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Selected methods in mass balance estimation of Waldemar Glacier, Spitsbergen

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Abstract: Traditional mass balance measurements by stake readings and snow surveying have been conducted annually since 1996 on the Waldemar Glacier (= Waldemarbreen) in northwest Spitsbergen, Svalbard. Several indirect methods were also used for estimating its mass balance. These methods were divided into two major groups: climatological and geodetic. A comparison of the latest map (2000) with that of 1978 and climatological records enable us to calculate the change in the mass balance of Waldemarbreen over 34 years. These methods include air temperature and degree-day (PDD) models. The average mass balance of Waldemarbreen, computed by climatological methods, was -0.42 m a^{-1} of water equivalent (w.e.) for the period 1970–2004, and -0.51 m w.e. for 1996–2004. These balances were compared with the glaciological balance for the period 1996–2004, -0.53 m w.e.. The mass balance was also computed using geodetic method, giving -0.52 m of w.e. from 1978 to 2000. It is suggested that, from these results, the approach used for Waldemarbreen might be also useful for estimation the mass balances of other small Svalbard glaciers which terminate on land.

Key words: Arctic, Svalbard, mass balance, glacier.

Introduction

There are many direct measurements of glacier mass balance done in the framework of the GTN-G network led by the GCOS/GTOS (Haeberli 1995, 2004, IAHS (ICSI) /UNEP/UNESCO 2003, 2005; Haeberli *et al*. 2002; Frauenfelder *et al.* 2005). The World Glacier Monitoring Service (WGMS) has been responsible for collecting and publishing standardized data on glacier changes since 1986. Corresponding data bases and measurement networks form an essential part of the Global Terrestrial Network for Glaciers (GTN-G: operated by the WGMS) as a pilot project within the Global Climate Observing System (GCOS), (Frauenfelder *et al*. 2005). Waldemarbreen is a part of this international glacier mass balance programme.

Continuous mass balance records for the period 1980–2003 are available for 30 glaciers in North America, South America and Eurasia (IAHS (ICSI)/UNEP/UNESCO 2003, 2005). Each glacier studied in such remote areas as Svalbard, or generally the entire Arctic, is important for understanding the effects of contemporary climatic changes. Indeed, many regard estimation of the value of glacier mass balance as indispensable as an indicator of these changes. Certainly, temporal cumulative mass balance trends in a region indicate climate variability (Klok and Oerlemans 2004; Kuhn 1986; Oerlemans and Fortuin 1992).

Glaciers are dominant in Svalbard's relief; covering over 60% of the archipelago (Hisdal 1985). Systematic studies on mass balance include seven Svalbard glaciers (IAHS (ICSI)/UNEP/UNESCO 2003, 2005, Sobota 2005, 2007a, b). Although the analysis in this paper refers only to Waldemarbreen, other Kaffiøyra glaciers including Irenebreen, which has been investigated since 2001, and Elisebreen since 2005 have also been studied. These investigations are ongoing.

Glaciological methods of mass balance estimation involve repeated point measurements at the glacier surface to determine the rates of ablation and accumulation. These methods involve estimation of local mass balance using ablation poles, supplemented by studies of the snow cover in pits. The data collected are then used to calculate the balance for a given hydrological year, either beginning and ending at a specified date (the fixed date system), or from one summer surface to the next (the stratigraphic system), (Østrem and Brugman 1991; Kaser *et al*. 2003; Hubbard and Glasser 2005). The data on the mass balance of Waldemarbreen was derived from the direct field measurements conducted since 1996.

An attempt to assess the mass balance of Waldemarbreen through indirect methods was also undertaken. The direct method refers to the period 1996–2004, while the indirect way was done for a longer period, *i.e.* 1970–2004 mass balance estimation of Waldemarbreen. Generally, it is based on the high correlation between mass balance and the selected meteorological parameters. Such methods include temperature and degree-day (PDD) models. Additionally, the change in mass balance has been estimated on the basis of cartographical material from the years 1978–2000. The geodetic method compares the two surfaces, defined by identical surveys at two different times (Rabus and Echelmeyer 1998; Hubbard and Glasser 2005).

The results of the mass balance studies of Waldemarbreen are quite similar to other Svalbard glaciers which terminate on land (Hagen *et al.* 2003; IAHS (ICSI)/UNEP/ UNESCO 2003, 2005; Sobota 2005, 2007a, b) and thus provide a conspectus of this phenomenon over the last decades. The obtained results verify both the validity and the accuracy of these methods. They make it possible to define and recognise the variable elements of the glacier balance over many decades of years preceding this particular study period. These methods were divided into two major groups: climatological and geodetic.

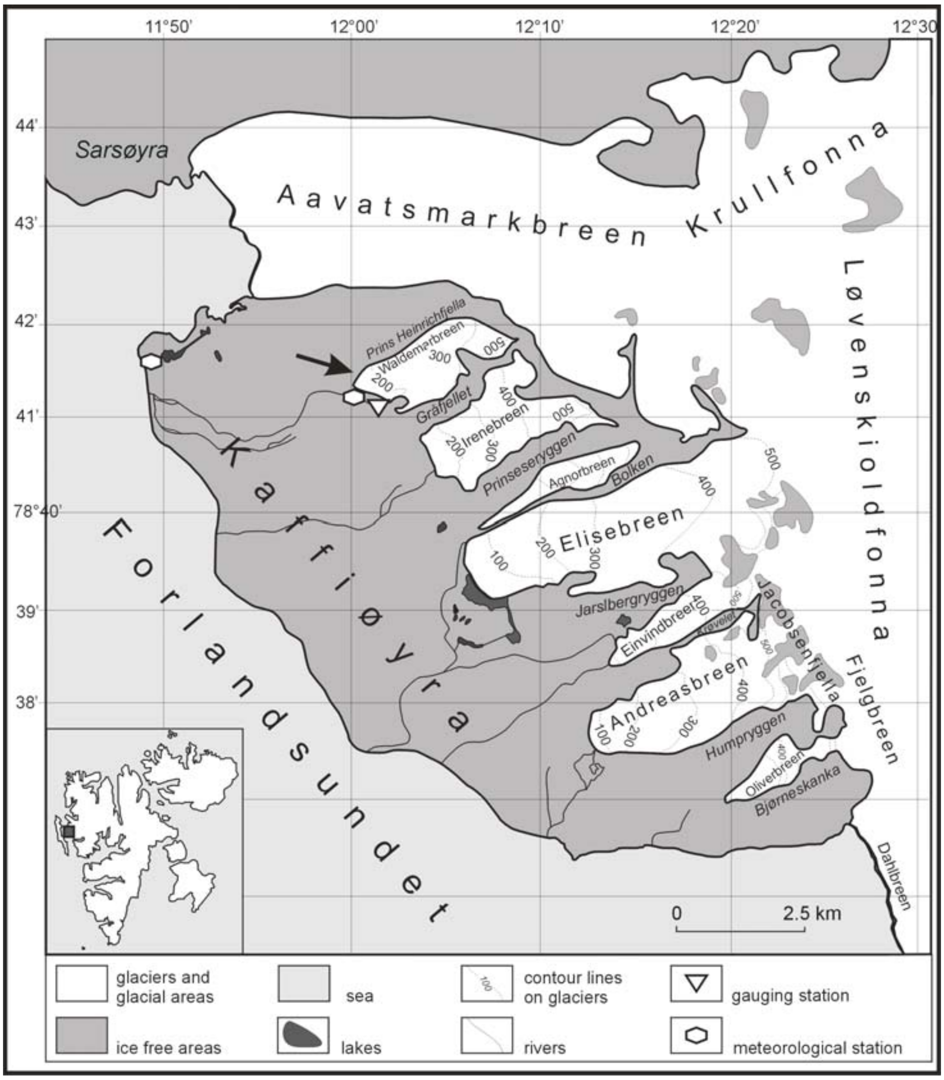

Fig. 1. The location of Waldemarbreen on Kaffiøyra, NW Spitsbergen.

Study area

Waldemarbreen is located in the northern part of the Oscar II Land, Kaffiøyra, north-western Spitsbergen (Figs 1–2). Kaffiøyra is a coastal lowland situated on the Forlandsundet. In the north it is bordered by Aavatsmarkbreen, which terminates in Hornbaek Bay, and, in the south, by Dahlbreen and the bay of the same name. In the east, Kaffiøyra is bordered by seven glaciers which descend from the Prins Heinrich and Jacobson mountains. From north to south, these are: Waldemarbreen, Irene-breen, Agnorbreen, Elisebreen, Eivindbreen, Andreasbreen and Oliverbreen (Fig.

Fig. 2. The Waldemarbreen in summer time (2006).

1). The glaciers are a dominant element in the landscape of Kaffiøyra, covering approximately 255 km^2 (Lankauf 2002).

Waldemarbreen is about 3.5 km long and has an area of 2.6 km^2. The ice originates in one cirque and flows from an elevation of more than 500 m to the present snout at 130 m a.s.l.

Glaciological method

Direct glaciological measurements of the mass balance of Waldemarbreen were taken between 1996 and 2004. Apart from the components of the glacier balance, selected meteorological parameters: air temperature, precipitation, wind velocity and direction were measured both on the glacier and at Kaffiøyra. The glacier runoff was also measured (Fig. 1). The measurements of surface ablation were made every 5 days from July to September each year. The measurements were taken at 22 points on the glacier surface (Fig. 3). Such a relatively dense network of poles enables us to estimate fairly the value of ablation at any given altitude, as well as the influence of the local conditions on its size. All the ablation poles were drilled 10 m deep with a steam driven *Heucke Ice Drill* (Heucke 1999). The values of surface ablation (snow, firn and ice) were converted into water equivalent (w.e.). A density for the ice of 0.9 g cm^{-3} was used to convert ablation thickness to water equivalent. Where snow was found on the glacier, the appropriate snow density was applied to the computations.

Measurements of snow accumulation were taken in April and in the early part of May each year (Grześ and Sobota 2000; Sobota and Grześ 2006). An aluminium probe was used to measure the depth of snow. The measurements were taken three times at every site. Snow pits were dug if a snow layer could not be penetrated through. The measurement sites were located with GPS and marked on the map. Snow density, structure, grain type and hardness values were recorded. The density of snow was measured in pits and at representative points (Fig. 3). The basis for calculations and graphic presentation of spatial variation of snow cover thickness resulted from 100 to 150 soundings, *i.e.* about 40 measurements per km^2.

The net balance was obtained as a sum of the interpolated local balances in successive elevation bands. It was obtained as a sum of summer ablation and snow accumulation. The balance year lasted from October to September of the next year. This period of time included both the entire accumulation and ablation seasons.

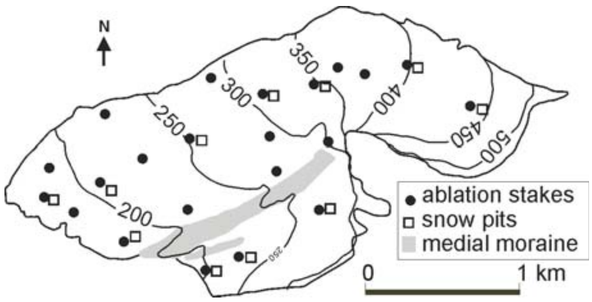

Fig. 3. The location of ablation stakes and snow pits on Waldemarbreen.

Error considerations. — Glaciological mass balance measurements errors are difficult to treat analytically because of the problems inherent in sampling and extrapolation (March 1998). Measurements of the mass balance based on the network of poles must inevitably contain some errors (Dyurgerov 2002; Hagg *et al.* 2004; Cogley and Adams 1998; Krimmel 1999). There is a standard measurement error, the value of which is similar for most glaciers. Errors are not only made in the measurements (a random error) but also by bias in the methodology (systematic error), or as, for example, having an insufficient number of stakes or neglecting to account for the percolating meltwater into the previous year's firn layer. Most random errors are attributable to a wrong reading at a single pole (Bhutiyani 1999; Dyurgerov 2002).

Systematic errors, which are mainly associated with the natural processes within the glacier, are difficult to calculate. Two of the biggest problems are internal accumulation (*i.e.* when melt water penetrates into cold subsurface layers and refreezes) and the size of superimposed ice. These two additional sources of accumulation can seriously complicate the mass balance measurements on glaciers (Rabus and Echelmeyer 1998). They closely reflect the intensity and duration of surface ablation, and the glacier's climate and hypsometry (Cogley and Adams 1998). As regards Waldemarbreen, this situation varies in different balance years, as a result of which, the problem of the error associated with the superimposed ice zone did not occur every year. Additionally, it was discovered that, owing to the glacier's relatively small area, this does not significantly influence the value of the total mass balance.

It was found, however, that the direct measurements of the mass balance of Waldemarbreen contained small errors due to occasional misreadings of the ablation poles. The error of the annual mass balance of Waldemarbreen, based on various methods and formulas (for instance: Pelto 1996; Rogerson *et al.* 1986; Cogley *et al.* 1996; Trabant and March 1999; Schneider and Jansson 2004) as well on direct field measurements, is considered to be about ± 0.20 m w.e.

Results of glaciological method

Both Waldemarbreen's area and the altitudinal difference between the accumulation zone and the ablation area are relatively small. Nevertheless, a spatial variation of ablation is obvious. That variation is caused by local glacier conditions: hypsometry and solar exposition, in partucular, as well as the number and the course of supraglacial streams (Sobota 1999). Every year the highest ablation values were observed at altitudes below 250 m a.s.l., as well as at the foot of the medial moraine. The most negative mean summer balance of the glacier was -1.21 m w.e. in 1998, whereas the least was -0.64 in 2000. The average summer balance of Waldemarbreen amounted to -1.00 for the period 1996–2004. In the years 1996–2004 the cumulated total ablation of Waldemarbreen was about -9.03 (Fig. 4).

As in the case of most mountain glaciers snow accumulation on Waldemarbreen increases with altitude. Regardless of its realtively small area, Waldemarbreen has shown great spatial variation of winter balance, over different years (Grześ and Sobota 1999, 2000). Winter balance was greatest in 1996 (0.75 m w.e.). The lowest snow accumulation was in 1999 (0.33 m w.e.). The average winter balance of Waldemarbreen for the period of 1996–2004 was 0.47 m w.e. (Fig. 4).

Table 1

Annual mass balance of Waldemarbreen in 1996–2004

Year	Summer balance [m w.e.]	Winter balance [m w.e.]	Net balance [m w.e.]
1996	-0.72	0.75	+0.02
1997	-0.86	0.48	-0.38
1998	-1.21	0.42	-0.79
1999	-1.01	0.33	-0.68
2000	-0.64	0.32	-0.32
2001	-1.13	0.36	-0.77
2002	-1.15	0.63	-0.51
2003	-1.18	0.45	-0.73
2004	-1.14	0.50	-0.64
1996–2004	-1.00	0.47	-0.53

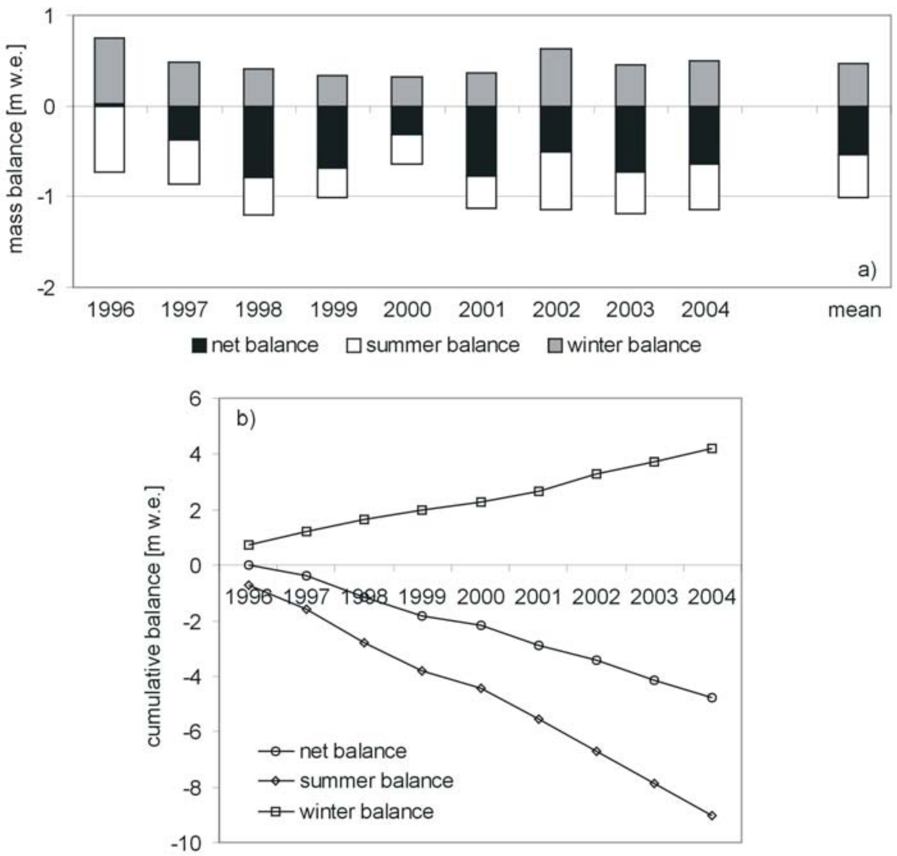

Fig. 4. Annual mass balance (a) and cumulative mass balance (b) of Waldemarbreen.

Wheras the mass balance of Waldemarbreen was similar in the glacier's lowest part in every year, the biggest differences occurred in its upper parts. Therefore, weather conditions and winter snow accumulation in that part of the glacier must have been decisive in determining the gradient of the net mass balance.

In 1996–2004 the pattern of the net mass balance of Waldemarbreen was very variable (Table 1). The positive value occurred in the balance year 1996, amounting to +0.02 m w.e. (Sobota 2000, 2004a, 2005; Fig. 4).

The mass balance of Waldemarbreen in individual years was influenced by various factors, and the role of both summer and winter balance differed accordingly. Only in 1996 and 2002 the winter balance play a dominant role. In 1997, 1999 and 2000 the influence of the winter and summer balance was similar, and in 1998, 2001, 2003 and 2004, summer ablation was crucial. Hence, even in the case of a relatively small glacier, the influence of the particular components of the balance may differ greatly in various years. The average mass balance amounted to -0.53 m w. e. in the years 1996–2004.

This analysis indicates that the net mass balance of Waldemarbreen is similar to the two small valley glaciers (Midre Lovénbreen and Austre Brøggerbreen) located in the north-western part of Spitsbergen in Kongsfjord area (IAHS (ICSI)/UNEP/UNESCO 2003, 2005).

Climatological methods

In order to estimate mass balance climatological methods are widely applied for glacier investigations. They are based on the correlation of mass balance elements with meteorological parameters. The strong influence of such elements as air temperature or precipitation on the values of summer ablation and winter accumulation means that we may place great reliance on these methods.

The analysis was based on the meteorological data for the years 1970–2004 collected at the weather station in Ny Ålesund (Climatolology Division, Norwegian Meteorological Institute, Norway), located 30 km NE of Kaffiøyra and are considered to be completely representative for Waldemarbreen. This indicated by the close correlation of the mean air temperature from 21 July to 31 August in the years 1975–2004 at Kaffiøyra (Przybylak and Szczeblewska 2002; Sobota 2003, 2004b), and that at Ny Ålesund during the same time (Fig. 5).

The glacier mass balance depends on weather conditions prevailing in a particular balance year. Two approaches may be used for estimation the mass balance based on summer air temperatures (Table 2). One uses the so-called positive degree-day (PDD) to estimate total mass balance (method 1). The other is based on the daily average air temperature in summer to estimate mass balance (method 2). The PDD-model has been widely used (for example: Braithwaite 1995; Braithwaite and Zhang 2000; Hock 1999). The method used here, however, is not exactly

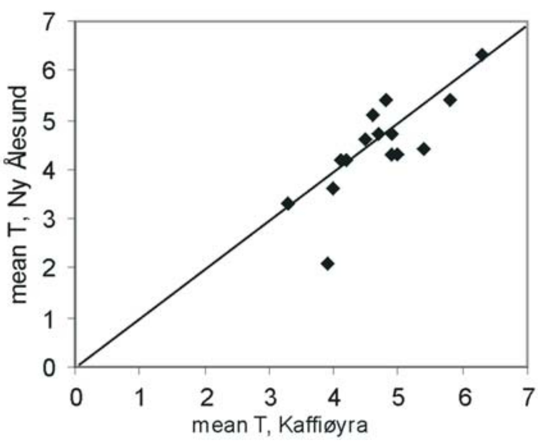

Fig. 5. Correlation between the average temperature (T 1C) for the period 21 July – 31 August in Ny Ålesund and on Kaffiøyra for the years 1975–2004 ($y = 1.014x–0.319$; $r^2 = 0.79$).

Table 2

Climatological and geodetic mass balance methods – comments

Method	Formula	Comments
Method 1	$bn_1 = -0.0034PDD_{VI–IX} + 0.88$ (1-1)	bn_1 – the mass balance in m w.e., $PDD_{VI–IX}$ – the sum of the positive degree-days, PDD (June–September). Equation (1-1) implies a degree-day factor 3.4 mm per degree-day. The standard error of the estimate of bn_1 is ± 0.20 m w.e.
Method 2	$bn_2 = -0.459T_{VI–IX} +0.90$ (2-1)	bn_2 – the mass balance in m w.e., $T_{VI–IX}$ – the average air temperature in °C (June–September). The standard error of the estimate of bn_2 is ± 0.15 m w.e.
Method 3	$bn_3 = P_{T \leq 0°C} + A$ (3-1) $A = -0.0024PDD_{VI–IX} - 0.15$ (3-2) $bn_3 = (P_{T \leq 0°C} + A) + \alpha$ (3-3)	bn_3 – the mass balance in m w.e., $P_{T \leq 0°C}$ – the sum of precipitation in a period with daily average air temperature ≤ 0 °C in m, A – ablation in m, $PDD_{VI–IX}$ – the sum of the positive degree-days in the period from June to September in °C, α – reduction coefficient introduced into the formula (3-1), which is 0.25 m w.e.
Method 4	$dV = \frac{S_1 + S_{i+1} + \sqrt{S_i \cdot S_{i+1}}}{3} \cdot dz$ (4-1) $dH = \frac{2dV}{n(S_t + S_{t+n})}$ (4-2)	dV – the change of the volume in a particular altitudinal zone, S_i – the surface between the lower contours of this zone on the superimposed maps, S_{i+1} – the surface between the contours restricting a particular altitudinal zone from the top on the superimposed maps, dz – the contour interval (Tański 1999), dH –the annual average change of the glacier thickness (of the surface height) in a particular altitudinal zone, dV – the change of the volume in the altitudinal zone, S_t – the surface of a particular altitudinal zone on the first map, S_{t+n} – the surface of the same altitudinal zone on the second map, n – the number of years which passed between the first and the second mapping

the same as established model; it is based, instead, on the relation between the sizes of the mass balance of the glacier and of the PDD. High correlation between the above parameters confirms the usefulness of the method.

The glacier mass balance was also estimated by way of a comparison of winter snow accumulation and summer ablation (method 3). The winter accumulation was calculated as the sum of precipitation in a given balance year (P), in a period with daily average air temperature ≤ 0°C (Table 2). Ablation was computed from sum of the positive degree-days (PDD) in the period June to September (A). A similar method has been used by others (Khodakov 1965; Krenke and Khodakov 1966; Ohmura 2001; Tangborn 1999). From Ny Ålesund precipitation values were used as the precipitation measurements in Kaffiøyra were carried out only in summer.

The correlation between the precipitation in Kaffiøyra and in Ny Ålesund is not as significant as that of the air temperatures. Consequently, the mass balance computed on the basis of the equation 3–1 is probably underestimated. Thus, the reduction coefficient a was introduced into the above formula (3–1). This relates to the difference in precipitation over these both areas, and 0.25 m w.e. is the adopted figure (Table 2).

Geodetic method

Geodetic methods involve detailed analysis of topography, and aerial and satellite photographs of the studied area (Bukowska-Jania and Jania 1988; Echelmeyer *et al.* 1996; Finsterwalder 1954; Furbish and Andrews 1984; Haakensen 1986; Krimmel 1999; Østrem and Haakensen 1999). The methods are based on a comparison of accurate topographic maps and the determination of the volume change for the period between the photogrammetric surveys. They enable a comparison of glacier mass balance in a region to be made over a period of time.

In order to estimate the mass changes of Waldemarbreen over a period longer than the direct field measurements, a method similar to the one proposed by Finsterwalder (1954) was applied (method 4, Table 2). Waldemarbreen was mapped in 1978 and 2000 (Lankauf 2002). The maps used were made at a 1:5 000 scale, with a contour interval every 10 m.

The first phase of this method involved digitalisation of the outlines of the glacier boundary and contours on the maps, from which the volume of the solid could be computed. In this case, the glacier was above the volume whose limits were defined by the geographic coordinates X and Y, and the altitude above the sea level represented by Z. The volume calculation determines the net volume between the upper part and the lower surface (Table 2). In this case, the 1978 map of Waldemarbreen constituted the upper surface, and the 2000 map the lower one. The volume of such a solid was computed by the means of a double integral, according to the three formulae: Trapezoidal Rule, Simpson's Rule and Simpson's 3/8 Rule (Tański 1991). As a result, three values were obtained and the net volume can be expressed as the average of these three.

Error considerations. — The climatological methods must inevitably contain some errors however limited. One such is the effect of including the meteorological data from a weather station located 30 km distant from the glacier, as well as of the variable values of both summer and winter balance in individual years. If the equations (1-1) and (2-1) are considered, the standard error of the expected value of the mass balance for each PDD value and the mean air temperature between June and September was ± 0.20 m w.e. and ± 0.15 m w.e., respectively (Table 2). The largest differences in the measured and modelled mass balances occurred in 1996 and 1998, *i.e.* in the years when the weather differed significantly from those in the other study seasons. Whereas, in 1996 the thickest snow accumulation was observed, in 1998, the exceptionally high mean air temperature of the summer season resulted in an intensified glacier ablation. It can be assumed, therefore, that for the years with an more intensive snowfall, the computed values must be underestimates, whereas they are overestimates for summer seasons which have above-average air temperatures. If the methods 2 and 3 are considered, the inclusion of winter snow accumulation values increases their accuracy considerably. This is because these methods are predominantly based on the weather conditions of the ablation season. In the case of method 3, its accuracy depends mainly on the precipitation value. The largest difference from the mean values was observed in the years of the highest snow accumulation. The standard error of these methods was about ± 0.20 m.

Errors inherent to the geodetic methods are much less time-dependent than possible systematic errors in the direct (glaciological) methods. Mass balance estimation based on the geodetic method is more accurate than the glaciological one over periods longer than a few years (Cox and March 2004).

The relatively small area of ice surface of Waldemarbreen significantly eliminates the errors associated with finding the new glacier boundary. Certainly, the value of some random errors measured from the analysis of the contour line course and their digitalisation is only of the order of 3 m in the horizontal direction. But it should also be stressed that there must be a certain contour-drawing error, which can be defined as systematic.

The relative error for the volume computation results when method 3 is applied may be estimated by a comparison of the results of the three methods: the Trapezoidal Rule, the Simpson's Rule and the Simpson's 3/8 Rule (Tański 1991). The relative error can then be given as a percentage of the average volume.

The total error in the area-average thickness change is a reflection of the influences of map construction error, that resulting from random contour error and the systematic errors. As these errors are independent, the total error is the square root of the sum of their squares (Sapiano *et al.* 1998). The total error in the thickness change of Waldemarbreen is thereby calculable on being in the range of 1 to 2 m.

Results and discussion

On the basis of the relationship between the net mass balance of Waldemarbreen, as measured in the years 1996–2004, and the positive degree-days (PDD-model), the mass balance was calculated for the period 1970–2004 (method 1). The correlation coefficient was -0.74. Satisfactory mass balance values of Waldemarbreen were obtained with relation to the daily average air temperature in the selected months (June–September). The correlation coefficient was -0.86 (method 2).

According to methods 1 and 2, the average mass balance of Waldemarbreen in the years 1970–2004 amounted to -0.45 ± 0.20 m w.e. and -0.39 ± 0.15 m w.e., respectively. The average mass balance of Waldemarbreen determined according to method 3 was -0.43 ± 0.20 m w.e. in the period of 1970–2004. This value is similar to the one computed with respect to the other proposed methods (Table 3, Fig. 6).

On the basis of all the climatological methods, the average mass balance of the glacier was estimated at -0.42 m w.e. in that period. By comparison, the mass balances of the glaciers Austre Brøggerbreen and Midre Lovénbreen were -0.46 m w.e. and -0.47 m w.e., respectively, in 1970–2004 (IAHS (ICSI)/UNEP/UNESCO

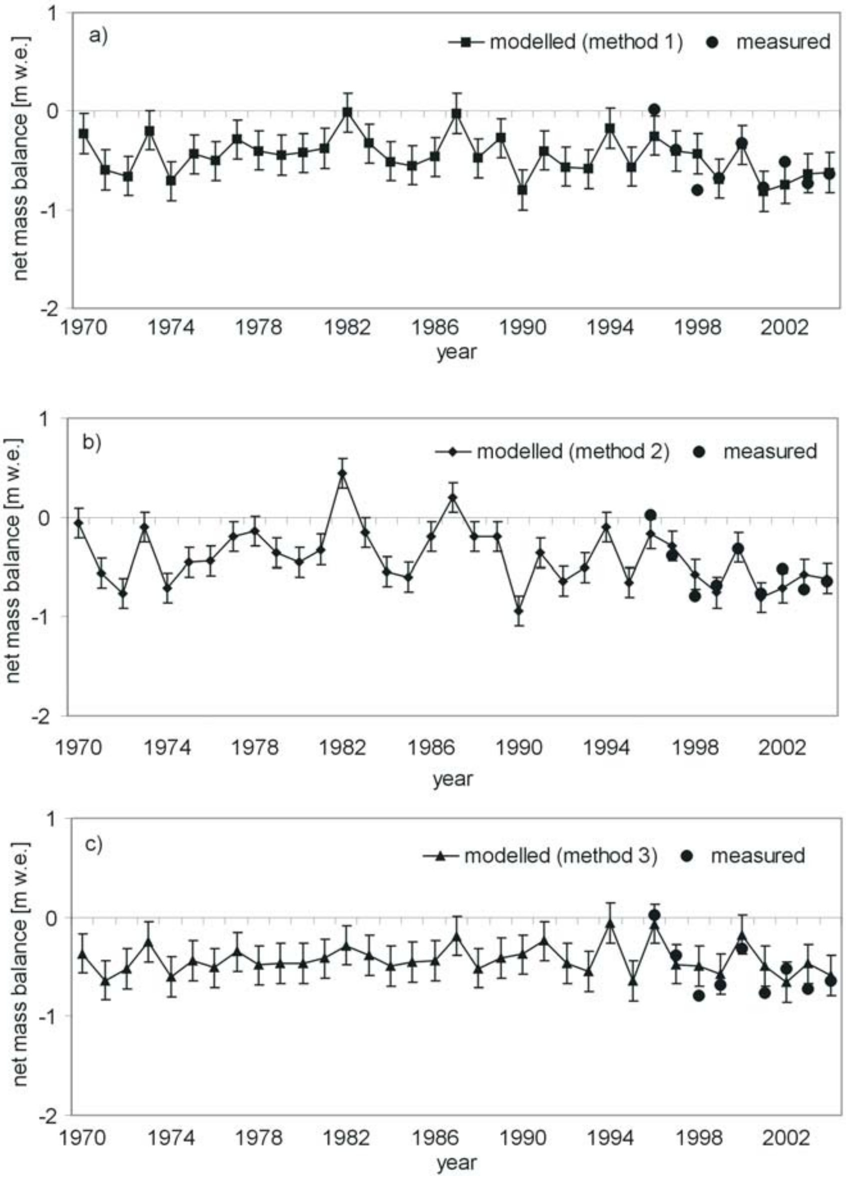

Fig. 6. Mass balance of Waldemarbreen with error columns measured and modeled: a) on the basis of the relationship between the net balance of Waldemarbreen and positive degree-days (PDD) in June–September for the period 1970–2004; b) on the basis of the relationship between the net balance of Waldemarbreen and the average air temperature in June–September for the period 1970–2004; c) on the basis of the precipitation and the air temperature in the period 1970–2004.

2001, 2003, 2005; Kohler *et al.* 2006). Hence, the values were similar. Furthermore, the time balance variability of both these glaciers and Waldemarbreen appear to confirm the accuracy of these methods. The biggest negative values were

Table 3

Mass balance of Waldemarbreen in m of water equivalent estimated on the basis of selected climatological and geodetic methods

Year	Measured	Method 1	Method 2	Method 3	Method 4
1970		-0.23	-0.06	-0.37	
1971		-0.60	-0.56	-0.64	
1972		-0.66	-0.76	-0.52	
1973		-0.19	-0.09	-0.25	
1974		-0.71	-0.71	-0.60	
1975		-0.44	-0.45	-0.44	
1976		-0.50	-0.43	-0.51	
1977		-0.29	-0.20	-0.35	
1978		-0.40	-0.14	-0.49	
1979		-0.45	-0.36	-0.46	
1980		-0.42	-0.45	-0.46	
1981		-0.38	-0.32	-0.42	
1982		-0.01	+0.45	-0.29	
1983		-0.33	-0.16	-0.38	
1984		-0.51	-0.55	-0.49	
1985		-0.55	-0.61	-0.46	
1986		-0.47	-0.20	-0.44	
1987		-0.02	+0.20	-0.19	
1988		-0.48	-0.19	-0.52	
1989		-0.27	-0.20	-0.41	
1990		-0.80	-0.94	-0.38	
1991		-0.40	-0.36	-0.24	
1992		-0.56	-0.64	-0.46	
1993		-0.59	-0.50	-0.55	
1994		-0.17	-0.10	-0.06	
1995		-0.57	-0.66	-0.64	
1996	+0.02	-0.25	-0.17	-0.07	
1997	-0.38	-0.41	-0.29	-0.47	
1998	-0.79	-0.43	-0.57	-0.49	
1999	-0.68	-0.68	-0.76	-0.57	
2000	-0.32	-0.34	-0.30	-0.18	
2001	-0.77	-0.81	-0.80	-0.49	
2002	-0.51	-0.74	-0.71	-0.66	
2003	-0.73	-0.63	-0.57	-0.47	
2004	-0.64	-0.62	-0.62	-0.59	
Average (1996–2004)	-0.53	-0.55	-0.53	-0.44	–
Average (1970–2004)	–	-0.45	-0.39	-0.43	–
Average (1978–2000)	–	-0.41	-0.34	-0.40	-0.52

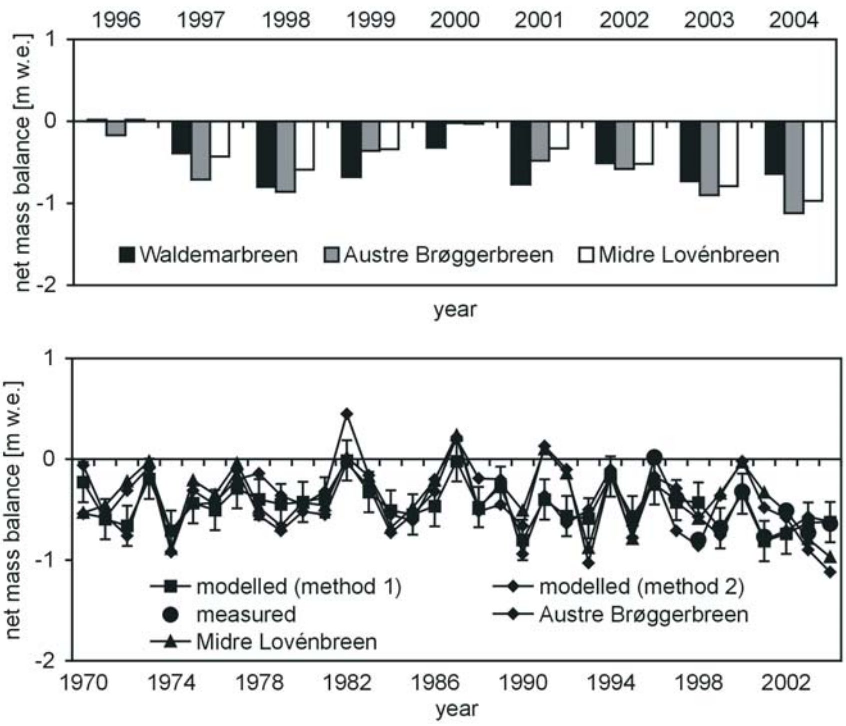

Fig. 7. Reconstructed and measured mass balance of Waldemarbreen compared with the mass balance of Midre Lovénbreen and Austre Brøggerbreen in the period 1970–2004 (IAHS (ICSI)/UNEP/UNESCO 2001, 2003, 2005; Kohler *et al*. 2006).

recorded in the early 1970s, in the mid-1980s, and the early 1990s and 2000s (Fig. 6). Figure 7 presents the mass balance of the Waldemarbreen compared to Midre Lovénbreen and Austre Brøggerbreen. The years with maximum and minimum values in their balances clearly match. The balance values are often quite similar, especially it respect of Midre Lovénbreen. It is clear, therefore, that the results of the research on the mass balance of Waldemarbreen are of some significance for establishing the size and changes of the mass balance for other glaciers in the north-western part of Svalbard.

Based on the geodetic method used the following values of the volume changes of Waldemarbreen were computed: (1) -0.0371 km^3 from the Trapezoidal Rule; (2) -0.0370 km^3 from the Simpson's Rule; and (3) -0.0372 km^3 from the Simpson's 3/8 Rule. Thus, the net volume of the glacier's mass reduction based on the above formula is -0.0371 km^3 and on the basis of this value, the average value of the surface thickness change could be computed 12.9 m. Applying an ice density value of 0.9 g cm^{-3}, it may be estimated that the cumulative average mass balance of the glacier amounted to as little as -11.6 m w.e. in the period of 1978–2000. According to this method, the average annual value of the glacier's surface thickness change amounted to 0.57 m., whereas the annual average mass balance of

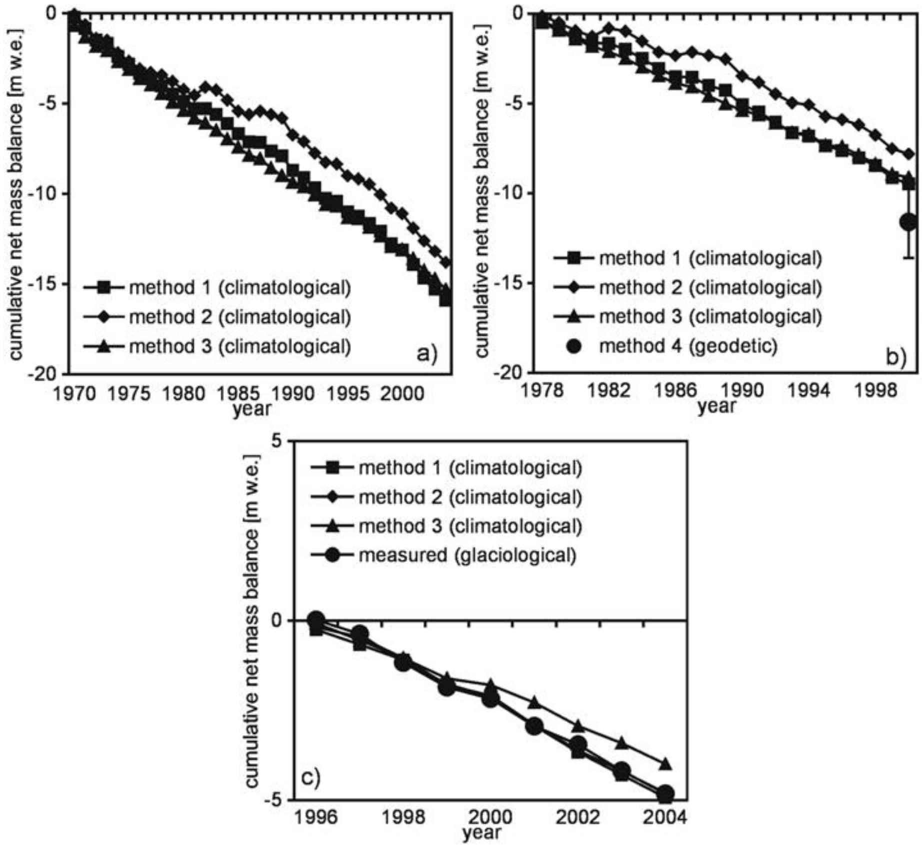

Fig. 8. Comparison of cumulative glaciological, climatological and geodetic mass balances: a) 1970–2004, b) 1978–2000, c) 1996–2004.

Waldemarbreen computed from this method amounted to -0.52 ± 0.09 m w.e. in the years of 1978–2000. This value is close to the measured mean annual mass balance of Waldemarbreen. It is also similar to the values obtained by the means of other methods (Table 3).

The comparison of the climatological and geodetic methods mass balance of Waldemarbreen was found to have been negative over the years, yet there have been years with a positive balance (Table 3). Regardless the balance values, of the method applied, were similar to other glaciers of Svalbard (Fig. 7).

The methods used have enabled the Author successfully to define the variability of the cumulative mass balance of Waldemarbreen (Fig. 8). It was found that the cumulative mass balance in the years 1978–2000 was -9.48 m w. e. (method 1), -7.82 m w.e. (method 2), and -9.12 m w.e. (method 3). Additionally, the geodetic method gave a value similar to that mass balance in the period 1978–2000, *i.e.* -11.60 m w.e. (Fig. 8). The value suggested by the geodetic method is larger, which is presumably a consequence of the estimated error of ± 0.09 m w.e., the cumulative value of which is ± 2 m w.e. This method, however, does show the mass balance changes of a glacier during a multi-annual period of time, if based on the analysis of just two maps drawn at different times. As a result, the geodetic method may be a very good way to estimate the mass balance of the glaciers for multi-annual periods when no direct glaciological measurements are not attempted. It must be remembered, however, that climatological methods also carry errors which result in differences in the cumulative values.

The average mass balance of Waldemarbreen computed according to the climatological methods amounted to -0.42 m w.e. for the period of 1970–2004, and -0.51 m w.e. for the period of 1996–2004 (Table 3). The error value for these methods is about ±0.20 m w.e. These values indicate an adequate level of correlation with the mean mass balance value obtained on the basis of the direct glaciological measurements over the same period (*i.e.* -0.53 m w. e. from 1996 to 2004).

The accuracy of the methods used may be increased to a limited extent by analyzing the energy balance of a glacier. In recent years several such approaches have been developed (Klok and Oerlemans 2002; Hock and Holmgren 2005; Oerlemans 2001). They need, however, application of automatic weather stations and numerous meteorological parameters (air pressure, windspeed, wind direction, air temperature and humidity) and all elements of surface radiation balance. The particular advantage of the climatological methods used by the Author is that they enable us to estimate the size of the mass balance of a glacier mainly on the basis of the simplest meteorological data, such as air temperature and precipitation.

Conclusions

The mass balance of Waldemarbreen has been estimated by both direct field glaciological measurements (1996–2004), and climatological and geodetic methods. As a result, the values of mass balance of this glacier may be estimated with some confidence for the years 1970–2004.

The mass balance of Waldemarbreen is primarily dependent on the mean air temperature of the summer season, and, secondly, on the winter snow accumulation. The exceptions are the years of significant snowfall and snow accumulation. Such a high dependence on the weather conditions confirms the notion that the mass balance of Waldemarbreen can be regarded as an indicator of climatic changes (IAHS (ICSI)/UNEP/UNESCO 2003, 2005; Haeberli 1995; Kaser 2001; Klok and Oerlemans 2004; Kuhn 1986).

A close similarity of the results obtained by the indirect methods and those obtained by direct methods suggests that their usage in estimation of mass balance may be regarded an extremly reliable. Certaintly, the formulae may be applied to other small Svalbard glaciers with some confidence.

The applied climatological methods (Table 2), which are based on the accessible meteorological data, constitute a good approach to determine the variability of the glacier mass balance for a period of several years (Table 3). On the other hand, the geodetic method, provides an illustration of the volume changes that take place over a span of many years and complement any direct measurement method which is conducted on a glacier.

The geodetic method used proved to be an accurate model for evaluating the volume changes and mass balance in multi-annual periods of time. Where there are no other information sources, this is the one of the substitute methods for the mass balance estimation of glacier. A similar method for assessment the thickness changes of certain Alaskan glaciers was employed by Echelmeyer *et al.* (1996), and Sapiano *et al*. (1998). Cox and March (2004) showed that every glaciological mass balance record needs to be calibrated regularly with a geodetic method.

The average mass balance value of Waldemarbreen for the years 1996–2004 may be regarded as representative of small valley glaciers of the north-western part of Svalbard. This conclusion is supported by the estimated values of mass balance for a long-period, which are based on selected climatological and geodetic methods. These methods enable us to select the years of the lowest mass balance, as well as the highest. Strict conformity of the results modelled on the basis of indirect (climatological and geodetic) and direct (glaciological) methods means that they can be reasonable alternatives for estimation of glacier mass balance in the years where direct field glaciological researches are impractical. The accuracy of the mass balance estimation may be increased significantly by using all the suggested methods, especially for a multi-year period.

The mass balance records on Waldemarbreen, Svalbard, are especially important because they are one of only a few long-term mass balance records on Svalbard.

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