Title: The physico-chemical properties of the snow cover of Spitsbergen (Svalbard) based on investigations during the winter season 1990/1991

Author: Piotr Głowacki, Marian Pulina

Citation style: Głowacki Piotr, Pulina Marian. (2000). The physico-chemical properties of the snow cover of Spitsbergen (Svalbard) based on investigations during the winter season 1990/1991. "Polish Polar Research" (2000, no. 2, s. 65-88).

POLISH POLAR RESEARCH	21	2	65–88	2000

Piotr GŁOWACKI[1,2] and Marian PULINA[2]

[1] Instytut Geofizyki
Polska Akademia Nauk
ul. Księcia Janusza 64
01-452 Warszawa, POLAND
e-mail: glowacki@igf.edu.pl

[2] Wydział Nauk o Ziemi
Uniwersytet Śląski
ul. Będzińska 60
41-200 Sosnowiec, POLAND
e-mail: pulina@us.edu.pl

The physico-chemical properties of the snow cover of Spitsbergen (Svalbard) based on investigations during the winter season 1990/1991

ABSTRACT: Investigations of the snow cover at the end of the winter 1990/1991 were carried out in several areas in West Spitsbergen, namely, Lomonosovfonna, Kongsvegen, Fridtjovbreen, Amundsenisen and that north of the Hornsund Fjord. The physical properties and chemical nature of precipitation and the snow cover were determined. The studies revealed high variation in the precipitation and the thickness of the snow cover: 317 mm w.e. (water equivalent) in the Hornsund area, 659 mm w.e. at Lomonosovfonna, 1076 mm w.e. at Fridtjovbreen and 1716 mm w.e. at Amundsenisen. The salt loads deposited in the snow cover in different parts of West Spitsbergen were also calculated (2.8 t/km^2 at Lomonosovfonna, 15.8 t/km^2 at Kongsvegen and 43.2 t/km^2 at Amundsenisen). An intensive process of demineralisation during the conversion of snow to firn was revealed, reaching as much as 90% during the first summer. An attempt to determine the anthropogenic element content using the pH values for the precipitation and snow cover was also made. A distinct correlation between the physico-chemical characteristic of snow layer and falling snow was found. On the basis of the quality of the precipitation and snow cover, West Spitsbergen has been classified into following provinces: (1) northern situated within Arctic High (Lomonosovfonna and Kongsvegen), (2) southern undergoing mainly moving air masses from the Arctic High and Greenland Low (Amundsenisen and Hornsund region).

Key words: Arctic, Spitsbergen, glaciology, meteorology, snow cover, snow chemistry.

Introduction

Studies of snow covers have an established pedigree. They have been conducted by Ahlmann (1933), Schytt (1964), Baranowski (1977), Pereyma (1983), Osokin and Khodakov (1985), Migała, Pereyma and Sobik (1988), Zagorodnov

(1988) and many others. The main objective of most of these was to determine the amount of the winter accumulation and its spatial distribution. Some concerned the physical properties of a snow cover and its stages of metamorphosis. However, these investigations were carried out by different working groups and in different areas. The aim of the present research was the simultaneous study of the accumulation field in different parts of Spitsbergen, using the same methods. The determination of the chemistry of snow precipitation was one of the most important objectives but studies of the changes of snow cover chemistry due to metamorphosis and melt-water percolation were also carried out.

The snow cover investigation on selected glaciers of Spitsbergen reported have was carried out as a part of a joint Norwegian-Polish-Russian glaciological programme. This research took place in Spring 1991 and involved five Spitsbergen glaciers (Fig. 1), Kongsvegen in the Ny-Ålesund (NW Spitsbergen), Lomonosovfonna Ice Cap (NE Spitsbergen), Fridtjovbreen (Central Spitsbergen), Amundsenisen and Hansbreen (S Spitsbergen). The research was also carried out during the Arctic winter from October 1990 to May 1991. At three glaciers, the firn of the last three years was also investigated. Some drilling was also carried out; for instance at the Amundsen Plateau, where an 11 m-deep bore-hole was drilled.

The research involved both trenches and snow drill cores and included detailed resolution of the stratification of snow and firn and determination of selected physical features (temperature, density, type and quality of snow and firn). The samples taken were investigated with respect to selected chemical features (pH, specific electrical conductivity – SpC, concentration of chloride ions). Some samples also were taken in order to determine their isotope content and chemical composition.

The studies carried out on the one-year-old snow cover in a relatively large area of West Spitsbergen concluded a several-year-long period of investigations. This research started in the Hornsund area in 1985 (Głowacki, Pulina and Wach 1990) and was enlarged in 1989 to include the Amundsenisen. Efforts were carried out simultaneously with the analysis of the precipitation and snow cover at coastal stations. At first, the studies were carried out at the Polish Polar Station in Hornsund, then at the Soviet Station in Barentsburg. In 1990, they were extended into the northern part of West Spitsbergen at the Norwegian Station in Ny-Ålesund. During the investigation programme, different research methods were used, starting with the establishment of particular classes of snow and firn and finishing with analytical methods (including field and spectrographic methods in laboratories). In the field, the methods used were those which appeared to be the most practicable. In the study area, the snow cover was sounded in a number of places and, thereafter, the most representative sites were selected for further investigations. The results of analytical and instrumental studies conducted in the laboratory were compared with the results of the less accurate analytical and instrumental methods carried out in the field. Compatible results, as obtained from field and laboratory

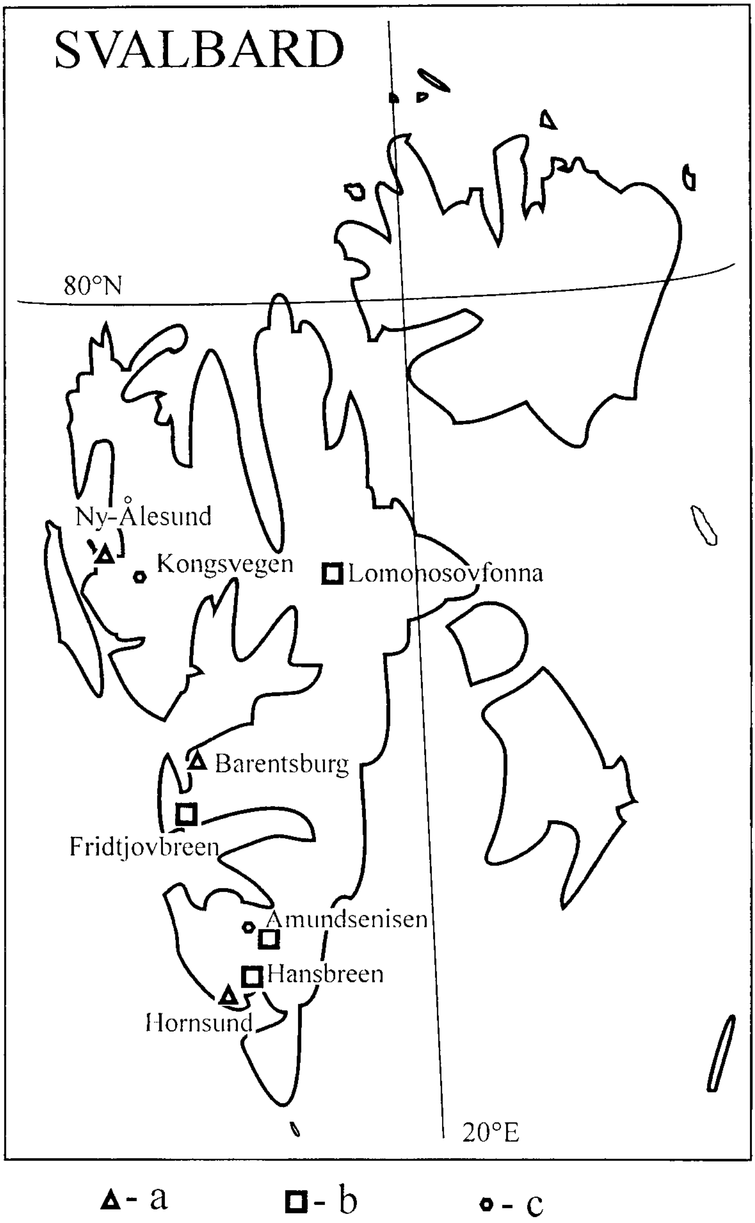

Fig. 1. Location of studies. a – coastal meteorological stations; b – snow trenches; c – snow and ice cores.

analytical determinations, indicate that a high standard of cleanliness is preserved during sampling. The research also has wider implications inasmuch as it is closely related to glaciological and geodetic studies concerning the mass balance and geometrical changes of the Spitsbergen glaciers.

Methods

Analysis of the chemical composition of snow precipitation was based on determinations carried out at two meteorological stations. At Barentsburg, 140 pH determinations, and in Hornsund, 60 pH and specific electrical conductivity determinations were made. The snow cover was studied at five sites on the glaciers within snow trenches and from bore-holecores. There 91 determinations of pH, electrical conductivity and chloride content were carried out.

Analysis of the 1-year-old snow cover was carried out both in trenches and bore-holes. Determination of individual beds representing successive snowfalls was based on the physical properties of snow and firn. Their classification was based on glaciological (Pulina 1991) and meteorological principles. The chemical properties of the snow were determined by analysing snow which had melted at room temperatures, the samples having been taken from the whole bed using a polythene bottle. For analytical purposes, the cores from a drill hole and the wall of a trench were carefully cleaned beforehand. Samples for macro-determinations were taken wearing surgical polythene gloves and samples for micro-determinations, a special disposable suit and mask. The determinations of the chemical composition of snow were carried out at the research stations using water samples taken just after snow melt (Krawczyk 1996). The concentration of hydrogen ions (pH) was determined using CP-311 pH-meter (accurate to 0.01 pH); SpC, using a CC-311 conductivity meter (accurate to 1 μS/cm) and chloride concentration (Cl^-), using an argentometric method (accurate to 2 mg/dm^3) (Markowicz and Pulina 1979).

The snow precipitation of the winter season 1990/1991 (from October 1990 to May 1991) was analysed. Where the sites are situated in accumulation zones, the winter snowfall may also include the beginning of the Arctic winter, which, in these latitudes, may start as early as September. This snow cover does not include the termination-of-winter period, which is usually at the end of May.

In the Hornsund area, measurement of precipitation pH was made for rainfalls and snowfalls higher than 0.5 mm w.e., directly after the fall. Elsewhere, the samples were taken from the snow trenches. 5 metre-long aluminium stakes were employed to separate the snow series of particular years. The stakes penetrated to the last accumulation layer.

Field Setting

The studies were made on two large ice fields: Lomonosovfonna (1200 m a.s.l.) and Amundsenisen (720 m a.s.l.) and three tidewater glaciers. Sampling of snow trenches and drilling were carried out on the highest flat surfaces of the ice fields within the accumulation zones of two glaciers: Kongsvegen (580 m a.s.l.)

and Fridtjovbreen (400 m a.s.l.) and at the equilibrium zone of the Hansbreen (320 m a.s.l.).

The two ice fields studied are situated along the central part of the island. Lomonosovfonna is sheltered by mountain ridges on all sides. Amundsenisen is sheltered by a mountain ridge from the east but it is very exposed to the west. At Amundsenisen, studies of snow cover and firn were carried out in 1972 (Baranowski 1977), 1980 (Pereyma 1983, Pulina 1984) and 1990 (Pulina 1991, Leszkiewicz and Pulina 1999); deep drilling down to the bed of the ice field was carried out in 1980 (Zagorodnov and Samoylov 1982, Pulina 1990). The valley areas of the glaciers studied range from 40 km^2 to more than 100 km^2 in extent; all lie meridionally. The Fridtjov Glacier has been investigated by the Institute of Geography, Russian Academy of Science since 1970 (Koytlakov 1985). Since the late seventies, the Hans Glacier has been the subject of experimental glaciological studies carried out by the University of Silesia and the Institute of Geophysics, Polish Academy of Sciences (Jania 1988, 1992, Pulina 1992, Głowacki and Leszkiewicz 1994, Jania and Głowacki 1996, Głowacki 1997). The Kongsvegen Glacier has been investigated by the Norsk Polarinstitutt since 1987 (Hagen and Liestøl 1990, Lefauconnier, Hagen and Rudant 1994, Pourchet *et al.* 1995, Kjetil and Hagen 1998).

The present studies have also been carried out on the non-glaciated raised beaches (Hornsund and Barentsburg) situated 10–40 m a.s.l.; close to the equilibrium line of the glaciers (Hansbreen), at 300 m a.s.l.; within the accumulation zone of glaciers (Fridtjofbreen, Kongsvegen) at 500–600 m a.s.l. and at the ice caps (Amundsenisen, Lomonosovfonna) at 700–1200 m a.s.l. Four of the areas studied are generally affected by western air mass circulation and also by local meteorological conditions (e.g. foehn wind phenomena). The only exception is Lomonosovfonna, which is influenced mainly by arctic-continental air masses from the Barents Sea.

Results

Lomonosovfonna, Olav V Land. — With respect to Lomonosovfonna, the snow trench was localised in the highest part of the ice plateau at 1200 m a.s.l. at the extension of the Nordenskiold Glacier (2 km north of Uranusfield; 28°49'10'' N, 17°30'20'' E) (Fig. 1). The trench was investigated on 17 April (a sunny, calm and frosty day, temperature -29°C). Within the 440 cm-deep profile, 3 separate beds were distinguished: a winter season 1990/1991 – 175 cm thick; the full hydrological year 1989/1990 – down to 330 cm; and the full hydrological year 1989/1988 – down to 440 cm (Fig. 2). The definition of bed thickness for the years previous to 1990/1991 was based on distinct ice layers, and changes of firn mineralization. Soundings of the snow cover thickness for the last winter season (1990/1991) revealed values of 140 cm on elevations and 275 cm in depressions.

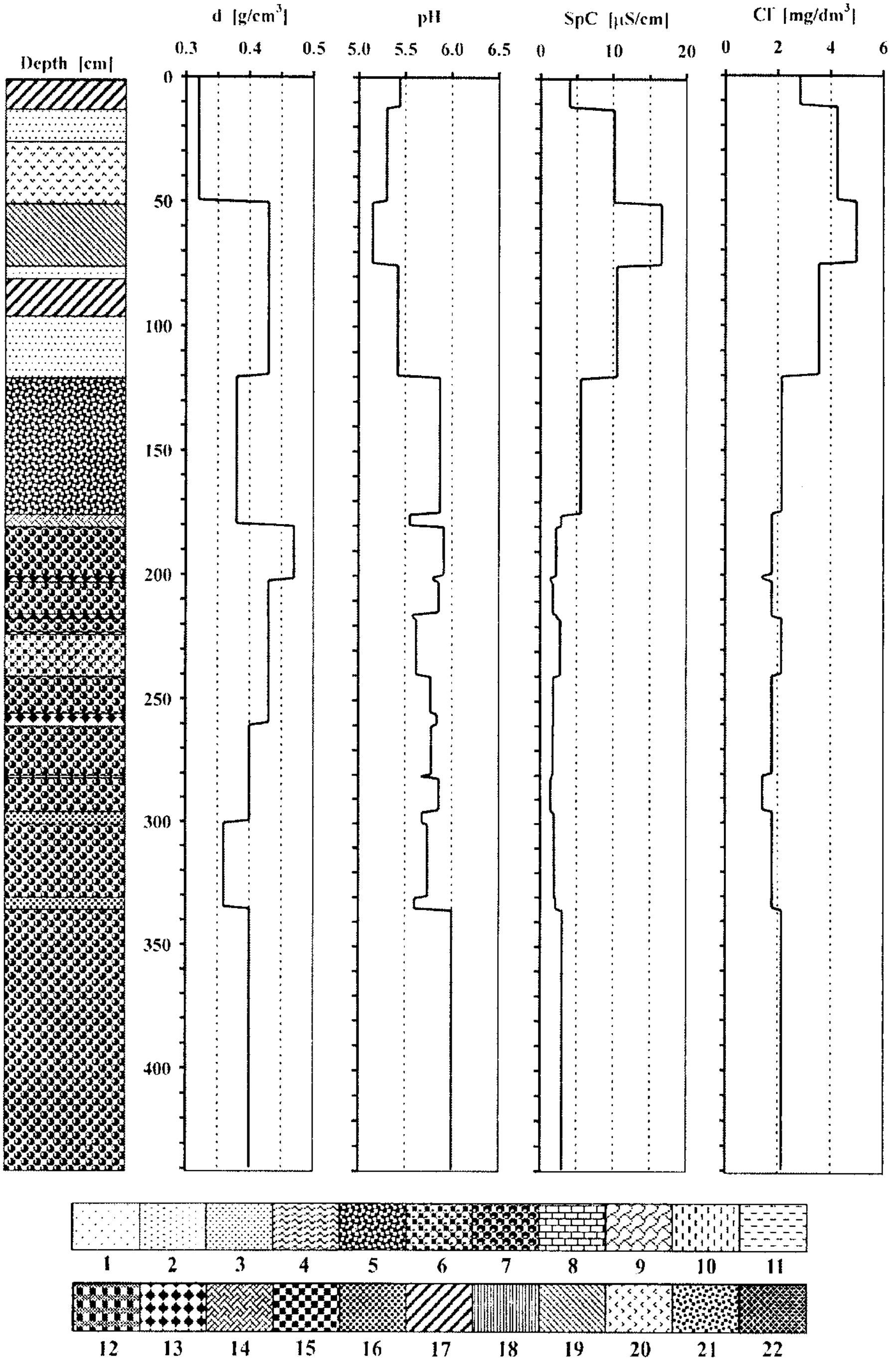

Fig. 2. The snow trench excavated on 17 April 1991 on the ice cap of Lomonosovfonna (1200 m a.s.l.).

Within the last winter season (October 1990 – April 1991), eight distinct layers were observed: from layers of soft, weakly-bonded snow (down to 50 cm from the surface), through fine-grained, alternately dense and loose snow (down to 120 cm) to coarse-grained loose snow interbedded with harder snow overlying névé-ice at a depth of 175 cm. The density of these layers was within the range 0.32–0.43 g/cm^3 which corresponds to an average value of 650 mm w. e. An increased total dissolved solids – (TDS) (about 10 mg/dm^3) was found in the layer of dense snow which was situated at a depth of 50–75 cm. This layer contained a considerable chloride concentration (about 5 mg/dm^3), which relates to the precipitation of 12–19 December 1990 and was observed in the snow cover in all the snow trenches studied on Spitsbergen. The lowest TDS was found in the surface and bed layers (2–3 mg/dm^3). The firn layers of earlier years have 2–5 times lower mineralisation. Variation of pH over the whole winter season was small (from 5.1 to 5.9). The lowest pH value relates to the December precipitation.

Amundsenisen, Wedel Jarlsberg Land. — The snow trench and ice core on the Amundsen Plateau was studied in the period 26 April to 6 May 1991 in the highest part of plateau at an altitude 720 m a.s.l. This is situated between Dungen Nunatak and Lysaskardet (77°15'45'' N, 15°39'35'' E) (Fig. 1). At this site, analysis of the snow cover of the 1989/1990 winter season had been carried out in the previous year. The 1990 trench was 325 cm deep. The 1991 trench was 370 cm deep and the core drilling reached a depth of 1132 cm (Fig. 3). The snow of the last accumulation season (1990/1991) was 456 cm thick. More than ten separate layers were distinguished here. Thin layers of fairly dense snow are the majority representatives in the upper part of this series, which reaches 195 cm. In the lower part, snow is transformed into firn-like snow and névé-ice. The density of snow here was in the range, 0.33 to 0.5 g/cm^3. The water equivalent of the whole series was 1716 mm. A considerable differentiation of the TDS and, in particular, chloride concentration was noted. The differences in TDS ranged from 9 to 47 mg/dm^3. The pH values varied from 4.4 to 5.5. One of the layers is very conspicuous; it has highest TDS and dates from 1990. The TDS is three times less in the firn layers which represent the start of accumulation in earlier years.

Kongsvegen, Kongsfjorden. — In 1990, snow samples were taken from this glacier which represented the precipitation of the winter season 1989/1990. A detailed determination of the chemical composition of these samples was carried out in the laboratories in New Hampshire (Arkhipov *et al.* 1992) and in some Norwe-

1 – fresh snow; 2 – fine-grained snow; loose; 3 – medium-grained snow; loose; 4 – partly crystallised snow, loose (transition stage between snow and firn); 5 – medium and coarse grained snow partly turned into firn; 6 – medium-grained firn; 7 – coarse-grained firn; 8 – glacier ice; 9 – firn ice; 10 – damp snow; 11 – wet snow; 12 – slush; 13 – loose névé-ice (ice layers with firned snow); 14 – dense névé-ice; 15 – compact névé-ice; 16 – superimposed ice; 17 – windblown snow; 18 – deflated snow; 19 – dense snow, not very compact; 20 – compact snow; 21 – very compact snow; 22 – extremely compact snow.

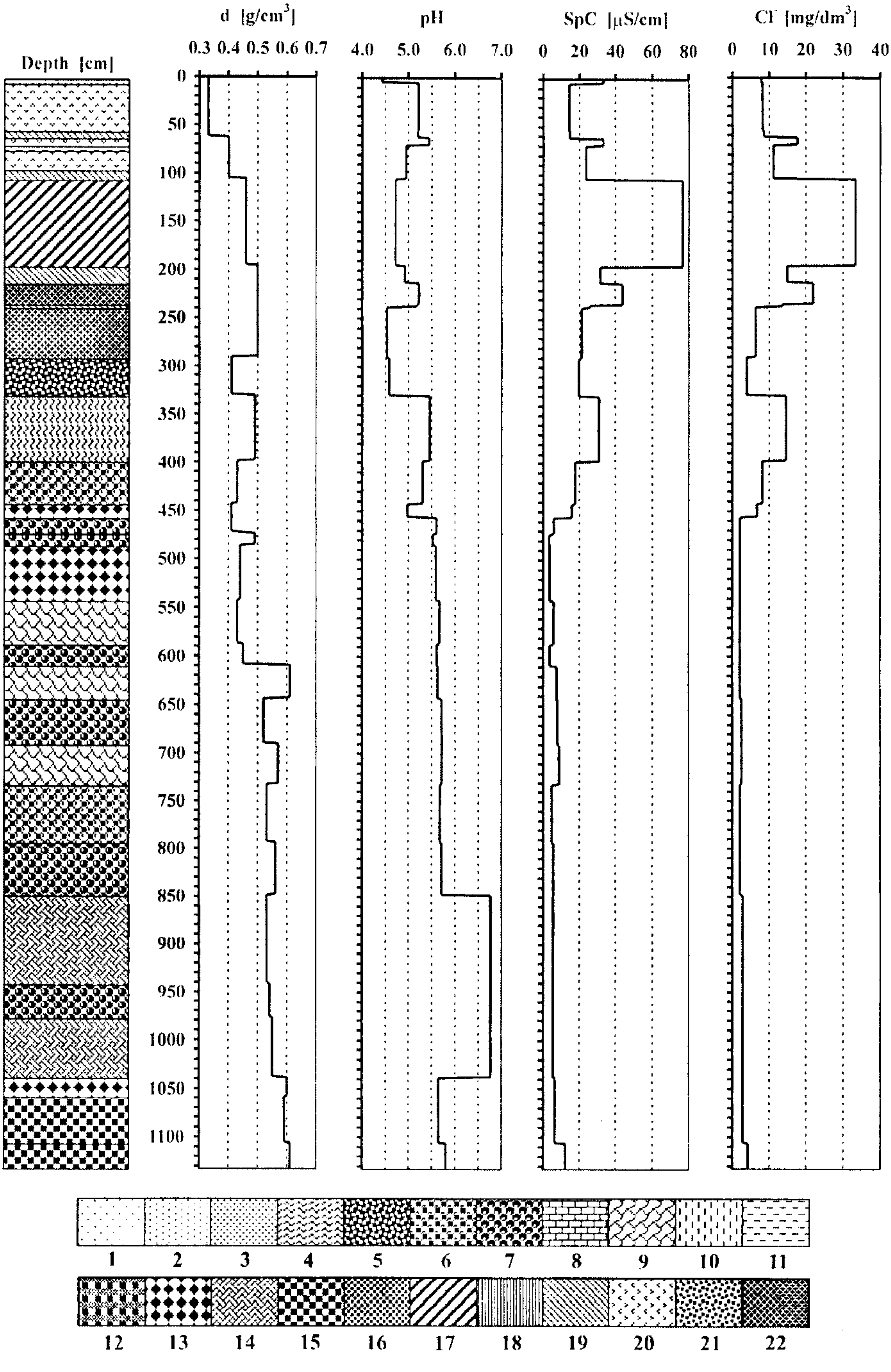

Fig. 3. Snow trench and ice core made on 26 April and 6 May 1991 on the ice field of Amundsenisen (720 m a.s.l.). Captions as for Fig. 2.

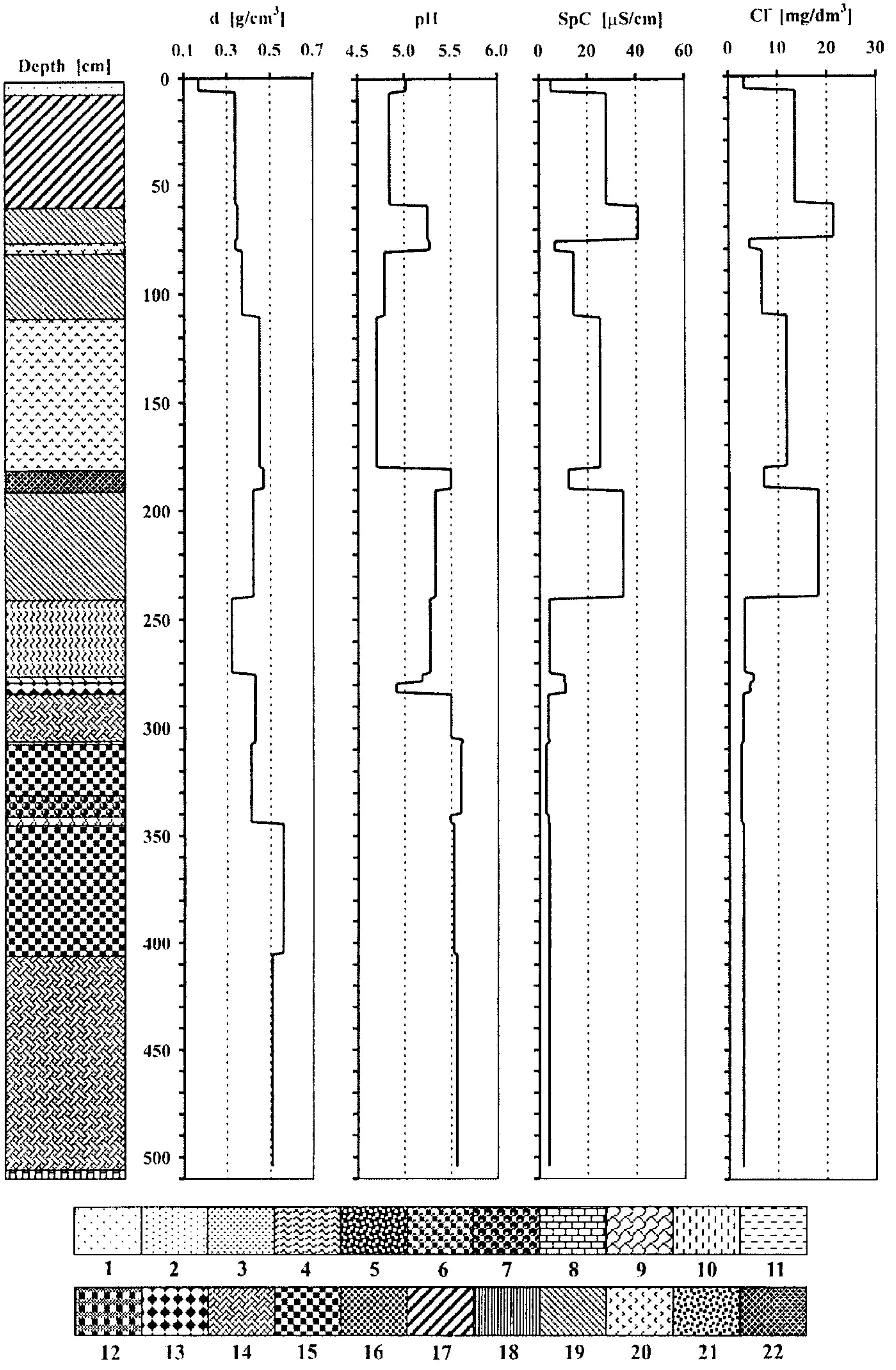

Fig. 4. Snow and ice core made on 13 May 1991 at Kongsvegen (580 m a.s.l.). Captions as for Fig. 2.

gian laboratories (unpublished). On 13 May 1991, core drilling was carried out to a depth of 505 cm in the firn field between Dronningfjella and Gjerstadfjella (78°48'15" N, 13°05'20" E) at an altitude 580 m a.s.l. (Fig. 1). The snow cover of the last winter season (1990/1991) was 283 cm thick and consisted of eleven distinct layers of finely particulate snow down to 50 cm, dense snow down to 240 cm and firn-like snow down to 283 cm (Fig. 4). The density of snow was within the range, 0.34–0.47 g/cm^3, the water equivalent of the whole series being 1042 mm. Considerable differentiation (3–25 mg/dm^3) of the snow TDS concentration of the last winter season was noted. The maximal concentration of chlorides was 21 mg/dm^3. Two layers, one dating from mid December 1990 and a second from the end of March 1991, were found to have the highest TDS. The highest pH was 5.5; however, there was much snow of pH less than 4.9.

Fridtjovbreen, Nordenskiöld Land. — The trench was located below the ice sheet of Austre Grønfjordbreen at an altitude of 400 m a.s.l. (77°52'45" N, 14°21'30" E) (Fig. 1). It was investigated on 3 April 1991. The thickness of the 1990/1991 winter series was 263 cm. More than ten layers could be identified, ranging in density from 0.17 g/cm^3 in fresh powdered snow to 0.45 g/cm^3 in firn-like snow and ice. The water equivalent for the whole winter season was 1076 mm. To a depth of 43 cm, soft snow was the majority constituent and, below, snow interbedded with névé-ice and ice dominated. In the middle part of the profile, a distinctive layer of wet snow was observed (Fig. 5). The TDS of snow is very variable, ranging from 4 to 29 mg/dm^3 with a maximum chloride content as much as 14 mg/dm^3. There is a distinctive layer relating to the snowfall of March 1991 which shows a large volume of TDS. The pH values were in the range, 5.95 to 4.9.

Hans Glacier, in Hornsund Fjord. — The trench on the Hans Glacier was investigated on 3 May 1991 in the equilibrium zone at an altitude of 320 m a.s.l. near the Hans Cabin glaciological station situated near Nordstetinen (77°05'26" N, 15°37'25" E) (Fig. 1). The last winter-season cover (1990/1991) was 310 cm thick and this overlies glacier ice. The ice of the previous winter season was not detectable there. More than 40 different layers were identified. This visible stratification starts at a depth of 50 cm. In the whole series, the snow shoews several different stages of morphogenesis and the lower parts consist of a 30 cm-thick layer of loose, coarse-grained, firn-like snow (Fig. 6). The density of snow and ice layers was within the range 0.18 to 0.52 g/cm^3. The temperature of the snow increases with depth; at the surface, it was -19.8 °C; at a depth of 60 cm, -8.8 °C; whereas, just above the ice surface at the bottom of the trench, only -5.2 °C. The water equivalent of the whole winter series was 1355 mm. The separate layers show a wide range of TDS from 5 to 81 mg/dm^3 with a chloride content as much as 5 mg/dm^3. A majority of the snow layers had pH less than 4.9, and some were as low as 4.4–4.6. The highest pH was 5.27. The layers corresponding to precipitation of December 1990, end of February and end of March 1991 were distinctive.

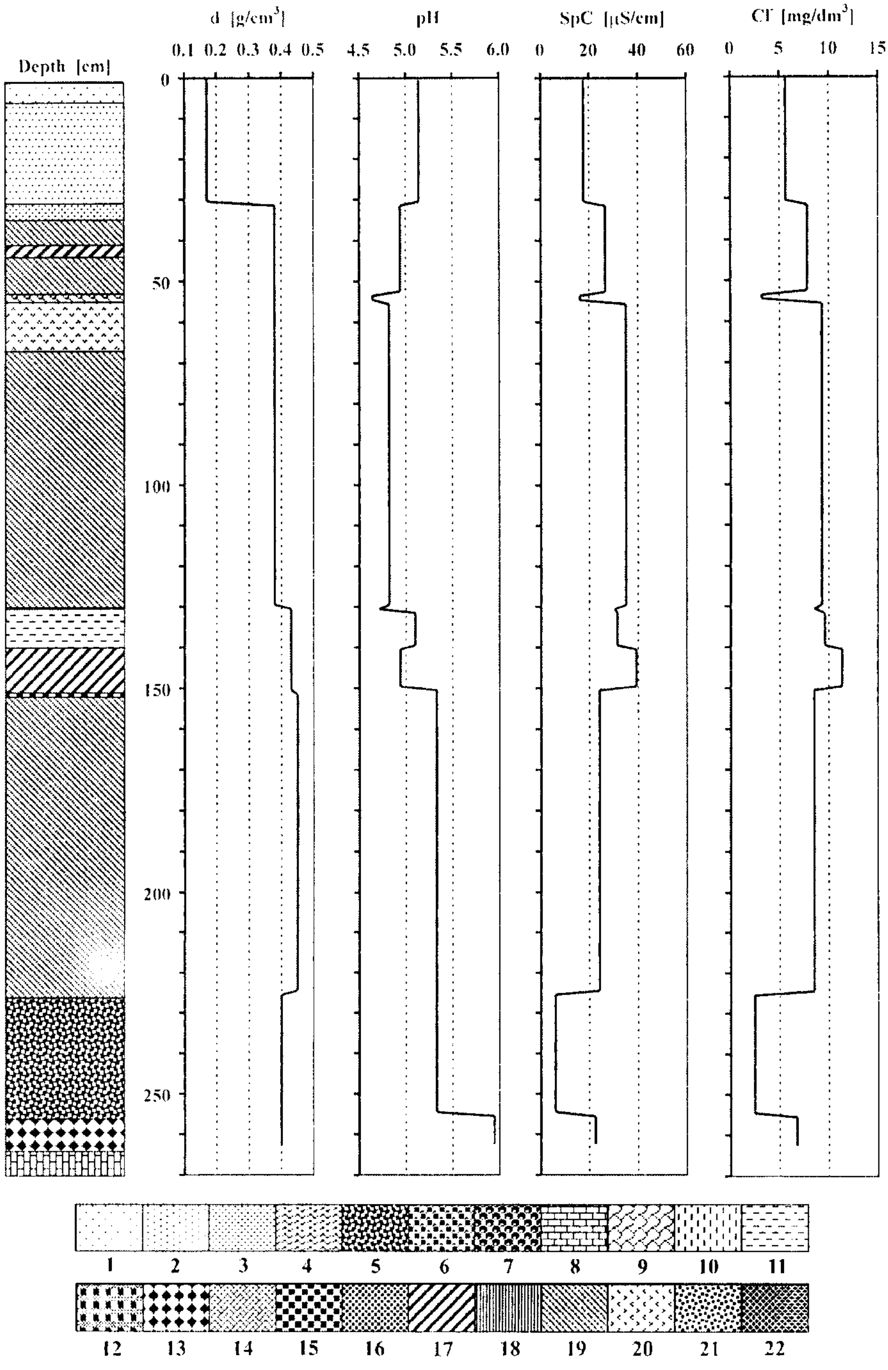

Fig. 5. Snow trench made on 3 April 1991 at Fridtjovbreen (400 m a.s.l.). Captions as for Fig. 2.

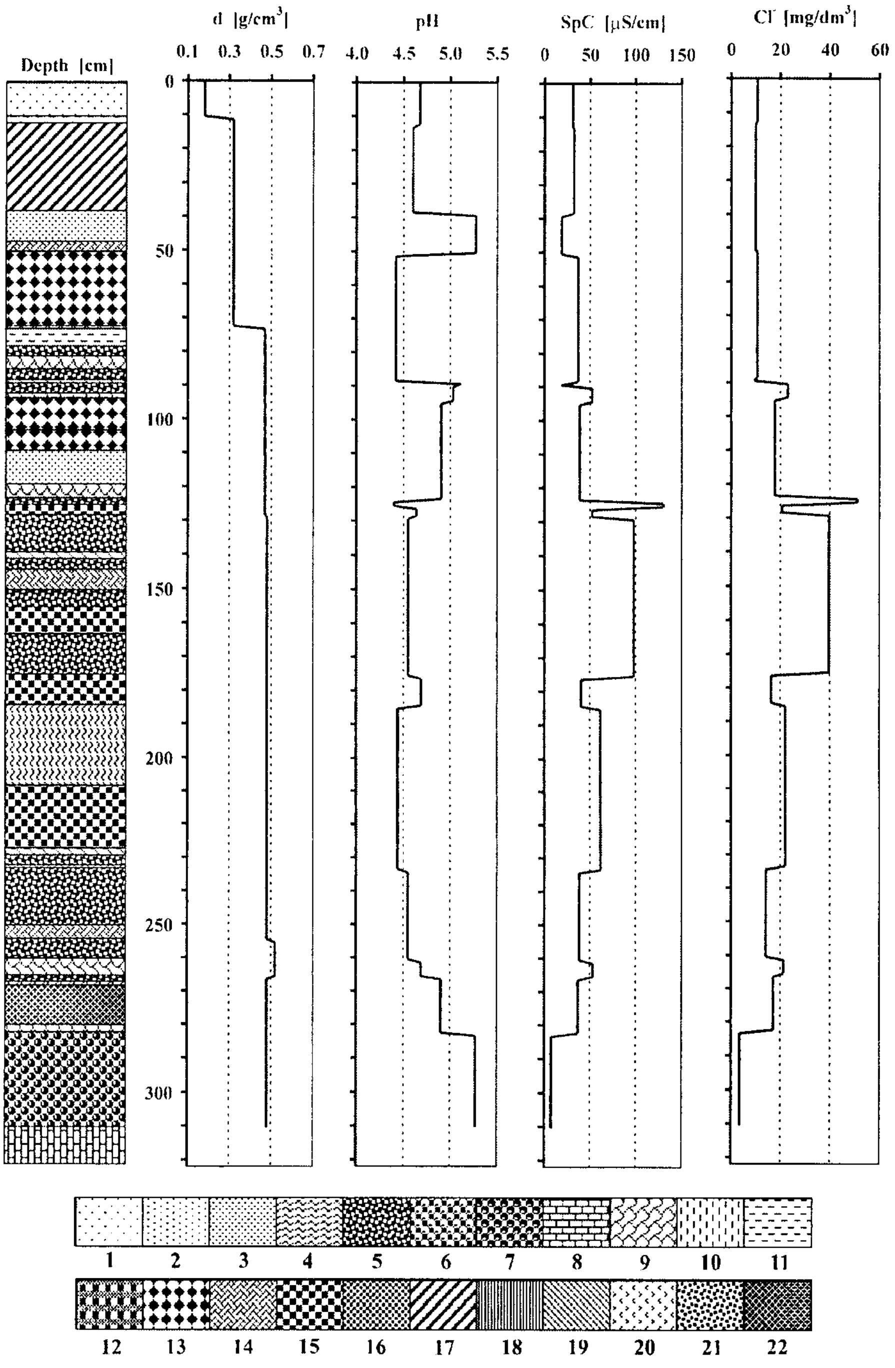

Fig. 6. Snow trench made on 3 May 1991 at Hansbreen (320 m a.s.l.).
Captions as for Fig. 2.

The snow cover at the coastal meteorological stations. — During the winter season 1990/1991, rain and snow precipitation was measured and analysed at the Barentsberg and Hornsund meteorological stations (Fig. 1). In the meteorological station at Ny-Ålesund, only the amount of precipitation was measured. At Barentsburg, the amount of snow precipitation was measured and pH measurements of large snowfalls were carried out. At Hornsund, a wider research programme was carried out which included measurement of snow precipitation, analysis of the snow cover in the Fugleberget Basin and on the slopes of Ariekammen, together with pH and SpC measurements.

At Barentsburg, the water equivalent of snow and rain precipitation of the winter season 1990/1991 was 469 mm. High values of pH (up to 7.40) were noted; this may be related to the smoke issuing from the Barentsburg Power Station, which uses local coal.

The water equivalent of precipitation on the non-glaciated coast of Hornsund was 317 mm. Its pH was very variable. Most precipitation was acid with an average pH of 4.5. The minimum value was 3.76 (end of December 1990) and the maximum, 6.95 (October 1990).

The SpC of the precipitation studied was generally high more than 90 µS/cm. The lowest SPC – 14 µS/cm was in October 1990. The highest SpC were observed in December 1990 (730 µS/cm). In the period from October 1990 to May 1991, the water equivalent of precipitation of the Ny-Ålesund area was 336 mm (Fig. 7).

Variations in the snow cover thickness

Snow precipitation in the winter season 1990/1991 was appreciably higher than in the several previous years. The thickest snow cover occurred on the Amundsenisen, where it exceeded 4.5 m (more than 1700 mm w.e.), a figure more than 5 times greater than that of the coastal meteorological station at Hornsund, where it was only about 300 mm w. e. However, increase of the snow cover thickness with altitude is variable (from 8 m a.s.l. in Hornsund Fjord to 720 m a.s.l. on the Amundsen Plateau). In the lower section, which includes the Hans Glacier, this increase was 350 mm w.e. for every 100 m. At the equilibrium line, the water equivalent was 1300 mm. In the higher section, *i.e.* to 700 m a.s.l., this gradient decreased to only 90 mm w.e. for every 100 m. The increase of water equivalent (y in mm w.e.) in the winter season 1990/1991 in the area between Hornsund Fjord and the Amundsenisen may be presented by the following equation (Fig. 8):

$$y = 411.82 + 2.6996x - 0.001497x^2 \qquad (r = 0.847)$$

where x is the height above sea level

The thickness of the snow cover is significantly reduced over the glaciers situated in the central and northern parts of Spitsbergen, even where they are close to

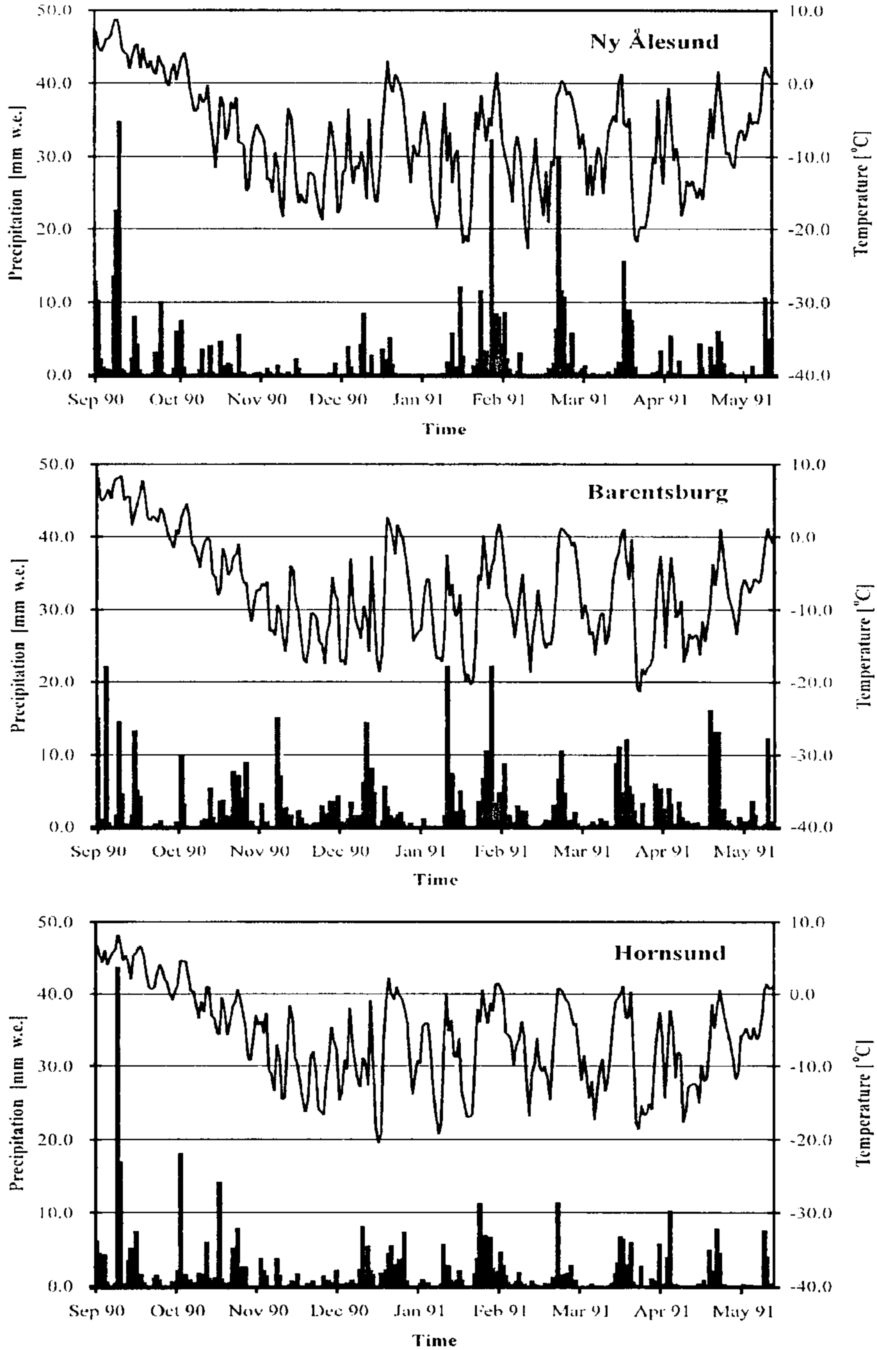

Fig. 7. Thermal conditions and precipitation during the winter of 1990/1991 at the coastal meteorological stations of western Spitsbergen.

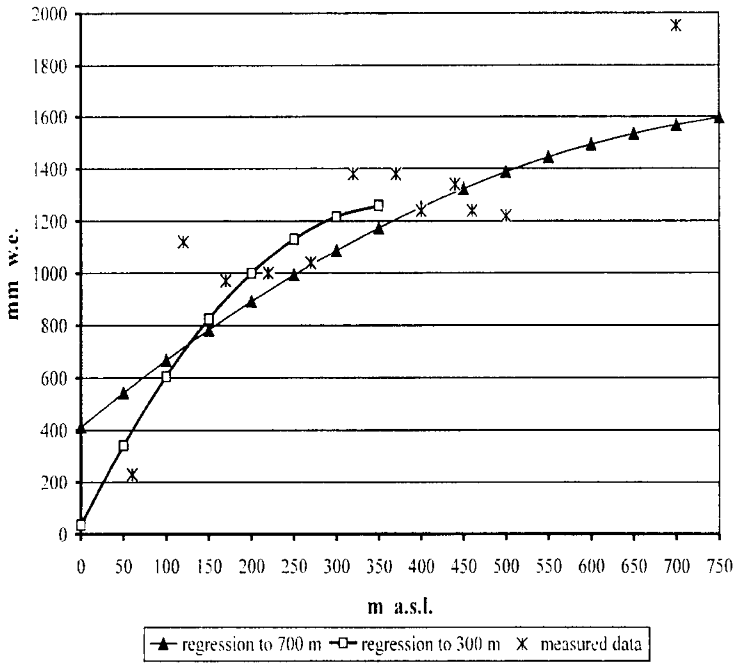

Fig. 8. Differentiation of the winter snow cover in South Spitsbergen in the spring of 1991 according to altitude above sea level. Measured data and data estimated from multinomial regression.

the western coast. In the highest ice field, Lomonosovfonna, the 1990/1991 winter accumulation amounts to only 70 mm w.e. In the case of the glaciers situated on the western coast of Spitsbergen, these values were at the Fridtjov Glacier – 1076 mm, and the Kongsvegen Glacier – 1042 mm. This trend is not matched by the precipitation registered at the coastal station of western Spitsbergen. An increase of precipitation was observed from Hornsund (317 mm w.e.) to Barentsburg (469 mm), whereas it decreased at Ny-Ålesund (336 mm w.e.).

Several precipitation periods may be distinguished for the winter of 1990/1991. The first was in October, the second in December, the third at December/January, the fourth at February/March, the fifth at March/April and the last at April/May. In all the profiles studied, the precipitation periods of December and end of March are the most distinctive, owing to their high TDS and low pH values.

The chemical nature of the precipitation and the snow cover

The pH of the snow cover. — The distribution of pH in the snow cover of the winter 1990/1991 shows a marked variability between the southern, central and northern parts of Spitsbergen (Fig. 9). The lowest pH values were observed in the

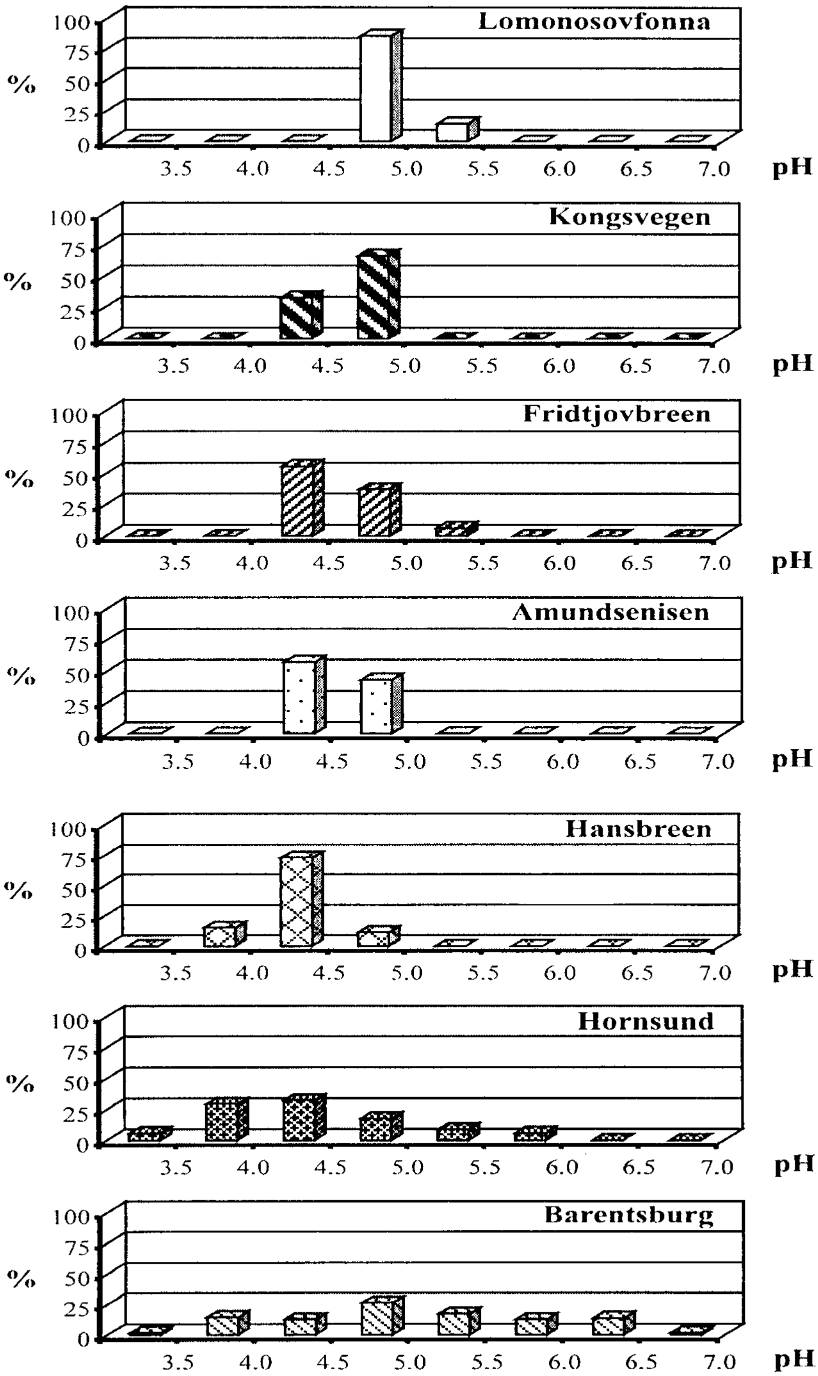

Fig. 9. Distribution of pH in the winter precipitation 1990/1991 in Spitsbergen.

area of Hornsund Fjord where snow of pH values within the range 4.5–5.0 dominated; however, 10% of snow samples studied had pH values which were much lower, 3.5–4.0. Acid rain (pH below 5.5) in this area was 77% of the total precipitation. In this area, several distinct snowfalls showing a low or very low pH were observed. At October/November the pH was 4.2, at the end of December, only 3.8 and at the beginning of February, 4.0. The February precipitation (10 mm w. e.) had also higher TDS (about 240 mg/dm^3). It should be emphasised that, disregarding the high TDS which came mainly from sea spray (which, of course, increased pH values), all the precipitation was very acid, and it is therefore difficult to avoid the conclusion. A pH of 4.1 was noted at the beginning of March, and the next precipitation series, with a low pH of 3.7, occurred at the end of April.

In mid-December, precipitation with higher TDS occurred (450 mg/dm^3), the pH of which was in the range, 4.5–6.0. Such a high pH was presumably caused by the buffering influence of sea spray. Precipitation showing the highest pH (6.5), accompanied by a relatively low TDS, occurred on 24–25 December 1990. At the Hans and Amundsenisen Glaciers however, acid precipitation still dominated and no layer having a pH lower than 4.0 was identified in the snow cover. Northwards from the Hornsund Fjord, the amount of acid precipitation clearly decreases. In the profiles excavated in the central and northern parts of Spitsbergen, precipitation having pH values lower than 5.5 dominated but precipitation with pH less than 4.5 is not found Fridtjovbreen and Kongsvegen glaciers. On the Lomonosovfonna pH lower than 5.0 were identified. In contrast, the amount of neutral-reaction snow clearly increases in this direction. At Lomonosovfonna, snow of neutral reaction comprises as much as 33% of an annual profile. In the area of Grønfjord near Barentsburg, large quantities of snow showing an alkaline reaction occur, presumably as a result of a considerable atmospheric pollution (dust) of anthropogenic origin. In some cases, the pH of this snow is as high as 7.4. Such phenomena also occur in the area of Piramiden and, sometimes, Longyearbyen.

The most acidic precipitation, that at the end of December and the turn of February and March, was identified in the snow covers of all the sites studied.

TDS and chloride concentration in the snow cover. — At the six sites where values of total mineralization of the winter snow cover were studied, much variability was noted. It has been concluded that the variability of mineralization is due mainly to the distance from the open sea and to the altitude above sea level but an additional influence was the location with respect to local and global atmospheric circulation. In the northern part of Spitsbergen, which is influenced by Arctic High during the greater part of winter, snows with low TDS predominate. At Lomonosovfonna, which is situated furthest from the sea and at the highest altitude, the snow shows the lowest TDS. There, layers showing TDS lower than 10 mg/dm^3 predominate (Fig. 10). A small percentage (12.5%) of layers of TDS from 10 to 20 mg/dm^3 were also observed. The total load of salt which accumulated in the snow cover during the whole winter season is an important indicator of TDS. At

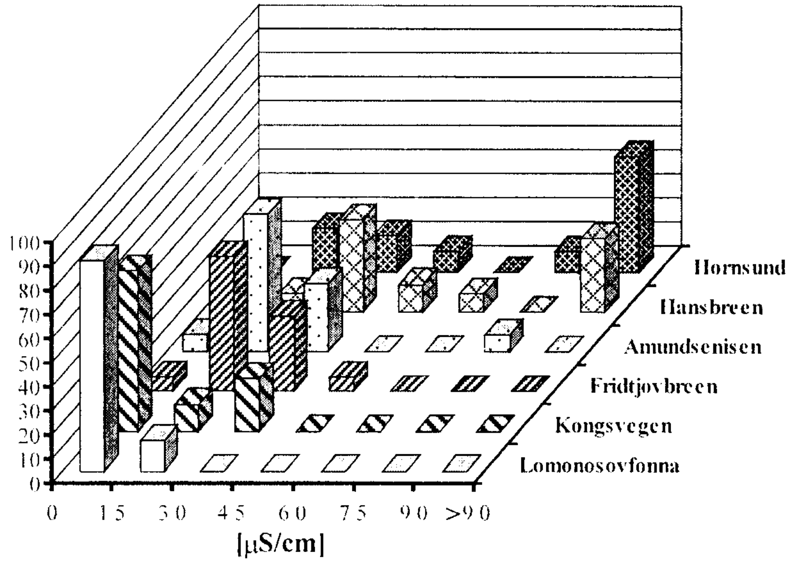

Fig. 10. Distribution of SpC in the winter precipitation 1990/1991 in Spitsbergen.

Lomonosovfonna, for the winter season 1990/1991, this was estimated at 2.8 t/km² of the ice field surface. For this area, the average coefficient of precipitation salinity was estimated to be 4 mg/m² × mm (Tab. 1).

Table 1

Characteristics of the snow cover and precipitation in West Spitsbergen during the winter of 1990/1991.

Sites of sampling	Depth of snow cover	Water equivalent	Load of salt in precipitation	Coefficient of salinity
	[cm]	[mm]	[t/km²]	[mg/m² x mm w.e.]
Station at Hornsund 8 m a.s.l.	—	317	23.8	75
Hansbreen 320 m a.s.l.	310	1377	41.7	30
Amundsenisen 700 m a.s.l.	442	1952	43.2	22
Fridtjovbreen 400 m a.s.l.	263	1076	17.8	16
Kongsvegen 580 m a.s.l.	283	1042	15.8	15
Lomonosovfonna 1200 m a.s.l.	175	659	2.8	4
Station at Barentsburg 40 m a.s.l.	—	469	—	—
Station at Ny-Ålesund 5 m a.s.l.	—	336	—	—

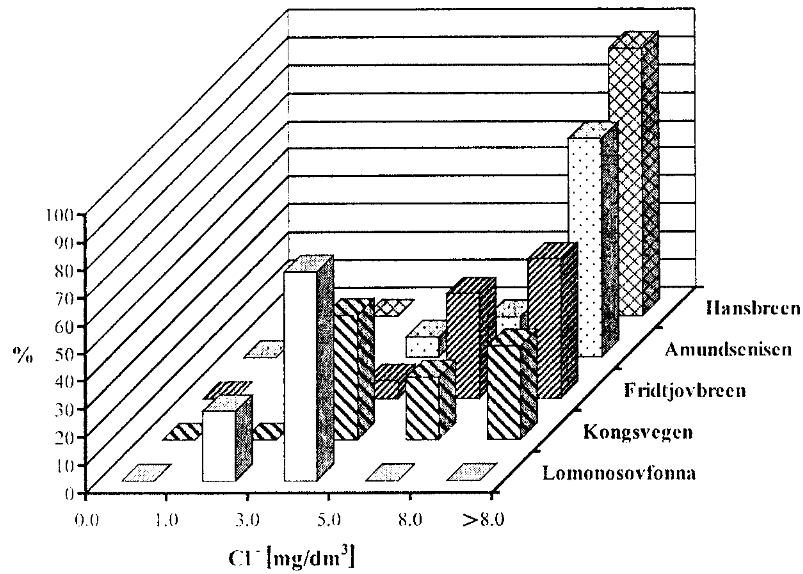

Fig. 11. Distribution of chloride concentration in snow of the winter series 1990/1991 for selected glaciers of Spitsbergen.

At Kongsvegen Glacier, which is situated much closer to the western sea coast, snow with mineralization up to 30 mg/dm^3 was observed (22% of all the precipitation) (Fig. 10). The total load of salt calculated from all the layers of the season studied reached 15.8 t/km^2, which increases the value of the salinity coefficient to 15 mg/m^2 × mm of precipitation (Tab. 1). Towards the central and southern parts of Spitsbergen, snow TDS within the range of 1–30 mg/dm^3 predominates whereas the amount of snow containing up to 40 mg/dm^3 increases (Fig. 10). Van Mijenfjorden is a boundary area which shows a very small TDS of the snow precipitation. In this respect, the situation is similar to that in central and northern parts of Spitsbergen. At Amundsenisen, there is even a snow layer showing SpC within the range 75–90 μS/cm.

South of Amundsenisen, where marine influences are greater, the snows usually have high TDS values (mainly above 50 mg/dm^3) and, in some cases at Hornsund, as much as 450 mg/dm^3 (Fig. 10). The load of salts which have accumulated in the snow bed studied at Hans Glacier was 41.7 t/km^2, and the salinity coefficient was 30 mg/m^2 × mm of precipitation. On the Hornsund coast, this coefficient was 75 mg/m^2 × mm of precipitation (Tab. 1).

On the basis of chloride content, the three following zones may be distinguished in the area of Western Spitsbergen:

- northern zone: snows of the central part contain from 1.1 to 5.1 mg/dm^3 chlorides; on the coast more than 8 mg/dm^3;
- central zone: there is a considerable increase in snowfall containing chloride concentrations from 5.1 to more than 8 mg/dm^3;

Table 2

Physico-chemical characteristics of the winter snow cover and precipitation in West Spitsbergen in 1990/1991; pH, SpC and concentration of chlorides.

Sites of sampling	pH			SpC [μS/cm]			Cl^- [mg/dm^3]		
	max.	min.	average	max.	min.	average	max.	min.	average
Hornsund	6.49	3.76	4.89	730.0	15.5	116.9	—	—	—
Hansbreen	5.27	4.42	4.56	130.0	7.7	56.6	51.12	3.55	23.01
Amundsenisen	5.46	4.43	5.00	76.6	14.4	28.9	33.37	3.91	12.81
Fridtjovbreen	6.95	4.64	5.01	46.7	6.1	27.1	13.85	2.45	8.01
Barentsburg	7.40	3.89	5.53	—	—	—	—	—	—
Kongsvegen	5.50	4.70	5.09	40.8	4.1	17.4	21.30	3.20	8.94
Lomonosovfonna	5.87	5.15	5.41	11.6	4.0	9.7	4.97	2.84	3.64

Table 3

Snow series in the winter of 1989/1990 and after one year of firnization in three accumulation zones in Spitsbergen.

Sample site	The annual snow cover (at the end of winter season 1989/1990)				The snow cover of the winter season 1989/1990 after one year of firnization			
	Thickness of snow layer	Water equivalent	Salt load	Coefficient of salinity	Thickness of snow layer	Water equivalent	Load of salt left	Coefficient of salinity
	[cm]	[mm]	[t/km^2]	[mg/m^{2}x mm w.e.]	[cm]	[mm]	[t/km^2]	[mg/m^{2}x mm w.e.]
Amundsenisen	382	1450.7	15.20	10	100	437	1.49	3
Kongsvegen	240	864.0	8.79	10	60	265	0.52	2
Lomonosovfonna	—	—	—	—	120	517	0.65	1

– southern zone – layers showing chloride concentrations from 8.1 to 52 mg/dm^3 predominate.

The importance of the Hornsund coast in this study should be emphasised; more than 95% of snow precipitation here shows chloride concentrations above 8.1 mg/dm^3, which, in Jansen, Block and Knack (1988) classification, is considered to be very high (Fig. 11).

In the accumulation area of Lomonosovfonna, Kongsvegen and Amundsenisen, an investigation of firn in the covers of earlier years was also carried out. At Lomonosovfonna, all the cover of the winter season 1989/1990 and part of the cover of the season 1988/1989 were analysed. The average water equivalent for the 1989/1990 cover was 517 mm while the total load of preserved salt was only 0.65 t/km^2 and the average SpC was 2 μS/cm (Tab. 3). For the Kongsvegen Glacier, the values were: 265 mm w.e., 0.52 t/km^2 of salt in the whole of the winter cover; 3.2 μS/cm average SpC. Before the firnization process started, this bed (according to analytical data derived from the snow trench made by J.O. Hagen, Norsk Polarinstitutt, in April 1990) had the following values: 864 mm w.e., 16.4 µS/cm average mineralization, 8.79 t/km^2 of total load of deposited salt. In case of Amundsenisen, the season 1989/1990 and period 1984–1989 were analysed. In the winter season 1989/1990, the water equivalent was 1443 mm; load of salt, 15.2 t/km^2 and the average SpC was 17 µS/cm. After ablation and firnization, this annual layer, shows a water equivalent of only 437 mm and an average SpC of 5.5 µS/cm. The salt load of 1.49 t/km^2 was preserved. It was noted that, in the older series from the period 1985–1989, the SpC was comparable to that of the intensively firnized series of 1989/1990.

Conclusions

Studies of various annual snow precipitation covers in glacier firn fields over a wide area of Western Spitsbergen produced the following results:

(1) The charting of an annual snow profile, differentiating the individual snowfalls, not only in respect of their physical nature (type of snow, water equivalent, etc.) but also their chemical characteristics (pH, total dissolved solids concentration (TDS), content of chlorides, *etc.*). A close correlation between the physico-chemical properties of individual snowfalls and the relevant snow layers in the winter snow cover can be demonstrated. The correlation model is currently being elaborated. Site observations carried out in snow trenches and ice-cores over a wide area of Spitsbergen, enable us to define a clear-cut spatial distribution of snow precipitation and its physico-chemical characteristics. They appear to be influenced by three elements, namely, (1) distance from the open sea, (2) altitude above sea level and (3) the specific location within the island, relative to its atmospheric circulation. This differentiation is best demonstrated in Western Spitsbergen during the winter season. It is manifested by the presence of two latitudinal provinces: a northern – one influenced by Arctic High (Lomonosovfonna and Kongsvegen) and a southern – influenced by Arctic High and Greenland Low (the southern slopes of Amundsenisen and the area of Hornsund).

(2) Values of the salt load, both in the whole winter series and in particular phases of snowfall have been obtained.

(3) In three areas, investigation of the firn of earlier seasons has been carried out; the physico-chemical properties have been compared on the basis of analytical methods applied to the snowfalls of the last winter season. The comparison of recent annual snow accumulation with older covers shows that washout of salts from the snow takes place rapidly early in the process of firnization; 80% of washout takes place then.

With respect to the northern part of Western Spitsbergen, the following features were noted: there is a relatively shallow gradient in the snow cover thickness between the western coasts and the central part of the island (Tab. 1); the TDS of snow is relatively small. Acid precipitation is relatively unimportant.

By contrast, in the southern provinces, the precipitation gradient is very high (Tab. 1). The TDS in precipitation is also very high and the load of salt which is delivered to the glaciers exceeds 45 t/km^2. Acid precipitation is appreciable here.

Apart from this very clear latitudinal differentiation of Spitsbergen in cryological terms, some distinct differences between western and eastern parts of the island were also noted. The extent of the latter is currently under investigation.

Acknowledgements. — The studies of snow cover were carried out by the following members of the expedition: the University of Silesia (P. Głowacki and L. Kolondra), the Norsk Polarinstitutt (J.O. Hagen), the Laboratory of Glaciology at Grenoble (B. Lefauconnier), the Institute of Geography, Russian Academy of Sciences (A.F. Glazovsky and M.Y. Moskalevsky) and the precipitation samples were collected and analysed by members of the XII Polar Expedition of the Polish Academy of Sciences (M. Włosek) and the Murmansk Institute of Meteorology, (B. Senetsky). The help forthcoming from all these expeditions and the people involved in these studies is much appreciated. During the field studies, the Polish Polar Station at Hornsund, the Station of the Russian Glaciological-Ecological Expedition in Barentsburg and Piramiden and also the Norsk Polarinstitutt Station in Ny-Ålesund provided help which is gratefully acknowledged. The research was supported by the Polish Committee for Scientific Research grant.

References

AHLMANN H.W. 1933. Scientific results of the Swedish-Norwegian Arctic Expedition in the summer of 1931. — Geogr. Annlr. Part VIII,15.

ARKHIPOV S., MOSKALEVSKY M., GLAZOVSKY A., MAYEWSKI P. and WHITLOW S. 1992. Snow cover geochemistry on the Kongsvegen Glacier and Amundsenisen (Spitsbergen). — *In*: Proc. 2nd Intern. Symp. Glacier Caves a Karst in Polar Regions. Univ. Silesia, Poland, Sosnowiec 1992: 7–20.

BARANOWSKI S. 1977. The subpolar glaciers of Spitsbergen seen against the climate of this region. — Acta Univ.Wratisl. 410: 1–157.

GŁOWACKI P. 1997. The mass balance of Hans Glacier in the light of cryochemical investigation. — *In:* Głowacki P. (ed.), Polish Polar Studies, 24th Polar Symposium, Warszawa, 1997. Institute of Geophysics of the Polish Academy of Sciences, Warszawa: 75–79.

GŁOWACKI P. and LESZKIEWICZ J. 1994. Physico-chemical properties of precipitation and snow cover in Spitsbergen in the winter season 1992/1993. — *In:* Zalewski S.M. (ed.), XXI Polar Symposium, 60 years of Polish research of Spitsbergen. Institute of Geophysics Polish Academy of Sciences, Warszawa 1994: 199–205.

GŁOWACKI P., PULINA M. and WACH J. 1990. Some geomorphological and hydrochemical processes in the active zone of permafrost in the Hornsund fjord (Spitsbergen) in the hydrological year 1985–1986. — Wyprawy Geograficzne na Spitsbergen, Sesja Polarna, Lublin 1990: 203–214.

HAGEN J.O. and LIESTØL O. 1990. Long-term glacier mass-balance investigations in Svalbard, 1950–88. —Ann. Glaciol., 14: 102–106.

JANIA J. 1988. Dynamiczne procesy glacjalne na Południowym Spitsbergenie w świetle badań fotointerpretacyjnych i fotogrametrycznych. — Prace Naukowe Uniw. Śl., 995, Katowice, 258 pp.

JANIA J. 1992. Excursion. — *In*: Glaciological Research in Svalbard, Current Problems. Field Workshop at the Polish Polar Station Hornsund, Spitsbergen, 26–30 April 1992, Uniw. Śl., Sosnowiec: V/10–V/34.

JANIA J. and GŁOWACKI P. 1996. Is the Hansbreen in South Spitsbergen (Svalbard) a surge-type glacier? — *In:* Krawczyk W.E. (ed.). 23rd Polar Symposium, Sosnowiec: 27–43.

JANSEN W., BLOCK A. and KNACK J. 1988. Kwaśne deszcze. Historia, powstawanie, skutki. — Aura 4.

KOTLYAKOV V.M. (ed.) 1985. Glatsyologia Spitzbergena. — Nauka Moscov, 200 pp.

KRAWCZYK W.E. 1996. Manual for karst water analysis. — Inter. Jour. Speleology. Handbook 1: Physical Speleology, Bologna, 51 pp.

LESZKIEWICZ J. and PULINA M. 1999. Snowfall phases in analysis of a snow cover in Hornsund, Spitsbergen. — Polish Polar Res., 20: 3–24.

LEFAUCONNIER B., HAGEN J.O. and RUDANT J.P. 1994. Flow speed and calving rate of Kongsbreen Glacier, Svalbard using SPOT images. — Polar Res., 13: 59–65.

MARKOWICZ M. and PULINA M. 1979. Ilościowa półmikroanaliza chemiczna wód w obszarach krasu węglanowego. — Prace Naukowe Uniw.Śl., 289, Katowice, 67 pp.

MELVOLD K. and HAGEN J.O. 1998. Evolution of a surge-type glacier in its quiescent phase: Kongsvegen, Spitsbergen, 1964–95. — Jour. Glaciol., 44: 394–404.

MIGAŁA K., PEREYMA J., and SOBIK M. 1988. Akumulacja śnieżna na południowym Spitsbergenie. — Wyprawy Polarne Uniwersytetu Śląskiego 1980–1984. Uniw. Śl. Katowice: 48–63.

OSOKIN N.I. and KHODAKOV V.G. 1985. Kompleks prirodnych ldov Spitzbiergiena. — *In:* Kotlyakov V.M. (ed.), Glatsyologia Spitzbiergiena, Nauka, Moskov:112–118.

PEREYMA J. 1983. Climatological problems of the Hornsund area, Spitsbergen. — Acta Univ. Wratisl., 714, 134 pp.

PULINA M. 1984. Hydrological and glaciological investigations on Bertil Glacier and in the Grønfjord region. — *In:* Field investigations performed during the glaciological Spitsbergen Expedition in 1983. Interim report. Uniw.Śl., Katowice: 39–46.

PULINA M. 1990. Geomorphological effect of the cryochemical process. — Questiones Geographicae, 13/14: 99–112.

PULINA M. 1991. Stratification and physico-chemical properties of snow in Spitsbergen in the hydro-glaciological year 1989/1990. — Wyprawy Geograficzne na Spitsbergen. Materiały Sesji Polarnej "Arctic Environment Research", UMCS, Lublin: 191–213.

PULINA M. 1992. Excursion. — *In:* Glaciological Research in Svalbard, Current Problems. Field Workshop at the Polish Polar Station Hornsund, Spitsbergen, 26–30 April 1992, Uniw. Śl., Sosnowiec, V/35–V/52.

POURCHET M., LEFAUCONNIER B., PINGLOT J.F. and HAGEN J.O. 1995. Mean net accumulation of ten glacier basins in Svalbard estimated from detection of radioactive layers in shallow ice cores. — Z. Gletcsher. Glazial. B 31: 73–94.

SCHYTT V. 1964. Scientific results of the Swedish glaciological expedition to Nordaustlandet, Spitsbergen 1957 and 1958. — Geogr. Annlr., 46: 243–281.

ZAGORODNOV V.S., 1988. Recent Soviet activities on ice core drilling and core investigations in arctic region. — Bulletin of Glacier Research 6: 81–84.

ZAGORODNOV V.S. and SAMOYLOV O.YU. 1982. Deep structure of Spitsbergen glaciers. — Mat. Glyatsiol. Issl., Moskov, 44: 58–64.

Received January 15, 2000
Accepted July 7, 2000

Streszczenie

Analizowano pokrywę śnieżną w końcu zimy 1990/1991 w kilku obszarach Spitsbergenu Zachodniego: Lomonosovfonna, Kongsvegen, Fridtjovbreen, Amundsenisen i północne otoczenie fiordu Hornsund (fig. 1). Określono właściwości fizyczne i skład chemiczny opadów oraz pokrywy śnieżnej (największej w ostatnim dwudziestoleciu). Stwierdzono duże zróżnicowanie opadów i miąższości pokrywy śnieżnej: 317 mm równoważnika wodnego (w.e.) w rejonie Hornsundu, 659 mm na Lomonosovfonna, 1076 mm na Fridtjovbreen i 1716 mm na Amundsenisen (fig. 2–8, tab. 1). Obliczono wielkość ładunku soli w pokrywie śnieżnej w różnych obszarach Spitsbergenu: 2,8 t/km^2 na Lomonosovfonna, 15,8 t/km^2 na Kongsvegen i 43,2 t/km^2 na Amundsenisen (tab. 1). Stwierdzono intensywny proces demineralizacji śniegu w trakcie jego firnizacji dochodzący do 90% w okresie pierwszego lata (tab. 3). Podjęto próbę określenia udziału elementów antropogenicznych poprzez analizę pH w opadach i pokrywie śnieżnej (fig. 9–11, tab. 2). Stwierdzono wyraźną korelację pomiędzy właściwościami fizykochemicznymi poszczególnych warstw śniegu, a faktycznymi właściwościami opadu śnieżnego. Pozwoliło to na porównanie wielkości opadów i ich zanieczyszczenia na tak rozległym obszarze badań.

Podzielono Spitsbergen Zachodni na prowincje i strefy ze względu na zróżnicowanie jakości opadów i pokrywy śnieżnej: północną – leżącą w obrębie wyżu arktycznego (Lomonosovfonna i Kongsvegen) oraz południową – w przeważającej części objętą przesuwającymi się masami powietrza z wyżu arktycznego i niżu grenlandzkiego (Amundsenisen i rejon Hornsundu).