



**You have downloaded a document from
RE-BUŚ
repository of the University of Silesia in Katowice**

Title: Distribution of snow accumulation on some glaciers of Spitsbergen

Author: Mariusz Grabiec, Jan Leszkiewicz, Piotr Głowacki, Jacek Jania

Citation style: Grabiec Mariusz, Leszkiewicz Jan, Głowacki Piotr, Jania Jacek. (2006).
Distribution of snow accumulation on some glaciers of Spitsbergen. "Polish Polar
Research" (2006, no. 4, s. 309-326).



Uznanie autorstwa - Użycie niekomercyjne - Bez utworów zależnych Polska - Licencja
ta zezwala na rozpowszechnianie, przedstawianie i wykonywanie utworu jedynie w celach
niekomercyjnych oraz pod warunkiem zachowania go w oryginalnej postaci
(nie tworzenia utworów zależnych).



UNIwersYTET ŚLĄSKI
W KATOWICACH



Biblioteka
Uniwersytetu Śląskiego



Ministerstwo Nauki
i Szkolnictwa Wyższego



Distribution of snow accumulation on some glaciers of Spitsbergen

Mariusz GRABIEC¹, Jan LESZKIEWICZ¹, Piotr GŁOWACKI² and Jacek JANIA¹

¹ Wydział Nauk o Ziemi, Uniwersytet Śląski, Będzińska 60, 41-200 Sosnowiec, Poland
<mgrabiec@wnoz.us.edu.pl> <leszkiew@us.edu.pl> <jjania@us.edu.pl>

² Instytut Geofizyki PAN, Księcia Janusza 64, 01-452 Warszawa, Poland
<glowacki@igf.edu.pl>

Abstract: We describe the spatial variability of snow accumulation on three selected glaciers in Spitsbergen (Hansbreen, Werenskioldbreen and Aavatsmarkbreen) in the winter seasons of 1988/89, 1998/99 and 2001/2002 respectively. The distribution of snow cover is determined by the interrelationships between the direction of the glacier axes and the dominant easterly winds. The snow distribution is regular on the glaciers located E-W, but is more complicated on the glaciers located meridionally. The western part of glaciers is more predisposed to the snow accumulation than the eastern. This is due to snowdrift intensity. Statistical relationships between snow accumulation, deviation of accumulation from the mean values and accumulation variability related to topographic parameters such as: altitude, slope inclination, aspect, slope curvature and distance from the edge of the glacier have been determined. The only significant relations occurred between snow accumulation and altitude ($r = 0.64-0.91$).

Key words: Arctic, Spitsbergen, snow accumulation, statistical data analysis.

Introduction

Climatic changes significantly transform the geographical environment. It may be indicated by continuous monitoring of glaciers in polar regions. The current negative trend of the Svalbard glacier mass balances is mainly caused by increased ablation. The role of climate warming in this process seems to be crucial. Snow accumulation is generally considered to be a stable factor, and it must obviously be a very important as it supplies the material for the glaciers. Also, climate warming increases evaporation, which may result in higher levels of precipitation. Significant increase of spring precipitation in Spitsbergen, predicted by Hanssen-Bauer (2002), may be reflected in an increased winter mass balance of the glaciers. Hence, the dynamics of climatic change may also have a significant influence on accumulation and, in turn, the mass balance of the glaciers.

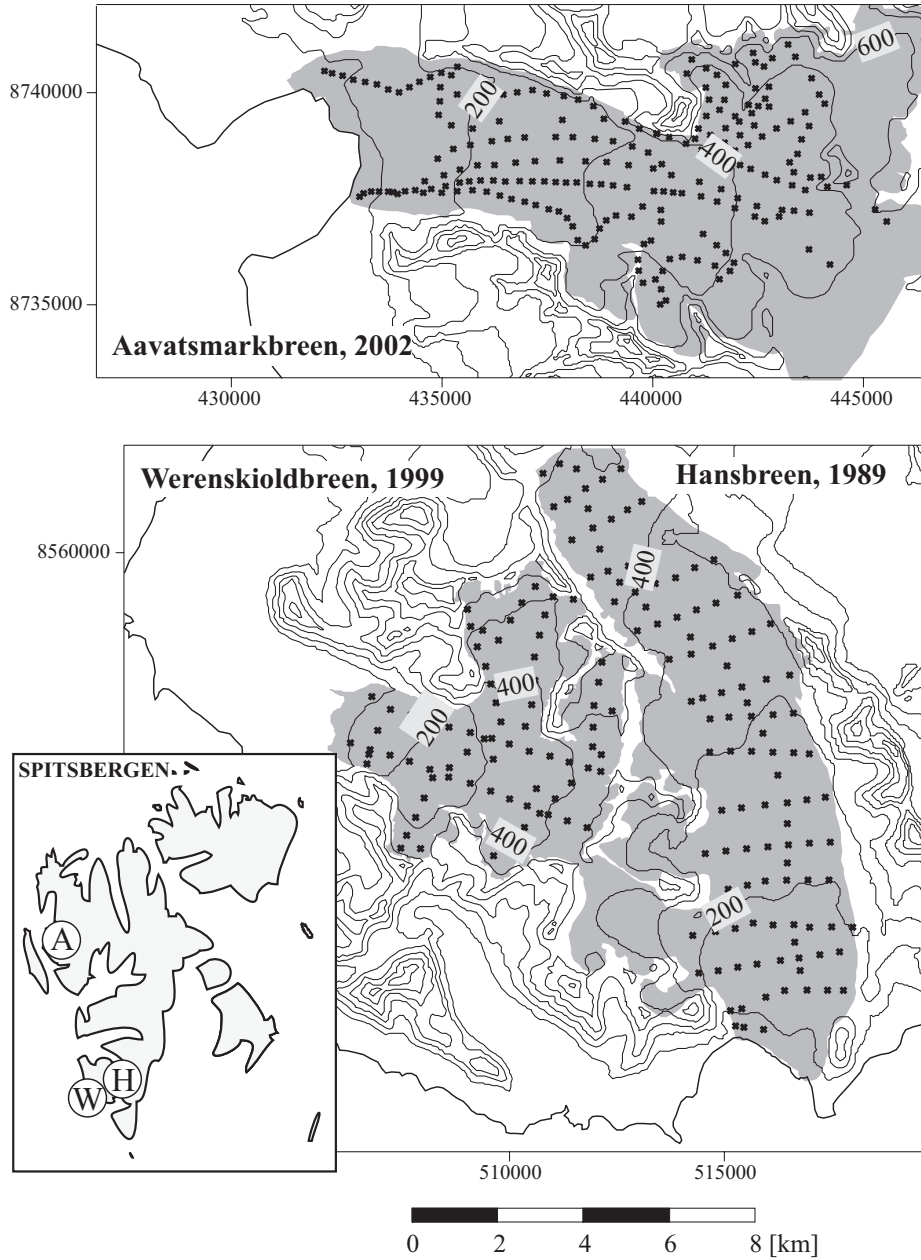


Fig. 1. Investigated areas, with glaciers marked in dark grey and snow sounding points marked with black crosses. Map projection UTM zone 33X WGS84.

The purpose of this study is to determine the factors which influence spatial variability of snow accumulation on three selected Spitsbergen glaciers: Hansbreen, Werenskioldbreen and Aavatsmarkbreen (Fig. 1). Two of these (Hans-

reen, Werenskioldbreen) are located in South Spitsbergen, (Wedel Jarlsberg Land), whereas Aavatsmarkbreen is located in Oscar II Land (NW Spitsbergen). The glaciers selected represent different types, both in terms of morphology and topography. The distribution of snow on the glaciers has been analysed and the reasons for the differences in accumulation distribution are discussed here. The seasons: 1988/1989 (Hansbreen), 1998/1999 (Werenskioldbreen) and 2001/2002 (Aavatsmarkbreen) have been chosen for this analysis.

Previous work on snow accumulation in Spitsbergen

The first surveys of snow accumulation were carried out by Ritter in 1931/1932 on the glaciers in the Kongsfjord vicinity: Austre Brøggerbreen and Midre Lovèn-breen (Ahlmann 1933). Data concerning the snow cover of the South Spitsbergen glaciers was collected by the Polish expeditions to Hornsund led by Kosiba (1960) in 1957 through 1959. Soviet expeditions started intensive investigations of glacier snow cover in the mid-1960s. In the summer of 1965, investigations were carried out on the ice complex: Nordenskiöldbreen–Lomonosovfonna–Opalbreen (Singer and Mikhailiov 1967; Mikhailiov and Singer 1975). This investigation of the snow cover accumulation sought to examine the accumulation of snow in a latitudinal profile from the east coast of the island towards its centre. In 1966–1967, expeditions of the Institute of Geography Academy of Sciences of the USSR carried out intensive investigations of snow on the glaciers in NW Spitsbergen (Holtedahlfonna, Isachsenfonna, Fjortende Julibreen and Kronebreen; Singer and Mikhailiov 1967; Mikhailiov and Singer 1975). In the same time, numerous accumulation surveys were carried out on the glaciers in the vicinity of Barentsburg (Fridtjovbreen, Grønfjordbreen, Vøringbreen; Mikhailiov and Singer 1975). In the spring of 1978, large-scale investigations of snow cover on various types of beds were started in Spitsbergen by the Institute of Geography, USSR Academy of Sciences. The investigations were variously conducted in valley floors and slopes, on numerous glaciers such as: Vøringbreen, Daudbreen, Aldegondabreen, Vestre Grønfjordbreen, Fridtjovbreen, Bertilbreen, Bogerbreen, Longyearbreen, and also on the plateaus of Isachsenfonna and Lomonosovfonna (Khodakov 1985).

Extensive investigations were carried out in South Spitsbergen in the spring of 1982 by a Polish expedition. Snow cover measurements were taken on the glaciers in Wedel Jarlsberg Land, Torell Land and Sörkapp, from the Greenland Sea to the Barents Sea (Migala *et al.* 1988). Ground penetrating radar (GPR) has played significant role in the accumulation analyses on the Spitsbergen glaciers during the extensive Norwegian research programme of 1997 (Winther *et al.* 1998). Surveys were carried out in nine regions. Radar profiles were also supplemented by traditional surveys of snow thickness, temperature, density and snow stratigraphy. Our study develops the previous work in respect of factors determining spatial variability of snow cover.

Study area

Aavatsmarkbreen is located in the NW part of Spitsbergen in Oscar II Land. It is a valley glacier, which ends at a 4 km-wide cliff in Hornækbukta Bay. The glacier runs straight and it is *c.* 15 km long. It covers an area of *c.* 75 km² (Lankauf 1999). The mean inclination of Aavatsmarkbreen is exposed to the west by *c.* 2.5°. Like most of the Svalbard glaciers, Aavatsmarkbreen is in recession. Between 1900 and 2000, the front of the glacier retreated *c.* 2.5 km (Lankauf 1999).

Hansbreen is located in the southern part of Wedel Jarlsberg Land. The axis of the glacier extends roughly N-S and is 15 km long. Hansbreen represents a valley-type glacier with a complex basin (Jania 1988), which ends with a cliff in Hornsund. The surface of the glacier is *c.* 56 km² and the average inclination angle is 2° (Jania *et al.* 1996). Mainly due to highly negative values of summer balance, in the average -1.3 m of water equivalent (w.e.), the net balance is generally negative (-0.38 m w.e.; Szafraniec 2002). Observations carried out on Hansbreen in the period 1989–2001 indicate that the average value of winter balance is almost 0.92 m w.e.

Westwards investigations of the snow cover have been carried out on Werenskioldbreen (Wedel Jarlsberg Land), which is also a valley-type glacier with well-determined borders. Its accumulation basin consists of three parts: a northern zone, which discharges ice through Skilryggbreen tongue; a central zone, the main Werenskioldbreen; and a southern zone, which is discharged by Angellisen glacial stream. The surface area of the glacier is 27.4 km², and its length is 9.5 km (data from 1980). The glacier course is generally straight with a slight deviation of the front northwards.

Methods

Surveys of the snow cover thickness were carried out by means of the well-established method using a snow probe, the accuracy of the readings being ± 1 cm. 447 soundings were performed (Fig. 1). Most of these were located on Aavatsmarkbreen (257) in 2002, 78 on Werenskioldbreen in 1999 and 112 on Hansbreen in 1989. The sounding location density varied from 3.4 locations per km² of the surface on Aavatsmarkbreen, to 0.9 locations per km² on Hansbreen. On Werenskioldbreen, the distribution was 2.9 locations per km². The location of measuring points on Hansbreen was prepared by means of a tacheometric method, whereas, in the other cases, coordinates of the points were determined by means of a GPS receiver.

The accumulation on the glaciers was estimated based on the mean snow density in snow pits dug in those areas. Three snow pits were dug on Werenskioldbreen at altitudes of 155, 307 and 441 m a.s.l. For Aavatsmarkbreen, density data were obtained from six snow pits located at 147, 189, 273, 364, 439 and 532 m a.s.l.. Density

data for Hansbreen were collected from 3 snow pits: at the front, in the central part and on the ice divide.

Parameters of digital elevation models

Digital elevation models (DEMs) of particular glaciers were applied in the investigation. All applied DEMs were based on an equal area grid, with cell sides of 100 m. The DEM of Werenskioldbreen was simplified from the 20 m grid cells model previously used for making an orthophotomap of the glacier at a scale of 1:25 000 (Jania *et al.* 2002; Kolondra 2002). Both model and the map were prepared from an infrared false colour aerial picture at a scale of 1:50 000 taken on 12 August, 1990. Universal Transverse Mercator (UTM) projection on the World Geodetic System 1984 (WGS 84) ellipsoid, was employed to prepare the DEM of Werenskioldbreen. A digital elevation model for Hansbreen was made in 1989, based on tacheometric surveys (Jania and Kolondra unpublished data) and presented in Mercator's (Gauss-Krüger) projection on the European Datum 1950 (ED 50) ellipsoid. The digital elevation model of Aavatsmarkbreen of 2001 was based on the results of kinematic GPS surveys of April 2001. The position of the ice cliff of the glacier was determined by means of an ASTER satellite image of 2001 (Perski *et al.* 2003). The DEM was prepared in UTM ED 50 projection.

Topographic parameters

The relationship between snow accumulation (or the related coefficients such as the deviations of the accumulation from the mean value and variability of accumulation) and five parameters of the relief have been analysed. They are altitude, slope inclination, slope curvature, aspect and distance from the glacier edge. Transformed digital elevation models have led to grid files containing values of slope angle, aspect and slope curvature. Values of topographic parameters have been calculated on the base of DEMs for each survey location of snow accumulation.

The "absolute altitudes" of survey points have been determined from the applied DEM. The "distance of the survey point from the edge of the glacier" means the length of a straight line between the survey location and the closest point on the glacier boundary. The "slope inclination" concerns the steepest direction and is shown in degrees, where 0° is a horizontal surface and 90° , a vertical slope. The "slope curvature" gives the characteristics of the slope *i.e.* it indicates whether the slope surface is concave (positive values), convex (negative values) or flat (0 value). The parameter has been measured in the direction of the highest inclination. "Slope aspect" is represented in degrees according to the direction of the highest inclination of the slope. It may take values from 0° to 360° , where 0° means the northern aspect and the values increasing clockwise.

As recommended by Marchand and Killingtveit (2001), in order to obtain more effective usage of the aspect parameter in correlation analysis, the values recorded in a circular scale ($0-359.9^\circ$) have been transposed to a linear scale

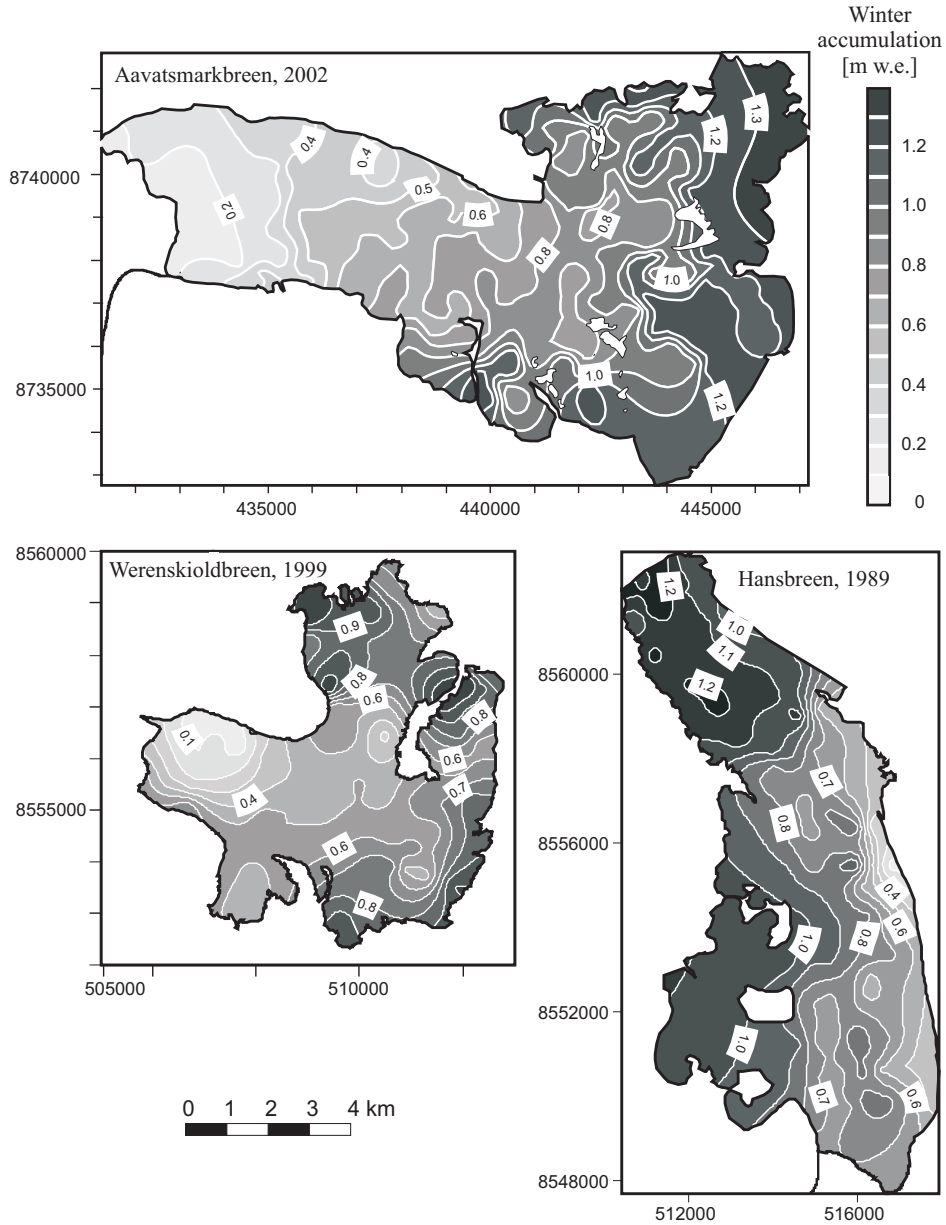


Fig. 2. Snow accumulation on Aavatsmarkbreen in 2002, Werenskioldbreen in 1998 and Hansbreen in 1989. Map projection: UTM zone 33X WGS84.

(0–180). Transformations have been performed 18 times; each time, the beginning of the linear scale has been moved clockwise 10°. Sets of values, termed here „ranked aspect”, have further been compared with the accumulation values so as to determine relationships between them.

Results

Spatial variability of snow accumulation on the glaciers

Aavatsmarkbreen. — The survey of spatial distribution of accumulation on the glacier was taken at the end of the accumulation season in April/May of 2002. Aavatsmarkbreen displays a typical pattern of accumulation distribution. Snow cover thickness increases with altitude quite regularly and accumulation contours are almost parallel with the topographic contours. Accumulation values increase from less than 0.2 m w.e. at the front to over 1.3 m w.e. in Krullfonna accumulation field (Fig. 2).

Accumulation values observed on the glaciers were related to their absolute altitude a.s.l. A linear relationship is obvious (Fig. 3) and thereby permits a determination of the theoretical mean value of accumulation at any point on the glacier, providing the altitude was known. A map of deviations of the accumulation values from the mean values was prepared on the basis of differences between the theoretical values of accumulation and those recorded (Fig. 4). The range of deviations on Aavatsmarkbreen is limited. Conditions favouring accumulation are in the central part of the main accumulation basin. Positive deviations of accumulation were also found on the southern part of the glacier. The lower part of the glacier is less favourable for deposition. Accumulation patterns on the small lateral glaciers vary significantly.

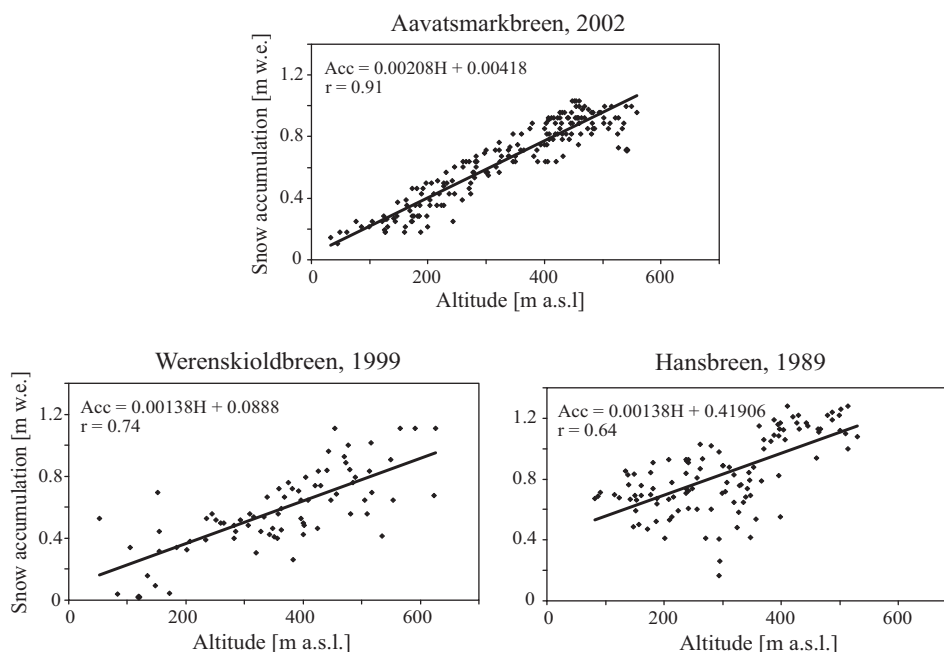


Fig. 3. Relation between the snow accumulation (Acc) and altitude (H).

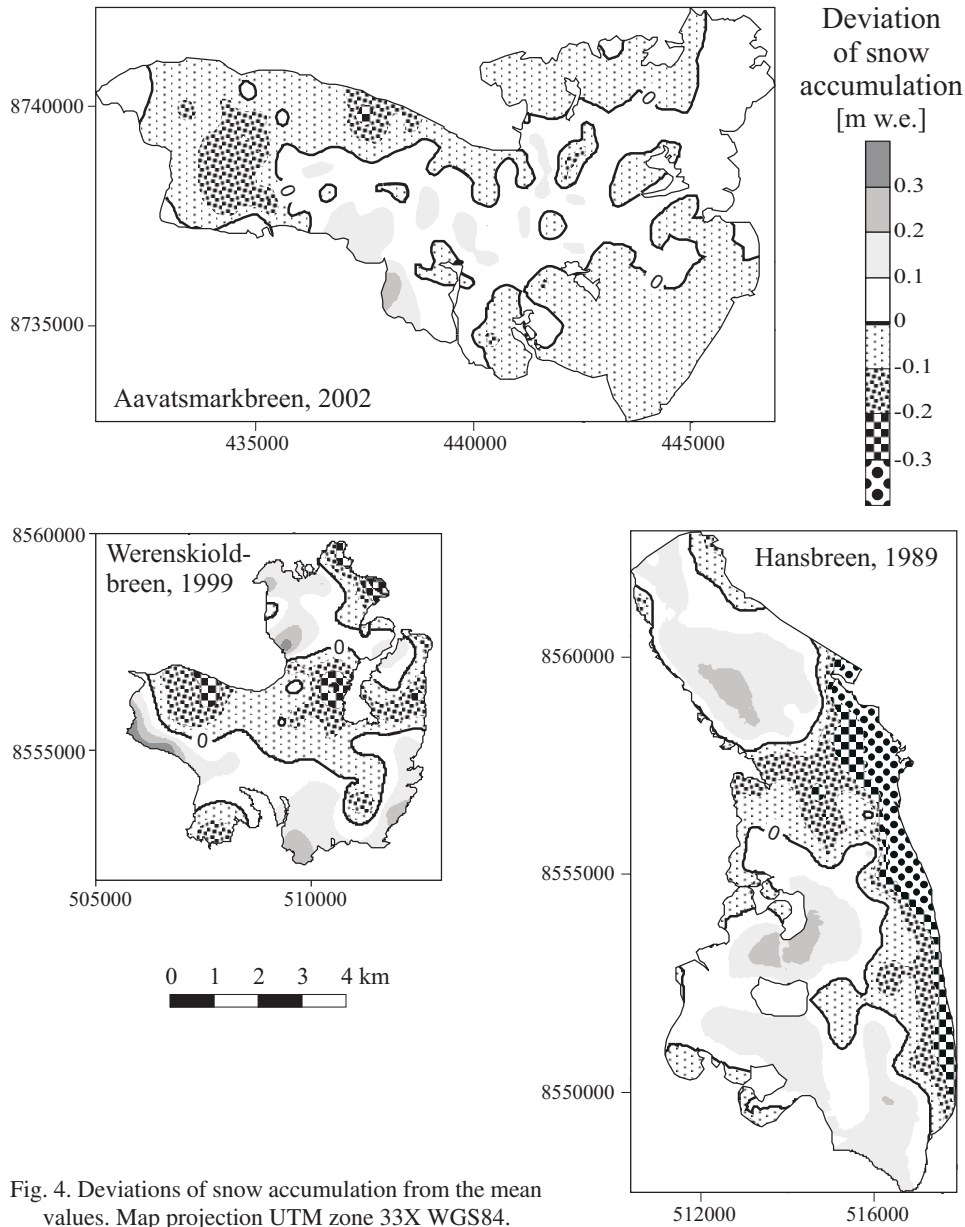


Fig. 4. Deviations of snow accumulation from the mean values. Map projection UTM zone 33X WGS84.

The spatial distribution of accumulation was determined mainly by the precipitation gradient. The state of the snow cover on the glacier appears to have been only slightly modified by wind. In any case, the prevailing easterly direction of winds was constrained here by the course of the glacier valley. Winds from Løvenskioldfonna did not reach any great velocity. Re-deposition of snow was thus very limited thereby promoting a regular distribution of accumulation.

Werenskioldbreen. — The map of snow accumulation on the glacier (Fig. 2) was based on surveys of the snow cover thickness taken in spring 1999. In the highest parts of the glacier, accumulation in that season reached a maximum of 1.1 m w.e. The spatial distribution of accumulation in the middle and upper parts of the main stream of the glacier was characterised by a fairly regular increase of accumulation relative to altitude. A much more significant disproportion has been observed in the lower part of the glacier where the tongue changes its course towards the north. Clearly, the SW part of the tongue was more predisposed to snow accumulation, values of 0.6 m w.e. being reached here. By contrast, accumulation in the northern part of the tongue was much lower, <0.1 m w.e. Snow distribution in the upper part of the Skilryggbreen, also showed a significant asymmetry, with dominant accumulation occurring in the western part.

A map of accumulation deviations from the mean values (Fig. 4) shows a distinct pattern of snow distribution. In the lower and the middle parts of the glacier, the “0” contour deviation is almost coincident with the glacier axis. Negative deviations can be observed on the N and NE sides of the axis and positive ones appear on the S and SW side. The maximum positive deviations were recorded in the places of potential snowdrifts, *i.e.* in the SW part of the front, in the W part of the Skilryggbreen and on the covered upper parts of the glacier. Negative deviations occurred in the N part of the front, the N, E, and NE parts of the Skilryggbreen stream and in the NE part of the main accumulation field.

The accumulation distribution observed in the season of 1998/99 was the result of the diversified exposure of the glacier surfaces to the major wind directions. The accumulation zone, consisting of several basins of different aspect, contributed to a diversification of snow distribution. The precipitation gradient played a major role in the formation of the accumulation cover in the straight main stream course of Werenskioldbreen. Skilryggbreen lies almost meridionally with most snow accumulation on its western side. This is presumably the result of snow drift caused by the dominant easterly winds. Snow accumulation on the SW side of the front may also be the result of snow drift, especially from the NE *i.e.* from Skilryggbreen. The winds from that sector are weaker on the less-inclined front, as well as on the orographic obstacle, represented by the slope of Angellfjellet where the transporting strength decreases and snow is thereby deposited. The converse can be observed on the northern part of the front, where blow-out is probably the dominant process. This may be one of the reasons for the shorter range and faster recession of Skilryggbreen tongue, when compared to the main stream.

Hansbreen. — Surveys of spatial distribution of accumulation on the glacier were performed at the end of the accumulation season (April/May) in 1989. The relationship between accumulation and absolute altitude above sea level was less demonstrable than on the other two glaciers. A gradient perpendicular to the slope of the glacier was observed, whereas an increase of accumulation in the central and the lower parts of the glacier was observed across its slope from east to west. The

minimum values of accumulation <0.2 m w.e. occurred in the eastern part at 300 m a.s.l. (Fig. 2). The upper part of the glacier forms a typical accumulation basin with maximum accumulation in its central and northern parts >1.3 m w.e.

The least favourable conditions for accumulation occurred in the eastern part of Hansbreen (Fig. 4). By comparison, positive deviations were observed in the accumulation basin in the upper and frontal parts of the glacier and on the lateral glaciers on the western side of Hansbreen (Tuvabreen and Deileggbreen).

Exclusively local climatic-topographic conditions seemed to be the reasons for spatial variability in the accumulation. Hansbreen is located transversely to the direction of the dominant winds, *i.e.* those from the E and NE (Wielbińska and Skrzypczak 1988). Easterly winds are obstructed by the Sofiekammen massif, which borders Hansbreen in the east. This obstacle causes air masses to rise on the windward slopes. Strong winds then descend on the lee slopes, where they blow out huge amounts of snow from the foot of the slopes and transport them westward. Wind directions may largely be responsible for the asymmetry and complicated model of snow distribution on Hansbreen (Leszkiewicz and Pulina 1999). The eastern part of the glacier, which has relatively low accumulation, corresponds to the places where strong winds occur. Higher accumulations on the western part of glacier may be due to snow drift. At the altitude of Kvitungisen, which is beyond the influence of the Sofiekammen Ridge, the spatial distribution of accumulation returns to the normal mode. This hypothesis concerning spatial variation of snow cover on Hansbreen has already been outlined by Jania (1994, 1997).

The relationship between accumulation and topographic parameters of the glacier surface

Among the topographic parameters, the altitude of the point is in the closest relationship with accumulation value. This relationship clearly results from the precipitation gradient and orographic precipitation. The correlation coefficient of accumulation and absolute altitude on the glaciers analysed is as much as 0.64–0.91 (Fig. 3, Table 1). The highest coefficient of correlation with absolute altitude was recorded on Aavatsmarkbreen, whereas it was much lower on Hansbreen. The determination of the linear regression of accumulation values, as related to altitude of the survey location, has enabled us to estimate a mean accumulation gradient on the investigated glaciers in particular seasons. The accumulation gradients on the glaciers in South Spitsbergen were similar *i.e.* 0.138 m w.e. per 100 m of altitude, although it contrasted significantly on Aavatsmarkbreen with 0.208 m w.e. per 100 m.

In some cases, slope aspect significantly influences snow accumulation on the Svalbard glaciers. Certainly, the relationship between accumulation and slope aspect is quite significant on Werenskioldbreen (Fig. 5). The highest mean accumulation was recorded on slopes which have a SE aspect and the values decrease markedly with the change of the aspect from SE to NW. The relationship between accumulation and slope aspect is confirmed by a statistically significant coeffi-

Table 1
 Correlation coefficient (r) of snow accumulation and variability of accumulation related to topographic parameters of glaciers. The significant relations of the level $\alpha = 0.05$ are marked with “+”, while statistically insignificant relations are marked with “-”; * directions in degrees of the prescribed value equal to 0 in a linear scale

Dependent and independent variables	Aavatsmarkbreen 2002		Werenskioldbreen 1999		Hansbreen 1989	
	r	$\alpha = 0.05$	r	$\alpha = 0.05$	r	$\alpha = 0.05$
Accumulation						
altitude m. a.s.l.	0.91	+	0.74	+	0.64	+
slope aspect	-0.29 (70°)*	+	-0.54 (130°)*	+	-0.33 (70°)*	+
slope inclination	-0.04	-	0.27	+	-0.01	-
slope curvature	0.07	-	0.02	-	0.23	+
Variability of accumulation						
altitude m a.s.l.	0.28	+	0.07	-	-0.48	+
slope aspect	-0.18 (110°)*	+	-0.28 (130°)*	+	0.18 (60°)*	-
slope inclination	0.11	-	0.2	-	0.27	+
slope curvature	0.09	-	0.09	-	-0.06	-
distance from the edge	-0.03	-	-0.47	+	-0.36	+

cient of correlation (ranked aspect 130° $r = -0.56$) (Table 1). In the case of Hansbreen, the slope aspect has less influence on the distribution of the mean accumulation (Fig. 5). Here accumulation values lower than the average were recorded on the slopes exposed to W and SW, whereas accumulation on the slopes exposed to E and NW was higher than average. The coefficient of accumulation correlation with the ranked aspect 70° (Table 1), $r = -0.33$, was much lower than that observed on Werenskioldbreen. The coefficient illustrates well the general tendency of the accumulation growth from the lowest values on the slopes exposed to SW to the maximum to the NE. Relatively large accumulations on Aavatsmarkbreen are concentrated on the slopes with NE, N, S and SE aspects (Fig. 5). Only low accumulations were recorded on W, SW, NW and E slopes. The correlation of accumulation with the ranked aspect 70° is -0.29 (Table 1).

The relationship between snow accumulation and slope inclination is statistically insignificant except of Werenskioldbreen (Fig. 6), where it is 0.27 (Table 1). On Hansbreen and Aavatsmarkbreen, mean values of accumulation are similar in all inclination ranges. There was a relatively high accumulation on the gentle slopes on Werenskioldbreen. The values of mean accumulation decreased significantly on slopes of between 2° and 4°, then they increased proportionally with increase of slope inclination.

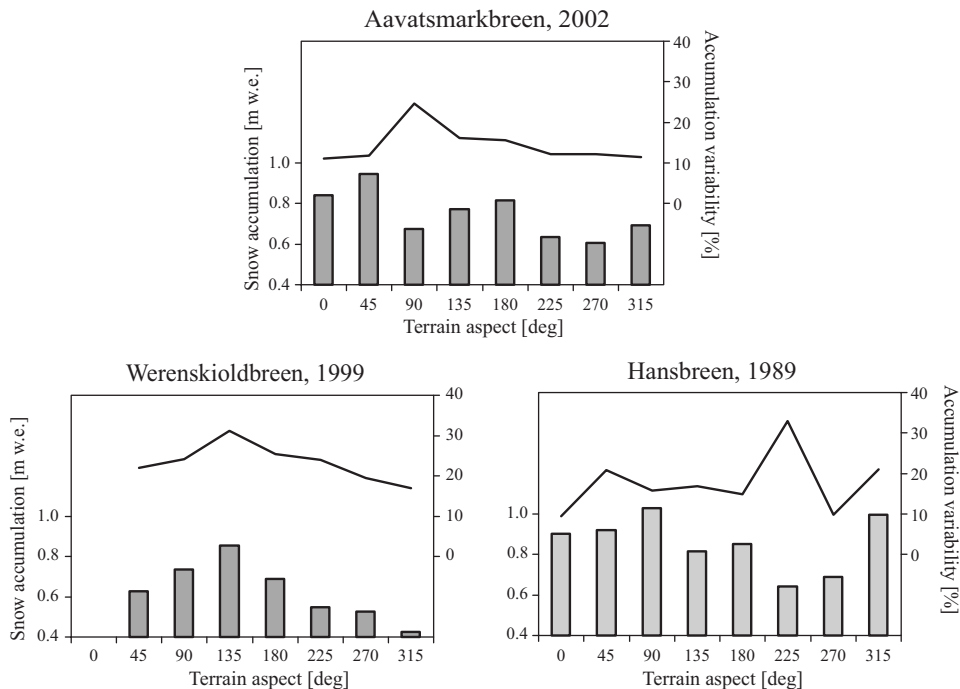


Fig. 5. Snow accumulation and accumulation variability in particular ranges of slope aspect.

Snow accumulation on the glaciers does not prove its unequivocal correlation with a slope-shape factor and a statistically significant coefficient of correlation between the above parameters was observed only in respect of Hansbreen ($r = 0.23$) (Table 1).

Coefficient of accumulation variability vs. topographic parameters

The “coefficient of accumulation variability” is the absolute deviation of accumulation from the mean for a given altitude. The coefficient has been applied to show which areas are more and which are less sensitive to accumulation changes.

Maximum variability of accumulation on Hansbreen was accompanied by the minimum accumulation on the slopes with a SW aspect (Fig. 5). Here, the estimated values of accumulation variability coefficient were $>30\%$. Werenskioldbreen and Aavatsmarkbreen (Fig. 5) have a similar distribution of the variability coefficient related to slope aspect. The maximum variability of accumulation occurred on slopes with SE and E exposure, after which the value of the coefficient decreases, reaching a minimum on slopes of NW aspect. The correlation coefficients of accumulation variability and the ranked aspects were low. The highest coefficient of correlation ($r = -0.28$) was recorded on Werenskioldbreen (Table 1).

The relationship between accumulation variability and slope angle is far from clear. Generally, the highest variability of accumulation occurs on the steepest

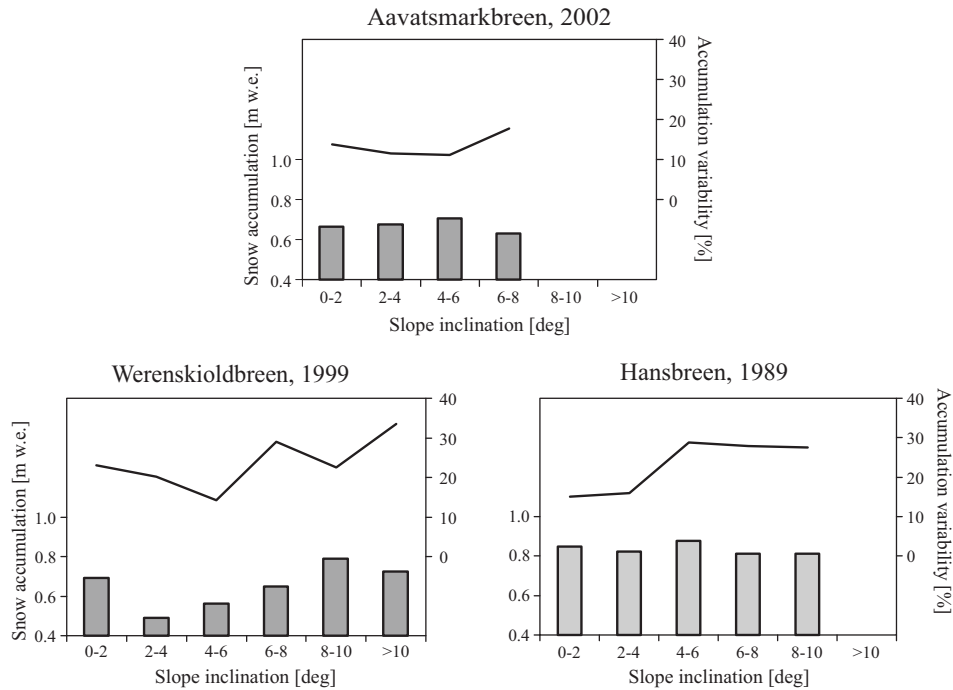


Fig. 6. Snow accumulation and accumulation variability in particular ranges of slope inclination.

slopes (Fig. 6). However, in most cases the increase of the accumulation variability coefficient relative to the slope inclination was statistically insignificant and correlation coefficients between those parameters reached maximum values of $r = 0.27$ (Table 1). No significant relationship between slope curvature and variability of accumulation on the investigated glaciers was evident.

An increase of accumulation variability in the direction from the axis to the edge of the glacier was observed in the cases of Hansbreen and Werenskioldbreen (Fig. 7). Negative correlation coefficients between the distance from the edge of a glacier and its accumulation variability are also demonstrable (Table 1). The closest relationship ($r = -0.47$) was recorded on Werenskioldbreen. The abnormally high increase of the coefficient of accumulation variability was observed in the zone 200 m from the edge, where the mean variability of accumulation exceeded 35%. Owing to low general variability of accumulation on Aavatsmarkbreen, the above regularities were not recorded.

An increase of accumulation variability relative to altitude was observed in respect of Werenskioldbreen and Aavatsmarkbreen (Fig. 8). The lowest variability of accumulation characterised the lower parts of the glaciers *i.e.* <200 m a.s.l., rarely exceeding the mean variability of accumulation for particular glaciers, whereas accumulation variability in the highest parts of the glaciers often exceeded 25%. A correlation of those two parameters with an opposite *i.e.* negative

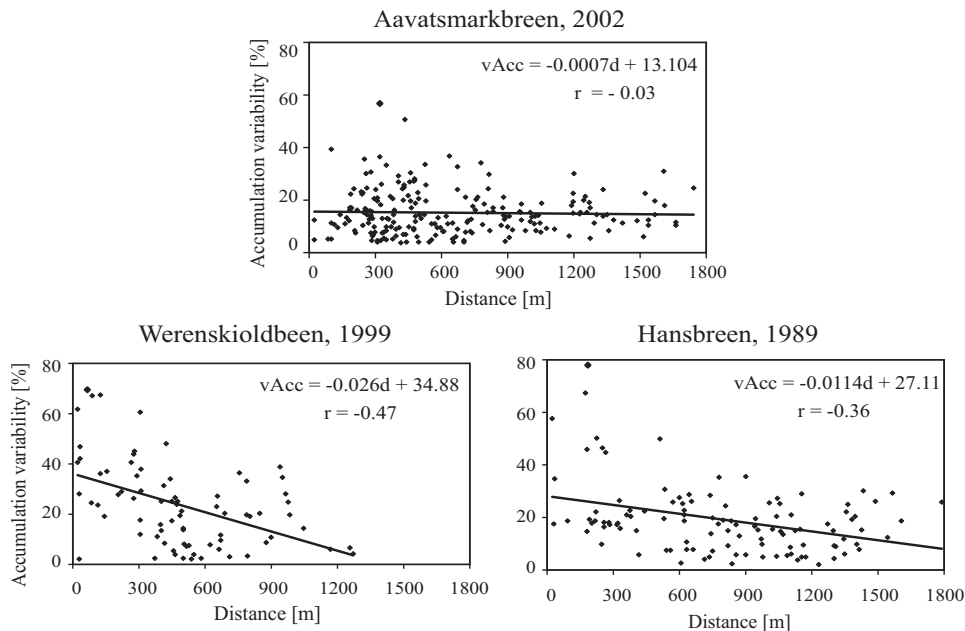


Fig. 7. Accumulation variability (vAcc) vs. distance from the edge of glaciers (d).

character was observed on Hansbreen ($r = -0.48$) (Table 1). Such a situation is associated with a significant variability of accumulation in the lower and the middle parts of the glacier and disproportion in the overall distribution of accumulation.

Discussion

Preparing a model of spatial distribution of snow accumulation on glaciers in Svalbard based on topographic variables has not been easy and it is clear that the influence of particular field parameters was different in each case analysed. In any case, many of relationships were non-linear (Blöschl 1999). However, a set of topographic parameters, which appear to have significant influence on distribution of the snow cover, may be established.

Absolute altitude seems to be the key topographic factor affecting the snow cover distribution on glaciers. Changes of accumulation relative to altitude are linear and deviations of accumulation from the mean value determined on the basis of the regression line may simply be explained by the influence of the other topographic factors. Nevertheless, altitude remains the most obvious and effective parameter applied for determination and forecasting of snow accumulation.

The amount of accumulation on the investigated glaciers depended on their slope aspect and was independent of the course of the glacier valley axes. The mean accumulation on the NE, E, SE slopes was clearly higher than on others. By

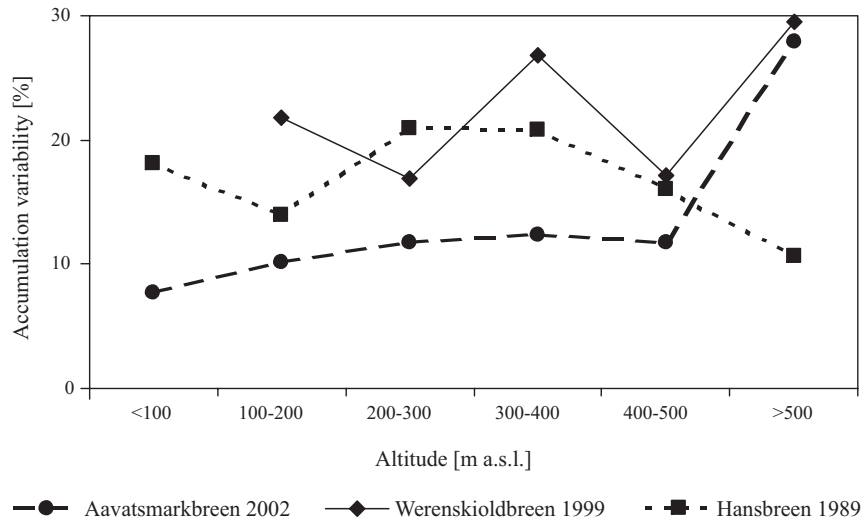


Fig. 8. Accumulation variability in particular ranges of altitude.

contrast, the minimum mean values of snow accumulation on glaciers occurred on slopes the aspect of which contained a westerly component. Such a system clearly corresponds to the most frequent air circulations and winds from easterly directions. Summarizing, windward slopes get more snow precipitation than leeward ones. Hence, disproportion in spatial distribution of snow accumulation on glaciers, which extend in a meridian direction, may be observed.

Slope inclination seems to have little influence on the amount of accumulated snow. Within the analysed range of the slope inclination, it was observed that accumulation increases relative to an increase of inclination. However, the tendency was not statistically significant and it was demonstrable in only certain cases. The accumulation surveys of the analysed examples were carried out on gently or moderately inclined slopes. The surveys were rarely carried out on slopes steeper than 10° and 23° at the most. A slight increase of accumulation may be expected on such surfaces, especially on windward slopes. The influence of slope inclination on accumulation may be expected to be rather more significant on slopes much steeper than those reported. Blöschl *et al.* (1991) accepted the lack of correlation between thickness of the snow cover and slope inclination in the range from 0° to 10°, but above that range, they assumed that tendency of decrease of the snow cover thickness was linear up to 60°, above which slopes would not retain any snow cover. Slope curvature may be expected to have a much more significant influence on snow accumulation in areas with a varied relief, but in generally flat glaciers the factor will play only a marginal role.

A decrease of accumulation variability values relative to distance from the edge of the glacier justifies measurements of snow thickness along the glacier axis. This factor significantly shortens the time necessary to carry out the snow accumu-

lation survey and increases its effectiveness. Positive deviations of accumulation from the average values in the lower part of a glacier may be related to accumulation of snow blown from the upper parts of the glacier. Topographic conditions in upper parts of glaciers are much more varied than in lower parts. Frequently, the accumulation field consists of several basins of varied aspect, absolute altitude, slope inclination *etc.* These factors result in accumulation conditions in the upper parts of glaciers which are much more complicated and varied than in the ablation zone. This is reflected by the high accumulation variability occurred in the more elevated areas in most of the cases analysed.

It should be emphasised that numerical values of the particular parameters strongly depend on the accuracy and density of the digital elevation model. The 100 m DEM grid generalizes a micro relief of the surface, which may have significant influence on the values of particular parameters. Hence, it is quite possible that the relationship of snow accumulation to such parameters as curvature and inclination of the slope will appear to be more significant when analysis using a DEM of smaller grid is applied. However, the DEM of a glacier surface of such accuracy would require a more demanding topographic or remote sensing effort.

According to the analysis on selected glaciers, it may be assumed that distribution of accumulation is related to the precipitation gradient on parts of glaciers with E-W axes. This results from the fact that the valley courses are the same direction as the dominant easterly winds in Spitsbergen. In that case, snow re-deposition is regular and only slightly disturbs the distribution in the altitude profile. It was observed that the model of snow accumulation distribution was much more irregular on those glaciers (or their parts), which were meridionally disposed. Especially significant disproportions in spatial layout of accumulation were recorded in the parts of glaciers surrounded by mountain ridges of high relative altitude. In those cases, the western parts of glaciers were much more favoured as accumulation values there were much higher than for those recorded on the eastern sides. The meridional trend of mountain ridges reduced wind forces from the east and thereby forcing air masses to follow the direction of the valley. The winds which passed the orographic obstacle then descended from a considerable altitude on the lee side and accelerate. The wind was then strong enough to start transport of snow which was earlier deposited at the foot of the slope. The material was blown out and transported, sometimes over considerable distances. On the opposite slope, the wind speed was reduced and the snow was deposited. The process probably caused irregularities in distribution of accumulation on those glaciers which run perpendicular to the dominating wind directions; *e.g.* Hansbreen, in respect of this investigation. Similar features of spatial distribution of accumulation have been found on the maps showing winter balance in the years of 1980–1984 on the meridionally-disposed glaciers Bertilbreen, Bogerbreen, Longyearbreen (Gus'kov 1983; Gus'kov and Troickij 1984, 1985, 1987).

Conclusions

According to the analysis of spatial distribution of snow accumulation on the selected glaciers and topographic factors influencing it, we deduced the following main conclusions:

- The absolute altitude is the most significant topographic factor determining the snow cover distribution.
- The second factor which has influence on snow distribution is the slope aspect. Slopes with eastern component of the aspect are much more predisposed for snow accumulation. In accordance with the most frequent wind direction, snow is blown out from western, leeward slopes and deposited on eastern, windward slopes.
- Regular model of snow distribution related to the precipitation gradient occurs on glaciers of E-W axes consistent with the dominant direction of air masses flow. Disturbances in snow cover layout are noted on glaciers (or their parts) with valley courses perpendicular to the most frequent wind direction. Differences are strengthened by highly elevated mountain ridges surrounding the glaciers.
- High accumulation variability on glaciers is observed in the near of unglaciated slopes and in the upper parts of glaciers, which is due to relatively high topographic diversity of those areas.

References

- AHLMANN H.W. 1933. Scientific results of the Swedish-Norwegian Arctic Expedition in the summer of 1931. Part VIII. *Geografiska Annaler* 15: 161–216.
- BLÖSCHL G. 1999. Scaling issues in snow hydrology. *Hydrological Processes* 13: 2149–2175.
- BLÖSCHL G., KIRNBAUER R. and GUTKNECHT D. 1991. Distributed snowmelt simulations in an alpine catchment 1. Model evaluation on the basis of snow cover patterns. *Water Resource Research* 27: 3171–3179.
- GUS'KOV A.S. 1983. Vodno-ledovy balans lednikov Shpitsbergena v 1977/78 balansovom godu. *Materialy Glyatsiologicheskikh Issledovaniy* 40: 182–185 (in Russian).
- GUS'KOV A.S. and TROICKIJ L.S. 1984. Vodno-ledovy balans lednikov Shpitsbergena v 1980/81 I 1981/82 balansovyh godah. *Materialy Glyatsiologicheskikh Issledovaniy* 51: 247–250 (in Russian).
- GUS'KOV A.S. and TROICKIJ L.S. 1985. Balans massy lednikov Shpitsbergena v 1982/83 balansovom godu. *Materialy Glyatsiologicheskikh Issledovaniy* 54: 211–213 (in Russian).
- GUS'KOV A.S. and TROICKIJ L.S. 1987. Vodno-ledovy balans lednikov Shpitsbergena v 1983/84 balansovom godu. *Materialy Glyatsiologicheskikh Issledovaniy* 59: 138–139 (in Russian).
- HANSEN-BAUER I. 2002. Temperature and precipitation in Svalbard 1912–2050: measurements and scenarios. *Polar Record* 38 (206): 225–232.
- JANIA J. 1988. Klasyfikacja i cechy morfometryczne lodowców otoczenia Hornsundu, Spitsbergen. In: J. Jania and M. Pulina (eds) *Wyprawy Polarne Uniwersytetu Śląskiego 1980–1984*. T. 2. Uniwersytet Śląski, Katowice: 12–47 (in Polish).

- JANIA J. 1994. *Field investigations during glaciological expeditions to Spitsbergen in the period 1992–1994 (interim report)*. Uniwersytet Śląski, Katowice: 40 pp.
- JANIA J. 1997. *Glacjologia. Nauka o lodowcach*. Wyd. II. Wydawnictwo Naukowe PWN, Warszawa: 359 pp. (in Polish).
- JANIA J., KOLONDRĄ L. and AAS H.F. (eds) 2002. *Werenskioldbreen and surrounding areas. Spitsbergen, Svalbard, Norway. Orthophotomap 1:25 000*. Uniwersytet Śląski, Katowice, Polska, Norsk Polarinstitut, Tromsø, Norge.
- JANIA J., MOCHNACKI D. and GADEK B. 1996. The thermal structure of Hansbreen, a tidewater glacier in southern Spitsbergen, Svalbard. *Polar Research* 15 (1): 53–66.
- KHODAKOV V.G. 1985. Sniezhnyj pokrov. In: B.M. Kotljakov (ed.) *Glaciologia Shpitsbergena*. Nauka, Moskva: 35–46 (in Russian).
- KOLONDRĄ L. 2002. Cyfrowa ortofotomapa – nowa forma danych kartograficznych w badaniach glaciologicznych (na przykładzie lodowców Werenskiold i Nann – S Spitsbergen). In: A. Kostrzewski and G. Rachlewicz (eds) *Funkcjonowanie i monitoring geosystemów obszarów polarnych*. Poznań: 173–186 (in Polish).
- KOSIBA A. 1960. Some results of glaciological investigations in SW Spitsbergen. *Zeszyty Naukowe Uniwersytetu Wrocławskiego B4 (Nauka o Ziemi 1)*: 1–30.
- LANKAUF K.R. 1999. Retreat of the Aavatsmark Glacier (Kaffiøyra Region, Oscar II Land) in XX century. In: *Polish Polar Studies. XXVI Polar Symposium*. Lublin: 134–151.
- LESZKIEWICZ J. and PULINA M. 1999. Snowfall phases in analysis of a snow cover in Hornsund, Spitsbergen. *Polish Polar Research* 20: 3–24.
- MARCHAND W.-D. and KILLINGTVEIT C. 2001. Analyses of the relation between spatial snow distribution and terrain characteristics. In: *58th Eastern Snow Conference*. Ottawa, Ontario, Canada: 71–84.
- MIGAŁA K., PEREYMA J. and SOBIK M. 1988. Akumulacja śnieżna na południowym Spitsbergenie. In: J. Jania and M. Pulina (eds) *Wyprawy Polarne Uniwersytetu Śląskiego 1980–1984*. T. 2. Uniwersytet Śląski, Katowice: 48–63 (in Polish).
- MIKHALIOV V.S. and SINGER E.M. 1975. Pitanie lednikov. In: L.S. Troickij, E.M. Singer, W.S. Koriakin, W.A. Markin and W.I. Mihalev (eds) *Oledinienie Shpitsbergena (Svalbarda)*. Nauka, Moskva: 106–152 (in Russian).
- PERSKI Z., JANIA J. and STOBER M. 2003. SAR-interferometric and GPS-surveyed flow velocities of two tidewater glaciers in NW Spitsbergen: methods and results. In: *Workshop on Arctic Glaciology and the MAGICS Annual Meeting, Abstracts*. Zakopane 22–26 February 2003: 26.
- SINGER E.M. and MIKHALIOV V.S. 1967. Akkumulacja sniegi na lednikach Shpitsbergena. *Materialy Glyatsiologicheskikh Issledovaniy* 13: 86–100 (in Russian).
- SZAFRANIEC J. 2002. Influence of positive degree-days and sunshine durations on the surface ablation of Hansbreen, Spitsbergen glacier. *Polish Polar Research* 23 (3–4): 227–240.
- WIELBIŃSKA D. and SKRZYPCZAK E. 1988. Mean air temperatures at definite wind directions in Hornsund, Spitsbergen. *Polish Polar Research* 9 (1): 105–119.
- WINTHER J.-G., BRULAND O., SAND K., KILLINGTVEIT C. and MARECHAL D. 1998. Snow accumulation distribution on Spitsbergen, Svalbard, in 1997. *Polar Research* 17 (2): 155–164.

Received 29 November 2005

Accepted 11 August 2006