are located on the western coast of the west Estonian archipelago (6.9°C at Vilsandi). The mean annual temperature at Estonian coastal stations has increased by 2.2–2.6°C between 1951 and 2020 (see Table S1 in Supplementary Information). The time series exhibited a quite stable temperature level during the early phase, a regime shift at the end of the 1980s, and a second more or less stable period with a higher temperature after the regime shift. The abrupt step-like warming since 1989 was > 1°C (Jaagus *et al.* 2017). The last year of the time series — 2020 — was the warmest due to the extremely high winter temperatures. Changes in monthly temperature are significant at all stations for all months, except January, June, and October (see Table S1 in Supplementary Information). The highest warming by more than 4°C has been observed in February and March. Higher trend values are also present in April and December. Changes in January temperature are statistically significant at some stations. Warming in June was significant only on the western coast of Saaremaa Island.

The frequency of westerly, south-westerly, and north-westerly winds has significantly increased during the winter season at several stations in Estonia during 1966–2008 (Jaagus and Kull 2011). Whereas instrumental data have indicated a decrease in mean wind speed at Estonian coastal stations during 1966–2013 (Suursaar *et al.* 2015), probably due to data inhomogeneity issues, there has been an increase in westerly wind component (Fig. 2c). Annual mean air flow direction has varied mostly within 50 degrees of azimuth (Fig. 2a,b) and according to the linear trendline, it has rotated clockwise by ~10° (westward). This partly explains the increase in u (westerly) wind component in West Estonia. The geostrophic westflow has probably increased during the same timeframe (e.g., Keevallik 2003, Johansson and Kahma 2016). On northerly exposed coast, however, the variations in meridional (v) component (Fig. 2d) is more relevant, and specifically its northerly subset (see e.g., Suursaar 2010). Because of regionally prevailing SW winds, the northerly subset has been stronger during lower v-values, e.g., during 1985–2010 (Fig. 2d).

The highest numbers of stormy days have been observed at Vilsandi and Sõrve. A clear stormy season in Estonia begins in September

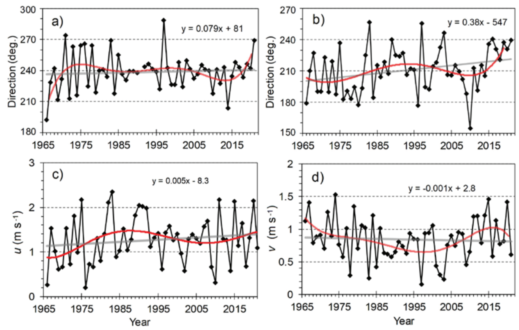

Fig 2. Variations in annual average air flow direction at (a) Vilsandi and (b) Kunda, wind velocity *u* component at (c) Vilsandi and *v* component at (d) Kunda in 1966–2021.

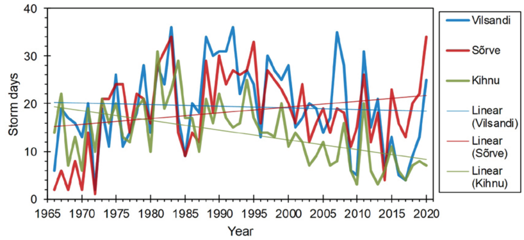

Fig 3. Annual number of stormy days at three coastal stations (see Fig. 1) during 1966–2020.

and ends in February or even March. There are very few stormy days in spring and summer. Because of a large interannual variability, it is difficult to find trends in time series of the number of stormy days (Fig. 3). A statistically significant decrease is evident at Kihnu. In addition to the reduction in the annual number of stormy days, a declining trend is also present for the entire stormy period (September–March), for autumn (September–November (see Table S2 in Supplementary Information). It is possible that the decrease at Kihnu (Fig. 3) may be caused by the growth of trees in recent decades around the meteorological observation site, which is rather difficult to incorporate into the analysis (Jaagus and Kull 2011), and due to data inhomogeneity, which has been induced by changes in measurement routines and instruments (e.g., Suursaar 2015). Apart from that, the number of stormy days has also significantly decreased at Vilsandi in autumn and in September, whereas there were no changes at Sõrve. The trends in the number of storm days indicate a minimum in the beginning of the study period, a maximum in late 1980s and early 1990s, and a decreasing trend in the latest part of the time series. Nevertheless, the year 2020 again had many storms, especially at Sõrve (Fig. 3). The number of extremely stormy periods has gone down during the past decade (Table 1). The most recent such period took place in 2015.

The total number of days with sea ice in semi-enclosed bays (Pärnu Bay) is more than double that along the western coast of the archipelago (Ristna; Table 2). It has decreased by 6–13 days per decade at six stations along the western coast of Estonia in the period 1951–2005 (Sooäär and Jaagus 2007) and the trend has continued (Fig. 4; Table 2). The first appearance of sea ice is now delayed by up to two months and the final disappearance occurs earlier by the same length of time. As a result, the number of days with sea ice has declined dramatically, by 47 days at Kunda and by 93 days along Kihnu (Fig. 4; Table 2). The changes in the ice cover on the northern coast of Estonia (i.e., in the Gulf of Finland) have been less notable than on the western coast (e.g., Jaagus 2006b).

Long-term variations in sea level and wave conditions

Depending on postglacial rebound rates at different locations, long-term trends in relative sea level (RSL) vary along the Estonian coastal margin (Table 3; Fig. 5). In fact, the trends are also different at open-sea sites, as recently detected using satellite altimetry and hydrodynamic modelling (Madsen *et al.* 2019). RSL has decreased by 7.9 cm at Ristna tide gauge and increased by 9.2 cm at Narva-Jõesuu over the past 72 years (Table 3). The difference is due mainly to different postglacial uplift rates (Suursaar and Kall 2018) but also depends on the exposure to main storm wind directions, and hence, the long-term changes in wind characteristics (Suursaar and Kullas 2006).

Earlier local sea-level rise and apparent land uplift/subsidence estimations frequently suffered from intra-site redundancies (as they were partially dependent upon each other). Recent Fennoscandian uplift models, such as NKG2016LU

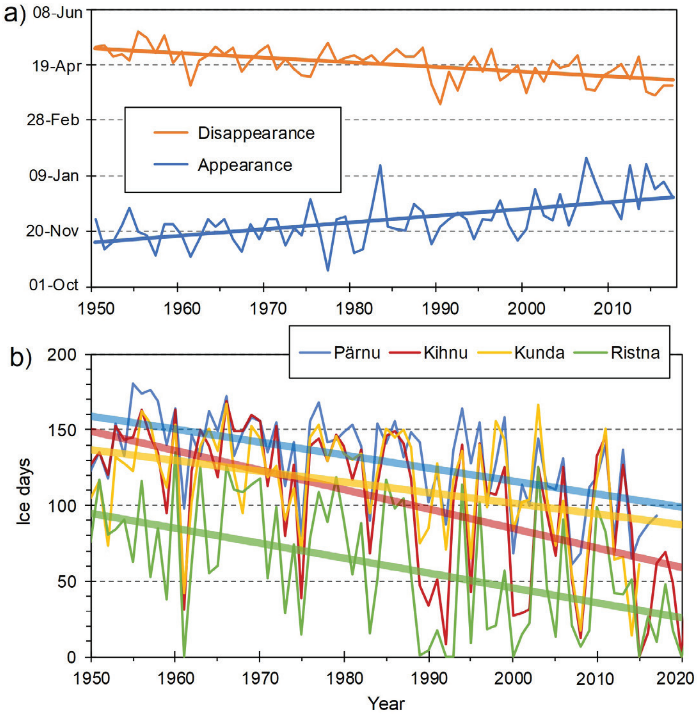

Fig 4. Trends in sea ice: (**a**) Time series and linear trends in the dates of the first appearance of sea ice and its final disappearance at Pärnu during 1949/50–2016/17; and (**b**) Time series and linear trendlines of the number of days with sea ice at four coastal stations in Estonia (see Fig. 1).

Table 1. Extremely stormy periods together with maximum mean 10-min wind speeds (Max Wind, m s^{-1}) and maximum sea levels (MaxSL; cm in BK77) at Pärnu and Narva-Jõesuu during the storm events.

Period	Max. wind	No. of stormy days	Max. SL in Pärnu	Max. SL in Narva-Jõesuu
16 Oct.–29 Dec. 1967	29	20	253	169
22 Sept.–11 Nov. 1969	24	15	191	193
11 Oct.–29 Dec. 1971	21	22		
9 Oct.–12 Dec. 1973	24	25		
20 Nov.–31 Dec. 1975	24	17		
2–29 Nov. 1978	22	15		
26 Oct. 1980–15 Jan. 1981	28	23		
23 Sept. 1983–19 Jan. 1984	23	46		169
7 Nov.–9 Dec. 1986	22	13	161	193
24 Sept. 1988–26 March 1989	22	55		
26 Jan.–24 March 1990	25	27		
2 Nov. 1991–13 March 1992	28	41	184	179
3 Jan.–6 Feb. 1993	20	18	172	167
27 Sept. 1994–1 March 1995	25	43		134
28 Nov.–26 Dec. 1999	25	16		170
27 Oct.–17 Nov. 2001	26	15		183
22 Jan.–10 March 2002	25	20		
14 Dec. 2004–16 Jan. 2005	28	15	275	194
28 Oct.–28 Dec. 2013	22	23	151	171
27 Nov.–26 Dec. 2015	23	11	164	

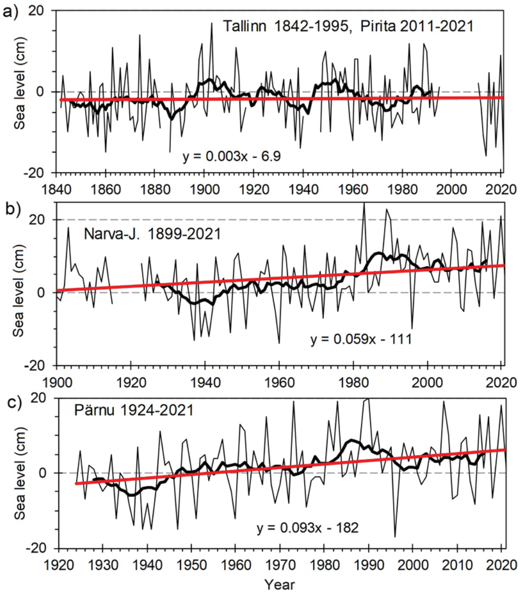

Fig 5. Variations in annual mean sea levels at selected Estonian tide gauges in the BK77 system together with moving averages and linear trendlines.

(Vestøl *et al.* 2019), describing geocentric and relative-to-geoid uplift, have contributed significantly in separating sea-level variability components. Thus, considering those local uplift rates (Table 3), the "absolute" sea-level trends can be constrained. In the Estonian coastal sea, the absolute rise has been 2.3–2.9 mm yr^{-1} during 1950–2021, but any other selected interval would yield slightly different estimate, firstly, because there is a considerable interannual variability in relative sea level, and secondly, the global (eustatic) sea level is rising (IPCC 2021). Also, the time series of annual mean sea levels reveal some unclear long-term cycles (Fig. 6), which are likely linked to similar variations in large-scale atmospheric circulation, and the NAO (Suursaar and Sooäär 2007, Jaagus and Suursaar 2013, Johansson and Kahma 2016). Quite possibly, the same quasi-cyclicity is also reflected in elevated, rhythmic beach ridge patterns and palaeo-coastlines (Suursaar *et al.* 2022).

Maximum sea levels have clearly increased in the Estonian tide gauges (Fig. 6). This finding seemingly contradicts the previous finding regarding local storminess (e.g., Fig. 3), but can be explained as follows: a) vegetation growth around weather stations and instrument changes have introduced inhomogeneity into long-term wind statistics (Jaagus and Kull 2011); b) although the mean wind speed has

Table 2. Mean values and trend values, i.e. mean changes per decade, of the first appearance and the final disappearance of sea ice, and of the number of days with sea ice in 1949/50–2016/17. All trend values are statistically significant at least on $p < 0.05$ level.

Station	Average values			Trend values (days per decade)		
	First sea ice	Last sea ice	Duration	First sea ice	Last sea ice	Duration
Pärnu	30 Nov.	19 Apr.	130	6.1	–4.2	–8.6
Kunda	25 Nov.	14 Apr.	114	6.2	–3.1	–7.0
Kihnu	11 Dec.	10 Apr.	103	9.5	–7.6	–12.9
Ristna	03 Jan.	19 Mar.	62	2.9	–6.0	–9.0

Table 3. Average sea levels in EH2000 and BK77 systems (cm), local uplift, relative (RT) and absolute (AT) sea-level trends (cm yr^{-1}), and sea-level changes by trend at five tide gauges in the period 1950–2021.

Station	Average EH2000	Average BK77	Uplift (cm yr^{-1})	RT (cm yr^{-1})	Change (cm)	AT (cm yr^{-1})
Ristna	23.1	–3.0	0.345	–0.110	–7.9	0.24
Heltermaa	20.5	–2.5	0.285	0.004	0.3	0.29
Virtsu	20.3	–0.7	0.225	0.029	2.0	0.25
Pärnu	22.2	3.2	0.165	0.066	4.7	0.23
Narva–Jõesuu	24.5	5.5	0.165	0.128	9.2	0.29

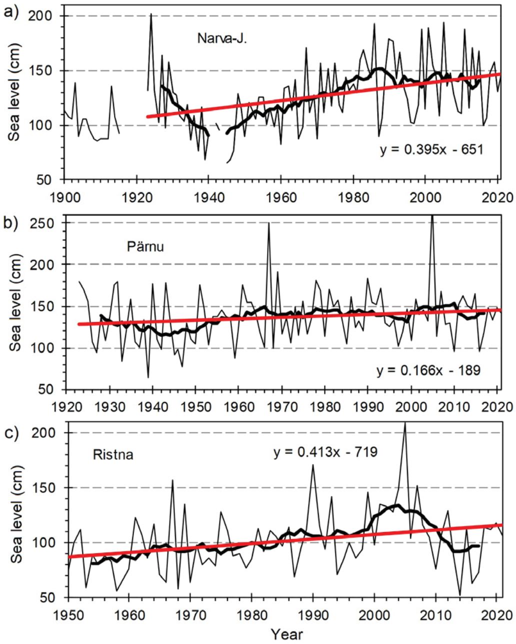

Fig 6. Long-term variations in annual maximum sea levels in the BK77 system together with moving averages and linear trendlines.

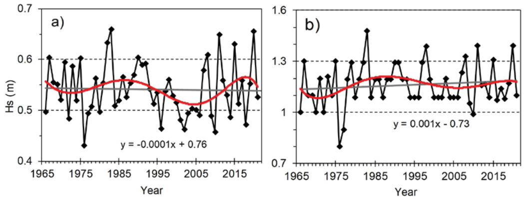

Fig 7. Hindcast wave conditions near Harilaid (~1–2 km off the coast, depth 14 m) from 1966–2021 — (**a**) Annual averaged significant wave heights (Hs); and (**b**) 90-percentiles. To illustrate quasi-cyclic long-term variations, 6th order polynomials are added to the graphs but the added linear trends are statistically not reliable.

not increased, the westerly component has, and the W-exposed Estonian coast is particularly sensitive to that change (Fig. 2; Suursaar *et al*. 2015); c) a considerable decrease in sea-ice duration and the absence of protective ice cover allows higher water level and wave impact during winter storms (Table 1). Especially sensitive to coastal flooding due to storm surges are shallow bays, like the Pärnu Bay (Suursaar *et al*. 2006, Tõnisson *et al.* 2008, 2019), where the time series include two outlier-like (yet accurate) values in 1967 (253 cm) and in 2005 (275 cm; Fig. 6; Table 1).

Wave conditions at the westerly exposed Cape Kelba near Harilaid Peninsula have seen 20–30 year cycles, that in broad terms correlate with storminess (Fig. 3), wind *u*-component (Fig. 2c), and the NAO (Suursaar *et al.* 2015). Considering the longest available time-span of 1966–2021, the waves have been somewhat higher in the 1980s and in the 2010s but lower between 1995–2010 (Fig. 7). The long-term linear trend, however, is not reliable. The instrumentally homogeneous period in 2004–2021 (Fig. 8) is too short in climatic sense, and the trends are not reliable due to the large variability. There is a clear seasonality in wave conditions with up to 2–3-fold difference between summer and late autumn. Especially high wave episodes have occurred on westerly exposed coasts in winters of 2005, 2006/07, 2011/12, and 2015/16, as well as on northerly exposed coasts in 2008/09 and 2020/21 (Fig. 8). However, the wave model did not consider the actual ice conditions, which would require a separate analysis beyond the scope of this study (e.g., Suursaar 2010, Tuomi *et al*. 2011, Najafzadeh *et al*. 2022). It is important to keep in mind, though, that whereas the coastal sea off the Cape Kelba is mostly ice-free, the northern coast of Estonia experiences much more seasonal sea ice. Considering the fact that ice conditions have turned milder (Fig. 4), there is a high chance that the northerly winter storms are increasingly destructive on the northern coast of Estonia.

Morphosedimentary changes at study sites

General overview

Figure 9 presents a summarised overview of shoreline changes at the coastal study sites analysed over four sub-periods. In general, changes within the study sites were the fastest in the north-western Estonia (Luidja and Tareste on Hiiumaa Island and Kelba on Saaremaa). Although these sites are indeed exposed to the strongest winds and waves encountered along the Estonian coastline (Tõnisson *et al*. 2008,

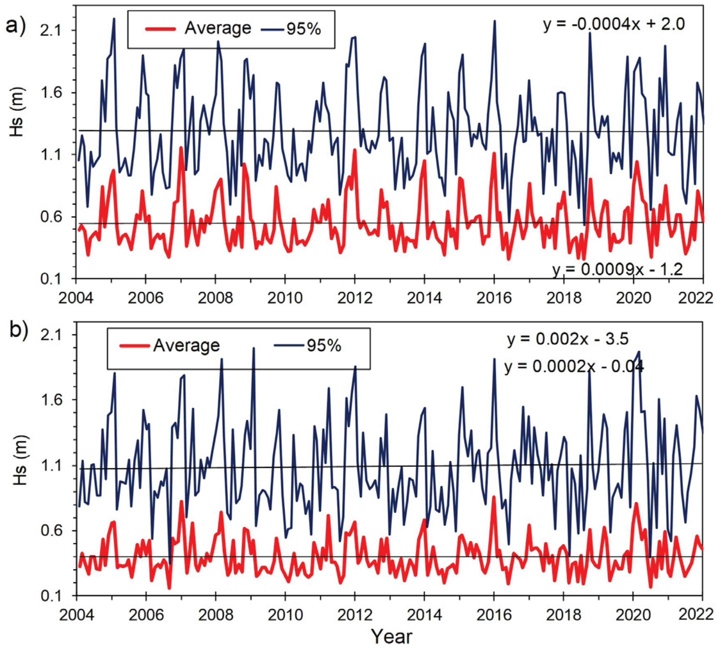

Fig 8. Monthly averages and 95-percentiles of hindcast significant wave height near (**a**) Harilaid and (**b**) Suurupi during the period represented by statistically homogeneous wind input data (2004–2021).

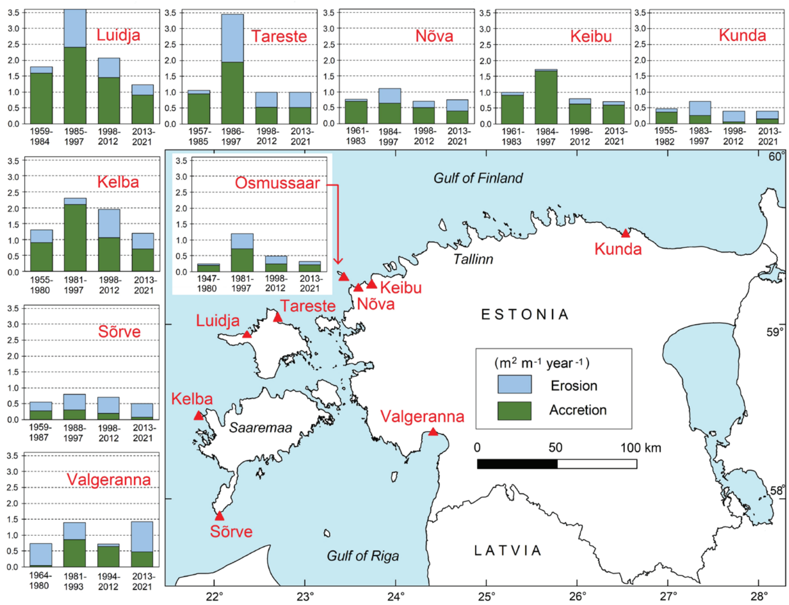

Fig 9. Cumulative shoreline change rates at nine coastal study sites (erosion-transport-accumulation complexes). Areal changes are divided into four periods, y-axis units in $m^2\ m^{-1}\ yr^{-1}$.

2011, Giudici *et al*. 2023), the different lithological and morphometrical properties of the sites do not allow additional inferences at this point. However, the variations between the sub-periods show a rather synchronous pattern with maximum values (up to 3.6 $m^2\ m^{-1}\ yr^{-1}$) between ca. 1981 and 1997 (Fig. 9). The cumulative shoreline changes in other sub-periods generally comprised approximately two thirds of those for the higher period. The share of erosion and accretion differed considerably among the study sites. Erosion dominated at Sõrve, Valgeranna, and Kunda, with accretion characterising at the other sites. In general, the share of erosion slightly increased from the initial (ca. 1955–1983) to the latest (2013–2021) interval. This shift was especially prominent at Kunda and Sõrve (Fig. 9).

Gravel-dominated shores

Gravel-dominated shores can be exemplified by Kelba, Osmussaar, Sõrve and Kunda study sites. Considering the areal change during the first period (1955–1980) by Kelba, the change has been only 1.3 m^2 m^{-1} yr^{-1}. Erosion accounted for one quarter of it (Fig. 9). A rapid acceleration of shoreline changes began at the end of the 1980s coinciding with a sudden increase in storminess (Jaagus *et al.* 2017, Fig. 3). During the following period (1981–1997), the rate of changes at Kelba nearly doubled (~2.3 m^2 m^{-1} yr^{-1}) while the share of erosion remained the same (Fig. 9). The height of eroded beach ridges was up to 4 m, whereas the freshly formed ridges did not exceed 1.5 m, being temporarily flooded. Thus, the growth of accretion sections outpaced the retreat of erosional areas.

This abrupt shift in climatic forcing is also reflected in longer annual increments of spit growth and the formation of a new lagoon at Kelba (Fig. 10b). The extreme storm Gudrun in 2005 played a critical role during the subsequent phase (1998–2012). Although the mean rates of changes diminished slightly (~2 m^2 m^{-1} yr^{-1}), the share of erosion reached 50% due to the direct impact of that storm. Subsequently, a new stage of development commenced, which is characterised by equilibrating to new climatic conditions. The intensity of shoreline processes has declined significantly during the latest period (2013–2021), including the share of erosion, with the period being comparable to the first one. The northward turn of wind (and hence, wave) directions (Fig. 2) has probably weakened the stress to the SW-exposed Cape Kelba. It seems that a new equilibrium state has been achieved and some minor changes are occurring mainly at the distal part of the spit. The situation in the Osmussaar Island study site has been similar, as when the activity rates increased by 4–5-fold at the end of the 1980s, and then have calmed down during the latest phase (Fig. 9), as the study site has more frequently appeared to be on the shade side (Suursaar *et al*. 2013).

At Cape Kelba, the relationships between storm parameters and coastal processes are quite clear (Fig. 10b). Continuous accumulation of new beach ridges elongates the gravel (pebble-cobble) spit. The material accumulated on new ridges is eroded and transported by westerly and particularly north-westerly storm surges from the submarine shoals located southwest of Harilaid. A comparison of aerial photographs from different times and extensive fieldwork revealed an elongation and widening of the recurved looped spit. As a result of storm Gudrun in 2005, the high rate of erosion along the root area caused spit elongation by > 75 m at Cape Kelba. Increments of spit growth are clearly delineated by ridge positions, and sediment flux is well correlated with storm data (Fig. 3, Table 1). In spring 2022, freshly formed beach ridges at the terminus of the spit attached to the cape and isolated the lagoon from the sea (Fig. 10b).

At Sõrve site (see Fig. S2 in Supplementary Information), the rate of changes during the first period (1959–1987) has been relatively low (~0.5 m^2 m^{-1} yr^{-1}), with ~40% share of erosion. It increased by 1.5 to 2.0 times (0.8 m^2 m^{-1} yr^{-1}) in the following period (1988–1997), with erosion providing approximately 60% of the total changes. A reduction in the activity of shore processes (0.66 m^2 m^{-1} yr^{-1}) occurred during the third period (1998–2012), but the intensity of erosion was up to 70% of the areal changes. It is interesting that the most recent period (2013–2021) at Sõrve (on Saaremaa Island) is similar to the first one (~0.5 m^2 m^{-1} yr^{-1}) but the relative contribution of erosion reached nearly 80%. The study site is exposed to the NE and E and an increase of northerly storms in recent years may be the reason for intensified erosion. Another factor is probably a decrease in sea ice (Fig. 4).

The study site at Kunda is characterised by a complex structure of deposits where sand is often mixed with pebbles, cobbles, boulders, and gleyic sediments. Despite the different location, the morphodynamic patterns largely resembled those at the previously discussed localities. Still, according to the analysis of annual field data, the shore processes have been stabilised at these study sites in the recent decades (Fig. 9).

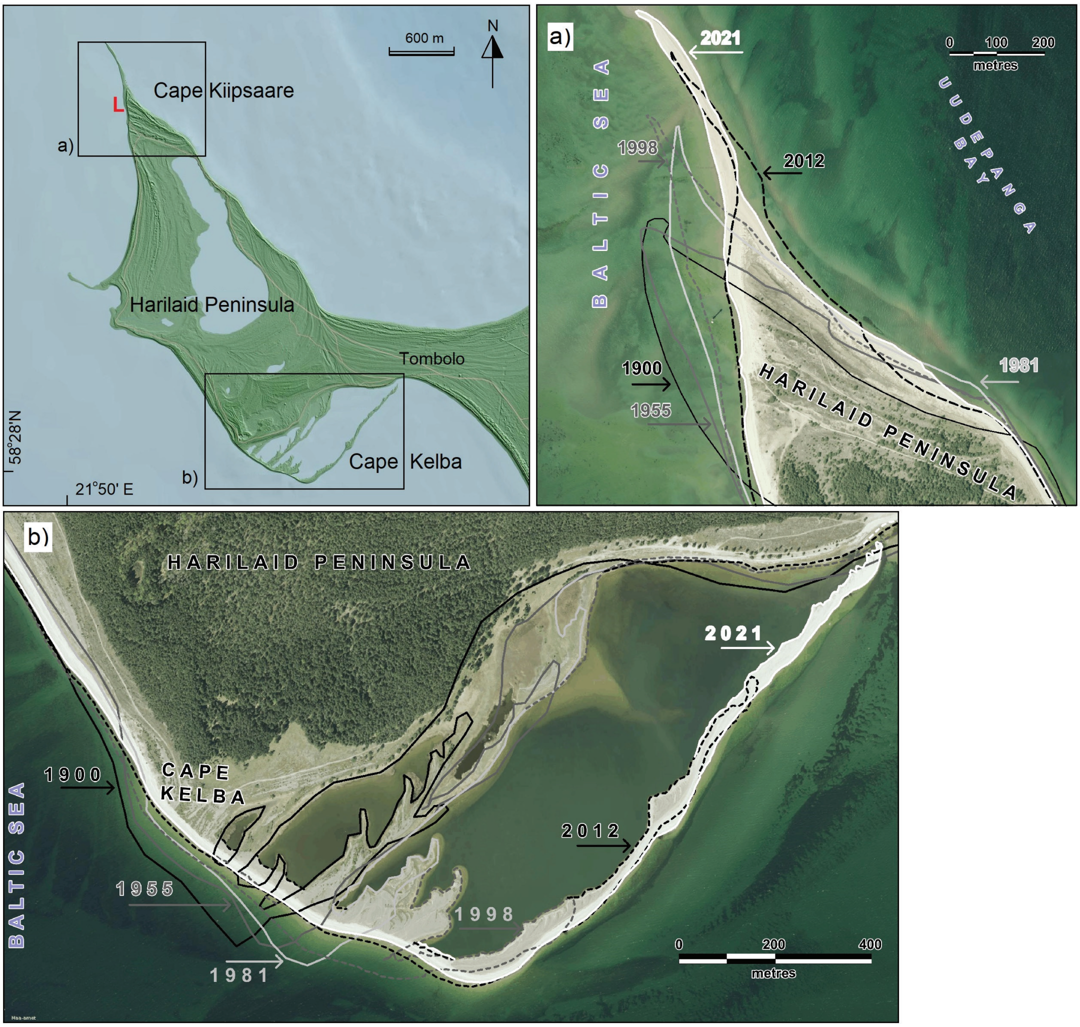

Fig 10. (**a**) Rotation and erosion of sandy Cape Kiipsaare (1900–2021) and (**b**) the corresponding accretionary segment of gravel spit at Cape Kelba. "L" on locator map — the Kiipsaare lighthouse (see also: Fig. S3 in Supplementary Information). Background images by the ELB.

Sandy shores

Study sites with sandy shores are in the northern part of the Harilaid Peninsula (Cape Kiipsaare and the tombolo), in Hiiumaa (Luidja), and in Valgeranna (Fig. 1). Erosion on the western coast of Harilaid is revealed by the position of the Kiipsaare lighthouse (close to the Cape Kelba; Fig. 10), which is currently situated in the sea (see Fig. S1 in Supplementary Information). The beacon was initially erected at the centre of the cape (> 100 m from the contemporary shoreline) in 1933. Based on the extrapolation from aerial photographs and field measurements, the west coast of Cape Kiipsaare has receded nearly 2 m yr^{-1} over the past 3–4 decades (Fig. 10a). At the turn of the century, the lighthouse was located right on the beach and leaning up to 9° off vertical. Today it is situated on the flat seabed, ~50 m offshore and is nearly vertical again, with shoreline recession in this area decelerating recently.

The main reason for the migration of the cape was intense erosion on the western coast and southward transport of sand where it was re-deposited. Part of the eroded sediment accumulated on the north-eastern and eastern coasts of Harilaid. This deposition has contributed to widening of the connecting tombolo (isthmus) between the peninsula and Saaremaa Island to the east. Although erosion has dominated on the western coast of Harilaid, the correlation between shoreline changes and stormy periods is not clear (Tõnisson *et al*. 2011, 2013). A northward turn of wind directions (although not large: Fig. 2) and decline in ice cover (Fig. 4, Table 2) can be the other reasons for such changes.

The comparison of large-scale orthophotos reveals widening of the connecting tombolo (Fig. 10) by 90 m to the north over the past 25 years and the formation of at least three new sandy dune-capped ridges parallel to the shoreline. Similar elevated palaeoridges can be found at altitudes between 4–25 m a.s.l. in the other parts of Estonia but not at lower elevations as here. Also, the GPR survey has revealed that the internal structure of these new ridges is very similar to the ancient set, which have likely formed during periods of increased storminess like the recent ones (Suursaar *et al.* 2022).

In 2019, at Harilaid, the first set of magnetic susceptibility measurements was made at 5 or 10 cm intervals in trench walls, guided by visible sedimentological variations, with recently published results presenting this approach as a potential proxy for past event sedimentation (Buynevich *et al*. 2023a). The most recent analysis of the Gudrun-related storm ridge at the Harilaid tombolo shows HMC concentrations with similar magnetic patterns to those at Cape Kiipsaare just to the northwest (Buynevich *et al*. 2023b). Similarly, rapid retreat at Tareste study area (near Tõrvanina campground; see Fig. S3a in Supplementary Information) both generates new HMCs and exposes the relict ones (see Fig. S3b in Supplementary Information), which are not present in older (800–1000 yr BP) sections of nearby Tahkuna strandplain.

Analysis of morphodynamic changes along the northerly exposed Luidja beach on Hiiumaa Island revealed that the shoreline dynamics during the first period (1959–1984) have been rather slow with minor areal changes (1.8 m^2 m^{-1} yr^{-1}) and accumulation prevailing (nearly 90% of changes) like on many other sandy beaches in Estonia. In 1985–1997, in relation to an abrupt shift in atmospheric circulation regime, many shore processes intensified by more than a factor of two (~3.7 m^2 m^{-1} yr^{-1}). The share of erosion increased quickly up to one third of all changes and an extensive flux of deposits was typical of that period. The formation of new sandy spits and incremental growth of their termini was also characteristic. Like on gravel coasts, the intensity of processes and the rate of change during the following period (1998–2012) also diminished (to ~2.2 m^2 m^{-1} yr^{-1}) at the Luidja study site. However, the relative contribution of erosion remained the same. The rate of active processes has slowed down even more (to 1.2 m^2 m^{-1} yr^{-1}) and erosional component further decreased to ~30% during the latest period (2013–2021). A new equilibrium state has been achieved and only minor changes were documented. Although the areal changes on sandy beaches over the past decade have significantly declined, the share of erosion is still relatively high, particularly for shorelines exposed to the NW, N, and NE. This can be explained by relatively low height of freshly formed accumulation areas, which can be easily transformed even by moderate waves and surges.

Scarp beaches and human intervention

At Järve-Mändjala scarp-beach complex (Fig. 1), a scarp recession by ~10 m has been observed since 1991 (Fig. 11). The retreat of the 3.9-m-high Järve erosional scarp (zone A, Fig. 11) was fast in 1991–2000 (2.0 m^3 m^{-1} yr^{-1}) and 2000–2005 (2.7 m^3 m^{-1} yr^{-1}), and much slower (0.7 m^3 m^{-1} yr^{-1}) in 2005–2021. Firstly, the eroded material was (partially) stored along the foot of the scarped dune-ridge (zone B, Fig. 11), but thereafter, the erosion expanded to the submarine slope as well. In this coastal segment (zones A and B combined), 2.1 m^3 was carried away on average per linear shoreline metre per year in 1991–2021. The affected scarp (3–6 m in height) was ~2 km long at Järve. In recent decades in general, the scarped duneridge and beach has been losing sand through longshore sediment drift towards the East, which congests Nasva port passage. Still, the width of the Järve beach did not change much immediately

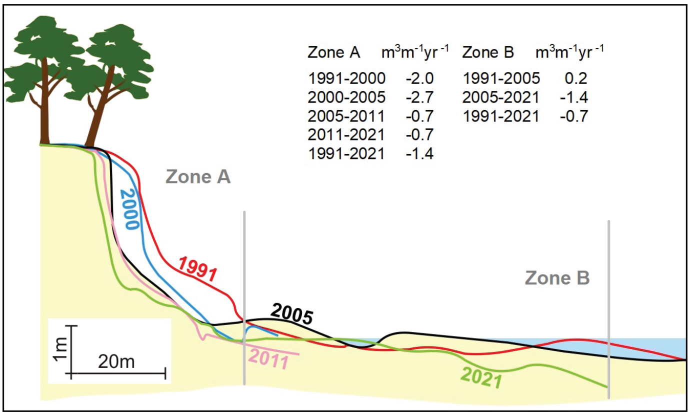

Fig 11. Scarp recession at Järve, Saaremaa Island (Fig. 1). Volumetric changes (m^3 m^{-1} yr^{-1}) in the scarp (zone A, horizontal extent 33 m) and profile changes across its submarine slope (zone B, extent 78 m) in 1991–2021.

after extreme storms, like in 2005 (Tõnisson *et al.* 2008). The sand that was eroded from the receding scarp accumulated on the nearshore seabed, reducing its gradient at first (Fig. 11) and transported to the East afterwards. A similar response was noticed at Valgeranna beach (Fig. 9) when intense storms eroded the dune scarp, and the beach area did not experience substantial changes.

The Valgeranna study site is a sandy beach with a heavy human influence. In addition to natural processes, the site has very strong adverse effects triggered by an inappropriate concrete structure (seawall and revetment) that protects infrastructure (Doberan Café) erected too close to the shoreline (Tõnisson *et al.* 2019). Here, the land uplift in relation to geoid is the lowest (~1.7 mm yr^{-1}) among the study sites, being slower than the mean sea level rise in this area (Table 3).

The first period of 1964–1980 in Valgeranna is characterised by slow changes (0.75 m^2 m^{-1} yr^{-1}) like at all the other study sites (Fig. 9). Nearly 90% of total changes came from erosion. This can be explained by a storm in 1967 that impacted mainly the SW coast of Estonia and was associated with record-high storm surge (2.53 m above mean sea level at Pärnu) and concurrent extensive inundation in Pärnu city (Tõnisson *et al.* 2008). As at other study sites, the speed of shoreline changes nearly doubled (1.4 m^2 m^{-1} yr^{-1}) in 1981–1993, but the share of erosion decreased to one third. Intensive accumulation of sand around the outlet of Audru River occurred over the second period (1981–1993). Consequently, erosion in the vicinity must have been quite intense. The third period (1994–2012) revealed a reduction in the rate of changes (0.75 m^2 m^{-1} yr^{-1}), while almost no erosion was recorded. The storm Gudrun eroded great volumes of sand from the scarp, with subsequent accumulation on the nearshore, keeping the shoreline profile more or less stable. The seawall of the Doberan Café built after Gudrun, started to hinder the longshore sediment transport and was functioning as a reflective wall to waves during high sea level conditions. The consequences were clearly visible by the end of the most recent period (2013–2021) when the changes were rapid (1.4 m^2 m^{-1} yr^{-1}) and the share of erosion reached ~2/3 of the total. This is the only study site in Estonia where a significant increase both in shore processes and morphological changes along the beach has recently occurred.

Discussion

The interplay of variations in wind, waves, sea level, sea-ice and coastal morphodynamic metrics can be exceedingly intricate in the Baltic Sea (e.g., Orviku *et al.* 2003, Suursaar *et al.* 2008, Eelsalu *et al.* 2022, Soomere *et al.* 2022, Różyński and Cerkowniak 2024). At the beginning of the 21st century, we began a series of more systematic, process-oriented investigations with the main focus on Kiipsaare and Kelba study sites on Harilaid Peninsula in Estonia (Figs. 9, 10). Coastal sections of varying exposure and structure, such as sandy beaches in the north (Cape Kiipsaare) and downdrift gravel beach ridges in the south (Cape Kelba), have undergone major, yet different, types of changes (Fig. 10b). The earlier accumulative shoreline positions on the Cape Kiipsaare are well marked by a series of parallel compound beach/dune ridges, which cross the current coastline at an angle of 50–55^o (Fig. 10a). Shore processes during the past century have caused the NW-most point of the peninsula (flying spit) to migrate to the northeast, becoming longer and narrower. The dominant process along the western coast of the cape is erosion, as evident by a scarp formed as a result of many strong storms since the beginning of the 1980s.

Research over the past decades indicates that accumulative coasts, particularly sandy and fine-gravel beaches, are most vulnerable to the sea level rise (e.g., FitzGerald *et al*. 2008, Jarmalavičius *et al.* 2016, Różyński and Cerkowniak 2024), absence of sea-ice cover in winter when frequent strong storms accompanied by high sea level are impacting the coasts (Orviku *et al*. 2003, 2009, Tõnisson *et al*. 2008, 2013). This combination induces intense erosion, transport, and accumulation of sediments above the mean sea level and inland of the mean shoreline, and leads to substantial changes in coastal morphology persisting for years or even decades. As any kind of kinetic energy (from wind, waves, or currents) is roughly exponentially proportional to velocity (e.g., Leppäranta and Myrberg 2009), the energy of extremely strong (dominant) storms is many times higher than that of more frequent weaker (prevailing) events. Also, in terms of mean sea-level conditions, the incident wave energy is typically concentrated and released near the mean shoreline. If sea level is high with storm surge occurrences (due to tangential wind stress and antibarometer effect), the wave energy focused and then dissipated above the mean shoreline dramatically alters coastal morphology (Orviku *et al.* 2003).

Most vulnerable to stormy winds and waves are areas located on the western coasts of Estonia, which are exposed to the Baltic Proper. Rapid changes on depositional shores may occur quite often in a situation when the equilibrium profile has not fully recovered before the next event. A cyclone Gudrun (on 7–9 January 2005) was a perfect example of such a combination. In Estonia, it was among the strongest storms on record in meteorological terms, being somewhat comparable to events on 6–7 August 1967, 18 October 1967, 23 January 1995, and 27 October–2 November 1969. However, as a result of high initial levels of the Baltic Sea, the fast-traveling cyclone with a favourable trajectory and strong SW-W winds created a record high storm surge (275 cm) in Pärnu, as well as at many other locations along the west Estonian coast (Suursaar *et al.* 2006). Gudrun induced clearly visible changes in the development of shores and the dynamics of beach sediments over almost entire Estonian coastal margin. Powerful storm waves combined with high sea level caused substantial changes in coastal geomorphology along multiple depositional sections on Saaremaa Island, as well as along the mainland Estonia (Tõnisson *et al.* 2008, 2011). Similarly, Gudrun caused massive coastal morphodynamic response in Latvia and Lithuania (Jarmalavičius *et al*. 2016, Kelpšaite-Rimkiene *et al*. 2021), while further away from the storm track, e.g., in Poland and Germany, there have been their own, quite different "storms" of the century (Hünicke *et al.* 2015, Wolski and Wiśniewski 2020).

As for the depositional consequences (post-storm or downdrift), changes caused by Gudrun at the terminus of Sõrve spit are noticeable when comparing the photos taken before and after the storm (see Fig. S2 in Supplementary Information). At Järve-Mändjala study site, wave action (from S, SW) was stronger at the beginning of Gudrun, but weaker when the wind turned from SW to NW, the fetch was reduced, and sea level started to drop (Tõnisson *et al.* 2008). The scarp receded by 4 m during Gudrun (Fig. 11). Thereafter, the retreat continued at a slower rate (Fig. 9). The seabed ~50 m from the shoreline has steepened. The eastward longshore sediment transport is maintained by infrequent storms during the recent decade, so the study site experiences sediment deficit. This, in turn, creates favourable conditions for greater beach erosion during subsequent extreme storm events (e.g., Bird 1985).

During the past 15 years, not a single storm similar to Gudrun has impacted the coast of

Estonia, although some stormy periods have been registered, such as storms Berit and Ulli in winter 2011/2012 and Saint Jude in October 2013. The hydrological characteristics of the storm Saint Jude were rather powerful but its impact was clearly visible only on the western coast of Saaremaa and at Valgeranna. Due to elevated sea level and high waves, the scarp at Kiipsaare lighthouse receded at a mean rate of 1 m per hour (Tõnisson *et al.* 2016). By the end of the storm, the scarp was flattened and ~20-m-wide belt of fresh sand covered the formerly vegetated area. The spit at Cape Kelba quickly elongated and some gravel was washed over the older beach ridges, thereby shifting the spit landward.

During the 10 years following storm Saint Jude, the coastal processes have more or less stabilised and the seashores have attained a morphodynamic equilibrium in Estonia. For greater changes, much stronger westerly storms would be required to overcome a suite of thresholds and to re-establish a new equilibrium. For instance, while at Kiipsaare erosion has been the dominant process since the beginning of the 20th century and until Saint Jude in 2013, the situation has drastically changed in the past decade. The climatic databases clearly show a reduction in westerly storm impact and an increase in winds from the N and NE. Recession of the western coast of Cape Kiipsaare has decelerated over the recent decade as a consequence, with stronger erosion occurring along the northern and northeastern side of the cape. As a result, the shoreline there has retreated ~20 m and the top of the cape has turned back to a westerly orientation (Fig. 10a). A new ridge, which is parallel to the shoreline has grown to > 2.5 m a.s.l. and is oriented almost perpendicular to the older set. Similar ridges, perpendicular to the older ones, have also formed ~2000 years ago on Ruhnu Island (Muru *et al.* 2018), which shows that shifts in forcing conditions have occurred in the past and will likely occur in the future, too.

However, some notable beach erosion in the past decade have been registered in NW and N Estonia, for example, on Hiiumaa Island, as well as at Keibu and Nõva. This is likely attributed to an increased share of NW, N, and NE storms, as well as to a substantially reduced duration of sea-ice cover (Figs. 3, 4). On the northern coast to the East from Kunda, reconstruction of the port in Sillamäe two decades ago blocked the eastward longshore sediment transport. It was assumed that such an interruption of sediment flux would result in much higher rates of erosion along Sillamäe Beach, but 20 years of monitoring indicates relative stability. The higher share of N and NE winds and waves have probably supplied the beach with new sediment from other directions, which were previously not as dominant a source (Tõnisson *et al*. 2014).

Consequently, following abrupt shifts in climatic conditions, the coasts have started to adjust to a new equilibrium state (Tõnisson *et al*. 2019). This is reflected in increased sediment transport volumes, including accelerated erosion in source areas and sediment transport segments, and in rapid expansion of accumulation regions. Meanwhile, effects of extreme storms, such as Gudrun, can affect the character of shore processes for decades or even longer by incorporating more deposits into active sediment transport zones. In addition to natural causes, inappropriate anthropogenic impact may result in accelerated disappearance of beaches, which, in turn, may be amplified by rising sea level (Bird 1985, Weisse *et al.* 2021, Różyński and Cerkowniak 2024). At our study sites (Fig. 9), whatever the forcing (climatic or human-induced) may trigger a cascade of rapid and difficult to predict morphodynamic responses until a new balance is achieved.

Conclusions

Understanding the structure, dynamics, and development of a suite of geomorphic shore types and their responses to hydrodynamic forcings is crucial for ecosystem conservation and for managing adaptable and resilient coastal communities. Research along depositional seashores during the past half-century in Estonia has revealed the following:

(1) In the period 1951–2020, annual mean surface air temperature at coastal stations in Estonia has significantly increased by 2.2–2.6°C. Recent changes in wind regime, sea level, wave climate,

and sea ice conditions have caused temporal morphodynamic variations along coasts. However, since the middle of the 20th century until the 1980s, the shore processes were rather slow. Slow erosion on the seabed and slow expansion of the beaches was typical, and strong storms with substantial impacts were exceptional.

(2) Following an abrupt shift in the regime of climatic forcing since the end of the 1980s, the frequency of storms and high sea levels increased, and the duration of sea ice cover diminished. This triggered rapid changes along depositional shores — strong erosion of older beach formations, retreat of shorelines and scarping along exposed sectors, expansion of accumulation areas in wave-shadow areas, as well as formation and extension of spits due to intensified longshore sediment transport.

(3) Over the period since the second half of the 1990s until 2012, a decrease in shore processes occurred despite the extreme storm Gudrun in January 2005. Although Gudrun caused extensive floods and beach destruction, it reduced the impact of subsequent storm events. For instance, fine-grained sediments were winnowed from the swash zone and transported either far inland or back into the sea, while the coarser material persisted and armoured the shore against further erosion.

(4) The past decade is characterised by a decrease in storminess and intensity of coastal changes. The beaches are adapting to fair-weather background conditions in a new equilibrium state. The sandy beaches with an intensive longshore sediment transport (e.g., Järve Beach on Saaremaa) are characterised by a slow winnowing of fine-grained fraction in the currently relatively calm weather conditions. Coarser-grained sediments remain on the beach and the nearshore slope is steepening. This creates favourable preconditions for beach erosion during future intense storms.

(5) New accumulative beach formations have started to form on Cape Kiipsaare on Saaremaa Island, and are oriented almost perpendicular to the older ones. This is likely due to a change in regional atmospheric circulation over the past decade, the increase in northerly winds and waves, and a mode shift in shore processes.

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