An estimation of snow accumulation on Svalbard glaciers on the basis of standard weather-station observations

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ABSTRACT. Winter precipitation in the form of snow is the major factor determining accumulation on Arctic glaciers. In this paper, I present a simple method to assess snow accumulation on the glaciers of Svalbard. I deduce snow accumulation from the sum of winter precipitation and the fraction of precipitation of different types at a reference weather station. The accumulation is then converted to a relevant point on the glacier, using an accumulation gradient and a location coefficient. I apply this algorithm of accumulation assessment to eight glaciers of southern and central Spitsbergen using data from 23 seasons. On the basis of measured accumulation data, the mean error of the calculated accumulation, with no distinction of precipitation types, amounted to 23%. When the distinction between precipitation types is used for glaciers of southern Spitsbergen, the average error of estimation was 19%. Errors result from factors influencing accumulation distribution over the glacier elevation profile (e.g. glacier topography, orography of its surroundings, precipitation inversion). Application of this accumulation algorithm may provide a crucial method of estimating mass balance for glaciers not included in permanent monitoring.

INTRODUCTION

The mass balance of Arctic glaciers is a crucial indicator of climatic change. The most important factor responsible for determining glacier mass supply is winter snow accumulation. The accumulation at the end of the winter season at any point on the glacier is a function of gains and losses of snow during this period. In winter, snowfall is the main control on glacier mass. Other factors influencing net winter accumulation (e.g. snowdrift, sublimation, melting and avalanche supply) are much less important than winter snowfall. Thus, it is assumed that the snow accumulation at a given point on a glacier is approximately equal to the sum of precipitation over a given period. The attempt at assessing the snow accumulation can be boiled down to the task of determining the total amount of precipitation in a season of accumulation. In this paper, I present a simple model for snow accumulation on Svalbard glaciers. The aim is to estimate local snow accumulation based on location, altitude, and data from a nearby permanent weather station.

Spatial distribution of the snow cover on Svalbard's glaciers has been examined in many ways on the basis of numerous field surveys, on both regional and local scales (Mikhaliov and Singer, 1975; Khodakov, 1985; Migała and others, 1988; Kohler and others, 1997; Winther and others, 1998, 2003). The variability of snow accumulation has rarely been compared to recorded precipitation at weather stations, due to weak statistical relations between such elements. According to Hagen and Liestøl (1990), the correlation coefficient between snow accumulation of austre Brøggerbreen and the sum of winter precipitation at Ny-Ålesund station, located in the immediate vicinity of the glacier, was only 0.63. Errors in precipitation measurements are one possible reason for such weak correlation between actual mass accumulation and recorded precipitation. Errors in precipitation measurements

cause the true precipitation to be overestimated by about $50\% \, a^{-1}$ compared with measurements from the Ny-Ålesund station (Hanssen-Bauer and others, 1996; Førland and Hanssen-Bauer, 2000). Measurement errors become more severe with increasing wind strength and with decreasing temperature.

THE ALGORITHM OF ACCUMULATION ASSESSMENT

Algorithm description

To assess the amount of accumulation at any point on a Svalbard glacier, I used the following equation:

$$\mathrm{acc}_{(l, h_i)} = \left(B_{h_0} L_{\mathrm{c}} \right) + \left(B_{h_0} L_{\mathrm{c}} \frac{(h_i - h_0)}{100} \tau \right), \qquad (1)$$

where $\mathrm{acc}_{(l, h_i)}$ is snow accumulation (mm w.e.) on a glacier situated at a distance l from the open water at a point located at a height of h_i; B_{h_0} is winter accumulation (mm w.e.) at a reference station at altitude h_0; L_{c} is the location coefficient; and τ is the accumulation gradient, i.e. the relative accumulation increase per 100 m (%).

The distance from open water is measured in a straight line between a weather station (l) or point located in the center of the glacier equilibrium line (d) and the nearest point on the coast of the open sea. Coasts composed of fjords, small bays and straits are not used to calculate distance.

B_{h_0} is estimated on the basis of the sum of winter precipitation measured at the weather station and may be calculated by:

$$B_{h_0} = K P_{h_0}, \qquad (2)$$

where P_{h_0} is winter (October–May) precipitation (mm) at a reference station at altitude h_0, and K is the efficient accumulation correction coefficient.

Table 1. Mean values of sums of winter precipitation (October–May) from the normal period 1961–90 for the Spitsbergen stations (Førland and others 1997), the distance to the open sea, and converting equations of location coefficient (L_c)

Station	Mean values of sums of winter precipitation (October–May)	Distance from station to open sea	Location coefficient L_c
	mm	km	
Sveagruva	202	38	$L_c = 1.9079e^{-0.017d}$
Isfjord Radio	305	0	$L_c = 2.3396e^{-0.017d}$
Svalbard Lufthavn	119	50	$L_c = e^{-0.017d}$
Longyearbyen	134*	51	$L_c = 2.3798e^{-0.017d}$
Ny-Ålesund	255	10	$L_c = 1.1853e^{-0.017d}$
Hornsund	235	7	$L_c = 1.1264e^{-0.017d}$

*Precipitation value for Longyearbyen is mean value from measurement periods and unchecked for a normal period.

Fig. 1. Locations of weather stations at Svalbard (triangles) and glaciers (filled circles) for which the assessment of accumulation was done: 1. Ny-Ålesund; 2. Isfjord Radio; 3. Svalbard Lufthavn; 4. Longyearbyen; 5. Sveagruva; 6. Hornsund. I. Vestre Grønfjordbreen; II. Austre Grønfjordbreen; III. Fridtjovbreen; IV. Bogerbreen; V. Gløtfjellbreen; VI. Renardbreen; VII. Werenskioldbreen; VIII. Hansbreen.

The efficient accumulation correction coefficient K calculates seasonal accumulation rates from the total winter precipitation. The value of K is affected by two factors: error in precipitation measurements, which increases K, and the effect of rain, which decreases K. It is important to consider rain because not all winter precipitation is actually accumulated. Rain episodes included in total winter precipitation do not influence accumulation increase. Consequently, it could be assumed that accumulation is equal to the sum of real solid precipitation. K can be expressed as

$$K = \frac{k_s P_{s_{h_0}}}{P_{h_0}}, \tag{3}$$

where k_s is the correction factor for solid precipitation assumed to be equal to 1.85 as suggested by Førland and Hanssen-Bauer (2000), and $P_{s_{h_0}}$ is winter (October–May) solid precipitation (mm) at a reference station at altitude h_0.

The K coefficient is a function of solid precipitation rate in the total winter precipitation and may range from 0 to 1.85. If only winter precipitation data with no distinction of types are available, K is assumed to be equal to 1.1. This value of K is valid when 60% of measured precipitation occurred as snowfall. This value is the average solid precipitation rate in the winter seasons 1975–96 at Ny-Ålesund (Førland and Hanssen-Bauer, 2000).

Precipitation is characterized as a factor of great spatial variability, due mainly to surface topography and orography. In order to determine spatial regularities in the winter precipitation distribution, the sums of precipitation at weather stations have been compared with their distances from open water. Most weather stations are located along the coast at low elevation. This allows us to assume that most weather-station data were collected at sea level. Differences in precipitation at particular stations are a function of continental influence, so the further a station is situated from open water, the lower the precipitation. Table 1 shows mean values of the sums of precipitation from October to May from the normal period 1961–90 for six Spitsbergen stations (Ny-Ålesund, Isfjord Radio, Svalbard Lufthavn, Longyearbyen, Sveagruva and Hornsund). The locations of weather-stations are shown in Figure 1. The average values of precipitation show a strong relation with

distance from open water (Fig. 2). Regression analysis of the data in Table 1 made it possible to describe the long-term average of winter precipitation at Spitsbergen stations (p_w, given in mm) as a function of distance from open water (l, given in km):

$$p_w = 293.35e^{-0.0153l}. \tag{4}$$

This equation explains 89% of the variation in mean winter precipitation on western and southern Spitsbergen. For the following calculations I assume that the above relationship is valid for each winter season.

The location coefficient describes the relation between the sum of winter precipitation at a site located at a given distance from the open water and precipitation at a particular station. On the basis of Equation (4), the location coefficient L_c has been calculated:

$$L_c = \frac{293.35e^{-0.0153d}}{293.35e^{-0.0153l}}, \tag{5}$$

where d is the distance between a glacier's equilibrium line and the open water.

The coefficient L_c has been calculated for every weather station separately. Using the conversion formula, the sum of winter precipitation will be greater at points nearer to the sea and smaller at points farther inland in comparison with sums recorded at the reference station. With a view to limiting potential errors in further accumulation assessments, meteorological points closest to the analyzed glacier have been used as reference stations.

The value of sea-level accumulation obtained using the above calculation is then converted into accumulation at a given altitude of measurement point, according to the applied accumulation gradient τ. This gradient is defined as the increase in percentage of accumulation at sea level
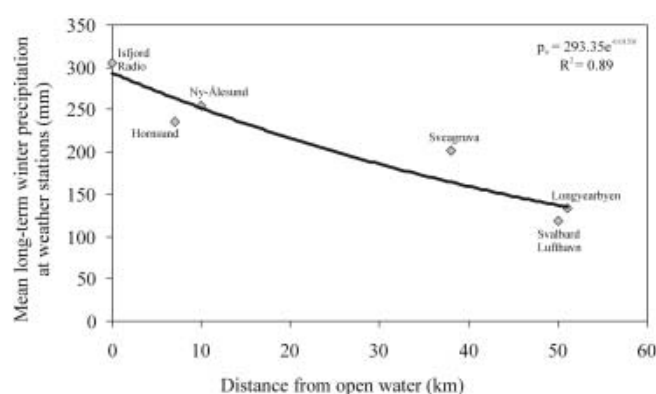
Fig. 2. Relations of mean precipitation in the winter seasons 1961–90 in a normal period at Spitsbergen stations with the distance to the open sea.

per 100 m of elevation change. This is a simplification that assumes accumulation variability is due only to changes in absolute altitude and that ignores the influence of topographic factors and possible inversion of precipitation. Elevation above sea level, however, is the most important factor for determining the accumulation variability on glaciers, hence the obtained value assumed to be used as the mean snow accumulation at a given altitude. The accumulation gradient is not a constant value but increases proportionally with increasing accumulation at sea level. In this study, the accumulation gradient 0.4–0.8 has been tested and appears to be valid.

Analysis of error assessment

The measured accumulation was compared with elevation using a regression. The regression line shows a good approximation of normal accumulation conditions over the elevation profile. As a test of accumulation assessment, I compared the regression line with the results of calculations.

Over the examined elevation ranges, I established mean deviations from the regression line S using the following method:

$$S = \frac{\left| \int_{z_{min}}^{z_{max}} A_M(z)\,dz - \int_{z_{min}}^{z_{max}} A_R(z)\,dz \right|}{z_{max} - z_{min}} \tag{6}$$

when functions $A_M(z)$ and $A_R(z)$ do not intersect in the range $(z_{min}; z_{max})$, and

$$S = \frac{\left| \int_{z_{min}}^{z_a} A_M(z)\,dz - \int_{z_{min}}^{z_a} A_R(z)\,dz \right|}{z_{max} - z_{min}}$$
$$+ \frac{\left| \int_{z_a}^{z_{max}} A_M(z)\,dz - \int_{z_a}^{z\,max} A_R(z)\,dz \right|}{z_{max} - z_{min}} \tag{7}$$

when functions $A_M(z)$ and $A_R(z)$ intersect in the range $(z_{min}; z_{max})$, where $A_M(z)$ is the linear function of evaluated accumulation vs elevation above sea level, $A_R(z)$ is the linear function, i.e the regression line of the measured accumulation vs elevation above sea level; z_{min} is the altitude (m a.s.l.) of the lowest accumulation measurement point located on a glacier; z_{max} is the altitude (m a.s.l.) of the highest accumulation measurement point located on a glacier; and z_a is the altitude (m a.s.l.) of intersection of functions $A_M(z)$ and $A_R(z)$.

Table 2. Precipitation data and location of glaciers selected for verification of the accumulation model. Reference stations: Isfjord Radio[*]; Hornsund[†]; Svalbard Lufthavn[‡]

Glacier	Season	Sum of winter precipitation at reference station	Distance to sea
		mm	km
Fridtjovbreen	1966	303[*]	13
Austre Grønfjordbreen			14.5
Vestre Grønfjordbreen	1967	345[*]	14.5
Bogerbreen			49
Gløttfjellbreen			65
Renardbreen	1987	162[†]	12.5
Werenskioldbreen	1994	251[†]	6
	1999	225[†]	
	2000	182[†]	
	2001	264[†]	
	2002	137[‡]	
Hansbreen	1989	168[†]	12
	1990	320[†]	
	1991	332[†]	
	1992	256[†]	
	1993	199[†]	
	1994	251[†]	
	1995	244[†]	
	1996	350[†]	
	1997	200[†]	
	1998	253[†]	
	1999	225[†]	

For an easier comparison of errors of various glaciers and seasons, deviations have been converted into percentage values, where 100% stands for the mean measured accumulation in examined elevation profile (A_s) of a given glacier:

$$S[\%] = \frac{S}{A_s} \times 100\%. \tag{8}$$

RESULTS

The algorithm of accumulation assessment has been applied to eight glaciers for which snow accumulation data over the full range of glacier elevation are known. The data are valid mainly for points located along the central axes of these glaciers. The glaciers are as follows: Hansbreen, Werenskioldbreen and Renardbreen in southern Spitsbergen; Fridtjovbreen, austre and vestre Grønfjordbreen on the west coast; and Bogerbreen and Gløttfjellbreen located in the centre of the island (Fig. 1). For glaciers in the central and western part of Svalbard, data exist for the years 1966 and 1967 (Mikhaliov and Singer, 1975). For Renardbreen, data are available for 1987 (Piasecki, 1988). For Werenskioldbreen, data are available for 1994 (Jania, 1994) and 1999–2002 (P. Głowacki, unpublished data). For Hansbreen, data are available for 1989–99 (P. Głowacki, unpublished data) (Table 2). In total, 23 seasons of accumulation data for the glaciers were analyzed.

Isfjord Radio was used as the reference station for defining accumulation on glaciers of central and western Spitsbergen. For the southern region, Hornsund station was used, except for the 2001/02 season when, due to the lack of data, meteorological observations from Svalbard Lufthavn were used instead (Table 2).
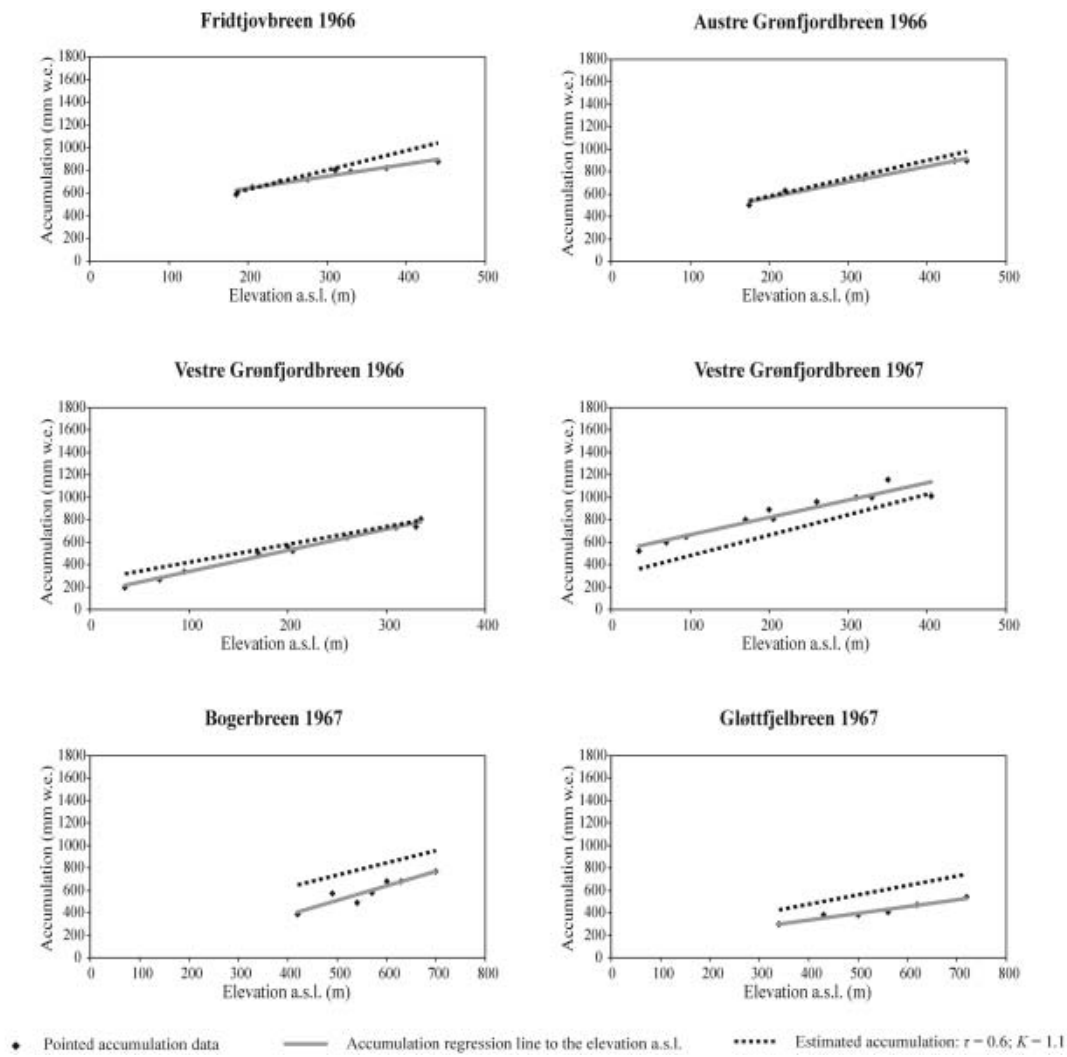
Fig. 3. Observed and modeled values of accumulation on Fridtjovbreen, austre Grønfjordbreen, vestre Grønfjordbreen, Bogerbreen and Gløtfjellbreen in the years 1966–67.

Table 3. Maximum and mean errors of snow accumulation assessment for defined coefficients of precipitation correction (k_a) and precipitation gradient (τ). The smallest values of errors are in bold

τ	k_a	Maximum error S_{max}		Mean error S	
		max.	mean	max.	mean
		%	%	%	%
0.3	1	109.4	68.9	65.5	43.0
	1.25	95.8	55.2	58.8	33.0
	1.5	82.1	**43.5**	56.4	**25.5**
	1.75	94.8	**41.1**	82.4	**25.7**
	2	126.6	45.5	108.5	31.0
0.4	1	98.4	57.9	60.4	36.1
	1.25	82.5	43.0	50.5	26.5
	1.5	102.0	**39.5**	79.2	**25.5**
	1.75	140.3	46.4	109.1	31.4
	2	175.5	58.1	138.9	41.8
0.5	1	87.6	47.7	55.4	30.1
	1.25	96.2	**38.6**	68.4	**24.3**
	1.5	140.9	44.8	102.0	29.9
	1.75	185.7	58.7	135.7	41.3
	2	230.4	74.2	169.4	54.5

Snow accumulation assessment based on precipitation data with no distinction of precipitation types

When only the sum of winter precipitation at weather stations is available, the efficiency accumulation correction coefficient K is assumed to be a constant value equal to 1.1. The snow accumulation was estimated using the accumulation gradient τ in a range 0.4–0.8 (Table 3). The lowest error of accumulation assessment was obtained with the application of $\tau = 0.6$. The mean error of accumulation estimation for analyzed glaciers in that case amounted to 23%. Average errors range between 4% (Werenskioldbreen 2002) and 43% (Hansbreen 1989), with a median value of 16% (Table 4). The full results of accumulation estimation are presented in Figures 3–6.

Snow accumulation assessment based on precipitation data with distinction of precipitation types

The procedure presented below has been applied only to glaciers on southern Spitsbergen (Hansbreen, Werenskioldbreen and Reanardbreen) where it is possible to distinguish solid precipitation using data from Hornsund station. I assumed that all precipitation on days with an average
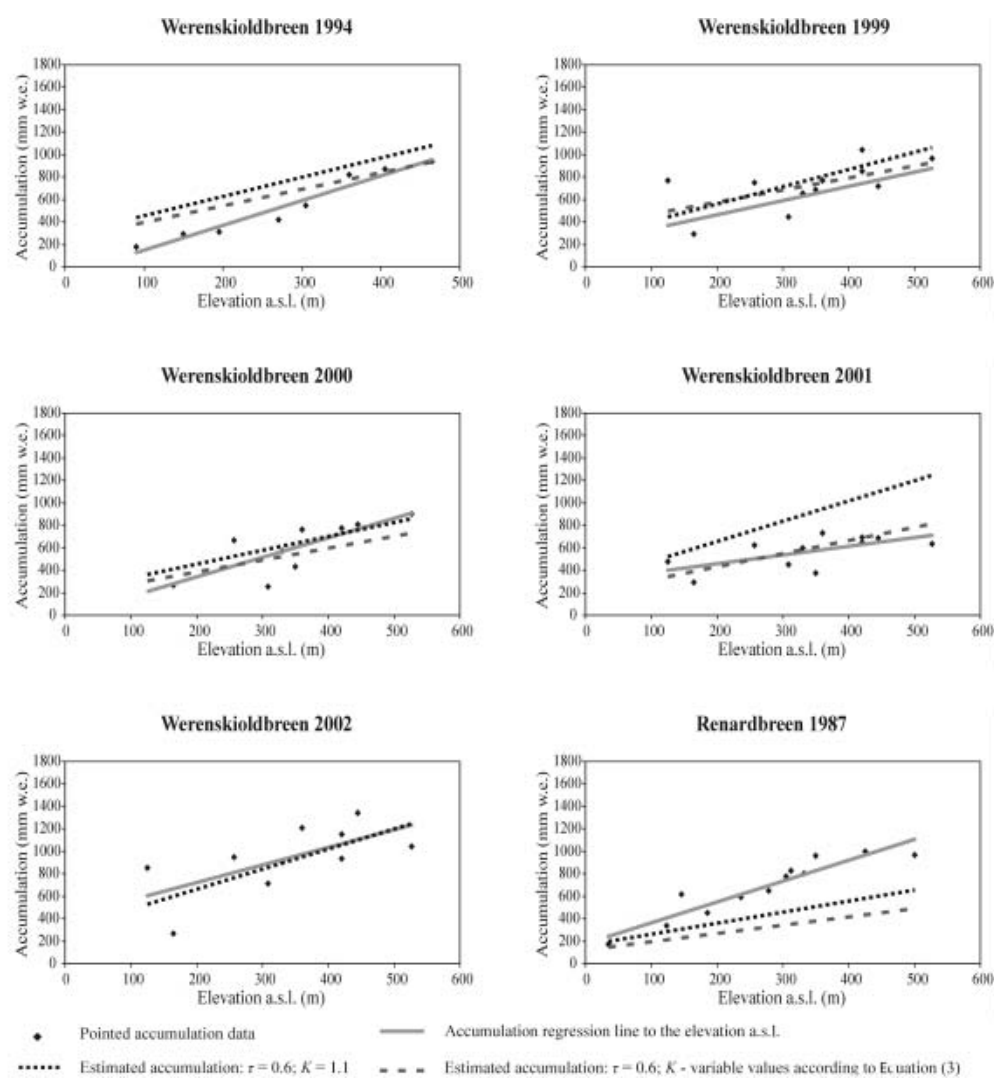
Fig. 4. Observed and modeled values of accumulation on Werenskioldbreen in 1994 and 1999–2000 and Renardbreen in 1987.

Table 4. Values of coefficients k_a and τ assuming optimum accumulation assessment. The best-matched values of coefficients in each investigated season are in bold

Glacier	Season	$\tau = 0.3$		$\tau = 0.4$		$\tau = 0.5$	
		Mean error	k_a	Mean error	k_a	Mean error	k_a
		%		%		%	
Renardbreen	1987	23.5	2	13.6	2	**6.8**	**2**
Werenskioldbreen	1994	20.0	1.5	**12.5**	**1.25**	13.2	1.25
	1999	**2.8**	**1.75**	5.7	1.25	8.1	1.25
	2000	**6.7**	**1**	9.0	1.5	10.0	1.25
	2001	**2.6**	**1.5**	13.4	1	29.5	1
Hansbreen	1989	31.0	2	20.9	2	**10.8**	**2**
	1990	8.5	1.5	8.6	1.5	**2.1**	**1.25**
	1991	6.6	1.75	7.0	1.75	**5.2**	**1.5**
	1992	20.4	2	17.5	1.75	**15.8**	**1.5**
	1993	23.4	2	12.2	2	**1.1**	**2**
	1994	33.0	1.75	17.1	1.5	**15.9**	**1.25**
	1995	17.7	2	15.0	1.75	**12.6**	**1.5**
	1996	**16.4**	**1**	19.1	1	34.7	1
	1997	28.0	2	17.9	2	**8.6**	**2**
	1998	21.7	2	10.2	2	**1.2**	**2**
	1999	24.0	2	12.9	2	**1.8**	**2**
Mean error		17.9		14.5		11.1	

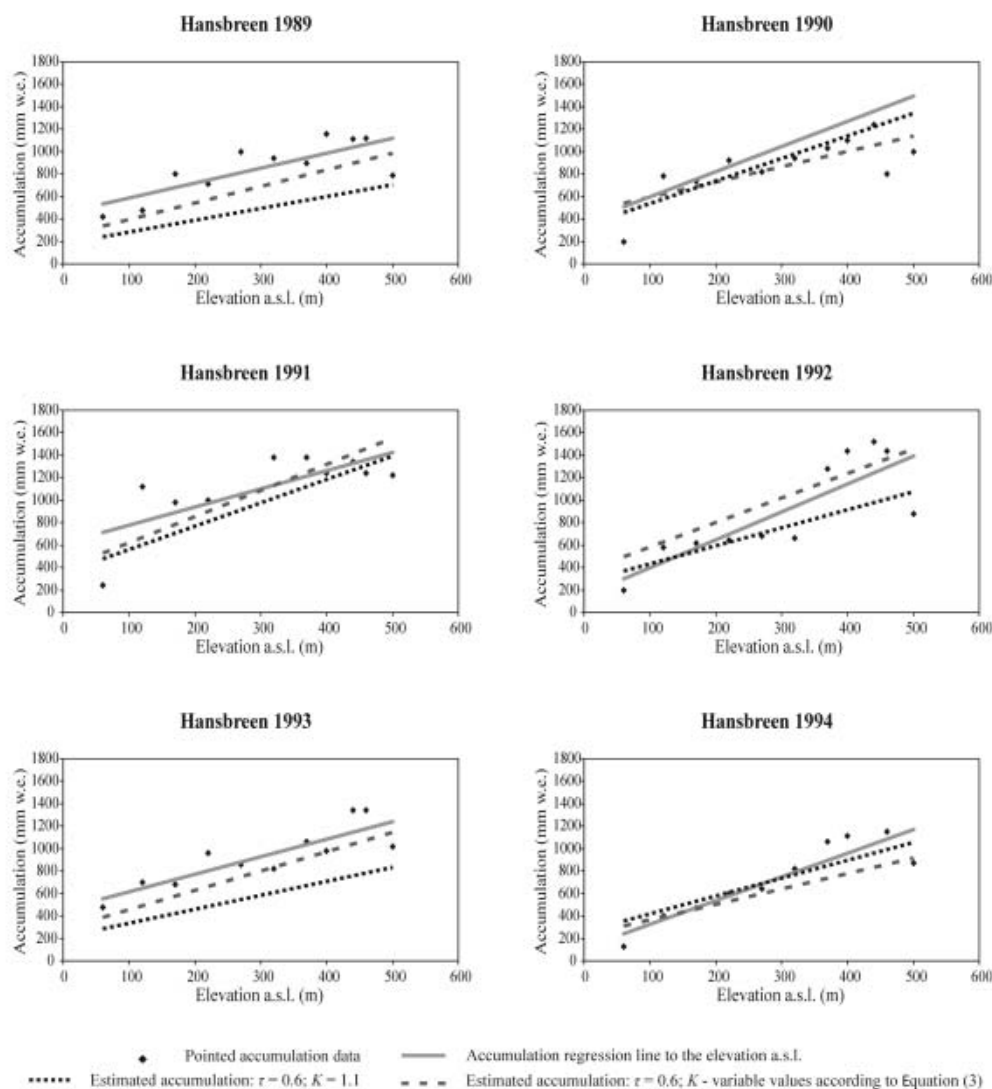**Fig. 5.** Observed and modeled values of accumulation on Hansbreen in the years 1989–94.

temperature $\leq 0.5°C$ was snow (after Førland and Hanssen-Bauer, 2000). I used an accumulation gradient of $\tau = 0.6$, which was determined as outlined above. The results of the accumulation assessment and the errors are presented in Table 4 and Figures 4–6. Using this method, the mean error of the accumulation estimation for the glaciers is 7% lower than the results of assessment using the sum of winter precipitation only.

DISCUSSION

The processes that lead to variations in snow accumulation over glacier surfaces are one of the reasons for the accumulation assessment errors. The algorithm does not explain variations in accumulation related to, for example, glacier topography, orography of the surroundings, snowdrift and precipitation inversion. These influences have a noticeable effect in the upper part of Hansbreen. In many seasons, the snow accumulation measured at 500 m a.s.l. was substantially smaller than that measured at a stake located ~50 m lower. Hansbreen also has an asymmetric accumulation distribution, with greater accumulation on the western side of the glacier than on the eastern side (Jania, 1994). This pattern is common on glaciers oriented perpendicular to

prevailing winds (e.g. Bogerbreen and Bertilbreen; cf. Gus'kov, 1983; Gus'kov and Troitskiy, 1984, 1985, 1987). This leads to significant differences in accumulation across the glacier at the same altitude.

The errors of estimation could also be caused by microrelief of the glacier's surface that contributes to snow accumulation (concave forms) or erosion (convex forms). Intensive redistribution of blowing snow out of the convex form has been observed on land-based glaciers fronts (e.g. Werenskioldbreen). In such cases, the algorithm will overestimate accumulation.

Other sources of error arise from approximations and assumptions. For the calculation of the location coefficient L_c, the glacier has been considered as a point object. As a result of this simplification, the distance from open water has been measured between a point located in the center of the glacier equilibrium line and the nearest point on the coast of the open sea. This could cause substantial errors where glaciers extend long distances from the sea coast towards the center of the island. One may consider a hypothetical glacier terminating in the open sea, the most distant point of which is located 20 km from the open water. The difference in the sum of winter accumulation at sea level between those two extreme points of the glacier, calculated on the
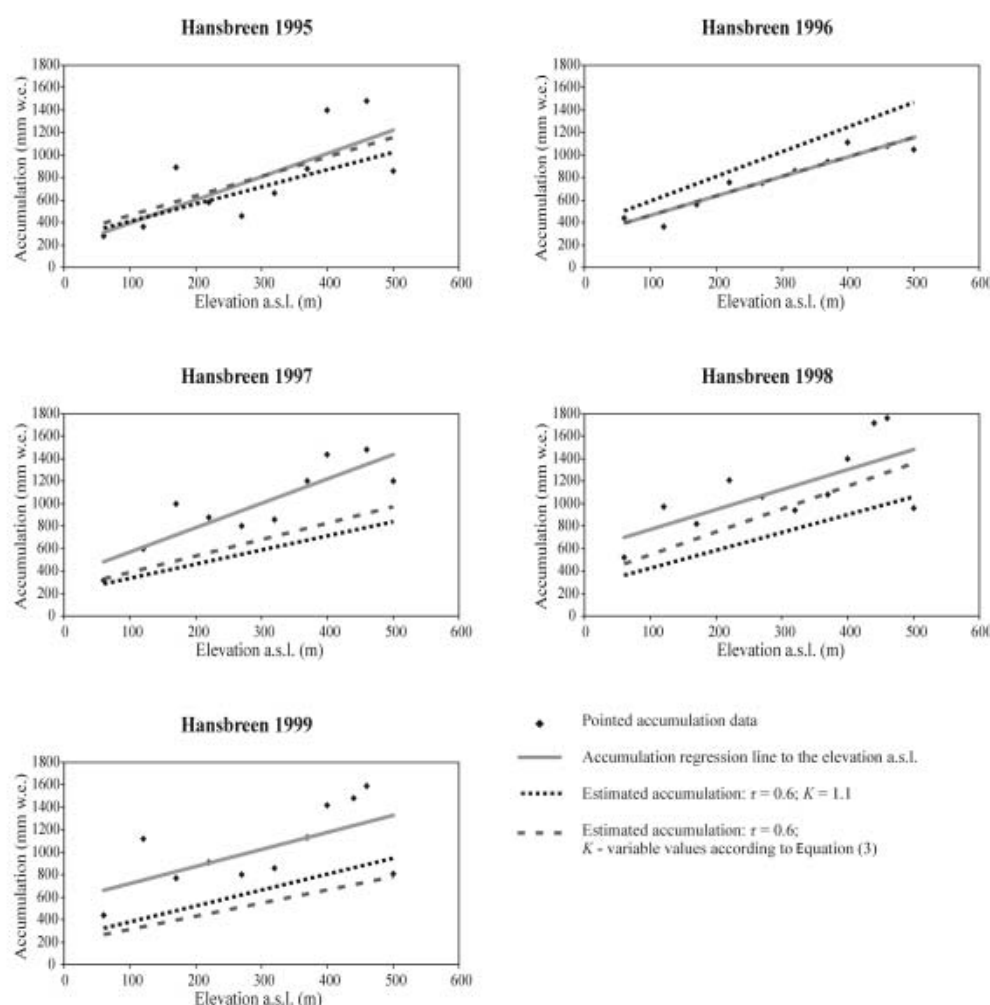
Fig. 6. Observed and modeled values of accumulation on Hansbreen in the years 1995–99.

basis of Equation (4), amounts to 26.4%. Applying the constant distance to the open water for every point on the glacier's surface, the accumulation on sites located nearest to the sea is underestimated, whereas the accumulation at the most distant points is overestimated.

The accuracy of the efficient accumulation correction coefficient (K) is determined by the quality of precipitation data. The K coefficient is dependent upon the solid precipitation rate in relation to the total winter precipitation. If there are no data on precipitation type, any approximation (e.g. use of temperature criterion or constant solid precipitation rate) would be a source of error. Additionally, the correction factor for solid precipitation (k_s) gives only a rough approximation of the true value of precipitation.

The observed accumulation gradients τ are not constant in space and time as has been assumed in this study. The τ factor on Hansbreen in the years 1989–99 ranged from 0.41 to 1.04. The differences between the τ value applied in the accumulation assessment ($\tau = 0.6$) and the observed accumulation gradient could result from snow distribution disturbances on glaciers discussed above.

CONCLUSIONS

The results show a simple way to estimate accumulation for any point on Spitsbergen glaciers. The proposed

evaluation procedure is mainly intended for use on western and central Spitsbergen. This is because insufficient meteorological data are available from the eastern part of the island and because of difficulties in verifying the accumulation approximation on glaciers of eastern Spitsbergen.

The minimum requirements for the accumulation estimation are the sum of winter precipitation at the nearest weather station and the location of the analyzed site on a glacier, i.e. distance from open water and elevation. The results of accumulation assessment are closer to actual values when the sum and rate of solid precipitation have been applied. Precipitation type is the most important factor determining snow accumulation.

The application of the presented algorithm allows for calculation of the accumulation on glaciers of central and southern Spitsbergen with an accuracy of 19–23%. The errors result from the exclusion of factors disturbing accumulation distribution in the elevation profile (e.g. glacier topography, orography of the surroundings, precipitation inversion) as well as assumptions and approximations. The focus of future work will be centered on the reduction of errors.

The application of my accumulation algorithm may provide a crucial element of mass-balance evaluation for glaciers not included in permanent monitoring.

ACKNOWLEDGEMENTS

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