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Snowfall phases in analysis of a snow cover in Hornsund, Spitsbergen

ABSTRACT: Conditions influencing formation of a snow cover in southern Spitsbergen in Hornsund during the winters 1988/1989 and 1989/1990 are presented. Winter snow cover consists of several overlaid layers which correspond to particular snowfall phases, distinguished on the basis of analysis of occurrence of winter precipitation and development of a snow cover in numerous snow pits. Five snowfall phases during the winter 1988/1989 and three during the winter 1989/1990 were determined. A genetic classification, including specific features of a snow cover in Spitsbergen, was applied to describe snow layers in pits. The classification covers metamorphic changes of snow: dry metamorphosis, wet metamorphosis without freezing, wet metamorphosis with freezing, and aeolian metamorphosis. Precipitation, strong winds, and winter thaws are the factors which mostly influence formation of a snow cover in the Hornsund region. Most winter precipitation is connected with inflow of relatively warm air masses from the Norwegian Sea. Short term winter thaws which occur afterwards, result in formation of a characteristic ice-crust on a snow cover. The ice-crust layer protects a snow cover against deflation. It is also a marker band which enables dating of snow. Ice crust layers are almost always the borders between particular snowfall phases. Strong winds ($V \geq 8$ m/s) significantly transform a surface layer of snow. Snow deflation, which is locally quite intensive, occurs mainly at seashore plains, mountain ridges and convex slopes.

Key words: Arctica, Spitsbergen, snow cover.

Introduction

The paper presents development of a snow cover in winter in southern Spitsbergen. A glacier and a non-glaciated area, affected differently by winds which re-

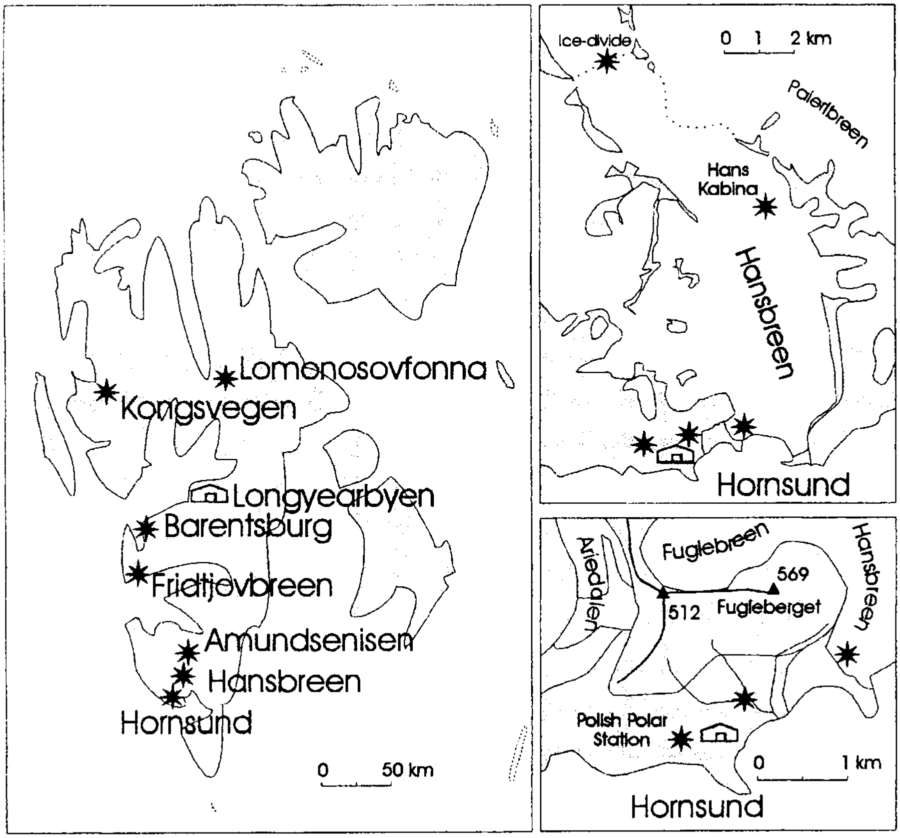

Fig. 1. Location of snow investigation sites and research stations.

moved a snow cover, were examined. Relation between meteorological conditions and development of a snow cover were analysed.

Nival research was carried out in the vicinity of the Polish Polar Station in the winters 1988/1989 and 1989/1990. Numerous snow pits were dug at the Hans Glacier and in the adjoining area, while detailed investigations were carried out in the neighbourhood of the Polish Polar Station (Fig. 1). Research was based on meteorological data from the Polish Polar Station as well as from the Russian station at Barentsburg. Data base for nival and meteorological observations from southern Spitsbergen were prepared at the Department of Geomorphology of the University of Silesia.

Volume, rate and chemistry of precipitation are strictly connected with inflow of air masses. A cause-effect relation between air circulation in Spitsbergen and precipitation was available from weather forecast maps of the Arctica and the North Atlantic. The authors used the German weather maps (Boden Deutscher Wetterdienst), broadcasted in Offenbach in the winter 1988/1989. Types of air circulation, determined by Niedźwiedź (1987) for the Svalbard region, were applied in analysis of these maps.

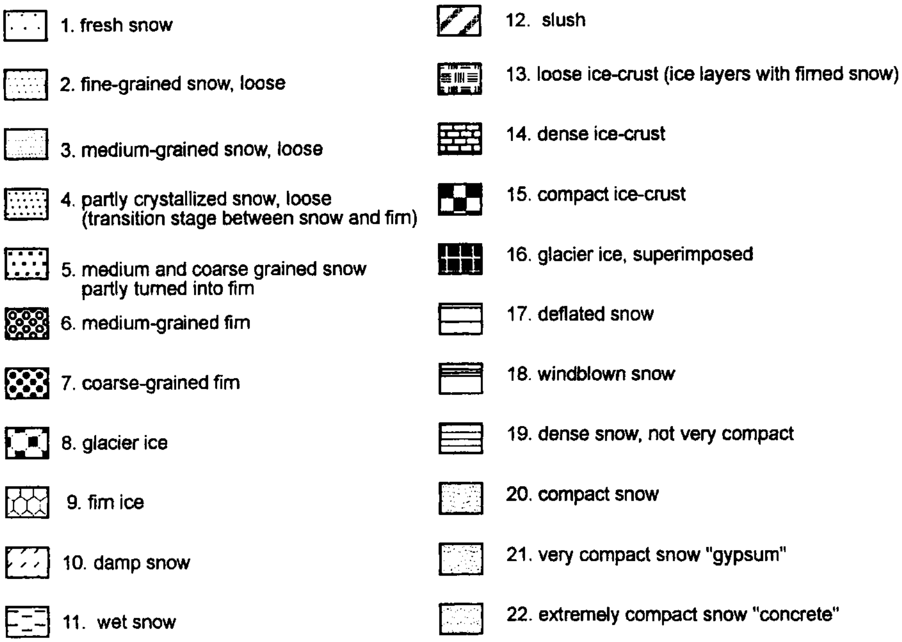

Fig. 2. Snow classification.

Research methods enabled to describe a snow cover, to reconstruct snowfall phases and to determine meteorological and physico-chemical elements that accompanied development of a snow cover. This method can be applied to:

- reconstruction of characteristic features of a whole winter, in spite of a lack of detailed investigations during a polar night – lacking data are provided from analysis of a snow cover at the end of winter, although such reconstruction is slightly limited;
- studies of precipitation pollution – in this case, proper analysis of a snow profile is important, especially when vast areas are examined;
- comparison of snow profiles in different areas.

Genetic classification of snow, firn and ice was used to describe snow layers in pits (Fig. 2). This classification corresponds to international standards (Kotliakov 1984) and comprises also specific features of a snow structure in Spitsbergen. It classifies transformation of snow *i.e.* dry metamorphosis (nos 1–9), wet metamorphosis without (nos 10–12) and with freezing (nos 13–16), and aeolian metamorphosis (nos 17–22).

Winter meteorological elements in southern Spitsbergen

Seasons in polar countries are distinguished on the basis of climatic, hydrological, glacial and other criteria. This item was studied in Spitsbergen by Baranowski

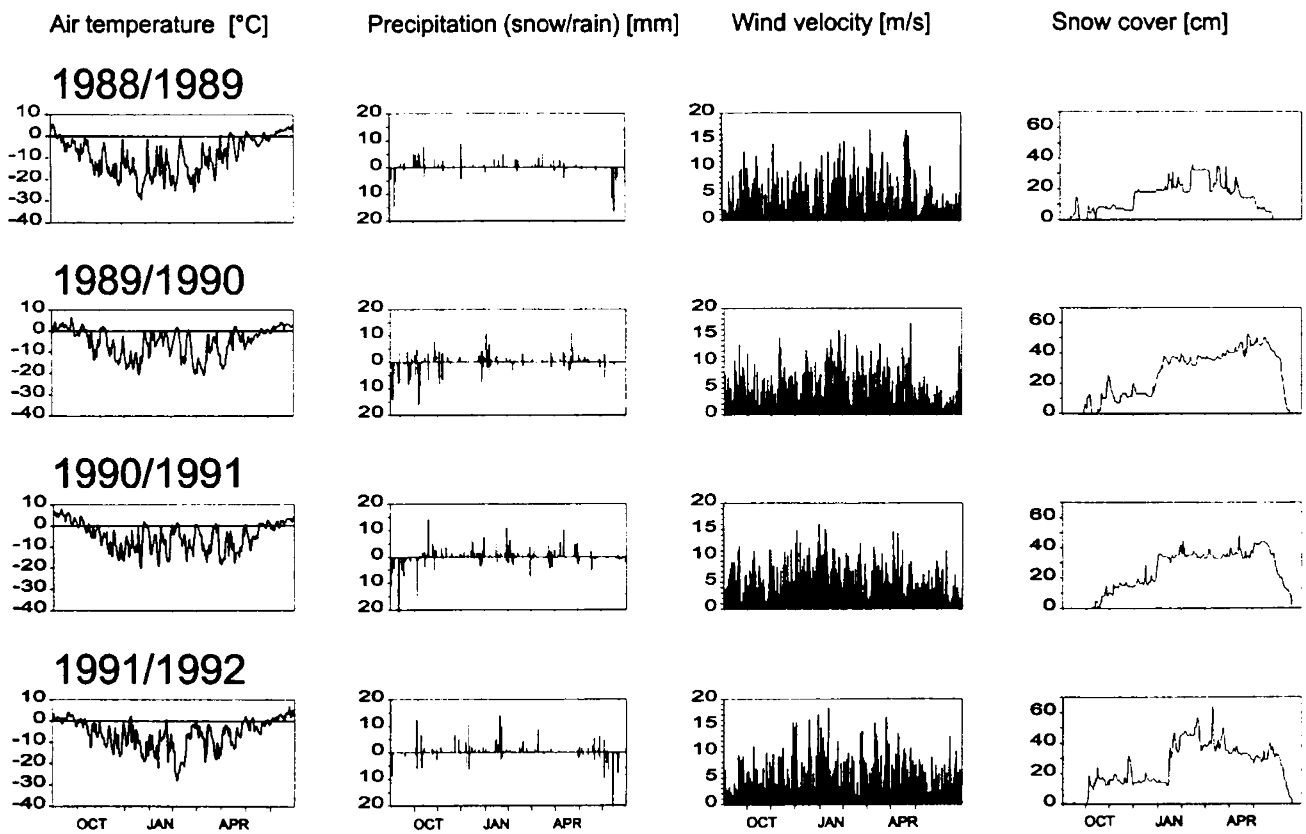

Fig. 3. Daily course of selected meteorological elements at the Polish Polar Station in Hornsund during the winters 1988/1989 – 1991/1992. Air temperature in mean values, precipitation in 24 hour totals (snow – upper values, rain – lower values), wind velocity in mean values of 8 observations in 24 hours, thickness of a snow cover.

(1968), Markin (1975), Pulina *et al.* (1984) and Leszkiewicz (1987). Criteria of the latter are applied in this paper. They include transformations of a snow cover. According to this classification, the following seasons can be distinguished: early winter, winter, early spring, spring, summer and autumn.

Early winter is usually a short or even a very short transitional period with a temporary snow cover. Winter has a permanent snow cover and lasts more than seven months. Early spring is a period with thawing but without outflow of meltwaters, and lasts three to four weeks.

The most important meteorological factors forming a snow cover in winter are:
- snow precipitation – a snow cover gets thicker,
- strong winds with velocity ≥8 m/s, transporting much snow, deposited in concave wind-protected landforms; however, considering total balance in the vicinity of the Polish Polar Station, snow is mostly blown out to a sea;
- winter thaws – surface of a snow cover melts, water freezes below and forms an ice-crust, protecting a lower snow layer from deflation; however, extremely strong winds, exceeding 30 m/s in gusts, can destroy a thin and weak ice-crust.

Typical daily changes of selected meteorological elements during the winters 1988/1989–1991/1992 at the Polish Polar Station in Hornsund are presented (Fig. 3).

Winter 1988/1989

The winter 1988/1989 in southern Spitsbergen began and terminated few weeks earlier if compared with a perennial average (Table 1). It was frostier and longer than usually, and lasted seven and a half month. The early winter was short – only six days long. On September 10–15, a less active depression formed over the Arctic Sea and caused inflow of cold arctic air masses from the northwest. The temperature dropped from 4.5°C to 0°C. Hence, the following depression which formed in the Iceland region and moved towards Spitsbergen, resulted in first precipitation at the lowland in the vicinity of the Polish Polar Station. Such was a beginning of winter as all the following thaws after September 16, were of the winter type *i.e.* they were short and a snow cover has not melted out. Winter in the mountains started a week earlier (September 9/10).

Despite of a lack of thaws, a snow cover was not permanent in the vicinity of the Polish Polar Station. Strong winds at the end of September and in mid-October completely blew out a snow in vast areas. A permanent snow cover in the lowland appeared on 17th October, apart from small areas where snow deflation was particularly intensive.

A snow cover has developed gradually, layer by layer, starting in the lowland in mid-October and lasting until the first decade of April; corresponding interval in upper parts of the Hans Glacier occurred from mid-September till mid-April. This process, as it has been already mentioned, was interrupted many a times by wind which blew out a snow to a sea or moved it from one place to another.

Table 1

Length of early winter, winter and early spring, and comparison of climatic conditions in the winters 1988/1989 and 1989/1990 in the vicinity of the Polish Polar Station. Strong wind (velocity ≥8 m/s) which transports much snow. Hornsund PAS – Hornsund Station of the Polish Academy of Sciences, Hornsund US – Hornsund Station of the University of Silesia.

Climatic characteristics of winter		Units	Winter 1988/1989	Winter 1989/1990
Early winter			Sept. 10–15	Sept. 22–Oct. 16
		[number of days]	6	25
Winter			Sept. 16–May 1	Oct. 17–May 16
		[number of days]	228	212
Early spring			May 2–25	May 17–June 15
		[number of days]	24	30
Winter thaws		[number of days]	12	22 (18)
		[number of days]	25	50
Snowfall phases		[number of days]	5	3
Phases of snow deflation		[number of days]	8	8
Air temperature	average	[°C]	-11.9	-7.9
	maximum		3.2	4.1
	minimum		-32.1	-25.1
Precipitation		[mm]	170.0	256.0
Water equivalent of a snow cover at the end of winter	Hornsund PAS	[mm]	70	240
	Hornsund US		206	334
	Hans Glacier		774	895
	Ice-divide		781	1201
	Amundsenisen		–	1115
Wind	average	[m/s]	5.8	6.3
	maximum	[m/s]	25	23
	strong wind	[% of observation periods]	33.7	37.1

Major precipitation that formed a snow cover in the vicinity of the station occurred in the second half of October and the first half of November (phase of snowfall 1), the first decade of December (phase of snowfall 2), in January (phase of snowfall 3), the second decade of February (phase of snowfall 4) and the first decade of April (phase of snowfall 5). A six-day thaw in the second decade of April started permanent and final degradation of a snow cover.

Snow precipitation varies in pH and conductivity, equivalent of solute concentration (Fig. 4). Extreme conductivity, equal to 2020 μS/cm, results from secondary contamination of snow by sea aerosol, transported by a strong wind.

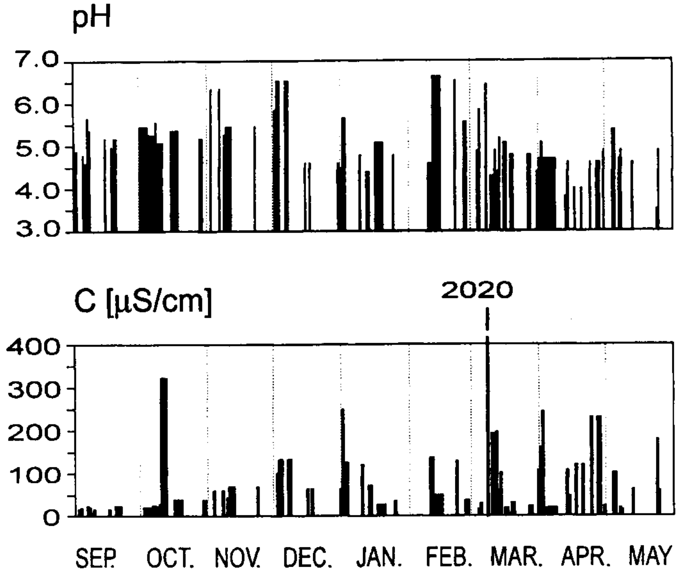

Fig. 4. Precipitation at the Polish Polar Station region in Hornsund (Spitsbergen) in the winter 1988/1989; presented are electric conductivity C and pH of snow.

In the beginning of May 1989, two pressure systems formed near Spitsbergen: anticyclone in the east with its centre over Novaya Zemlya and a depression with atmospheric front over Iceland, approaching from the southwest. Eastwards-moving depression was blocked by an anticyclone. Hence, the depression stopped in the Spitsbergen region and was active six days there until it completely filled up. Warm air masses moving from the south, foehn wind in Hornsund and rise of temperature, followed by a long lasting thaw, resulted from such meteorological conditions. It was the end of winter and a beginning of early spring in southern Spitsbergen.

Snow melting in the vicinity of the Polish Polar Station was slow. It was interrupted in mid-May by ten days of cool weather. Final melting of snow patches took place from 27th May until 17th June. Snow melting on the Hans Glacier was obviously slower. Detailed melting of a snow cover in tundra near Calypsobyen (southern coast of Bellsund) in 1987 was presented by Rodzik (1988).

Winter 1989/1990

Meteorological conditions during the winter 1989/1990 were more similar to a perennial average than during the previous winter. The winter 1989/1990 started on 17th October and terminated on 16th May. It was preceded by early winter, 25 days long. During the early winter in the first decade of October, a snow cover in the vicinity of the Polar Station completely melted away. A permanent snow cover started to develop on 17th October. Three large snowfall phases: October–November, December–January and March–April influenced its formation. These phases were separated by relatively long periods with no or slight precipitation.

Precipitation was 50% higher than during the previous winter. Relation of the water equivalent of a snow cover to total winter precipitation was equal to 93%, which proves that less snow was blown out. This phenomenon needs further explanation as winds in winter 1989/1990 were slightly stronger than during the previous winter. Different number of thaws during both periods seem to be the main reason for such differences in amount of a blown out snow (Table 1). During the winter 1989/1990, a number of thaws was two times higher what created more ice-crusts, and the latter slowed down a deflation. A snow cover melted away between 17th May and 15th June in the winter 1989/1990 in the vicinity of the Polish Polar Station.

Comparison of examined winters

Such comparison of the winters 1988/1989 and 1989/1990 is based on data from the meteorological station in Hornsund. The winter 1988/1989 was longer, more frosty and with a few days of thaw only (Table 1). Winter precipitation (its type, volume and intensity) was found to have been connected with atmospheric circulation (Table 2). Available synoptic charts contain slight gaps, but they should not have significant influence on a final result. Synoptic charts and precipitation data from the Hornsund region enabled statistical correlation between atmospheric circulation and total precipitation, covering 80% of days with precipitation in winter and early winter 1988/1989. During these days, 91% of the total precipitation occurred. The precipitation in the winter 1989/1990 was 50% higher than during the previous winter. The correlation between the water equivalent of the snow cover at the end of the winter and the total precipitation level was equal 93%, proving less intensive deflation. This phenomenon needs further explanation as winds in the winter 1989/1990 were slightly stronger than during the previous winter. The main reason of such differences in amounts of the blown out snow might be different number of thaws in both periods (Table 1). During the winter 1989/1990 number of thaws was two times higher which caused higher number of ice-crusts hindering the deflation process.

Considering influence of thaw on a snow cover, three types of thaws can be distinguished:

- early winter thaws, when a snow cover does not occur, what favours development of ice on a ground surface,
- mid-winter thaws, usually short (a few or a dozen of hours), caused by inflow of warm and humid air masses from the Norwegian Sea, accompanied by intensive precipitation (wet snow, snow with rain or rain); ice-crust layers that usually form, can be significantly important to determine a snow stratigraphy,
- late winter, early spring and later thaws cause destruction in vertical structure of a snow cover.

Table 2

Relations between atmospheric circulation and chemistry of precipitation in the vicinity of the Polish Polar Station in Hornsund (South Spitsbergen) in winter and early spring 1988/1989 (16th September 1988 – 23rd May 1989).

Origin of air masses	Number of days	Precipitation [mm]	pH	Electric conductivity [mS/m]
Norwegian Sea	17	58.1	5.0	11.8
West Scandinavia	12	28.1	5.1	9.7
East Scandinavia	8	11.0	5.1	6.3
Barents Sea (S)	11	8.5	5.0	9.1
Barents Sea (N)	16	17.4	5.2	19.5
Novaya Zemlya	4	6.5	5.0	2.2
Arctic Sea	5	3.3	5.7	7.6
Greenland Sea	8	18.0	5.2	12.9
Stationary air masses	5	6.9	5.2	2.2
Total or average	86	157.8	5.2	8.4
Other cases (not covered by statistics)	22	15.6		

Winter thaws are caused by inflow of warm humid air masses to Spitsbergen from the southwest. Such situation is possible when a cyclone, formed in the vicinity of Iceland, moves towards southern Spitsbergen. It brings intensive precipitation: rain, snow with rain and snow. Precipitation during thaws constitutes a half of the total winter precipitation. Durıng a thaw, lasting 25 days in 1988/1989, 42% of the total winter precipitation occurred. A year later, these values were much higher: 50 days with 58% of the total precipitation.

Analysis of weather charts enabled to determine the origin of air masses over southern Spitsbergen. Strict connection could be observed between inflow of warm sea air and occurrence of major winter precipitation (Table 2). Relatively warm air masses from the Norwegian Sea and the southern Barents Sea produced 62% of winter precipitation.

Additional statistical analysis (course of correlation function) enabled to discover 27-days long, cyclic period of meteorological changes connected with air circulation.

Vertical gradient of precipitation

Precipitation at higher altitudes in Spitsbergen has not been thoroughly examined, because meteorological stations are located in a coastal zone (Leszkiewicz

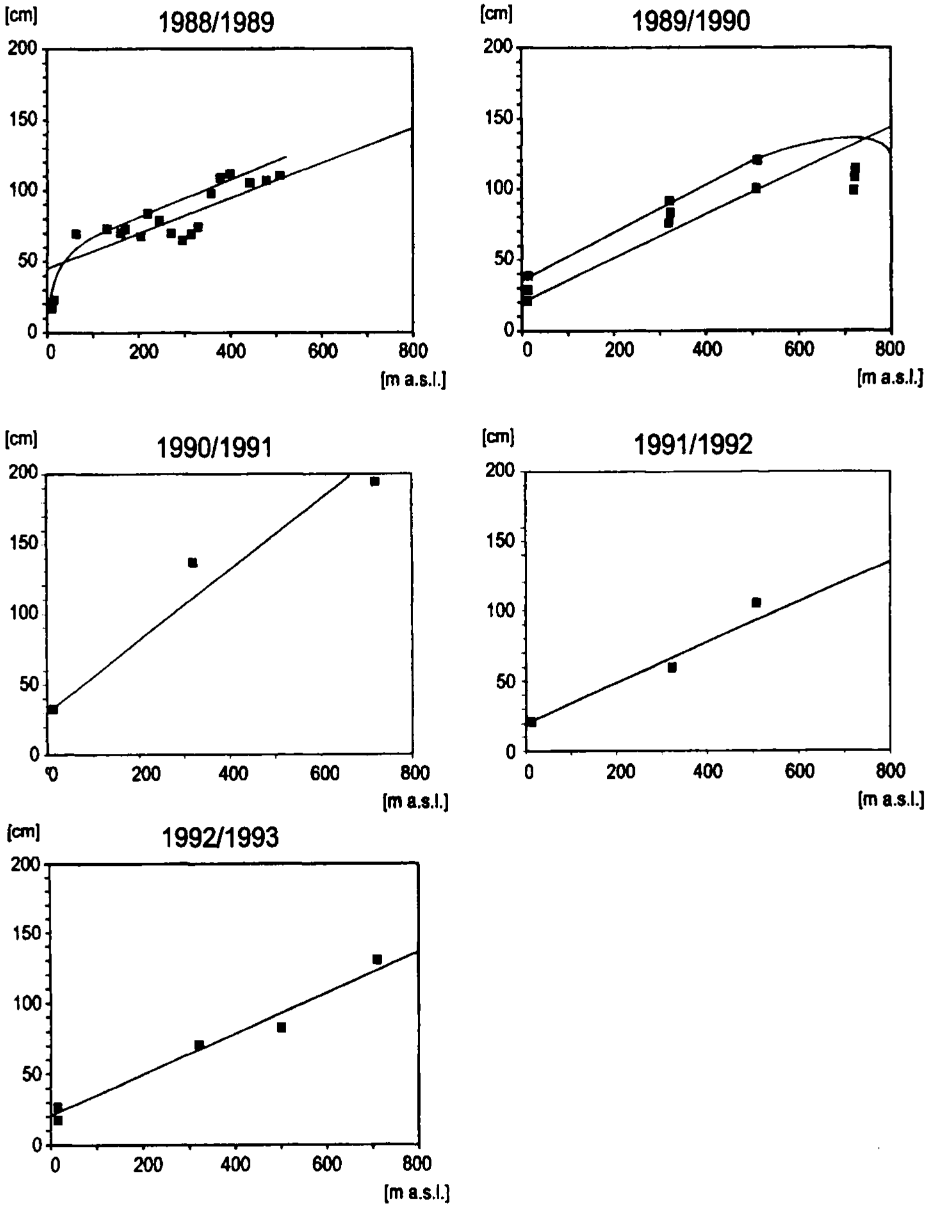

Fig. 5. Thickness of a snow cover at the end of winter related to the altitude in the Hans Glacier region, winters 1988/1989 – 1991/1992; measurements points and rough approximation of linear or curvilinear trend in snow pits at the end of winter.

1987). Therefore, nivation on glaciers at the end of winter (April–May) is of crucial significance for examination of a vertical gradient of precipitation. Results of measurements of a snow-cover on the Hans Glacier during a five-years period

Table 3

Vertical gradient of precipitation in Hornsund in 1988/1989 – 1992/1993.

Altitude	Precipitation [mm]		
m a.s.l.	Annual*	Winter	Summer*
0	466	247	219
100	839	463	376
200	1142	656	486
300	1382	824	558
400	1566	968	597
500	1699	1089	610
600	1788	1185	603
700	1835	1257	578
800	1846	1306	541

* – approximate estimated values

(from the end of the winter 1988/1989 to 1992/1993), were used to estimate vertical gradient of precipitation in Hornsund (Fig. 5). The estimation was prepared in two stages:

1. Calculation of the precipitation gradient was limited to a winter (September/October – May).

2. Results were used to estimate annual gradients covering a whole polar year (from September/October to September/October next year). Vertical gradient of precipitation in spring, summer and autumn was assumed to be the same as the gradient during a preceding winter. Results for winter and summer obtained in this way, presented a varying accuracy. Winter results are quite accurate, while the summer ones are rough estimations only.

The method of statistical calculation was based on measurements of snow and local conditions on the Hans Glacier and its vicinity. The following assumptions were made when calculating an algorithm of a vertical gradient:

1. To calculate a water equivalent of a snow cover, its average density was assumed to be equal to 384 kg/m^3.

2. The best equation to describe a vertical gradient is a square polynomial (differences between the square polynomial and a linear equation are very slight):

$$P_w(H) = -0.0012H^2 + 2.2829H + 247.2 \qquad (n = 37; R^2 = 0.71)$$

where: P_w – thickness of winter precipitation [mm], and H – ground altitude [m a.s.l.].

3. Estimated share of winter precipitation in the annual total precipitation is equal to 53% at sea level (in the vicinity of the Polish Polar Station), and 84% at 700 m a.s.l. (Amundsen Plateau). Larger share of winter precipitation at higher altitudes results from longer winters in the mountains.

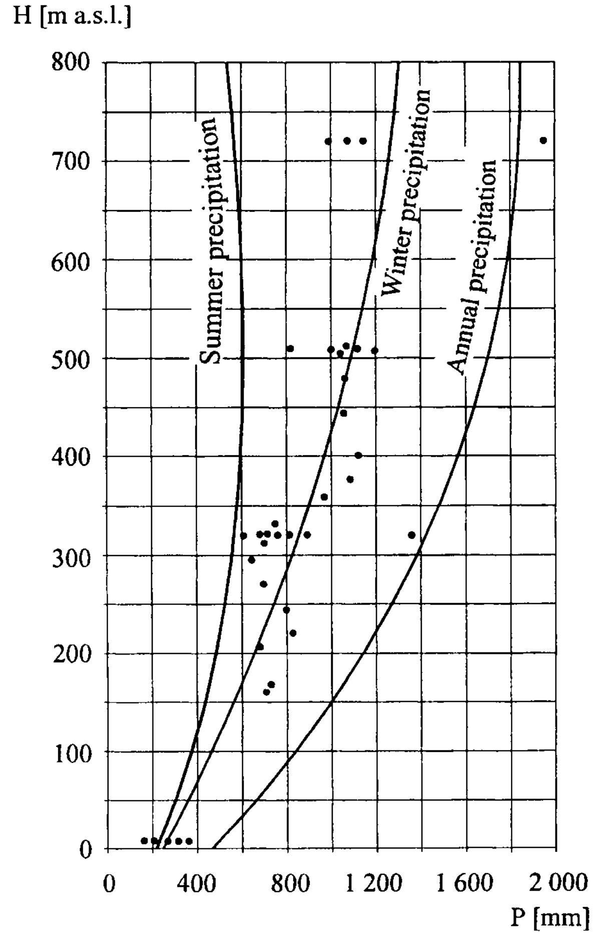

Fig. 6. Vertical gradient of precipitation (P) in the Hans Glacier region in 1988/1989 – 1992/1993.

4. Snow measurements were mostly taken in April, therefore a correction for snow precipitation in the following months (*i.e.* late-winter precipitation) was introduced. Quantitative importance of such precipitation rises with increasing altitude.

Results of the applied method are presented (Fig. 6, Table 3). Despite the approximate results, they are hydrologically and glaciologically significant. Winter precipitation forms a snow cover which is equal to accumulation on glaciers. Summer precipitation is most frequently a rain. Precipitation of snow is rare in summer and a snow cover is not formed as the snow melts quickly. Hydrological systems are mostly charged by snow and ice ablation, however summer precipitation plays also a significant role in this process.

Calculation used for low altitudes prove also a presence of a snow deflation effect in the vicinity of the Polish Polar Station. The calculated winter precipitation is 25% higher than the average perennial one.

Development of a winter snow cover

Each snowfall phase is a precipitation set in winter which forms a relatively homogenous snow layer. The layer is separated from the underlying and overlying ones by transition zones or discontinuous borders of varying origin. Ice-crust layers, formed by winter thaws, are the most significant borders between snowfall phases. The ice-crust layers are transition zones between consecutive phases. Each phase may be characterised by certain particular heterogeneity. Several internal subphases divided by minor, less significant borders, are to be distinguished there.

A phase is relatively a long period, with large snow precipitation and only a few breaks. The upper border of a layer is usually formed by wind (which is quite often very strong) or by a thaw. Radiation borders, caused by intensive sun radiation are quite rare. Radiation covers usually develop from March to May at lower altitudes during sunny weather when air temperature is below 0°C. Formation and type of phases depend on meteorological conditions and relief.

Snowfall phases in southern Spitsbergen

Typical snowfall forms in two phases. The first one starts when a cyclone approaches southern Spitsbergen from the southwest, bringing warm and humid maritime air masses. Temperature rises and a few-hour thaw occurs. Precipitation begins with rain, then rain and snow, and finally snow. Strong wind is accompanied by a blizzard. Precipitation does not occur if southern Spitsbergen is at a cyclone margin. However, strong wind causes a snowdrift.

The second phase starts when a cyclone moves eastwards, away from Spitsbergen. Temperature drops down and snow precipitation is gradually completely diminishing. Strong wind and snowdrift usually last longer than precipitation. Remodelling of a snow cover occurs. Wet snow freezes at bed of a snow cover and ice-crust is formed. Finally, weather conditions become stabilized.

A new snow layer does not form when trajectory of a cyclone runs to the south of Spitsbergen, because such episode is not accompanied by precipitation. However, a snow drift during a strong wind remodels a snow cover. In this case, a snow is blown out partly to a sea.

A new snow layer formed by precipitation can remain in a snow cover until end of winter, but it may be also completely blown away into a sea. In areas where deflation is especially intensive, the upper snow layer is protected by an ice-crust which usually forms after a thaw. This problem may be quite well illustrated by formation of a snow cover at the Polish Polar Station during two winter periods. The winter 1989/1990 was characterised by a two times higher number of thaw days than in the preceding winter (Table 1). Therefore, a number of ice-crusts in a snow cover is higher and they are better developed. In result, relation of water equivalent in a snow cover at the end of winter to the total precipitation during winter was equal to 94%, and only 41% the year before. During the first ten days in December 1988, an ice-crust was formed in the vicinity of the Polish Polar Station and it acted as a border layer for snow deflation until the end of winter.

Considering the above results, a question arises whether measurements at the Polish Polar Station are representative for the Hornsund region. The available data enable to answer the question. Location of the station is typical for a lower part of a sea coast where deflation is more intensive. There are areas without snow during a whole winter in the plain of Rålstranda (to the west of the station), due to a thin ice-crust on a ground. The following conclusions can be drawn therefore for the vicinity of the Polish Polar Station:

1. Data from the station cannot be applied for statistical estimation of a snow thickness on the Hans Glacier *e.g.* at the end of the winter 1988/1989 (Fig. 5).

2. There are significant stratigraphic gaps in a snow cover in the vicinity of the station, caused by blow-out of snow. Certain snowfall phases are completely blown out while they are very well preserved on the Hans Glacier and in other areas (Fig. 7). However, even in these cases, data from the station are important as they indicate presence of such phases.

More reliable results could be received when investigations were carried out in the vicinity of the Polish Polar Station but in the area where deflation is significantly less intensive. A research site is located 200 m to the north from the observatory, organised for environmental examination. Such investigations have been carried out by the University of Silesia, independently or in cooperation with the Polish Academy of Sciences (as a part of the project of the Polar Expeditions to Spitsbergen organized by the Polish Academy of Sciences). Unlike the Polar Station, the study site of the University of Silesia is representative for these parts of the coast which are protected against wind.

Snowfall phases within a winter snow cover

Annual sequence of a snow layer in the winter 1988/1989, analysed on 1st May 1989 (at the end of the period) is presented (Figs 7–9). The profile is located in the upper part of the Hans Glacier (ice-divide between the Vrangpeis Glacier and the Hans Glacier) at 500 m a.s.l. The pit presents a snow cover in the accumulation zone, 200 m above the equilibrium line. Relation between the snow profile and several meteorological parameters from the meteorological station in Hornsund (thaw occurrence factor, type and totals of precipitation, and wind velocity exceeding 8 m/s) and physico-chemical properties of snow in the pit (snow density, pH, conductivity) are presented (Figs 8–9).

Analysis of a snow cover is supported by a legend including description of the selected layers of snow, firn and ice (Fig. 6). It covers the snow classification, ap-

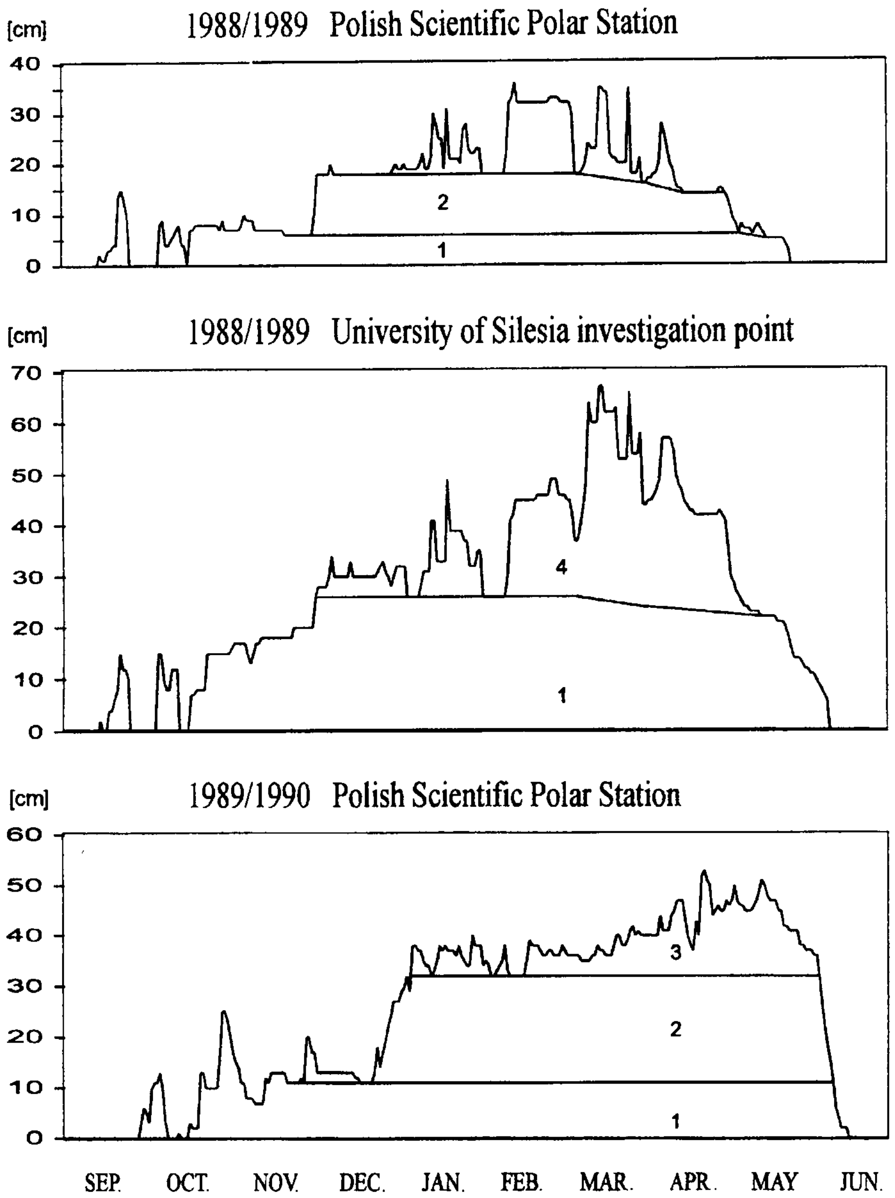

Fig. 7. Snow cover in Hornsund region during the winters 1988/1989 and 1989/1990). Numbers of snow layers (1–4) indicate snowfall phases; stratigraphic gaps in a snow cover result from significant deflation of snow.

plied by the authors which is based on the international standard (Kotliakov 1984). Analysis of figures enables relatively thorough investigation of layers of a snow cover and refers particular layers to the factors that influence their origin and metamorphosis.

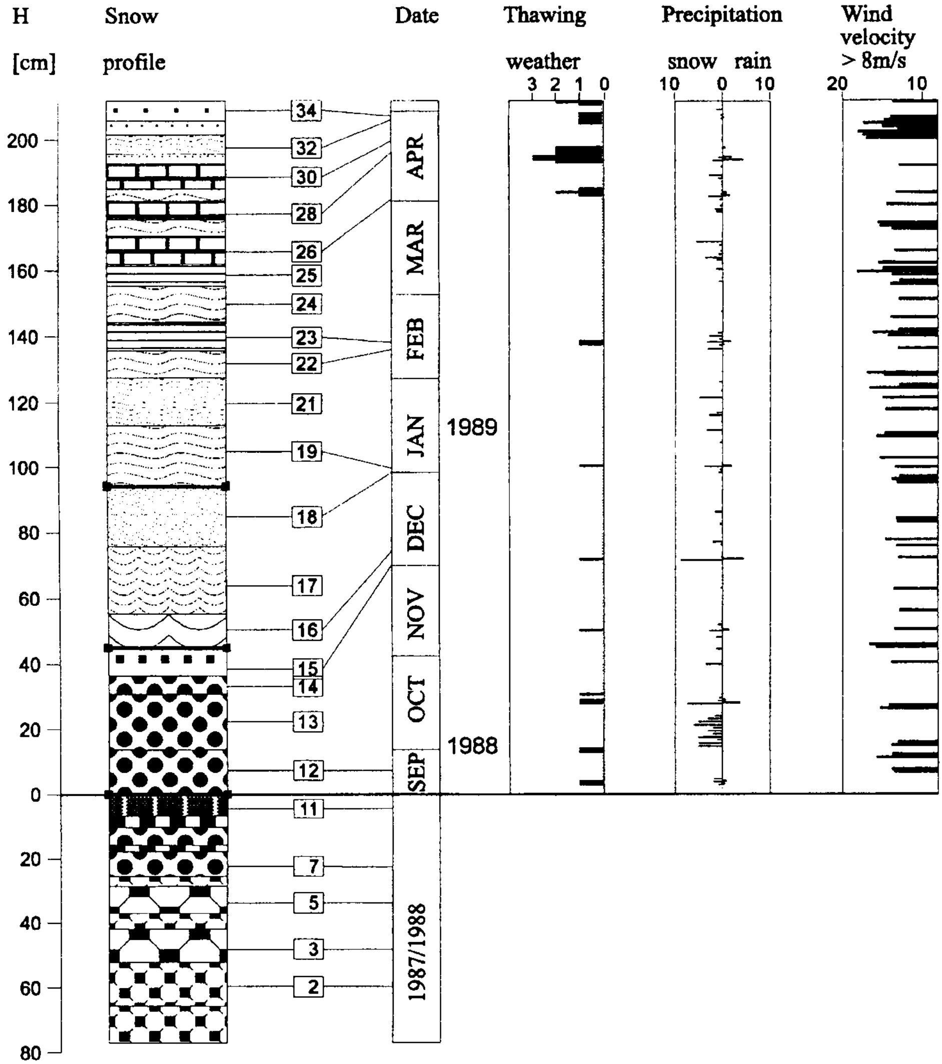

Fig. 8. Dating of snow layers in the upper part of the Hans Glacier, related to selected meteorological parameters as thaw indices, precipitation (snow or rain) and strong wind (V ≥8 m/s); numbers within rectangles indicate selected snow layers.

Selected snowfall phases and their influence on a snow cover

Five snow layers were distinguished in the snow cover of 1988/1989 (Figs 4, 8; Table 4). The main criterion used were internal ice-crusts in numerous snow profiles. In places without the ice-crust (*e.g.* up-glacier), borders of layers could not be determined in detail. Snow profiles (Fig. 9) indicate snowfall phases on a sea coast at foot of Fugleberget in the vicinity of the Polish Polar Station and at two other

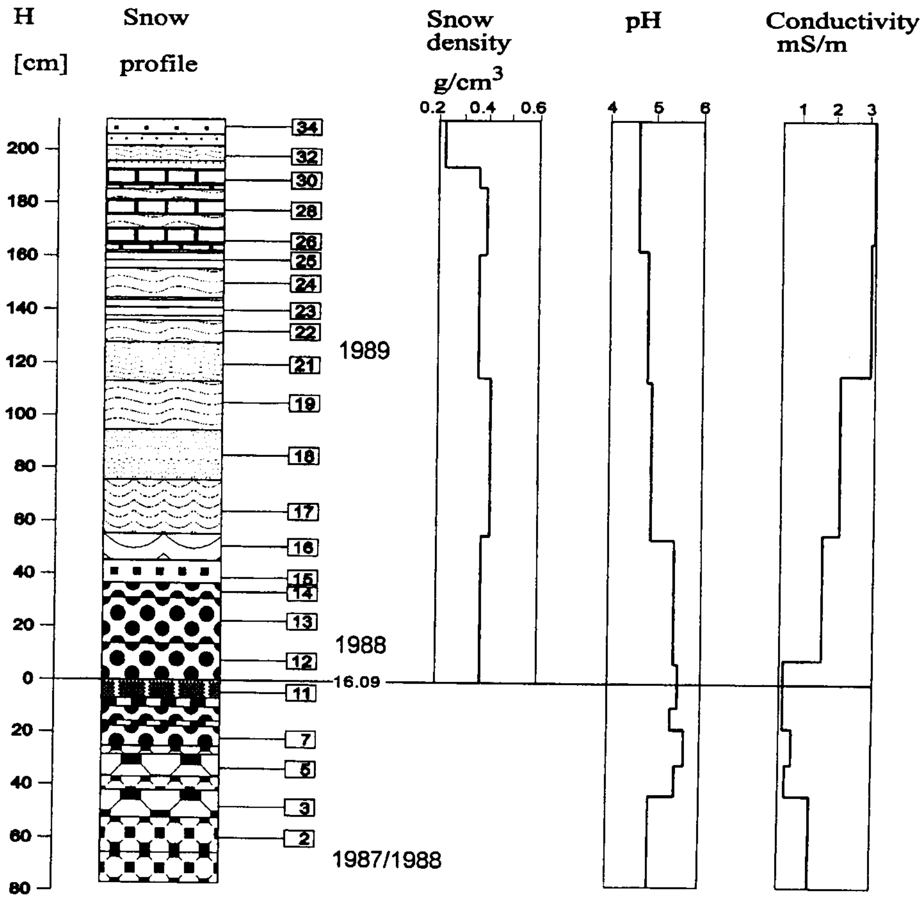

Fig. 9. Physical and chemical properties of snow, upper part of the Hans Glacier (ice-divide to the Vrangpeis Glacier) on May 1–2, 1989; numbers within rectangles indicate selected snow layers.

sites on the Hans Glacier: in its central part (Hans Kabina) and on the ice-divide to the Vrangpeis Glacier.

Phase 1 (16th September – 1st December, 1998, and 17th October – 1st December, 1988) – the first winter months. Characteristic is a significant metamorphism of snow. The first snow fell on wet ground or glacier ice, absorbed water and got frozen. There were also thaws at the beginning of winter. Settling in time resulted in significant amount of coarse-grained firn snow, and also coarse- and medium-grained snow on a glacier.

Phase 2 (2nd December, 1988 – 1st January, 1989) starts with a short thaw at the beginning of December. The thaw was significant at low altitudes. An ice-crust was formed which protected against snow deflation. On the Hans Glacier, the ice-crust occurred down-glacier, it was absent in a central part while significant layers were observed at the ice-divide. Amount of coarse-grained snow was much

Table 4

Snowfall phases at the Polish Polar Station in Hornsund and at Barentsburg during winters 1988/1989 and 1989/1990. Hornsund PAS – Hornsund Station of the Polish Academy of Sciences, Hornsund US – Hornsund Station of the University of Silesia.

Phase No.	Location of the station	Time of occurrence	Precipitation [mm]	Snow cover	
				thickness changes [cm]	changes in water equivalent [mm]
Winter 1988/1989					
1.	Hornsund PAS	Oct. 18 - Dec. 1	26.6	6	19.8
	Hornsund US		33.7	20	66.0
2.	Hornsund PAS	Dec. 2 - Jan. 1	20.0	9	24.2
	Hornsund US		32.2	12	4.4
3.	Hornsund PAS	Jan. 2 - Feb. 10	20.6	-2	-0.8
	Hornsund US		29.4	-6	-8.0
4.	Hornsund PAS	Feb. 11 - Mar. 31	33.2	0	14.4
	Hornsund US		50.1	28	110.4
5.	Hornsund PAS	Apr. 1 - May 1	23.1	-3	15.9
	Hornsund US		30.9	-12	33.0
Winter 1989/1990					
1.	Hornsund PAS	Oct. 16 - Dec. 25	80.2	13	33.0
	Barentsburg	Oct. 10 - Dec. 25	177.9	88	
2.	Hornsund PAS	Dec. 26 - Feb. 28	97.9	23	97.0
	Barentsburg		81.3	42	
3.	Hornsund PAS	Mar. 1 - May 16	82.1	42	138.0
	Barentsburg				

lower than during the phase 1. The snow was strongly affected by wind, especially on a glacier – it was compact or very compact.

Phase 3 (2nd January – 10th February, 1989) began when an ice-crust, formed during a thaw at the beginning of January (Fugleberget and Hans Kabina sites), has already existed. A significant border between snow layers appeared as ice-crust at the ice-divide. However, wind structures predominated there and snow was very compact.

Phase 4 (11th February – 31st March, 1989) was very similar to the previous one, with compact and very compact snow. There was a significant border (ice--crust) between the phases 3 and 4. Neither an ice-crust nor a significant border occurred at the ice-divide.

Phase 5 (1st April – 1st May 1989) was a decline of winter. Formation of this phase was completed in a pit located at the ice-divide only (the other two pits were dug in the first half of April). Numerous thaws in April had significant influence. They caused formation of thick ice-crust layers at the ice-divide. Formation of a snow cover at lower altitudes terminated in mid-April. Apart from thaws, a snow cover has been destroyed by extremely strong winds (April 20–27).

Phases which were older than a year could be hardly distinguished, however more easily in higher regions (*e.g.* Amundsen Plateau) where snow has been less transformed (Głowacki and Leszkiewicz 1994; Głowacki and Pulina *in press*).

A typical snowfall phase consists of a series of consecutive layers. It is underlain by an ice-crust layer, followed by a main layer which is usually compacted by wind, with significant stratigraphic gaps due to snow deflation or lack of precipitation.

Final remarks

Results of analysis of the winter snow cover presented in the paper suggest possible reconstructions, not only of snowfall phases but occasionally also of meteorological conditions which have created a snow profile. Such conclusion results from a detailed comparative analysis of snow and firn layers. They were deposited in definite meteorological conditions and were analysed by the authors, both during formation of a snow cover and later, when a snow layer was transformed.

The authors find it possible to distinguish snowfall phases when full information concerning time of precipitation is available from a meteorological station in the neighbourhood (*i.e.* snow layers can be correlated with time of precipitation). Snowfall phases can be also distinguished in a snow cover if no meteorological data are available, but such layers cannot be dated in this case.

To obtain information concerning snowfall phases and the accompanying meteorological situation, detailed analysis of a snow profile exposed in a snow pit, dug at the end of the winter is needed. The work consists of the following tasks: distinguishing particular layers and contacts between them, determination of snow and firn type, and measurements of physical and chemical properties. A legend of snow and firn origin (Fig. 2) as well as measurements of snow density and basic chemical analysis (specific electric conductivity of melted snow, pH, concentration of chlorides, *etc.*) are used for this purpose.

Some rules were observed by the authors during their research in Spitsbergen:

1. Snowfall phases are significantly connected with periods of intensive snow precipitation.

2. Physico-chemical properties of snow layers, especially the ones formed after precipitation of varied solute concentration, help to distinguish particular layers.

3. Chemical properties in older layers, formed at the beginning of winter or earlier, are not so distinct due to demineralization.

Distinguished snowfall phases enable reconstruction of several meteorological elements (particularly a volume of snow precipitation) in areas without meteoro-

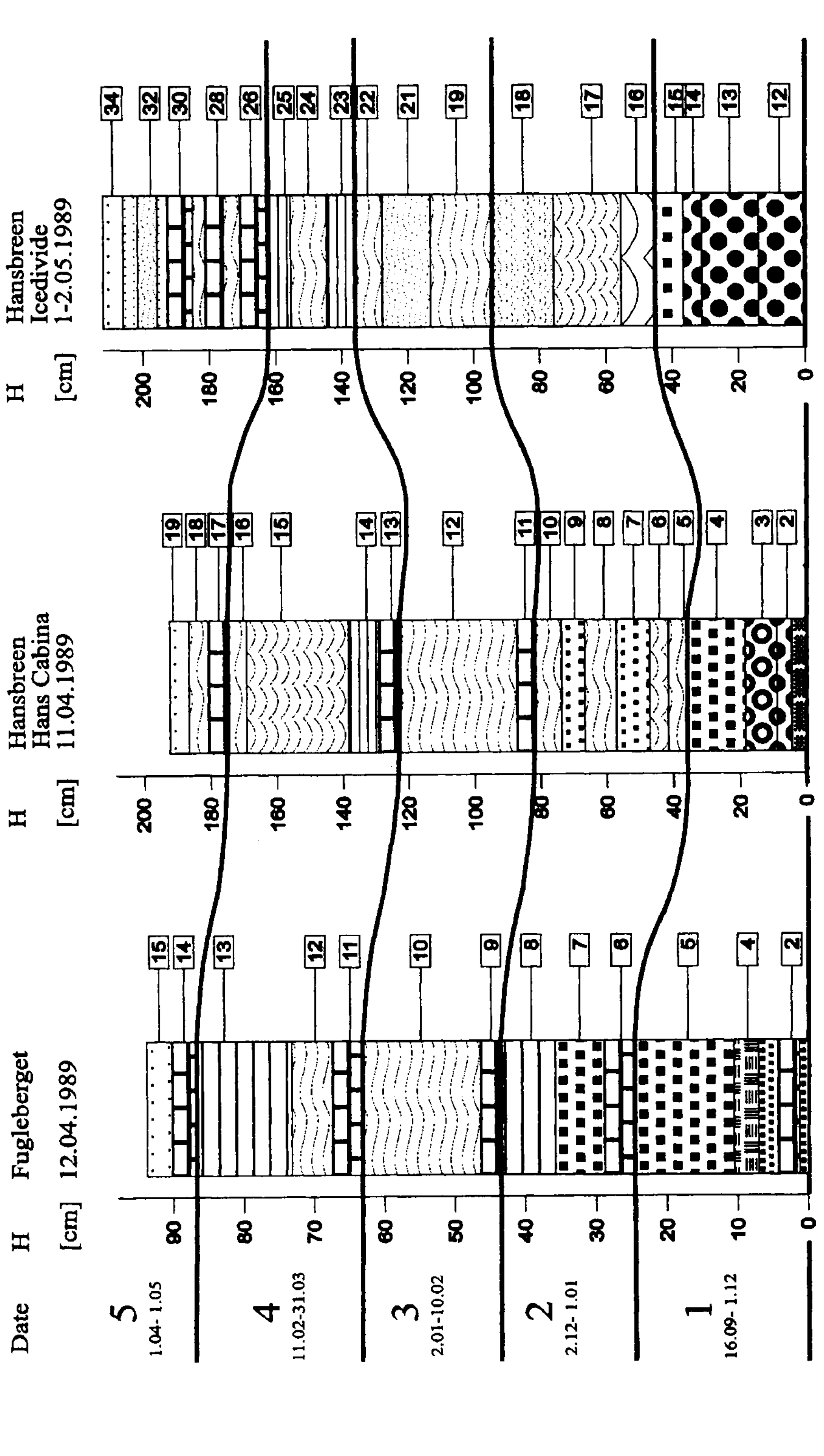

Fig. 10. Snowfall phases in selected snow sections. Dates correspond to particular phases and digging of pits; numbers within rectangles indicate selected snow layers.

logical stations. The authors collected data from other parts of Spitsbergen, back to the seventies. The data from 1988–1995, when systematic investigations were carried out, following the rules which had been approved in the previous years, seem to be particularly interesting. Elaboration of these materials will probably significantly improve our knowledge about a snow cover in vast areas of Spitsbergen and abrupt changes during the last large glacier retreats.

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Streszczenie

Przedstawiono warunki kształtowania się pokrywy śnieżnej w rejonie Hornsundu na południowym Spitsbergenie w sezonach zimowych 1988/1989 i 1989/1990 (fig. 1, 3–4; tab. 1). Znacząca część opadów zimowych związana jest z napływem stosunkowo ciepłych mas powietrza z SW i S – znad Morza Norweskiego (tab. 2). Występują wówczas krótkotrwałe odwilże zimowe, prowadzące do tworzenia charakterystycznych warstw lodoszreni w pokrywie śnieżnej. Silne wiatry od strony morza powodują niekiedy wtórne zanieczyszczenie śniegu przez aerozol morski. Przewodnictwo

elektryczne śniegu różni się wówczas znacząco od typowego tła, osiągając ekstremalną wartość 2020 µS/cm (fig. 4).

Na podstawie wyników badań niwalnych z lodowca Hansa z zim 1988/1989 – 1992/1993, określono wielkości zwiększania się rocznej sumy opadów atmosferycznych wraz ze wzrostem wysokości terenu (fig. 5–6, tab. 3). Uwzględniono odmienne środowiska zalegania śniegu tj. lodowiec oraz obszar niezlodowacony – w różnym stopniu podatne na wywiewanie śniegu.

Zimowa pokrywa śnieżna składa się z kilku nałożonych na siebie warstw śniegu, odpowiadających poszczególnym fazom jego sypania. Na podstawie analizy czasu występowania zimowych opadów atmosferycznych (fig. 2) i rozwoju pokrywy śnieżnej w licznych profilach (fig. 7–9) wydzielono pięć faz sypania śniegu w zimie 1988/1989 i trzy fazy sypania w zimie 1989/1990 (fig. 10, tab. 4). Do opisu warstw śniegu w profilach zastosowano klasyfikację genetyczną, uwzględniającą specyfikę struktury śnieżnej na Spitsbergenie (fig. 2). W klasyfikacji uwzględniono metamorfizm śniegu: metamorfozę suchą (poz. 1–9), metamorfozę wilgotną bez zamarzania (poz. 10–12), metamorfozę wilgotną z zamarzaniem (poz. 13–16) i metamorfozę eoliczną (poz. 17–22).

Silne wiatry (V ≥8 m/s) oraz odwilże zimowe w znacznym stopniu przekształcają powierzchniową warstwę śniegu. Proces wywiewania śniegu osiąga lokalnie duże rozmiary – zachodzi głównie w obrębie równin nadmorskich, grzbietów górskich i wypukłych stoków. Ponieważ znaczny efekt wywiewania ma również miejsce na stacji meteorologicznej w Hornsundzie, założono dodatkowe stanowisko pomiarów śniegu, który w lepszym stopniu odzwierciedla wysokość opadu dla obszarów nisko położonych. Lodoszreń tworząca się po odwilży zimowej, konserwuje pokrywę śnieżną i chroni ją przed wywiewaniem. W pokrywie śnieżnej pełni rolę warstwy przewodniej, umożliwiając datowanie. Warstwy lodoszreni są najczęściej granicami pomiędzy poszczególnymi fazami sypania śniegu.

Wydzielenie faz sypania pozwala na rekonstrukcję niektórych elementów meteorologicznych (szczególnie wielkości opadów śnieżnych) w obszarach, gdzie brak stacji meteorologicznych.