POLISH POLAR RESEARCH
vol. 36, no. 4, pp. 369–390, 2015 doi: 10.1515/popore-2015-0019

Multidecadal (1960–2011) shoreline changes in Isbjørnhamna (Hornsund, Svalbard)

Piotr ZAGÓRSKI [1]*, Jan RODZIK [1], Mateusz MOSKALIK [2],
Mateusz C. STRZELECKI [3], Michael LIM [4], Małgorzata BŁASZCZYK [5],
Agnieszka PROMIŃSKA[6], Grzegorz KRUSZEWSKI [7], Anna STYSZYŃSKA[8],
and Artur MALCZEWSKI [9]

[1] *Wydział Nauk o Ziemi i Gospodarki Przestrzennej, Uniwersytet Marii Curie-Skłodowskiej,*
Al. Kraśnicka 2cd, 20-718 Lublin, Poland

[2] *Instytut Geofizyki, Polska Akademia Nauk, Centrum Studiów Polarnych KNOW,*
ul. Księcia Janusza 64, 01-452 Warszawa, Poland

[3] *Instytut Geografii i Rozwoju Regionalnego, Uniwersytet Wrocławski,*
Pl. Uniwersytecki 1, 50-137 Wrocław, Poland

[4] *Northumbria University, Engineering & Environment, Wynn Jones Building 201,*
Northumberland Road, Newcastle upon Tyne NE1 8ST, UK

[5] *Wydział Nauk o Ziemi, Universytet Śląski, Centrum Studiów Polarnych KNOW,*
ul. Będzińska 60, 41-200 Sosnowiec, Poland

[6] *Instytut Oceanologii, Polska Akademia Nauk,*
ul. Powstańców Warszawy 55, 81-712 Sopot, Poland

[7] *Wydział Nawigacyjny, Akademia Morska, ul. Sędzickiego 19, 81-374 Gdynia, Poland*

[8] *Katedra Urbanistyki i Planowania Regionalnego, Politechnika Gdańska,*
ul. Narutowicza 11/12, 80-233 Gdańsk, Poland

[9] *TPI Sp. z o.o., ul. Bartycka 22, 00-716 Warszawa, Poland*

*<piotr.zagorski@poczta.umcs.lublin.pl> * corresponding author*

Abstract: A section of a gravel-dominated coast in Isbjørnhamna (Hornsund, Svalbard) was analysed to calculate the rate of shoreline changes and explain processes controlling coastal zone development over last 50 years. Between 1960 and 2011, coastal landscape of Isbjørnhamna experienced a significant shift from dominated by influence of tide-water glacier and protected by prolonged sea-ice conditions towards storm-affected and rapidly changing coast. Information derived from analyses of aerial images and geomorphological mapping shows that the Isbjørnhamna coastal zone is dominated by coastal erosion resulting in a shore area reduction of more than 31,600 m^2. With ~3,500 m^2 of local aggradation, the general balance of changes in the study area of the shore is negative, and amounts to a loss of more than 28,000 m^2. Mean shoreline change is -13.1 m (-0.26 m a^{-1}). Erosional processes threaten the Polish Polar Station infrastructure and may damage of one of the storage buildings in nearby future.

Key words: Arctic, Spitsbergen, coastal erosion, sea-ice, shore ice, fjord system.

Introduction

The Arctic coast represents a critical zone characterized by "rapid and severe environmental changes, which have serious implications for communities living on coastal resources" (Forbes *et al.* 2011). Recent developments in arctic coastal studies have predominantly focussed on permafrost, particularly along the fringes of the Beaufort and Siberian Seas, which are characterized by some of the most rapid erosion rates in the world (Overduin *et al.* 2014). The high rates of erosion observed along the coasts of northern Eurasia and North America have been linked with thermoabrasion of ground ice directly exposed to the operation of coastal processes (Are 1988; Wobus *et al.* 2011). The acceleration in the rate of abrasion has been associated with both the extension of the ice-free period and an increase in the number of storms entering Arctic region (Lambert 2004; Barnhart *et al.* 2014). In their seminal paper on Arctic coastal erosion, Lantuit *et al.* (2012) analysed 61,000 km of Arctic coast and reported a mean erosion rate of 0.5 m a^{-1}. The erosion rates derived ranged from 1.15 m a^{-1} in the American Beaufort Sea to 0 m a^{-1} along the Svalbard Archipelago. However, only limited proportion (approximately 8.7%) of the total Svalbard coastline was included in the analysis, as explained by Lantuit *et al.* (2012). More recently, Sessford et al. (2015a) studied the impact of terrestrial processes on erosion of unlithified cliffs developed along inner fjords of Svalbard and observed that erosion rates of ice-poor cliffs are (0.34 m a^{-1}) are more consistent by slower than in cliffs with higher ice-content (0.47 m a^{-1}).

In this paper, we aim to improve the understanding of the Svalbard coastal dynamics through analysing shoreline changes along the unconsolidated coast of Isbjørnhamna (Hornsund, SW Spitsbergen) over the last 50 years (1961–2011).

Study area

The focus of this study is a 3 km stretch of coast of the Isbjørnhamna embayment in the north-western part of the Hornsund fjord (SW Spitsbergen, Svalbard), where the Polish Polar Station (PPS) is located. The hydrography in Isbjørnhamna (Fig. 1) depends on both the boundary between the oceanic and fjord conditions (processes of water, material and energy exchange and mixing) and where fjord waters meet inflows of freshwater from melting glaciers, river runoff, and precipitation from the landward margins (Cottier *et al.* 2010). Water circulation in fjords generally follows an annual cycle. Its dynamics is determined by external factors such as wind, freshwater inflow, and tides (Skardhamar and Svendsen 2010). The geometry of the fjord basin also plays a significant role in water circulation. As with many fjords in Spitsbergen, Hornsund is classified as a wide fjord (Svendesen *et al.* 2002; Skardhamar and Svendsen 2010). This results

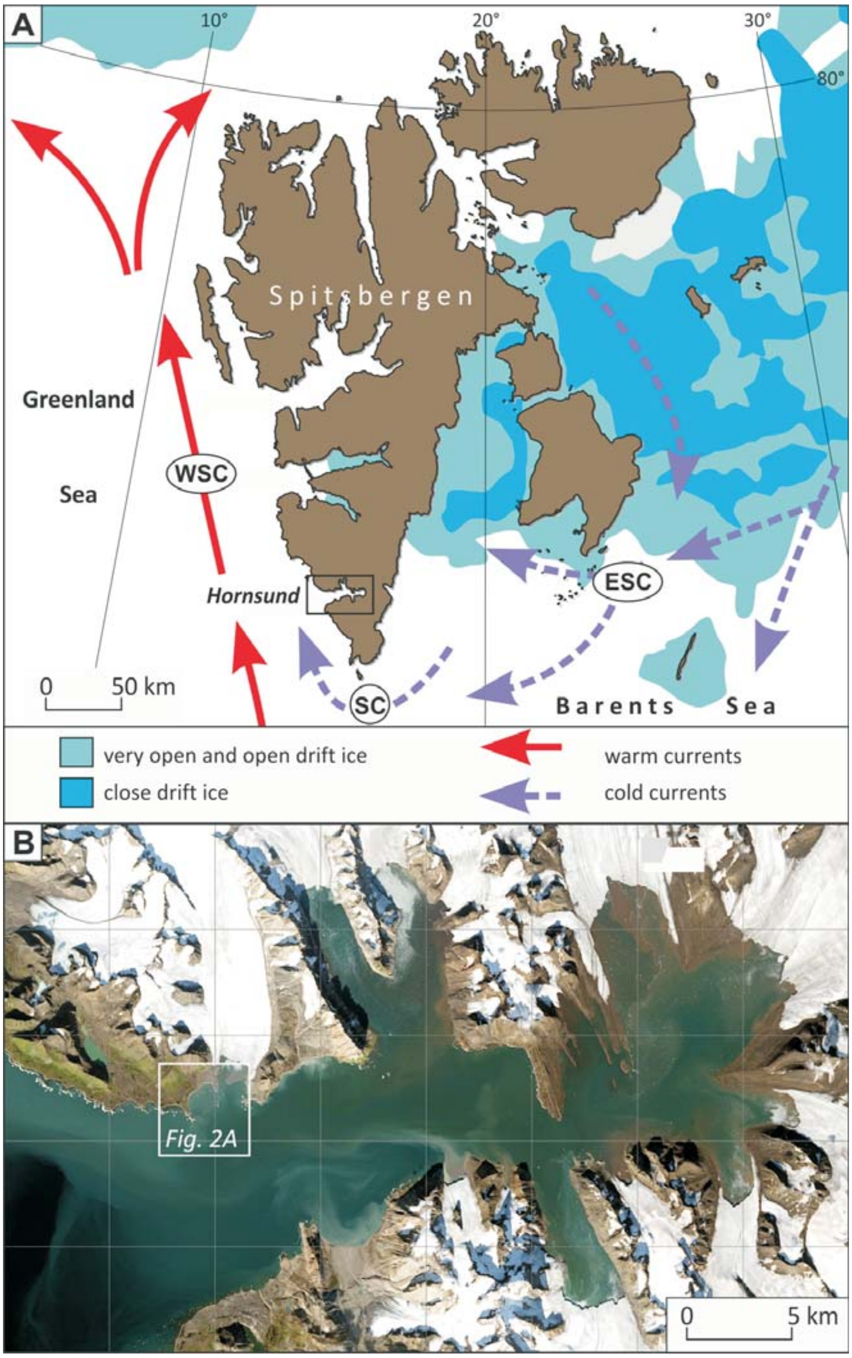

Fig. 1. Location of the study area: A – Svalbard Archipelago with the main ocean currents and sea ice extents in December 27th 2007 (source: Sea Ice Service, Meteorologisk Institutt, Norway): WSC – West Spitsbergen Current, SC – Sørkapp Current, ESC – East Spitsbergen Current; B – satellite image of Hornsund taken on 24h of August 2013 (source: U.S. Geological Survey, Department of the Interior).

in a general circulation pattern where warm, salty waters of the West Spitsbergen Current (WSC) flowing north along the continental shelf, mix with cooler, less saline shelf waters of the Sørkapp Current entering the fjord along the southern coast. The inflow of warm oceanic waters at a certain depth forces the outflow of cool and fresher waters in the surface layer, causing an estuarine circulation pattern, largely modified by surface contact winds (Inall and Gillibrand 2010). The circulation of surface waters in Hornsund is additionally affected by tidal currents. Regular semidiurnal tides occur in the fjord with range from 0.8 to 1.8 m (Siwecki and Swerpel 1979; Węsławski *et al.* 1993; Urban-Malinga *et al.* 2009). The spatial orientation of the fjord, its position in relation to the open sea, and the orography of its surroundings determine the wave action conditions, predominantly wind waves and oceanic swell. Eastern winds, although frequently reaching considerable strength, result in short, low waves due to the limited fetch length (approximately 17 km from the Treskelen Peninsula) and the diffraction processes. Western winds generate long, high wind waves, as well as oceanic swell. Short-term waves can reach a height of approximately 1 m but long swell waves from the open sea can reach heights of approximately 5–6 m (Florczyk and Latała 1989).

Isbjørnhamna, and particularly its western shore, is not subject to the direct operation of oceanic swell, however, swell indirectly reaches the western shore as a result of wave diffraction along the Wilczekodden headland, resulting in wave direction change which in turn determines the development of the longshore current flowing NNE (Fig. 2A).

Easterly winds are dominant (44.1%), with significant contributions from the north-east (17.7%) and west (12.1%). In summer, the occurrence of westerly and south-westerly winds increases – in July 19.3% and 15.4%, respectively. The mean annual wind velocity amounts to 5.6 m s^{-1}, with light winds in June, July, and August (3.9–4.1 m s^{-1}), and higher mean monthly wind speeds in January, February, and March (7.0–7.2 m s^{-1}) (Marsz and Styszyńska 2013) (Fig. 2B).

The climate of the south-western coast of Spitsbergen is classified as subpolar marine (Marsz and Styszyńska 2013). The mean (1978–2012) annual air temperature in the area of the PPS amounts to -4.1°C. The warmest month is July with the mean temperature of 4.4°C, and the coldest months are January, February, and March with a mean temperature of -10.5°C. Both negative and positive temperatures may occur in each month. The mean annual precipitation amounts to almost 445 mm, and 30% of precipitation occurs in solid form. The highest mean monthly precipitation of 68.3 mm occurs in September, and the lowest in May (20.1 mm).

Since continuous meteorological observations began at the PPS (1978), a trend of gradual warming has been recorded, predominantly caused by the increasing inflow of warmer Atlantic water to the Arctic Ocean (Piechura and Walczowski 2009; Walczowski and Piechura 2011; Walczowski *et al.* 2012). This is accompanied by a gradual increase in air and ground temperature, atmospheric pressure and pressure gradient, precipitation, and wind velocity (Marsz and Styszyńska 2013).

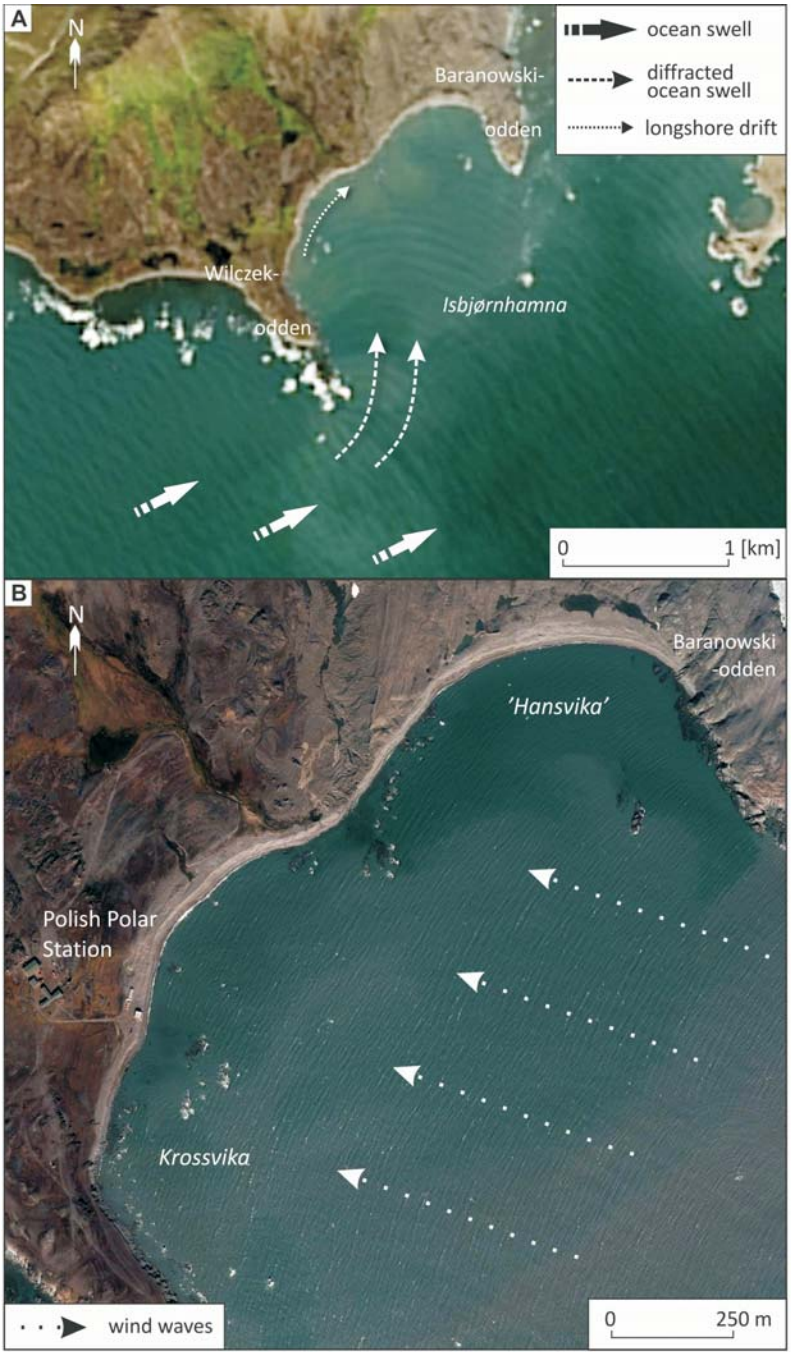

Fig. 2. **A**. The impact of oceanic waves on Isbjørnhamna coast (Image courtesy of the U.S. Geological Survey, Department of the Interior). **B**. The impact of wind waves in Isbjørnhamna is associated with glacier winds descending from local tide-water glaciers (source: aerial photo background from 2011, Topo Svalbard, http://toposvalbard.npolar.no).

Fig. 3. Sea-ice cover before the spring-melt season of 2007.

The presence of various types of ice is an extremely important element affecting the coastal evolution (Fig. 3). Sea ice in the Hornsund may develop as autochthonic ice deep in the fjord, or drift into the fjord sea ice from the neighbouring water bodies (Kruszewski 2011). Sea ice presence may be limited to several weeks at a time by destabilising wave (Görlich and Stepko 1992) and tidal processes. In addition to sea ice, Hornsund is frequently filled with glacier ice in the form of icebergs and growlers originating from glacier calving (Błaszczyk *et al.* 2013). During summer to autumn, glacier ice is the prevailing type of ice encountered in the fjord system (Jahn 1977; Rodzik and Zagórski 2009; Kruszewski 2010, 2011).

The coastal evolution is also influenced by the presence of coastal ice, which generally protects all types of shores from erosional processes (Rodzik and Zagórski 2009). On the shore of Isbjørnhamna, coastal ice usually commences in October, reaching a maximum thickness and extent in April before its gradual degradation (Rodzik and Wiktorowicz 1996). Occasionally, in favourable conditions (delayed spring, lack of storms and rainfall and a considerable amount of entrained sediments), the ice-foot persists until July (Giżejewski and Rudowski 1994), and remnants covered with beach sediments have even been observed at the beginning of August, *e.g.* in 1982, 1991, and 2005. Over the last two decades, a clear tendency in delayed initiation of coastal ice and ice-foot development has been recorded, and consequently limits their size and persistence (Rodzik and Zagórski 2009). The general decrease in the sea ice cover noted around Spitsbergen (Marsz and Styszyńska 2013), thought to be linked to the increasing temperature of the WSC waters (Beszczynska-Möller *et al.* 2012; Walczowski *et al.* 2012), affects coastal ice development, and leads to reduced duration of sea ice cover in fjords, as well.

In terms of geological structure, the coast of Isbjørnhamna is located in the area of metamorphic rocks of the *Hecla Hoek* complex. Two basic groups of rocks can be distinguished here. The first, the Isbjørnhamna group (the Ariekammen Formation), is represented by gneisses, paragneisses, sandstones, siltstones, and limestones with strands of quartz, and laminae of marbles. The second is the Eimfjellet group (the Steinvikskardet and Torbjørnsenfjellet formations), represented by quartzites, crystalline shales, and amphiboles (Birkenmajer 1958, 1990). Such rock types often develop cliffs and uplifted marine terraces as well as underwater skerries that are revealed during low tide.

The sourrondings of Isbjørnhamna include three main groups of relief, *i.e.* the slope, coastal, and glacial landforms (Pękala 1989). Currently, the local landscape is intensively transformed by the operation of periglacial and paraglacial processes. Periglacial weathering and paraglacial reworking of landforms supply the coastal system with the following types of sediments:

- gravels and sands from proglacial and nival rivers as well as from abrasion and physical weathering of rock cliffs developing storm ridges within the swash zone (Jahn 1961, 1968; Pękala 1989);
- gravels and sands enriched in fine fractions from aeolian and fluvial transport derived from uplifted marine terraces elevated at 4.5–6 m a.s.l. and altered by frost weathering and permafrost-related processes (Karczewski *et al.* 1981; Pękala 1989);
- fluvioglacial sediments, transported from the glacier forefield and moraine belts and interacting with uplifted marine terraces;
- glacial sediments, deposited directly in the marginal zone of the Hansbreen (a system of ice-cored frontal and lateral moraines), as well ground and fluted moraines (Pękala 1989; Jania 1998; Karczewski *et al.* 2003).

Materials and methods

The dynamics of coastal changes were determined based on archival data, differential global positioning system (DGPS) measurements, and terrestrial laser scanning (TLS). The shoreline in this study is defined as the upper abrasion edge – cliff (sections 1–5) and ephemeral storm ridge formed during the high water level (section 6) (Fig. 4). The shoreline positions of Isbjørnhamna were determined for the following years:

- 1960 – vertical aerial photographs (S60 7338 and 7339) from 15 August 1960 taken by Norwegian Polar Institute. The error of determination of the range of the abrasion edge amounted to ±1.5–2 m. The photographs (stereopairs) were processed in the StereoPhoto Maker 4.2 software in the form of anaglyph permitting stereoscopic vision and mapping of coastal landforms.
- 1990 – ortophotomap (Kolondra, 2003), on the basis of 1990's aerial photos provided in digital form by the Norwegian Polar Institute, with a stated accuracy of ±1.5 m.
- 2011 – direct DGPS measurements and laser scanning. DGPS measurements were performed by means of DGPS receivers by Leica (Fig. 5A). The "*Stop-*

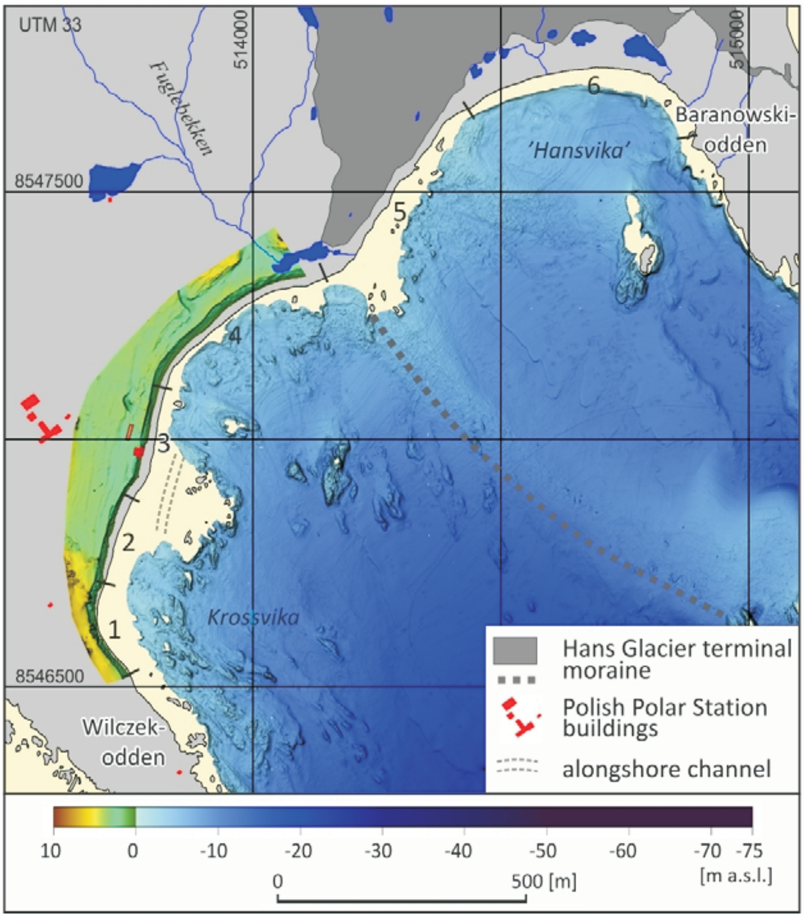

Fig. 4. Seabed topography of Isbjørnhamna and the location of shore sections 1–6. White area – bottom out of reach of echo sounding observations (source: depth data from The Norwegian Hydrographic Service with permit number 13/G722).

-*Go*” differential method was applied (DGPS, postprocessing). Series of point data were transformed to the UTM system (33 N, WGS 84). An accuracy of ± 5–10 cm was achieved. TOPCON GLS-1500 scanner was used to derive a point cloud to a range of 150 m and a stated accuracy of ± 6 mm. TLS data provided the basis for generating a raster map (DEM) with a basic field of 0.8 m. Laser scanning was performed only for sections 1–4 (see Fig. 4).

The comparison of aerial images and processing of field data was performed using ArcGIS software followin8g the approach used by Zagórski (2011) for coastal change study in Bellsund, western Spitsbergen or Brown *et al.* (2003) in Elson Lagoon, Alaska. The studied coastal zone was divided into 25 m wide sections resulting in 86 segments in total. For each section, the net area balance was calculated (P_n), considering the position of shoreline in particular measurement terms (Fig. 4):

Fig. 5. The sections of Isbjørnhamna coast: section 1 (**A**), section 2 (**B**), section 3 (**C**), section 4 (**D**), section 5 (**E**) and section 6 (**F**). Photo: P. Zagórski (A, B, C, D, F) and J. Kwaczyński (E).

$$P_n = P_{na} - P_{nb}$$

where: P_{na} – increase in coastal section area [m^2] in a given period associated with landward migration of shoreline, P_{nb} – decrease in coastal section area [m^2] in a given period associated with seaward migration of shoreline.

The mean value of shoreline shift P_n (landward or seaward) obtained from the formula was divided by 25, resulting in the mean value of shoreline shift (landward or seaward) for a given section in a given time period. The method was also applied to calculate the total area balance (P) for the respective sections (Table 1). Using this approach, areas with the highest and lowest dynamics of changes in particular periods were determined.

Table 1

Net area balance and shoreline changes occurring at the Isbjørnhamna coast in each period – for section locations refer to Fig. 6.

Section	Length of section [m]	Area [m^2]			Mean shoreline change		Maximum shoreline change	
		decrease	increase	balance	[m]	[m a^{-1}]	decrease	increase
1960–1990								
1	320	-182.1	–	-182.1	-0.6	-0.02	-1.31	–
2	130	-315.7	–	-315.7	-2.4	-0.08	-3.53	–
3	200	-1043.6	–	-1043.6	-5.2	-0.17	-8.43	–
4	530	-42085	–	-4208.5	-7.9	-0.26	-13.86	–
5	370	-2044.7	68.7	-1976.1	-5.3	-0.18	-13.75	1.81
6	600	-3772.6	2004.5	-1768.1	-2.9	-0.10	-46.18	11.64
Total	2150	-17134.9	2073.2	-15061.7	-7.0	-0.23	-46.18	11.64
1990–2011								
1	320	-230.0	–	-230.0	-0.7	-0.03	-1.55	–
2	130	-349.77	–	-349.8	-2.7	-0.13	-5.19	–
3	200	-1403.94	–	-1403.9	-7.0	-0.33	-9.49	–
4	530	-4518.11	–	-4518.1	-8.5	-0.40	-17.82	–
5	370	-3459.8	–	-3459.8	-9.4	-0.45	-28.59	–
6	600	-300.7	4165.8	3865.1	6.4	0.30	-5.89	13.18
Total	2150	-16534.1	4165.8	-12368.3	-5.8	-0.28	-28.59	13.18
1960–2011								
1	320	-411.6	–	-411.6	-1.3	-0.03	-2.44	–
2	130	-658.9	–	-658.9	-5.1	-0.10	-8.72	–
3	200	-2447.16	–	-2447.2	-12.2	-0.24	-16.11	–
4	530	-8720.02	–	-8720.0	-16.5	-0.32	-21.44	–
5	370	-5452.9	0.7	-5452.3	-14.7	-0.29	-40.56	–
6	600	-2159.2	3554.4	1395.2	2.1	0.04	-44.92	20.30
Total	2150	-31675.9	3555.1	-28120.8	-13.1	-0.26	-44.92	20.30

In addition to shoreline position data, the classification of the coastal types found at Isbjørnhamna has been examined. Based on site investigation, supplemented with bathymetric data, the following types of coast have been distinguished: abrasive, accumulative, and complex.

Results

Characteristics of Isbjørnhamna coastlines. — The coast at Isbjørnhamna includes several distinct, geomorphologically determined sections. Changes in the coastline of the marginal rocky sections have not been analysed due to their high stability and measurement difficulties. Beyond the rocky margins, 6 sections have been distinguished with the following character: (1) abrasive – at Krossvika; (2, 3, 4) abrasive/transport/accumulative – in the area of the PPS Hornsund; (5) abrasive-transport – in the zone of moraines at Hansbreen; and (6) accumulative – at Hansvika (Fig. 4). This zonation has permitted the detailed analysis of fragments of the coast characteristic of key geomorphological features.

Section 1 is oriented SE-NW and has a length of 320 m. It represents the southern fragment of the investigated coast and is located at the base of Wilczekodden (Krossvika). The coastline here is characterised by cliffs formed in uplifted (4.5–6.0 m a.s.l) marine terrace deposits (Figs 4, 5A). The cliffs are comprised of the Ariekammen Formation represented by gneisses, sandstones, mudstones and limestones with veins of quartz (marble liners) (Karczewski *et al.* 1981; Pękala 1989; Birkenmajer 1990), and are capped by a 1.0–0.5 m thick gravel layer. The cliffs form a rugged and irregular coastline, and are fronted by a 60–80 m wide rocky shore platform with numerous skerries.

The coastline at section 2 has a SSW-NNE orientation and a length of 130 m. It is located south of the PPS (Figs 4, 5B). The coast here is shaped by the interaction of marine processes and uplift, which forms a stepped series of gravel deposits (1.5–2.0 m thick) resulting in a 4.5–6.0 m high coastal slope (Karczerwski *et al.*1981; Pękala 1989). The base of the slope transitions into a rocky platform rich in skerries. At its top, a sub-horizontal terrace shows traces of tidal influence over a width of up to 20–25 m.

This section is highly transformed by human activity in the form of rock armour defending the "Banachowka" store and consequently it protrudes seawards slightly from adjacent sections. The beach and uplifted marine terraces are further altered by the operation of heavy machines and boats. The foreshore zone contains skerries that extend almost 150 m seawards and develop ridges parallel to the shore. A shore-parallel channel extends between the shore and the nearest ridge (Fig. 4).

Section 4 is oriented SW-NE and has a length of 530 m. The section is shaped by an interacting factors including fluvial, fluvioglacial, and coastal processes (Figs 4, 5D). An extensive gravel storm ridge, reaching widths up to 50 m, is the dominant feature of this section. In the southern part of the section, the storm ridge transitions into a flat surface enriched with weakly-preserved relict storm ridges and inactive channels generated by a stream draining the Fuglebekken catchment. In the northern part of the section, the storm ridge is truncated by an alluvial fan, which limits the outflow of the stream waters and produces a small lake in spring and early summer before lake water can seep through the thawed storm ridge.

Section 5 has a SW-NE strike and a length of 370 m. Coastal processes erode and redistribute sediments from the Hansbreen ice-cored moraine, which developed during the Little Ice Age (Karczewski *et al.* 1981; Pękala 1989) (Figs 4, 5E).

Section 6 has a W-E orientation and a length of 600 m. It covers the arcuate bay (local name: Hansvika) between the Hansbreen ice-cored moraine complex and the Baranowski Peninsula. The area is covered with moraine deposits reworked by proglacial streams (Pękala 1989; Jania 1998; Karczewski *et al*. 2003). The coast here is accumulating with a well-developed storm ridge (Figs 4, 5F). Small lakes develop periodically in the gravel-dominated beach ridge and the foreshore is scattered with sparse skerries on the shore platform.

Seabed morphology. — The seabed relief at Isbjørnhamna has a direct effect on morphogenetic processes shaping the coastal zone. The shore platform extends to a depth of up to 10–15 m, steeply sloping directly to the main channel of Hornsund. It is divided by the ridge of the terminal moraine of Hansbreen, which extends underwater adjacent to the coastline until it emerges in section 3 (Jania 1998) (Figs 4, 5). Hansvika (sections 5 and 6), the water body between the moraine and Baranowskiodden, has depth slightly exceeding 10 m, the seabed consisting predominantly of fine-grained sediments. However, numerous boulders and skerries occur to the west, along the line of outwash from an ice-moraine rampart.

According to Giżejewski *et al.* (2010), in the western part of the Isbjørnhamna seabed (between Wilczekodden and underwater moraine) the sediment cover is discontinuous and occurs only in depressions. In this part of Isbjørnhamna, a wide, *ca*. 200 m, zone of skerries also occurs crossing uneven, lithologically controlled terrain. Along Wilczekodden (Krossvika; Fig. 4), compact belts of skerries run parallel to the shoreline. Further north, submerged rocks are located at a distance of several tens of metres from the shore. A channel parallels the shore with orientation SSE-NNW and mean depth of approximately 1 m (Fig. 4).

Coastal evolution. — Due to the relatively long 30 year period between measurements, it is difficult to determine the dynamics of short-term changes in the shoreline restricting interpretation to the general evolutionary tendencies along the Isbjørnhamna coast over a 51 year period. The first epoch of change, 1960–1990, was generally a period of coastal emergence and transition from glacial to marine and subaerial process controls. This transition was particularly visible in the area of Hansvika (sections 5, 6; Fig. 4), where until the mid-1970's, Hansbreen terminated in the sea. During the accelerated retreat of the glacier front, an intensive accumulation of glacial sediments occurred here. In the remaining sections, a negative shore balance, i.e. erosion, was recorded (Figs. 4, 6, 7; Table 1).

The smallest changes were recorded in section 1 (Fig. 6) located on the east side of Wilczekodden, within the Krossvika. The net balance resulted in shore erosion exceeding 180 m^2. This erosion produces a mean section retreat of 0.6 m (-0.02 m a^{-1}). The changes gradually increased northwards (sections 2–4). In section 3, however, lower shore retreat was recorded in the proximity of PPS building (Fig. 6). For section 4, the calculated mean retreat of the shoreline amounted to almost 8 m (-0.26 m a^{-1}), with a maximum exceeding 13.9 m at the mouth of a stream draining the Fuglebekken catchment during the 1960's.

Smaller changes occurred in section 5, the morainic deposits surrounding Hansbreen. Between 1960 and 1990, the area decrease amounted to almost 2,000

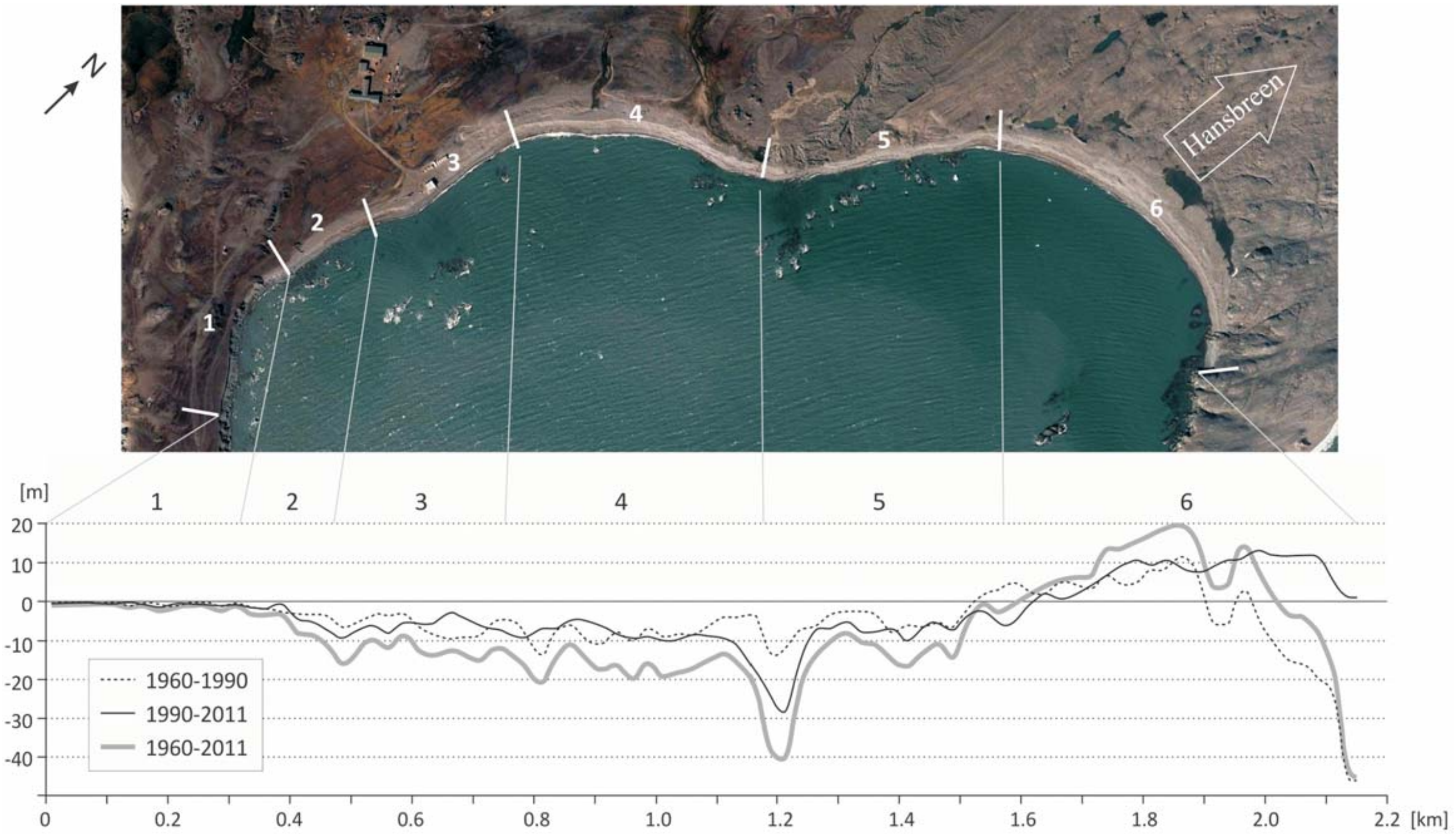

Fig. 6. Shoreline change of Isbjørnhamna coast in years 1960–1990, 1990–2001, 1960–2011 (Background image: Norwegian Polar Institute, Topo Svalbard service, http://toposvalbard.npolar.no).

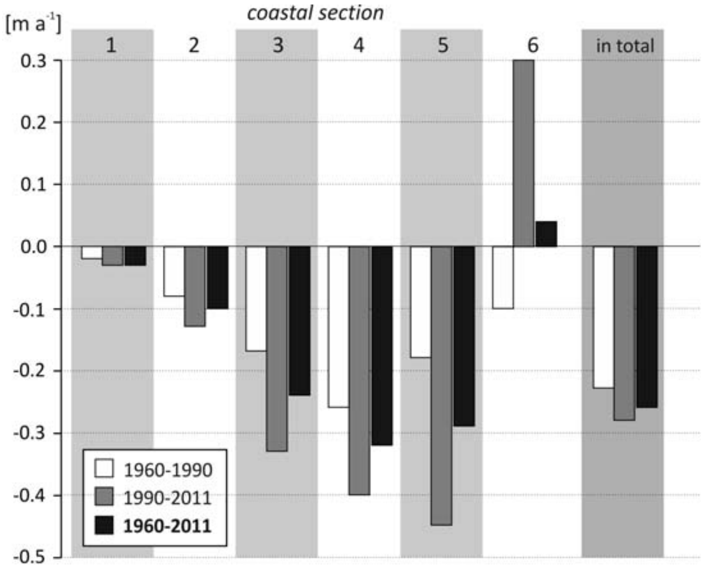

Fig. 7. The mean annual change in the shoreline in separate coastal sections (1–6) of the Isbjørnhamna shoreline.

m^2. This loss is equivalent to more than 5 m (-0.18 m a^{-1}) of retreat, with a maximum exceeding 13.7 m (-0.47 m a^{-1}). In the north-eastern part of the described section, aggradation of the shore by 1.8 m (+0.06 m a^{-1}) occurred. According to archive data, an extension of the moraine reaching several km occurred in the early 1980's.

The greatest changes during the period 1960–1990 were recorded in section 6 (Hansvika). According to the aerial photograph analysis (S60 7418), in 1960 Hansbreen covered almost the entire Baranowski Peninsula and the northern coast of Hansvika. The retreat of Hansbreen in the mid 1970's separated the glacial snout from Hansvika revealing an arcuate bay and producing a maximum retreat of 46.2 m (-1.5 m a^{-1}). To the western end of the section a gravel storm ridge was formed (Fig. 5). Proglacial waters supplied significant amounts of terrigenous sediments to the coastal zone, resulting in aggradation of the shore of more than 11.6 m (+0.38 m a^{-1}). The mean balance for section 6, calculated for period 1960–1990, however, is negative (-1,768 m^2), indicating a mean retreat of the shoreline by 2.7 m (-0.1 m a^{-1}).

With the exception of the bay at Hansvika, an acceleration in the rate of abrasion has been recorded during the period 1990–2011 (Figs 4, 6, 7; Table 1). Even in section 1, where the shore is relatively resistant to the effects of marine processes, the shore area decreased by an average of 230 m^2, equivalent to a retreat rate of -0.03 m a^{-1}.

Exceptional changes occurred in sections 2, 3, and 4, which has particular implications for the functioning of the PPS. An 8.5 m (-0.04 m a^{-1}) retreat of the gravel ridge in section 4 took place, with a maximum retreat of almost 18 m (-0.85 m a^{-1}) (Fig. 6). This resulted in a significant reduction in the number of lagoons around the Hansbreen moraine deposits. The most significant erosion that occurred between 1990 and 2011 was observed in section 5. The morainic "cape" exposed in its southern part retreated by a mean of 9.4 m (-0.45 m a^{-1}), with a maximum of 28.6 m (-1.36 m a^{-1}). Considerable reductions were also detected in the area of the gravel ridges. By contrast, section 6 recorded aggradation of 3,865 m^2, resulting in the seaward shift of the shoreline by a mean distance of 6.4 m (+0.3 m a^{-1}) and a maximum of 13.2 m (+0.63 m a^{-1}).

Discussion

Whereas shoreline changes in Svalbard were typically studied along low-energy or transitional shores located in inner-fjord settings (*e.g.* Strzelecki 2011; Zagórski 2011; Zagórski *et al.* 2012, 2013; Sessford *et al.* 2015b; Strzelecki *et al.* 2015), the coast of Isbjørnhamna is a high-energy coast. Low-energy shores are largely developed by terrigenous processes. Oceanic swell reaches transitional shores less frequently than high-energy ones, but it still plays a considerable role in shoreline changes.

The analysis of shoreline changes of Isbjørnhamna over the 51 year period from 1960 to 2011 reveals erosion (particularly in sections 1–5, Fig. 6) amounting to a shore area reduction of more than 31,600 m^2. Simultaneously, in section 6, from the 1970's, aggradation of the shore occurred by more than 3,500 m^2 illustrating the local complexity of shore changes in close proximity to retreating glaciers. The general balance of changes in the study area of the shore is negative and amounts to a loss of more than 28,000 m^2.

The lowest rate of shoreline retreat was recorded in section at 1–0.02 m a^{-1}. The cliffed shore here is rocky making it relatively resistant to abrasion. The section constitutes part of the eastern shore of the Wilczekodden Peninsula striking. The adjacent cape protects section 1 and diffracts waves so that they move parallel to (or even away from) the shore, minimising wave erosion. The wide zone of skerries also protects the shore from short and low waves from the middle of the fjord, while glacier ice deposited in the swash zone limits waves during easterly winds (Fig. 3). The surface of the terrace directly adjacent to the cliff edge shows no evidence of storm waves (Figs 2, 4, 5A).

The concentrically propagating diffracted waves progress north-, and eastwards along the curved shore topography (Fig. 2). The increasing tidal energy available is manifested in the increasing height of the storm ridge, which increases from 3.5 m in section 2, to 4 m in section 3, and 5 m in section 4. The changes detected in the shore also increase in the same direction. The highest mean decrease was recorded within sections 4 and 5, retreating by 16.5 m (0.27 m a^{-1}) and 14.7 m (0.29 m a^{-1}), respectively. In section 5, the maximum values of reduction of the coastal zone occurred on the moraine cape (40.56 m or 0.29 m a^{-1}) where the intensity of erosion was driven by the deglaciation of the ice core of the ice-moraine rampart of Hansbreen. A maximum value of shore reduction (approximately 45 m) was observed in section 6, where the deglaciation of the terminus of Hansbreen initially occurred. The maximum retreat of the shoreline was measured in section 4, amounting to 21.44 m (Table 1).

The presence and abundance of skerries strongly influences shore erosion. In section 2 and at the beginning of section 3, skerries constitute compact reefs, emerging during low tide. They largely attenuate wave energy and the water flowing through them drives a north easterly current in an alongshore channel. This outflow can amplify waves in sections 4 and 5, where scattered skerries occur and the waves approach perpendicular to the shoreline (Fig. 2).

The longshore current causes eastward transport of sediments up to section 6. (Hansvika; Fig. 4). Episodic westerly waves diffract around Wilczekodden cape causing diagonal wave attack along the eastern shore of Hansvika and the western shore of Baranowskiodden. Westerly waves suppress longshore currents in the Hansvika resulting in sediment accumulation, shore aggradation, and storm ridge formation. Sediment redistribution over the seabed occurs under the operation of a near-bottom compensation currents evidenced by series of ripplemarks in channel-like depressions at Isbjørnhamna (Fig. 4), as well as by Acoustic Doppler Current Profiler measurements (ADCP RDI Workhorse 600) carried out in summer 2013, where discharges of approximately 7–9 cm s^{-1} were recorded.

The location of the shoreline of Isbjørnhamna in 1960, 1990, and 2011 reflects systematic retreat over the period. The trend is consistent for a major part of the coast, with the exception of section 6. The observations suggest that the erosion process is temporally variable, with higher rates of erosion occurring in the autumn-winter season 2007/2008, for example, resulting from later than usual cooling (Styszyńska 2009; Rodzik and Zagórski 2009). In years subject to the early appearance and delayed melting of ice cover in the bay, in addition to the advanced development of shore ice, as occurred in 1992 and 1993, the shore was not destroyed but aggraded from the foreshore (Rodzik and Wiktorowicz 1996). Therefore, the tendency for erosion or aggradation depends on the degree of ice cover in coastal waters and on the shore and on the intensification of autumn-winter storms.

The mean annual intensity of shore retreat in the years 1990–2011 increased significantly relative to the period 1960–1990. In the 21st century, the persistence of sea ice cover in the bay has been considerably reduced, both regarding marine allochthonic as well as autochthonic ice and glacial ice (Styszyńska 2009). The persistence of ice on the shore has also decreased (Rodzik and Zagórski 2009). In the first decade of the 21st century, a change in the conditions of ice cover development was observed in the area of Hornsund. This was largely controlled by thermal conditions. The minimum temperatures occurred in March. The winter seasons 2005/2006, 2007/2008, and 2009/2010 were subject to particularly warm early winter months (Styszyńska and Rozwadowska 2008; Styszyńska 2009; Kru-

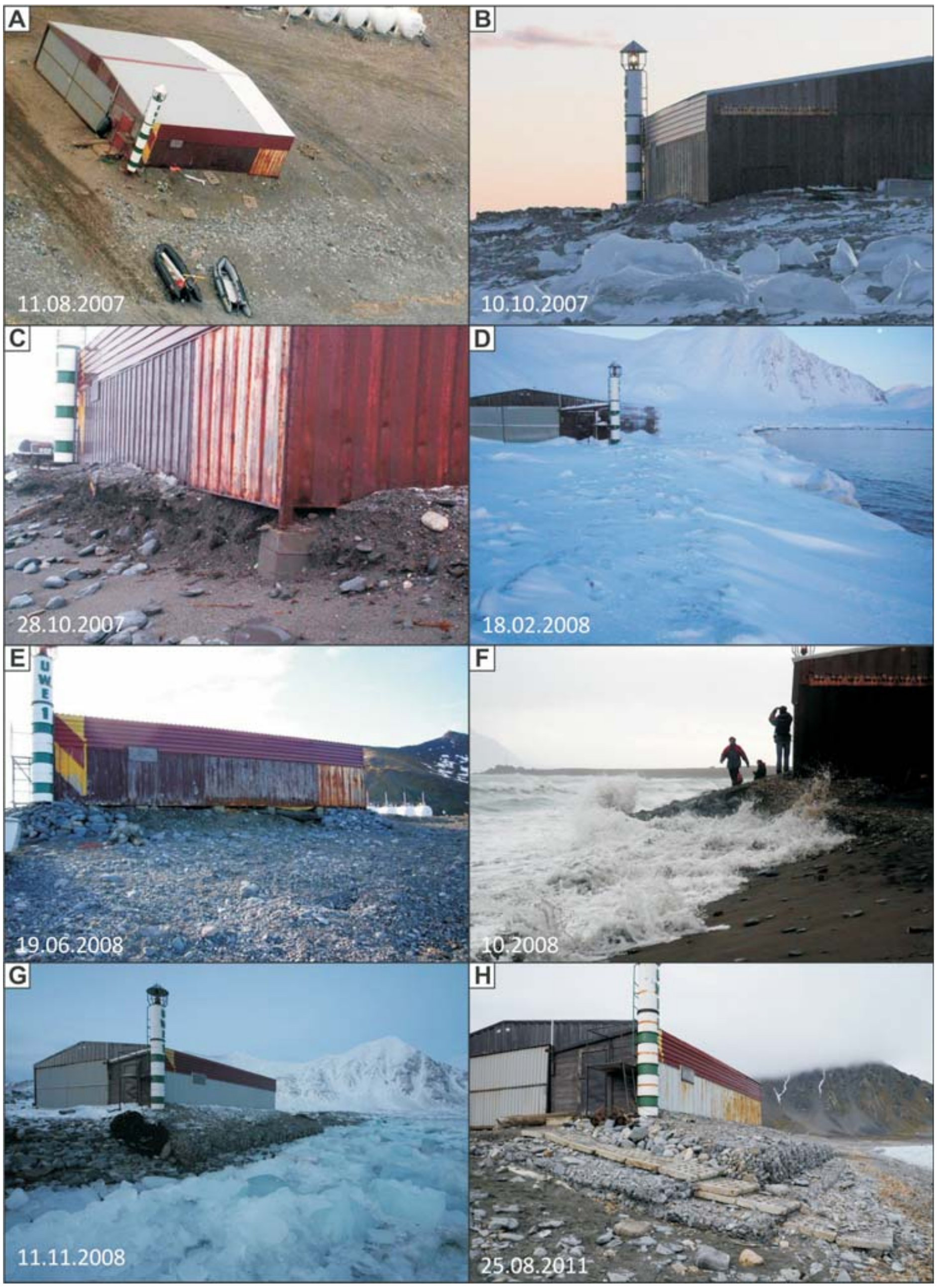

Fig. 8. The effects of coastal erosion processes in the area of harbour building of Polish Polar Station – "Banachówka" and methods of its protection. Photo: M. Błaszczyk archive (A–D, F), J. Kwaczyński (E, G), P. Zagórski (H).

szewski 2011). The shift of the thermal minimum to the end of winter is typical of the 21st century and suggests the transition to an increasingly oceanic climate in

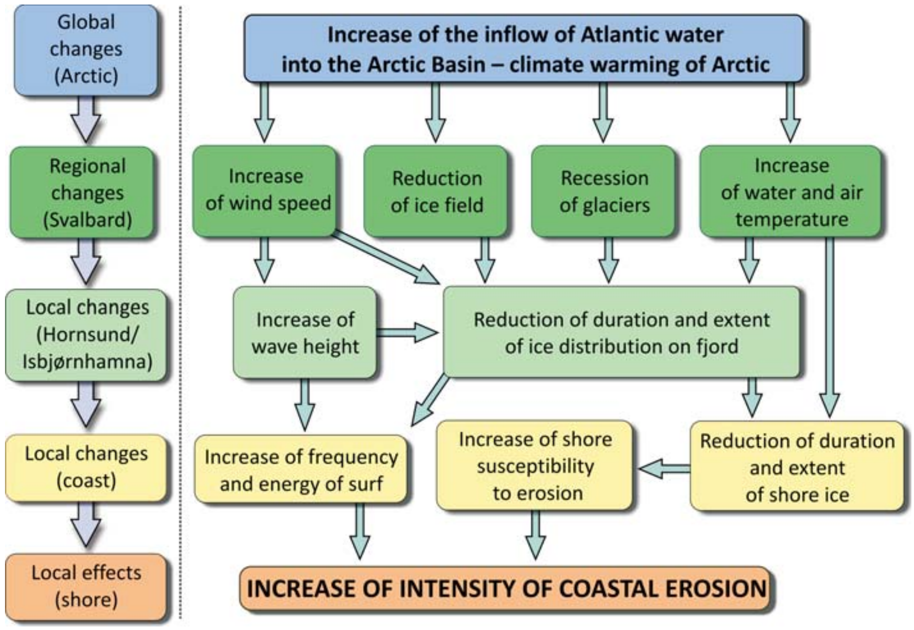

Fig. 9. Oceanographic/climate/glacial controls of increased coastal erosion in Isbjørnhamna (Hornsund).

SW Spitsbergen. The transport of energy from the north Atlantic to the Arctic, mainly by the Norwegian Current and the WSC, has intensified in over recent decades and resulted in a reduced range of the polar ice pack (Walczowski and Piechura 2011). In the season 2007/2008, the smallest range of winter ice was observed at the coast of Spitsbergen (Fig. 1). In Isbjørnhamna, the waters and shore of the bay were still not covered with sea ice in January 2008 (J. Kwaczyński, personal information), and in the first months of winter the water temperature remained positive (Styszyńska 2009). Storm waves freely attacked the initially accumulative shore, causing intensive abrasion and damage to one of the buildings of the PPS. Consequently, the shore was then protected here with gabions and then concrete slabs (Fig. 8). A considerable reduction in the tidal zone was observed, as well as an increase in its inclination and significant abrasion of the rock platform.

The increasingly dynamic erosion processes identified in this study demonstrate the sensitivity of Arctic coasts to global climatic shifts. The mechanism of warming of the Arctic is not the subject of this study, but its effect on the state of the ice cover on water and shore should be emphasised. A complicated cause-and-effect relationship between seasonal ice accumulations and degradation of the shore of Isbjørnhamna is presented in Fig. 9. It suggests that the most considerable changes are associated with the degree of sea ice cover on the waters and shore of the bay. Increasingly weak sea ice cover contributes to accelerated degradation of the shore. Ice cover on the shore directly determines whether the shore is protected or exposed to erosion by waves.

Conclusions

We draw the following conclusions from this study:

- Over the last 50 years the Isbjørnhamna coast has been dominated by erosion resulting in a shore area reduction of more than 31,600 m^2. The mean shoreline change is -13.1 m (-0.26 m a^{-1}). Erosional processes threaten the Polish Polar Station infrastructure and may damage of one of the storage buildings in nearby future.
- Isbjørnhamna shoreline changes are determined by the oceanic wave action in the diverse local conditions: exposure of the shore to diffraction waves, resistance of the shore to abrasion, configuration of the bottom of the bay, and the sea ice cover on its waters and shore. The tendency for abrasion and accumulation may change depending on changes in the configuration of the shore, particularly in the area of degraded ice cliffs or ice-moraine ramparts.
- Changes in the shoreline occur in steps, and result from the intensification of storms in periods of positive air temperature anomalies and lack of sea ice cover on the coastal waters and the shore. The tendency for abrasion or accumulation may change from year to year, depending on the ice cover on the coastal waters and the shore.
- The development tendencies in particular years are determined by the sea ice cover in autumn and winter months with high frequency of storms, particularly in the last three months of the year (October–December). The sea ice cover on the shore inhibits abrasion, but permits the discharge of sediments from the foreshore zone, and aggradation of the storm ridge.

Authors contribution

P.Z., J.R., M.M., M.C.S. and M.L. designed the study and wrote this manuscript. P.Z. and M.B., performed DGPS measurements, and analysed archival photos and Ortophotomap, M.M. performed bathymetry analysis, A.P., G.K. and A.S. provided climatic and oceanographic context of the study area. A.M. performed laser scanning.

Acknowledgements. — Data compilation for this work was prepared during National Science Centre project No. 2013/09/B/ST10/04141. The fieldwork and data collection was financed by: National Science Centre project No. NN 306 703840 “MORCOAST”, Polish-Norwegian Research Found project No. PNRF-22-AI-1-07 “AWAKE” and the statutory activity of the Institute of Geophysics Polish Academy of Sciences (bathymetry data from The Norwegian Hydrographic Service with permit number 13/G722, meteorological data and sea-ice conditions obtained during all year Polish Polar Expedition to PPS Hornsund). M.C. Strzelecki work is a contribution to the Foundation for Polish Science HOMING PLUS – grant no. 2013-8/12. M.C. Strzelecki is funded also by the National Science Centre FUGA Postdoctoral Fellowship and Foundation for Polish Science START scholarship. We acknowledge the staff of Polish Polar

Station in Hornsund for help during fieldwork in summer 2011. We thank the anonymous reviewer and Wiesław Ziaja for their very thoughtful and constructive comments which significantly improved this manuscript.

References

ARE F.E. 1988. Thermal abrasion of sea coasts (Part 1). *Polar Geography and Geology* 12 (1): 1–157.

BARNHART K.R., OVEREEM I. and ANDERSON R.S. 2014. The effect of changing sea ice on the vulnerability of Arctic coasts. *The Cryosphere Discuss* 8: 2277–2329.

BESZCZYNSKA-MÖLLER A., FAHRBACH E., SCHAUER U. and HANSEN E. 2012. Variability in Atlantic water temperature and transport at the entrance to the Arctic Ocean, 1997–2010. *ICES Journal of Marine Science*: doi:10.1093/icesjms/fss056.

BIRKENMAJER K. 1958. Preliminary report on the raised marine features in Hornsund, Vestsspitsbergen. *Bulletin de l'Academie Polonaise des Sciences, Série des Sciences Chimiques, Géologiques et Géographiques* 6 (2): 143–150.

BIRKENMAJER K. 1990. *Geology of the Hornsund area, Spitsbergen. Geological map 1:75,000, with explanations*. Polish Academy of Sciences, Committee on Polar Research, and Silesian University, Katowice: 1–42 (+ map).

BŁASZCZYK M., JANIA J.A. and KOLONDRA L. 2013. Fluctuations of tidewater glaciers in Hornsund Fjord (Southern Svalbard) since the beginning of the 20th century. *Polish Polar Research* 3 (4): 327–352.

BROWN J., JORGENSON T., SMITH O. and LEE W. 2003. Long-term rates of erosion and carbon input, Elson Lagoon, Barrow, Alaska. *In*: M. Phillips, S.M. Springman and L.U. Arenson (eds) *Proceedings, 8th International Conference on Permafrost, 21–25 July 2003*. Balkema Publishers, Zurich: 101–106.

COTTIER F.R., NILSEN F., SKOGSETH R., TVERBERG V., SKARDHAMAR J. and SVENDSEN H. 2010. Arctic fjords: a review of the oceanographic environment and dominant physical processes. *In*: J.A. Howe, W.E.N. Austin, M. Forwick and M. Paetzel (eds) Fjord systems and archives. *Geological Society, London, Special Publications* 344: 35–50.

FLORCZYK I. and LATAŁA A. 1989. The phytobenthos of the Hornsund fiord, SW Spitsbergen. *Polar Research* 7: 29–41.

FORBES D.L., RACHOLD V., KREMER H. and LANTUIT H. (eds) 2011. State of the Arctic Coast 2010 – Scientific Review and Outlook. *International Arctic Science Committee, Land-Ocean Interactions in the Coastal Zone, Arctic Monitoring and Assessment Programme*. International Permafrost Association, Helmholtz-Zentrum-Geesthacht, Germany: 178 pp.

GIŻEJEWSKI J. and RUDOWSKI S. 1994. Shore profile development at Wilczekodden, Hornsund, Spitsbergen. *In*: S.M. Zalewski (ed.) *21st International Polar Symposium, Warszawa*: 117–122.

GIŻEJEWSKI J., MOSKALIK M. and CIEPŁY M. 2010. Bathymetric map and morphology of the bottom of Isbjornhamna (Hornsund, Svalbard). *In*: M. Grabowski, K. Pabis and A. Konopacka (eds) *XXXIII Sympozjum Polarne. Nauka Polska w Międzynarodowym Roku Polarnym 2007–2009. Abstrakty,* Sosnowiec: 29 (in Polish).

GÖRLICH K. and STEPKO W. 1992. Hydrological phenomena related to sea-ice cover formation and presence in Hornsund, Spitsbergen. *In*: K.W. Opaliński and R.Z. Klekowski (eds) *Landscape, Life World and Man in High Arctic*. Institute of Ecology PAS Publishing Office, Warsaw: 83–92.

INALL M.E. and GILLIBRAND P.A. 2010. The physics of mid-latitude fjords: a review. *In*: J.A. Howe, W.E.N. Austin, M. Forwick and M. Paetzel (eds) Fjord systems and archives. *Geological Society, London, Special Publications* 344: 17–33.

JAHN A. 1961. Quantitative analysis of some periglacial processes in Spitsbergen. *Zeszyty Naukowe Uniwersytet Wrocławski, seria B* 5: 1–34.

JAHN A. 1968. Raised shore lines and terraces at Hornsund and postglacial vertical movements on Spitsbergen. *Polish Spitsbergen Expeditions 1957–1960*. PAS, III IGY/IGC Committee, Warsaw: 173–176.

JAHN A. 1977. Periglacial forms produced by shore ice at Hornsund (Spitsbergen). *Spitsbergen Expeditions II, Acta Universitatis Wratislaviensis* 387: 19–29.

JANIA J. 1998. The dynamics of Hans Glacier (Spitsbergen, Svalbard) and selected elements of relief in its forefield. Relief and Quaternary sediments of contemporary areas and Pleistocene glaciation in the Northern Hemisphere. UAM. *Seria Geografia* 58: 81–96 (in Polish).

KARCZEWSKI A., KOSTRZEWSKI A. and MARKS L. 1981. Raised marine terraces in the Hornsund area (northern part) Spitsbergen. *Polish Polar Research* 2: 39–50.

KARCZEWSKI A., RACHLEWICZ G. and SZCZUCIŃSKI W. 2003. Sediment textures in contemporary glacigenic environments with examples from Hansbreen, southern Spitsbergen. *Geologos* 6: 111–131.

KOLONDRA L. 2003. *Polish polar station and surrounding areas, Spitsbergen*. *Orthophotomap 1:5 000*. Katowice, unpublished.

KRUSZEWSKI G. 2010. Ice conditions in Hornsund (Spitsbergen) during winter season 2008–2009. *Problemy Klimatologii Polarnej* 20: 187–196 (in Polish).

KRUSZEWSKI G. 2011. Ice conditions in Hornsund (Spitsbergen) during winter season 2009–2010 (SW Spitsbergen). *Problemy Klimatologii Polarnej* 21: 229–239 (in Polish).

LAMBERT S.J. 2004. Changes in winter cyclone frequencies and strengths in transient enhanced greenhouse warming simulations using two coupled climate models. *Atmosphere-Ocean* 42 (3): 173–181.

LANTUIT H., OVERDUIN P.P., COUTURE N., WETTERICH S., ARE F., ATKINSON D., BROWN J., CHERKASHOV G., DROZDOV D., FORBES D., GRAVES-GAYLORD A., GRIGORIEV M., HUBBERTEN H.W., JORDAN J., JORGENSON T., ØDEGÅRD R.S., OGORODOV S., POLLARD W., RACHOLD V., SEDENKO S., SOLOMON S., STEENHUISEN F., STRELETSKAYA I. and VASILIEV A. 2012. The Arctic Coastal Dynamics database. A new classification scheme and statistics on arctic permafrost coastlines. *Estuaries and Coasts* 35: 383–400.

MARSZ A.A. and STYSZYŃSKA A. (eds) 2013. *Climate and Climate Change at Hornsund, Svalbard*. The publishing house of Gdynia Maritime University, Gdynia: 402 pp.

OVERDUIN P.P., STRZELECKI M.C., GRIGORIEV M.N., COUTURE N., LANTUIT H., ST-HILAIRE-GRAVEL D., GÜNTHER F. and WETTERICH S. 2014. Coastal changes in the Arctic. *Geological Society, London, Special Publications* 388: 103–129.

PĘKALA K. 1989. Quaternary deposits of the Hans Glacier forefield (Hornsund, Spitsbergen). *In*: J. Repelowska-Pękalowa and K. Pękala (eds) *Wyprawy Geograficzne na Spitsbergen*. UMCS Press, Lublin: 191–204 (in Polish).

PIECHURA J. and WALCZOWSKI W. 2009. Warming of the West Spitsbergen Current and sea ice north of Svalbard. *Oceanologia* 51 (2): 147–164.

RODZIK J. and WIKTOROWICZ S. 1996. Shore ice of Hornsund Fiord in the area of the Polish Polar Station in Spitsbergen during the 1992/1993 winter. *In*: J. Repelowska-Pękalowa and K. Pękala (eds) *Wyprawy Geograficzne na Spitsbergen*. UMCS Press, Lublin: 191–195.

RODZIK J. and ZAGÓRSKI P. 2009. Shore ice and its influence on development of the shores of south-western Spitsbergen. *Oceanological and Hydrobiological Studies* 38 Supplement 1: 163–180.

SESSFORD E.G., BÆVERFORD M.G. and HORMES A. 2015a. Terrestrial processes affecting unlithified coastal erosion disparities in central fjords of Svalbard. *Polar Research* 34: 24122.

SESSFORD E.G., STRZELECKI M.C. and HORMES A. 2015b. Reconstruction of Holocene patterns of change in a High Arctic coastal landscape, Southern Sassenfjorden, Svalbard. *Geomorphology* 234: 98–107.

SIWIECKI R. and SWERPEL S. 1979. Oceanographical investigations in Hornsund, 1974–1975. *Oceanografia* 6: 45–58.

SKARDHAMAR J. and SVENDSEN H. 2010. Short-term hydrographic variability in a stratified Arctic fjord. *In*: J.A. Howe, W.E.N. Austin, M. Forwick and M. Paetzel (eds) Fjord systems and archives. *Geological Society, London, Special Publications* 344: 51–60.

STRZELECKI M.C. 2011. Schmidt hammer tests across a recently deglacierized rocky coastal zone in Spitsbergen – is there a "coastal amplification" of rock weathering in polar climates? *Polish Polar Research* 32: 239–252.

STRZELECKI M.C., MAŁECKI J. and ZAGÓRSKI P. 2015. The Influence of Recent Deglaciation and Associated Sediment Flux on the Functioning of Polar Coastal Zone – Northern Petuniabukta, Svalbard. *In*: M. Maanan and M. Robin (eds) Sediment Fluxes on Coastal Areas. *Coastal Research Library* 10: 23–45.

STYSZYŃSKA A. 2009. Ice condition in Hornsund and its foreshore (SW Spitsbergen) during winter season 2007/2008. *Problemy Klimatologii Polarnej* 19: 247–267 (in Polish).

STYSZYŃSKA A. and ROZWADOWSKA A. 2008. Ice condition in Hornsund and its foreshore (SW Spitsbergen) during winter season 2006/2007. *Problemy Klimatologii Polarnej* 18: 141–160 (in Polish).

SVENDSEN H., BESZCZYNSKA-MÖLLER A., HAGEN J.O., LEFAUCONNIER B., TVERBERG V., GERLAND S., ØRBÆK J.B., BISCHOF K., PAPUCCI C., ZAJĄCZKOWSKI M., AZZOLINI R., BRULAND O., WIENCKE Ch., WINTHER J.G. and DALLMANN W. 2002. The physical environment of Kongsfjorden – Krossfjorden, an Arctic fjord system in Svalbard. *Polar Research* 21 (1): 133–166.

URBAN-MALINGA B., DRGAS A., AMERYK A. and TATAREK A. 2009. Meiofaunal (re)colonization of the Arctic intertidal (Hornsund, Spitsbergen) after ice melting: role of wrack deposition. *Polar Biology* 32: 243–252.

WALCZOWSKI W. and PIECHURA J. 2011. Influence of the West Spitsbergen Current on the local climate. *International Journal of Climatology* 31 (7): 1088–1093.

WALCZOWSKi W., PIECHURA J., GOSZCZKO I. and WIECZOREK P. 2012. Changes in Atlantic water properties: an important factor in the European Arctic marine climate. *ICES Journal of Marine Science* 69 (5): 864–869.

WĘSŁAWSKI J.M., WIKTOR J., ZAJĄCZKOWSKI M. and SWERPEL S. 1993. Intertidal zone of Svalbard, macroorganism distribution and biomass. *Polar Biology* 13: 73–79.

WOBUS F., SHAPIRO G.I. HUTHNANCE J.M., MAQUEDA M.A.M. and AKSENOV Y. 2013. Tidally induced lateral dispersion of the Storfjorden overflow plume. *Ocean Science* 9: 885–899.

ZAGÓRSKI P. 2011. The shoreline dynamic of Calypsostranda (NW Wedel Jarlsberg Land, Svalbard) during the last century. *Polish Polar Research* 32 (1): 67–99.

ZAGÓRSKI P., GAJEK G. and DEMCZUK P. 2012. The influence of glacier systems of polar catchments on functioning of the coastal zone (Recherchefjorden, Svalbard). *Zeitschrift für Geomorphologie* 56 (Supplement 1): 101–122.

ZAGÓRSKI P., RODZIK J. and STRZELECKI M.C. 2013. Coastal geomorphology. *In*: P. Zagórski, M. Harasimiuk and J. Rodzik (eds) *Geographical environment of NW part of Wedel Jarlsberg Land (Spitsbergen, Svalbard)*. UMCS Press, Lublin: 212–245.

Received 16 June 2015
Accepted 12 October 2015