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Attribution of alterations in coastal processes in the southern and eastern Baltic Sea to climate change-driven modifications of coastal drivers

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Abstract
The main drivers of coastal processes, such as wave activity, variations in the water level, ice cover, and wind drift, may act differently in different segments of marginal seas with complex shapes. We analyse how the relative role of these drivers on the evolution of sedimentary shores changes along the southern and eastern Baltic Sea. While changes in the average water level have a strong impact along the southern shores of the Baltic Sea, rapid increases in the water level extremes affect most of the eastern subbasins of the Gulf of Finland and Gulf of Riga. The presence of a two-peak structure of predominant winds creates a fragile balance of alongshore sediment transport on the northeastern part of the Baltic proper and the Gulf of Riga. This balance could be changed by a rotation of predominant wave directions by a few degrees. Severe waves usually occur on the southern shores of the sea during water levels that are close to the long-term mean, while synchronisation of strong waves and high-water level is common on the eastern shore. The presence of sea ice is uncommon and insignificantly damps coastal processes in the southern part of the sea but the frequent presence of ice cover and freezing temperatures during the windy season stabilise the beaches of the north-eastern shores. Climate driven changes in ice cover duration may lead to erosion of many beaches in this part of the sea. The core message is that the impact of a single manifestation of climate change may vary greatly in different parts of the Baltic Sea and the reaction of coastal processes to this impact is substantially site-specific.

Keywords
Baltic Sea; Climate change; Coastal drivers; Coastal changes

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1. Introduction

Climate change is often cited as a primary driver of accelerated coastal change (Blum and Roberts, 2009; Nicholls and Cazenave, 2010; Davis, 2011; Valiela et al., 2018; Bidorn et al., 2021). A particular reflection of this perception is that much of the world's sandy coastline is suffering from degradation (Bird, 2008; Luijendijk et al., 2018). Erosion has been documented in numerous locations around the world. This process has been particularly extensive in low-lying areas (Zhang et al., 2004; Cai et al., 2009; Sinitsyn et al., 2020), and apparently has accelerated over recent decades.

Climate change becomes evident in a variety of processes that affect the development of shores of seas and oceans. On a large scale, the increase in global mean sea level is almost certainly the most significant driver of change (IPCC, 2019). This increase has been documented for almost a century and has accelerated in the recent decades (Oppenheimer et al., 2019). In particular, sea level rise (SLR) has been identified as the principal forcing component of large-scale shoreline retreat. This is a particularly severe driver in subsiding coastal areas (Shirzaei et al., 2021), including parts of inland seas, such as the vicinity of Sharm El-Sheikh on the Sinai Peninsula (Seleem et al., 2011) or the southern Baltic Sea (Harff and Meyer, 2011). Other well-known examples are the loss of sea ice in northern regions (Polyak et al., 2010) and changes to wave properties in many areas (Erikson et al., 2022).

However, attribution of observed changes at the coast to climate change-driven impacts and associated changes in even the main drivers remains challenging. The reason is that multiple factors and processes, such as sediment availability, local features of the wave climate, tidal range, extensive spatiotemporal variation in the properties of storm surges and/or shifts in the trajectory of low-pressure systems, as well as the effects of human interventions, also affect the evolution of shores (e.g., Jackson et al., 2019; Gao et al., 2020). Consequently, the signal of climate change may frequently be masked by the remarkably complicated behaviour of shores, at different temporal and spatial scales. Its identification and attribution is a complicated task made even more difficult by the distinct regional variability.

To mitigate and adapt to climate change, it is necessary to understand how climate change may affect coastal drivers and thus coastal evolution. In particular, it is essential to distinguish the signal of climate change-driven changes from natural variability. For example, sandy beaches may exhibit specific morphodynamic cycles of natural evolution over time scales of several years (Pilkey and Cooper, 2014), perhaps resulting from significant changes to the sediment budget (e.g., Mahmoud et al., 2021). A seaward movement of sediment during storms is an intrinsic component of the idealised cut-and-fill cycle (Brenninkmeyer, 1982). It may take months to years for the beach to return to its pre-storm state, but in most cases it does. This is also the case in the Baltic Sea where beach recovery takes much longer than the loss of sand (e.g., Różyński, 2005; Ostrowski et al., 2016). The intermediate changed beach state is sometimes mistakenly considered to be indicative of erosion. It is thus essential to recognise whether this natural cycle is being interrupted by additional pressures, such as an increase in storminess or changes in the properties of storms, which may be hidden within a longer-term cycle of change.

Human interventions may also cause major changes on the beach, both locally – by blocking sediment transport or altering transport processes – and at greater distances from the site of intervention (e.g., Huang, 2022). There is a large body of research on human-driven changes to coastal processes in the Baltic Sea region, see, e.g., a detailed overview of beach nourishment activities in Poland by Boniecka and Kubacka (2024). As our aim is to identify specifically those changes that can be linked to climate change-driven changes to coastal drivers, we omit the discussion of situations in which anthropogenic impacts dominate or are likely to be very significant.

1.1 Changing drivers of coastal processes of the Baltic Sea

Coastal areas of the Baltic Sea have experienced a multitude of changes in their functioning since adequate measurement data sets became available. Such data cover mostly only a few decades. A common feature of its southern and eastern sedimentary shores is the intensification of coastal processes (Orviku et al., 2003; Suursaar et al., 2015; Ryabchuk et al., 2011a,b) and the acceleration of coastal erosion in many locations (Ryabchuk et al., 2012, 2020; Łabuz, 2015, among many others). This general pattern is modulated in some locations by a switch between accumulation and erosion (e.g., Ostrowski et al., 2016) or by a systematic alongshore shift of the locations of accumulation and erosion (Uścinowicz et al., 2024). The general perception is that this intensification reflects, at least to some extent, the impact of climate change in the Baltic Sea region (BACC, 2015; HELCOM, 2021; Weisse et al., 2021).

Some weather patterns and parameters that are affected by climate change play a fundamental role in coastal evolution. Global warming has reduced the length of Baltic Sea ice period and the extent of sea ice cover (Vihma and Haapala, 2009; Haapala et al., 2015). This trend is expected to continue in the future. Sea level is rising (see Weisse et al., 2021 for an overview and further references) and will continue to rise in the Baltic Sea, possibly at even faster rates than in the rest of the World Ocean (Grinsted, 2015). This driver is crucial for the southern Baltic Sea (Harff and Meyer, 2011) but it has limited impact in the northern, uplifting part of the sea. Additionally, short-term strong variations in the water level at the shoreline (e.g., storm surges), especially extreme water levels that may involve wave setup (Su et al., 2024), may significantly affect the impact of waves on the shore. The role of atmospherically driven water level variations is particularly large because of the negligible amplitude of tides in the Baltic Sea (Weisse et al., 2021).

The role of large-scale atmospheric circulation patterns is unclear. In particular, the North Atlantic Oscillation (NAO) that governs the intensity of the main coastal drivers, such as wind and wave fields, has high interannual variability but does not show a significant trend over the last century (HELCOM, 2013; Meier et al., 2022). The overall wind speed and significant wave height (SWH) have not systematically increased in the Baltic Sea region over the last century (Hünicke et al., 2015). However, changes in the directional distribution of winds in several areas of the north-eastern Baltic Sea (Jaagus and Kull, 2011; Kelpšaitė and Dailidienė, 2011; Krek et al., 2016) that have the longest fetch for the predominant south-western winds have caused changes to the properties of storm surges and wave set-up heights (e.g., in the Gulf of Finland, Pindsoo and Soomere, 2015). In particular, modifications of the directional structure of (stronger) winds in winter (Bierstedt et al., 2015) have likely affected the properties of storm surges in the downwind areas, such as the Gulf of Finland and the Gulf of Riga. Weather patterns that drive elevated levels across the entire sea have become more persistent (Soomere and Pindsoo, 2016; Männikus et al., 2019; Rantanen et al., 2024). Thus, it is likely that many low-lying coastal areas of the Baltic Sea will suffer from flooding and will experience a higher rate of coastal erosion in the future (Różyński, 2023).

Processes at the shoreline often serve as highly sensitive indicators of climate change-driven changes in the hydrometeorological drivers. In particular, wave-driven sediment transport is a feasible marker of changes (Soomere et al., 2015a). The wave height in fetch-limited conditions is roughly proportional to the wind speed squared. The intensity of sediment transport is related to the wave height to the power of approximately 2.5 (USACE, 2002). Therefore, even a slight increase in wind speed may affect the sediment transport at much higher rates. The sediment budget of the (north-)eastern shore of the Baltic Sea reflects a fragile balance of alongshore transport driven by a two-peak wind pattern (Soomere and Keevallik, 2001). Thus, even a small change in the directional structure of the predominant winds can lead to the instability of major landforms (Viška and Soomere, 2012). Although wind is clearly a primary driver for moving sand on a dry beach and building (fore)dunes (e.g., Dluzewski et al., 2023), we have not identified any substantial conclusions relating to the changing role of wind on these processes in the international research literature. For this reason, we only consider the role of wind implicitly, via alterations of wave fields and storm surges.

The reasoning provided leads to four core drivers of coastal processes in the Baltic Sea: relative sea level change, short-term (seasonal to hourly) water level variations (including extreme water levels and wave setup), changes in the ice cover, and wave-driven transport.

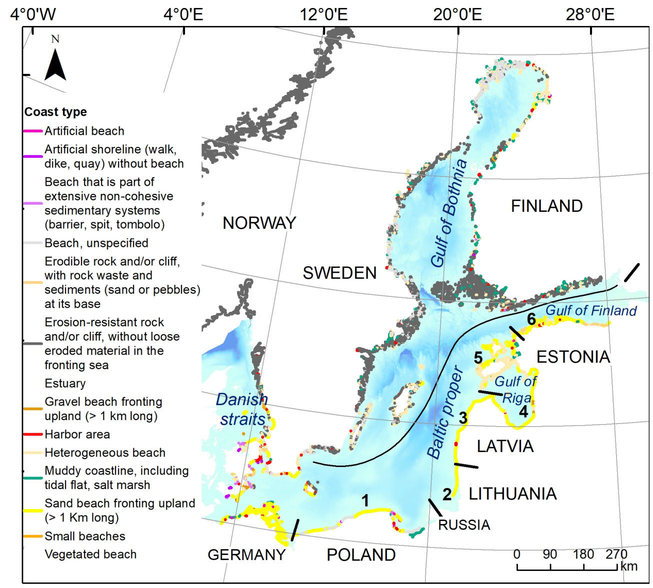

Figure 1. Location scheme of the study area on the southern and eastern Baltic Sea coast and its separation into six domains applied in the analysis (numbers along the shore) (right panel). The black line indicates the division of bedrock and sedimentary coasts. Coastal domain 4 covers the interior of the Gulf of Riga. Coastal domain 5 includes the western part of the Estonian coast from the entrance to the Gulf of Riga (Irbe Strait) to the entrance of the Gulf of Finland. We do not discuss the processes on limestone cliffed coasts in several sections of the Estonian shore in domains 5 and 6. Coloured lines (legend provided on the figure) along the coast show the coast type accessed from the European Marine Observation and Data Network (https://emodnet.ec.europa.eu/en/geology).

1.2 Challenges in the identification of climate change-driven influences

It is customary to separate the drivers in question into clusters with different spatial and temporal scales. Spatial separation is naturally governed by the geology and geometry of the Baltic Sea (Figure 1). As the Baltic Sea has a very complex shape, the properties of some of these drivers (e.g., wave impact in terms of wave energy flux arriving at the coast) may vary significantly over even short distances (Soomere and Eelsalu, 2014). Their balance and local impacts depend on the orientation of the shoreline, the fetch length, the level of exposure to predominant wind and wave directions, and other hydrodynamic peculiarities, and are often modified by anthropogenic actions (Weisse et al., 2021; Reckermann et al., 2022).

The specification of the temporal scales of these drivers is an even more complicated issue. Common categories are long-term and short-term processes, and extreme events. Post-glacial uplift is an almost constant background process. The relative change in sea level and changes in ice cover are long-term processes. As they work differently and become evident in different sea areas, we keep them separate. Wave-driven alongshore transport may be described at very different temporal scales. Local water level variations extend from seasonal fluctuations to short-term variations and extreme water levels that include wave setup.

Another difficulty arises in determination of the analysis period. It is generally desirable to define the specific time period and explain when the changes are considered to have started. However, we do not know beforehand which time period contains a clear signal. The course of, for example, the world temperature, with a plateau in the 1950s–1970s (the hiatus of climate change), is just one variable of climate change. Other variables may have their plateaus over different time periods. For this reason, we do not set any exact time window and try to retrieve a common signal from analyses performed for different time windows, to minimise the impact of a particular observation period on our conjectures.

Furthermore, we want to understand and demonstrate which changes in coastal processes could be attributed to climate change. This exercise relies largely on (the rates of) changes that are, ideally, independent of the particular period. As ideal conditions never occur in coastal science, it is important to use in as many long-term studies as possible, irrespective of the time period covered.

The biggest problem with the kind of analysis we try to perform is that almost every source used its own time window. To our understanding, the best strategy is to retrieve the common signal from multiple sources that address processes over different (partially overlapping) time periods. Only if different studies tell basically the same story, does it make sense to suggest a link to some of the climate change-driven forcing factors.

It may happen that different sources have identified different trends for the same variable. For example, Soomere and Räämet (2014) and Sokolov and Chubarenko (2020, 2024) have revealed disparate trends in wave height. Interestingly, both results are reliable. That is, both papers demonstrate that there have been no radical changes in wave heights in the Baltic Sea since the 1970s, when the upward trend of global air temperature resumed. This agreement actually shows that rumours about increased storminess in the Baltic Sea basically reflect the perception in some small regions and that this perception is not applicable to the entire Baltic Sea. Moreover, this tells us that changes to wave-driven alongshore sediment transport are either local or generated by changes in wind parameters other than speed, most likely by changes in wind direction.

The existing evidence signals that substantial changes to the drivers of coastal processes have occurred not only in different locations but also at different points in time. For example, a major change in the direction of geostrophic air flow over the southern Baltic Sea occurred in 1987/1988 (Soomere et al., 2015a), while regime shifts in the properties of the generalised extreme value distribution for water level extremes in the Gulf of Riga occurred in 1984 and 1990/1991 (Kudryavtseva et al., 2021). Given this situation, identifying or establishing a reference point in time for climate change-driven processes may inadvertently exclude some of these processes from consideration.

The Baltic Sea coasts are massively developed, from major ports and moles to small-scale shore protection works. These influences evidently contribute to the course of coastal processes and usually make it impossible to single out climate change-driven effects. Perhaps the most impacted segments are some parts of the Polish coast (e.g., the Hel Peninsula, sometimes called Hel Spit), the eastern part of the Vistula Spit close to Baltiisk, several segments along the western and northern part of the Sambian Peninsula, and the vicinity of the port of Klaipėda and the large Latvian harbours. These locations are omitted from the analysis below. Some of these locations are addressed in older Russian-language sources. However, since the methods used and accuracy reached in these sources do not always match contemporary standards, their use is complicated, and such sources are employed only occasionally.

1.3 Response of coastal areas to changing drivers

This study focuses on the possible attribution of observed changes on sedimentary shores of the Baltic Sea to various variables related to climate change in the region, based on the existing pool of relevant research data. A formal attribution involves precise quantification of the impact and its links to particular drivers. This is particularly challenging for coastal processes due to the scarcity of long-term high-resolution observations of shoreline changes and the lack of data on variations in the volume of sedimentary beaches in the study area. For this reason, we attempt to combine existing observational knowledge with the outcome of various simulations of waves, water level, and alongshore transport. The emphasis is on situations where certain processes may have accelerated due to climate change.

Specifically, we discuss the possible link between single manifestations of climate change and changes to the main coastal drivers discussed above along the southern and eastern shores of the Baltic Sea. The primary goal is to highlight the varying roles of different drivers across coastal segments and to identify which of these factors may have contributed most significantly to changes in hydrodynamic loads on the coast, and potentially on the shoreline. A specific focus is on the spatial variations of these links.

In short, the main goals are to (i) understand which drivers (and their changes) predominate in climate change-driven alterations of different segments of the southern and eastern Baltic Sea shores, and (ii) estimate whether the changes to the shores may reflect climate change. This knowledge is essential to determine mitigation measures for current and future marine-driven impacts and for the sustainable management of the coastal zone.

The gradients of single manifestations can be identified to some extent for the shores of the southern and eastern Baltic proper, the Gulf of Riga, and the Gulf of Finland. The situation in the westernmost part of the Baltic Sea, including the German coast in Mecklenburg-Vorpommern and the island of Bornholm is not only different but also much more complicated. This largely landlocked water body experiences a relative rise in sea level. This driver alone has a very limited impact on coastal processes. This region is much less affected by changes in wind and wave patterns because the wave climate is relatively mild (Cieślikiewicz and Paplińska-Swerpel, 2008; Soomere et al., 2012) and there is no indication of changes in wave height (Kudryavtseva and Soomere, 2017). Sea ice is uncommon and thus the impact of its loss is marginal. Although extreme water levels are some of the highest in the entire Baltic Sea (Andrée et al., 2023), the number of high storm surges is only a fraction of what is observed at the more eastern sedimentary shores of the Baltic Sea (Wolski et al., 2014). Therefore, it seems not viable to single out the impact of climate change on coastal processes in this region based on the pool of existing research even though the entire coast of Pomeranian Bay is often considered as one structure

(Hoffmann et al., 2005; Lampe et al., 2011). For this reason, we focus on the shores east of the Swina Gate located at 14.3°E.

We start from a short overview of the characteristics of coastal areas of the Baltic Sea, introducing the geological and geographical settings and summarising the basic features of hydrodynamic processes that drive most of the coastline evolution in particular areas. This material is followed by a discussion of the spatially variable intensity and intermittent role of the main coastal drivers in the Baltic Sea. A particular aim is to highlight the changes these drivers have experienced since the 1970s, as earlier data is scarce. Still, when available and applicable, we also employ both older data (mainly reflecting water level and shoreline relocation) and newer data that cover shorter time periods. Finally, we aim to connect changes along the coast to changes in specific coastal drivers, identify regions where individual drivers predominantly influence the nature or intensity of coastal processes, and illustrate basin-scale gradients of these individual drivers.

2. Coastal drivers and domains

The identified most important coastal drivers in the Baltic Sea – relative sea level change, short-term water level variations (including extreme water levels), and the properties of waves and sea ice – often combine to play a fundamental role in forcing coastal processes and shoreline changes (Orviku et al., 2003; Ryabchuk et al., 2011a, 2012; Harff et al., 2017; Orviku, 2018; Weisse et al., 2021; Eelsalu et al., 2022), as well as in the formation of several marine-driven coastal hazards. As mentioned above, much slower processes such as isostatic land uplift or subsidence, or long-lasting fluvial sediment supply, although they may modify long-term coastal evolution (Stive et al., 2002; Sallenger et al., 2012; Harff et al., 2017), are not considered here.

The relative contribution of these processes to the sediment budget and shoreline change is very location-specific (Sallenger et al., 2012; Toimil et al., 2020a,b) and varies strongly along the Baltic Sea coast (Weisse et al., 2021). The response of a specific stretch of the coast to a particular combination of these forcing components depends largely on site-specific geomorphological features (Masselink et al., 2011; Ranasinghe, 2016; Harff et al., 2017).

The Baltic Sea coasts (Figure 1) can be divided into two main categories based on their structural properties (Gudelis, 1967; Harff et al., 2017). The bedrock-based shores are characteristic of its western and northern parts. They extend from south-east Sweden to the north, including the entire Sea of Bothnia and the Gulf of Bothnia (Larson and Hansen, 2013) and the entire coast of Finland along the north-east Gulf of Finland. Bedrock coasts are extremely stable with respect to hydrometeorological forcing and are not considered in this review. The sedimentary segments in this coastal area are short. In most cases, they are pocket beaches with limited sediment availability. Most of these beaches are stabilised by postglacial uplift (Harff and Meyer, 2011). They are also not considered here.

The southern and eastern margins of the Baltic Sea include the shores of Denmark, Germany, Poland, the Kaliningrad District of Russia, the Baltic States, and Russia to the west of the Saint Petersburg flood protection facility. This fairly young coastal complex primarily consists of long sedimentary or easily erodible segments (Furmańczyk, 2013; Jensen and Schwarzer, 2013; Kosyan et al., 2013; Sørensen, 2013; Tõnisson et al., 2013), which are often interconnected by alongshore sediment transport (Harff et al., 2017). Large sections of this shoreline are relatively straight. Only the shores of Germany, Estonia and the eastern part of the Gulf of Finland are more fragmented (Harff et al., 2017, Orviku, 2018). Some parts of the Estonian shoreline consist of stable limestone cliffs. These sections are also excluded from our analysis.

Based on the reasoning in section 1.1, we focus on sedimentary coasts from Poland to the eastern Gulf of Finland (Figure 1). A natural border of the study area is at the Swina Gate, as its moles serve as a major obstacle to sediment transport along the coast. This area is divided into six domains based on the orientation of the shoreline and the possible difference of the relative contribution of the main coastal drivers to the evolution of the shoreline (Figure 1). The separation points at Cape Taran, Irbe Strait, and the entrance to the Gulf of Finland naturally split the sedimentary system of the study area into almost independent parts. The choice of the separation point between domains 2 and 3 at the Latvian-Lithuanian border is more arbitrary and reflects the presence of an inflexion point between a convex and a concave appearance of the coastline. In the following, we use the term "domain" to denote parts of this division whereas the term "coastal segment" or "section" has the meaning of a shorter piece of the shoreline (including single beaches).

We use below the terms "southern", "south-eastern", "eastern" and "north-eastern" Baltic Sea (shores) to colloquially link the analysis with the approximate geographical location. There are no clear geographic borders between these regions. There is also no consensus on how to separate these areas that intrinsically overlap to some extent. For example, the scheme of Leppäranta and Myrberg (2009) suggests that a separation point could be in the middle of the Gdańsk Bay. From the perspective of alongshore sediment transport, Cape Taran on the Sambian Peninsula is a more justifiable point for separating the southern and eastern Baltic Sea. The abrupt turn by ~90° of the coastline of this cape gives rise to a major divergence area of wave-driven sediment transport (Harff et al., 2017; Weisse et al., 2021) and thus serves as a natural separation point of sedimentary systems to the east and south of the cape.

The term "southern Baltic Sea" mostly applies to domain 1 and "south-eastern Baltic Sea" to domain 2. The "eastern Baltic Sea" generally covers domains 3, 4 and 5 but sometimes also domain 2, and the "north-eastern Baltic Sea" mostly applies to domain 6.

3. Changes to coastal drivers

3.1 Relative sea level

The primary background provision for the position of the shoreline is the relative sea level (RSL, Ranasinghe, 2016; Harff et al., 2017; Toimil et al., 2020a,b). The change in RSL is due to a combination of vertical movement of the land, global sea level rise, and local effects. As mentioned above, most of the bedrock shores of the Baltic Sea experience a drop in RSL, while the RSL rise is characteristic of its sedimentary shores. The rates of RSL change vary along the shore and may differ even over relatively short distances (Milne et al., 2009; Nicholls et al., 2021). This rate varies considerably on different segments of the Baltic Sea coast (Rosentau et al., 2007; Hünicke et al., 2015; Suursaar and Kall, 2018; Madsen et al., 2019; Männikus et al., 2020).

The Baltic Sea coastal observation stations provide several long sea level records covering more than 100 years. More than 45 stations provide at least 60 years of data (Hünicke et al., 2015). The recorded and modelled Baltic Sea water level data have been analysed in many publications at the regional to local level (see Madsen et al., 2019; Männikus et al., 2019; Pindsoo and Soomere, 2020; Weisse et al., 2021; and references therein).

Madsen et al. (2019) reconstructed absolute and relative sea level trends in the Baltic Sea, analysing their variability from 1900 to 2014. Their work was based on a statistical reconstruction of sea levels using monthly tide gauge observations, with model reanalysis serving as a reference. The RSL trends from 1915–2014 were dominated by the land uplift or subsidence signal (Figure 2). The RSL trend in the southern Gulf of Finland and in the coastal area along the western Estonian Archipelago is mostly from −1 to −2 mm yr^{-1}. This trend is close to zero along the northern coast of Latvia but increases in the southern part of this area by up to 1 mm yr^{-1} (Madsen et al., 2019). Water level recordings from Latvian coastal stations in 1961–2018 exhibit a similar weak increase in RSL of up to 1 mm yr^{-1}. The rate of this increase is slower than the global eustatic sea level rise (Männikus et al., 2020), despite the fact that eustatic sea level rise in most of the Baltic Sea basin exceeds the global average. The RSL increases by about 1 mm yr^{-1} over 100 years of data for most of the Lithuanian coast and for the entire Polish coastal area (Madsen et al., 2019). The increase has been much faster, 2–4 mm yr^{-1}, in the period 1950–1990 (see Rotnicki and Rotnicka (2010) for an overview) and thus clearly exceeds crustal subsidence in the area (about 1 mm yr^{-1} in terms of apparent vertical crustal movements relative to sea level) (Rosentau et al., 2012).

The rise of RSL is uneven in different periods along the coast of Lithuania and the Curonian Lagoon. The average rate of RSL rise in 1898–2002 was approximately 1.3 mm yr^{-1} (Dailidienė et al., 2006). The rate increased at the beginning of 1970s and has reached 3 mm yr^{-1} at all tide gauges in Lithuania (Dailidienė et al., 2006). Navrotskaya and Chubarenko (2012) estimated the RSL rise on the southern coast of the Baltic Sea about 1.7–1.9 mm yr^{-1} at Baltiisk (from records in 1860–2006) and at Kaliningrad (1901–2006). The increase was faster, about 3.6–3.7 mm yr^{-1}, in Kaliningrad and Baltiisk 1959–2006. Satellite-based estimates of sea level trends in the Baltic Sea over

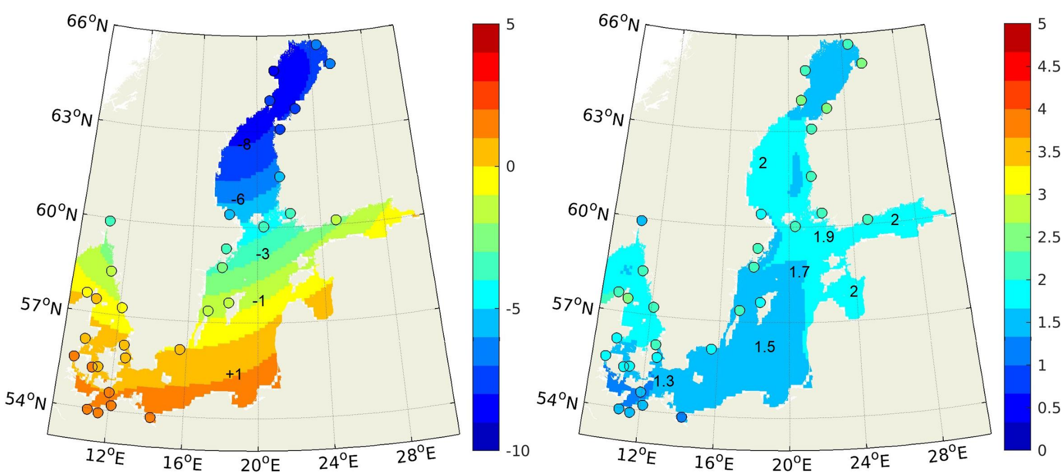

Figure 2. Sea level trends (mm yr^{-1}) derived from reconstructed sea level and tide gauges, 1915–2014. Left: relative to land; right: the eustatic sea level component. Only tide gauges with an adequate record length have been included. The trends at tide gauges may exceed (by up to 1 mm yr^{-1}) the trends in the offshore area. Reproduced from Madsen et al. (2019), licensed under CC BY 4.0.

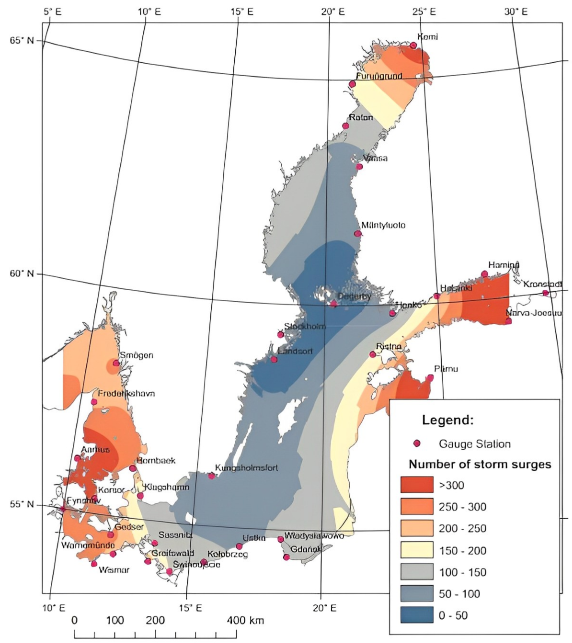

Figure 3. Number of storm surges ≥ 70 cm in the Baltic Sea during 1960–2010. Reproduced from Wolski et al. (2014), licenced under CC BY-NC-ND 4.0.

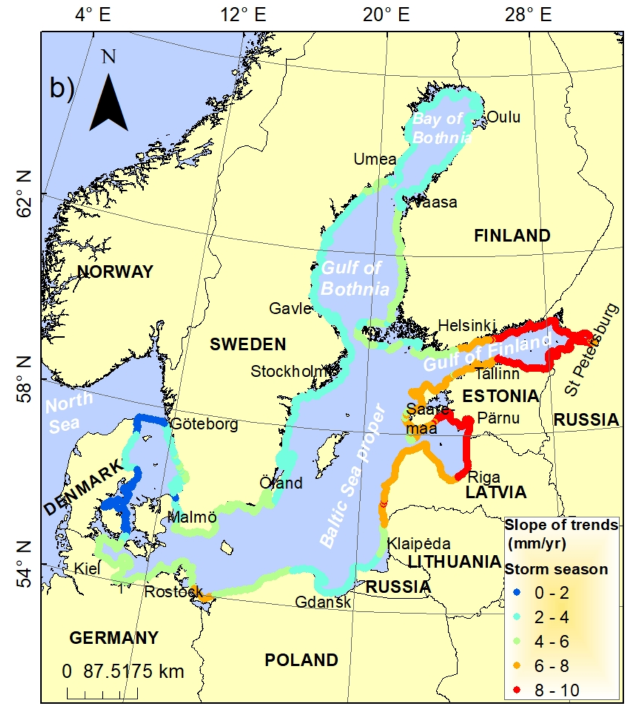

Figure 4. Slope (mm yr^{-1}) of trends of simulated water level maxima in 1961/1962–2004/2005 in 12-month long time periods (so-called stormy seasons) from June to May of the subsequent year. The trends are evaluated using the classic least square linear fit. Reproduced from Pindsoo and Soomere (2020), License Number 5933110158653 by Elsevier.

the years 1993–2014 also exhibit a much higher rise of RSL, 3.4 ± 0.7 mm yr^{-1} (Madsen et al., 2019). These findings are consistent with the general perception of relative SLR acceleration over the last decades (Nerem et al., 2018).

3.2 Extreme water levels

While it is usually unclear how to attribute the impact of slow changes to the average water level to changes to beaches, situations with extreme water levels frequently lead to substantial erosion (e.g., Pye and Blott, 2008). This is also the case in the Baltic Sea (Łabuz and Kowalewska-Kalkowska, 2011; Łabuz, 2022, 2023a,b). The long-term rise in sea level clearly contributes to the increase in the severity (McInnes et al., 2003) and the probability of occurrence (Prime et al., 2015) of coastal flooding. Fast and extreme coastal changes may be created by strong wave events that occur during periods of extremely high nearshore water levels when waves reach unprotected sediment in higher parts of the shore. Extreme storm surges often drive short-term but still the most severe episodes of coastal erosion (Vousdoukas et al., 2018). Storm surge frequency, extent, and exact location depend on the trajectories of low pressure systems and peculiarities of the coastal area, such as the orientation and shape of the coastline and the bathymetry of the sea bottom (McInnes and Hubbert, 2003). Shores with extensive shallow-water sea areas are generally under the highest pressure with respect to storm surges.

In the Baltic Sea, the spatial distribution of extreme water levels varies greatly along the coast (Suursaar and Sooäär, 2007; Averkiev and Klevannyy, 2010; Eelsalu et al., 2014; Soomere et al., 2015b; Wolski and Wiśniewski, 2020). Storm surges tend to be most intense and last longer in the north-eastern and eastern subbasins of the Baltic Sea – the Gulf of Finland, the Gulf of Riga, and the Bay of Bothnia (Wolski et al., 2014; Soomere et al., 2015b; Wolski and Wiśniewski, 2020). The frequency of very high water levels is lower along the coast of the West Estonian Archipelago, Latvia and Lithuania (Figure 3) (Wolski and Wiśniewski, 2020). Although this conjecture is based on interpolated data, with no data from the coastal sector from Gdańsk to Pärnu being involved, this outcome is consistent with other studies in the area.

Various tide gauges along the Baltic Sea coast reveal an increase in the number of storm surges (Jaagus and Suursaar, 2013; Wolski et al., 2014). The number of storm surges (defined as the water level ≥70 cm above zero to the reference datum Normal Amsterdam Peil) in 1960–2010 has increased considerably at some stations in the eastern and southern Baltic Sea (Wolski et al., 2014). For example, the average number of surges has increased from 6.8 to 10.8 per year at Narva (Narva-Jõesuu), almost doubled at Ristna (southwest of the island of Hiiumaa), from an average of 2.1 to 4.1 per year, and has increased from 8.7 to 11.8 per year at Pärnu. The relative increase has been even higher at some Polish tide gauges: in Gdańsk from 1.4 to 3.1 and in Świnoujście from 1.9 to 3.8 per year (Wolski et al., 2014). A larger number of storms in the second half of the 20th century has caused an increase in the number of extremely high water level events in Estonian coastal waters (Jaagus and Suursaar, 2013). More than 70% of such events during 1903–2011 occurred since the 1960s. There are also a few regions, for example the eastern Gulf of Finland, where the number of storm surges has decreased (Zakharchuk et al., 2021).

Single recorded values of extreme water levels have also increased along many sections of the Baltic Sea coast. On average, annual water level maxima have increased dramatically at all Estonian tide gauges (Jaagus and Suursaar, 2013). The increase rates range between 3.2 and about 9 mm yr^{-1} (values consider land uplift rates). The modelled changes in extreme water levels in the Baltic Sea exhibit a similar highly variable spatial pattern. Annual maximum water level values based on Rossby Centre ocean (RCO) model data have increased from 1.5 to 10 mm yr^{-1} in 1961–2005 (Pindsoo and Soomere, 2020). The areas that have the highest number of storm surges in the eastern Baltic Sea (Figure 3) also have the fastest increases in extreme water levels (Figure 4). A large relative increase in the number of high surges in this area (Wolski et al., 2014; Wolski and Wiśniewski, 2020) appears not to be accompanied by an equally powerful increase in their severity (Pindsoo and Soomere, 2020). In the eastern Gulf of Finland, extreme water levels (in terms of annual maxima or maxima over 12-month long periods from July to June of the subsequent year) have increased with a rate of 8–10 mm yr^{-1}. This increase is not linked to the duration of storm surges. A large part of the Gulf of Riga exhibits similar increase rates, about 6–9 mm yr^{-1}. Most of the increase in these locations stems from stronger local storm surges (Pindsoo and Soomere, 2020). These changes appear to be related to changes in the directional structure of strong winds. Extreme water levels have increased near Klaipėda with a rate of 6–8 mm yr^{-1} and of 5–7 mm yr^{-1} in the south-western Baltic Sea. More than half of this increase appears to be due to a similar increase in the water volume of the entire Baltic Sea during large inflow events. The rest of the Baltic Sea shores experienced an increase in annual water level maxima around 4 mm yr^{-1} mostly because of an increase in the excess water pressed into the sea by western winds (Soomere and Pindsoo, 2016; Pindsoo and Soomere, 2020). Lorenz and Gräwe (2023) argue that decreasing trends of extreme water level heights are evident in many Baltic Sea locations, most notably in the Bay of Bothnia and Gulf of Finland, and also remark that modelling extreme sea levels relies heavily on a particular representation of storms in the atmospheric forcing data.

The duration of a storm surge event can significantly modulate flood extents and add to the level of danger in certain areas (Kupfer et al., 2024). It takes time for the water to flow inland, e.g., via narrow valleys, to flood areas behind dunes, and it also takes time to erode the shore. In this context, a long duration (~12 h) of water level above the critical threshold (1.7 m) in Pärnu in January 2005 (Suursaar et al., 2006) greatly contributed to the complexity of the situation, with sea water in places extending up to 1 km inland from the usual shoreline. At more than 90% of the tide gauges worldwide, the duration of storm surges showed an increasing trend (Feng et al., 2023). The typical duration of high sea levels (≥0.7 m relative to zero of tide gauge) has increased by approximately 30% in the Baltic Sea (Wolski and Wisniewski, 2021). The duration of extreme water levels is prolonged in the bayheads and has a clear annual cycle in the Baltic Sea, longer in winter and shorter in summer (Wolski and Wisniewski, 2023).

The information presented on changes in extreme water levels indicates a clearly increased risk of flooding in recent decades in some coastal areas of the Baltic Sea. However, a recent reanalysis of the Baltic Sea extreme water levels reveals no consistent long-term increasing trend (Meier et al., 2022). The future of extreme water levels is also uncertain. It is likely that the discussed changes in extreme water levels may stem from the decrease in the sea ice extent and duration, a possible turn in strong wind directions and an increase in the duration of events that press the North Sea water into the Baltic Sea (Pindsoo and Soomere, 2020; Rantanen et al., 2024). The distinct spatial patterns of extreme water level trends (Pindsoo and Soomere, 2020; Lorenz and Gräwe, 2023) signal that the impact of climate change may vary greatly along the Baltic Sea coastal areas and that the increase in the storm surge heights is not uniform along the coast.

3.3 Sea ice

The presence of sea ice greatly affects not only circulation patterns and the formation of high and low water levels but also the energy flux of surface waves and thus coastal dynamics at higher latitudes (Tuomi et al., 2011; Najafzadeh et al., 2022, 2024). Sea ice is extremely vulnerable to climate change and particularly to global warming in the seasonally ice-covered water bodies where even small variations in temperature may lead to substantial changes in the properties and extent of ice.

The impact of sea ice is twofold. On the one hand, the impact of waves on nearshore sediment is almost negligible during the periods when the nearshore is covered by sea ice or when the sediment is frozen. The decrease in sea ice duration and in the extent of the ice cover inherently leads to intensification of coastal processes (Overeem et al., 2011; Sinitsyn et al., 2020), including an increase in the local water level setup with increasing fetch (Barnhart et al., 2014). This result has been observed in sedimentary coastal areas in the north-eastern Baltic Sea (Orviku et al., 2003; Tõnisson et al., 2011; Ryabchuk et al., 2011a, 2020). On the other hand, sea ice may cause extensive relocation of finer sediment via drift of sediment frozen into ice (Miner and Powell, 1991). This process may involve direct changes to the beach morphology and both alongshore and cross-shore sediment transport (Barnes et al., 1994), and may result in both erosion and deposition (Barnes et al., 1993) as well as in relocation of large boulders to a height of several metres above sea level (Orviku et al., 2011). Some beaches of the south-eastern coast of the Gulf of Finland are often subject to ice attacks (Järvelill, 2019). This type of impact of ice extends to the southern coast of the Baltic Sea (Girjatowicz and Łabuz, 2020). The rates and mechanisms of these processes have been until now poorly quantified and the transport properties are virtually unpredictable (Dodge et al., 2022). As the description of the relevant analysis is almost missing in the Baltic Sea conditions (Leppäranta 2012, 2013), we focus on the protective role of sea ice.

The annual maximum sea ice extent and the ice season length are widely used to estimate changes in sea-ice properties. In the Baltic Sea, there has been a significant decrease by about 20% in the annual maximum ice extent over the past 100 years (Vihma and Haapala, 2009; HELCOM, 2013; Haapala et al., 2015). This is one of the largest changes in the driving forces of coastal processes over the last century. The decrease in sea ice duration has a varying pattern in the Baltic Sea. In the northern part of the sea (Bay of Bothnia) the decrease is 18 days/century. Much faster changes have been observed in the Gulf of Finland. The analysis of sea ice conditions during the period 1927–2012 at the coastal site of Tvärminne, located near the western entrance of the Gulf of Finland, showed a decrease in the duration of ice season by almost 30 days (Merkouriadi and Leppäranta, 2014). The length of the ice season has decreased by 41 days/century in the eastern part of the gulf. This decrease is even faster (31 days on average) in the last 50 years, that is, 62 days/century (HELCOM, 2013). The decrease rate is almost the same on the shores of Estonia (Sooäär and Jaagus, 2007). The most dramatic changes have occurred on islands of the West Estonian Archipelago where the duration of the sea ice cover has decreased by 1.5–2.5 months over years 1950/1951–2004/2005 (Jaagus, 2006; Sooäär and Jaagus, 2007).

In the southern Baltic Sea, the length of the ice season decreases from east to west and from the inner waters toward the open sea areas (Girjatowicz, 2011, Girjatowicz and Świątek, 2020). The ice conditions in the coastal lagoons of the southern Baltic Sea are more severe than in the southern Baltic proper; see Girjatowicz (2011) and Girjatowicz and Świątek, (2020) and references therein. The formal decrease in the number of days with ice is in some locations slower than in the northern regions (Girjatowicz and Świątek, 2021) apparently because the average ice season duration has been relatively short in the past, and about half of the years in the period 1950–1990 had no ice at all in the open parts of the Polish coast (Girjatowicz, 2011). The most significant relative changes thus occur at the latitudes of the Gulf of Finland. These changes in ice conditions are consistent with the observed increase in temperature (Girjatowicz and Świątek, 2021). A likely reason is an increase in the intensity of winter westerlies (Jaagus, 2006; HELCOM, 2013), which bring more heat to the Baltic Sea region. The significant long-term decrease in the sea ice duration has clearly exceeded the large level of natural variability and is attributed with high confidence to global climate change (Meier et al., 2022).

3.4 Wind climate

Wind speed is an appropriate parameter to use for the identification of variations in storm surges, wave climate and associated geomorphological changes to the coastal areas (Dean and Dalrymple, 2002). The attempts to describe the long-term changes in storminess by means of trends in the average wind speed do not necessarily characterise these changes correctly. The results are sensitive with respect to the time period and particular location. They may characterise site-specific peculiarities or change in the measurement routine rather than change in wind properties (Weisse et al., 2005; Feser et al., 2015). The overall perception is that the Baltic Sea region has not experienced any overall trend in mean wind speed (BACC, 2015).

Changes in overall storminess for the Baltic Sea region are analysed from the proxy of atmospheric pressure data in 1800–2000 by Bärring and von Storch (2004). The results do not indicate any significant long-term changes in storminess over fairly large decadal variations. Many authors attribute changes in wind patterns to their natural variability due to large-scale atmospheric circulation that determine the wind, wave and storm surge "climate" in the region (Feser et al., 2015). Storms were more frequent in the 1980s and 1990s in some parts of the sea. This feature has been reflected in several studies of the number of storm days in the northern Baltic proper (Orviku et al., 2003). This sort of local intensification of storm activity in the 1990s could be attributed to changes in the trajectories of cyclones: many centres of cyclones were concentrated into a relatively narrow region of the Sea of Bothnia in this decade (Bärring and von Storch, 2004). It is thus likely that the observed local and regional decadal-scale fluctuations in the wind speed are part of natural climate variability and do not necessarily mean any systematic increase in storminess (Hünicke et al., 2015).

The magnitude of sediment transport and the course of coastal processes are sensitive to wave approach direction. As characteristic to relatively small semi-sheltered water bodies, the Baltic Sea waves usually follow the wind direction and often approach the shore at a large angle. Therefore, changes in the wind direction may substantially alter the functioning of the coast. Such changes may result in large spatio-temporal variations of alongshore sediment transport patterns (Viška and Soomere, 2013). Several studies emphasise possible changes in the directional structure of winds in the Baltic Sea region (Dailidienė et al., 2006; Kelpšaitė and Dailidienė, 2011; Soomere et al., 2017; Pindsoo and Soomere, 2020, Männikus et al., 2020), but few studies have attempted to quantify these variations (Jaagus and Kull, 2011; Keevallik, 2011; Bierstedt et al., 2015).

An analysis of wind observations on the island of Vilsandi on the eastern coast of the Baltic proper indicates a clear shift in the average air-flow direction in January, when the biggest change occurred (Keevallik, 2011). This property reflects the result of separately averaging zonal (west-east) and meridional (south-north) components of wind velocity over the time period of interest. The average airflow direction, from the south-east in 1966, rotated about 90° to the south-west by the year 2003. Such a rotation is not a local phenomenon. The changes in the airflow are controlled by the large-scale atmospheric processes (Keevallik, 2011), and are possibly related to the shift in trajectories of deep cyclones in the north Atlantic and the widening of the North Atlantic storm track to the north-east (Lehmann et al., 2011). An analysis of geostrophic wind patterns suggests that the air-flow direction over the southern Baltic Sea abruptly turned by 40° at the end of the 1980s (Soomere et al., 2015a). This feature was transient at the Gulf of Finland latitudes (Keevallik and Soomere, 2014) but apparently is one of the reasons for a multitude of regime shifts in time series of different observed phenomena in Estonia around 1990 (Kotta et al., 2018).

A change in the air-flow direction does not necessarily mean that storms are blowing from different directions than in the past. Significant alterations in the frequency of occurrence of winds from different directions (called wind directions for simplicity below) were determined in several meteorological stations in Estonia 1966–2008 (Jaagus and Kull, 2011). Similarly to changes in the air-flow (Keevallik, 2011), the strongest changes were found in the winter season. Remarkably, 12 of the 14 stations showed a clear increase in the frequency of westerly winds in January. Jaagus and Kull (2011) concluded that the observed shift of wind directions from east to west is related to changes in large-scale atmospheric circulation. Similar processes have been observed on Lithuanian stations (Dailidienė et al., 2006; Kelpšaitė and Dailidienė, 2011).

Further analysis of variability in wind directions for the entire Baltic Sea region based on climate simulations coastDat2 and HiResAFF for the period 1948–2009 also reveals a clear shift in wind directions (Bierstedt et al., 2015). The wintertime mean and extreme winds have rotated more to south-westerly direction. No trends were detected in other seasons.

It is therefore safe to say that considerable changes in the directional structure of wind fields have occurred in the Baltic Sea region since the 1950s even though different studies based on different data, locations and study duration highlight different aspects of these changes. These changes are evidently reflections of large-scale phenomena and are best visible in air-flow properties. The biggest changes occurred during the relatively windy autumn and winter seasons (Bierstedt et al., 2015; Soomere et al., 2015a) when the strongest storms usually occur. This shift results in more frequent westerly or north-westerly winds. This change is one of the likely reasons why storm surges occur more frequently and are systematically higher on the eastern side of the Gulf of Riga and the Gulf of Finland. Another likely reason is clustering of low pressure systems that push additional water into the Baltic Sea. This mechanism, proposed by Soomere and Pindsoo (2016) and quantified by Rantanen et al. (2024), contributes to the preconditioning of the Baltic Sea level and thus to the formation of extreme water levels.

3.5 Wave climate

The sediment volume transported alongshore is commonly assumed to be roughly proportional to the amount of wave energy flux that reaches the nearshore per unit length of the coastal segment and to the deviation of the approach direction of the waves from the shore normal (USACE, 2002). The absence of clear trends in wind speed means that climate change-driven changes in wave height are small in the Baltic Sea (Räämet and Soomere, 2011; Kudryavtseva and Soomere, 2017). Therefore, changes to the wave approach direction, even if they are smaller than the rotation of air-flow, may substantially impact the intensity to coastal processes. This includes the possible presence of longer waves from other directions than in the past because of longer fetch and also possible higher surges and changes to the properties of wave run-up and set-up. Although waves usually rework sediment in a narrow belt along the shore, they may entrain a large amount of sediment into the active pool of coastal sediment from higher parts of the coastal profile during periods of elevated water level events in ice-free times. Therefore, a combination of rotation in the predominant wave directions, an increase in the local water level or its extremes, and/or the absence of sea ice may even more strongly influence the shores than an increase in the wave height.

In the Baltic Sea, instrumental wave measurements have been available since the 1970s (e.g., Broman et al., 2006; Tuomi et al., 2011). As their spatial coverage is limited and the time series have gaps in winter, wave hindcasts provide equally valuable information to detect the changes in the Baltic Sea wave climate (Soomere and Räämet, 2014; Björkqvist et al., 2018). The main shortcoming of offshore measurements and modelling is that wave properties in the nearshore have large uncertainties.

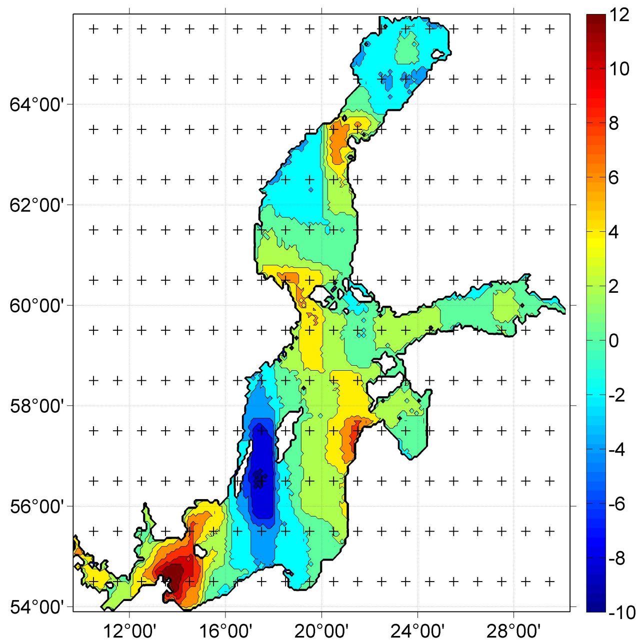

Figure 5. Numerically simulated changes in the annual mean significant wave height (cm, the interval between isolines 2 cm) for 1970–2007. Reproduced from Soomere and Räämet (2014), License Number 5933101259072.

The wave fields in the Baltic Sea are extremely variable in both space and time (Räämet and Soomere, 2011; Soomere and Eelsalu, 2014). In particular, extensive regional changes in the annual mean observed wave height have been reported in some locations (e.g., Kelpšaitė et al., 2011). However, the overall long-term wave activity in 1970–2007 reconstructed using geostrophic winds in idealised ice-free conditions indicates almost no changes in basin-wide wave properties (Räämet and Soomere, 2011). The highest increase in SWH was probably on the Latvian Baltic proper coast (Figure 5). Wave activity decreased to the west and south of Gotland. Decadal variations in the annual mean SWH contain a strong signal for most of the the Baltic Sea domains (Soomere and Räämet, 2014) with typical duration of periods with higher and lower wave activity about 10–12 years.

More importantly, Soomere and Räämet (2014) suggested that changes in the wave properties in different Baltic Sea areas under idealised ice-free conditions may be completely different in different decades. Although the forcing (adjusted geostrophic) winds of these simulations had low spatial resolution and generally did not provide adequate replication of wave time series (Räämet and Soomere, 2021), it is likely that these winds mirrored the major changes in the atmospheric pressure patterns in the area and therefore reflected changes in large-scale wind properties. These results were reiterated by Sokolov and Chubarenko (2020, 2024) using contemporary ERA-Interim wind information, with basically the same conclusion: the severity of the Baltic Sea wave climate has not changed significantly over the last decades.

The analysis of wave properties in 1958–2002 for a location near the Polish coast (Różyński, 2010) revealed coupling of wave properties with the monthly North Atlantic Oscillation (NAO) index and an oscillation of wave properties in January with a period of 8 years but no long-term trend. Wave properties near the German coast of the Baltic Sea (Dreier et al., 2020) and in the Gulf of Gdańsk area (Badur and Cieślikiewicz, 2018) identified large multi-decadal, spatial and seasonal variability of the changes depending on the direction of exposure of the coast. An increase in the SWH of up to 5% was identified in locations exposed to westerly directions (Badur and Cieślikiewicz, 2018). Sokolov and Chubarenko (2020) found a decrease in the SWH by 2–3 cm per decade, which was the fastest in the south-eastern part of the sea. All of these simulations agree that there has been no systematic increase in wave heights in the Baltic Sea proper.

Some local wave modelling efforts also indicate different patterns of changes for differently exposed coastal areas. The SWH of the highest waves (99th percentile, equivalently, the threshold for the highest 1% of waves) has increased since the 1960s, on the western side of Saaremaa at Kelba which is exposed to the west (Suursaar et al., 2015). The opposite pattern of changes was identified at Letipea in the eastern Gulf of Finland. This site is open to winds from northern directions and showed a decrease in the 99^{th} percentile of SWH (Suursaar et al., 2015). Satellite altimetry data since the 1990s reveals an increase in the SWH of 0.5 mm yr^{-1} in the western Baltic proper (Kudryavtseva and Soomere, 2017). Changes in the basin-wide average SWH have a strong meridional pattern: an increase in the central and western parts of the sea and a decrease in the east (Najafzadeh et al., 2021). These changes are likely caused by a rotation of wind directions rather than by changes in the wind speed.

The described variety of changes in the SWH could be explained by the changes in the local wind directions that stem from a shift in deep cyclones pathways (Lehmann et al., 2011) that influence wave fields differently in different sea areas. The detected shift in the airflow in January suggests that strong winds in this month predominantly blow from the west-south-west. Winds from these directions bring strong waves to the western coast of Latvia, Lithuania, and Estonia. They also drive high water levels in the eastern Gulf of Riga and the Gulf of Finland but do not necessarily produce high waves on the northern shore of Estonia. This (mis)match of the wind direction and geometry of the coast may be the reason why visually observed wave heights have decreased at Narva-Jõesuu, in the eastern Gulf of Finland (Räämet et al., 2010). The modelled wave heights have decreased in the nearby location of Letipea (Suursaar et al., 2015). Interestingly, visually observed wave directions at Narva-Jõesuu demonstrate a systematic rotation of about 90° (Räämet et al., 2010). Although such observations contain large uncertainties and are sensitive with respect to changes in local wind properties, the overall pattern of reported changes in wave parameters along the southern coast of the Gulf of Finland matches well the described changes in wind patterns.

4. Changes to coastal processes in single domains

4.1 Southern coast of the Baltic Sea

We start the discussion of processes on the southern coast of the Baltic Sea for the coastal area from Swina Gate to Cape Taran (domain 1, Figure 1). We focus mainly on about 500 km of geomorphically varying Polish coastline that covers the largest part of this domain. About 400 km of it is flat and sandy with dunes with a height from a few metres to more than 40 m (Musielak et al., 2017), with the remaining area consisting mostly of glacial-origin, relatively easily erodible cliffs (Łabuz, 2005; Łabuz et al., 2018). The entire Polish coast is barred, with typically 2–3 sandbars present (Musielak et al., 2017). The coastline (except for the Gdańsk Bay area) is orientated in the west-southwest (WSW) to east-southeast direction and thus is exposed to winds that are frequently directed alongshore.

This long section appears to be an almost straight line on large-scale maps. In reality, its different segments have greatly different approach angles of waves generated by predominant strong westerly winds. The coastline orientation turns by more than 30° at the northernmost location of Poland. The magnitude and direction of coastal processes and their forcing changes radically along the shores of Gdańsk Bay and Vistula Spit and is strongly modulated by anthropogenic interventions at many locations (Osadczuk et al., 2024).

The alternating generally westerly (usually SW or WSW) and northerly winds cause variable direction alongshore sediment transport in some locations of this domain (Figure 6) (Harff et al., 2017). Northerly winds are infrequent but they have the longest fetch and may create the highest waves near the Polish coast. During these events, waves approach most of the shore at a relatively small angle and thus cause only moderate alongshore transport. On the western part of the Polish shoreline the fetch length of westerly winds is small, and thus the created waves are relatively weak. As a result, the long-term net alongshore sediment transport has different direction in different segments of the Polish coast. It is predominantly to the west in the westernmost segment of this coast. The net transport has a variable direction in the area from Koszalin Bay to Ustka Bay. It is predominantly to the east from Ustka Bay to the tip of the Hel Peninsula. It also has a variable direction in the interior of Gdańsk Bay, and particularly on

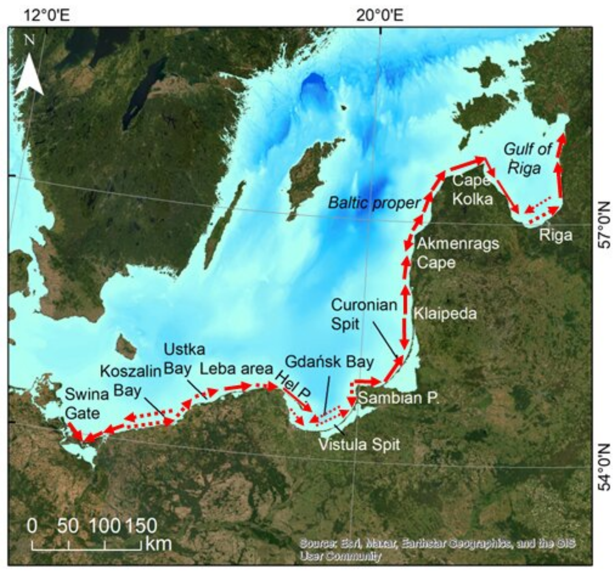

Figure 6. A generalised view of the long-term alongshore sediment transport pattern on the southern and eastern shores of the Baltic Sea. "Hel P." is the Hel Peninsula and "Sambian P." is the Sambian Peninsula. The dotted lines reflect variable-direction transport. See references to the sources used in Harff et al. (2017). Amended from Harff et al. (2017).

the shores of Vistula Spit where both the coastline orientation and openness to the predominant wind directions vary significantly along the shore (see Harff et al., 2017 and references therein). It is likely that, as is typical for the eastern Baltic Sea shores (Soomere and Viška, 2014), several coastal segments have different net transport directions in different years.

The southern coast of the Baltic Sea is considered to have a moderate risk of extreme water levels (Wolski and Wiśniewski, 2020) even though it may experience extremely high water levels occasionally (see, e.g., Wolski et al., 2014). Elevated sea levels occur on the Polish coast during cyclones travelling from the North Sea and the Norwegian Sea to the east and southeast. Storm surges above 1 m occur predominantly under northerly winds (Łabuz, 2009, 2022, 2023a,b; Łabuz and Kowalewska-Kalkowska, 2011). Strong waves characteristic for this direction with long fetch, can result in dramatic erosion of the beach and dune system during such events (Łabuz, 2009, 2022, 2023a,b; Łabuz and Kowalewska-Kalkowska, 2011; Musielak et al., 2017) and lead to a major loss of sediment on the upper beach owing to intense cross-shore transport.

The Polish coastline is chronically affected by land subsidence (Ågren and Svensson, 2007). The marine-driven pressure on this shore section is augmented by eustatic water level rise. The sea level rise has clearly accelerated

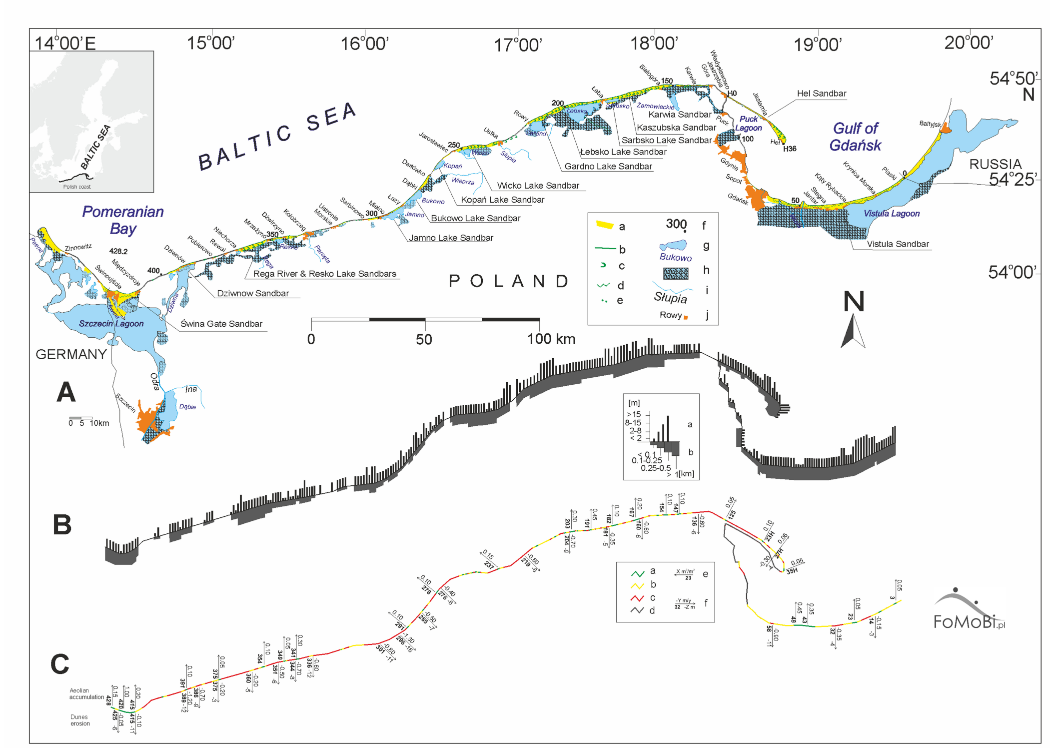

Figure 7. Current state of the Polish coast. A – coast map, a – sandbars, b – foredunes, c – formerly shifting parabolic and barchan dunes, d – formerly shifting transverse ridges, e – dunes on moraine coast, f – coast kilometrage, g – lakes, h – wetlands, swamps, i – rivers, j – settlement. B – dune coast location, a – dune coast height, b – sand barrier width (Łabuz, 2005). C – coast dynamics between 2002–2012, dune coast changes, a – accumulation, b – stable, c – erosion, d – no data, e – accumulation value on selected kilometre: X-amount in m^3 per m^2 of the dune, f – erosion rate value on selected kilometre: Y – retreat rate in m per year, Z – total retreat in m. Hel Sandbar is the Hel Peninsula and Vistula Sandbar is Vistula Spit. Reproduced from Łabuz (2013) with publisher permission.

in this area. While it was estimated at about 1 mm yr^{-1} in Madsen et al. (2019) on a century scale, it has been 2–4 mm yr^{-1} during 1951–1990 and rose even up to 4.4–7.7 mm yr^{-1} during 1970–1990 (Rotnicki and Rotnicka, 2010). Systematic (albeit slow) sea level rise may strongly contribute to the formation and magnitude of compound flooding (e.g., Xu et al., 2023) as discussed for the neighbouring domain 2 (Čepienė et al., 2022). As a result, the Polish coast is under strong stress created jointly by the vertical geological movement of the land, the global sea-level rise, and the exposure to high winds and storm surges. Thus, it is expected to exhibit low durability and is under constant threat of erosion during storm surges (Łabuz, 2014, 2022, 2023a,b). Currently, about 40% of the Polish coast is vulnerable to moderate and high erosion rates (Łabuz, 2013). Any increase in the intensity of hydrodynamic drivers may thus substantially change the natural coastal evolution of long sections of the Polish coastline.

The Polish coast has been naturally accretionary in the long term as evidenced by the presence of extensive dunes and underwater bars. However, recent decades show a systematic decrease in the length of the naturally accumulating coastal sections (Łabuz, 2013). Long sandy sections affected by erosion are becoming common, with fewer and shorter accumulating sections. Łabuz (2013) argues that more than 70% of coastal foredunes that were covered by vegetation in the past have been recently eroded. Only 15% of the Polish coastline is currently accumulating (Figure 7).

The long-term average retreat rate over the 100 years period (1875–1983) of the Polish shores comprised of soft sediments is about 0.1 m yr^{-1} (Zawadzka-Kahlau, 1999). This rate has varied greatly in different time periods. In the 1960s to the mid-1980s, the average retreat rate along the entire Polish coast was about 0.5 m yr^{-1} (Zawadzka-Kahlau, 1999; Pruszak and Zawadzka, 2005). This process has greatly accelerated on the western coast since the mid-1980s. The retreat rate is currently up to 0.9 m yr^{-1} (Łabuz, 2009). Single extreme events can result in much higher local retreat rates, up to 5–9 m per event (Łabuz, 2009, 2022, 2023a,b; Łabuz and Kowalewska-Kalkowska, 2011).

The Polish coastal processes exhibit remarkable spatial and temporal variability. Although most of the segments are erosive, several sections show high accretion rates. For example, the Swina Gate area (Figures 6, 7) on

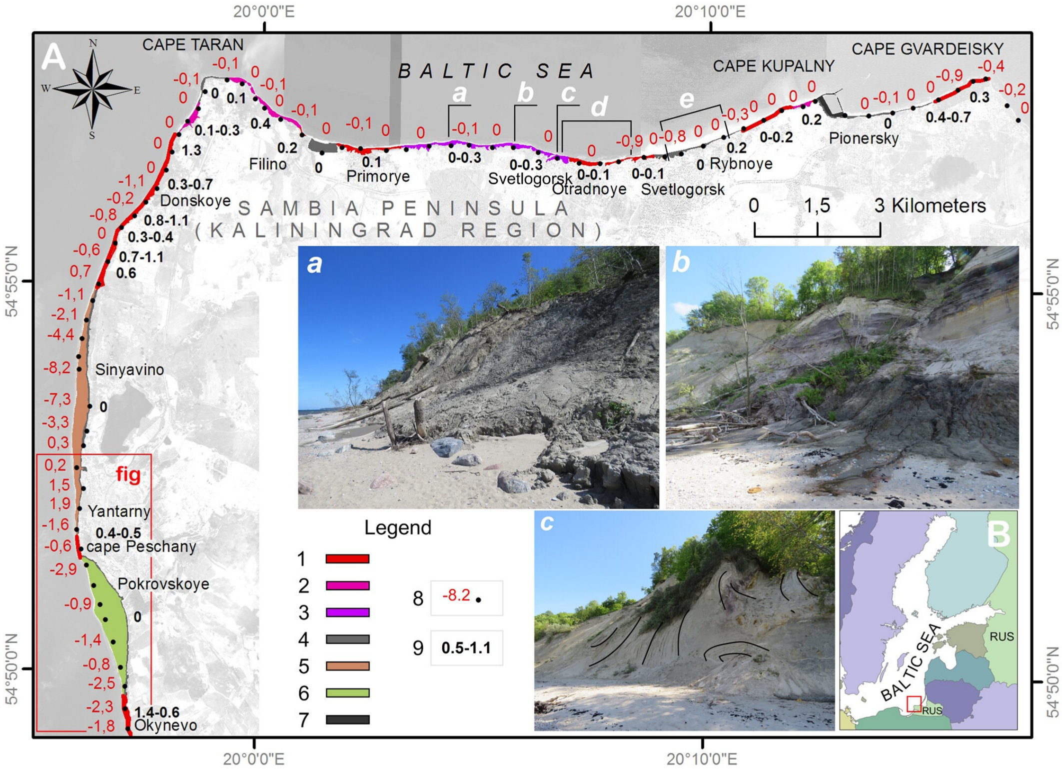

Figure 8. Coastal changes along the Sambian Peninsula. Numbers 1–7 represent morphogenetic coastal types according to Shepard (1948): skerries (1), sand accretion alluvial coast (2), moraine (bouldery) erosion coast with local pocket coarse grained beaches (3), erosion dominated coast on Holocene marine terrace, straightening (4), erosion dominated coast on Holocene marine terrace, straightened, sand accretion coasts (5), sand accretion coast with cuspate foreland (6), technogenic (7). Measuring points of "Baltberegozaschita" (8) and points of retrospective analyses of coastal escarpment and beach position according to remote sensing data (rates of escarpment shift in m yr^{-1}) (9). Landslide and erosion processes of the coastal cliffs of the northern coast of the Sambian Peninsula (a, b). Glacial dislocations of Quaternary deposits (c). Please see rest of the photographs (d, e, and fig.) in Ryabchuk et al. (2020). Reproduced from Ryabchuk et al. (2020, Fig. 5 (A)).

the western end of the Polish coast experienced strong accretion in 1938–2012. The dune baseline (equivalent to the dune toe in literature) advanced, on average, about 91 m (Dudzińska-Nowak, 2017). The average advance rate varied from 0.3 to 3.6 m yr^{-1} with the fastest rates on both sides of the Swina Strait (Dudzińska-Nowak, 2017). This accumulation area persists mainly due to local geomorphological conditions that give rise to the presence of a sediment convergence zone (owing to a favourable combination of coastal orientation and its exposure to the predominant wave directions). The impact of coastal engineering structures also favours accumulation in this area.

Climate change may control foredune and dune development through wind, rainfall and temperature properties (García-Romero et al., 2019). Changes to the (fore)dune system have been systematically investigated along the Łeba Barrier in the central section of the Polish coast (e.g., Rotnicka, 2011; Dluzewski et al., 2023). However, the time series are too short to identify potential climate change-driven alterations. This area displays consistent sediment transport to the east (Figure 6). Nevertheless, historical data for this part of the coastline demonstrates alternating retreating and advancing sections, as discussed in Deng et al. (2017).

Prevailing westerly winds drive an eastward alongshore sediment movement along much of the Polish coast (see Rotnicki and Rotnicka, 2010 and references therein), except in the coastal segment from Swina Gate to the middle of Koszalin Bay, and in the area of Puck Bay and Puck Lagoon. The area of intense sediment transport to the east covers the entire northern coast of the Hel Peninsula. About 60% of the northern shore of this narrow 35 km long sandy feature retreated during the 20th century (Deng et al., 2017). The most rapid erosion occurred 1957–1991 on its western segments. Contrarily, its eastern sections are dominated by accumulation. Alongshore sediment flux is the only sediment source for the development of the entire spit. This is demonstrated well by the gradual advance of its eastern end (Deng et al., 2017). The south-eastern tip of the Hel Peninsula is a discontinuity of sediment transport and the sedimentary system of the Hel Peninsula is completely isolated from the similar system at the eastern and western shores of Gdańsk Bay (Figure 6) in the sense that there is no wave-driven sediment exchange between these systems.

The Hel Peninsula protects part of the interior of Gdańsk Bay against high waves (Kovaleva et al., 2017). The area fully or partly sheltered against westerly winds stretches from the eastern end of the Hel Peninsula to approximately the middle of the Vistula Spit. The area to the east of Gdańsk is open to strong waves from northerly directions. These waves drive sediment from the north-east to the south-west (Figure 6) (Chechko et al., 2008). The balance of the impact of waves from different directions, and thus the magnitude and direction of this transport substantially varies along the Vistula Spit. Their combination supports morphological stability with accumulation up to 0.5 m yr^{-1} in the middle section of the spit (Ostrowski et al., 2014), depending on the exposure and orientation of a particular segment (Kobelyanskaya et al., 2011). Breakwaters close to the Strait of Baltiysk (entrance to the Port of Kaliningrad) provide an obstacle for the alongshore sediment drift. Their presence apparently results in some erosive sections over 4–7 km south-west of the Baltic Channel (Chechko et al., 2008, Ostrowski et al 2012).

Similarly to the southern shore, coastal processes on the eastern shore of Gdańsk Bay are substantially controlled by anthropogenic influences (Ryabchuk et al., 2020) linked to the exploitation of geological resources (Ostrowski et al., 2014) and prevailing alongshore sediment transport to the south. Amber mining was very active in the region in the 20th century. The dumped material was incorporated into sediment transport dynamics to artificially accrete local beaches. When this kind of nourishment ceased, intense coastal retreat subsequently occurred up to 20 m yr^{-1} (Ryabchuk et al., 2020). The general perception derived from the literature is that processes on this spit have been substantially altered by the construction of moles at the entrance to the Port of Baltiisk (Babakov and Chubarenko, 2019). The southern part of the Vistula Spit is additionally affected by the recent construction of another navigation channel and its jetties. Therefore, it is unlikely to distinguish the signal of climate change from the anthropogenic impact in this area.

The changes of long-term and recent rates of erosion along the north-eastern side of Gdańsk Bay, from the Strait of Baltiysk to Cape Taran (Kaliningrad, Russia), indicate a recent acceleration of coastal erosion in several parts of the area (Figure 8). Recent rates (2008–2018) of coastal retreat have increased considerably in some shorter coastal sections, varying from a retreat of 8.2 m yr^{-1} to an advance of 2.8 m yr^{-1} (Figure 8, Ryabchuk et al., 2020; the location of the fastest shoreline advancement apparently being located outside the area represented in the figure). Large parts of the eastern part of Gdańsk Bay require nourishment to stabilise the shore and mitigate erosion (Ostrowski et al., 2014).

The increased erosion has motivated the implementation of many shoreline protection measures. Such measures were commenced on the Polish coast starting from the early 1900s and now exceed 136 km in length. For example, the recreational area on the western side of Gdańsk Bay on the Hel Peninsula experiences the strong pressure of human activities. About 2/3 of the long sandy coastline of its northwestern shore is constantly retreating and requires artificial nourishment (Łabuz et al., 2018). Thus, about 26% of the coastline is stabilised artificially (Pruszak and Zawadzka, 2008).

Beach protection measures and the construction of harbour structures have substantially affected the natural evolution of the coastline along domain 1. This is another reason why attribution of the described changes to climate change is not straightforward. Although the impact of harbours and other coastal engineering structures is usually local, the increased rates of changes along the domain 1 coast likely represent the combined effect of climate-change driven and human drivers. Nevertheless, strong wave-driven sediment transport to the east (e.g., Szmytkiewicz et al., 2021) is a natural feature of this region where the predominant waves approach from westerly directions (Zeidler et al., 1995). This transport to the east (or north-east along the Vistula Spit) has built over millennia several large-scale sandy landforms, such as the Hel Peninsula and the Vistula Spit. The magnitude of this transport may be slightly modified by the relative sea level rise and/or changes in wave properties (Różyński and Lin, 2021) but it is expected to continue in the future as well.

4.2 South-eastern coast of the Baltic Sea

A natural separation between domains 1 and 2 (Figure 1) is the major change in orientation of the south-eastern Baltic Sea coastline by almost 90° at Cape Taran at the north-western tip of the Sambian (Samland) Peninsula (Figure 8). This cape is a major divergence point where net sediment transport driven jointly by south-western (SW), western and NNW winds is directed to the south and to the east (see Figure 6 and Harff et al., 2017). Although SW waves often cause sediment transport to the north, the resulting net transport is almost entirely unidirectional in the vicinity of Cape Taran according to Harff et al. (2017). The closest convergence points of this transport are apparently on the Vistula Spit to the south and along the Curonian Spit to the east of Cape Taran. In this sense, the situation is radically different from that near Cape Kolka (see below) or along the Hel Peninsula (see above) where a different type of transport discontinuity is associated with rapid accumulation.

Domain 2 with the total length of 200 km stretches from the tip of the Sambian Peninsula (Cape Taran) close

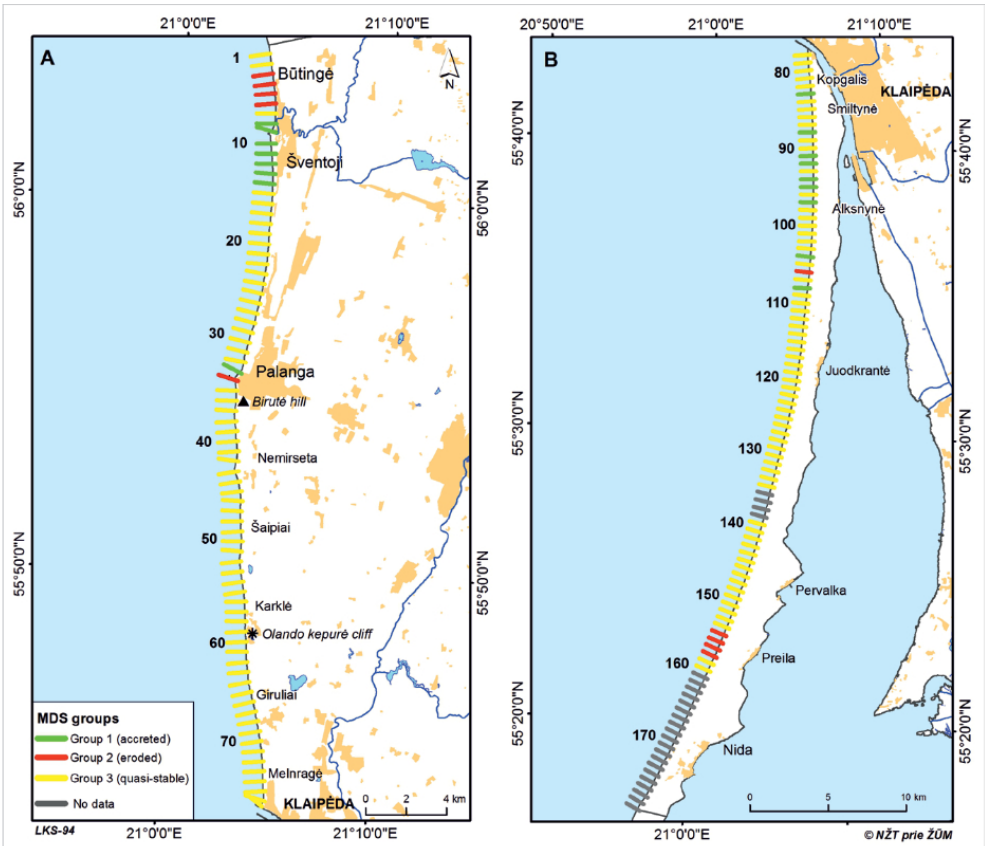

Figure 9. Assessed pattern of shoreline changes along the coast of Lithuania since 1947–2010. The changes over time are characterised using transect groups, analysed through nonmetric multi-dimensional scaling (nMDS) applied to non-transformed data from four time periods for both the mainland coast (1947–1984, 1984–1995, 1995–2005, 2005–2010) and the Curonian Spit (1946–1977, 1977–1995, 1995–2005, 2005–2010). Group 1 (green): accretion pattern prevails; Group 2 (red): erosion prevails; Group 3 (yellow): quasi-stable coastal segments. Reproduced from Bagdanavičiūtė et al. (2012) with publisher permission.

to the border of Lithuania and Latvia. Its northern end is associated with the area of frequent divergence of alongshore sediment transport close to the border (Viška and Soomere, 2013). This feature is driven by the joint impact of alongshore variations in the coastline orientation and degree of exposure to the predominant wave fields (Figure 6). This location is also described as a sediment transport discontinuity in other studies (Ulsts, 1998; Soomere and Viška, 2014; Harff et al., 2017).

The coastal area of this domain is driven by a complex system of drivers and processes (Ryabchuk et al., 2020) resulting from the relationship between two predominant wind and wave directions. Waves from the SW and west are more frequent than waves from northwest (NW) (Kelpšaitė and Dailidienė, 2011) but N-NNW storms may be particularly destructive (Bobykina and Stont, 2015; Bobykina et al., 2021). In this domain, RSL rise is about 1.5 mm yr^{-1} (Madsen et al., 2019).

The northern coast of the Sambian peninsula is characterised by rapid beach erosion and active landslides (Figure 8). The long-term (1936–2013) average retreat rate in this area varies from 0.1–0.3 m yr^{-1} (Ryabchuk et al., 2020). Only in a few locations, has the beach not retreated or been stabilised by coastal protection measures. The recent (2008–2018) retreat rate has increased towards Cape Kupalny (Figure 8) up to 0.3 m yr^{-1}. The most intense erosion, with average retreat rates of 0.4–0.7 m yr^{-1}, has occurred near Cape Gvardeisky (Ryabchuk et al., 2020). Shoreline retreat between the northern shore of the Sambian Peninsula and the Curonian Spit 2007–2017 has been less than 0.25 m yr^{-1} (Karmanov et al., 2018). Preventive protection measures have stabilised the shorelines in the vicinity of resort towns. However, these measures have caused an even greater sand deficit in downdrift locations, resulting in narrower beaches and more erosion to the east (Karmanov et al., 2018).

Domain 2 has the largest dune system on the Baltic Sea coast, the 98 km long Curonian Spit. Most of this coastal barrier is dominated by accumulation, except for a few erosion locations. The largest erosion area is located in the southernmost 15 km segment of the spit (Badyukova et al., 2018; Karmanov et al., 2018). Over the last 70 years, the shoreline has retreated up to 100 m (Boldyrev and Teplyakov, 2003). In 2007–2017, unstable sections were eroding at a rate of 1–2 m yr^{-1}. The average erosion rate for the same period over the entire segment was about 0.4 m yr^{-1} (Karmanov et al., 2018). This situation is alarming because there are no foredunes in the fast-eroding section and the sand deficit is already impacting the massive dune system at Zelenogradsk. The low-lying forest adjacent to the shore is flooded during strong storms and thus is extremely vulnerable during strong wave events (Karmanov et al., 2018).

The rest of the Curonian Spit is mostly stable. Its middle and northern segments form a large part of the coastline of Lithuania. It has a considerable amount of sediment on the beach, a well-developed dune system, and 1–4 underwater bars in the nearshore area (Gudelis, 1998, see Bagdanavičiūtė et al., 2012). Bagdanavičiūtė et al. (2012) used various sources to reconstruct the long-term shoreline changes on the Lithuanian side of the Curonian Spit in 1947–2010 during which there were long periods of accretion. The most significant changes occurred between 1955 and 1977, when intense accretion led to shoreline progression in some locations up to 60 m. This process was reversed to relatively slow retreat during 1977–1995. In 1984–1995, the average retreat was only about 5 m. In the next 15 years, 1995–2010, accumulation dominated. Therefore, the coast has been either accumulating or stable over most of its length (Figure 9).

The rest of the coastline of domain 2 from Klaipėda to the border of Lithuania and Latvia is mostly stable, with few short erosive sections that are likely driven by the impact of coastal structures (e.g., Šakurova et al., 2023). The reversal of the direction of net sediment flux to the north of Klaipėda and the presence of a divergence area at the Lithuanian-Latvian border stem from the change of the coastline orientation. In essence, it is caused by the interplay of the two predominant wave energy approach directions (Viška and Soomere, 2012; Soomere et al., 2024) with the orientation of the Lithuanian coastline. This interplay apparently provides long-term stability to the system. It is likely that this stability in the area from the middle part of the Curonian Spit to the northern end of domain 2 is most vulnerable with respect to changes in wave propagation directions (Viška and Soomere, 2012). Although domain 2 is affected by an increase in RSL (see section 3.1), only a few locations suffer from shoreline erosion. The apparent main reason for stability is intense alongshore sediment transport that provides enough sediment from neighbouring areas (Viška and Soomere, 2012; Bagdanavičiūtė et al., 2012). Consequently, the core driver for this domain, possibly affected by climate change, is the balance of wave systems driven by the two predominant wind directions. This situation is much less affected by large coastal engineering structures, such as jetties at the Klaipėda Strait (Žilinskas et al., 2020; Kondrat et al., 2021) or beach nourishment activities on the Lithuanian mainland shore (Karaliunas et al., 2020; Pupienis et al., 2024). Unlike the situation on the shores of Cape Taran, these activities, even though they modify the course of coastal processes locally, do not mask the impact of the two predominant wind directions on the country scale.

4.3 Coastline of Latvia: Baltic proper

Domain 3 covers the Latvian shore of the Baltic proper. It is an approximately 250 km long, relatively straight coastal area that extends from the Lithuanian-Latvian border to Cape Kolka, and consists mainly of two shore types – gently sloping sandy coasts and cliffed coasts. Cliffed abrasion segments, with a clearly defined scarp or bluff consisting of relatively soft sediments, are common in the area. They are interspersed with gently sloping, generally advancing depositional beaches (Gudelis, 1967; Eberhards, 2003; Eberhards et al., 2006; Soomere and Viška, 2014). Coarse sediments, such as sandy gravel, pebbles, and boulders, mostly characterise the underwater part of the beach profile. A sandy strip is present throughout the entire section near the waterline, and relatively wide sandy beaches occur frequently (Ulsts, 1998; Eberhards, 2003; Lapinskis, 2010; see also Viska and Soomere, 2013).

The entire domain generally suffers from a deficit of fine-grained sand (Ulsts, 1998). This deficit is often partially offset by sediments eroded from the cliffs and, to some extent, by sediments supplied by river flow (Ulsts, 1998; Eberhards, 2003; Lapinskis, 2010). Similar to domain 2, most of this domain is impacted by a bidirectional wind and wave system (Eelsalu et al., 2024) that creates variable-direction sediment transport (Jankowski et al., 2024). The 70 km long transition area along the Irbe Strait from Cape Oviši to Cape Kolka is less impacted by waves from the NNW. The strongest impact on this section is caused by waves approaching from SW that drive powerful almost unidirectional alongshore sediment transport (Knaps, 1966). The nearshore and shore mostly consist of fine-grained sand, have several nearshore sandbars, and are less affected by erosion (Ulsts, 1998). Similarly to the Vistula Spit or the Curonian Spit, the coastal segment along the Irbe Strait is a major accumulation area where most of the arriving sediment is deposited (Knaps, 1966; Eberhards, 2003). Cape Kolka, the northernmost point of the Kurzeme Peninsula, is another discontinuity location in the system. It is the end point of most of the alongshore sand flow along the eastern shore of the Baltic proper, from where only a small fraction of the sediment is further transported to the sedimentary system of the Gulf of Riga. This flow starts at Cape Taran, Kaliningrad Oblast, Russia (Eberhards, 2003; Harff et al., 2017) and some entrained sand grains would be transported to Pärnu Bay in the Gulf of Riga if there were no man-made barriers (Soomere and

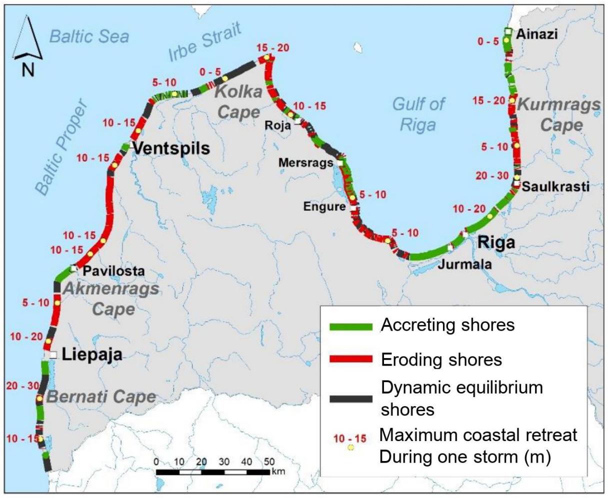

Figure 10. Assessed changes along the coast of Latvia. Compiled using data from Ulsts and Bulgakova (1998), Eberhards and Lapinskis (2008).

Viška, 2014). Such transport would take many years and is only possible because of extensive short-term and inter-annual variations in the transport direction that override the influence of convergence and divergence points. For example, in 1984 the transport pattern differed greatly from the usual and the common sediment flux divergence areas did not prevent sediment transit.

This coastal area of domain 3 develops mainly under the impact of two predominant systems of strong waves that arrive from SW and NNW (Soomere, 2003; Eelsalu et al., 2024) often at a large angle with respect to shore normal and produce strong and directionally varying alongshore transport. The implications of their presence are somewhat different from those described for the Polish, Kaliningrad, and Lithuanian shores. The wave-driven transport has a variable direction to the south of Cape Akmenrags but is mainly directed to the north between this cape and Cape Kolka (Soomere and Viška, 2014).

Unlike all other domains, domain 3 does not contain any bays deeply cut into the mainland, the seabed deepens relatively rapidly, and strong winds commonly blow obliquely to the shoreline. These features are not favourable for the formation of high storm surges in the area compared to the neighbouring areas or to the interior of the Gulf of Riga. The maximum recorded sea level has reached 1.74 m (in the Baltic height system 1977, BK77) at Liepaja. This is clearly lower than the maximum 1.86 m at Klaipėda (Dailidienė et al, 2006). The highest recorded values decrease towards Cape Kolka down to 1.61 m (Männikus et al., 2020), whereas they reach above 2 m along the southern and eastern shores of the Gulf of Riga. The rate of change of RSL based on the tide gauges is almost 1 mm yr^{-1} (Männikus et al., 2020). Interestingly, this rate is smaller than the corresponding rates in neighbouring domains in Estonia and at Klaipėda.

Long-term coastal changes 1935–2007 were detected from topographic maps and from planimetric surveys along some sections of the coast (Eberhards and Lapinskis, 2008). Coastal retreat reached 80–150 m at Cape Bernati near the southern border of the domain and to the north of Cape Akmenrags and Pavilosta (Jurkalne region). These are the fastest eroding segments of the Latvian Baltic proper shore (Eberhards, 2003). The eroding segments are interspersed with accumulating sections (Figure 10). In spite of massive sediment flow towards Cape Kolka, the coastline retreated more than 150 m on the north-eastern side of Cape Kolka during this period (Figure 10). This feature apparently reflects the deposition of most of the arriving sand in relatively deep water to the north of Cape Kolka. Only a small fraction of the sand is moved into the Gulf of Riga, and the north-western coast of this gulf has an acute sediment deficit.

As above, the pattern of eroding and accretion sections reflects the particular combination of the orientation of the coastline with respect to the predominant SW and NNW winds. The average long-term retreat range was between 0.5–1.5 m yr^{-1} and reached up to 2.5–3.5 m yr^{-1} at Cape Kolka and to the north of the major ports of Liepaja and Ventspils (Eberhards and Lapinskis, 2008). Since the 1990s, the mean rate of coastal retreat has increased to 2–3 m yr^{-1} and reached 3.5–4 m yr^{-1} in coastal segments near Cape Bernati and Cape Kolka (Eberhards and Lapinskis, 2008).

Some anthropogenically driven structural changes in sediment supply near the larger ports of Liepaja and Ventspils were caused by the construction of harbour breakwaters and moles at the end of the 19th and the beginning of the 20th century. These modifications trap sand at the updrift side of Liepaja and Ventspils harbours and intensive erosion has occurred in the downdrift areas of these ports (Figure 11) (Eberhards, 2003; Eberhards and Lapinskis, 2008). The coastal retreat to the north of the city Liepaja reached 300–350 meters during the second half of the 20th century and the process has continued in the 21st century (Eberhards and Lapinskis, 2008).

Similarly to domain 2 and particularly to the Curonian Spit, the existing balance of alongshore sediment transport is apparently fragile in domain 3. While the above-described changes in the wave height may have amplified the transport, they evidently have not caused any major alterations of its qualitative features. Changes in the predominant wind directions (or in the balance between wave energy approaching from these directions) have the potential to reverse the overall net transport (Soomere et al., 2015a). These changes may substantially reshape the current distribution of eroding and accumulating areas or drive faster erosion in areas near the three capes mentioned above.

Also similar to the situation in domain 2, the length of

Figure 11. Remnants of old fortifications to the north of Liepaja harbour that were originally built at the end of the 19th century on the landward side of dunes. Photo by T. Soomere, 2013. The rate of erosion on this coastal sections is estimated −4.3 m yr^{-1} (±0.3) over the period 1984–2016 by Luijendijk et al. (2018; https://aqua-monitor.appspot.com/?datasets=shoreline).

the ice season has decreased rapidly in domain 3 (Klavinš et al., 2016). The average ice season length in 2001–2011 was 45–49 days, a significant decrease from the 1950s, when the average number of ice days fluctuated close to 100 (at Liepaja). This process is definitely a manifestation of climate change. However, as the ice season is relatively short in this domain, these changes have a much less relative impact on the magnitude and course of coastal processes compared to domains 4, 5, and 6.

The major accumulation and erosion spots observed along domain 3 (Figure 10) can be associated with numerically retrieved areas of convergence and divergence estimated in Soomere and Viška (2014) using Coastal Engineering Research Council (CERC) method and wave time series simulated using adjusted geostrophic winds (Soomere and Räämet, 2011). The strongest divergence areas along Cape Bernati and Cape Akmenrags (north of Pavilosta) coincide well with observations (Figure 10) and with the perception that greater erosion around headlands often occurs because of refraction driven concentration of wave energy that creates a more energetic environment near headlands. The simulations also indicate that the highest net sediment transport occurs along the coast of the Irbe Strait. This coherence of simulated sediment transport intensity and patterns based exclusively on wave data versus observed shoreline changes indicates that coastal processes in domain 3 are mostly driven by waves. Consequently, it is likely that an increase in the intensity of coastal processes in some locations along domain 3 reflects changes in wave forcing rather than the impact of other drivers.

4.4 Gulf of Riga

The nearshore of the Gulf of Riga (domain 4) from Cape Kolka to Pärnu Bay consists mostly of mixed sediments and fine-grained sand (Ulsts, 1998; Viška and Soomere, 2013). Nearshore sandbars are common along the Latvian coastline of the gulf but scarce in the Estonian part of the gulf. They are mostly parallel to the coast and extend to about 4 m deep water (Eberhards, 2003; Eberhards and Lapinskis, 2008). As mentioned above, only a small fraction of sediment brought to Cape Kolka along the Baltic proper shore is moved by northerly winds to the south toward the bayhead of the Gulf of Riga. The dominant sediment flux direction is counterclockwise in the Gulf of Riga with some short reversals between Cape Kurmrags and Saulkrasti on the eastern coast of the gulf (Knaps, 1966; Ulsts; 1998, Eberhards, 2003). The potential bulk and net transport along the southern and eastern shores of this gulf is about a quarter of that along the Baltic proper shores of Latvia (Soomere and Viška, 2014).

The wave fields in the Gulf of Riga are almost totally separated from waves that develop in the Baltic proper. Consequently, wave systems that shape the open Baltic Sea coast and the shores of the Gulf of Riga may have greatly different properties. This means inter alia that the storms that affect the coasts of the Baltic proper generally impact the shores in the Gulf of Riga differently. In particular, the patterns of interannual variations in the net and bulk transport on the shores of the Gulf of Riga are different from those on the Baltic proper shore of Latvia (Soomere et al., 2011).

The RSL rise is negligible in most of the Gulf of Riga (Reiniks et al., 2010; Männikus et al., 2020). However, this domain is particularly vulnerable to high storm surges (Figure 3) that are the result of a combination of the (mis)match of the configuration of the gulf and the particular storm. Strong storms from particular directions may push large amounts of water into the gulf (Suursaar and Sooäär, 2007) so that the sea level in the eastern and southern parts of the gulf exceeds the level in the Baltic proper by more than 1 m for a period of about 2 days (Männikus et al., 2019). The maximum water level recorded at Pärnu reached 2.75 m (BK77) above the long-term mean, 2.31 m at Skulte, 2.15 m at Salacgriva and 2.24 m at Daugavgriva Riga (Männikus et al., 2019).

Large parts of the Gulf of Riga freeze every year. This feature adds an important nuance to the course and intensity of coastal processes as sea-ice conditions considerably affect the shallow nearshore areas that tend to be frozen during harsh winters. The presence of ice and the freezing of coastal sediment prevent both alongshore sediment transport and the loss of fine sediment to the deeper sea areas.

The coasts of the Gulf of Riga as seen from topographic maps and orthophotos (Eberhards and Lapinskis, 2008) have been generally stable during the years 1935–1990. They apparently are in dynamic equilibrium, with weak erosion or accretion (Figure 10). Some sections of the western and eastern coasts have suffered from erosion. The long-term mean retreat ranges are from 0.5–0.6 m yr^{-1} to 1–3 m yr^{-1} in some coastal segments (Eberhards and Lapinskis, 2008). Field observations and coastal monitoring show that the erosion rate and the length of affected areas have increased between 1992 and 2007 compared to the previous 50-year period. The total retreat of the shoreline has reached 20–40 m in the western and southern parts of the gulf with an average recession rate of 1.5–2.6 m yr^{-1}. The most affected are coastal segments near Roja, Engure, Ragaciems, and Jurmala. The retreat is as high as 2–5 m yr^{-1} in the eastern part of the gulf near Saulkrasti and Cape Kurmrags (Eberhards and Lapinskis, 2008). This section also has several smaller temporary reversals of wave-driven sediment flux (Figure 6, note that the scale of Figure 6 does not resolve details of sediment transport in the Gulf of Riga) (Soomere and Viška, 2014).

Numerical simulations of potential sediment transport using the CERC method show a similar pattern of changes along the coasts of the Gulf of Riga. They highlighted potential erosion areas near Saulkrasti and indicated a higher sediment transport rate near Cape Kurmrags (Soomere and Viška, 2014). The simulated data does not match closely changes retrieved from the observations in the coastal area from Cape Kolka to Riga. Certain differences between the observations and the outcome of sediment transport simulations may arise from ignoring the ice cover and the impact of high storm surges in the Gulf of Riga (Soomere and Viška, 2014). These aspects may be crucial for the evolution of the beaches in this seasonally ice-covered region that may have very high water levels for specific wind directions. A possible reason for pressures on the shores could be related to a change in the regime of extreme water levels in the Gulf of Riga (Männikus et al., 2020; Kudryavtseva et al., 2021) or to a rotation of strong winds. The loss of ice may lead to further intensification of wave-driven coastal processes (Najafzadeh and Soomere, 2024). These tendencies have been previously observed – a significant decrease of ice cover duration over the last 60 years from approximately 130 days to 68–76 days in the Gulf of Riga (Klavinš et al., 2016).

4.5 West Estonian Archipelago

Coastal domain 5 (Figure 1) stretching along the shores of the West Estonian Archipelago contains numerous gravel, shingle, or sand pocket beaches. The entire region has a complicated, and in places irregular and fragmented, shape, with many bays of different size cut deeply into the mainland and surrounded by extensive shallow areas. The predominant wind directions from SW and NNW (Soomere, 2003) correspond to the longest possible fetch lengths in the entire Baltic Sea. Therefore, this situation is favourable for creating one of the most energetic wave conditions in the Baltic Sea, with SWH possibly reaching over 9.5 m (Soomere et al., 2008; Björkqvist et al., 2018). It is one of the areas with the highest wave energy potential in the Baltic Sea (Soomere and Eelsalu, 2014) even though waves often approach the shore at large angles. These features make domain 5 particularly susceptible with respect to wind direction in single storms. Indeed, very intense coastal processes are often reported for this area (Kont et al., 2007; Suursaar et al., 2008; Tõnisson et al., 2011).

Additional pressure on the coastal zone is created when high sea levels occur simultaneously with high wave events. The highest recorded sea levels ($>$2 m at Ristna, BK77) most likely represent the joint contribution of storm surge and wave-induced set-up (Eelsalu et al., 2014). The RSL has generally decreased in this domain by about 1–2 mm yr^{-1} (Kall et al., 2016). This process to some extent stabilises beaches of this archipelago. However, the lack of sediment supplies renders the area vulnerable with respect to strong wave and elevated sea level events. Rapid loss of sea ice in the region (Sooäär and Jaagus, 2007) adds another changing driver to the system (Orviku et al., 2003).

The potential of combined impact of these drivers can be demonstrated using the Harilaid Peninsula, the most actively monitored site for coastal processes in this region. It is located near the sea area where the roughest wave conditions were projected to occur in the Baltic Sea during the prominent 2005 January storm (Soomere et al., 2008). The peninsula hosts a remarkable benchmark – Kiipsaare Lighthouse. This tower-type structure was build in 1933 in the middle of the NW part of the peninsula about 100 m from the waterline (Figure 12). Over time, waves have gradually eroded the western coast of the peninsula while depositing sediment along its eastern coast. As a result, the

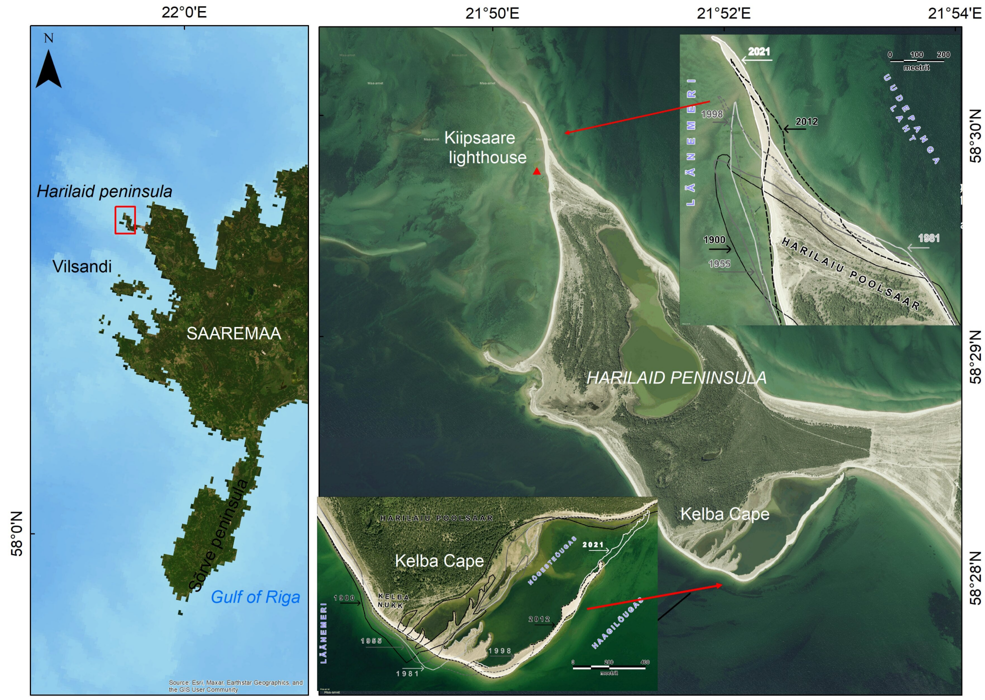

Figure 12. Changes on the western coast of the West Estonian Archipelago at the Harilaid Peninsula. Right panel: location map of coastal observation sites on northern and southern part of the Harilaid Peninsula. Figures showing shoreline changes at the Harilaid Peninsula and Cape Kelba are reproduced from Kont et al. (2022) with permission by the authors.

structure now stands in shallow water, about 50 meters from the shore.

This notable shift reflects particularly intense coastal processes in the West Estonian Archipelago. Consequently, the lighthouse's changing position relative to the shoreline has drawn significant interest from researchers as a valuable indicator of coastal changes and their intensity (Orviku et al., 2003; Suursaar et al., 2015). The reconstructed shoreline changes of the Harilaid Peninsula since 1900 rely on historical maps, photos, and other sources (Kont et al., 2011). Although the earlier maps are not sufficiently precise to quantify the exact location of the shoreline, there exists rich observational evidence of the shift of the shoreline (Tõnisson et al., 2011, 2013). The northern shoreline of the peninsula shifted at an average rate of approximately 2 m yr^{-1} from the 1950s to the end of the century. This rate accelerated in the 1980s to about 3 m yr^{-1}. During a single storm, the shoreline eroded by up to 30 m (Orviku et al., 2009). The changes to the coast at this site are thus extremely intermittent and the average rate of change does not necessarily reflect the complexity of the process. This evidence confirms once again that the biggest changes to the coast occur during individual very strong storms, possibly from an unusual direction.

During the period 1900–1955 the north-western shoreline of the peninsula shifted by 25 m towards the east (Figure 12). The shift in 1955–1981 was much faster and reached about 40 m (Tõnisson et al., 2013). During the years 1988–2008, the northern part of the beach eroded substantially (Figure 12). The northern tip of the peninsula sharpened and narrowed until 1998. It was considerably reshaped after 2008 when it lost a clearly expressed tip and the shoreline was shifted considerably towards the south (Figure 12). It is likely that the described rapid and massive changes of this uplifting peninsula are caused by a combination of less sea ice (Orviku et al., 2003; Sooäär and Jaagus, 2007) and changes in the direction of strong winds in some storms.

Another interesting rapidly developing site is an actively developing area called Cape Kelba (Figure 12). Suursaar et al. (2015) note that coastal processes have gradually intensified there since 1950. The advance rate of the shoreline for any single section of this landform is now up to 5 times that of a half century ago.

4.6 Southern and eastern part of Gulf of Finland

Similarly to domain 5, the southern shore of the Gulf of Finland (domain 6) has a variety of different coastal environments, from extensive limestone cliffs to several bays that are deeply cut into the mainland. Long coastal segments have pebble and boulder protection. The domain also contains small pocket beaches, ancient sand dunes, and a long sandy beach near the Narva River mouth (Orviku, 2018). In general, this coastal zone can be characterised by a predominance of glacial deposits with a relatively small thickness of overlying sandy sediments (Divinsky et al., 2021). It experiences glacioisostatic uplift of about 1–3 mm yr^{-1}, with higher rates in the west (Kall et al., 2014) and a near-zero rate of recent relative sea level rise (Madsen et al., 2019). These conditions are expected to slightly stabilise the beaches, even though most beaches in this domain suffer from a deficit of fine-grained sediments.

Many beaches along the southern coast of the Gulf of Finland are geometrically sheltered from moderate and strong winds from SW. Almost all such beaches are open to the north. Similarly to the situation in the West Estonian Archipelago (Eelsalu et al., 2014), infrequent but strong NNW storms may create substantial wave set-up heights that result in higher sea levels than could be expected from the classic storm surge data (Pindsoo and Soomere, 2015; Soomere and Pindsoo, 2016), and can drive massive erosion of sandy beaches (Orviku, 2018). Extreme storm surges, up to 4 m above the long-term mean water level may occur in the easternmost Gulf of Finland (Wolski and Wiśniewski, 2020) and exceed 2 m in the vicinity of Narva (Suursaar et al., 2006). This feature is complemented by the conjecture that extreme water levels have systematically increased up to 10 mm yr^{-1} in the eastern Gulf of Finland (Pindsoo and Soomere, 2020). Fortunately, the highest water levels usually do not occur simultaneously with the strongest waves in the eastern part of this domain (Pindsoo and Soomere, 2015).

Similarly to western Estonia, limited sediment availability in the eastern Gulf of Finland and in the Neva Bight with the combination of other discussed drivers makes beaches of this coastal area extremely vulnerable during long-lasting storms in the absence of stable sea ice in wintertime (Ryabchuk et al., 2011a). The loss of sea ice has the largest impact on the shores of the eastern Gulf of Finland compared to coastal environments of the north-eastern Baltic Sea in terms of potential changes in wave energy flux (Najafzadeh et al., 2022).

The analysis of changes to the beaches in the southern Gulf of Finland relies on remotely measured data (Julge et al., 2014; Eelsalu et al., 2015; Sergeev et al., 2018; Eelsalu et al., 2022), modelled wave data (Soomere et al., 2008; Divinsky et al., 2021) and GPS monitored data combined with archive material (Ryabchuk et al., 2011a,b). The annual rate of coastal retreat is uneven. It is less than 0.5 m yr^{-1} during low storminess periods (Sergeev et al., 2018) whereas for stormy years it may reach about 3 m yr^{-1} (Sergeev et al., 2018; Eelsalu et al., 2015). The easternmost Gulf of Finland is particularly vulnerable with respect to wave-dominated erosion (Ryabchuk et al., 2011a,b; Sergeev et al., 2018) because high waves often approach the shore at large angles. The estimated average retreat was about 0.56 m yr^{-1} in 1989–2009 and reached 1.45 m yr^{-1} in 2009–2017 (Sergeev et al., 2018).

5. Discussion

The presented material provides insight into possible links between changing natural drivers of coastal processes and their implications in terms of various spatial patterns and temporal variations of coastal processes. The situations where coastal processes were mainly impacted by anthropogenic activities or when links of this kind were doubtful are intentionally left out of the analysis of these links in this section.

The existing evidence indicates that different drivers play different roles in the various domains of sedimentary shores of the Baltic Sea (Figure 13). The main reason for the spatially varying roles and relative importance of various drivers is the specific combination of the shape of the sea, the spatially varying strength of several drivers (e.g., sea ice) and the strongly anisotropic nature of wind fields (Leppäranta and Myrberg, 2009). This anisotropy naturally generates similar anisotropy of wave properties (which are generally higher in the eastern part of the sea, Björkqvist et al., 2018) and extreme water levels (which are generally higher and more frequent in the north-eastern subbasins of the sea, Wolski and Wisniewski, 2020, 2021, 2023).

The background for the development of coasts is the change in the average water level. This driver is the strongest in the southern part of the sea, where a combination of slow crustal subsidence with the signal of global sea level rise via the Danish straits has led to a systematic relative sea level rise of up to 2 mm yr^{-1}. This process has accelerated since the middle of the last century, most significantly along the Polish coastline (Rotnicki and Rotnicka, 2010). It is highly likely that this systematic and fairly rapid relative sea level rise has expedited the coastal retreat process along the Polish coastline (Łabuz, 2013, 2015) (Figure 13). Global warming and the associated sea level rise in the North Sea are the main contributors to the relative sea level increase in this domain. Thus, the enhanced erosion along the coast of Poland can be attributed partially at least to climate change with a high likelihood.

It is also likely that the impact of global sea level rise accelerates to some extent coastal processes on the shores of the Kaliningrad District, however, its magnitude is apparently smaller than the impact of waves. An increase in the relative sea level of about 15 cm in the last 100 years is also evident along the coast of Lithuania (Dailidienė et al., 2006). This change might cause shoreline retreat (according to the controversial Bruun Rule) of sandy beaches by about 10 m. However, this change, is hardly distinguishable from all other factors that affect the active sandy environment of the Curonian Spit and the Lithuanian shore. Moreover, no systematic shoreline retreat is identified in that particular section (Bagdanavičiūtė et al., 2012, 2015). This conjecture apparently reflects several other mechanisms that stabilise sedimentary beaches, most importantly the sufficient sediment availability in multiple sand

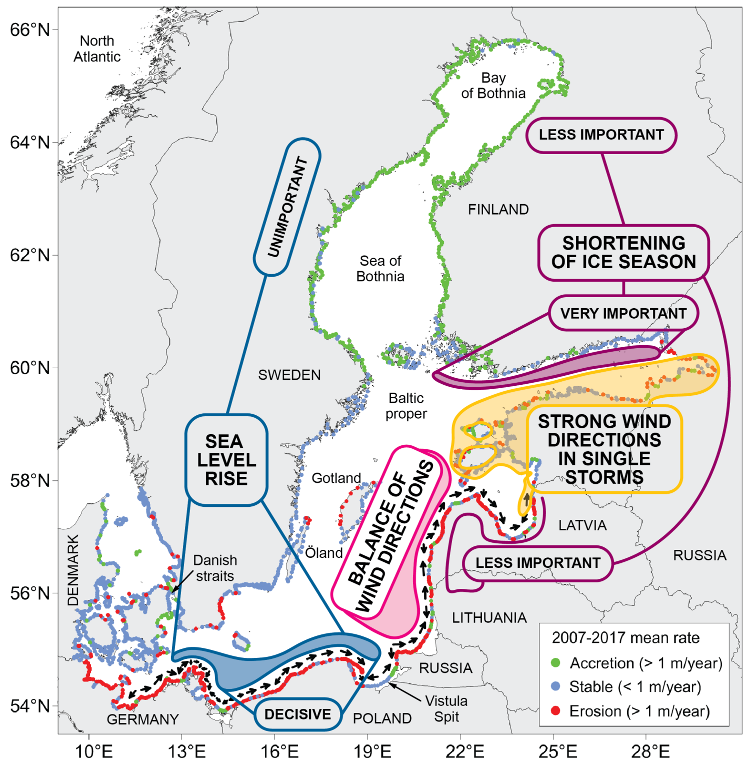

Figure 13. Location scheme of the Baltic Sea and spatially varying role of main drivers of coastal processes. The background map that characterizes vulnerability of the Baltic Sea shores with respect to erosion and the long-term direction of wave-driven sediment transport is taken from Weisse et al. (2021; published under CC-BY-4.0, ©Authors) and is used with permission of its compiler, Dr. Wenyan Zhang. The rate of mean annual coastline change from 2007 to 2017 in the Baltic Sea (color scale in the lower right corner of the image) is based on a combination of satellite data for sandy beaches (Luijendijk et al., 2018) and field measurements for other coastline types extracted from the European Marine Observation and Data Network (EMODnet) https://emodnet.ec.europa.eu/en/geology database. The primary alongshore sediment transport direction along the sandy southern Baltic Sea coast, indicated by the arrows, is based on existing literature compiled by Harff et al. (2017). Graphics representing the role of main driving factors are created by Kaspar Ehlvest. Reproduced from Soomere (2024). Licence number 96486 by Oxford University Press.

bars in the nearshore of the Curonian Spit (Janušaitė et al., 2022). Also, sediment flux from the neighbouring area (Kaliningrad District where erosion dominates) or changes in other hydrometeorological patterns (e.g., wave direction) may stabilise Lithuanian beaches.

The relative sea level rise is very small or negligible on the Latvian shores (Männikus et al., 2020 based on estimates from Reiniks et al., 2010). The shores of Estonia and the Russian part of the Gulf of Finland experience post-glacial uplift (Kall et al., 2014) and have been until now immune to climate-driven sea level rise. There is therefore a distinct gradient in the magnitude of impact of (relative) sea level rise, from a well-defined contribution to the acceleration of coastal processes in the south-west to virtually no impact to the north of latitudes of the Gulf of Riga.

Wind waves are the main source of energy for coastal changes. The direction of predominant moderate and strong winds is such that most waves approach the shores of Poland from the west and generate wave-driven net sediment transport almost exclusively to the east. This systematic process has straightened the entire coastline and created massive landforms such as the Hel Peninsula and the Vistula Spit. There is no evidence regarding the impact of climate change-driven variations in wave directions on this sediment transport. The identified changes hint that waves approach this shore segment more from the west rather than from the south-west. Such changes may have even decelerated the net transport. The same conjecture applies to the more or less straight sections of the southern shore of the Gulf of Finland, where strong eastern winds seem to be back (Pindsoo and Soomere, 2015).

The shores of most of the Kaliningrad District (Sambian Peninsula) are oriented in a way that allows a significant portion of strong waves to approach the beaches at a relatively steep angle, driving sediment transport away from

Cape Taran. This feature has made this part of the Baltic Sea shore prone to erosion over millennia. Small changes to the wave heights or wave approach directions are unlikely to change this situation, wich eventually will persist also in any possible future climate.

The waves generated by the bidirectional pattern of predominant strong winds have created a delicate balance of coastal processes along the Baltic proper shores of Lithuania and Latvia (Figure 13). While waves generated by frequent SW winds carry sediment to the north, waves excited by less frequent but sometimes even stronger northerly winds (Soomere and Keevallik, 2001) drive sediment transport to the south. This situation suggests that climate change-driven changes to any of the Baltic Sea wave properties will become evident first in this coastal domain from Sambian Peninsula to Cape Kolka. Such changes have been identified so far only in numerical simulations (Soomere et al., 2015a).

The observed variations along the coast of Lithuania (including the Curonian Spit) support this conjecture. It is common to observe a cyclic pattern of changes along this coastline. Most of the storms that drive severe erosional events along the Curonian Spit are short (1–2 days) (Boldyrev et al., 1990 as cited in Ryabchuk et al., 2020; Jarmalavičius et al., 2016) and blow from SW or NW (Kelpšaitė and Dailidienė, 2011) while after the 1980s NW winds are much less frequent in Lithuania. Post-storm recovery usually restores the shoreline almost entirely (Kelpšaitė-Rimkienė et al., 2021). This feature apparently reflects a directional balance between wave systems during storms and waves that are prevalent most of the time. Some locations with systematic erosion on the Lithuanian coast are likely the result of engineering structures in port areas or other human activities.

The situation is similar on the Latvian shore of the Baltic proper, except that there is massive net sediment transport to the north between Cape Akmenrags and Cape Kolka, especially near the Irbe Strait. The reason is that the southern shore of Irbe Strait is protected against waves excited by the "balancing" northerly storms but still regularly impacted by long and high waves excited by SW storms. Due to the limited availability of fine sediment in this area compared to the Lithuanian shores, many sections of the coast experience erosion. Damage caused by exceptional storms is not easily offset by natural recovery processes. The system of sedimentary shores from Cape Taran to Pärnu Bay has a complicated pattern of mostly counterclockwise wave-driven sediment drift that also contains a few divergence points and reversals (Viška and Soomere, 2013; Soomere and Viška 2014). Simulated potential bulk wave-driven sediment transport along these coasts increased during 1970–2007 at a $>95\%$ level of statistical significance (Figure 14) (Soomere et al., 2015a). As the increase in wave heights was only marginal (Soomere and Räämet, 2014; Sokolov and Chubarenko, 2024), this growth was apparently driven by a systematic change in the wave approach direction. As it continued for almost 40 years, it is safe to attribute it to climate change.

Another feature that eventually can be attributed to climate change is a radical alteration of the temporal course of potential net transport from the year 1990 (Soomere et al., 2015a) (Figure 14). As the periods for increase and decrease in this quantity were relatively short, the relevant trends were statistically significant at approximately 90% level. This turn in the trend can be explained, as above, by a systematic change in the wave approach directions. To the eyes of the authors, the described changes in wind properties and the associated wave patterns are among the strongest evidence of climate change-driven manifestations in the Baltic Sea basin.

As the transport rates are particularly large along the Latvian and Lithuanian shores, it is likely that these shores are more sensitive with respect to climate-driven changes in wave forcing than Polish shores or the coasts of the Kaliningrad District. The impact of changes to wave properties becomes evident more locally in the Gulf of Riga, West Estonian Archipelago, and Gulf of Finland where most sedimentary compartments and beaches are small and many of them located in bayheads of bays deeply cut into mainland. These beaches often have very limited sand resources but remain stable until a strong storm approaches from a particularly unfavourable direction or the properties of some other drivers (extreme water level, wave setup, or sea ice) change considerably as explained in Section 4.5. Some of them are stabilised by a specific synchronisation of the course of water level and wave properties (Eelsalu et al., 2022).

An example of potentially climate change-driven effects on wave climate and related sedimentary systems can be inferred from processes on the NW of Saaremaa (Section 4.5). The changes in the Kiipsaare Lighthouse relative location to the shoreline could be related to the change in the dominant airflow direction. From 1966 to 2003 the airflow direction rotated by up to 90° in winter months (most notably in January) when strongest wave conditions occur and the majority of the yearly sediment transport also occurs (Keevallik, 2011). This change evidently reflects more frequent strong SW winds and associated longer and stronger waves from the SW. This pair of impacts could explain the changes in the development of this peninsula that have led to almost total reshaping of Cape Kiipsaare and its adjacent area this century.

The examples provided suggest that changes to the properties of waves affect different shore segments of the Baltic Sea substantially differently. In the southern and south-eastern domains the impact of these changes, even if relatively large, seems to be limited to variations in the magnitude of long-term processes. On the contrary, even small changes in the balance of wave systems arriving from different directions may radically reshape the existing pat-

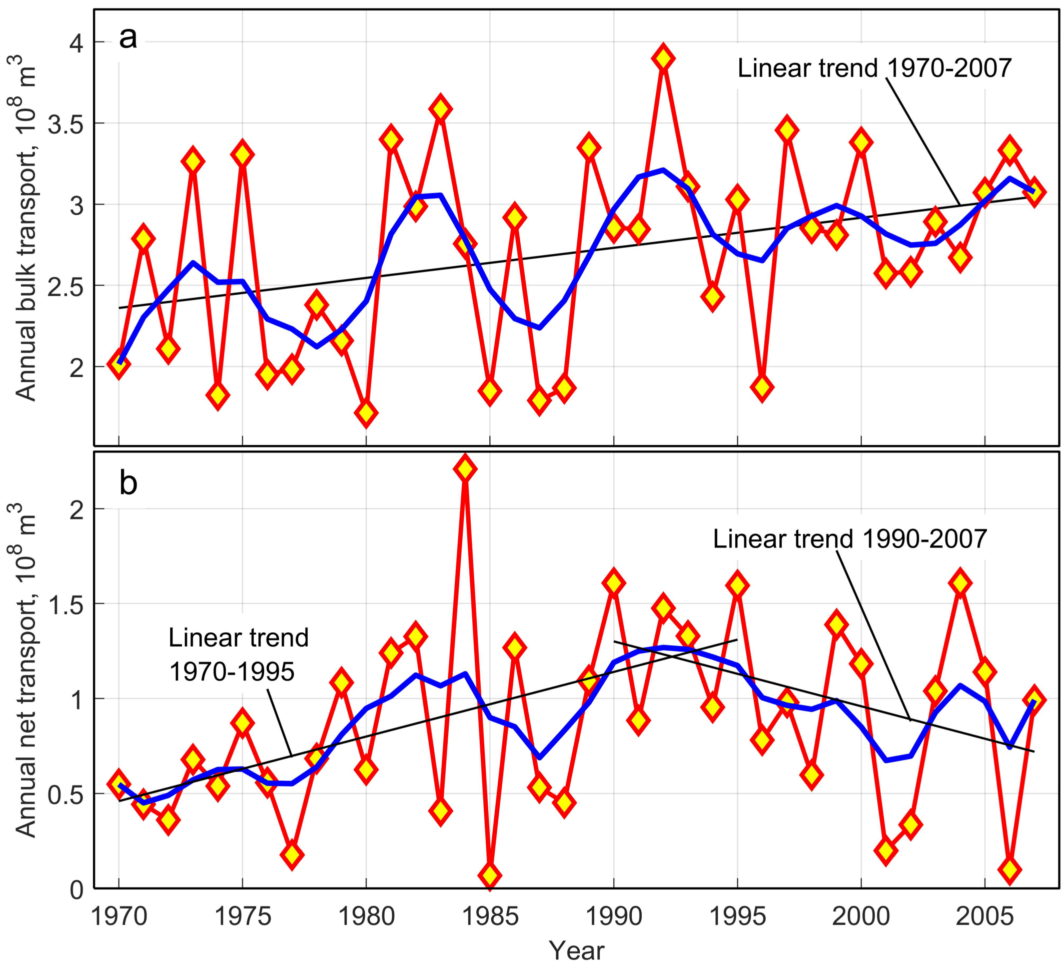

Figure 14. Bulk (a) and net (b) annual wave-driven potential sediment transport rate along the entire eastern coast of the Baltic Sea evaluated by the CERC model forced with wave time series from the WAM wave model driven by adjusted geostrophic winds (Soomere and Räämet, 2011). Reproduced from Soomere et al. (2015a).

tern of net sediment transport and thus also some erosion and accumulation areas on the eastern shore. Such changes have apparently already happened. The third kind of impact is on the strongly fragmented shoreline of Estonia where storms from an unusual and unfavourable direction may greatly damage some usually sheltered beaches.

An associated and often ignored consequence of strong waves is their ability to produce additional increases in water level (wave setup). The contribution of this process is apparently small or negligible in most of the southern and south-eastern Baltic Sea shore. A concealed consequence of the presence of the above-described bidirectional wind pattern means that strong waves usually arrive at the shore at a relatively large angle in this area. The situation is different in the Gulf of Riga, West Estonian Archipelago, and Gulf of Finland where many storms apparently drive substantial local setup (Soomere et al., 2013). This phenomenon may considerably contribute to extreme water levels in the area (Eelsalu et al., 2014).

As wave setup is sensitive with respect to the match of the geometry of the shoreline and the wind direction, changes to its properties, even if estimated using various proxies (Soomere et al., 2013), may help in attributing potential changes in coastal processes with climate change-driven alterations in the driving forces. This kind of analysis for the vicinity of Tallinn Bay indicated that strong easterly wave storms (that were not recorded for many decades, Keevallik, 2003) returned to the area from winter 2012/2013 (Pindsoo and Soomere, 2015). This conjecture is supported by wave measurements. The all-time highest SWH 5.2 m, recorded for the first time in November 2001 in a westerly storm, was repeated in November 2012 during an easterly storm (Pettersson et al., 2013). This change, although not yet reflected in the coastal literature, most likely reflects climate change and has the potential to greatly modify coastal processes in segments of the southern shore of the Gulf of Finland that are open to the east. However, there are not enough research data as yet to identify the related changes to coastal processes or to attribute these to climate changes.

An even more important factor affecting coastal processes is an exceptionally high water level. While in tide-dominated water bodies the probability of having strong waves is, in essence, the same during each tidal phase, the situation is different in non-tidal water bodies, such as the Baltic Sea, where wind-driven elevated water levels are often synchronised with strong waves (Kudryavtseva et al., 2020; Eelsalu et al., 2022). This synchronisation may adjust the basic properties of beaches, such as the closure depth (Soomere et al., 2017). As described above, very large water levels occur more frequently in the westernmost, northernmost, and easternmost parts of the Baltic Sea. It is therefore likely that changes to the properties of the highest water levels affect coastal processes in the most significant way in the eastern Gulf of Finland and the Gulf of Riga (Figure 13).

Systematic changes in the annual water level maxima during 1961–2005 in the entire interior of the Baltic Sea are most likely generated by a longer time series of atmospheric events that press water into the Baltic Sea and increase the entire sea level (Pindsoo and Soomere, 2020; Rantanen et al., 2024). They are thus another manifestation of climate change in this water body. This component of the coastal processes drivers affects more or less equally all shores; however, it is not clear how to separate its impact from that exerted by sea level rise. Another variation of this change has led to a rapid increase in the annual maximum water level in several locations. This process in the Gulf of Finland and on the Lithuanian shore apparently stems from a change in wind direction in some storms and thus has a direct link with climate change. This process is more complicated in the Gulf of Riga (Männikus et al., 2019).

The examples presented indicate that the impact of this driver varies throughout the study area, even though its role has not yet been specifically identified. Although different authors use different thresholds for surges, a clear pattern of changes still becomes evident from the existing information. Namely, high surges have become both more frequent and higher in the north-eastern domains of the study area (Wolski and Wisniewski, 2020, 2021, 2023). High surges have become more frequent but not considerably higher in the south, where the absolute number of high surges (independent of the threshold) remains much lower than in the north-east. Therefore, contrary to the impact of sea level rise, the contribution of very high water levels to coastal processes is apparently negligible in the south and south-east of the Baltic Sea. Its magnitude increases for the shores of the Baltic States and peaks in the eastern Gulf of Riga and the Gulf of Finland (Pindsoo and Soomere, 2020).

The presence of sea ice and the change in its impact on coastal processes is obviously climate change-driven. Its magnitude appears to be fairly small to the south of the latitudes of Latvia (domains 1–3) where the ice season is generally short. However, many of the changes that have occurred along the coastal areas of the Gulf of Riga, West Estonian Archipelago, and along the coast of Gulf of Finland strongly depend on the (loss of) sea ice (Figure 13). The absence of ice means unfrozen sediment, more frequent and higher storm surges, and much more wave energy approaching the shoreline. The impact of the loss of ice evidently increases from the south-west to the north-east. This driver clearly plays a role in the increasing intensity of coastal processes on the shores of the West Estonian Archipelago (Orviku et al., 2003), may be dominant in the eastern Gulf of Finland (Ryabchuk et al., 2011a) and possibly important in the Gulf of Riga as well (domain 4, Najafzadeh et al., 2024). Somewhat unexpectedly, the current rapid loss of sea ice has the largest impact in terms of average wave properties on the shores of the eastern Gulf of Finland and is weaker in the north of the Baltic Sea (Najafzadeh et al., 2022). This feature reflects the general perception that climate driven-changes to ice properties are the largest at the latitudes of the Gulf of Finland (Matti Leppäranta, personal communication, 02.12.2022). In this context, it is likely that changes to all main coastal drivers (except for sea level rise) currently affect most strongly the shores of the Gulf of Finland. This potentially means a higher vulnerability of the beaches and increased erosion rates on many parts of the coast of the Gulf of Finland in the near future. Sergeev et al. (2018) suggest that under the 'pessimistic' scenario of extreme storm frequency, many shorelines in the eastern Gulf of Finland could retreat by 7–8 meters from their 2017 positions by 2027.

Finally, we note that an obvious limitation of our analysis is that it relies on statistics of water level, wind and waves, and properties of single storms, and it overlooks the potential impact of storm sequences. It is well known that beach profile evolution and thus also changes to the shoreline under specific storm sequences may be radically different from such an evolution under single storms when less energetic wave conditions have had an opportunity to recover/refill the beach (Baldock et al., 2017). Storm groups sometimes do not allow the profile time to recover and may produce changes typical of less frequent, longer duration, and more intense storms (Birkemeier et al., 1999). The seabed change is not necessarily proportional to the storm power of single events within the cluster. This may result in greater change to the beach also during less severe subsequent storms (Dissanayake et al., 2015; Różyński, 2023) and may make it not possible to scale-up single-storm erosion studies into predictions of cluster-storm erosion (Coco et al., 2014) but still does not necessarily mean increased beach erosion by storm sequences (Angnuureng et al., 2017; Eichentopf et al., 2020).

Another obvious limitation of the analysis is the omission of riverine sediment flux into the study area. This position is probably applicable for the shores of Latvia, Lithuania and Estonia where the inflow of sand from rivers is fairly minor. However, this flux is clearly non-negligible for many sections of Polish beaches. These aspects definitely need to be considered in future studies.

6. Conclusions

A common signal over the last decades along sedimentary shores of the southern and eastern Baltic Sea is intensification of coastal processes and accelerated coastal erosion in many locations. Despite the complicated nature of coastal changes and their drivers, the existing pool of research makes it possible to distinguish spatially varying roles of core drivers of coastal evolution in some locations.

The properties and intensity of the factors that drive a large part of the coastal evolution are highly variable along the coast of the Baltic Sea. Moreover, changes to the main coastal drivers, such as sea level, waves, and sea ice, have different roles in different areas. This is one of the reasons why both the implications and impact of climate change vary considerably along the coast of the Baltic Sea.

The impact of climate-driven sea level rise is the strongest in the southern part of the sea where global sea level rise is greater than crustal subsidence and likely contributes to the coastal retreat. This impact can be attributed with high likelihood to the climate change. The magnitude and role of this driver decrease to the north-east, and it becomes insignificant to the north of the latitudes of the Gulf of Riga. On the contrary, the possible impact of an increase in extreme water levels is greatest on the eastern shores of the Gulf of Riga and Gulf of Finland and moderate elsewhere.

The frequent presence of ice cover during the windy part of the cold season stabilises the beaches of the north-eastern shores. Global warming has significantly decreased the extent of the sea ice and the duration of the ice season length in the Baltic Sea. Variations in the impact of this driver have a complicated spatial pattern. Changes in the ice regime are minor in the southern part of the Baltic Sea, where frozen sea is uncommon. The impact of these changes is greatest at latitudes of the Gulf of Riga and the Gulf of Finland, where a significant decrease in the ice season length has already greatly reduced the natural protection of beaches and possibly promoted higher rates of coastal erosion.

Changes in wave properties appear to influence the magnitude of coastal processes primarily along the southern shores of the Baltic Sea, south of Cape Taran, and the northern shores of Estonia. The shores of the West Estonian Archipelago, Latvia, and Lithuania function under a delicate balance of wave systems generated by south-western and northerly winds. Modifications of this balance have the strongest impact, including changes in the entire sediment transport pattern in this domain. The impact of possible changes to strong wind directions in single storms and associated wave setup phenomena is apparently limited to pocket beaches in Estonia.

The core message of the analysis is that (i) the impact of individual manifestations of climate change varies greatly in different parts of the Baltic Sea and (ii) the reaction of coastal processes to this impact is extremely heterogeneous, substantially site-specific, and becomes evident in varying ways across different coastal segments and sub-basins of the sea.

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Conflict of interest

None declared.

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