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Winter snow accumulation and discharge from the Waldemar Glacier, northwestern Spitsbergen in 1996–1998

ABSTRACT: Studies of a snow cover on the Waldemar Glacier have been carried out during three spring seasons. In spite of its small area, there is considerable spatial variation in snow deposition on the Waldemar Glacier, different during successive seasons. Winter snow accumulation was the highest in 1995/96 (75 cm in water equivalent), but almost similar in 1996/97 and 1997/98, equal to 48 cm and 42 cm w.e., respectively. Snow cover shows specific physico-chemical features, with many sorts of snow different in its structure, hardness, density and moistening. All analysed snow profiles comprised layers of different grain size and hardness. Volume of water trapped in naledies was estimated to about 457,000 m^3 in May 1998. The average winter runoff from the glacier was estimated to 0.024 m^3/s *i.e.* about 9 l/s.km^2.

Key words: Arctica, Spitsbergen, Waldemar Glacier, snow accumulation, winter discharge, naled.

Introduction

The Waldemar Glacier is located in the northern part of the Oscar II Land, northwestern Spitsbergen (Fig. 1). Measurements were done in the first half of May during three successive seasons. They were assumed to correspond roughly with the maximum snow deposition in winter. The main goal of investigations was to determine water resources in snow and to estimate input in the mass balance equation for the Waldemar Glacier. The measurements comprised the whole catchment basin of the glacier (4.03 km^2) and referred to thickness, density, water equivalent, structure, vertical temperature distribution and electrical conductivity. An attempt was undertaken to evaluate runoff from the glacier in winter, based on observations of water migration in a snow cover at the glacier margin and in the extraglacial area.

Methods

An aluminium probe was used to depth measuring in a snow cover. The measurements were taken three times at every site. Snow pits were dug if a snow layer could not be passed through. Measurement sites were located on the map in scale 1:1000 (Lankauf 1995) and with a use of GPS. Basic measurement sites were the ablation poles installed during a preceding summer. Samples for snow density were collected with a steel cylinder, 100 cm^2 in cross-section. Their weight was assessed with professional dynamometric balance, accuracy to 5 g. Temperature and electrical conductivity were measured with equipment of the company "Elmetron". The basis for calculations and graphic presentation of spatial variation of snow cover thickness resulted from 125 to 155 soundings, about 40 measurements per 1 km^2.

Outline

The so-called snow photograph is the basis for estimating snowfall in areas excluded from systematic observations. Precipitation on the western shore of Spitsbergen is about 400 mm annually. According to Hagen *et al.* (1993), the central part of the island does not get even that much. Precipitation on glaciers in western Spitsbergen often exceeds the equivalent of a snow layer, 2–4 m thick. Snow cover is for 250–270 days a year there and, according to Migała, Pereyma and Sobik (1988), it is a predominating surface element with all climatic and hydromorphological consequences. In case of such a small glacier, snow blowing and its deposition on lee-ward side of every elevation and at foot of a snout is significant. Catabatic winds and local orographic conditions are the main factors responsible for variation of a snow cover thickness (0–6 m) in the catchment basin of the Waldemar Glacier.

For assessment of a glacier mass balance, snow share in annual precipitation is extremely important. The closest meteorological station is located in Ny Alesund. In 1995 a snow share was equal to about 80% there, while the average snow share was about 69% in 1991–1997. Such values can be assumed as representative for Kaffiøyra. Not only snowfall and winter retention determines mass balance, but anemometric conditions are also considerably important. Variation in thickness of a snow cover in the Waldemar Glacier catchement basin exceeds 6 m. Ice-cored moraines and the steepest parts of a snout are not covered with snow. Snow redeposition is limited by warmings in winter as well as occurrence of wind-resistant ice layers that make further snow redeposition more difficult. Snow redeposition starts playing significant role at wind speed over 4 m/s. Using a simple snow deflation gauge, it was determined for low snowstorms in May 1997 and 1998. At wind speed 4.8–5.0 m/s the snow wind drift index was equal daily to about 1000 kg per 1 m^2 cross-section. At wind speed below 5 m/s (3.8–4.2 m/s), the snowdrift index was considerably lower. Its values reached up to 300–350 kg per

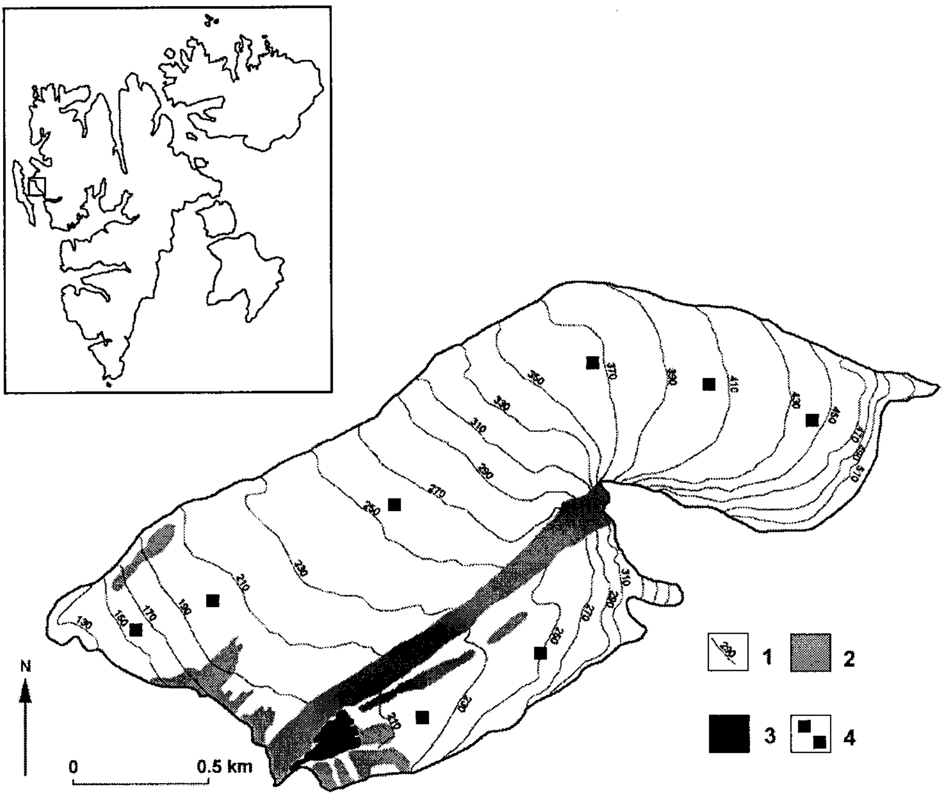

Fig. 1. Map of the Waldemar Glacier, northwestern Spitsbergen.
1 – contour lines, 2 – median and surface moraine, 3 – ice-dam lake, 4 – snow pits.

1 m^2 cross-section daily. The measurements were taken on medium hardness surfaces *i.e.* R2, according to a classification of the International Commission of Snow and Ice (ICSI).

Therefore, description of snow conditions on the basis of a single snow photograph must be treated as approximation of real conditions on a glacier only.

Seasonal and spatial variation of snow accumulation

Spatial distribution of snow thickness on a glacier is implied by local conditions, independent on weather. Snow accumulation is larger with higher altitude on most glaciers and it is due to different weather conditions at individual parts of a glacier. This phenomenon is especially distinct in case of glaciers with large difference in altitude between firn field and front part. In spite of its small area, the Waldemar Glacier shows great spatial variation of snow accumulation, different during individual

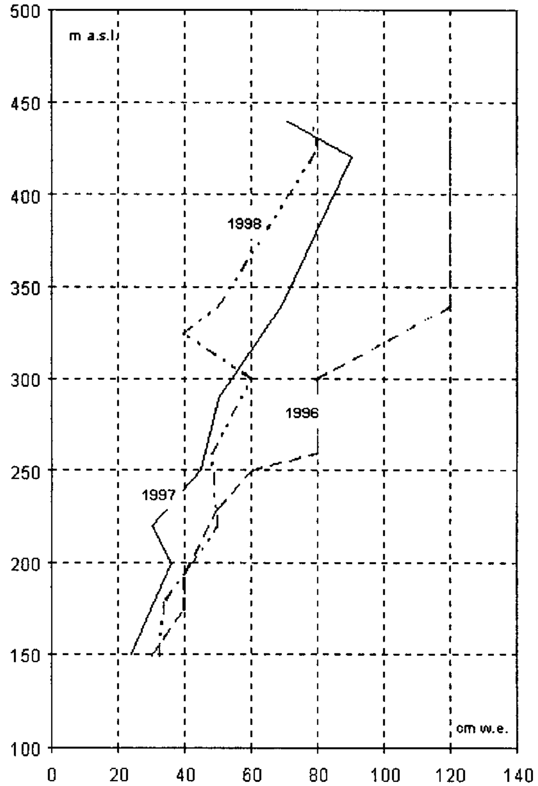

Fig. 2. Vertical variation of snow accumulation on the Waldemar Glacier in 1996–1998.

seasons. The highest rise of snow accumulation with altitude was observed in 1996 (Fig. 2) and the gradient of accumulation was equal to 30 cm w.e. per 100 m in altitude. During this season, snow accumulation was the highest, mainly in the firn field. Gradients in 1997 and 1998 were equal to 20 and 16 cm w.e., respectively, per 100 m altitude. Predominant wind direction (Jania 1993) and snow cover thickness at a glacier snout play also significant role in redeposition of snow. At snout of the Waldemar Glacier there are places without a snow cover. Much snow is deposited in the Waldemar River gap. Snow redeposition determines also larger accumulation, which was noted among others on glaciers in South Spitsbergen by Migała, Pereyma and Sobik (1988). Interrelations between snow deposition and altitude are confirmed by the correlation coefficient equal to 0.95–0.85.

Considerable spatial variation of snow deposition is noted on the Waldemar Glacier (Fig. 3). During the winter 1995/96, the thickest layers of snow occurred in a northern part of the glacier, both in its firn field and at foot of Grafjellet which surrounds the glacier from the south (Fig. 3). The highest water equivalent was equal to 120 cm. The lowest thickness of a snow cover was observed at snout of the

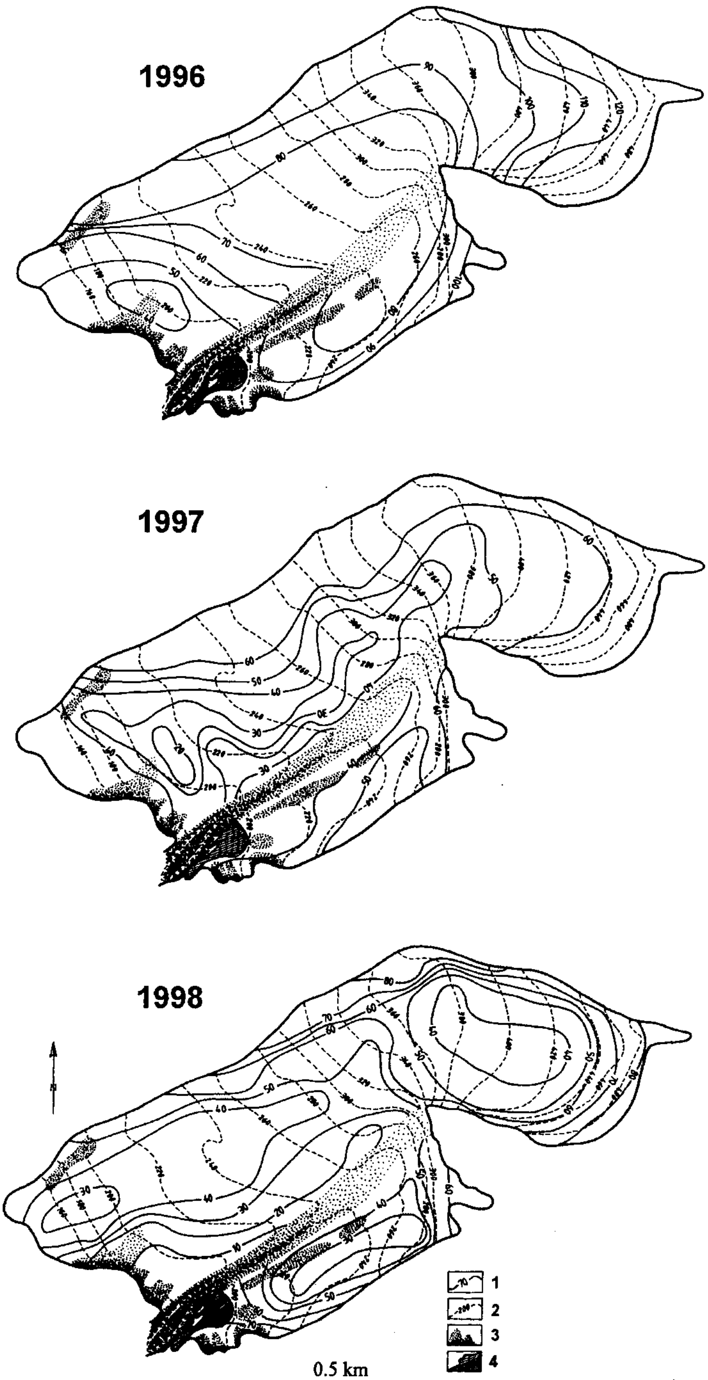

Fig. 3. Map of snow accumulation on the Waldemar Glacier in May 1996–1998. 1 – snow accumulation isolinies (in cm w.e.), 2 – contour lines, 3 – median and surface moraine, 4 – ice-dam lake.

glacier and at foot of the median moraine (up to 30 cm w.e.). In 1997 spatial distribution of snow was similar, although deposition reached only a half of the previous volume, mainly in the firn field (60 cm w.e.). Record of winter snow deposition in 1998 was very much similar (Fig. 3). The thickest layer of snow, 60–80 cm w.e., occurred on the glacier at foot of the surrounding mountains. Slightly less snow was noted in the centre of the firn field, due to intensive blowing out. Snow accumulation at snout of the glacier and at foot of the median moraine was the lowest (10–20 cm w.e.), similarly as during the previous seasons.

Winter snow accumulation was the highest in 1995/96 (75 cm w.e.). It was similar in 1996/97 and 1997/98, and equal to 48 and 42 cm w.e., respectively. Mikhaliov and Singer (1975) as well as Jania and Hagen (1996) recorded similar values for the other glaciers in Svalbard. Average snow accumulation was estimated to 75 cm w.e. for the Midre Løven Glacier in 1967–93 (Jania and Hagen 1996). This glacier has similar morphometry as the Waldemar Glacier but occurs about 35 km to the north. Such value is not much different from the average snow accumulation in 1995–98 on the Waldemar Glacier, equal to about 60 cm w.e.

There is a typical pattern of snow deposition on the Waldemar Glacier every winter. The largest accumulation is noted in the firn field and at foot of mountains, and most glaciers follow this rule. However, the lowest snow accumulation is more complex, because thinnest snow covers occur at a glacier snout up to 220 m a.s.l. and at foot of a median moraine, due to blowing out by wind and the highest glacier slope. The glacier snout up to 200 m a.s.l. is inclined at 10–11° (Lankauf 1997). Summer ablation is determined considerably by spatial variation of winter snow accumulation. Asymmetry in snow cover thickness is noted nearly at all altitudes. Similar pattern of snow distribution was described on the Hans Glacier (Jania 1993). The lowest snow cover thickness is connected with the highest surface ablation. In 1995–98 snow accumulation on the Waldemar Glacier was equal to 160 cm w.e. and 100–130 cm on the average at the equilibrium line altitude (ELA) what is similar to the other glaciers in this part of Svalbard (Koryakin, Krenke and Tareeva 1985).

Snow cover characteristics

Snow cover has specific physico-chemical features. Many sorts of snow can be distinguished in a vertical profile, different in their density, hardness and moisture. Very distinct snow layers are frequently limited by sharp boundaries. Snow structure reflects weather conditions at time of deposition. Snow surface is transformed by snow deposition, melting, evaporation, erosion and sublimation. Physico-chemical features including temperature, electrical conductivity and hardness, as well as structure of a snow cover were examined on the Waldemar Glacier. Individual parameters were analysed according to snow features and symbols used by the International Commission of Snow and Ice (Colbeck *et al.* 1990).

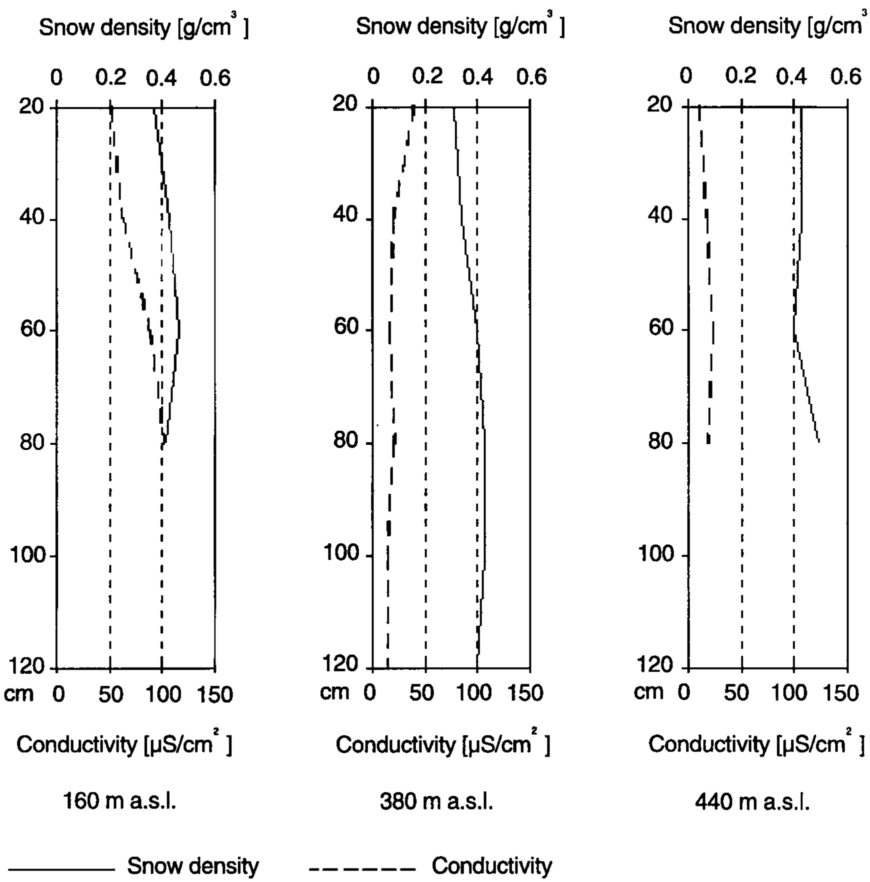

Fig. 4. Snow density and conductivity on the Waldemar Glacier in May 1998.

Density is a most important feature of a snow cover. Sample weights were measured with professional dynamometric balance accuracy to 5 g. Snow density on the Waldemar Glacier is from 0.31 to 0.52 g/cm^3. It is the lowest in a surface layer (Fig. 4), in which there is mainly fresh and low-compacted snow. Density increases usually considerably with depth due to compaction of the upper snow layers. In the bottom part of a snow cover there is commonly a layer of strongly blown-out, coarse-grained snow of lower density. Average snow density on the Waldemar Glacier was equal to 0.42 g/cm^3 in 1997 and 0.41 g/cm^3 in 1998. In South Spitsbergen the average snow density was equal to 0.4 and 0.5 g/cm^3, respectively (Migała, Pereyma and Sobik 1988).

High correlation between snow depth and its temperature was observed at most measurement sites. Values of this correlation were equal to -0.87, -0.90 and -0.92. The temperature on the surface is the highest and decreases distinctly with depth. The highest temperature on the surface was equal to -2.4°C at 260 m a.s.l. in 1998.

In 1997 the lowest snow temperature -10.1°C was measured at depth 100 cm, while in 1998 the lowest value -9.7°C was noted at depth 60 cm and altitude 440 m. The average snow temperature on the Waldemar Glacier is -7.4°C.

Analysis of snow pits indicated large differentiation of a snow cover in 1998. On the other hand, snow cover was quite homogeneous in 1997 (Fig. 5). Fine- and medium-grained snow prevailed, with vertical homogeneity, and interbeddings and ice layers were absent. Low (R2) and medium (R3) hardness degree of snow predominated, and the only ice layer occurred at 380 m a.s.l.

Structure of a snow cover was much more complex in 1998 (Fig. 5). Fresh and fine-grained snow was discovered on the surface in most snow pits, whereas frozen and coarse-grained snow was found directly on ice. Its hardness was from low (R2) to very high (R6), and numerous ice layers were found. Most of them occurred at 410 and 440 m a.s.l. Ice layers could result from catabatic winds blowing during snow deposition, accompanied by short warmings resulting in melting of snow. In the discussed profiles snow size composition and hardness were highly diversified. In the profile at 440 m a.s.l. there were fresh, fine-, medium- and coarse-grained snow types as well as solid frozen snow. At 410 m a.s.l. there were fresh, fine-, medium- and coarse-grained snow types as well as frozen snow with numerous ice layers. Great number of ice layers was also noted in a snow cover at the glacier snout (160 and 220 m a.s.l.). Ice layers occurred in lower parts of all the profiles, and therefore they were formed at the beginning of winter. This conclusion finds its confirmation in warmings easily indicated by the temperature recorded at the meteorological station at Ny Alesund. Ice layers are an important index of seasonal beginnings at different parts of the glacier. In spite of numerous ice layers, in 1998 winter snow accumulation started in the firn field of the Waldemar Glacier. More common ice layers at a glacier snout indicate the end of summer.

Naledies and winter discharge from the Waldemar Glacier

Naledies belong to the least examined glacial phenomena in Spitsbergen. Akerman (1980) distinguished 4 types of Spitsbergen naledies: the first one accompanies outflow of groundwater, the second is connected with ice-cored hills named pingos, the third with rivers and the fourth with outflow of glacial water. In literature most attention is paid to geomorphological role of naledies (Jewtuchowicz 1962, Olszewski 1982) whereas Baranowski (1977) was the first one who focused on interrelation of naledies and thermic-moisture types of glaciers.

Jania (1993) points out that naled research is very difficult from methodological point of view, because snow cover mantles naledies and moreover, the latter form during polar night and at low temperatures. As far as methods of investigation and explanation of naledies development are concerned, considerable progress was made while examining the Werenskiold Glacier (Krawczyk and Pulina 1983;

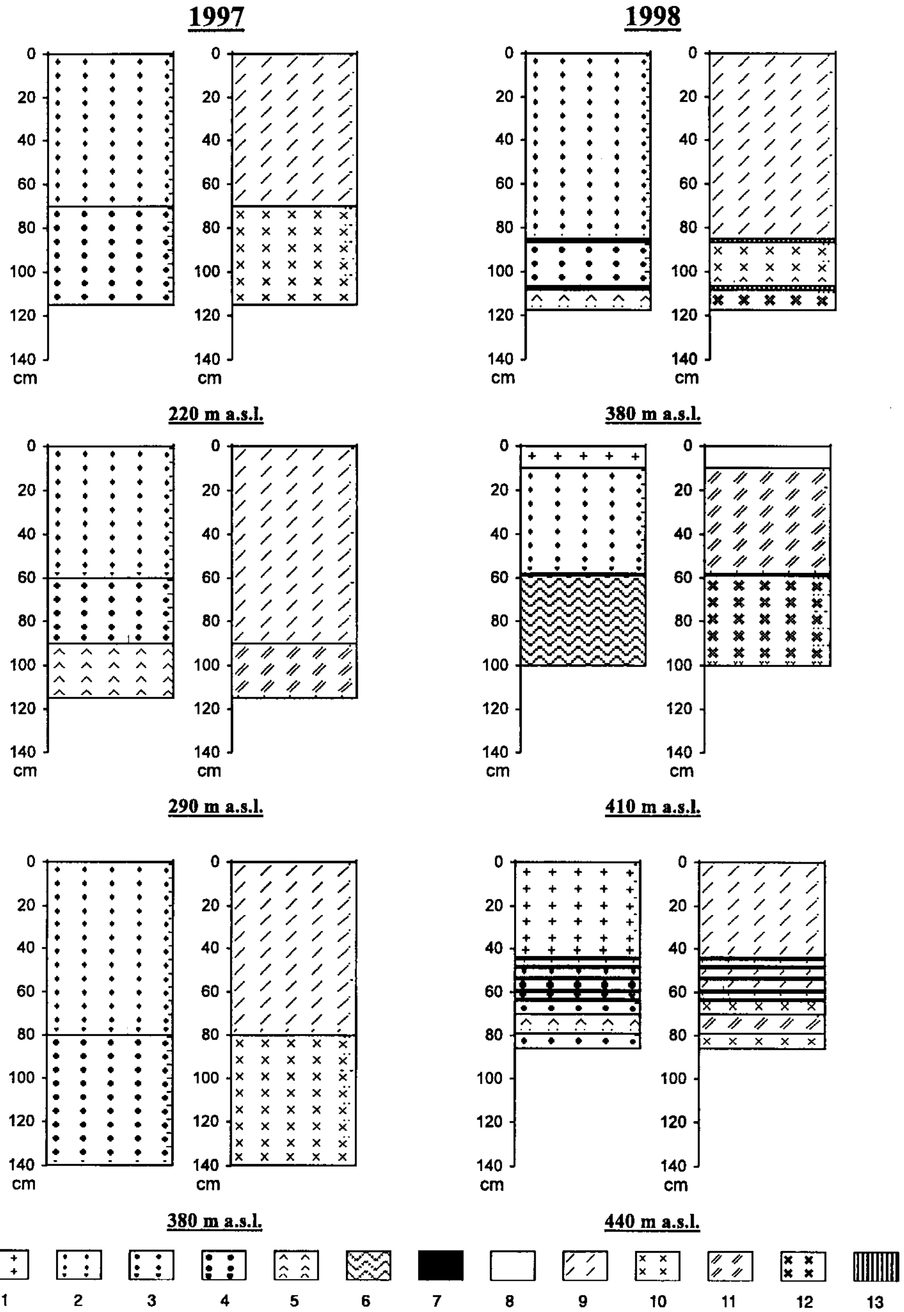

Fig. 5. Snow profiles at selected altitudes on the Waldemar Glacier according to ICSI in May 1997–1998. Snow grain size and type: 1 – fresh snow, 2 – fine-grained snow, 3 – medium-grained snow, 4 – coarse-grained snow, 5 – coarse-grained snow, strongly metamorphosed (hoar snow), 6 – frozen snow with ice layers, 7 – ice layer. Hardness of deposited snow: 8 – very low (R1), 9 – low (R2), 10 – medium (R3), 11 – high (R4), 12 – very high (R5), 13 – ice (R6). Location of snow pits on Fig. 1.

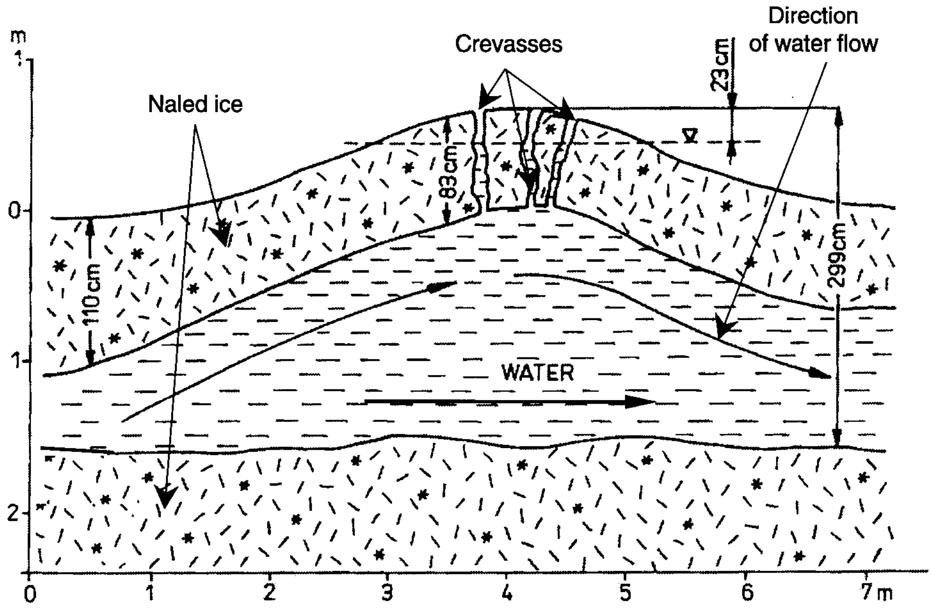

Fig. 6. Typical naled on the Waldemar Glacier.

Pulina 1984, 1986; Krawczyk 1992; Krawczyk and Wach 1993). Pulina (1984) described complex cryochemical processes, relation between chemical composition and water circulation in a glacier.

Naledies occur in forefields of all glaciers in Kaffiøyra. As far as the Waldemar, Andreas and Olivier Glaciers on Kaffiøyra are concerned, naledies exceed their morainal zones. In 1938 Klimaszewski (1960) observed naledies in proglacial zones of the Irene and Elise Glaciers in the same region. Glacier retreat made the contemporary naledies be limited to the inner zones, covering as much as 20% of their area (Grześ and Lankauf 1997), and this estimation was confirmed by observations in spring 1997 and 1998. The fact that naledies exceeded inner zones of the Waldemar, Andreas and Olivier Glaciers results from their small capacities. No clear relation between sizes of naledies and glaciers was found.

Specific pattern of naledies can be observed on the Waldemar Glacier. At the end of the 1960s temporary glacial water outflow about 25 m above its frontal part has started. On the glacier a supraglacial naled was formed, according to the terminology of Olszewski (1982). Significant difference in albedo leads to deformation of a glacier snout. The elevation was formed on a naled and glacier ablation decreased. The naledies of the Waldemar Glacier are formed in 4 zones *i.e.* supraglacial, inner, water gap and proglacial ones. Areal extent of naledies depends on water migrations in a snow cover. Its thickness increases due to capillary absorption of a snow cover and snow interception by damp surface. Sub-naled and in-naled channels work from the very moment of naled development up to its total disappearance. The main outflow courses end up with ice uplifts and water overflows onto the surface. Such channels start linear degradation of naledies in the l ate spring.

Naledies form a complex net of channels. Blockage of this system leads to pressure increase and intrusion of water into a snow cover lingering on the surface. If it contacts with layers of ice, characteristic naled hill-like forms develop (Fig. 6), occurring on the whole ice-coating surface. The water gap of the Waldemar River is filled with 7–8 m of snow during winter. Thus, there are very good conditions for sub- and intra-nival outflow routes.

The amount of water trapped in naledies was estimated. It was equal to about 457,000 m^3 in May 1998. The average winter outflow from the glacier was estimated to 0.024 m^3/s i.e. about 9 l/s from 1 m^2. Pulina (1986) estimated the average winter outflow from the Werenskiold Glacier to 0.084 m^3/s *i.e.* 3 l/s from 1 m^2. Taking into account significant differences in glacier size and incomparable measurement periods, the value for the Waldemar Glacier seems to be very high.

Snow and ice block a water gap of the Waldemar River throughout winter and spring. Water was found in most snow pits and holes drilled in naledies. Its electrical conductivity was not only high but also changeable. The maximum electrical conductivity reached 680 mS/cm^2 on 5th May 1998. The next day, 6th May 1998, it was only 370 mS/cm^2 although the water sample was collected at the same spot. Electrical conductivity was equal from 490 to 640 mS/cm^2 in water samples collected simultaneously at some locations on May 10, 1998, whereas it reached from 550 to 580 mS/cm^2 on May 2, 1998. Such considerable time and spatial variation of electrical conductivity is an indirect evidence of complex network of water migration channels as well as water intrusions in naledies and snow covers. Freezing water becomes a part of naled.

Highly conductive and large outflow in winter supports the idea of its supply with water from deep circulation. An overdeepening seems to exist underneath the ablation zone of a glacier and in this very place the meltwaters are collected. The ice crevasse, formed probably over a rocky step, was filled with water at the end of the ablation season in 1998 and its depth was equal to 26.5 m in 1995 and 16.5 m in 1998. Water table occurs at depth 12 m at the beginning of each ablation season.

Further research on estimating winter outflow from the glacier is still needed. The quoted winter discharge from the Waldemar Glacier was not included in the winter balance.

Conclusions

Snow deposition and water discharge from the Waldemar Glacier were measured each season in the first half of May. This period was assumed roughly to comprise maximum snow deposition in winter.

In spite of its small area, the Waldemar Glacier presents great spatial variation of snow deposition. The highest rise in snow accumulation with altitude was observed in 1996, with the accumulation gradient 30 cm w.e. per every 100 m, whereas in 1997 and 1998 there were 20 and 16 cm w.e., respectively. Snow cover at front of a glacier reacts significantly on the gradient. In this zone a snow wind-blown redeposition takes place. In a frontal part of the Waldemar Glacier there are places without a snow cover. The highest water equivalent is equal to 120 cm. The lowest snow cover thickness was observed at front of the glacier and at foot of the median moraine (up to 30 cm w.e.). In 1997 spatial distribution of snow was similar. Winter snow accumulation was the largest in 1995/96 (75 cm of w.e.). It was similar in 1996/97 and 1997/98, equal to 48 and 42 cm w.e., respectively.

Snow density on the Waldemar Glacier is equal from 0.31 g/cm^3 to 0.52 g/cm^3 and the average snow temperature is –7.4°C. The lowest density is noted in the surface snow. The average snow density was equal to 0.42 g/cm^3 in 1997 and 0.41 g/cm^3 in 1998. On glaciers in South Spitsbergen the density was equal to 0.4 – 0.5 g/cm^3 (Migała, Pereyma and Sobik 1988).

Fine- and medium-grained snow prevailed, vertically homogenous, without interbeddings and ice layers. A snow cover of 1998 was much more complex than a year before. Fresh and fine-grained snow was discovered on the surface in most snow pits, whereas frozen and coarse-grained snow was found in a layer directly on ice. The hardness values ranged from low (R2) to very high (R6). For example at 440 m a.s.l. there were fresh, fine-, medium- and coarse-grained sorts of snow as well as a solid frozen snow. Ice layers are important indicators of seasonal beginnings at different parts of a glacier. More ice layers in a frontal part of a glacier indicate that summer lasted longer there. Ice layers play significant role in snow deposition. Moreover, their existence proves that short-term melting of snow is possible despite deposition of fresh snow.

Naledies develop in forefields of all the Kaffiøyra glaciers. As far as the Waldemar, Andreas and Olivier Glaciers on Kaffiøyra are concerned, naledies exceed their marginal zones. The naledies of the Waldemar Glacier form in 4 zones i.e. supraglacial, inner, water gap and proglacial ones.

Volume of water trapped in naledies was estimated. In May 1998 it was equal to about 457,000 m^3. The average winter outflow from the glacier was estimated to 0.024 m^3/s *i.e.* about 9 l/s from 1 m^2.

There is an overdeepening under the ablation zone of the glacier. It is indicated in the glacier longitudinal profile, network of streams and contour lines, crevasses and directions of ice movement.

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Streszczenie

Lodowiec Waldemara położony jest na Równinie Kaffiøyra w północno-zachodnim Spitsbergenie (fig. 1). Głównym celem badań było określenie zasobów wody w śniegu i ocena przychodowej części równania bilansu masy lodowca Waldemara. Pomiary zimowej akumulacji śniegu i zimowego odpływu prowadzone były na lodowcu Waldemara w pierwszej połowie maja każdego sezonu. Założono, że badania z tego okresu odpowiadają maksymalnym wartościom akumulacji śniegu.

Podstawą do obliczeń i graficznego przedstawienia przestrzennego zróżnicowania miąższości pokrywy śnieżnej było od 125 do 155 sondowań. Daje to około 40 pomiarów na km^2.

Lodowiec Waldemara pomimo niewielkiej powierzchni cechuje się dużą zmiennością przestrzenną akumulacji. Również w przypadku tego lodowca stwierdzono wspomnianą powyżej prawidłowość. Miała ona różny charakter w poszczególnych sezonach zimowych. Największy wzrost akumulacji śniegu z wysokością stwierdzono w 1996 roku (fig. 2), a gradient akumulacji wyniósł 30 cm równoważnika wody na każde 100 m wysokości. W tym samym roku stwierdzono także największą akumulację śniegu, zwłaszcza w części firnowej. W latach 1997 i 1998 wartości te były znacznie mniejsze i wynosiły odpowiednio 20 cm i 16 cm r.w. na 100 m wysokości. Zimą 1995/96 akumulacja śniegu była największa wynosząc 75 cm r.w. W latach 1996/97 i 1997/98 była podobna, wynosząc odpowiednio 48 cm i 42 cm r.w. W przestrzennym rozkładzie zimowej akumulacji śniegu na lodowcu Waldemara obserwuje się pewne prawidłowości w każdym sezonie zimowym. Największa akumulacja występuje w części firnowej i u podnóża stoków górskich, najmniejszą stwierdzono w strefie czołowej do wysokości 220 m n.p.m. i u podnóża moreny środkowej (fig. 3).

Na lodowcu Waldemara przeprowadzono szczegółowe pomiary cech fizyczno-chemicznych (temperatura, konduktywność, twardość) i struktury pokrywy śnieżnej. Gęstość śniegu wahała się od 0,31 do 0,52 g/cm^3, a średnio wyniosła 0,42 g/cm^3 w 1997 roku i 0,41 g/cm^3 w 1998 roku (fig. 4). Średnia temperatura śniegu na lodowcu Waldemara wynosi -7,4°C. Szczegółowa analiza ścian szurfów wykazała bardzo duże zróżnicowanie cech i charakteru pokrywy śnieżnej w 1998 roku. Z kolei pokrywa śnieżna nie była zróżnicowana w 1997 roku (fig. 5). W większości odkrywek w warstwie powierzchniowej przeważał śnieg świeży i drobnoziarnisty, z kolei w warstwie nad lodem występował silnie przemarznięty śnieg gruboziarnisty. Twardość śniegu była od słabej (R2) do bardzo dużej (R6). Na uwagę zasługuje fakt występowania licznych lodoszreni (fig. 5).

Nalodzia lodowca Waldemara składają się czterech charakterystycznych części: supraglacjalnej, strefy wewnętrznej, przełomowej oraz proglacjalnej (fig. 6). Stwierdzono, że o przestrzennym zasięgu nalodzi decydują warunki migracji wody w pokrywie śnieżnej. Na podstawie kartowania dokonano szacunku ilości wody zgromadzonej w nalodziach. W maju 1998 roku wyniosła ona około 457 000 m^3, z czego 66% (300 000 m^3) przypada na strefę wewnętrzną z przełomem. Średni wypływ zimowy z lodowca oceniono na 0,024 m^3/s, co daje około 9 $l/s\ km^2$.