BOREAL ENVIRONMENT RESEARCH 16 (suppl. A): 117–137 © 2011
ISSN 1239-6095 (print) ISSN 1797-2469 (online) Helsinki 31 March 2011

Coastal erosion processes in the eastern Gulf of Finland and their links with geological and hydrometeorological factors

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Received 23 Nov. 2009, accepted 1 Sep. 2010 (Editor in charge of this article: Kai Myrberg)

Ryabchuk, D., Kolesov, A., Chubarenko, B., Spiridonov, M., Kurennoy, D. & Soomere, T. 2011: Coastal erosion processes in the eastern Gulf of Finland and their links with geological and hydrometeorological factors. *Boreal Env. Res.* 16 (suppl. A): 117–137.

Potential reasons for the drastic intensification and step-like nature of coastal erosion in the Neva Bay area (to the east of the cape Peschany–Lebyazhye line), the easternmost part of the Gulf of Finland, are analysed based on field observations and hydrometeorogical data from adjacent areas. Beaches in this area consist of easily erodible Quaternary deposits that evolve under overall sediment deficit and are relatively vulnerable with respect to changes in the external forcing factors. It is demonstrated that the most extreme erosion events occur when high waves excited by long-lasting western or south-western storms attack the coast during very high storm surges in the absence of stable sea ice. Since 2004 the frequency of occurrence of such combinations has increased mostly owing to, late freezing of the bay and an increase in the number and severity of extreme erosion events in the future is likely. The coasts are also under gradually increasing anthropogenic pressure. Submarine mining operations in the nearshore and construction of large-scale coastal engineering structures such as the Flood Protection Facility may have considerable impact upon the coasts.

Introduction

The complexity of the dynamics of the Baltic Sea and its subbasins extends far beyond the typical features of water bodies of comparable size (Leppäranta and Myrberg 2009). It becomes especially evident in the nature and variability of driving factors of coastal processes in the Gulf of Finland. First of all, marine meteorological conditions reveal remarkable anisotropy and highly specific patterns in this basin (Soomere and Keevallik 2003, Savijärvi *et al*. 2005). Further, predominant winds blow obliquely with respect to the axis of the gulf, giving rise to wave systems with a specific orientation (Kahma and Pettersson 1994, Pettersson 2001, 2003, Pettersson *et al.* 2010) that frequently differs from the wind direction. This gulf is one of the three Baltic Sea basins — in addition to the Gulf of Bothnia and the Gulf of Riga — where significant amounts of ice forms every winter (Leppäranta and Myrberg 2009) and play a considerable role in its functioning (Kawamura *et al.* 2001, Leppäranta and Myrberg 2009).

An overview of geology and geological history of the Gulf of Finland is presented in the collection (Raukas and Hyvärinen 1992). The beaches of its southern and northern coasts are completely different. The northern coast is characterised by extremely stable coastline that mostly follows bedrock formations (Granö and Roto 1989). In contrast, the eastern and southern sedimentary coasts develop quite rapidly, predominantly under the effect of wave action (Orviku and Granö 1992). The coasts along Estonia belong to a rare type of young, relatively rapidly uplifting beaches, many of which are located in bays deeply cut into the mainland (Soomere *et al.* 2008b). They form an interesting class of almost equilibrium beaches located in an essentially nontidal, wave-driven and highly compartmentalised coastal landscape. These beaches, although often suffering from a certain sediment deficit, are stabilised by the postglacial land uplift.

Differently from large sections of the coasts of the Baltic Proper, Gulf of Bothnia or Gulf of Riga, which express relatively simple geomorphic and lithodynamic features (e.g. the almost straight eastern coast of southern Baltic Proper or stable archipelago areas along the Swedish and Finnish coasts), understanding of physics and dynamics of lithohydrodynamic processes along many coasts of the Gulf of Finland is still a challenge. The combination of the small size of this water body and the complexity of its coasts makes it susceptible with respect to changes in the external forcing factors.

The length of the Russian part of the Gulf of Finland shoreline (not accounting for islands) is about 520 km. Its north-western section (around Vyborg, former Viipuri) mostly consists of stable bedrock formations (Granö and Roto 1989). The evolution of beaches in the south-western section of this department (in particular, coasts in Luga Bay and Koporye Bay that are relatively well sheltered from predominant directions of strong winds) apparently is similar to that of the beaches along the northern coast of Estonia. The most common type of coasts here are the embayed coasts which are straightening with sediment erosion and accumulation. The most stable beaches are located in deeply indented bays.

A specific subclass of the coasts form beaches in the Neva Bay area (Fig. 1). Differently from other coastal sections, these beaches are largely open to the west, that is, in the direction of one of the longest fetches in the Baltic Sea (up to 400 km). Strong westerly storms frequently bring here high and relatively long waves that cause predominant littoral drift to the east. The largest variations of the water level in the entire Baltic Sea up to 4.21 m over the long-term mean sea level occur in this area. As the coasts obtained their contemporary shape only a few millennia ago, they apparently have not reached an equilibrium state. The geometry of the Gulf of Finland (Fig. 1) is such that littoral drift is mostly stopped by headlands at the entrance to the Neva Bay area. As a result, the magnitude of sediment supply from the Gulf of Finland into Neva Bay is very modest.

It is, therefore, not unexpected that the central marine-induced hazard to the coastal zone in this area is the potential coastline retreat. About 40% of the coasts of Neva Bay are currently heavily eroded. During frequently occurring high storm surges the erosion processes distress practically all the coasts. On top of that, more than 20% of the coasts are under strong anthropogenic pressure that extends from small coastal engineering structures up to complete transformation of geological environment along some sections.

The problem of coastal erosion is most urgent for the Kurortny (“Resort”) District located along the northern coast of the bay from Cape Lautaranta to the Flood Protection Facility (Fig. 2). This district has a great importance as a unique recreational area for the entire north-western region of Russia hosting 14 sanatoriums and boarding houses. An international resort complex to be located in this district is currently in the planning stage. It is also a key nature protection and conservation area hosting three nature reserves including Komarovo Beach — a complex of unique sand beaches and coastal dune landscapes.

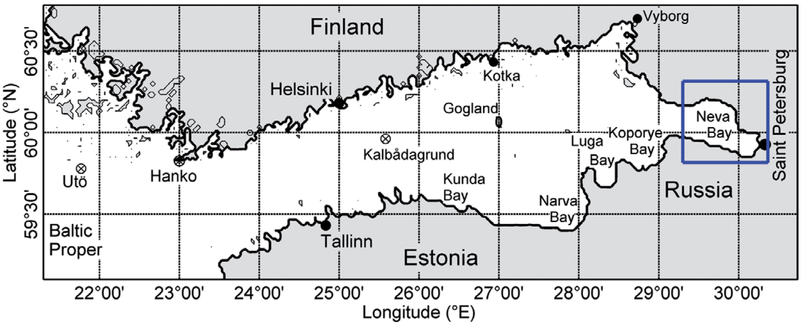

Fig. 1. Location of the Neva Bay area in the Gulf of Finland. The box near Saint Petersburg represents the area presented in Fig. 2.

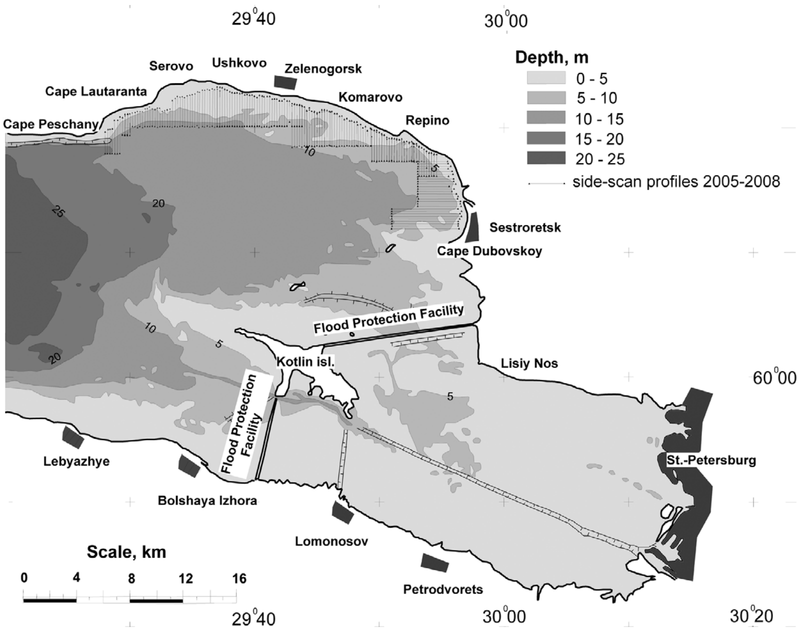

Fig. 2. Map of the study area and the location of side-scan sonar profiles performed by VSEGEI in 2005–2008.

This environment, however, is extremely vulnerable and experiences gradually increasing pressure. The basic purpose of this study is to identify the main natural and technogenic factors that may impact coastal processes in the area in question and to estimate their significance in the coastal development.

A large part of the discussion below is based on the results of recent investigations by the Department of Marine and Environmental Geology of A.P. Karpinsky Russian Geological Research Institute (VSEGEI) in 2000–2009, the details of which have been presented in (Ryabchuk *et al*. 2007, 2009a, 2009b, among others). These studies were aimed at the detection of the basic features of lithohydrodynamic processes on both the northern and southern coasts of the Neva Bay area with a particular target to locate the most intensely eroding coastal areas. Some of such areas are located within important recreation zones such as the Kurortny District on the northern coast or near Bolshaya Izhora village on the southern coast of the gulf (Figs. 2 and 3). The remote sensing data show that the average rates of the shoreline retreat within the Kurortny District are 0.5 m year^{-1}, while the maximum rates reach 2 m year^{-1} (Sukhacheva and Kildushevsky 2006, Ryabchuk *et al*. 2007, 2009). The total beach recession between 1990–2005 reached as large values as 25–40 m in the vicinity of Serovo, Ushkovo and Komarovo villages. Within some areas intense erosion is observed

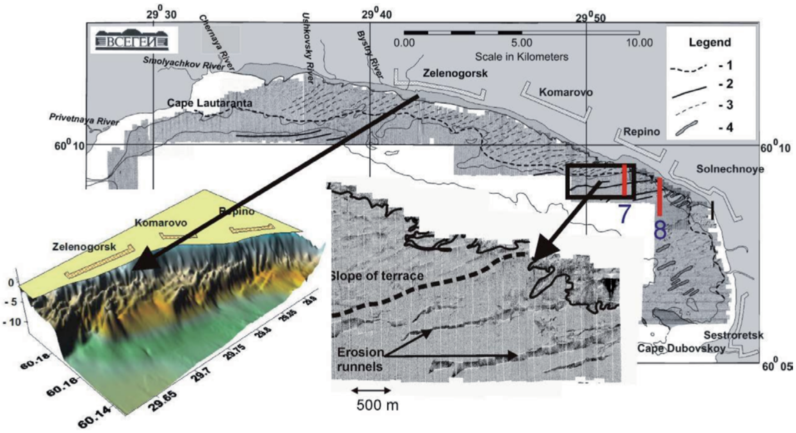

Fig. 3. Side-scan sonar mosaic of the nearshore zone bottom and 3D image of bathymetry of the northern coastal zone with a submarine terrace: 1 = edge of the submarine terrace; 2 = erosion runnels; 3 = sand ridges on the terrace surface; 4 = boulder and pebble areas and glacial till ridges. 7, 8 = profiles shown in Fig. 4.

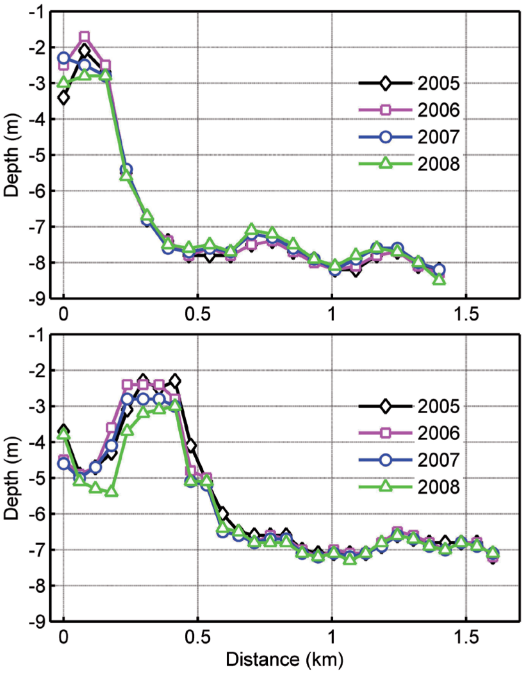

Fig. 4. An example of rapid erosion of sea bottom at the seaward end of the underwater terrace. Top panel: profile 7; bottom panel: profile 8 (*see* Fig. 3). The bottom was almost unchanged in 2005–2006 but lost almost one meter in height in 2007 and in 2008.

in the upper part of the nearshore coastal slope (Fig. 4).

On the background of the discussed long-term shoreline retreat some abrupt erosion events have been identified in the area in question in recent past. Given the location of the beaches deep in Neva Bay and the overall geometry of the Gulf of Finland (which together shelter the bay from most of strong wind directions), it is not unexpected that infrequent events of structural erosion that occur in relation with certain extreme events may give rise to a clearly pronounced step-like manner of coastal evolution in this area.

The specific feature of the Neva Bay area is that impact of even quite strong storms here is minor when the sea is ice covered. The lengthening of the ice-free time in the recent past (Jevrejeva *et al*. 2004) has apparently created more opportunities for strong westerly storms to attack the coasts. This trend is especially dangerous for the Neva Bay area because the largest increase in storminess occurs in February (Jaagus *et al*. 2008), that is, during the season in which the sea has been ice-covered in the past.

Intense coastal erosion processes are usually caused by a combination of various natural and anthropogenic factors. Studies into recent destructions of sedimentary coasts in the Baltic Proper (Orviku *et al*. 2003, 2009) suggest that an increase in the frequency of the occurrence of the combination of three factors — high water level, rough seas, and absence of ice in the nearshore zone — may be responsible for the intense erosion of the coasts of the Neva Bay area. Our central aim is to check this hypothesis based on existing geomorphic and hydrometeorological data in the light of recent events of extensive coastal erosion. As such events are mostly driven not by statistical features of forcing factors but by their unusual combinations, we leave aside statistical analysis of trends in the forcing factors and concentrate on case-by-case analysis of single events.

The paper is organized as follows. We start from a short description of the available pool of marine geological, geomorphic and hydrometeorological data. Based on this data, next we present an overview of these key geological and geomorphic features of the coastal sections in question that can be related to the unusual combinations of hydrometeorological forcing factors. From the extensive historical hydrometeorological data set, we select issues that are expected to govern the most intense events of coastal erosion: strong storm events, severe floodings and data about the ice cover. Unfortunately, there is virtually no information about wind wave regime in this area. For this reason we shall relate the occurrence of high waves only qualitatively with the strength and estimated duration of the storm events. Further on, a detailed comparison of the selected data reveals a clear interdependence between the cases of the simultaneous occurrence of unfortunate combinations of these three forcing factors with the course of evolution of the coasts in 2004–2008. Finally, we discuss the potential impact of coastal engineering activities (such as building of hard structures or sand mining) on the course of coastal processes.

Data and methods

A complex study of the coasts and the nearshore of the eastern Gulf of Finland was performed by the VSEGEI in 2000–2009. Field observations, sediment sampling and measurements of beach profiles were performed onshore. Marine geological studies of the nearshore bottom adjacent to the Kurortny District consisted of more than 900 km of side-scan profiling (CM2, C-MAX Ltd., UK) with a search swath of 100 m, 50 m and 25 m using a working acoustic frequency of 102 and 325 kHz as well as echo-sounding at frequencies of 200 kHz and 455 kHz (Fig. 2). Surface sediment samples were taken with the use of grab-corers and Niemisto corers. A large pool of profiles located perpendicular to the shoreline with the distance between profiles 185 m (in case of search swath of 100 m) allowed construction a side-scan mosaic of the entire study area (Fig. 3). Repeated profiling (with a total length of about 400 km) has been used to establish the properties of bathymetry and sediment dynamics.

In the analysis below we extensively use the data base of the State Institution "Saint Petersburg Center for Hydrometeorology and Environmental Monitoring with Regional Functions" (below referred to as SISPCHEMRF). It includes meteorological data from first fragmentary observations and monthly reports of the Russian Academy of Science in 1726–1834, time series from the Saint Petersburg meteorological station since 1877, Kronshtadt station since 1861, Lomonosov station since 1861 and regular meteorological data (temperature, atmospheric pressure, cloudiness, wind rate and direction, precipitation, snow cover) since 1930. The data set also contains marine observations (sea level, water temperature, wind speed and direction) from 10 coastal meteorological stations around the Gulf of Finland since the 1920s. Specifically, we shall use below the Floods Catalog conducted by the SISPCHEMRF. It reflects about 307 floods higher than 160 cm above mean water level that have occurred during the history of Saint Petersburg between 1703–2008. The longest time series in marine meteorology has been gathered in Kronshtadt since 1805 (www.meteo.nw.ru).

Geological and geomorphic features of the eastern Gulf of Finland

A major prerequisite for a high activity of coastal processes is the geological structure of the area in question. The upper part of the geological sequence in the vicinity of shoreline of the Neva Bay area, both on dry beach and nearshore, consists of relatively soft Quaternary deposits (Fig. 5). Landward from the shoreline they are represented by Late-Pleistocene glacial, glaciofluvial, glaciolacustrine and Holocene lacustrine, marine, alluvial and aeolian deposits; mainly till, clay, sand and peat (Malyasova and Spiridonova 1965, Znamenskaya and Cheremisinova 1974). In the nearshore surface glacial till, glaciolacustrine clay and Holocene sand

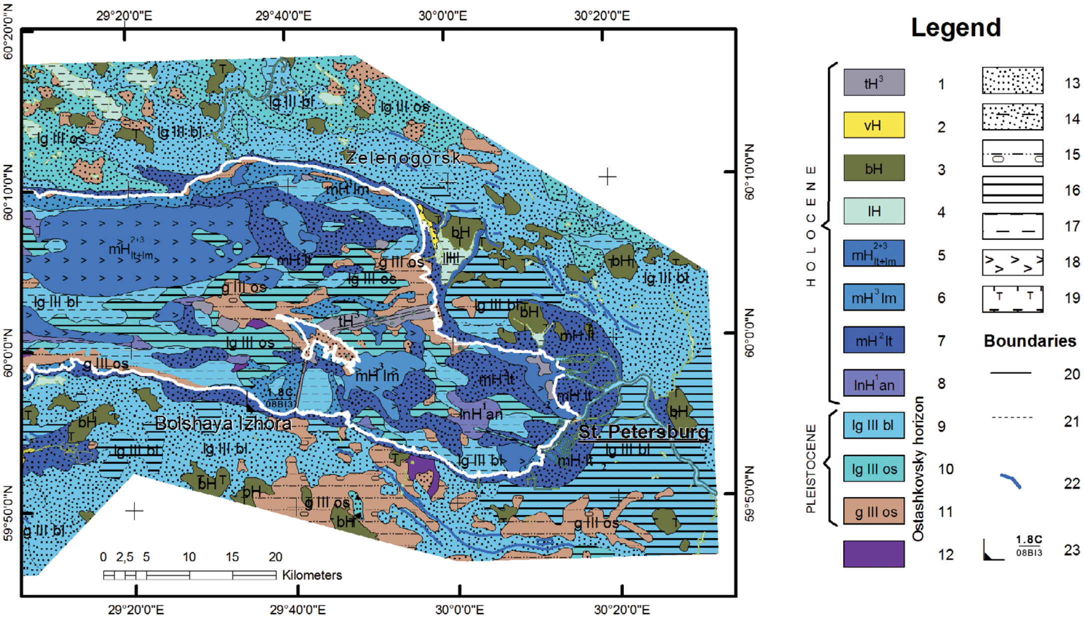

Fig. 5. The map of Quaternary deposits in the Neva Bay area: 1–8 = Holocene deposits and 9–11 = Pleistocene deposits. 1 = Technogeic deposits; 2 = Aeolian deposits; 3 = biogenic deposits; 4 = lacustrine deposits; 5 = Limnea marine deposits; 6 = Litorina and Limnea marine deposits; 7 = Litorina marine deposits; 8 = Ancylus Lake deposits; 9 = Baltic Ice Lake deposits; 10 = limno-glacial deposits of Luga stage; 11 = glacial deposits; 12 = preQuaternary bedrocks; 13 = sand with gravel and pebble; 14 = sand; 15 = sandy till; 16 = varved clay; 17 = clay; 18 = mud; 19 = peat; 20 = stratigraphic boundaries; 21 = lithologic boundaries; 22 = coastal sand ridges; 23 = sites of dating (age in thousand years, method/sample number).

dominate (Spiridonov *et al*. 1988, Spiridonov *et al*. 2007). All these deposits are easily erodible.

The distribution of surface sediments in the Neva Bay area is shown in Fig. 6. Among these deposits, till is frequently playing an important, sometimes twofold role. Usually it contains a large number of pebbles, cobbles and boulders. In the process of its erosion the finer sediment is relatively rapidly carried away by waves and currents. The pebbles, cobbles and boulders, however, are mostly immobile and form after some time a stone belt on the beachface and in the nearshore. This feature is typical for till beaches in the Gulf of Finland and such belts have been identified in a number of studies of the structure of the nearshore. Such stone belts prevent the coasts and the underlying deposits from further erosion and make the entire beach almost insensitive with respect to typical levels of hydrodynamic factors (Orviku 1974). They also provide protection against several technogenic factors such as vessel waves (Kask *et al*. 2003, Parnell *et al*. 2008). An adverse feature of such belts, especially when they cover the entire surf and swash zone is that no finer sediments are released from the protected coastal sections. Their effect, therefore, may be equivalent to the presence of a seawall and may lead to sediment starvation (deficit) and more intense erosion downdrift from coastal section hosting such a belt.

Boulder belts are widely spread between Cape Lautaranta and Solnechnoye village (Ryabchuk *et al*. 2007). From the total length of about 45 km of this coastal zone some 19 km host boulders both on the shore and in the nearshore zone. At places such boulder belts are located only at certain depths or are interspersed with several longshore sand bars. Within areas of intense erosion, however, sandy sediment between boulders is rare. Only after infrequent events of strong eastern winds (which transport sand from the usual accretion zones back to transit or erosional areas) areas covered by thin layer of sand occur among stone belts. Such a layer can be up to 0.2 m thick, but usually its thickness does not exceed 0.05–0.1 m and it is very irregular.

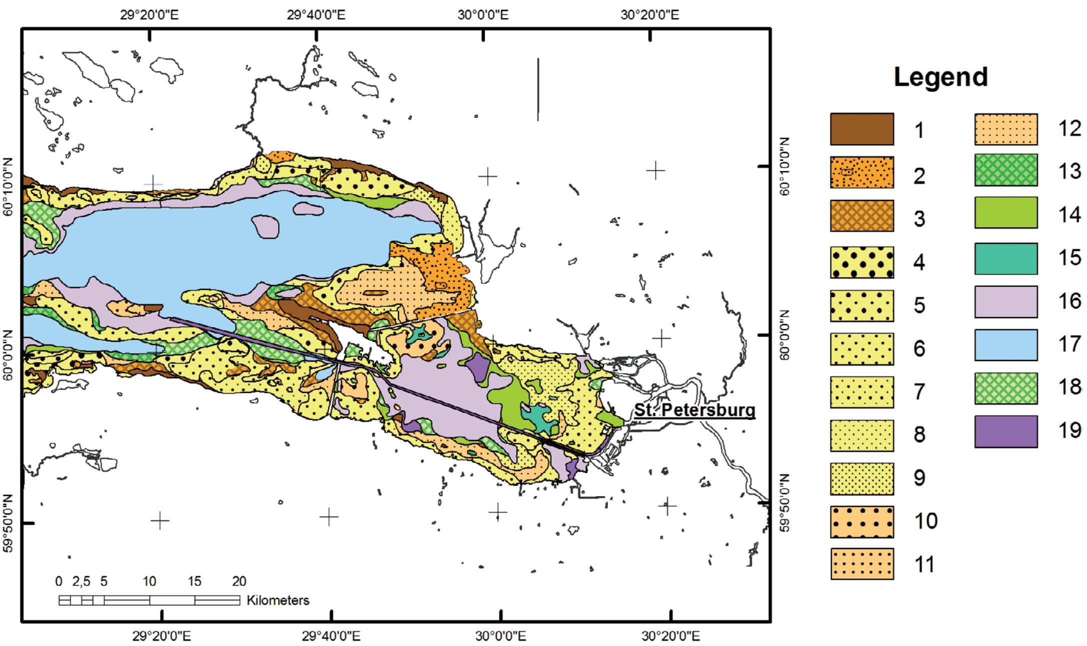

Fig. 6. Map of surface sediments in the Neva Bay area. 1: sand with boulders; 2: boulders, pebbles; 3: sand with pebble and gravel; 4–9: well sorted sands: 4: coarse-grained; 5: coarse to medium grained; 6: medium grained; 7: medium to fine grained; 8: fine grained; 9: very fine grained; 10–12: poorly sorted sands: 10: mainly coarse grained; 11: mainly medium grained; 12: mainly fine grained; 13: clayey sand; 14: sandy silt; 15: silt; 16: silty clayey mud; 17: clayey silty mud; 18: silty clayey mud with sand; 19: submarine outcrops of Quaternary deposits. We use the following classification: grain diameter > 2.0 mm corresponds to gravel, pebbles, and boulders; 0.05–2.0 mm to sand; 0.005–0.05 mm to silt and < 0.005 mm to clay.

The major sand accretion section, with a total length of 15.5 km is located between Solnechnoye and Dybovskoy Cape. Certain coastal sections (about 4 km in length) are protected by huge bushes of water plants and a few parts (2 km) by hard coastal engineering structures. The sandy beaches have a high recreational value and therefore their evolution is essential for the development of the district. They, however, have a limited amount of sand in their active body. The beaches are 30–40 m wide in sections that contain dunes but usually boulders are found already at small distances offshore. At some places 2–4 sand bars are observed that are interspersed with boulders or till outcrops in the runnels.

The beaches in the Kurortny District are located in the area of uplift which to some extent stabilizes the coastline. The entire shoreline between Cape Lautaranta and Solnechnoye is oriented in the WNW–ESE direction and forms quite a large angle with respect to the largest waves reaching this coastal section from the west. Therefore, the most intense wave-induced littoral drift naturally occurs in this section during western and south-western storms. The attack angle of waves propagating to this section from the open part of the Gulf of Finland decreases to almost zero at Solnechnoye where longshore sediment flow to the east ceases and a sand accretion zone is found. Accordingly, the magnitude of sediment flux along the northern coast tends to diminish in the eastern direction. In the vicinity of Zelenogorsk it is close to 30 000 m^3 m^{-1} $year^{-1}$, while near the Repino village it becomes below 20 000 m^3 m^{-1} $year^{-1}$ and in the vicinity of Solnechnoye it almost ceases (Leont'yev 2008).

Several features of the nearshore bathymetry play an important role in coastal processes in this area. Recently it has been demonstrated that a 1.5–2 km wide submarine terrace is located at depths of 3–4 m (Ryabchuk *et al*. 2007, Ryabchuk *et al*. 2009a). Its foot is located at depths of 8–12 m (Fig. 3). The presence of such a terrace may substantially alter the intensity and/or direction of storm waves and thus considerably modify the properties of coastal processes and littoral drift. In particular, its presence usually reduces the intensity of sediment loss from the vicinity of shoreline in the process of gradual elongation of the equilibrium beach profile because less material is needed to fill the seaward end of this profile.

Comparison of the recent survey with old nautical charts has shown that the offshore edge of the terrace is being eroded and retreats (Ryabchuk *et al*. 2007). The sea bottom seaward from the terrace contains several erosion runnels (Fig. 3). Repeated surveys confirm that the location and shape of these runnels are quite stable in spite of their small relative depth (0.3–0.5 m). Their bottom contains numerous ripples of about 0.2 m in height separated from each other by a distance of 0.5–1 m. The surface of the terrace and the sea bottom near its foot are covered by fine to medium sand while the bottom of the runnels (incl. ripples) consists of coarser sand. The described features suggest that typical near-bottom water velocities are highest in the runnels. Therefore, it is probable that the runnels frequently host intense seaward near-bottom currents. They eventually channel back to open sea the excess water forced to the vicinity of the coastline by wind and waves similarly as rip currents do. As the flow velocities apparently are relatively high in the runnels, they may serve as an important way of sediment loss to offshore (Ryabchuk *et al*. 2009a).

Another important feature is the structure of the coastal profile in the sediment accumulation area near Solnechnoye. The shallow nearshore terrace is very narrow here (just about 500 m). Seaward from it there is a relatively steep slope down to a depth of 5–6 m. It is highly probable that the shallow part of the profile has not reached the full width of the corresponding equilibrium profile. In the process of its lengthening under severe wave conditions, a significant amount of sediment is transported from the terrace to its foot. This is an apparent reason why the accretion beaches — the widest in the area — are not growing any more in this coastal section (Ryabchuk *et al*. 2007).

In conclusion, geological and geomorphic features of the northern coast of the Neva Bay area from Cape Lautaranta to Solnechnoye combined with the prevailing approach direction of the largest waves are favorable for the presence of intense littoral drift and, consequently, high overall activity of coastal processes. This coastal section forms a single large erosional-accretional lithodynamic system in which longshore sediment transport occurs almost entirely to the east. As littoral flow around Cape Lautaranta (which is protected by a belt of boulders, *see* above) is fairly small, the major erosion areas are located in the western part of this compartment and accretion takes place in the section from Solnechnoye to Cape Dubovskoy. In the long-term perspective, the entire shoreline of this compartment undergoes smoothing as a result of erosion, transit and accretion processes. The coasts thus can be classified as straightening coasts (group IIIA according to Kaplin 1973).

Hydrometeorological drivers of coastal processes

The described geological and geomorphic factors act in long-term run, in geological time scales of at least hundreds and generally thousands of years, and cannot explain the nature of recent intensification of coastal erosion. Namely, a series of severe storms accompanied with high surges in autumn 2006–winter 2007 caused abrupt erosion events that have changed the appearance of many sections of the coast after more than decades of previous, relatively slow development. The water level rose more than 2 m above the long-term mean in Saint Petersburg during these events. Extensive erosion of dunes occurred along the entire 3 km part of the shore where they exist at Komarovo village and along some sections of the coast at Solnechnoye. The extent of changes to the dunes, documented immediately after the storms on 29 October 2006 and 11 January 2007, was observed for the first time within, at least, last 20 years.

The storms may even have substantially changed the overall course of coastal processes because since 2007 the coastal dunes have not been naturally restored. Similar intensification

Fig. 7. Consequences of an extreme flooding in November 1924 in Kurortny District, Komarovo and Repino villages (from Ryabchuk *et al.* 2009a; reprinted by permission from Estonian Academy Publishers).

of coastal erosion has been described in several other regions of the eastern coast of the Baltic Sea (Orviku *et al*. 2003, Eberhards *et al*. 2009). There is even doubt that the destructions of beaches due to the more frequent occurrence of high water levels and intense waves, and the lengthening of the ice-free time have overridden the stable development of several sections of the Baltic Sea coasts (Orviku *et al*. 2003, Soomere *et al*. 2008c).

The reasons for such an extensive reaction of the coast to these storms in the area in question apparently can be established to some extent by means of an analysis of the typical properties of the major hydro-meteorological factors impacting the evolution of this coast — wind waves, water level fluctuations (floods and/or storm surges) and ice conditions. Serious damage to the beach is usually caused either by the high magnitude of the impact of a single factor or by long-lasting influence of certain combination of different factors. The largest wave heights are observed in the Neva Bay area during strong western and south-western winds that are the strongest in the eastern Gulf of Finland (Soomere and Keevallik 2003) and also correspond to the longest fetch. The long-term impact of the predominance of waves approaching from these directions becomes evident as the prevailing littoral drift to the east.

Typically, the largest impact to the Baltic Sea coasts is observed in the case of storms that cause simultaneously high surge and rough seas (Orviku *et al*. 2003). Such combinations are especially dangerous for the coasts of the Neva Bay area that host the largest storm surges in the Baltic Sea basin. The most terrible coast damage in the history was observed during catastrophic floods accompanied by storm surges indeed (Fig. 7).

The lithohydrodynamic regime in the eastern Gulf of Finland has a pronounced seasonal variability that largely follows the similar variability of meteorological fields. Coastal processes are quite slow in spring and summer when usually no strong, long-lasting storms hit the Neva Bay area. Cyclonic processes are much more active over Scandinavia in autumn and winter and lead to frequent storm surges and rough seas in the eastern part of the Gulf of Finland and Neva Bay provided their trajectory is favorable for building up high westerly winds in the Gulf of Finland. The most frequent long-lasting (from 24 hours to 2–3 days) western and south-western winds are observed from October to December. Therefore, the most intense coastal erosion takes place during late autumn and early winter.

Wind and wave fields

The properties of wave fields in the Neva Bay area during western and south-western winds are mostly governed by the properties of wind over the entire fetch area, that is, by spatial wind patterns over most of the northern Baltic Proper and the Gulf of Finland. Winds that are responsible for the growth of surface waves are usually much stronger offshore than those observed on the coast (Niros *et al*. 2002). The only observation site in the Gulf of Finland that

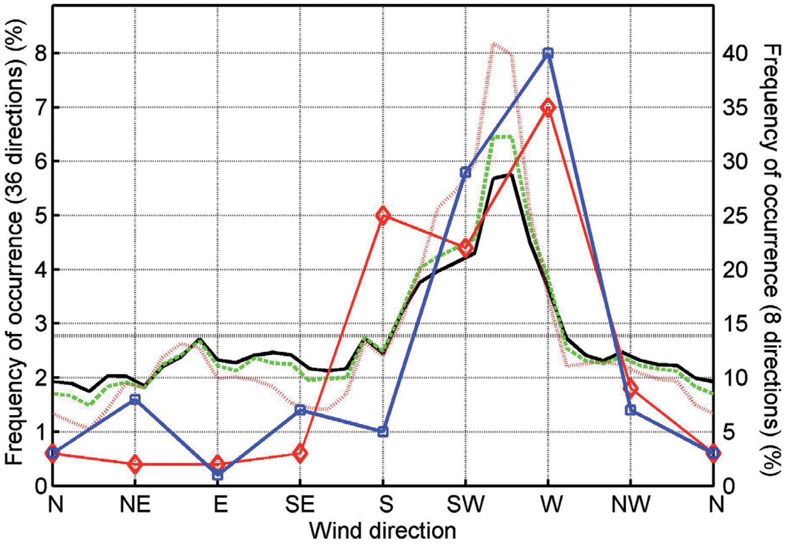

Fig. 8. Directional distribution of all winds (black line), winds > 5 m s^{-1} (green dashed line) and strong winds (> 10 m s^{-1}, red dotted line) at Kalbådagrund (Fig. 1) for 1981–2003 and directional distribution for winds > 5 m s^{-1} in Kronshtadt (blue squares) and Lisiy Nos (red diamonds) for 2004–2008. The Kalbådagrund data have the angular resolution of 10°. The horizontal dotted line represents the average frequency of occurrence of winds for this angular resolution. The data from Kronshtadt and Lisiy Nos are presented with an angular resolution of 45° and also contain all cases when the gust speed exceeds 15 m s^{-1}.

represents well the open sea wind properties is Kalbådagrund (Fig. 1), a caisson lighthouse in the central part of the gulf (59°59´N, 25°36´E). The Kalbådagrund data (Fig. 8) reflect well factual properties of those open sea winds which create substantial wave loads in as remote area as Narva-Jõesuu (Laanearu *et al.* 2007). This suggests that Kalbådagrund data also reflect well the properties of winds that are responsible for the largest wave loads in the Neva Bay area.

There is numerous evidence about the increase in storminess both in the Baltic Proper (Orviku *et al.* 2003, Jaagus *et al.* 2008), and in the western part of the Gulf of Finland (Soomere *et al.* 2008c). The storminess, estimated from the patterns of geostrophic winds, was at a high level in the beginning of the 20th century for a large part of this area. The frequency of storms thereafter declined until around 1965 but during the second half of the century it increased almost to the levels of the first decades of the 20th century (Alexandersson *et al.* 1998). Similar trends have been noticed for the wind speed over Estonia (Kull 2005). These changes in forcing eventually are responsible for many trends and changes in both hydrodynamic and coastal processes; for example, for an apparent change in the long-term trend of relative mean sea level along the Finnish coast and an increase in the annual maxima of the sea level (Soomere *et al.* 2008c).

The described changes, however, not necessarily become evident in all regions of the Baltic Sea. Moreover, the changes evidently have occurred differently in different seasons. For example, long term time-series of monthly mean wind speed over Estonia shows significant change in annual wind speed distribution: wind speed has increased in late autumn and winter (e.g. December and January) while decreased in warm period, most in August (Kull 2005).

The above properties of wind regime are also clearly evident in local wind data, the most suitable from which for the study area are data from Kronshtadt (Kotlin Island) and Lisiy Nos (northern coast of the Neva Bay, Fig. 2). The mean annual wind speed at Kronshtadt is 4.7 m s^{-1}, that is, by about 30% smaller than at Kalbådagrund. For this reason, we rely on the analysis of the number of days with wind speed > 5 m s^{-1} which is almost equivalent to the number of days with gust speed exceeding 15 m s^{-1}. The directional distribution of winds > 5 m s^{-1} is almost the same for Kalbadagrund and Kronshtadt for 2004–2008 (where such winds predominantly blow from the west and south-west) whereas at Lisiy Nos an appreciable portion of south winds were recorded in 2004–2008 (Fig. 9).

Comparison of the discussed data for 2004–2008 with historical data for 1925–1982 (Climate of Leningrad 1982) reveals certain (but not significant) recent increase in the frequency of severe winds (Table 1). The distribution of the average number of days with strong winds in Lisiy Nos in each month shows that almost no changes have occurred in spring and summer, but the number of stormy days has considerably increased in September–January (Fig. 9).

The most important changes in regions adjacent to the study area are connected with changes in the directional structure of winds (Kull 2005). Namely, during the last 40 years there has been significant increase in the frequency of south-western winds and decrease of southern and eastern winds all over Estonia. Such a change may well be responsible for a large part of intensification of coastal processes in the Neva Bay area where the intensity of wave fields may largely change even when there are small changes in the wind directions.

Sea level

The annual maximum values of the sea level have significantly increased on the Finnish coasts during the last 70 years (at 99% level); mostly during the latter half of the 20th century (Johansson *et al.* 2001). This trend evidently contributes substantially to the increased intensity of coastal processes in the Neva Bay area. The most significant sea level variations in the eastern Gulf of Finland apparently occur as a result of combined effect of wind-induced storm surge and progressive long waves that are resonantly excited by cyclones moving along the Baltic Sea and the Gulf of Finland (Eremina *et al.* 1999). While wind-induced surges and the local wave-induced set-up events (the height of which is defined by the local properties of wind speed, short surface waves and the profile of the coastal zone) are mostly of local nature, the water level changes caused by an approaching long wave also depend on the geometry of the affected sea area and on the properties of this wave far offshore. The basic physical mechanisms effects affecting the water level changes induced by propagation of long waves at the coast are shoaling and geometrical focusing (narrowing of the cross-section of the basin, Dean and Dalrymple 1991). The geometry of the Neva Bay area is such that the propagation of long waves into the eastern part of the gulf is accompanied by a rapid water level increase.

The first flood in the history of Saint Petersburg was reported three months after the ceremonial foundation of the city during the night of 31 August 1703. The water in the Neva River mouth raised up to 7 foots (210 cm) over its typical level. According to the Floods Catalog, during the history of Saint Petersburg (1703–2008) 307 floods higher than 160 cm have occurred. Three of them, one in each century, were catastrophic. On 21 September 1777 the water level reached 3.21 m. The ever highest surge (4.21 m) occurred on 19 November 1824. The highest

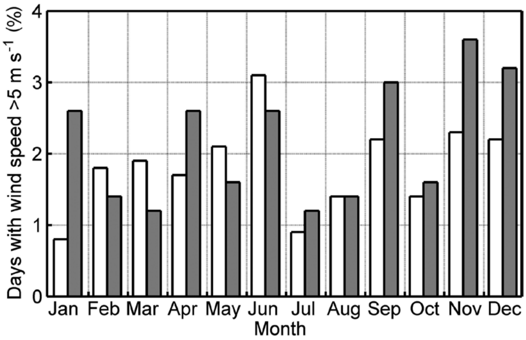

Fig. 9. Average number of days with winds > 5 m s^{-1} (or with gusts > 15 m s^{-1}) in Lisiy Nos in 1925–1982 (white bars) and in 2004–2008 (grey bars) in different months.

Table 1. Number of days with wind speed > 5 m s^{-1} (or with gusts > 15 m s^{-1}) in Kronshtadt and Lisiy Nos.

Station	Kronshtadt	Lisiy Nos
Average (Climate of Leningrad 1982)	–	22
2004	11	28
2005	8	21
2006	6	18
2007	11	24
2008	13	37
Average (2004–2008)	10	25

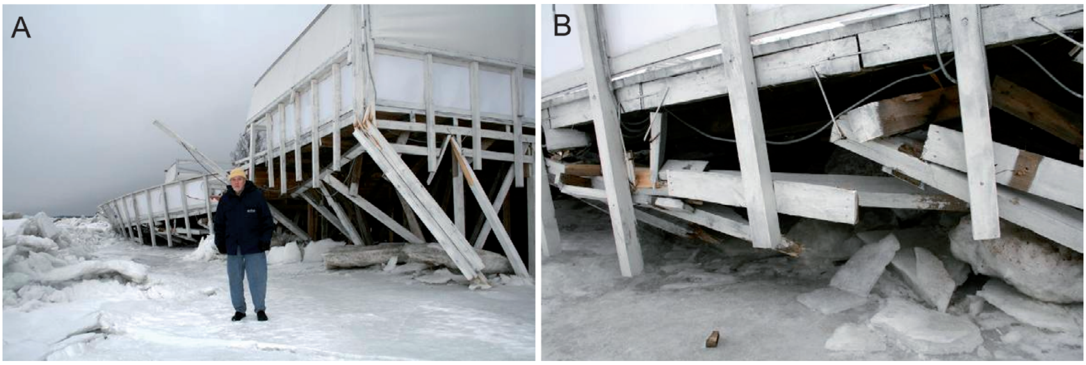

Fig. 10. Beach restaurant broken by ice (Komarovo village, 2 February 2008).

water level of the 20th century (3.80 m) was filed on 23 September 1924. The second part of the 20th century did not establish new flood maxima and the highest water level (2.91 m) during this period took place on 15 October 1955.

The number of floods was almost at the same level in the 18th and 19th century (75 and 77, respectively). The frequency of floods increased considerably in the 20th century (138 events) whereas 57 cases were registered during the first half of century and as many as 81 in the second half. The increased frequency in high water levels persists also in the beginning of the 21st century: already 17 floods have taken place during eight years. There are, however, several other 8-year periods in the past that have hosted the same or even larger numbers of floods. For example, 15 floods took place in 1759–1767 and 21 floods occurred in 1866–1874. The largest number of floods in a single year (10) was recorded in 1983. This number is the largest contribution to the statistics of floods in 1977–1985 when 25 floods occurred. Finally, 28 floods occurred in 1983–1991 (Pomeranets 2005).

The described statistics demonstrates that the occurrence of floods in Saint Petersburg is highly variable. The number of floods in a single year varies from none to ten. Floods can take place in any season and any time of a day. The frequent flood season is September–December when about 80% of all the floods occur, and the rarest is April–July. About 60% of floods happened in evening and night time.

The parameters of floods in 2004–2008 (when the floods exclusively occurred during the autumn–winter season) are given in Table 2. The data indicate that the highest floods in the northern Baltic Proper and in Saint Petersburg are not necessarily created by the same storm. For example, windstorm Gudrun (7–9 January 2005) excited the ever highest water level in many places over western Estonia and on both the coasts of the Gulf of Finland (Soomere *et al*. 2008a) but the surge height in Neva Bay was not exceptional.

Ice conditions

The impact of the presence of ice on beaches and coastal infrastructure could be twofold. The stable ice in the nearshore zone completely damps wind waves and substantially weakens nearshore currents. The ice serves, therefore, as a natural protection of sand beaches and dunes from the impact of wind storms. On the other hand, during some hydrometeorolocal conditions both the fast and drift ice can form dangerous ridges, especially in conditions of floods or storm surges, which can cause extensive destruction of dunes, trees, coastal engineering structures and sometimes even buildings located at distance of tens of metres from the coastline (Fig. 10). Also, "ice erosion" that becomes evident, for example, as motion of boulders frozen into thick coastal ice, may remove a part of the protecting stone belt and in this way open some sections of the beach to the direct wave impact. As the windiest season in the northern Baltic Proper usually occurs when the eastern Gulf of Finland is ice-covered (Soomere *et al*. 2008c), changes in the

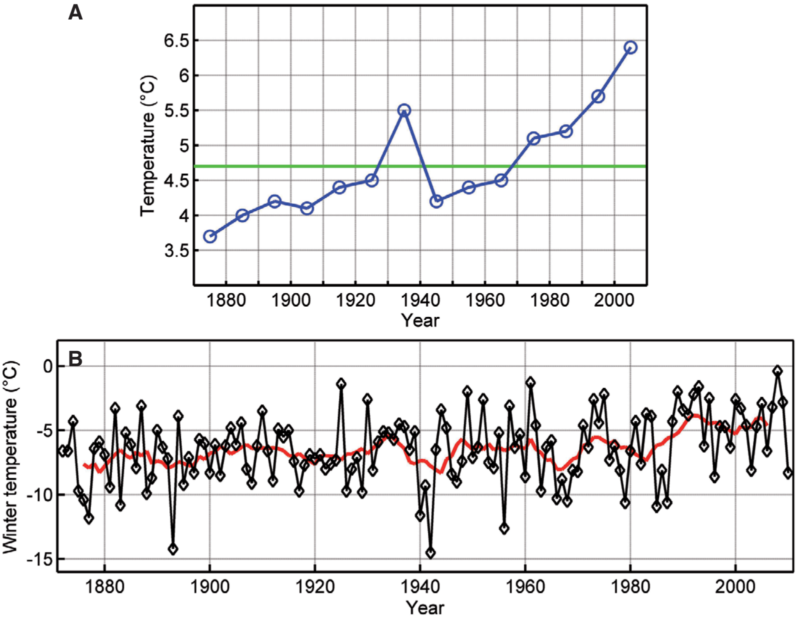

Fig. 11. Average temperature in Saint Petersburg in 1870–2008: (**A**) average decadal temperature (the overall mean is indicated by the horizontal line); (**B**) average winter temperature (the red line shows 10-year average). Data courtesy of the SISPCHEMRF.

ice conditions may have extensive consequences on the course and intensity of coastal processes.

Recent studies into ice conditions in the Baltic Sea (Jevrejeva *et al*. 2004, Sooäär and Jaagus 2007) have identified a clear decrease in the duration of the total ice period during the last century. The relevant changes and trends usually follow similar long-term changes in temperature. There is clear increasing trend in the average temperature of about 0.2 °C per decade in the study area since the 1870s although some irregularity of the trend occurred in 1935–1945 (Fig. 11a). The trend, however, is not uniform over the year: the comparison of the avarage monthly temperature of last decade (2000–2009) with the long-term average (Table 2) reveals that monthly temperatures are clearly higher now in December (7 years from 9) and January (8 cases from 10). The avarage winter temperatures show a similar increasing trend (Fig. 11b).

Table 2. Average monthly temperature of the last decade and the long-term average in Saint Petersburg. Data courtesy of the SISPCHEMRF. Months with the temperatures higher then the long-time average are set in boldface.

Month	Long-term average 1961–1990	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
January	–7.8	**–4.5**	**–2.6**	**–4.5**	–9.5	–8.2	**–1.6**	**–5.8**	**–2.5**	**–1.8**	**–3.5**
February	–6.8	**–2.4**	–6.9	**–0.6**	**–5.8**	**–5.5**	**–6.4**	**–1.1**	**–1.1**	**–0.1**	**–3.9**
March	–2.2	**–0.5**	–3.8	**0.5**	**–1.6**	**–0.5**	–6.1	–6.2	**3.6**	**0.4**	**–0.8**
April	4.1	**8.1**	**8.0**	**6.1**	2.3	5.0	**4.6**	**5.4**	**5.2**	**7.0**	**4.3**
May	10.9	10.5	10.2	**12.4**	**12.1**	**11.1**	**11.1**	**11.8**	**12.3**	**11.0**	**12.1**
June	15.6	15.5	15.2	**16.8**	13.0	14.8	15.5	**17.0**	**16.0**	15.1	15.0
July	17.7	**18.2**	**21.8**	**20.8**	**21.4**	**18.5**	**20.1**	**19.2**	**18.5**	**17.8**	**18.2**
August	16.2	**16.6**	**16.8**	**18.8**	**16.6**	**17.8**	**17.9**	**18.9**	**19.6**	16.1	**16.2**
September	11.1	10.6	**12.7**	**11.7**	**12.4**	**13.2**	**13.6**	**14.2**	**12.1**	10.7	**13.9**
October	5.7	**8.8**	**7.1**	1.5	5.1	**6.5**	**7.7**	**8.1**	**7.5**	**8.7**	4.6
November	0.1	**2.6**	–0.9	–2.2	**2.4**	**–0.1**	**3.5**	**1.7**	**–0.7**	**3.0**	**2.4**
December	–4.6	**–0.5**	–8.8	–9.7	**–0.7**	**–0.7**	**–3.6**	**3.0**	**0.8**	**–0.8**	–5.1
Mean	5.0	**6.9**	**5.7**	**6.0**	**5.6**	**6.0**	**6.4**	**6.4**	**6.8**	**7.3**	**6.2**

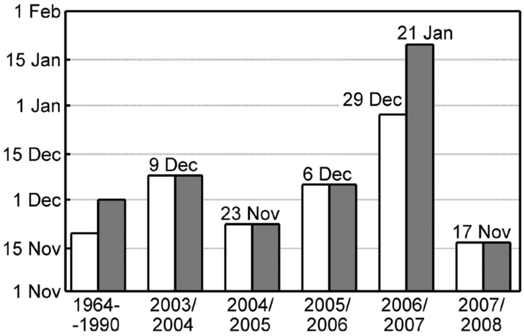

Fig. 12. Dates of first ice appearance (white bars) and ultimate freezing (grey bars) in 2004–2008. The left-most column indicates the relevant average dates for 1964–1990.

The warmer temperatures in December and January lead to later freezing dates (Fig. 12). The absence of ice during the months when the severe storms are quite frequent may substantially modify both the course and intensity of coastal processes. Analysis of the dates of freezing for the last 5 years indicates that Neva Bay was exceptionally ice-free in December 2006–January 2007 (Fig. 12). This feature opened a way for the most intense erosion events observed during the last years.

Extreme erosion events

Let us consider now in detail whether or not recent rapid erosion events in the area in question are connected with unusual constellations of wave, water level and ice conditions. Field observations revealed no extreme erosion events in the Kurortny District in winter 2004/2005 although several strong storms occurred in autumn 2004. For example, on 13–18 September 2004 western and south-western winds at Lisiy Nos several times reached 15–16 m s^{-1} and on 23 and 31 December 2004 southern and south-western winds reached 17–19 m s^{-1}. During these events, the above-discussed combination of factors favorable for rapid coastal erosion did not occur and no substantial loss occurred to the coasts. As these storm events were short, wave heights apparently remained moderate. There were no storm surges exceeding 1.4 m during the second half of 2004 (Table 3 and Fig. 13). While November storms took place in iceless conditions (but fortunately were relatively modest), in December solid ice was formed along whole the shore of Kurortny District.

The winter in question contains cyclone Gudrun, one of the most significant storms during the last years (Suursaar *et al*. 2006, Soomere *et al*. 2008a). As a result of strong cyclonic activity, the Baltic Sea level was very high (+0.7 m) already before the storm (Suursaar *et al*. 2006). Rough wave conditions and high surge caused by Gudrun caused terrible floodings and severe damage on many coasts in the south-eastern Baltic Sea and Estonia (Tõnisson *et al*. 2008). It is remarkable that this storm excited extremely high water levels in the entire Gulf of Finland. New sea level records were established at Tallinn and at Toila (whereas at the other sites along the southern coast the water level was close to the historical maxima), and in all four Finnish stations on the southern coast of Finland (Suursaar *et al*. 2006, Soomere *et al*. 2008c).

This event also led to two significant floods (on 8 and 9 January, respectively) in Saint Petersburg. The water level at Gorny Institute reached 2.39 m (Fig. 13), which is quite a high but not an exceptional flooding for Saint Petersburg. The reason for a relatively moderate level of

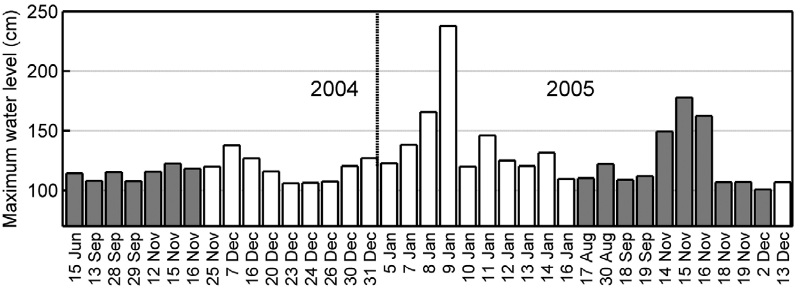

Fig. 13. Maximal water levels (> 1 m above the long-term mean) in 2004–2005 at the Gorny Institute water level measurement post. White bars indicate the ice cover.

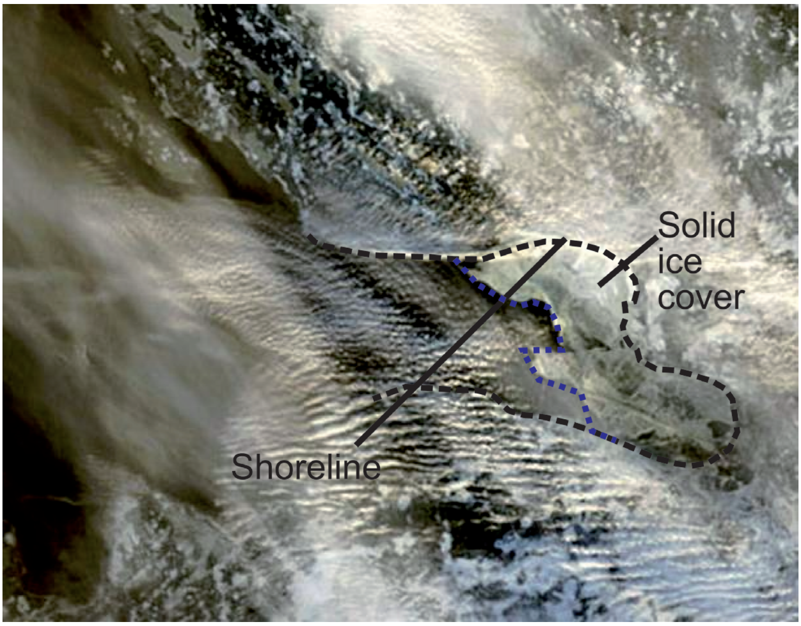

Fig. 14. Solid ice near the Kurortny District coast. Satellite image 8 January 8 2005 (provided by Dr. Leontina Sukhacheva, Institute of Remote Sensing Methods for Geology (VNIIKAM)).

flooding apparently is that the surge was mostly wind-driven and no long waves were formed during the storm. Exceptionally high and long waves penetrated into the Gulf of Finland during this long-lasting storm (Soomere *et al*. 2008a). Therefore, two out of three conditions for a severe erosion event were satisfied. The storm, however, had almost no impact on the beaches of the Kurortny District that were protected by the presence of thick solid ice (Fig. 14) formed already at the end of November.

During autumn 2005 stormy winds were observed many times. On 23 and 26 October 2005 the entire Neva Bay experienced southern and south-western winds up to 17 m s^{-1} (south-western wind even reached 20–23 m s^{-1} in gusts). As the storm events were short and the wind direction was unfavorable for creation of high surge, the water level did not reach 1 m above the long-term mean. Two floods were registered on 15 November (Table 3 and Fig. 13) in which water level reached 1.83 m above the long-term mean. These November storms provided the most dangerous conditions for coastal erosion because they occurred in ice-free conditions. As the surge heights remained moderate, no serious damage occurred. On 12–13 December wind speed increased to 16–18 m s^{-1} in Lomonosov (southern coast of the gulf) and 18–19 m s^{-1} in Ozerki station (northern coast, to the west of the Kurortny District). The water level rose 1.06 m above the long-term mean. As the ice cover has already been formed along the entire coast of the Kurortny District, the coasts did not suffer.

High wind speeds also frequently occurred during the autumn in 2006. Two floods (> 1.6 m

Table 3. Floods in Saint Petersburg in 2004–2008. No water levels exceeding 160 cm were registered in 2004.

Number according to catalog	Date	Maximum water level (cm) in Baltic System (BS)	Time of maximum (local time)
296	8 Jan. 2005	165	02:05
297	9 Jan. 2005	239	11:40
298	15 Nov. 2005	169	02:00
299	15 Nov. 2005	183	23:20
300	28 Oct. 2006	225	05:20
301	15 Dec. 2006	191	05:50
302	10 Jan. 2007	225	15:12
303	16 Jan. 2007	179	02:26
304	16 Jan. 2007	168	22:00
305	18 Jan. 2007	171	19:00
306	3 Feb. 2008	198	15:24
307	16 Nov. 2008	187	03:56

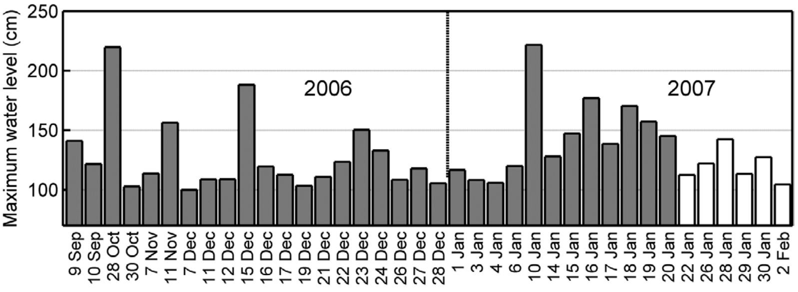

Fig. 15. Maximal water levels (> 1 m) in 2006–2007 at the Gorny Institute water level measurement post. White bars indicate the ice cover.

over the long-term mean) took place in iceless conditions. A severe storm, observed by all stations in Neva Bay, occurred on 27–28 October (Fig. 15). First south-western, then western and north-western storm was strong and long-lasting. The average wind speed reached 15 m s^{-1} (gusts 20–24 m s^{-1}) between midnight and 09:00 on 28 October. The storm caused a very high water level (2.2 m above the long-term mean). Significant wind events were also observed in November (for example, western and north-western wind reached 19 m s^{-1} on 8 November). Another flood (1.88 m above the mean level) occurred on 15 December (Fig. 15). Western and south-western winds reached 15–20 m s^{-1} on 15 and 20 December. As these storms occurred in ice-free time, the above three conditions for high impact on the coasts were simultaneously satisfied. It is, therefore, not unexpected that they caused abrupt intensification of coastal processes in the Kurortny District.

High cyclonic activity continued in January 2007 in the eastern Gulf of Finland. In January there were as many as four floods (Fig. 15): 2.21 m above the mean level on 10 January, two events with the largest level 1.73 m on 16 January and 1.7 m on 18 January. The water level was unusually high on many other days: 1.2 m on 11 January, 1.28 m on 14 January, 1.47 m on 15 January 1.39 m on 17 January, 1.57 m on 19 January and 1.45 m on 20 January (Fig. 15). The strongest (south-western) wind with the average speed > 10 m s^{-1} and gusts up to 20–23 m s^{-1} was observed from midnight to noon on 10 January. During three days (16–18 January) the south-western to western wind was a bit weaker (17–18 m s^{-1} in gusts). As many of these storms were also long-lasting, severe waves occurred together with very high water level on several occasions.

The protecting role of coastal ice (in terms of consequences of its absence) became clearly evident during this stormy period. The beginning and middle of January was extremely warm. Although the first appearance of ice was registered on 28 December, a solid ice cover was formed as late as in the third week of January (Fig. 16). Consequently, severe wave impact on the beaches and dunes continued during most of the month. Field observations confirmed that the storm during the highest flood (10 January) most heavily damaged coastal dunes along a 3 km long coastal section at Komarovo that was not protected by ice (Fig. 17).

In the eastern part of Kurortny District (Repino and Solnechnoye), however, there was a narrow belt of ice near the coast (Fig. 16) in January. This belt effectively protected the coastal sediments and in these sections the largest impact was caused by earlier autumn storms.

The year 2008 was the warmest year during the last decades, with the average temperature by 0.2 °C higher than in the second warmest (1989) year. The winter of 2008 was also the warmest during whole period of observations (since 1881) in Saint Petersburg. The cyclonic activity was comparatively low during January. Relatively short stormy events (southern and south-western winds) were observed on 13, 19 and 20 January, with gust speed up to 16–18 m s^{-1}). The cyclonic activity was larger in February, with storms on 2–3 and 22–23 February. There was a flood on 3 February (Fig. 15), accompanied by gusts of western and south-western winds up to 20–24 m s^{-1}. Although the winter of 2007/2008 was relatively warm, solid ice was formed quite early, in November 2007. Owing to its presence the winter storms did not cause any substantial damage to the coast.

Fig. 16. The beginning of the solid ice formation near Kurortny District coast. Satellite picture from 17 January 2007 (provided by Dr. Leontina Sukhacheva, VNIIKAM).

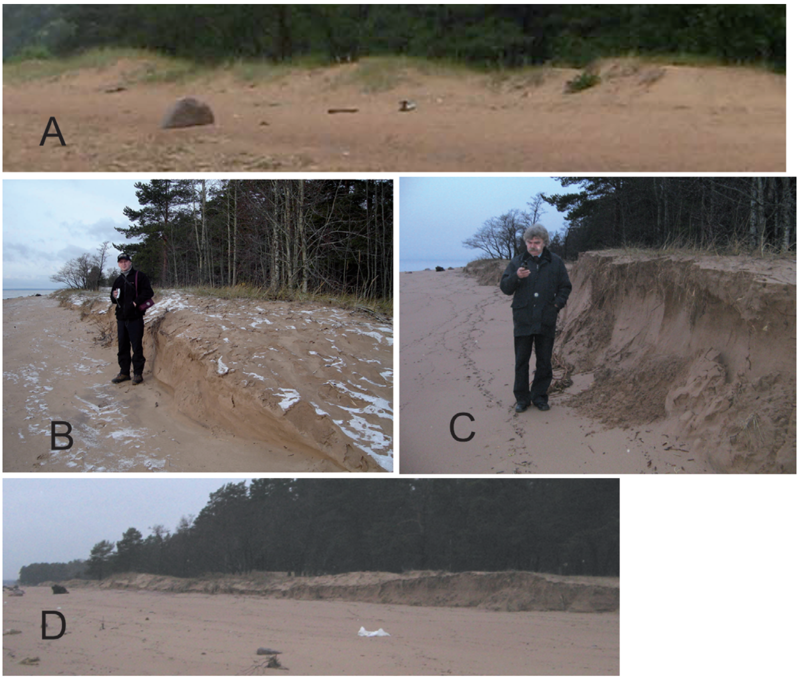

Fig. 17. Progressive damage of the coastal dunes in Komarovo village during autumn and winter 2006/2007. **A**: June 2006; **B**: 29 October 2006; **C** and **D**: 11 January 2007 (Ryabchuk *et al*. 2009a; reprinted with permission from Estonian Academy Publishers).

During summer time, high wind speed events were rare and short over all the discussed years. The autumn stormy season began in October 2008 but the winds remained moderate until 16 November when the western wind reached 17–20 m s^{-1} and a flood with maximal water level 1.87 m was registered (Fig. 18). On 23–24 November the wind speed was up to 17–18 m s^{-1}. There was no ice during the described events. Therefore, two out of three above-discussed

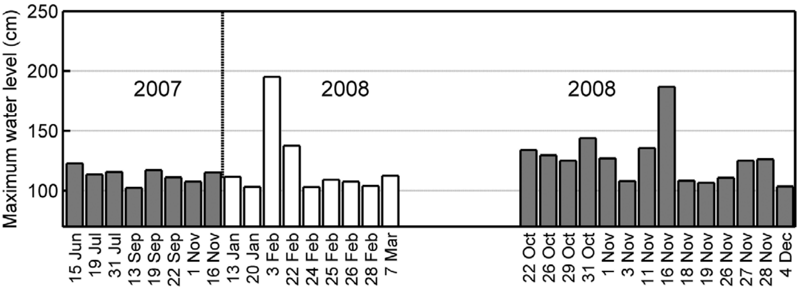

Fig. 18. Maximal water levels (> 1 m) in 2007–2008 at the Gorny Institute Water Level Measurement Post. White bars indicate the ice season.

conditions were favorable for coastal degradation. The wind direction during the November storm, however, was from south-east, which is very rare and not dangerous for the Kurortny District because of short fetch. The erosion remained moderate also in October because (as discussed earlier for the autumn 2005) the sea level remained moderate. During the next strong storm on 31 December the coast was already protected by solid ice cover.

Human influence

Along with the combinations of various natural driving forces, different anthropogenic activities may at times substantially influence the coastal system. Most frequently, irregular measures for shore protection, undertaken by proprietors and holders of beach infrastructure, result in extensive negative impact to the adjacent sections of the coast (Ryabchuk *et al*. 2009b). Usually this impact is more or less local but it may rapidly lead to clearly expressed geomorphic consequences such as the decrease in the beach width, degradation of dunes, changes in the boulder belt, etc. For example, unprofessional coastal protection of a recently developed recreation zone in Komarovo caused erosion of a sandy beach and the coastline retreat up to 10–12 m along a 200 m section of the shore. The process continues in spite of efforts of the owner to stabilize the situation, including local beach nourishment in spring period.

The impact of large hydrotechnical constructions (such as quays and jetties that serve as groins stopping the littoral drift) can be more serious. For example, a 90 m long jetty was constructed in 1911 perpendicularly to the beach in Zelenogorsk (former Terijoki) for Imperator's Yacht Club. The analysis of old charts, archive photos, remote sensing data from different decades (including results of an air survey made in 1932) and field observations reveals that during the century the impact of the jetty has caused total degradation of sand beaches along about 1.6 km of the shore to the east (that is, downdrift) of the jetty. Since 1950s there have been attempts to prevent the further retreat of the coasts using seawalls and other "hard" coastal protection structures. As a result, not only the recreational value of the beaches has drastically decreased but also the efforts have not been able to stabilize the situation: the shoreline eastward of the jetty has retreated by up to 100 m between 1909–2006 (Ryabchuk *et al*. 2009a).

The modern coastal engineering methods have made it possible to estimate more or less definitely the impact of such constructions on the coastal zone. A much more complicated task is to estimate the impact of submarine sand extraction on the coastal system. Submarine sand mining took place in 1970–1992 in sandy terrace between capes Flotsky and Peschany to the west of the Kurortny District. The total volume of extracted material was about 150 million m^3. As a result, large parts of the nearshore at depths less than 19 m were affected.

Although it is difficult to definitely relate the impact of the sand mining with changes in the coastal zone, some implications are straightforward. An apparent negative consequence of the sand removal is the reinforcement of the natural sediment deficit in the Kurortny District that is located downstream of longshore sediment flow. In particular, the area of longshore sand bars in front of Cape Lautaranta was significantly narrowed. Since 1990 the submarine sand mining did not take place and the area of sand bars has been stable (Ryabchuk *et al.* 2009a).

Finally, a huge coastal engineering structure that may possible impact the coastal zone — the Flood Protective Facility (Fig. 2), to be completed by 2011 — is currently under construction adjacent to the region discussed in this paper. A modeling study undertaken by Dr. K. Klevanny (personal communication) has shown that during extreme floods when the flood gates will be closed, the water level outside of the facility (incl. in the range of the Kurortny District) can rise by 0.2–0.3 m higher than now. This feature eventually will lead to more frequent occurrence of extreme erosion events.

Conclusions

The presented study first documents recent drastic intensification of coastal processes and destruction of dunes in the Neva Bay area, the easternmost part of the Gulf of Finland. Beaches in this bay are largely open in the direction of one of the longest fetches in the Baltic Sea. The coasts are relatively young and apparently have not reached an equilibrium state. The geometry of the Gulf of Finland and Neva Bay is such that only storms from a narrow range of directions may cause high wave loads and storm surges in this area.

The coasts in question are jointly impacted by several geological, geomorphic, hydrometeorological and anthropogenic factors, the magnitude of which may vary in a wide range depending on a particular event and region. The geological and geomorphic factors determine the long-term coastal zone development. The most important prerequisite for relatively rapid coastal erosion in this area is the composition and properties of coastal deposit. The coasts mostly consist of easily erodible Quaternary deposits (clays and sands). They evolve under overall sediment deficit which is partially augmented by numerous boulder belts formed as a result of glacial till erosion. Moreover, some specific, small-scale features of the nearshore bottom (such as submarine terrace erosion, erosion runnels and other points of sediment loss) play a very important role in the entire erosion process.

The most extreme erosion events are controlled by a specific combination of hydrometeorological factors. Such events occur when three unfavorable conditions take place simultaneously: (i) long-lasting western or south-western storms that bring high waves to the area in question, (ii) high water level (more than 2 m above the mean level as measured by the Gorny Institute water level measurement post, and, most importantly, (iii) absence of stable sea ice during such events. Since 2004 the frequency of occurrence of such unfortunate combinations apparently has increased. The expected tendency towards further warming in winter periods and later dates of the appearance of stable sea ice, most probably, will lead to the increase in the frequency (and possible also severity) of storms, high water levels (especially wind-driven storm surges) combined with a decrease in the duration of ice cover (that has protected the coast against strong storms in late autumn–early winter time in the past). Therefore, an increase in the number and severity of extreme erosion events could be expected in the future.

Another important driver of potentially adverse impacts to the coastal areas at places are technogenic impacts. Small coastal engineering structures and irregular recreation activity usually have a local impact on the adjacent parts of the shore. More serious impact, albeit not exactly quantified yet, can have submarine sand and gravel mining operations within nearshore zone and building of large-scale coastal engineering structures such as the Flood Protectection Facility.

Acknowledgements: This research is supported by Russian Foundation for Basic Research (RFBR), projects number 08-05-01023 and 08-05-92420-BONUS_a, Estonian Science Foundation (Grant No. 7413), targeted financing by the Estonian Ministry of Education and Research (grant SF0140077s08), and Marie Curie RTN SEAMOCS (MRTN-CT-2005-019374). We would like to thank our colleagues Yu. Kropatchev, E. Nesterova, T. Bodryakov, A. Sergeev, B. Stepanov and G. Suslov for for their help during cruises and laboratory investigations. We are greatful to Dr. V. Zhamoida, Dr. A. Grigoriev and Dr. S. Manuylov for advisable comments helping to prepare the paper. Our special thanks are to Dr. L. Sukhacheva (Laboratory of Coastal Zone Research of Institute of Remote Sensing Data in Geology) for the long-term successful cooperation and presented materials. TS thanks the Finnish Meteorological Institute for presenting the Kalbådagrund wind data.

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