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Icings and their role as an important element of the cryosphere in High Arctic glacier forefields

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Abstract. This study investigates icings and their role as an important element of the glacier forefields observed in the Kaffiøyra region in Svalbard. The emergence or disappearance of icings is one of the effects of changes observed in the area of a glacier and its catchment in the High Arctic. Icings were observed both in summer and spring in 1996–2015. The main objective was focused on the location and surface changes of the icings, as this is important for their responses to changes which occur across the cryosphere. In the forefields of most glaciers in the Kaffiøyra region, a generally declining trend is observed in the size of icing fields, with only occasional periods in which it increased. During the last five years, they have not been so large as they were in the preceding years. The degradation of High Arctic icings mainly occurs in summer, generally as a result of surface and mechanical ablation. The reach of icings is rather variable and their surface and thickness tend to change year by year, depending on hydrological conditions in the glacier's system. Regardless of the causes of icings' formation, their size, range and reach are related to the intensity of melting during a given season, which is conditioned by the weather, and especially by the winter outflow from a glacier.

Key words:
icings,
glacier,
outflow,
Svalbard,
Arctic

Introduction

The emergence or disappearance of icings is one of the effects of changes observed in the area of a glacier and its catchment in the High Arctic. Their presence is mainly connected with thermal and hydrological processes that occur within the area of a glacier.

Icings from various parts of Svalbard have been described by Liestøl (1976), Baranowski (1982), Åkerman (1982), Pulina (1984), Gokhman (1997), Grześ and Sobota (2000), Bukowska-Jania (2003, 2007), Grześ (2005), Hodgkins et al. (2004), Sobota (2009, 2011) and others. The occurrence of icings in Svalbard is irregular and closely connected with the topography of glacial forefields, but especially with the hydrological and thermal regimes of their glaciers. This has been described in detail in different geomorphological situations by Bukowska-Jania and Szafraniec (2005).

Bukowska-Jania (2003) states that icings are masses of frozen water, developed as layered column ice as a result of consolidation of successive underground or surface water flows in the cold season of the year. Glacial icings are a type of icing formed by water flowing out of a glacier in winter. To complete the classification, Åkerman (1982) identifies some types of icing on Spitsbergen: the first type occurs with groundwater outflows (also associated with pingos), while the second is associated with rivers, and the last with glacial water outflows.

Large icing fields develop every winter in the forefields of a number of Svalbard glaciers (Bælum and Benn 2011). Baranowski (1982) estimated the icing cover at the Werenskioldbreen at 0.5 km^2 and its thickness at 2–4 m. In the forefields of 217 Svalbard glaciers, the icing cover area is estimated to reach 12.3 km^2 (Bukowska-Jania and Szafraniec 2005). In the Bellsund region, the largest icing areas occur in front of the Recherchebreen, Renardbreen and Antoniabreen (up to 2 m thick) and smaller (up to about 1 m) are found in front of the Scottbreen (Bartoszewski 1998).

Icings occur in the forefields of all glaciers in the Kaffiøyra region (Olszewski 1982; Bukowska-Jania 2007; Grześ and Sobota 2000; Sobota 2013, 2014). Icings in the forefield of Kaffiøyra region glaciers were observed in 1938 (Klimaszewski 1960) and every year from 2002 to 2009.

The main source of water in glacial rivers in the High Arctic is melting ice (Bartoszewski 1998; Rachlewicz 2009; Nowak and Hodson 2013; Sobota 2014; Nowak and Sobota 2015). The amount of water carried by streams flowing from a glacier is closely related to the amount of ablation (Sobota 2000; Milner et al. 2009). The vast majority of the volume of the water, as much as 85–90%, outflows from the glacial catchments of the High Arctic during the polar spring and summer (Bartoszewski 1998; Rachlewicz 2009; Sobota 2014). Little runoff is also recorded in winter, as evidenced by frequent icing covers (Grześ and Sobota 2000; Sobota 2011).

The main objective of this study is to analyse icings in the area of Kaffiøyra. To this end, icings in the forefields of most glaciers in the region have been examined, with observations carried out both in summer and from winter to spring. Investigations focused on the location and surface changes of the icings, as this is important for their responses to changes which occur across the cryosphere.

Study area and methods

The Kaffiøyra region with the adjoining Aavatsmarkbreen (75 km^2) and the Dahlbreen (132 km^2), as well as the six glaciers flowing down into the Kaffiøyra, comprise an area of about 310 km^2. It accounts for a mere 12% of the area of Oscar II Land. Mountain chains, valley glaciers and their marginal zones, together with the coastal part of the Kaffiøyra, constitute up to 103 km^2 (Fig. 1).

Seven land-terminating glaciers are located in the Kaffiøyra region (Fig. 1). These include valley glaciers descending down onto the plain: Waldemarbreen, Irenebreen, Elisebreen, Agnorbreen, Eivindbreen, Andreasbreen and Oliver (Table 1).

The fluvial system of the Kaffiøyra region consists of rivers draining individual glaciers' basins. In their catchment areas, rivers often form dense, complex systems of river channels. The individual basins vary in length and number.

The longest river in the Kaffiøyra region is the Waldemar River (about 5.5 km), and the shortest is the Oliver River (about 1 km). Streams are fed mostly by waters from glacial ablation, followed by water from melting permafrost and snow cover melting in the catchment. There are many courses that are only open from time to time during a season. The rivers of the Kaffiøyra region are characterised by highly variable water levels and high discharges (Sobota 2013, 2014).

In the years 1975–2015 the average air temperature during the summer season in the Kaffiøyra region was about 5.0°C, while in the years 1997–2010 it was 5.3°C (Sobota 2013). The increase in the air temperature noted in the Kaffiøyra region (Przybylak et al. 2012; Sobota et al. 2013) is well in accordance with the general trend observed in Svalbard and in many areas of the Arctic (Chylek et al. 2009; Førland et al. 2009; Nordli et al. 2014).

The Kaffiøyra region glaciers have had a negative mass balance in recent years. From 2006 to 2010, the average mass balance of the Kaffiøyra glaciers amounted to -57 cm of the water equivalent (Sobota 2013). In the last five years (2011–2015) the average mass balance was more negative, and was about -112 cm w.e.

The Kaffiøyra glaciers' negative mass balance is reflected in the changes in their surfaces and the location of their fronts. The area occupied by glaciers ending on land in the Kaffiøyra region decreased by an average of about 42% between the time of their maximum advances and 2010 (Sobota 2013).

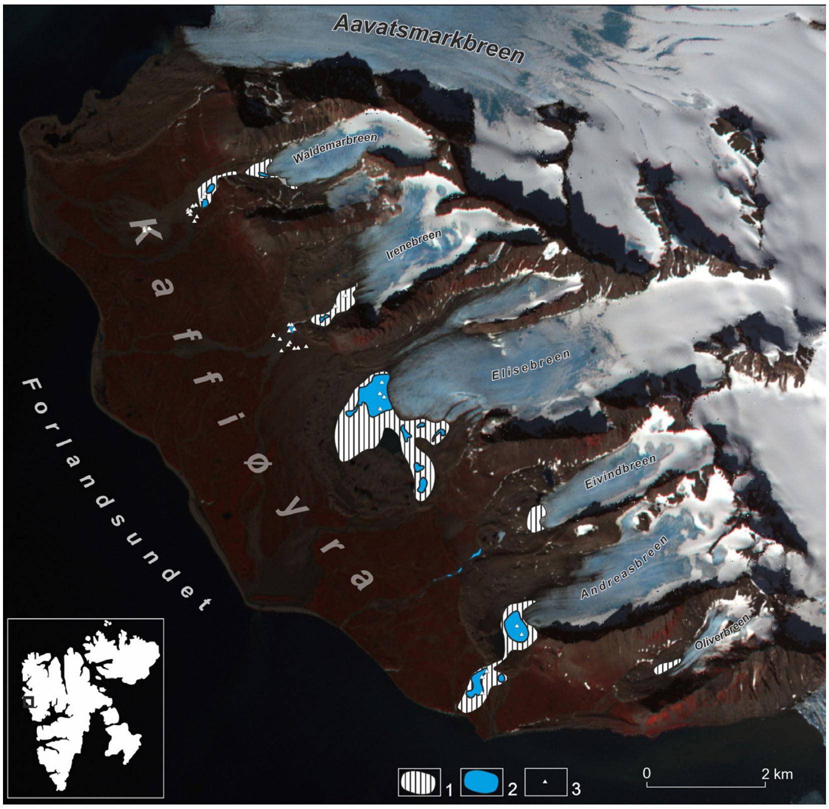

Fig. 1. Location of icings in the Kaffiøyra region: 1 – areas where icings were observed in the selected years (Grześ 2005, modified), 2 – icings in the years 2008–2015, 3 – icing mounds in 2009–2014

Kaffiøyra region glaciers are polythermal – with cold ice and a temperate surface layer – during summer (Sobota 2013). In winter, all of the ice is below the melting point and temperate layers are probably present in basal sections of the glacier. This supposition is supported by the presence of icings in the forefield of glaciers. A similar thermal regime has been reported for other Svalbard glaciers (Jania et al. 1996; Hodgkins et al. 1999; Degard et al. 2007; Willis et al. 2007; Grabiec et al. 2012).

Observations and measurements of icings in the Kaffiøyra region were conducted in the years 1996–2015 in summer and spring. The icing fields and mounds (having a diameter from several centimetres to about 20–30 m and extending clarity above the surface) were located using GPS and through analysis of satellite images. The mid-resolution AS-

Table 1. Summarised data of Kaffiøyra region glaciers and area of icings at their forefields

Glacier name	Geographical coordinates#	Glaciers			Icing area	
		Area	Width	Length	1	2
		(km^2)	(km)	(km)	(km^2)	(km^2)
Waldemarbreen	78.67796° N 12.058421° E	2.40*	0.7–1.3	3.3	0.15	0.03
Irenebreen	78.663574° N 12.119139° E	3.87*	1.0–1.5	3.8	0.19	0.02
Elisebreen$	78.648506° N 12.249668° E	10.09*	1.2–1.8	6.2	1.63	0.37
Eivindbreen	78.63098° N 12.291656° E	1.88**	0.2–0.6	3.2	0.11	0.03
Andreasbreen	78.61461° N 12.290277° E	4.38**	0.8–1.8	3.9	0.72	0.24
Oliverbreen	78.60717° N 12.370010° E	0.81***	0.1–0.7	1.5	0.06	0.00

– after www.placenames.npolar.no; $ – without Agnorbreen; * – area in 2015; ** – area in 2014; *** – area in 2010, 1 – total area where icings were observed in the selected years; 2 – area in the years 2008–2015.

TER was used for determination of icings and position in the selected years. Dowdeswell and Benham (2003) estimated that the error in calculated displacement for the 15 m ASTER data is sub-pixel, within a quarter to half a pixel (3.75–7.5 m).

Each year, photographic evidence was collected, and each summer measurements were taken of the volume of runoff from the Waldemarbreen (Sobota 2014). In some of the years, the measurements also included winter runoffs.

Results

Icings in the forefields of the Kaffiøyra region glaciers were observed every year for the period 1996–2015 (Fig. 1). The largest icings can be found in the forefield of the Elisebreen however, in different years their reach and size varied (Fig. 2).

The icing fields in front of the Irenebreen are not so large, and have become some of the smallest in the region in recent years (Table 1). They primarily occur in the south part of the marginal zone and in the main channel of the river flowing out of the glacier in summer (Fig. 3). The surface area of icing fields in individual seasons was similar, albeit generally decreasing.

A large icing field was found in the forefield of the Andreasbreen in all seasons (Table 1, Fig. 4).

The icings of the Waldemarbreen comprise four characteristic parts: supraglacial, internal, a breach zone and a proglacial part (Fig. 5). Their total surface area was approx. 0.15 km^2. The icings have also varied in terms of surface and reach in recent years. Their area and thickness have been observed to decrease considerably. In the north part of the forefield, a large icing field was observed, whose surface area tended to shrink year by year (Fig. 6). This caused significant changes in the direction of the glacial runoff.

In individual years, icings covered up to 4–5 km^2 of the forefields of the Kaffiøyra glaciers and the largest of them were formed in front of the Elisebreen. Their total surface area was approx. 1.6 km^2 and the thickness reached as much as 7–8 m, as it was in the catchment of the Waldemar River. At the beginning of some recent summer seasons, the ic-

Fig. 2. Icings at the forefield of Elisebreen: 1, 2 – during summer; 3, 4 – during spring. Photo by I. Sobota and A. Tretyn

ings still reached a few metres thick at the glacial breach (Fig. 5).

A complex system of channels is formed within icings. When the water is blocked, the pressure increases and the water intrudes into the snow cover on the surface. If there is a layer of ice in the way, characteristic icing mounds develop (Fig. 7). The structure of an icing mound has been described, for example, by Grześ and Sobota (2000), and Bukowska-Jania (2003).

Snow cover seems to play an important role in the development of icing mounds. The water which flows out of a glacier moves in and on the snow cover until it runs out of energy in sub-zero air temperatures (Grześ 2005). The water, when blocked by snow, can accumulate and flow out under pressure, quickly freezing over. Icing mounds are important for the evaluation of the extent of distribution of an icing, as they usually indicate its maximum reach (Grześ 2005). They occurred in large numbers in the forefields of most of the Kaffiøyra glaciers each year, most often as an end result of subglacial water outflows.

The extent of spatial distribution of icings is determined by the conditions of water migration in the snow cover. Their thickness increases through capillary absorption of water by the snow cover and interception of water from snow falling on the wet surface. From emergence until complete disappearance, icings use under-surface and internal channels. Main runoff routes end with ice uplifts and water outflows onto the surface. The channels trigger subsequent linear degradation of the icings in late spring (Grześ and Sobota 2000). The icing ice forms into peculiar thin columns (needles) which easily fall apart in the degradation phase (Fig. 8).

The winter outflows may occur a few times during one season, thus extending the existing icing fields, including during negative air temperatures (Fig. 9).

Discussion and conclusions

Icings in the area of Kaffiøyra occurred during each spring season of the years 1996–2015 (Fig. 1). Their

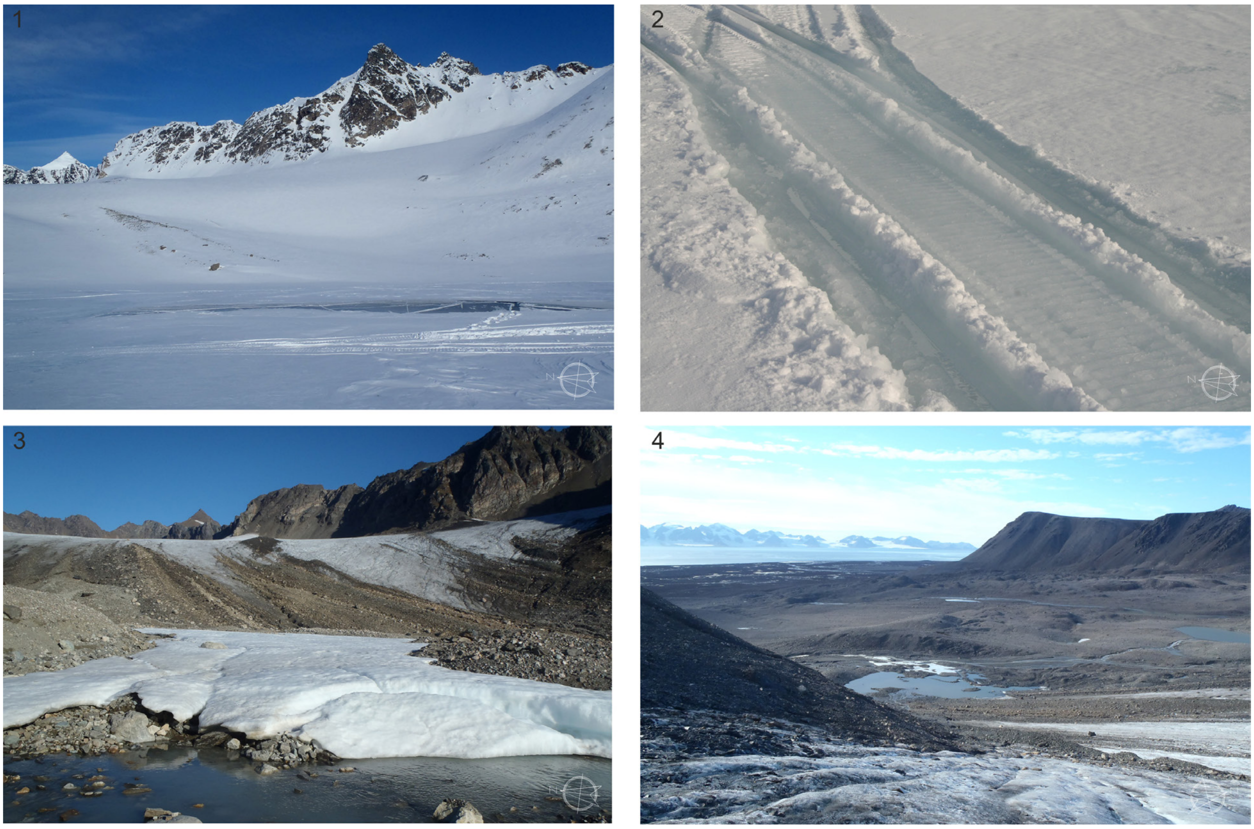

Fig. 3. Icings at the forefield of Irenebreen (Sobota 2011, modified)

long-term presence has been observed by Zapolski (1977), Olszewski (1977, 1982), Lankauf (2002) and Grześ (2005). In recent years, the icings have emerged mainly in the internal marginal zones of glaciers.

At the Waldemarbreen, Andreasbreen and Oliverbreen, icings reach beyond the marginal zone, which is assumed to be due to the zones' limited capacity. However, the surface areas of icings outside these zones have tended to be substantially smaller in recent years. This results from glacial recession and increase of internal areas, as well as a general trend towards reduced size and durability of icings.

The reach of icings is rather variable, and their surface and thickness tend to change year by year, depending on hydrological conditions in the glacier's system. Bukowska-Jania (2003) considers the following factors to be crucial to the surface and thickness parameters of icing fields at the end of a winter season: the volume of water flowing out of the glacier in winter; the frostiness of the winter, which determines water-freezing conditions; and the topography of the glacial forefield, where the icing field develops.

The icings of the Svalbard glacial forefields mainly originate from winter outflows of subglacial waters. Unfortunately, estimated volumes of such winter outflows are scarce. It was assessed that in May 1998 the average winter outflow from the Waldemarbreen was 0.02 m^3s^{-1} (Grześ and Sobota 2000). Pulina (1986) determined that the average winter outflow from the Werenskioldbreen was 0.08 m^3s^{-1}. Hodgkins et al. (2004) estimated that of the Scott Turnerbreen to be 0.01 m^3s^{-1}.

Winter water outflows from the Waldemarbreen in Kaffiøyra still happen, but the resulting icings are not so vast any more. However, at the very front of the glacier, in its northern part, the icing field has been observed to re-emerge along with a small water lake over the last 2–3 years. The field is situated among the youngest series of ablation moraines (Fig. 10). This indicates the hydrological conditions on the glacier. The phenomenon was particularly evident in the seasons of 2009–2010 and 2013–2014, that is, the years when there was a substantial thickness of snow cover, mainly within the accumulation zone of the glacier. An increase in the snow cover thickness, affecting glacial water drainage (percolation), might have contributed to the restoration of possibly disappearing layers of warm ice, whose presence is one of the conditions for winter glacial outflows to occur.

An intensified melting of glaciers, on the other hand, may cause a decline in the percolation area in the accumulation zone of the glaciers (Jania 1997), which is mainly responsible for the conveyance of water into the glacier and affects its thermal conditions. This can lead to a gradual transition of the glacier from a warm, polythermal type, into a cold one (Willis et al. 2007), which contributes to the reduction of winter outflows and the emergence of icings.

Traditionally, the presence of large icings has been interpreted as evidence of warm-based pol-

Fig. 4. Icings at the forefield of Andreasbreen. Photo by I. Sobota

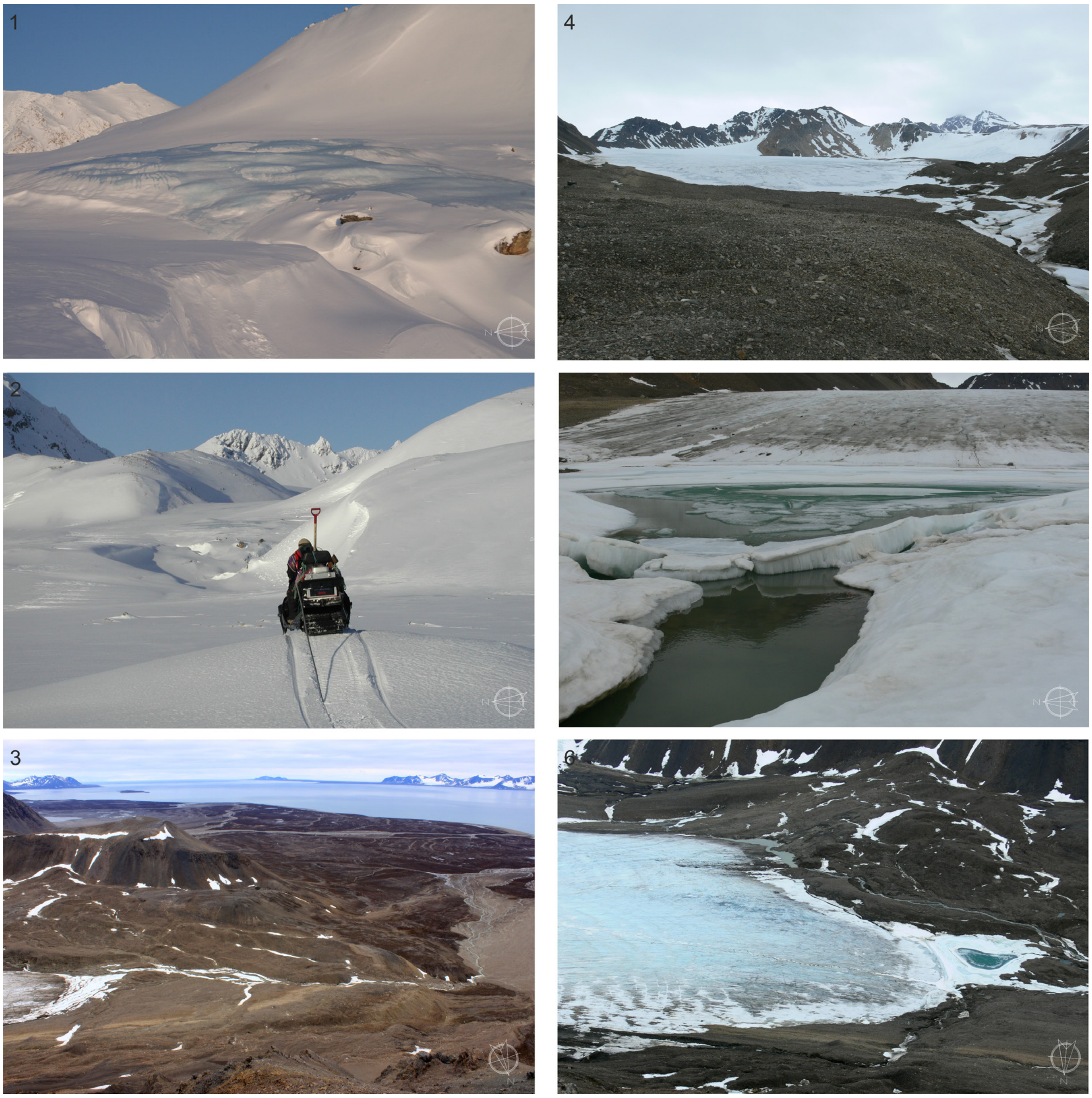

Fig. 5. Icings at the forefield of Waldemarbreen: 1 – icings of the river gorge zone (spring), 2 – icings of the proglacial zone (spring), 3, 5, 6 – icings of the internal zone (summer), 4 – icings of the river gorge zone (summer). Photo by I. Sobota

ythermal conditions (Hagen et al. 2003), under which, water can be produced subglacially throughout the year (Bælum and Benn 2011; Sobota 2011). Głowacki (2007) also associates the formation of icings with the occurrence of warm ice layers in the body of a polythermal glacier. On the other hand, some researchers claim that icings may also emerge in the forefields of cold glaciers, and that their presence does not necessarily confirm the thermal type of the glacier (Hodgkins et al. 2004). Baranowski (1977), Björnsson et al. (1996), Jania et al. (1996), Bukowska-Jania (2003) and Sobota (2013) have also noted a connection between the emergence of icings and thermal types of glaciers. The formation of icings in the forefield of small glaciers in the area of Kaffiøyra may indicate their polythermal nature. It can hardly be assumed that such substantial winter outflows from the glaciers can be possible without some presence of warm ice at the melting point.

The degradation of High Arctic icings mainly occurs in summer, generally as a result of surface and mechanical ablation (Fig. 11). Snow conditions largely determine the reach of the icings; the sooner the snow cover melts, the more intensive is the degradation because the appearance of icing ice. The streams flowing across icing fields are also important. Their intensity strictly depends on local weather conditions and the rate at which the feeding glacier melts.

In each season, the majority of icing mounds emerge in the same places, specifically in the area of internal glacial moraines. It is difficult to identify the exact moment of their formation, but, since they emerge most often as a result of winter outflows from glaciers, this must happen in the winter/spring months. One of the mechanical effects of icing mound degradation is the collapse of their roofs (Fig. 2), which leads to the formation of small lakes and icing streams (Fig. 12). The mounds can also be decomposed from the bottom, if there are any voids between the base and the roof of the icing. Situations like this are mainly typical for the terminal phase of the ablation season. The intensity of those factors is therefore closely connected with changes occurring on the glacier and in its catchment area.

The emergence of icings is primarily connected with the intraglacial water circulation system and the processes that shape it. Weather conditions are important there as well, and the precipitation in a given year. As far as non-meteorological factors are concerned, the degree of development of the supra-, in- and sub-glacial drainage, hydrological determinants and the water balance of the glacier are the most significant. Glacial water outflows may take place both in summer (surface runoff mainly) and in the winter season (in- and sub-glacial outflow). At an appropriately low air temperature, the water that flows out under pressure can freeze and form an icing cover. If drainage is obstructed or hampered, icing mounds may also develop.

In the forefields of most glaciers in the Kaffiøyra region, a generally falling trend is observed as regards the size of icing fields, with isolated periods in which it increased. During the most recent five years, they have not been so large as in the preceding years. The decrease of icing extent may be due to fact that some glaciers may be gradually transforming from a polythermal into a cold type. The increase of icing extent may be due to higher average winter temperatures, with more frequent melt events on the one hand and increasing water discharge during winter on the other.

One of the effects of changes observed within a glacier and its catchment in the High Arctic is the emergence or disappearance of icings. Their existence is mainly related to the thermal and hydrological processes taking place on the glacier. Regardless of the causes of their formation, their size, range and reach are related to the intensity of melting during a given season. The build-up is conditioned by the weather, and especially by the winter outflow from a glacier.

Fig. 6. Changes and disappearance of the northern icing field at the forefield of Waldemarbreen in July

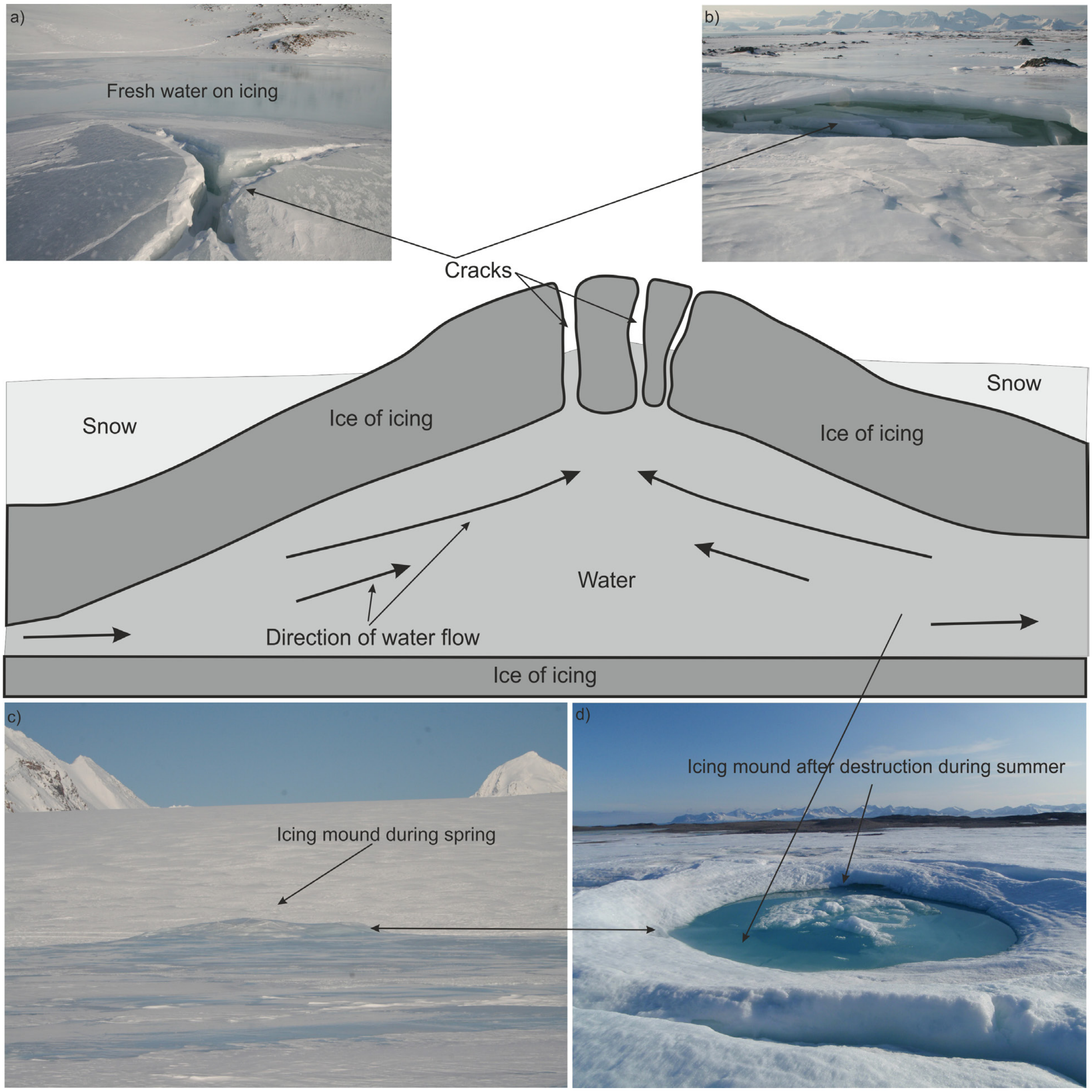

Fig. 7. Icing mound scheme (Grześ and Sobota 2000; Sobota 2013, modified). Samples from the forefields of the Kaffiøyra region glaciers: Irenebreen (a), Aavatsmarkbreen (b) and Elisebreen: taken in spring (c) and after destruction of the upper part in summer (d)

Fig. 8. Column structure of icing ice

Fig. 9. Fresh water on the icings in the front of the Irenebreen during the winter season

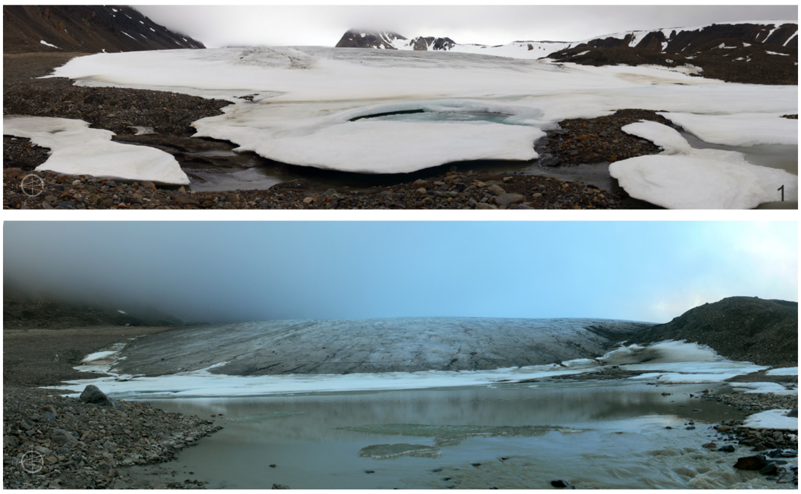

Fig. 10. Icings in the front of the Waldemarbreen: 1 – at the beginning of summer, 2 – at the end of summer

Fig. 11. Icings in the front of Elisebreen: 1 – during the spring, 2 – during the summer

Fig. 12. Lakes and streams resulting from destroyed upper parts of icings

The presence or absence of icings may indicate a thermal transformation of the glacier, a change in the water retention characteristics within its catchment, and – above all – changes in the functioning of its internal drainage system.

Icing fields constitute a very important element of the cryosphere in the High Arctic, as they are not only an indicator of the thermal and hydrological properties of the glaciers, but also of the intensity of contemporary changes occurring in the region.

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