

## 20 Environmental Impacts – Coastal Erosion and Coastline Changes

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### Abstract

Climate change is having an undeniable influence on coastal areas. This chapter describes the growing threat of climate change on the Baltic Sea coastline, with an emphasis on field research focused on storm surges and coastal retreat. The main climatic factors driving change in the Baltic Sea coastal zone are wind, waves, storm surges, ice jams and flooding. The cumulative effects of these drivers are also important. For example, a costly coastal protection scheme in one area may result in coastal erosion in another. Natural as well as man-made coastal features are experiencing unprecedented change; important natural habitats, coastal settlements and local economies are all being affected. The extent of storm surge impacts depends on the exposure of a shoreline to a surge event. The submergent and soft coastal relief of the southern Baltic Sea area is under most threat; the rate of retreat depending on the frequency and strength of the storm surges. The rate of coastal retreat has also increased in recent years due to sea-level rise and loss of beaches.

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## 20.1 Introduction

The coastal zone is one of the most dynamic environments in the world, because it is where different geospheres interact. Taking place over a range of time scales, these interactions cause dynamic coastal rebuilding, referred to as coastal morphodynamics. The factors responsible for change in the coastal zone may be grouped into geological and geomorphological, hydrodynamic, biological, climatic and anthropogenic factors. The main geological factors – sediment type, arrangement and resistance of sediment structures, and isostasy – are the basis of the morphological processes and the development of coastal relief.

Geomorphological processes are influenced by many external forces, including climatic factors such as precipitation rain and wind. They are responsible for the development of typical relief forms and sediment supply. Biological factors mainly concern the influence of plants and are responsible for the development of particular coastal types. Anthropogenic factors refer to the many human activities taking place within the coastal zone: settlements, industrial development, agriculture, deforestation and coastal protection. The coastal system is a dynamic complex of sensitive factors and typically responds in a non-linear morphological manner (Dronkers 2005). The wide range of natural and human influences on the Baltic Sea coastline makes it difficult to identify the specific effects of climate change. Exposure to wind is a key factor for coastal development. Climatic conditions greatly influence the inflow of material to the coastal zone, by determining the amount and origin of terrigenous material supplied to the coastal zone as well as the amount of biogenic material produced and supplied to the sediments.

The combination of sea-level rise, land subsidence and isostatic rebound creates both emergent and submergent coasts. Emergent coasts are identifiable by accumulative landforms or ancient coastlines recorded in the relief or sediment structures on land. Submergent coasts occur where rising sea level and subsidence cause coastal retreat, and where water is entering and eroding land features. Crest movements show the 'sinking' of the southern Baltic Sea coast and uplift in Scandinavia. For instance, glacial isostatic adjustment (GIA) has caused the coastal zone in Estonia to emerge throughout the Holocene (last 10,000 years), with current uplift rates of 1.0–2.8 mm yr<sup>-1</sup> and with maximum uplift located on the north-western coast (Vallner et al. 1988; Ekman and Mäkinen 1996). Transgression is expected with the sinking of the coast (Harff and Meyer 2007) (for more information on land movements due to GIA see Chapter 9).

The main coastal features in the Baltic Sea region are sand or gravel spits with diversified dunes, cliffs cut in a variety of sediments and low-lying areas such as lagoons, wetlands and salt marshes (Fig 20.1). Accumulative features like sand spits or beaches are formed by currents and waves. Dunes developed on sandy spits are higher origin forms accumulated in the past or now. They are developed as aeolian forms shaped by wind. Cliffs may be cut into hard rock or into soft clays, tills and sands and are usually higher order relief forms shaped by erosion processes like waves or landslides.

Different types of Baltic Sea coast may be distinguished based on the strength of the factors affecting the various geological structures of the coastal zone. Most Baltic Sea coastlines and coast types were formed during the last deglaciation and the subsequent Holocene sea transgression. Unconsolidated glacial sediments were shaped into moraine hills separated by low-lying fluvio-glacial valleys. High, soft moraine hills attacked by waves were shaped into relatively steep cliffs. Sea transgression flooded low-lying areas, creating shallow bays, lagoons and swampy areas. In such areas, sediment accumulation by long-shore currents often created emerging barriers. The southern Baltic Sea coast is mainly composed of moraine cliffs (made by glacial tills, clays and fluvio-glacial sands) and sandy or gravel coasts developed as spits. Abundant sand sediment has led to the creation of various sandspits, with the longest occurring on the southern Baltic Sea coast, such as the Vistula and Curonian Sandspits. Lagoons, shallow sea bays and coastal lakes were formed on low-lying coast, where organic accumulation and sedimentation dominated. Spits such as islands or barriers develop where sediment, moving alongshore, is deposited at the mouth of estuaries and other places with an abrupt change in the direction of the coast (Trenhaile 1997). Several sandy barrier islands occur on the German Baltic Sea coast (e.g. Hiddensee) others, built by gravel or pebbles, in Estonia.

Owing to long-shore transport and the origin of land features, the Polish, Lithuanian and Latvian coastlines are effectively aligned, with sandy barriers separating valleys, deltas, lakes and lagoons from the open sea. The German and Danish soft coasts are more circuitous, due to numerous bays, peninsulas and islands.

The northern part of the Baltic Sea coast is mainly formed by isostatic uplift due to the loss of glacial cover in Scandinavia. In some places accumulative forms occur in bays or river deltas. Finland and Sweden have emergent coasts where abundant skerries form archipelagos. Some U-shaped fjords were formed by glaciers in rocky, mainly igneous beds (Fig 20.2B) with the presence of some sandy, accumulative barriers or

beaches. Rocky limestone or chalk beds, found in Estonia and on the Baltic Sea islands, have formed cliff coasts (Fig 20.2E, Fig 20.2F).

## **20.2 Characteristics of coastal types around the Baltic Sea**

The Scandinavian coast is mainly covered by hard rock, such as igneous, sandstone or limestone forms. It has been shaped by glaciers that have formed U-shaped fjords or flat coastal forelands. In the Bothnia Gulf there is a skerry-type coast, which due to uplift is formed by many small islands. Skerries are commonly formed by rocky blocks that emerge from the water, separated by ice-shaped channels. The bedrock geology of the southwest archipelago consists of fractured and faulted Precambrian granites and schists of the Fennoscandian Shield that comprise the peneplain surface that slopes gently southwest (Schwartz et al. 1989). The following sections describe the coastal types by country. See Figs. 20.1 and 20.2 for the main the coastal types occurring in the Baltic Sea region.

### **20.2.1 Finland**

Small patches of dune landscape are widespread on the Finnish coast, formed mainly from skerries (Fig 20.2A) and post-glacial beaches on rapidly rising coastlines (Hellemaa and Doody 1991). The uplift rate is up to  $9 \text{ mm yr}^{-1}$ , particularly in the Gulf of Bothnia. The dune landscape consists of parallel ridges separated by low, wet depressions arranged parallel to the coastline. The ridges are generally no higher than 8 m, but where uplift is slower, a few reach 20 m. The south-western coast of Finland near the Åland Islands has many skerries, forming a huge archipelago. In total there are some 73,000 islands along the coast of Finland.

### **20.2.2 Sweden**

The Swedish coastline is over 13,500 km long. Due to continuous uplift in the northern section, only the southern part of the Skåne coast is at risk of erosion (Fig 20.2D). The present rate of land uplift by isostatic rebound varies from zero in southern Skåne to a maximum of  $0.9 \text{ mm yr}^{-1}$  along the coast of the Bothnian Bay (Hanson 2002, see also Chapter 9 and references therein). Low coasts dominate in Sweden and active cliffs cut into tills and fluvio-glacial sediments are found in the south of the country. The rest of the coastline comprises low or average height cliffs made of hard rock, partly covered by glacier deposits such as till, sand or gravel. The northern part of the Bothnian coast is mainly low-lying and comprises igneous rocks and gravel. In Sweden, coastal dunes mainly occur on the southern coast in Skåne and Halland (Malmö-Ystad) and in spots along the Gulf of Bothnia on low coastal areas and small barrier islands or spits among the cliffs. The dunes reach heights of 10–15 m as ridges parallel to the coastline. The counties most affected by coastal erosion are Skåne, Blekinge and Halland (European Commission 2004).

### **20.2.3 Denmark**

The Danish coastline of the Baltic Sea varies in shape and origin. In some places the coast is formed by cliffs ('klints'), as in the southern part of the island of Zealand. One of the famous Cretaceous-Tertiary klints occurs south of Copenhagen – a 14 km long rocky cliff formation, mainly of chalk and limestone with Quaternary deposits on top. In other places Quaternary deposits form the cliff with klint structures below ground (Prior 1977). Salt marshes, also called meadows, sink at a rate of  $1\text{--}2 \text{ mm yr}^{-1}$ . Danish coastal systems are subject to erosion at rates of up to  $3\text{--}5 \text{ m yr}^{-1}$  (Clemmensen et al. 2011). The islands of Gotland (Sweden) and Bornholm (Denmark) are mainly formed from rock with small areas of coastal sand dunes.

### **20.2.4 Germany**

Two-thirds of the German Baltic Sea coastline is being eroded. The coastline is divided between the two German states of Schleswig-Holstein in the west and Mecklenburg-Vorpommern in the east. The Schleswig-Holstein coastline is 637 km long with 148-km long soft cliffs and is generally in a retreat state due to sea-level rise (Hofstede 2008). The Mecklenburg-Vorpommern coastline is almost 1945 km long in total with an external coast of 376 km; of the latter, steep cliffs cover 128 km and flat sections 248 km. Approximately 70% of this coast is in recession (Gurwell 2008). More than half of the coastline is 'bodden' coast – shallow bays and inlets cut off from the sea by islands, peninsulas and spits (Sterr 2008). This coast was shaped during and after the last glaciation, with prevailing glacial and postglacial features and sediments, with low and soft cliffs. Natural coastal dunes are rare on the German Baltic Sea coast, and those that do occur are mostly found on the Darss Peninsula, Usedom Island and Rügen Island. The Darss Peninsula is a sandy spit covered by parallel ridges separated by wet, low depressions. Among these are sandy barriers that have developed as separate islands, like Hiddensee which is built from marine and aeolian deposits. These structures of marine origin have developed by long-shore transport of eroded soft moraine cliffs. Small dunes

have developed on low parts of Rügen Island, mainly on the beaches, and are derived from fluvio-glacial deposits and chalk rocks. The chalk cliffs are unstable (Wahle and Obst 2009) and mainly covered by typical moraine deposits (Fig 20.2E). The south of Rügen Island is formed by low, soft cliffs made from tills and clays, covered by sands. Some cliffs on Usedom Island reach heights of 50 m. In other places, low coastal cliffs are formed from bottom moraine deposits. The remainder of the German Baltic Sea coast is formed by moraine cliffs with an average height of 5–15 m and fronted by narrow beaches. Among them are lowland areas with wetlands – salt marshes or coastal meadows. This type of coast has vegetation typical of swampy saline areas. In coastal areas with low hydrodynamic stress (common in bodden areas), peatlands may develop and reed beds may replace the beach (Lampe and Janke 2002). In places where the coast is formed of low-lying valleys, as between Kiel and Heiligendamm on the western German Baltic Sea coast, many coastal sections are protected by artificial dykes (Fig 20.2I).

### **20.2.5 Poland**

The Polish coast is aligned and formed of loose sediments with beaches up to 35 m wide on average. Extensive dune fields formed after the glacial recession can be found on the Polish coastal plains, where sandy dunes cover over 80% of the 500 km long coastline (Łabuz 2005). The dune fields are mainly situated in the direct vicinity of the coast but may reach 4 km in width and incorporate inland dunes, formed by sands transported by wind from the beach or fluvio-glacial deposits. These are usually aeolian sand dunes forming transgressive ridges. The highest dune is 56 m, with the highest wandering dune 42 m; both on the Łebska Sandspit (Fig 20.2L). The coastal dune fields usually have a cliffed seaward slope with beaches in front (Fig 20.2K). In several places the depressions separating individual dunes on the dune coast are over 5 m deep. In such places the land is threatened by flooding due to heavy precipitation, ice melt or storm surges. To protect low-lying areas, coastal dunes in Poland need to be 4.6–4.8 m in height and beaches need to be 2–2.5 m in height after nourishment (Boniecka and Zawadzka 2006). One third of the sandy coast is formed by typical parallel coastal ridges, most of them eroded. Elsewhere, accumulation due to long-shore currents transporting sediments from eroded cliffs results in the development of beaches 60 m wide or more. Accumulative tendencies are seen on the Swina Gate Sandspit, at the end of the Hel Peninsula, at the mouth of the Vistula River or on the Łebsko Lake Sandspit (Łabuz 2005). Foredunes of less than 10 m in height are still developing in these places. Soft Quaternary moraine cliffs cover 65 km of the Polish coast, among them high formations (up to 95 m) of glacial deposits (tills and clays) covered by fluvio-glacial sand (Fig 20.2G) and lower formations of till covered by limnic and organic deposits (Subotowicz 1982). The longest sections of moraine cliff occur along the western part of the coast, and locally on its eastern part. Reed habitats are found on the banks of lagoons and lakes and also along Puck Bay. The Vistula Sandspit is bordered by lowland depressions and the mouth of the largest southern Baltic river, creating a typical sandy deltaic coast in Gdańsk Bay. Low-lying areas of 3 m above mean sea level (amsl) or less are vulnerable to sea-level rise, and are at risk of flooding or ground water soaking (Rotnicki and Borówka 1990). Washover fans marking storm surges develop up to 3.5 m amsl (Łabuz 2012).

### **20.2.6 The Kaliningrad region (Russian Federation)**

The eastern Baltic Sea coast comprises a range of soft, low moraine cliffs and low sandy coasts with sand dune fields. The only significant sand barriers are the Vistula and Curonian sandspits, the longest on the Baltic Sea coast, which have largely eroded foredunes and partly stabilised large sandy dunes (Boldyrev et al. 2010). The Vistula Sandspit is shared by Poland and the Kaliningrad region of the Russian Federation. The Curonian Sandspit stretches from the high, unstable moraine coastal cliffs of the Sambian Peninsula (Fig 20.2H) in the Russian Federation to the channel of the Curonian Lagoon near Klaipėda in Lithuania. This part of the Russian Baltic Sea coast is mostly being eroded, with the rate of erosion accelerating in recent years (Chubarenko et al. 2009; Boldyrev et al. 2010).

### **20.2.7 Lithuania**

The Lithuanian coastline is 160 km long and has large shifting sand dunes stretching for about 70 km, mainly on the Curonian Sandspit, bordering low-lying land along the Curonian Lagoon. The sea front is a sandy beach up to 80 m wide. The proper coastline of 90 km in length (Povilanskas 2002b) is mainly formed of coastal dune ridges up to 10 m high. Some dune sections are being eroded by storms. Between 1990 and 2003, accumulative coasts decreased from 40% to 11%, while erosive stretches increased to 27% (Milerienė et al. 2008; Jarmalavičius et al. 2012). The highest annual retreat exceeds 2.2 m.

### **20.2.8 Latvia**

The Latvian Baltic Sea coast is about 497 km long. The coast on the Baltic Proper is 183 km long and mainly exposed to the west, with the remainder in the Irbe Strait and Gulf of Riga (Eberhards 1998, 2003). The Baltic Proper coast and the western and southern coasts of the Gulf of Riga comprise soft cliff face formed by Quaternary deposits (Eberhards 2003). Hard, rocky cliffs of 4–6 m in height formed of Devonian sandstone and siltstone and covered by Quaternary deposits are found along the Vidzeme coast of the Gulf of Riga (Eberhards 2003; Koltsova and Belakova 2009). Dune coasts (Fig 20.2J) can also be found, mainly in the Gulf of Riga. Almost 69% of the Latvian coast is highly vulnerable to erosion (Eberhards 1998, 2003).

### **20.2.9 Estonia**

Land uplift has created a series of different landforms along the 3800 km of Estonia's coast. Most of the coastal area of Estonia emerged from the regressive sea and had a deficiency of sediment drift, coastal formations are therefore low (Ratas et al. 2011). Coastal dune landscapes covering about 200 km<sup>2</sup> are found behind sandy beaches along 340 km of the coast (Ratas et al. 2008). Dunes mainly develop where river mouths or deltas provide sand and are typically low ridges 2–8 m high and 30 m wide. Due to land uplift (2–2.5 mm yr<sup>-1</sup>), coastal dunes are found inland of the present coastline (Vallner et al. 1988). Most of the Estonian coast is low-lying and covered by moraine deposits with developing coastal meadows, gravel shores and a silty and low limestone coast (Fig 20.2C). The largest Estonian islands, Hiiumaa and Saaremaa, are 1–10 m amsl with narrow gravel beaches and spits, with visible erosion and movement of low spits (Suursaar et al. 2008). The northern coast located on the Gulf of Finland comprises numerous peninsulas and bays, shaped in rocks with many small beaches of pebbles and sand. The north-eastern coast, where the coastline is mainly straight with some forelands building shore and shore face, is mostly sandstone and limestone cliffs of up to 56 m – klint (Fig 20.2F). The Estonian coast is young and develops quickly due to uplift. Prograding beaches are stable but lacking sediment and are vulnerable to storm surges.

### **20.2.10 Russian Federation**

The Russian coast to the south of the Gulf of Finland is mainly formed of low peninsulas built of moraine deposits with boulders in some places, and covered by unconsolidated sand. Beaches are narrow, consisting mainly of gravel and boulders. The northern coast is characterised by a very stable coastline mainly formed of bedrock formations. The southern sedimentary coast developed rapidly under wave action. Significant amounts of ice form every winter in the Gulf of Finland. Neva Bay, 21 km long, is a naturally low area of swampy meadows. Due to risk of flooding, a dam was built across Neva Bay to protect the low coast around St. Petersburg (Orviku et al. 2003). The northern coast of the gulf is higher with some sandy deposits on moraine and older bedrock.

## **20.3 Erosion of specific coastal types in relation to climate change**

This section describes the erosion of different coastal types in the Baltic Sea region: forelands, beaches, coastal meadows, wetlands, sand spits, dunes, moraine soft cliffs and rocky coasts. Figure 20.3 shows the geographical distribution of the main coastal types.

### **20.3.1 Forelands and beaches**

Forelands (or promontories) are low-lying areas between the waterline and higher elevations further inland that are extended towards the sea. They may be rocky, till, gravel or sandy platforms that are formed by storm surges cutting into land deposits. Forelands are mainly present on rocky coast and accompanied by bays indented in the land. They can be found in the south-western and northern part of Baltic Sea basin. The beach is an accumulative landform, formed by silt, sand or gravel deposited in the coastal zone. Beach shape and morphological parameters such as width or height provide information about coastal processes and development.

The low-lying part of the Baltic Sea coast is vulnerable to sea-level rise (see Chapters 9 and 14). For instance, the spectacular sandy beaches of Estonia between Narva-Jõesuu and Meriküla have already suffered damage from strong storms in recent decades. One likely cause is the decline in sand supply from the Narva River since it was dammed in 1956 and a hydropower plant built (Kont et al. 2008). Estonian beaches are already shrinking due to an increase in storm frequency (Orviku et al. 2003, see also Chapter 4). Spits still develop occasionally, but erosion now prevails due to major storms such as those in 2005 and 2007 (Tõnisson et al. 2008). Gravel and pebble beaches on Saaremaa Island were strongly affected by the January 2005 storm Gudrun and the storm resulted in beach deposits being moved inland by 15–30 m (Tõnisson et al. 2008). The shoreface was covered in boulders and accumulation was observed in shallow lagoons.

Despite isostatic uplift, the erosion of sandy beaches has prevailed throughout Estonia in recent decades: in some places the sea has even advanced inland, with beach erosion reaching  $1.5 \text{ m yr}^{-1}$  (Orviku et al. 2003). With no evidence of rising sea level, the observed beach erosion must be largely due to the recent increase in storm frequency in the eastern Baltic Sea and the decline in protective sea ice. Westerly and south-westerly storm winds in autumn and winter can raise sea level up to 2.6 m above the summer level (Kont et al. 2008).

In Latvia, cuts in coastal Quaternary deposits and sandstone also mark an increase in erosion processes (Eberhardts et al. 2006). Some Lithuanian beaches have recently vanished due to westerly storm surges (Povilanskas 2002a; Dailidienė et al. 2006). Near Palanga and Olando Cape, coastline sediment loss reaches maximum values of almost  $180 \text{ m}^3 \text{ m}^{-1}$  (Žilinskas 2005). The height of Lithuanian beaches is 2.6–3.2 m (Jarmalavičius 2012). Between 1993 and 2008 there was no visible beach recession but the coastline retreated by 10 m on average (Jarmalavičius et al. 2012). Coastal protection measures are currently used to prevent land erosion near Palanga and other coastal resorts (Žilinskas et al. 2006).

Beaches in the Kaliningrad region have become narrower: decreasing from 25–40 m in 1984 to 5–15 m in 2000 (Gurova 2004). Near Sokolniki, there was an accumulative coast with a 20 m wide beach and dunes of up to 5 m high. Now there is serious erosion of the coast and a vanishing beach (Shishkina 2010). Average beach width in the Russian part of the Curonian Sandspit shrank by 10–20 m between 1984 and 2003 and height lowered by 0.2–0.5 m (Gurova 2004).

On the Polish coast, beaches lower than 3.5 m amsl are washed away by heavy storm surges each year (Łabuz 2009a,b). The storm surge of 14 January 2012 reached 4 m amsl (Łabuz 2014). Due to increasing storm frequency in recent decades (see Chapter 4), longer sections of beaches require replenishment. Coastal towns which experienced annual erosion of 0.3–0.7 m now have a nourished beach (Boniecka and Zawadzka 2006). Storms with water levels higher than 0.7 m amsl erode the entire beach as well as the top of coastal dunes or cliffs. For storms such as those in 2001, 2004 and 2006, erosion can amount to 2–5 m (Musielak et al. 2007). During a storm surge with a water level 1.7 m amsl, the beaches of the Hel Peninsula were completely flooded. Almost every year, two-thirds of the Hel Peninsula beaches need replenishing. Between 2002 and 2012, beaches on the Polish part of the Wiślana Sandspit shrank in width by 12 m in total (Łabuz 2012) and in the preceding 19-year period (1984–2001) beaches on the Russian part of the Wiślana Sandspit shrank by up to 18 m (Kobelyanskaya et al. 2009). Many sandy beaches along the Gulf of Finland have recently been severely damaged by frequent storm surges, despite extensive protective measures (Ratas et al. 2011).

At Flakket on the Danish island of Anholt in the Kattegat, the low foreland formed as a flat platform covered by gravel and sand, had been enlarging up until 1934 due to uplift. Since then it has eroded at rates of up to  $6.5 \text{ m yr}^{-1}$ . Beach-ridge sediments, formerly up to 500 m wide, have mostly disappeared on the northwest side of Flakket. Between 2006 and 2010, erosion rates of up to  $10 \text{ m yr}^{-1}$  were recorded (Clemmensen et al. 2011). Water levels of 1.02 m amsl reach parts of the foreland once a year; while levels of 1.63 m amsl during storm surges (return period 20 years) affect the entire structure. Wave erosion has led to rapid coastal retreat and in the area immediately east of the local harbour a short stretch of shoreline is now only 25 m from the island's main road. Erosion rates elsewhere along the dune shores in the Kattegat are up to  $2 \text{ m yr}^{-1}$  (Clemmensen et al. 2011).

### 20.3.2 Coastal meadows and wetlands

Coastal meadows and wetlands (marshes and mires) are mainly found in Estonia and to a lesser extent in Sweden, Latvia and Finland. An increase in sea level should theoretically cause a change in the composition of the vegetation of Baltic Sea coastal wetlands (Vestergaard 1997) and gradually displace them in an inland direction. No data are available on accretion processes in low-tidal meadows like those found along the Baltic Sea coast. Loss of meadow area will depend on the relation between the rate of sea-level rise and the rate of accretion. If accretion keeps pace with sea-level rise, then no loss will occur; if accretion is less than sea-level rise then the loss will start from the seaward edge of the meadow. A third consequence of sea-level rise may be increased wave erosion along the seaward edge of the meadow that will tend to narrow the lower meadow (Vestergaard 1991).

Sea-level rise could strongly affect Estonia, due to its long coastline and extensive low-lying coastal areas, although the land uplift rate is higher here than in the south-western part of the Baltic Sea basin. Estonian coastal wetlands and mires are already shrinking due to climate change (Kont et al. 2007). Flat and low-lying coastal zones that experience isostatic and tectonic uplift should be stable, despite the activation of coastal processes, presumably due to global climate change, that has been observed in Estonia since the mid-1970s

(Orviku et al. 2003). A hypothetical 1 m rise in global sea level would roughly reinstate the coastline position of the 1700s, forcing local plant communities to migrate inland (Kont et al. 2008) and would submerge many small islands. The Estonian coast shows frequent sea-level fluctuations due to changes in the precipitation/evaporation balance, river discharge, and storms, but no evidence of a long-term rise in sea level (Kont et al. 2008). Westerly and south-westerly storms can cause short-term surges and extensive flooding on the Estonian coast (with maximum storm surges of 2.53 m above the Kronstadt zero), whereas the highest water-level rise in the open sea rarely exceeds 2.0 m (Kont et al. 2008, see also Chapter 9). On erodible shores, the fine-grained fractions are entirely washed out during a surge. However, the shingle ridges and boulder fields that remain are extremely resistant to further erosion. Virtsu, an important port connecting the Estonian mainland with the islands of Saaremaa and Muhu, is expected to undergo significant change. The peninsula upon which Virtsu is situated could eventually be divided into many islets. A rise in sea level of 72 cm (in the north) to 80 cm (in the south) would inundate more than 76 km<sup>2</sup> of Estonian territory, including all reed beds and most coastal meadows. Several plant communities and biotopes of rare species – including unique orchids – would disappear (Kont et al. 2008). In the absence of coastal protection measures, an inland migration of coastal landforms and plants would be inevitable. The areas most vulnerable to sea-level rise in the coastal wetlands near Pärnu are flooded during storms (Kont et al. 2007). The Estonian lowland may be affected by flooding up to 300 m inland. Such areas may need special protection, as sea-level rise would have socio-economic impacts, particularly on recreational areas. Water impact on the sandy coastal zone has long been observed in many sections of the eastern Gulf of Finland (Orviku et al. 2003). The high rate of coastal erosion there results from the specific features of this water area, like the morphology, shallowness and local wave field (Ryabchuk et al. 2009).

Rising sea level causes a landward shift in the meadows and a growing thickness of the organic material, whereas a fall in sea level leads to surface drying and mineralisation and a lowering of its surface; described for the German coast by Lampe and Janke (2002). Moreover, black peat layers have developed due to peat oxidation caused by a fall in either groundwater or sea level. Coastal meadows located no higher than 0.5 m amsl on the German coast seem to be in greater danger than those in Estonia.

The eastern part of the Gulf of Finland is especially prone to coastal flooding during westerly storms. The highest recorded flood in St. Petersburg occurred on 7 November 1824, when the water level reached 4.21 m amsl (Kurennoy and Ryabchuk 2011). During the storm Gudrun (January 2005, Tönisson et al. 2006) an early forecast for the maximum surge in St. Petersburg was 3.7 m. Even floods not exceeding 1.9–2.2 m caused extensive coastal erosion and sediment resuspension in many coastal areas near St. Petersburg when accompanied by strong wind waves. Such events are particularly damaging to the coastal zone as they hinder the recovery of beaches, destroy buildings along the coast and lead to unrecoverable dune erosion, as seen in the eastern Gulf of Finland (Ryabchuk et al. 2009). A significant increase in annual and winter storm frequency in the latter half of the 20<sup>th</sup> century has been observed in the Gulf of Finland (Orviku et al. 2003, see also Chapter 4). Low-lying coastal areas in Finland (e.g. Helsinki) are also at risk of flooding during heavy storm surges like the one in 2005.

### **20.3.3 Sandspits and coastal dunes**

Sandspits are coastal deposition features commonly found from the south-western to the south-eastern part of the Baltic Sea coastline. The predominance of westerly winds is shaping coastal dunes that develop on sandy shores from sand delivered from wide beaches. The last extreme event caused by westerly winds was in December 2013, when hurricane Xavier rebuilt southern Baltic Sea coastal beaches and dunes. These east-blowing winds are also responsible for developing storm surges causing coast erosion on the Curonian Spit (Lithuania and Russia); near Zelenogradsk the erosion rate is 0.69–0.79 m yr<sup>-1</sup> (Fedorova et al. 2010). Heavy erosion was recorded after hurricane Anatoly on 4–5 December 1999 on the west-facing sandy coasts in Lithuania, Latvia, Russia and Estonia.

Lithodynamical processes along the sandy Lithuanian coast have changed over the past couple of decades due to ever stronger storm surges (Visakavičius et al. 2010). The storms of 2–6 October 2006 washed away the foredune north of Palanga's pier. In Poland this storm caused heavy coastal erosion on 1 October, with a dune retreat of 5–8 m (Łabuz and Kowalewska-Kalkowska 2010). Estonian coastal dunes erode due to coastal retreat, as shown by several studies (Ratas et al. 2008). The storm Gudrun (9 January 2005) caused a surge of 2.75 m in Pärnu, Estonia. Erosion on Saaremaa Island, Pärnu Bay and the Gulf of Finland was significant after this event (Tönisson et al. 2006). Near Tallinn, the beach lowered and dune retreat was up to 5 m. The erosion due to this storm was ten times greater than that during the previous 20 years. High surges

on the Russian coast of the Gulf of Finland in autumn 2006 and winter 2007, with water levels 2 m amsl, totally changed the dunes in cut off cliffs of up to 2 m high (Ryabchuk et al. 2011).

The sandy Latvian coastal zone has changed considerably in recent decades, presumably due to global warming, anthropogenic factors, and increasing storm damage (Eberhards and Saltupe 1995). The sandy coastline of the Gulf of Riga was particularly strongly affected by erosion and recession during extreme storms in 1992 and 2001, with dune erosion of 20–30 m in a single storm event (Povilanskas 2002a). Detailed studies show that erosion is more frequent than accumulation along the Latvian coast, with loss rates of 3–14 m<sup>3</sup>/m per year (Soomere et al. 2011). For the Baltic Proper, the mean rate of shore retreat is 3–8 m yr<sup>-1</sup>, with a maximum of 10–18 m yr<sup>-1</sup> or more (Eberhards 2003). Coastal dune retreat in Latvia following Hurricane Erwin in January 2005 was 1.5–7 m on average, with a maximum of 15 m north of Liepaja (Eberhards et al. 2006). The only and longest section with accumulative tendencies is on the western coast of the Kurzeme Peninsula.

The Polish coast is mainly formed of soft sandy sediments, with an average rate of retreat of 0.5–1.5 m yr<sup>-1</sup> (Zawadzka-Kahlau 1999). Dunes of up to 4 m in height are washed out or reduced by storm surges along the Polish coast. Behind them, storm washover fans in interdune depressions are a strong indicator of storm erosion (Łabuz 2009a). In 1995–2009, two to three storms per season completely washed away the low, new foredunes in places where the beach was less than 3 m amsl (Łabuz 2009a). In 2001–2004, storms caused greater dune retreat than the long-term annual mean for the Polish Baltic Sea coast (Musielak et al. 2004). The storm surge of 23 November 2004 caused severe erosion of up to 7 m in the western part of the Polish dune coast (Łabuz and Kowalewska-Kalkowska 2011). Dune erosion during the storm surge in October 2009 exceeded 5–9 m (Łabuz and Kowalewska-Kalkowska 2010). In recent years, foredunes have been heavily eroded along the western Polish coast (Dudzińska-Nowak and Furmańczyk 2009; Łabuz 2009b; Furmańczyk et al. 2011). On the central and eastern coast, the maximum retreat of sand dunes was 1–2 m yr<sup>-1</sup> (Zawadzka-Kahlau 1999). Today erosion after each storm surge reaches 3–6 m; extreme erosion after storms in 2009 and 2012 reached 6 m yr<sup>-1</sup>. Low coastal dunes were completely washed away and in some places need replacing by artificial dikes or concrete walls. The situation is similar along more than two-thirds of the Hel Peninsula, where beach nourishment, groynes and other measures protect the narrow land against flooding. Coastal dunes on the Wiślana Sandspit along the Polish and Russian section were eroded in autumn and winter of 2006 and 2007 (Kobelyanskaya et al. 2009). Other studies show the Wiślana and Curonian spits to be continuously eroded, with a recent increase near the Bałtyjsk Strait (Volkova et al. 2004; Chubarenko et al. 2009). The heavy storm surge of 2014 caused dune retreat of up to 5 m on the Wiślana Sandspit near the Polish-Russian border, and substantial erosion in the eastern and middle part of the Polish coast (Łabuz 2012). The exposed western Lithuanian coast is also strongly threatened by storm surges (Dailidienė et al. 2006). Erosion has totally consumed the foredunes along the Curonian Sandspit over past couple of decades.

The German Baltic Sea sandy coast between Warnemünde and Darss Peninsula is eroding rapidly (Kortekaas et al. 2010). Near Warnemünde and on the west coast of Darss, erosion has reached 3 m since the mid-20<sup>th</sup> century (Kortekaas et al. 2010), probably due to heavy waves attacking the exposed west coast in winter. The November 1995 storm event caused material loss from the sandy shores of Usedom Island (Schwarzer et al. 2003). The situation was similar on the western and central Polish coast, where sea level reached 2 m amsl and coastal dunes retreated 5–10 m (Łabuz 2005). Erosion along the dune shores in the Kattegat is up to 2 m yr<sup>-1</sup> (Clemmensen et al. 2011).

#### **20.3.4 Moraine soft cliffs**

The moraine soft cliffs of the Baltic Sea region were formed during the last ice age and mainly extend from the southern (Denmark, Germany, Poland, southern Sweden) to the south-eastern coastline (Kaliningrad region and part of Latvia and Estonia coast).

The high soft cliffs of the Sambian Peninsula (northwest of Kaliningrad) erode at least 1–1.5 m yr<sup>-1</sup>, with a maximum of up to 10 m yr<sup>-1</sup>, and rates have increased over the past decade (Chubarenko et al. 2009). Along the Latvian or Lithuanian coast, the average rate of retreat may be 1–2 m yr<sup>-1</sup> (Povilanskas 2002a; Eberhards 2003). In Latvia, the long-term mean rate of cliff retreat was 0.5–0.6 m yr<sup>-1</sup> in the latter half of the 20<sup>th</sup> century, reaching a maximum of 1–1.5 m yr<sup>-1</sup> along particular stretches 10–20 m high (Jūrkalne area). After 1980/1981, rates of coastal retreat became two to five times higher, reaching 1.5–4 m yr<sup>-1</sup> (Eberhards and Saltupe 1995). Soft cliffs in Latvia retreated 0.5–4 m on average after the storm surge of Hurricane Erwin in January 2005 (Eberhards et al. 2006). The severe storms of 1993, 1999 and 2001 each caused a coastal retreat of 3–6 m, with a maximum of up to 20–30 m at the dune coast of Cape Bernāti (Eberhards 2003).

Cliff dynamics along the Polish Baltic Sea coast indicate that the main erosion factors are rainfall and storm surges, with cliff erosion rates of up to  $1.5 \text{ m yr}^{-1}$  (Subotowicz 1982; Zawadzka-Kahlau 1999; Florek et al. 2008). Cliffs may become unstable when the toe is undercut by waves (Prior 1977). Cliff retreat is also related to intense rainfall triggering landslides. Mudslide debris discharged from the cliff slope channels onto the foreshore and forms elongated rounded lobes, helping cliff retreat. Slides are usually caused by high water content in the soil after heavy rain. Landslides caused by heavy rain occurred in 2007 and 2009 on the western Polish coast. On the German Baltic Sea coast, the average rate of shoreline retreat is about  $0.4 \text{ m yr}^{-1}$  (Sterr 2008). Sea-level rise is expected to increase cliff erosion on the German coast and to increase the supply of sediment to the coastal zone (Hoffmann and Lampe 2007). Today, the maximum retreat on the western part of the coast is  $2.5 \text{ m yr}^{-1}$  at Heiligenhafen, near which marine accumulation creates a sandy spit (growth  $2\text{--}3 \text{ m yr}^{-1}$ , Hofstede 2008). One of the highest rates of cliff abrasion in Germany is in the area of the Streckelsberg scarp, on the outer shoreline of Usedom, as shown by comparing the old Swedish map of 1695 with a map for 1986. Maximum coastal retreat here exceeds 300 m (Schumacher 2002). The mudslides of the Eocene cliff clays in Denmark are also connected to climatic events (Prior 1977). Landslides extend up to 300–400 m inland. The combination of high water levels and strong wind has often resulted in severe damage to the soft cliffs coast of the Ystad municipality. In southern Sweden the soft moraine cliffs have retreated  $1\text{--}1.5 \text{ m yr}^{-1}$  over the past 150 years (Hanson 2002). The highest Baltic moraine cliffs of Wolin Island in Poland are retreating due to storm surges by  $0.3\text{--}1.5 \text{ m yr}^{-1}$  (Kostrzewski and Zwoliński 1995).

### **20.3.5 Rocky coasts and hard cliffs**

Rocky cliffs in Sweden and Finland are resistant to marine erosion, and are mainly formed from hard granites. The Latvian low cliffs of hard sandstone, covered with a thin layer of Quaternary deposits, are eroded on average by over  $0.5 \text{ m yr}^{-1}$  by westerly storm surges (Eberhards 2003). Danish and Estonian klints are eroded by storm surges but also by weathering of chalk and limestone. In Denmark, cliff erosion reaches  $0.5 \text{ m yr}^{-1}$ . The German chalk cliffs on Rügen Island also erode, with landslides occurring after heavy rain. The maximum retreat of the Jasmund chalk cliff is over  $1 \text{ m yr}^{-1}$  (Lampe 1996).

## **20.4 Potential climatic threats to coastal areas**

Climate-related ocean-atmosphere oscillations, such as the North Atlantic Oscillation (NAO) in the northern hemisphere, can lead to coastal changes (Viles and Goudie 2003). In recent decades, an increase in North Atlantic storm frequency has been linked to a strongly positive NAO index (Chapter 4). Many coasts experience erosion and habitat loss but only a few studies clearly define the relationship between observed coastal land loss and the rate of sea-level rise (Zhang et al. 2004). Although many studies have shown that periods of increased storminess increase coastal erosion and change, it is not always possible to relate increases in coastal storm frequency to specific modes of climatic variability (Viles and Goudie 2003).

### **20.4.1 Sea-level rise**

Sea-level rise within the Baltic Sea is well documented (Richter et al. 2007, Chapter 9). Sea-level rise is being observed at coastal stations along the southern Baltic coast up to the southern part of Estonia in the east and in southernmost Sweden in the west (Harff and Meyer 2007, Chapter 9). On the Polish coast, sea-level rise was  $0.6\text{--}1.5 \text{ mm yr}^{-1}$  in the last century but increased to  $2.2\text{--}3.9 \text{ mm yr}^{-1}$  during the last 20 years (Pruszek and Zawadzka 2008, Chapter 9 and Fig. 9.7). The southern Baltic coast is sinking at a rate of  $1\text{--}2 \text{ mm yr}^{-1}$  (Siegel et al. 2004; Sterr 2008; Pruszek and Zawadzka 2008; Clemmensen et al 2011).

Rising sea levels are expected to exacerbate coastal erosion in southern Sweden and to increase flood risk along its western and southern coasts. Rocky northern Sweden is less prone to flooding and erosion as the rise in sea level is being counteracted by land uplift. The settlements most affected by increased flood risk are along the Skåne coast and the town of Göteborg in Västra Götaland (European Commission 2004). In Poland over half the densely populated low-lying coast is threatened by sea-level rise (Rotnicki and Borówka 1990; Zeidler et al. 1995; Łabuz 2012).

Sand dunes may be affected by rising sea level, changes in erosion/accretion patterns, and changes in groundwater level, as reviewed by Carter (1991). For dunes, the most likely response to changes in sea level is a two-way redistribution of the sand: seaward movement and deposition of eroded material below the new sea level, and landward sand drift resulting in new foredune growth behind the eroded dune as well as sand deposition on older dune land further inland. Groundwater level is a major factor in plant distribution in coastal dunes (Carter 1991) and may strongly influence dune slack vegetation. The sequence of soil moisture changes in dune slacks may, however, be modified by sand movements that change the shape of the dune

system. As sea level rises, estuaries and lagoons attempt to maintain equilibrium by raising their bed elevation. This will change environmental conditions, increasing the threat to low-lying coastal areas such as marshes and wetlands. Some current areas of salt marsh and wetlands could decrease or even disappear. Salt water intrusion and the resulting changes in coastal ecosystems are a problem in the northern Curonian Lagoon. An important area in this lagoon is the Nemunas river delta, with its ecologically significant wetlands as well as agricultural land. Low coastal areas in Estonia are permanently under threat from rising sea level (Kont et al. 1997; Orviku et al. 2003). In Poland, low coastal areas behind dune belts on postglacial valleys or surrounding coastal lakes are threatened by future sea-level rise (Rotnicki and Borówka 1990). The land area up to 3–3.5 m amsl could be gradually flooded as sea level rises. These areas are widely distributed along the Polish and German coast and are used for agriculture and human settlements. Many lowlands on the German coast are vulnerable to sea-level rise; some densely populated (Sterr 2008). Coastal settlements are also at risk in Poland, Lithuania, Latvia and Estonia.

#### **20.4.2 Storm surges**

The greatest storm surges on the southern Baltic Sea coast come from the northeast (Schwarzer et al. 2003; Kowalewska-Kalkowska and Kowalewski 2005; Pruszek and Zawadzka 2005). On the southern Baltic Sea coast severe surges were recorded in January 2002, 2012, November 1995, 2004, 2006, and October 2009 (Schwarzer et al. 2003; Florek et al. 2008; Gurwell 2008; Łabuz 2009b, 2012). The most destructive storm surges to coastal areas are those with a water level 2 m amsl. The most catastrophic sea surges on the Polish coast overflow all relief forms lower than 3.5 m. The eastern Baltic Sea coast is mainly affected by westerly storms (Žilinskas 2005; Visakavičius et al. 2010; Kelpšaitė and Dailidienė 2011; Soomere et al. 2011). The Lithuanian and Latvian coasts are exposed to the west and vulnerable to erosion. In Estonia, more extreme sea levels and storm surges are associated with warmer winters (Suursaar et al. 2003). Storms, driven mainly by westerly winds, change the position of pebble capes and other spits. Neva Bay in the eastern Gulf of Finland is open to the west, with one of the longest fetches in the Baltic Sea – up to 400 km. Strong westerly storms cause a predominant drift to the east and erode the coast (Ryabchuk et al. 2011). At present, the coast in these countries is threatened more by major storm surges than by sea-level rise. Such surges were reported in November 2001, September 2004, and January 2005 and 2007 (Tõnisson et al. 2006, 2008; Suursaar et al. 2003, 2008; Koltsova and Belakova 2009; Dailidienė et al. 2011).

In the Gulf of Finland the frequency of stormy days varied greatly during the latter half of the 20<sup>th</sup> century, from a minimum in the 1960s to a maximum in the last two decades (Orviku et al. 2003). Repeated floods were reported in 2004–2008, with strong winds of 20–23 m s<sup>-1</sup> causing ice jams, water damming and high waves (Kurennoy and Ryabchuk 2011). In Denmark, most storm damage occurs when water level rises at least 2 m (Sorensen et al. 2009). The Russian coast of the Gulf of Finland was totally changed after storms on 29 November 2006 and 11 January 2007 (Ryabchuk et al. 2011). Each storm surge reached a water level of 1.5–2 m amsl. In Lithuania, changes in the wind and wave regime in the latter half of the 20<sup>th</sup> century intensified the natural sediment transport and accelerated coastal erosion or stopped accumulation processes (Kelpšaitė and Dailidienė 2011). Consequently, Lithuania is now more at risk of flooding due to storms (Visakavičius et al. 2010).

The extent of coastline erosion and retreat depends both on the height and duration of the sea surge. Storms of similar magnitude coming immediately after other storms may have much less geomorphic effect than those which occur in isolation (as all the geomorphic work will have been done by the preceding storms). This effect was observed in Poland between November 2001 and February 2002 with several storm surges in which shoreline retreat and dune sand volume erosion was in total comparable to the first two events in November. Similar situations occurred in 2006/07 in Poland, Germany and in 2007 in Estonia and Russia. Alternatively, long clusters of storms may have a compounding, more serious geomorphic effect than would the same number of events operating in isolation (Viles and Goudie 2003). The combination of a major rise in water level in winter months together with the shortening of the ice season may significantly increase the frequency of events that had previously been very rare (Räämet and Soomere 2011). Specifically, an increase in the frequency of three factors together – high water level, rough seas, and the absence of ice in the nearshore zone – may be responsible for the intense erosion of depositional coasts in the eastern Baltic Sea.

#### **20.4.3 Land erosion and habitat loss**

Owing to storm effects, almost two-thirds of Polish coastal dunes are eroded (Zawadzka-Kahlau 1999; Pruszek and Zawadzka 2005; Łabuz 2009b). The 75% of the sandy coast with low lying hinterland is at risk of flooding (Rotnicki and Borówka 1990; Łabuz 2012). Almost 75% of German sandy coasts are threatened

by erosion (Sterr 2008). The situation is similar in Lithuania, Latvia and Estonia (Eberhards 2003; Milerienė et al. 2008; Ratas et al. 2008). Over 65% of the Latvian coast is eroded (Eberhards 2003). About 40% of the Russian Neva Bay coast has recently been heavily eroded (Ryabchuk et al. 2011). With no data between storm events it is hard to estimate when coastal changes occurred (Suursaar et al. 2008).

Land erosion is highlighting the need for effective coastal protection measures. However, in some areas, so far accumulated coastline (mainly sandbars) is shrinking due to the use of coastal protection measures. This is because coastal protection measures used in one place may reduce the transfer of sand from land to longshore drift and thus its accumulation in another. This problem will increase, for example in Poland where almost 6% of the coast has been stabilised over the past ten years.

Erosion reduces the area available for plant and animal communities. As a result, coastal habitats are likely to be highly sensitive to sea-level rise (Vestergaard 1991, Chapter 16). The entire vegetation of cliff slopes is threatened by repeated landslides. Many such habitats are listed in Natura 2000 ([www.natura.org](http://www.natura.org)). Dune erosion also causes loss of valuable coastal habitats (Łabuz 2012, Chapter 16). As sand dunes develop beyond the direct influence of seawater, dune vegetation is less vulnerable to sea-level rise than coastal meadow vegetation.

#### **20.4.4 Precipitation and river discharge**

Increasing precipitation will increase river flows and thus flooding in low-lying coastal areas. Levels of coastal lakes can vary greatly in response to changes in rainfall in their catchment and to changes in evapotranspiration. After the spring melt of 2010, large amounts of water from coastal swamps broke through the narrow dune belt near Kołobrzeg on the Polish west coast. Seawater entered the brackish environment, completely destroying this fragile habitat (Łabuz 2012). Furthermore, increasing precipitation may increase river flows and encourage vegetation growth (Viles and Goudie 2003). Heavy rainfall is a destabilising factor for soft cliffs and caused landslides in Poland in 2007 and 2008 (Łabuz 2012).

On the other hand, reduced river input to the southern part of the Baltic catchment in future (see Chapters 5 and 12) could reduce the supply of sediment for beaches or spit rebuilding (Kont et al. 2008). River mouths reinforced by breakwaters hinder long-shore sediment movement, leading to sediment build-up on one side of the river mouth and a lack of sediment on the other. In recent years, beaches in western Estonia have become narrower due to a decline in runoff from rivers (Kont et al. 2008). As the beach is lost, fixed structures or coastal land nearby are increasingly exposed to the direct impact of storm waves and may be damaged or destroyed unless new protective measures are taken to disrupt these natural coastal processes.

#### **20.4.5 Ice cover melt**

Decreased ice-cover duration in the Gulf of Finland in the recent past (see Chapter 8) has reduced the protection of coastal sediments during the stormy period (Ryabchuk et al. 2011), even though ice jams pushed onto land by waves may also cause erosion of dunes and cliffs. Ice jams were observed on the southern Baltic Sea coast in the winters of 1995, 2003, 2010 and 2011. Their impact was seen in narrower and lower beaches after ice melted in late spring. On the northern Baltic Sea coast, ice sheets may have a bigger impact on the coast. In February 2008 in Neva Bay, ice strongly eroded coastal land and human structures (Ryabchuk et al. 2011). On the other hand, declining ice cover in the northern Baltic Sea would mean greater potential for coastal erosion due to wave action.

### **20.5 Conclusion**

The Baltic Sea coasts are already experiencing the adverse impacts of climate change, mainly due to changes in sea level and storminess. Coasts are particularly vulnerable to extreme events. The response of the coastal system varies over different time scales, owing to changes in local dynamics or geo-morphological conditions as well as to the intensity of the driving forces. Identifying the contribution of climatic change to geomorphic change can be difficult, and its importance will also vary regionally (Viles and Goudie 2003). The main drivers of change in coastal geomorphology are geological structural resistance, changes in sea level, long-shore currents and storm surges. These factors are responsible for both coastal erosion and accumulation, as well as for the emergence and variability of beaches. Coastal protection measures are major factors at the local scale. At the regional and global scale, coastal erosion is induced by an increasing number of severe storm surges and sea-level rise. These factors are leading to the following:

- loss of sediment for coastal rebuilding
- loss of valuable dynamic coastlines

- loss of coastal resilience
- loss of valuable natural habitats
- loss of economic value and private property
- unpredictable land change due to extreme storm events
- increasing cost to society in terms of coastal protection measures.

The impact of climate change on coasts is exacerbated by the increasing need for coastal protection by human activities (Bardach 1989; Beukema et al. 1990; van der Meulen 1991). There are two main types of management strategy. The first is to stabilise the existing coastline and thus protect coastal and neighbouring areas from future change. The second, which is more resilient and depends on human adaptation to coastal change, accepts that in some places the coast would be not protected and would be left in its natural state. The costs for adapting to climate change are generally much lower than the costs of damage incurred through a lack of adaptation. Local communities are currently best prepared for extreme events; very few local administrations are attempting to estimate costs associated with the risks of future climate change. Projecting future costs is also complicated because different local authorities may prefer different coastal development and management policies, for example for protection against coastal erosion. European projects like ASTRA (Astra-project 2007), EUROSION (European Commission 2004), SINCOS (Richter et al. 2007) or MICORE (Ferreira et al. 2009) have provided new data and insights regarding storm effects on the Baltic Sea coast. Administrative borders in coastal areas and efforts for coastal protection differ among Baltic Sea countries, even between neighbouring nations. Some management actions are complicated by the morphodynamic changes caused by artificial coastal stabilisation in some places and its natural disruption in others. The coastal zone is a linear environment that knows no national or decision-making boundaries. Decadal-scale climatic change and variability may initiate a pulse of activity that results in a complex, non-linear landscape response.

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## Figure captions

**Fig. 20.1** Features and zones of the main Baltic Sea coast types. A – Soft cliff coast, B – Sandy coast with foredunes, C – Rocky coast

**Fig. 20.2** Coastal types of the Baltic Sea. A Skerries in the Gulf of Finland, Finland; B Igneous rock, low coast shaped by glaciers, Helsinki, Finland; C Low coast of glacier boulders, northern Estonia; D Wetlands in southern Sweden near Malmö; E Rocky, chalk cliff covered by moraine sediments with an abrasive platform instead of beach, Rügen Island, Germany; F High eroded cliff – klint coast in Estonia; G High soft moraine cliff coast of tills and fluvio-glacial sands, Wolin Island, Poland; H Typical cliff coast of tills and clays of moraine deposits, landslides on the beach caused by ongoing storm surge, Sambian Peninsula, Kaliningrad region, Russia; I Low, eroded coast without dune ridges in Heiligendamm, Germany; J Low coast of end moraine deposits covered by sands, Latvia; K. Retreating dune coast entered and covered peatbog, Kolobrzeg, middle Polish coast; L Sandspit dunes: shifting inland with typical accumulative foredunes, Lebsko Lake Sandbar, Poland (Photos: T.A.Łabuz).

**Fig. 20.3** Coastal types in the Baltic Sea region. A. Soft moraine cliffs; B. Sandy barriers and sandy dunes; C. Rocky cliffs; D. Skerries; E. Low coast, meadows, organic/wetlands