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Influence of snowpack internal structure on snow metamorphism and melting intensity on Hansbreen, Svalbard

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Abstract: This paper presents a detailed study of melting processes conducted on Hansbreen – a tidewater glacier terminating in the Hornsund fjord, Spitsbergen. The fieldwork was carried out from April to July 2010. The study included observations of meltwater distribution within snow profiles in different locations and determination of its penetration time to the glacier ice surface. In addition, the variability of the snow temperature and heat transfer within the snow cover were measured. The main objective concerns the impact of meltwater on the diversity of physical characteristics of the snow cover and its melting dynamics. The obtained results indicate a time delay between the beginning of the melting processes and meltwater reaching the ice surface. The time necessary for meltwater to percolate through the entire snowpack in both, the ablation zone and the equilibrium line zone amounted to *c*. 12 days, despite a much greater snow depth at the upper site. An elongated retention of meltwater in the lower part of the glacier was caused by a higher amount of icy layers (*ice formations* and *melt-freeze crusts*), resulting from winter thaws, which delayed water penetration. For this reason, a reconstruction of *rain-on-snow* events was carried out. Such results give new insight into the processes of the reactivation of the glacier drainage system and the release of freshwater into the sea after the winter period.

Key words: Arctic, Spitsbergen, Hornsund, snow cover, glaciology, meltwater.

Introduction

Snowpack is subject to dynamic transformations from the moment of its formation until its disappearance. The processes changing its physical properties are known as metamorphism. This phenomenon is complex and extremely diverse – both in time and space (Colbeck 1982; Fierz *et al*. 2009). In the period of an increased surface melting, a significant impact on snow metamorphism is exerted by the percolation of meltwater and liquid precipitation. As the result of the influx of solar energy to the surface of the glacier, the upper part of the snowpack transforms into meltwater. This water is the carrier of thermal energy, chemical contaminants and biota, hence it brings about the change in the physicochemical characteristics of the snowpack (Bengtsson 1982; Głowacki 1997; Harrington and Bales 1998; Björkman *et al*. 2014). The rate of the meltwater percolation through the snow cover is uneven and depends on the porosity of this medium. Melt-freeze crusts and ice formations induce the delay in the meltwater transport, which is triggered anew after those layers have melted (Colbeck 1972).

During the melting period, all three phases of the snow cover metamorphism may occur. Constructive metamorphism takes place under the condition of the temperature gradient (TG) in the snowpack. It causes the growth of hollow and cup-shaped crystals owing to the migration of water vapour towards the layers of a lower temperature. Process occurs efficiently until the difference in the snowpack temperature is at least 0.1–0.2°C cm^{-1} (Colbeck 1982). The formation of faceted crystals was also observed at the temperature gradient of 0.03°C cm^{-1} (Flin and Brzoska 2008), and even under isothermal conditions (Dominé *et al*. 2003), however this process is then significantly prolonged in time (Pinzer and Schneebeli 2009). Destructive metamorphism takes place at a steady temperature. It engenders rounding off crystals owing to the migration of water vapour from faceted forms to rounded forms. These aforesaid phases occur mainly during the accumulation period and at the initial stage of the melting period. At the later stage, the contribution of wet-snow metamorphism becomes dominant, during which the size of crystals and the density and wetness of snow gradually increase, while simultaneously the hardness of snow decreases (Colbeck 1982).

The temperature of the snow cover cannot be higher than the melting point, T_{melt} (0.0°C = 273.16 K), and continuous melting occurs from the moment when whole snowpack or individual layers reach this temperature. Once the temperature of the entire snow profile stabilises at the melting point, positive values of the energy balance of the snow cover must lead to intensification of melting processes (Marks *et al*. 2008).

Melting of the snow cover is an important process shaping the glacier mass balance (Bruland and Hagen 2002; Hagen *et al*. 2003; Sobota 2011, 2013; van Pelt *et al*. 2012). The variability of the snow cover in the summer period and the outflow of meltwater on the glaciers of the southern Spitsbergen were presented by Głowicki (1975), Baranowski (1977), Leszkiewicz (1987), Jania (1988, 1994), Jania and Hagen (1996), Bartoszewski (1998) and Pälli *et al*. (2003). The subsequent works were predominantly related to meteorological factors (Szafraniec 2002; Migała *et al*. 2006) and the formation of the glacial drainage network as well as the thermal structure of glaciers as a result of meltwater migration (Głowacki 2007; Piwowar 2009). There were also works on melting of the snow cover deposited in a non-glaciated area (Luks *et al*. 2011; Luks 2012).

Hansbreen is the most extensively studied among the glaciers of the southern Spitsbergen. This also applies to basic observations of variety of physical and chemical properties of the snow cover (Leszkiewicz and Pulina 1999; Głowacki and Pulina 2000; Leszkiewicz and Głowacki 2001; Głowacki 2007). However, the existing literature is notably lacking in observations concerning changes in the internal structure of the snow cover as the result of melting. The retention of meltwater in the snow cover is an important factor delaying the internal drainage and runoff from glacial systems. Meltwater, when it reaches the bedrock, acts as a sliding layer, which shapes the dynamics of the glacier flow. Subsequently, it engenders changes in the thermohaline circulation, which is an important factor responsible for shaping of the global climate (Walsh *et al*. 1998). The aim of the conducted research was a comprehensive investigation of the dynamics of melting of the snow deposited on Hansbreen, determination of percolation channels and the duration of meltwater percolation to the surface of glacier ice, considering the changes occurring within the snow cover with an increasing altitude.

Study area

The measurements were carried out at Hansbreen, located in the southern Spitsbergen, on Wedel Jarlsberg Land, over the Hornsund fjord, in the distance of *c*. 2 km north-east from the Polish Polar Station (Fig. 1). Hansbreen is a medium size tidewater glacier, which active calving front of the height of *c*. 30 meters and the width of *c*. 1.5 km terminates in the Hornsund fjord. The length of the glacier along the central line is 15.7 km, the average width 2.5–3.0 km, and a vertical extent *c*. 550 m. It occupies an area of *c*. 56 km^2, with the maximum thickness of the ice at 386 m and an average thickness of *c*. 171 m (Grabiec *et al*. 2012).

More than 75% of the bedrock of the glacier is located below the sea level (Jania *et al*. 1996). Hansbreen, like most of the glaciers of Spitsbergen, is a polythermal (subpolar) glacier. Lower parts of the glacier, extended from the active calving front to the equilibrium line altitude (ELA) at *c*. 370 m a.s.l., comprises a cold ice layer on the surface of the thickness of 40 m at glacier front up to 120 m in the region of the equilibrium line. Higher parts are composed almost entirely of temperate ice, except *c*. 15 m thick surface layer – seasonally chilled during the winter period (Jania *et al*. 1996; Migała *et al*. 2006; Grabiec *et al*. 2012). Such a thermal structure is typical of glaciers terminating in the sea (Blatter 1990). Since 1989, the mass balance of Hansbreen has been subject to regular monitoring (WGMS 2015).

The climate of Hornsund region is defined as suboceanic and humid, with the predominance of precipitation over evaporation. The mean multiannual air temperature equals -4.3°C, while the mean multiannual precipitation total is *c*. 434 mm (Łupikasza 2013; Marsz 2013). About 72% of the precipitation occurs during the accumulation period (September-May) and the share of solid precipitation to the annual cycle is around 30%. In recent years, a considerable increase in the amount of liquid precipitation has been observed, especially during winter months (Łupikasza 2013). The positive trend in the mean multiannual air temperature has been also significant, *i.e*. 0.97°C per decade over the years of 1979–2010. The change was predominantly affected by a higher air temperature in the winter

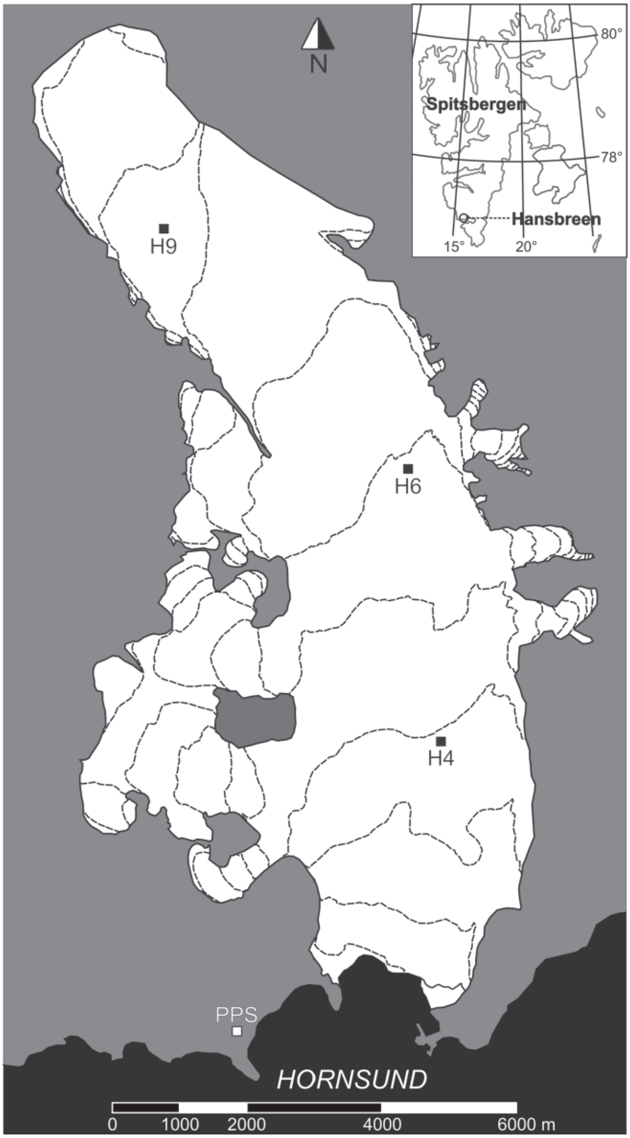

Fig. 1. Location of the study area: PPS – Polish Polar Station; black squares – ablation stakes with automatic weather stations; contour lines every 50 m.

months (Grabiec *et al*. 2012). Wind is the decisive factor conditioning the spatial distribution of the snow cover on glaciers. In Hornsund region, the prevailing wind blows from sectors NE, E, SE, representing 65% of the multiannual means observations (Styszyńska 2013a). This results in a significantly greater accumulation of snow in the western, and smaller in the eastern part of the Hansbreen.

Data and methods

Meteorological data. — The analysed data for the season of 2009/2010 come from two automatic weather stations (AWS) located on Hansbreen: H4 in the ablation zone (179 m a.s.l.) and H9 in the accumulation zone (420 m a.s.l.) (Fig. 1). AWS measurements that were used included air temperature (maximum, minimum and mean daily), snow cover thickness and net radiation. The technical specification of the used sensors is presented in Table 1.

The aforesaid data were employed to determine the moment of appearance and disappearance of conditions conducive to surface melting. Reconstruction of episodes of the winter thaw with liquid precipitation on the glacier was conducted using meteorological observations from Hornsund meteorological station (WMO 1003).

Glaciological data. — Study involved measurements from ablation stakes located in the ablation zone (H4 and H6) and accumulation zone (H9) of Hansbreen in the season of 2009/2010. Observations in the ablation zone were performed once per week, while in the accumulation zone – once per month. The observations from the ablation stakes were compared with the results of SR50 ultrasonic ranger. The measurements were utilised to determine the dynamics of the snow cover melting in the particular glacier zones, from the beginning of melting period until its completion.

Table 1

Technical specifications of the used sensors at automatic weather stations.

Model	Sensor	Sensitivity range	Accuracy	Resolution
CTD-Diver DI261	conductivity	0–80 mS cm^{-1}	±1.0%	±0.1%
	temperature	-20°C – +80°C	±0.1°C	0.01°C
	pressure	0–10 m H$_2$O	±1.0 cm H$_2$O	0.2 cm H$_2$O
Campbell Scientific Ltd. 107	temperature	-35°C – +50°C	±0.1°C	<±0.2°C
Campbell Scientific Ltd. SR50	distance to target	0.5–10.0 m	±1.0 cm or 0.4% distance	0.1 mm
Kipp&Zonen CNR1	net radiation	305–50000 nm	±10% daily totals	5–15 μV W^{-1} m^2
HFP01 Hukseflux	heat flux	-2000–2000 W m^{-2}	±3.0%	50 μV W^{-1} m^2

Reconstruction of the *rain-on-snow* events. — Due to the problem of regular measurements of precipitation on the glaciers, combined meteorological data from the Hornsund meteorological station and the AWS H4 were utilised. The information about the quantity and type of precipitation came from the coastal station. Identification whether or not liquid precipitation occurred during a particular time on the surface of the glacier was based on the information on the maximum air temperature and the thickness of the snow cover recorded at AWS H4.

Determination of the physical properties of the snow cover. — Snow pits were dug at three sites: H4 (3x), H6 (3x), H9 (1x). All measurements were performed with accordance to *The International Classification for Seasonal Snow on the Ground* (Fierz *et al*. 2009). The first series was carried out before the start of the surface melting, and then repeated after the beginning of melting period and during its intense stage. The measurements included total depth of the seasonal snow cover, thickness of the layers, shape and size of the grains, hardness, liquid water content and density of the snow. Particular emphasis was placed on the observation of the changes in the snow profiles engendered by the presence of meltwater, *e.g*. the presence of superimposed ice and ice columns, melt forms and increased wetness of the layers.

Measurements of the snow temperature and the heat flux transfer. — The observations were carried out at H4 site, during the period of 18.04–30.06.2010. Seven thermistors (Campbell Scientific Ltd. 107) were employed in snowpack profile, spaced every 25 cm. Heat flux sensor (HFP01 Hukseflux) was installed *c*. 20 cm below the surface of the snow. All the sensors were connected to data logger (Campbell Scientific Ltd. CR1000M), with a ten-minute interval of recording (Table 1).

Measurements of the duration of meltwater percolation. — The measurements were made at the sites of H4 and H6, with CTD-Diver loggers (Schlumberger Water Services) measuring electrical conductivity, temperature and pressure with one-hour interval of recording. The sensors were placed in plastic bowls and buried at the surface of glacier ice before the beginning of melting of the snow cover. Observations allowed to determine the average duration of meltwater percolation through the entire snowpack at the sites located in different glacier zones.

Results

Meteorological conditions. — The year of 2009 had been the eighth warmest year in the history of the observations at Hornsund meteorological station, dating back to 1978, which, given a relatively thin snow cover, resulted in the highest (since 2001) surface ablation of Hansbreen, *i.e*. -1.59 m w.e. (water equivalent) by 17.09.2009. The year of 2010 was distinctly cooler, which resulted in a lower mean annual air temperature (-3.5°C), a lower melting dynamics of the snow cover, and insignificantly longer presence of continuous snow cover than the multiannual mean values (Table 2). A similar situation occurred on Hansbreen, resulting in the net mass balance of only -0.01 m w.e. in the season of 2009/2010.

A continuous snow cover on the glacier developed in mid-October, but only after the first decade of December a substantial increase in its thickness was observed. This was caused by an exceptionally *warm* and rainy November (+5.9°C and 240% of the multiannual monthly total precipitation). Similar dependencies were also observed in October, December and January – the months during which the snow cover is formed (the ration of the total precipitation, including liquid precipitation, to the multiannual mean value was 310%; Figs. 2 and 3). The heavy rainfalls were conducive to the formation of layers of high hardness, both on the cooled surface of the snow cover and just below it. February and March were dry months, whereas April and May were typical in comparison with the multiannual values. The lowest monthly mean air temperature was registered in March (-13.2°C). Meteorological conditions measured on Hansbreen are presented in Figure 4.

Reconstruction of liquid and solid precipitation during accumulation season. — The course of the changes in the snow cover and the rate of melting processes are significantly affected by the conditions prevailing during the accumulation period. Ice formations and melt-freeze crusts associated with

Table 2

Characteristics of selected meteorological elements at the Hornsund station in the season of 2009–2010 in comparison with the multiannual values for 1978–2014.

	2009	2010	1979–2014
mean annual air temperature [°C]	-2.7	-3.5	-4.1
mean annual precipitation total [mm]	479.7	448.5	445.6
PRECIPITATION			
days with rain	113	98	129
days with snow	190	177	170
SNOW COVER			
mean depth	20	13	19
days with snow cover	231	258	256
days with snow cover ≥20 cm	141	117	107
WIND SPEED			
mean annual [m s^{-1}]	5.8	5.7	5.6
days with wind speed ≥10 m s^{-1}	180	175	162
days with wind speed ≥15 m s^{-1}	43	38	47

winter thaws and events commonly referred to as *rain-on-snow* events are of special significance. A marked increase in the frequency of their occurrence has been observed in recent years, both in the Hornsund area as well as throughout the Arctic.

The snow cover on Hansbreen had been accumulating gradually since the second decade of September. In November, several thaws and large amounts of liquid precipitation occurred, which was reflected in the course of the snow cover thickness recorded by SR50 sensor. The first significant snowfall occur-

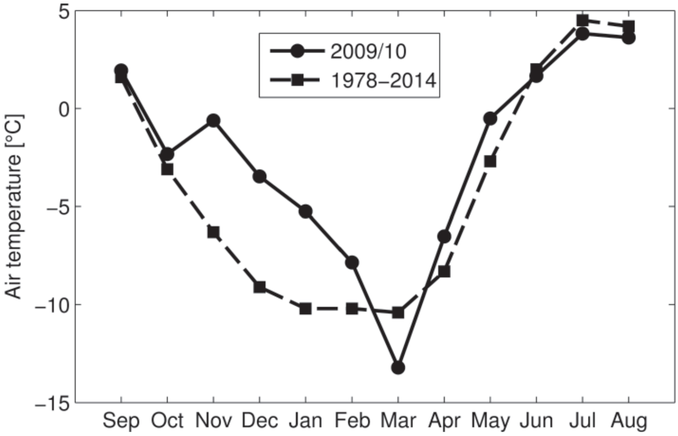

Fig. 2. The mean monthly air temperature (dots) at the Hornsund station in the season of 2009/2010 in comparison with the multiannual values of 1978–2014 (squares).

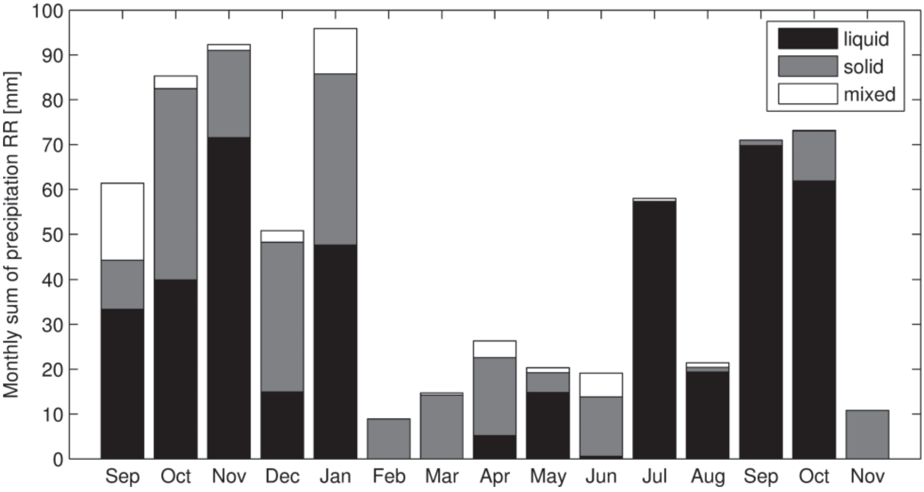

Fig. 3. Monthly precipitation totals at the Hornsund station in the season of 2009/2010 together with classification into different forms of precipitation.

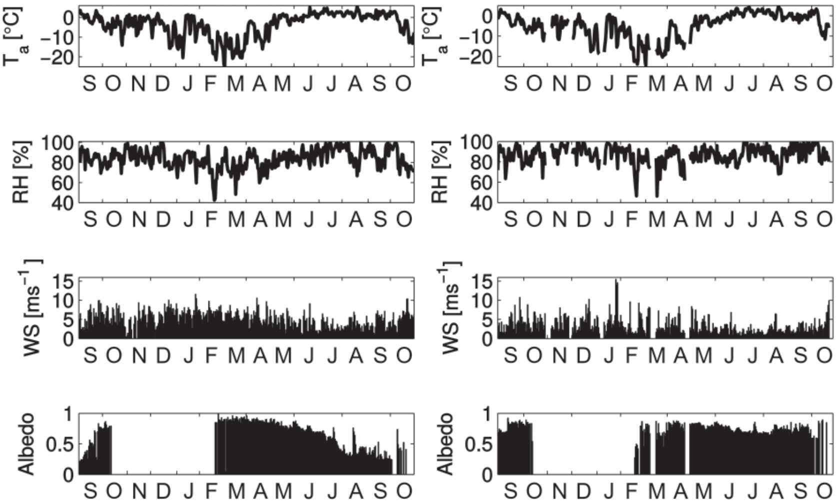

Fig. 4. Selected meteorological elements on Hansbreen H4 (left) and H9 (right) sites in the season of 2009/2010: air temperature (T_a), relative humidity (RH), wind speed (WS) and albedo.

red on Hansbreen in the second decade of December, when the snow thickness increased by 55 cm within 5 days. This period had been preceded by a brief thaw and rainfalls, which facilitated creation of a melt-freeze crust on the snow surface. Subsequent thaws along with rainfalls occurred not earlier than in mid-January (Fig. 5). The decrease in the snow cover thickness in early January was associated with a strong wind redeposition. Interestingly, despite the fact that AWS H4 registered positive T_{max} and the Hornsund meteorological station registered high rainfall (>20 mm), the loss of the snow cover of merely 5 cm was observed on the surface of the glacier. Such heavy rainfalls probably resulted in the formation of another melt-freeze crust.

The period of thaws was followed by heavy snowfalls, and thus the snow cover increased by 44 cm, up to 118 cm above the surface of the glacier ice. February and March were cold and lacking in thaw months, during which only snow accumulation took place. The decrease in snow thickness was caused merely by wind redeposition and subsiding of the snow cover. The last thaw during the accumulation period was observed at AWS H4 in the second decade of April. T_{max} rose slightly above zero, and the rainfall recorded that day (11.04.2010) in the coastal zone probably engendered creation of ice formations at the depth of 21 cm.

Dynamics of the snow cover melting. — The maximum thickness of the snow cover in 2010 was recorded at all presented sites at the beginning of May: 167 cm at H4, 266 cm at H6 and 463 cm at H9 (Fig. 6).

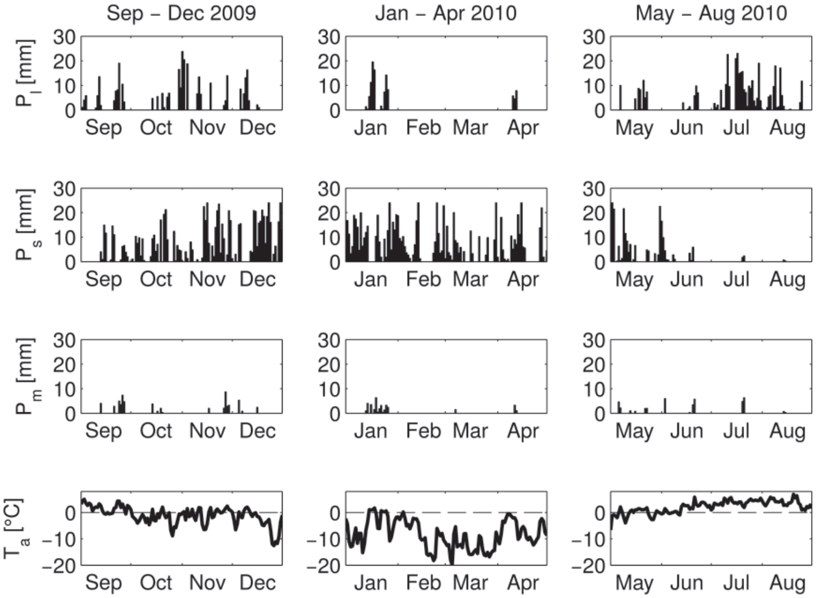

Fig. 5. The occurrence of particular forms of precipitation at the Hornsund station in the season of 2009/2010: liquid precipitation (P_l), solid precipitation (P_s), mixed precipitation (P_m), air temperature (T_a).

The melting season on Hansbreen lasted from the second decade of May to mid-October, although the first signs of snow melting, which launched the percolation of meltwater from the snow surface, occurred earlier, *i.e.* 6.05.2010. Consequently, the season was long, *c.* 3 weeks longer than in 2009, and due to a low air temperature the process of melting was not intensive and the snow cover disappeared gradually.

Large altitudinal difference between the glacier terminus and the highest located accumulation zone (*c.* 550 m a.s.l.) brings about a wide disparity of thermal conditions. The mean annual air temperature in 2010 in the ablation zone H4 was -5.2°C (1.7°C lower than at the Hornsund station), whereas in the accumulation zone H9 was equal to -6.6°C (3.1°C lower than at the Hornsund station). Correlation coefficient of these results with the difference in elevation between the two AWS (*c.* 230 m), indicates a temperature gradient decrease by an average of 0.64°C per 100 m. This induced, among others, the delay of the processes of melting of the snow cover accumulated on the glacier and the reduction of their dynamics, along with an increase in absolute altitude. Hence, the rate of the snow cover melting in the season of 2009/2010 was characterised by considerable steadiness. Within merely 10 days, the snow cover thickness was reduced by more than 5 cm, disappearing in the ablation zone by an average of 15 mm per day, with the maximum of up to 76 mm per day (Fig. 7),

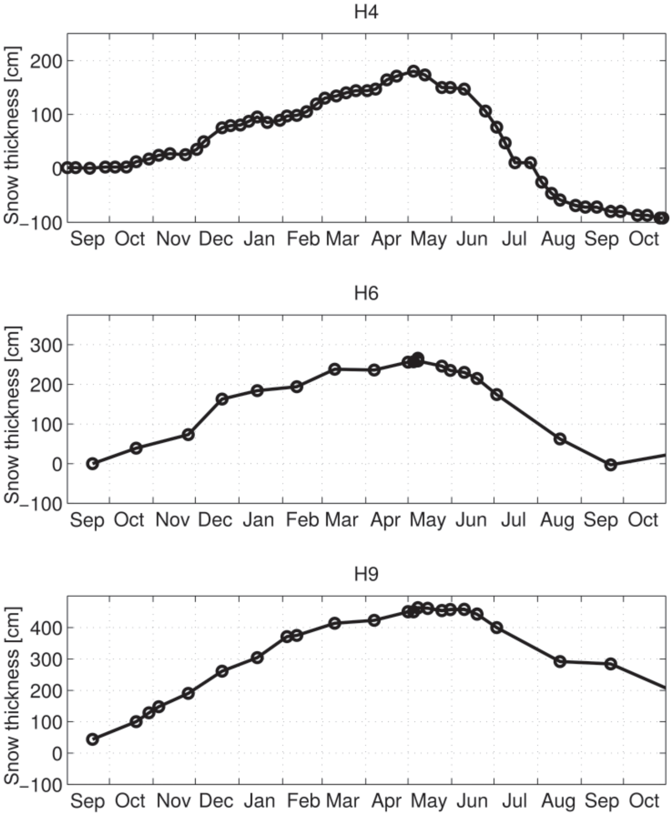

Fig. 6. Changes in the snow cover thickness at selected ablation stakes on Hansbreen in the season of 2009/2010, based on field measurements.

and respectively during 2 days in accumulation zone, the rate of melting averaged to 9 mm, with the maximum of up to 51 mm per day (Fig. 8). After the beginning of the melting period, there were still recorded episodes with snow cover growth. This took place mainly in the accumulation zone and was associated with the snow redeposition by the wind through the broad lowering of Kvitungisen – located on the ice divide between Hansbreen and Paierlbreen, and after small, solid precipitation episodes.

Snow properties and the metamorphism of the snow cover during the melting period. — In the period preceding melting (18–21.04.2010), a typical dependence between the increase of the density and grain size with depth was observed. The layers were predominantly composed of faceted crystals, which are characterised by high hardness (4–5), whereas the liquid water content in snow on all sites was equal to 0% within the entire snow profile (Figs. 9–11).

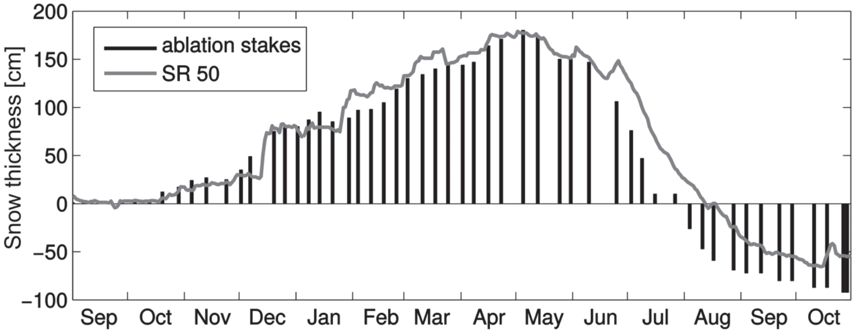

Fig. 7. Changes in the snow cover thickness on Hansbreen H4 site in the season of 2009/2010, based on field measurements and SR50 recording.

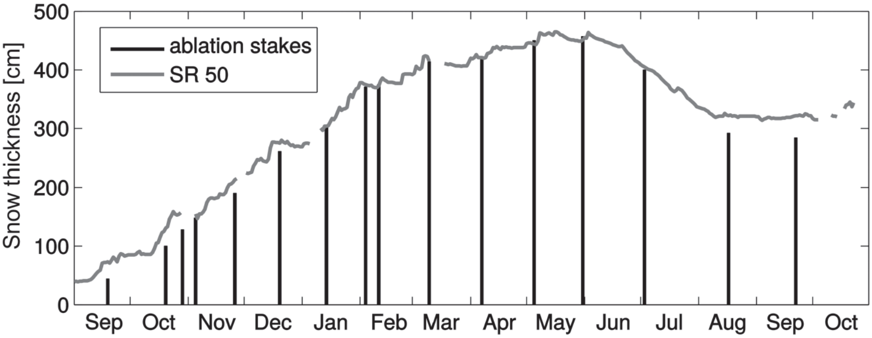

Fig. 8. Changes in the snow cover thickness on Hansbreen H9 site in the season of 2009/2010, based on field measurements and SR50 recording.

The mean density of the dry snow cover was between 0.42 g cm^{-3} (H4 site) and 0.44 g cm^{-3} (H6 site). At H9 site, the mean snow density was 0.44 g cm^{-3}.

The subsequent measurements, carried out at H4 (13.05.2010) and H6 (20.05.2010), revealed an increase of the snow wetness and density (0.46 g cm^{-3} and 0.47 g cm^{-3}, respectively). At H4, the wet snow reached the depth of 77 cm. At H6, where the profile was performed a week later, percolation of meltwater into the glacier ice surface was observed. It resulted in formation of slush at the bottom of the snowpack.

In the last series of snow pits at H4 (30.06.2010) and H6 (25.06.2010), heavily soaked snow cover was built mainly of coarse and very coarse melt forms and rounded crystals. As the result of an increase in the snow temperature up to the melting point, the thickness of the high hardness layers, which limited percolation, was reduced. Additionally, the meltwater accelerated the process of homogenising the shape and size of the crystals. This resulted in an

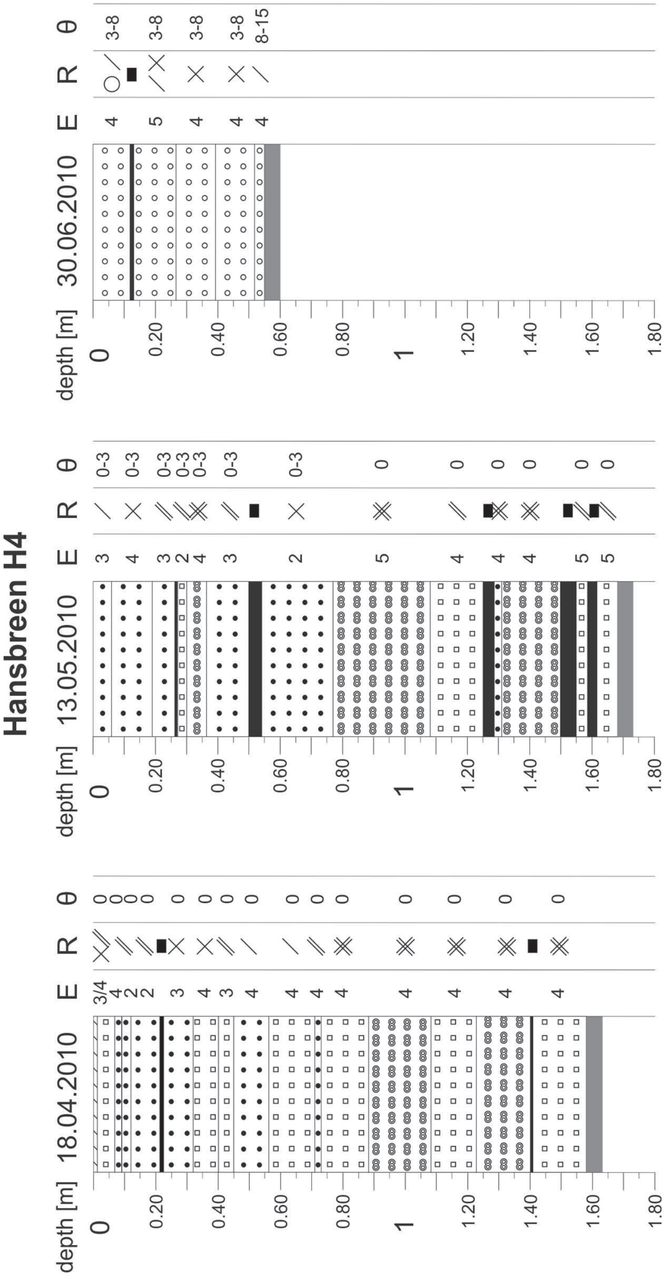

Fig. 9. The metamorphism of the snow cover at H4 site. For legend, see Fig. 11.

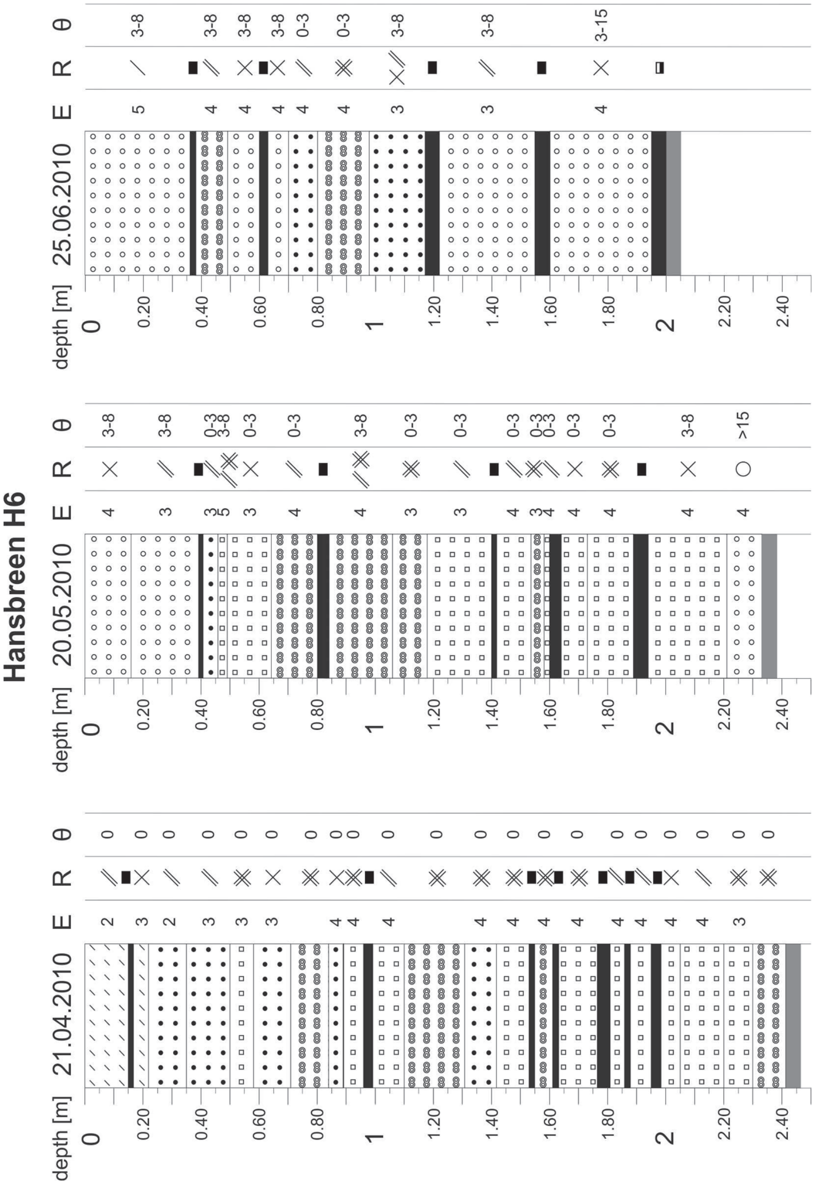

Fig. 10. The metamorphism of the snow cover at H6 site. For legend, see Fig. 11.

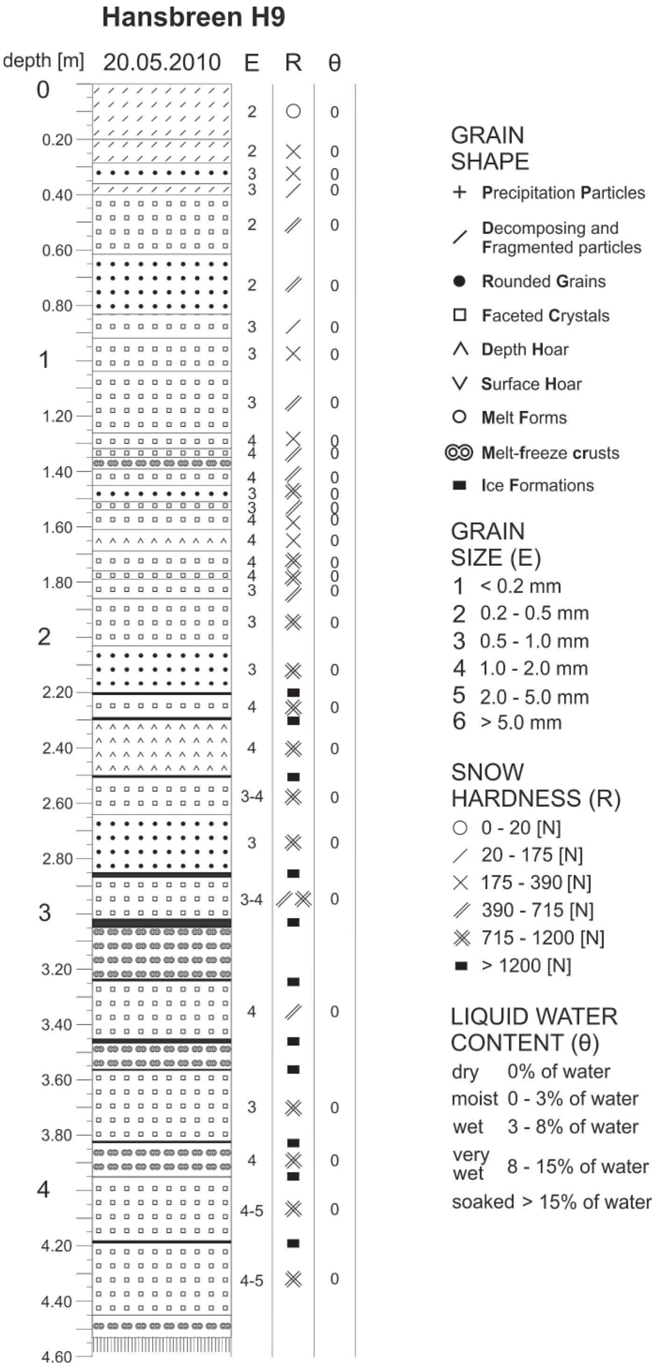

Fig. 11. The internal structure of the snow cover at H9 site.

overall increase in the snow density in the profiles up to 0.52 g cm^{-3} (H4) and 0.53 g cm^{-3} (H6). At H6, a five-centimetre layer of superimposed ice, engendered by the percolation of meltwater to the glacier ice surface, was observed.

Figure 12 shows the percentage contribution of basic crystal forms in the snow profiles. The predominant form of the crystals present in the snow pits before the beginning of melting were the faceted crystals, which ranged from 34% (H6) to 58% (H9). They are characteristic of the snow cover subjected to constructive metamorphism resulting from the snow temperature gradient. There was also a significant percentage contribution of melt-freeze crusts, which gradually decreased along with altitude. This confirms the occurrence of longer periods of positive temperature at the sites situated at lower altitudes.

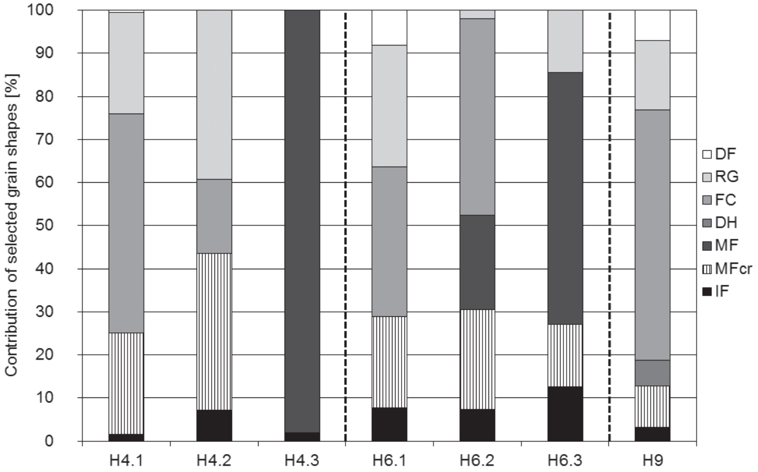

Fig. 12. The percentage contribution of selected grain shapes in the performed snow pits at the sites of H4, H6 and H9 on Hansbreen. Legend: DF – Decomposing and Fragmented particles, RG – Rounded Grains, FC – Faceted Crystals, DH – Depth Hoar, MF – Melt Forms, MFcr – Melt-freeze crusts, IF – Ice Formations.

Temporal delay in the heat transfer and meltwater within the snow cover. — The vast portion of the observations indicated that the values of the heat flux were positive. Their dynamic growth was observed after 10.05.2010, whereas after 12.05.2010 they permanently exceeded 0 W m^{-2}, which coincides with the assumed date of the beginning of the actual melting period in 2010.

The heat migration in the snow cover was possible to be observed until 22.05.2010, when the snow temperature in the entire vertical profile reached and stabilised at the melting point (Fig. 13). The air temperature and snow temperature showed a strong correlation, gradually decreasing along with depth. The values of correlation coefficient between the air temperature and the snow cover temperature at various depths are presented in Table 3. The average

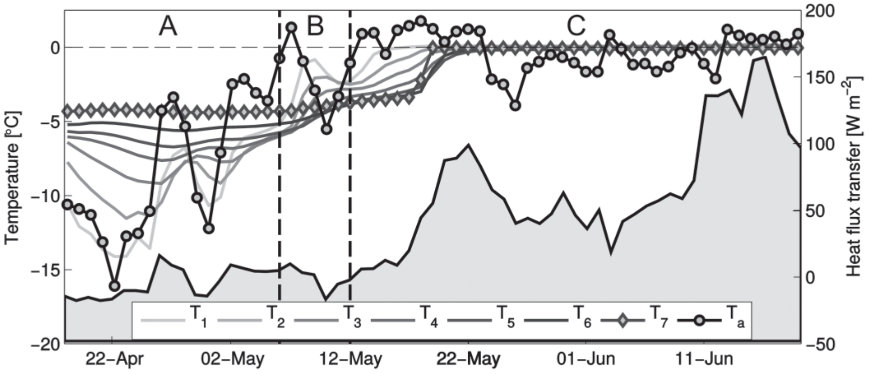

Fig. 13. The course of mean daily changes of the snow temperature at particular levels (T_1–T_7 – explanations in text), the air temperature (T_a) and heat flux transfer (coloured in grey) within the snow cover at the depth of 20cm on Hansbreen H4. Sub-periods: A – before melting, B – early-melting, C – melting.

duration of heat transfer into the snow amounted to *c*. one day per each 25 cm of the depth.

Based on the measurements of the temperature and the heat flux transfer in the snow cover, three sub-periods were determined:

First, before melting sub-period (until 06.05.2010, A on Fig. 13), from the installation of thermistors up to the day preceding the first evident thaw. It was characterised by the greatest daily fluctuations in the air temperature. The snow temperature increased along with depth, which was owing to the isolation of the bottom part of the snow profile from the conditions prevailing on the surface by the overlying layers of snow of high hardness (see Fig. 9). A definite delay in the migration of heat flux transfer in the snow profile was registered (Fig. 13).

The minimum air temperature influenced the minimum snow temperature at subsequent levels, reaching the glacier ice surface at the of depth *c*. 160 cm after seven days (22–29.04.2010). The greatest variability was observed in the air temperature ($\Delta T = 22.5$°C) and the upper part of the snow cover. The snow temperature at the glacier ice surface was almost constant during this sub-period (Table 4).

Second, early-melting sub-period (6–12.05.2010, B on Fig. 13); the shortest of the sub-periods, however substantial for understanding the mechanism of triggering meltwater release. On 6.05.2015, for the first time in the analysed period, the air temperature exceeded and continued above 0ºC for almost five hours. The following day was even warmer, with 23 hours of positive temperature and the mean daily air temperature of 1.3ºC. The raised temperature induced melting of the snow and thus formation of meltwater, which initiated the process of percolation. The following days were characterised by cooling, which continued until the end of the sub-period, *i.e*. 12.05.2010.

Table 3

The correlation coefficient of the mean daily air temperature (T_a) and the mean daily temperature of the snow cover at particular levels (T_1–T_7) on Hansbreen H4 without and with the delay of the heat flux.

Delay in snow cover	Thermistor (installation depth)						
	T_a/T_1 (10 cm)	T_a/T_2 (35 cm)	T_a/T_3 (60 cm)	T_a/T_4 (85 cm)	T_a/T_5 (110 cm)	T_a/T_6 (135 cm)	T_a/T_7 (160 cm)
without delay	0.925	0.834	0.751	0.688	0.645	0.593	0.505
1 day	**0.945**	0.900	0.814	0.730	0.675	0.614	0.529
2 days	0.889	**0.912**	0.862	0.780	0.716	0.646	0.555
3 days	0.817	0.883	**0.877**	0.821	0.764	0.689	0.582
4 days	0.766	0.841	0.863	**0.835**	0.790	0.713	0.595
5 days	0.772	0.819	0.845	0.834	0.799	0.730	0.618
6 days	0.808	0.826	0.838	0.831	**0.804**	0.745	**0.635**
7 days	0.816	0.831	0.834	0.825	0.803	**0.747**	0.621

During this period, the trend of the temperature in the snowpack became reversed – the temperature decreased with depth. The delay in the heat transfer in the snow cover occurring after the maximum air temperature of 7.05.2010 was also conspicuous. This has been reflected in the registered values of the maximum snow temperature.

Third, melting sub-period (after 12.05.2010, C on Fig. 13); it is distinguishable by the highest temperature of both the air and the snow in the entire snow profile. During this time, surface melting had its definite beginning, which was accompanied by an increased migration of meltwater through the snow profile and the processes of wet-snow metamorphism. The snow temperature decreased with depth. In contrast to the previous periods, during the melting sub-period the highest temperature differences were recorded at the largest depths.

The snow cover attained a high temperature homogeneity from 23.05.2010. The difference in the snow temperature between the various levels of snow on this day was equal to 0.3ºC, and over time gradually decreased. This indicates the start of the processes of wet-snow metamorphism, which means transforming grains into large size conglomerates, snow subsiding, and increasing of snow density. From that moment on, the further changes in the air temperature had no effect on shaping the temperature within the snow cover.

The distinct diversity in the snow temperature at particular levels indicated the presence of the temperature gradient (TG). It was observed almost exclusively in the first sub-period and merely in the upper layers of the snow cover, reaching the depth of 60 cm. The phenomenon occurred mostly during the night,

Table 4

The minimum (T_{min}) and maximum (T_{max}) temperature of the snow cover on Hansbreen H4, and the difference between these values (ΔT) at subsequent levels (T_a–T_7) in the determined sub-periods.

	Before melting period			Early-melting period			Melting period		
Thermistor	T_{min} [ºC]	T_{max} [ºC]	ΔT [ºC]	T_{min} [ºC]	T_{max} [ºC]	ΔT [ºC]	T_{min} [ºC]	T_{max} [ºC]	ΔT [ºC]
T_a	-21.7 (22.04)	0.8 (06.05)	22.5	-8.9 (10.05)	2.7 (07.05)	11.6	-5.1 (26.05)	7.7 (15.06)	12.8
T_1	-17.0 (23.04)	-4.8 (06.05)	12.2	-4.8 (07.05)	-0.8 (09.05)	4.0	-2.6 (12.05)	0.0 (10.06)	2.6
T_2	-11.9 (23.04)	-5.7 (06.05)	6.2	-5.6 (07.05)	-1.9 (10.05)	3.7	-2.6 (12.05)	0.0 (15.06)	2.6
T_3	-9.3 (26.04)	-5.9 (06.05)	3.4	-5.9 (07.05)	-2.8 (11.05)	3.1	-2.8 (12.05)	0.0 (17.06)	2.8
T_4	-7.7 (26.04)	-5.8 (06.05)	1.9	-5.8 (07.05)	-3.4 (11.05)	2.4	-3.4 (12.05)	0.0 (15.06)	3.4
T_5	-6.7 (27.04)	-5.7 (20.04)	1.0	-5.7 (07.05)	-3.9 (11.05)	1.8	-3.9 (12.05)	-0.1 (16.06)	3.8
T_6	-5.6 (28.04)	-5.1 (21.04)	0.5	-5.1 (07.05)	-4.0 (11.05)	1.1	-4.0 (12.05)	-0.1 (18.06)	3.9
T_7	-4.4 (29.04)	-4.2 (23.04)	0.2	-4.3 (07.05)	-3.8 (11.05)	0.5	-3.8 (12.05)	0.0 (20.05)	3.8

when the top layers of the snow cover underwent rapid cooling. Because of the short period when the TG occurred (several hours per day), the dynamics of constructive metamorphism processes were low before the beginning of the melting period. The only incidence of the TG after the beginning of melting was observed at the bottom of the snow cover, when the temperature on the glacier ice surface increased rapidly within merely one hour (+3.3ºC; 18.05.2010). This change was caused by refreezing of the meltwater from the snow cover surface, which formed a layer of superimposed ice – observed also 25.06.2010 at H6 site (Fig. 10).

Upon combination of temperature recordings by diver sensors and the starting point of surface melting determined on the basis of the previous observations, duration of the meltwater percolation through the snow cover was specified. At H4 and H6 (snow cover thickness of 157 cm and 271 cm, respectively), the migration of meltwater from the surface of the snow cover to its bottom lasted about 12 days (Fig. 14). At H6, the melting period began one day later, *i.e.* on 7.05.2010. At H4, the lower rate of percolation resulted mainly from a higher proportion of thin ice formations in the internal structure of the snow cover.

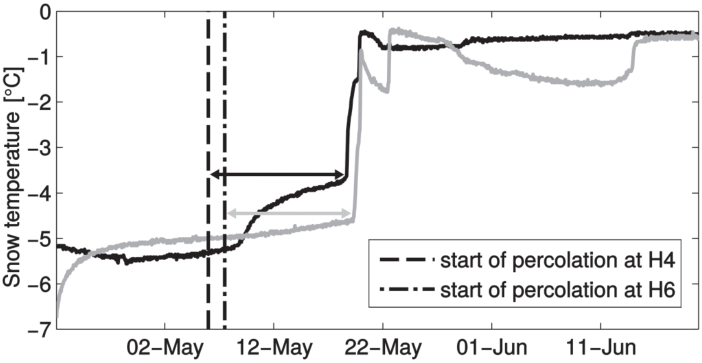

Fig. 14. The duration of the percolation of meltwater on Hansbreen H4 (black) and H6 (grey).

Discussion

The relations between air temperature, solar radiation and energy fluxes within snowpack. — Late accumulation season and early melting season is the period of dynamic changes in the physical properties of the snow cover. It is combined with a high variability of meteorological conditions, that affect the development of the snow cover internal structure. The upper part of the snowpack is the most susceptible to the processes of metamorphism owing to solar radiation and diversity of the air temperature near the surface. Snow, as a porous structure with a high permeability, is very sensitive to the transport of energy in the form of heat flux. Impact of those factors on the snow temperature is visible throughout the entire snow profile, while most frequently it extents to the depth of 20–30 cm (Fierz 2011). A similar dependency was observed in the ablation zone of Hansbreen, where daily temperature variation was characterised by a high correlation coefficient – above 0.90, up to the depth of 35 cm.

In the Hornsund region, the highest monthly sum of global radiation and its temporary intensity occurs in June, mainly due to the highest position of the Sun above the horizon (Głowicki 1985). The same relation was recorded on Hansbreen: 274.3 W m^{-2} (H4) and 310.7 W m^{-2} (H9) in June 2010. However, these values were much lower than observed on the tundra (Styszyńska 2013b). Previous observations emphasize that melting processes on the southern Spitsbergen are conditioned more by the air temperature and wind activity than the radiation balance (Baranowski 1977; Szafraniec 2002; Migała *et al*. 2006).

In comparison with multiannual meteorological data, the melting season of 2010 may be denoted as average, coinciding with the mean annual values. Clear differences were observed during an increase in the mean monthly air temperature of the winter and spring period. The lowest monthly mean air temperature was registered in March (-13.2°C). This reflects the contemporary observed trend of the annual temperature minimum shifting from the month of December to March (Soroka *et al*. 2010; Majchrowska *et al*. 2011).

Also, an intensive liquid precipitation were noticed during the winter, caused by the inflow of warm and humid air masses from the Norwegian Sea (Niedźwiedź 2013). They occurred mostly in December and January, resulting in the creation of melt-freeze crusts of large thickness, and ice formations, which were later observed in the structure of the snow cover accumulated on the glacier.

Winter thaws accompanied by rain, so-called *rain-on-snow* events, become a typical phenomenon characteristic of the recent changes in the climate of the Arctic (Ye *et al*. 2009; Westermann *et al*. 2011; Hansen *et al*. 2014; Cohen *et al*. 2015). The authors emphasise that this is an apparent effect of the raised air temperature in winter months, and predict a further increase in the frequency of these events.

Snow cover characteristics. — The snow stratigraphy on Hansbreen in the analysed season was typical for the snowpack located on glaciated areas, although presented some significant changes in relation to the contemporary climate changes, *i.e*. higher amount of melt-freeze crusts and ice formations within the snowpack. Similar features of the snow cover stratification were also observed on the other glaciers of Spitsbergen, *i.e*. Midtre Lovénbreen at the end of the accumulation season of 1998/1999 (Wadham and Nuttal 2002). Ice formations and melt-freeze crusts, which developed from freezing liquid precipitation, were deposited there much deeper, nevertheless, the period of raised temperatures occurred adequately earlier, in late November, 1998. In both cases, the occurrence of superimposed ice was registered, which thickness was increased (*c*. 5 cm) as the result of intensive percolation.

Hagen and Liestøl (1990) measured superimposed ice on Midtre Lovénbreen, where it reached the thickness of 5–20 cm. On many glaciers of the Arctic, it constitutes a major source of seasonal accumulation (Koerner 1970; Jonsson 1982). Taking into consideration the existing snow layers of high hardness, it may be noted that there are great similarities with the glaciers of Spitsbergen exposed to the influence of warm and humid air masses from the Norwegian Sea, being responsible for episodes of winter thaw (Leszkiewicz and Pulina 1999). The stratification of the snow cover is porous and discontinuous as well as spatially heterogeneous, which is typical of the snow cover present in polar and high mountain areas (Sturm and Benson 2004).

The mean density of the snow cover at the end of the accumulation season of 2010 at the presented sites was similar to the values observed on Waldemarbreen (north-western Spitsbergen) in 1997 (0.42 g cm^{-3}) and in 1998 (0.41 g cm^{-3}) by Grześ and Sobota (2000), however it was definitely higher than the value of 2005 (0.34 g cm^{-3}). The mean snow density on this glacier in 1996–2009 was 0.38 g cm^{-3} (Sobota 2013). The mean snow cover density on the glaciers of southern Spitsbergen is within the range of 0.40–0.50 g cm^{-3} (Migała *et al*. 1988), whereas Winther *et al*. (1998) determined the mean snow cover density on Svalbard as 0.37 g cm^{-3}. The specific, humid and mild climate of the south-western part of Spitsbergen engendered formation of melt-freeze crusts, and thus an increase in the snow density. This resulted in an elongation of the percolation and meltwater retention within snow cover, which supply glacial systems during the melting period.

Comparison of snow profiles from various glacier zones caused problems due to the different metamorphism stage of layers built from the same precipitation episodes. An increase over time in both the density of the snow and liquid water content was noticed at all study sites. The raise of the snow temperature effectively engendered a gradual decrease of the hardness of specified layers, bonding of the grains and an increase in grain size. The differences were related, in particular, to the shape of the grains in the subsequent measurement periods. Difficulties in comparing the results of the snow pit analysis from various glacier zones is an typical problem, emphasised also in previous snow studies on Hansbreen (Leszkiewicz and Pulina 1999; Głowacki and Pulina 2000; Leszkiewicz and Głowacki 2001; Głowacki 2007).

Melting intensity. — In recent years, on Hansbreen, two attempts to determine the melting intensity were conducted. Szafraniec (2002) created statistical models of melting rate based on the positive degree days. The results were slightly lower than those obtained in presented work, but calculations were based on period of significantly lower air temperature, *i.e*. 1989–1995. A large meteorological study of melting seasons 2003 and 2004 was presented by Migała *et al*. (2006). Measurements were also conducted using SR50 sensor. The snow melting intensity at H4 region was adequately 20 mm per day and 32 mm per day – values much higher than in 2010. Elongation of the melting period and slower disappearance of the snow cover in 2010 should be the consequence of a large diversity of the snow cover internal structure with a substantial contribution of high hardness layers and ice formations, which further delayed the processes of intensive surface melting. An important factor affecting melting dynamics is albedo, which decreases with the progress of melting. At the end of April on Hansbreen this ratio reached 0.85–0.90, then gradually reduced. In ablation zone (H4), albedo decreased to 0.25 – surface of the glacier ice, while in the accumulation zone (H9) was reduced to 0.70 – old snow with impurities (see Fig. 4).

The spatial distribution of the snow cover on Hansbreen was significantly higher in the eastern part of the glacier, which had been indicated in the previous studies (Grabiec *et al*. 2006). This is predominantly the result of wind circulation, which affects snow redeposition. In the analysed period, the share of the atmospheric circulation from the sectors SE, E, NE was significant – 92%

in April and nearly 80% in May (Soroka *et al*. 2010). Such observations are particularly important for an accurate estimation of the meltwater quantities (*i.e*. Głowacki 2007; Piwowar 2009) and calculations of the glacier mass balance (*i.e*. Szafraniec 2002; Migała *et al*. 2006).

Finally, our results should be considered as representative for Hansbreen and its immediate surroundings. The melting intensity is always combined with seasonal weather conditions but also closely related to topoclimatic conditions of the investigated area (Migała *et al*. 2008).

Conclusions

The dynamics of the snow cover melting is dependent not only on meteorological conditions and the thickness of the snow cover but also on its internal structure. Ice formations, which are often the result of winter *rain-on-snow* events, are of particular importance. They delay the meltwater migration. The rate of percolation may decrease along with the elevation of the glacier surface, due to the accompanying increase in the amount of ice formations in the internal structure of the snow cover.

The most important factors influencing the development of the snow temperature vertical distribution and the dynamics of its melting processes are the air temperature and insolation. The impact of the changes in the air temperature is noticeable throughout the entire snow profile, whereas, up to the depth of *c*. 35 cm, the variability of the snow temperature is synchronous with the air temperature changes, with correlation coefficient >0.90.

The climate warming, accompanied by an increase in winter thaws, may therefore paradoxically result in longer retention and limited runoff of meltwater from the snow cover.

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