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Influence of positive degree-days and sunshine duration on the surface ablation of Hansbreen, Spitsbergen glacier

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ABSTRACT: The results of a statistical analysis of the influence of the Hansbreen surface ablation relative to selected meteorological parameters (air temperature and sunshine duration) are presented here. Over the period 1989–2001 the lowest summer balance on the surface ablation of Hansbreen was recorded in 1994 (–0.56 m **w**ater **e**quivalent). Concurrently, both the air temperature (mean seasonal ~2.3°C) and the sunshine duration (seasonal sum ~278.9 h) were at their lowest. Owing, to the relatively high sunshine duration (676.5 h), the highest values were in 1998 (–1.71 m w.e.); likewise, in 2001 (–1.84 m w.e.) when a high air temperature (mean of 3.6°C) occurred. The statistical models erected on the basis of these data allow us to estimate fairly reliably the seasonal ablation of Hansbreen. The basis of these is the reasonably reliable relationship determinable between the seasonal sum of PDD (positive degree days) and the ablation intensity changes in respect of altitude above sea level. Sunshine duration is regarded here as being of very little significance in terms of increasing the accuracy of the models. The errors inherent in this models varies from 28% to as little as 7%. Shown models may eventually find application as a method of calculating the amount of water resulting from the decay of tidewater glaciers.

Key words: Antarctic, Spitsbergen, Hansbreen, surface ablation, sum of PDD.

Introduction

Surface ablation is one of the physical processes which lead to the destruction of a glacial mass. It is a reflection of changes in the supply of energy to the surface of the glacier. According to Baranowski (1977) the most important sources of energy for this process are those of sensible heat and solar radiation. These factors are characterised by some parameters such as air temperature, direct solar radiation and sunshine duration.

The relationship between surface ablation and climatic factors is a function of such physical features as melting, the energy balance of the glacier surface, meteorological conditions and the physical properties of ice (Röthlisberger and Lang

1987, Oerlemans 1988, Braithwaite and Olesen 1989, Laumann and Reeh 1993, Braithwaite 1995, Johannesson *et al.* 1995, Hock 1998, 1999). Physical modelling of ablation indicates that most of the energy which leads to melting is supplied by solar radiation and sensible heat.

Owing to the paucity of suitable data (systematic studies of energy balance components are conducted only for few glaciers), the application of physical data in the estimation of surface ablation is not usually possible. Experience shows that it is easier to model the ablation including statistical relationships between its worth and meteorological parameters, mainly air temperature. Such was the conclusion of Khodakov (1965), Krenke and Khodakov (1966), Moiseewa and Khodakov (1971), Baranowski and Głowicki (1975), Braithwaite and Olesen (1990). Formulae (especially those based on the sums of positive degree days[1]) may be applicable in such as the forecasting of floods, hydrological models, estimation of the volumes of meltwater delivered by glaciers, used to estimate the mass balance (Lefauconnier and Hagen 1990, Jania and Głowacki 1996).

A detailed study of the relationship between surface ablation of Hansbreen and air temperature and sunshine duration is presented here. The main objective of this study was to erect a sequence of models which allows us to estimate reliably the seasonal ablation volume. The importance of PDD sums and sums of sunshine duration in these estimates are appraised.

Data and methods

The following data have been used in this work: the air temperature and sunshine duration records from summer season (June–September) in the years 1989–2001 (obtained by courtesy of the Institute of Geophysics of the Polish Academy of Sciences – IGF PAN), mean daily temperature records measured near Hans Cabina at 316 m a.s.l. in summer season of 1994 and 1995 (Mochnacki, *unpubl.*) and records of the intervals of direct solar radiation in 25 July to 30 September 1989 and 1 June to 31 August 1990 (made available by T. Niedźwiedź). Data of mass balance include seasonal values of ablation and accumulation of Hansbreen from the period of 1989–1995 measured on 10–11 stakes along central line of the glacier (IGF PAN). During the testing of models the data were completed with the ones from the period of 1996–2001 (IGF PAN).

Statistical analysis of relationship between meteorological parameters and ablation using the spreadsheet of Excel from software the Microsoft Office (standard deviation s.d., correlation coefficient, linear regression, multiple regression, Student's test etc.) represents a fundamental part of this project.

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[1] The sums of positive degree days (PDD) – the sums of positive mean daily air temperatures in a given period.

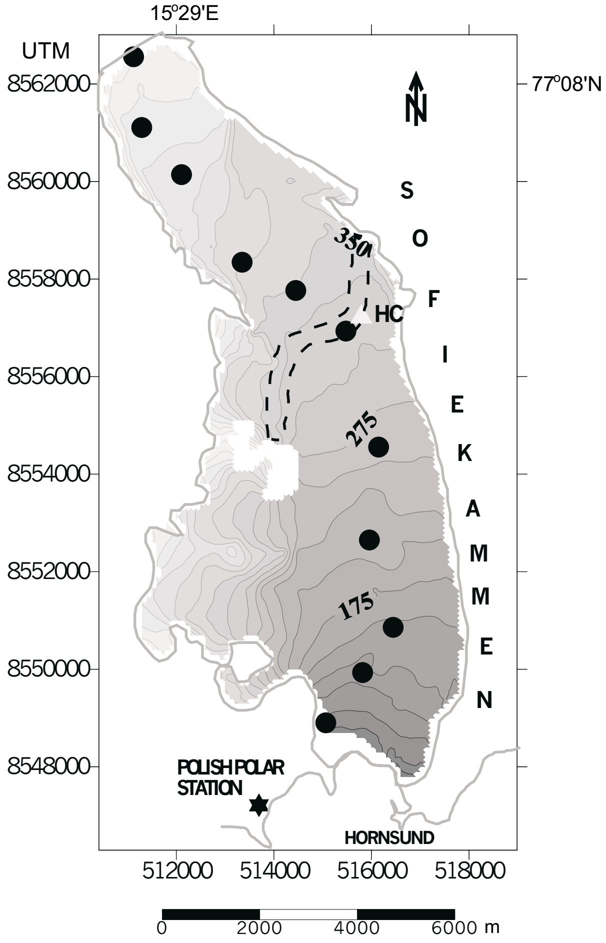

Fig. 1. Location of measurements stakes (circles) along the longitudinal profile of Hansbreen; HC – the Hans Cabina at the equilibrium line (dashed line) where measurements of air temperatures were done. Geodetic co-ordinates in the UTM/ED50 system (Utm zone – 33x – central meridian 15E).

About Hansbreen

Hansbreen, one of the glaciers of the Hornsund glacial basin (Jania 1988a), is located in the southern part of Wedel Jarlsberg Land (77°05'N; 15°38'E). It is an outlet – valley glacier within a complex basin (Jania 1988b) and it empties into Hornsund Fjord at a calving ice – cliff. Its surface slopes gently at <2°. Its length is c. 16 km and area c. 56 km^2. Its maximum thickness is c. 400 m. In respect of its basal layers, which are at the temperature of melting ice (temperate type), it is usually classified as a polythermal glacier. The surface layer, especially that part extending from the equilibrium line to the glacier front, features cold ice (temperature below melting point) (Jania *et al.* 1996).

In hydrological terms, this glacier shows a typical seasonal variability. The maximum run-off from the glacier takes place during the ablation season, most of this during July and August, when the discharge can be as much as 16 m^3 s. The annual run-off from Hansbreen was estimated to be 60 × 10^6 m^3 to 95 × 10^6 m^3 and the mean annual flow c. 1.8–3.0 m^3 s (Jania 1994, Jania and Pulina 1996).

Studies of the Hansbreen mass balance components date from the 1988/1989 season. These comprise readings taken at stakes placed along the central line of the glacier (Fig. 1), snow soundings and snow pits analysis (Jania and Głowacki 1996). These data (certainly those with respect to the accumulation observations) are generally considered to be representative of the whole of the glacier surface (Leszkiewicz and Pulina 1996). However, a complementary study of the Hansbreen ablation has yet to be attempted.

The small deviation (s.d.) from mean value (Table 1) of winter balance (s.d. = 0.13) is an important feature of the Hansbreen mass balance. The larger annual fluctuations reflect the summer balance (s.d. = 0.36) and, primarily, they determine the size of the surface net balance ($R^2 = 0.87$), which had a negative value over the whole study period.

Table 1

The mass balance of Hansbreen, 1989–2001 (data of IGF PAN).

Years	Winter balance m w.e.	Summer balance m w.e.	Net balance m w.e.	Mean altitude of ELA m a.s.l.
1989	0.91	–1,00	–0,09	365
1990	0.90	–1.44	–0.54	380
1991	1.16	–1.03	+0.13	280
1992	0.89	–1.16	–0.27	380
1993	0.93	–1.61	–0.68	400
1994	0.76	–0.56	+0.20	240
1995	0.76	–1.21	–0.45	390
1996	0.82	Lack of data		
1997	0.99			
1998	1.11	–1.71	–0.60	390
1999	1.01	–1.37	–0.35	350
2000	0.93	–1.41	–0.48	500
2001	0.78	–1.84	–1.07	500
Mean value	**0.92**	**–1.30**	**–0.38**	**382.3**

Owing to an increased precipitation (including snow), accumulation tends to increase relative to altitude. In southern Spitsbergen, the increase has been determined as 11–13 g cm^2 per 100 m of altitude (according to different sources) (Jania 1997). However, owing to a drop of temperature gradient, ablation decreases with respect to higher altitude. In case of Hansbreen the mean ablation gradient for whole of its surface was varying from 39 to 54 g cm^2 per 100 m in 1989–1995. The ablation gradient depends not only on changes of air temperature (as a function of

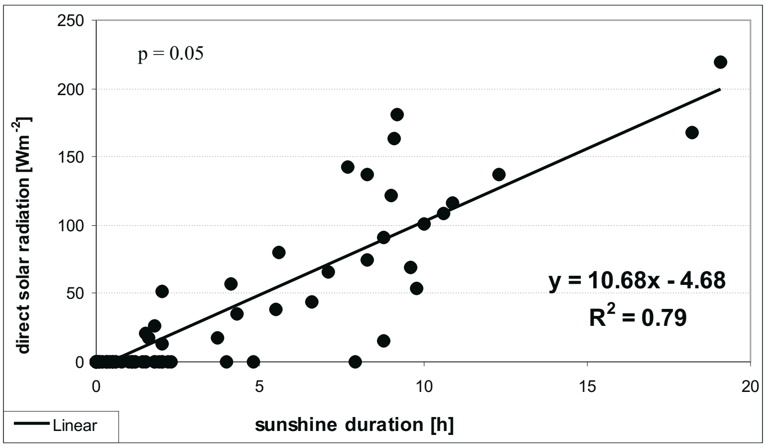

Fig. 2. Relation between mean diurnal direct solar radiation and diurnal sums of sunshine duration in Hornsund, 24 July – 30 September 1989 and June 1990 (data of T. Niedźwiedź and IGF PAN).

changes in atmospheric circulation). Also, solar radiation has an important influence and this is also altitudinally controlled: the greater the altitude, the greater its influence. Among other considerations, it finds a reflection in the variability of the ablation gradient. Up to an altitude of c. 270 m a.s.l. its value decreases linearly from 69 to 12 g cm^2 per 100 m but, above this, there are wide fluctuations. Moreover, on the accumulation plateau, an inversion has been demonstrated (more water is present here than in the lower zones).

As Hansbreen terminates in the sea, calving plays a very important role in mass loss. The annual calving loss in Hornsund is estimated to be of the order of 20×10^6 m^3 of w.e. (Jania and Głowacki 1996, Jania and Pulina 1996). At present the glacier is in recession by something like 30–40 m annually. In the period of 1936–1990 Hansbreen lost about 0.13 km^3 of ice (Jania 1994) and the average reduction of whole glacier surface was about 26.6 m of w.e. This value includes the volume lost due to forehead recession. Probably a surge activity may influence on this value but it is speculative (Jania and Głowacki 1996).

Meteorological parameters

As representative meteorological parameters, air temperature and sunshine duration measurements were used in the ablation analysis; these were supplemented by summer balances of the glacier (Table 2). In years of the higher summer balance, sunshine duration (1993, 1998) and temperature (1990, 2001) were also at their highest. Conversely, the lower the summer balance values (*e.g.* 1994), so correspondingly lower the values of sunshine duration and temperature.

Owing to a paucity of systematic measurements of the latter, the sunshine duration factor was used instead of direct solar radiation values. Nevertheless, the rela-

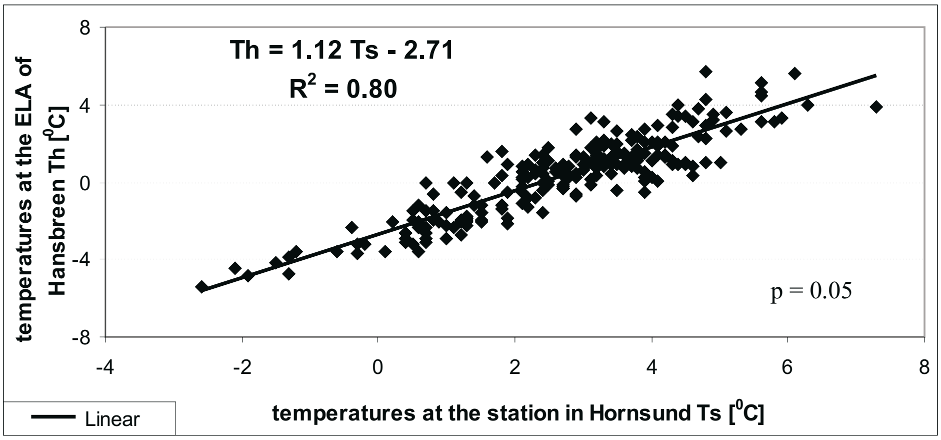

Fig. 3. Relation between mean diurnal air temperatures at the Hansbreen equilibrium line (Th) and changes of temperatures at the station in Hornsund (Ts) in the summer of 1994 and 1995 (data of IGF PAN and D. Mochnacki, unpubl.).

tionship between direct solar radiation and sunshine duration is well established at Hornsund; the coefficient of determination is of the order of 0.79 (Fig. 2).

The analysis sought to establish the relationship between air temperatures (Th), as measured at Hansbreen equilibrium line (316 m a.s.l.) in the summer season of 1994 and 1995, and temperatures (Ts) as measured at the Polish Polar Station, which is situated on a near-sea-level marine platform (Fig. 3).

The equation $Th = 1.12\ Ts - 2.71$ was used to calculate the mean daily temperatures at the Hansbreen equilibrium line in the other ablation seasons. From this, the thermal gradients could be calculated and the latter were used to reconstruct temperatures for each altitudinal zone of the glacier. Then, on the basis of such data, the seasonal sums of PDD were calculated for all zones. Concurrently, the duration of ablation season was determined. At the glacier front (60 m a.s.l.) this period lasts from 3 June to 22 September (116 days), whereas, on the accumulation plateau (500 m a.s.l.) – from 11 July to 19 August (40 days).

The sums of PDD were used to the further analysis.

The relationship of surface ablation to the selected meteorological parameters

In the statistical analysis it is important to recognize that:

1. The parameters measured at the station in Hornsund which were used in the modelling are typical for a tundra which is affected by oceanic air masses.

2. Any temperature lapse between the tundra and the glacier has not been taken into consideration (the two surfaces give rise to quite different radiation balances).

Table 2

Mean seasonal air temperatures, seasonal sums of sunshine duration in Hornsund and the summer balance (amount of melting water) of Hansbreen, 1989–2001 (data of IGF PAN).

Years	Air temperatures (°C)	Sunshine duration (h)	Summer balance (m w.e.)	/estimated meltwater discharge from the glacier (10^6 m^3 w.e.)
1989	2.9	447.0	–1.00	56.60
1990	4.2	462.2	–1.44	81.57
1991	3.1	632.2	–1.03	58.46
1992	3.5	549.4	–1.16	65.96
1993	2.5	681.0	–1.61	91.31
1994	2.3	278.9	–0.56	31.60
1995	2.9	472.5	–1.21	68.51
1996	2.6	476.3	–	–
1997	2.5	536.7	–	–
1998	3.3	676.5	–1.71	93.58
1999	3.5	351.9	–1.37	75.68
2000	3.3	669.8	–1.41	80.00
2001	3.6	317.0	–1.84	104.40
Mean	**3.1**	**504.0**	**–1.30***	**73.42***

* without data for the period of 1996–1997.

Table 3

Chosen regression statistics for presented models.

Models	Determination coefficients R^2	Number of row elements	Standard estimate error of ablation (ablation intensity)	$t_{0,05}$ observed	$F_{0,05}$ observed (v_1, v_2)
A.I.	0.72	60	405	12.27	–
A.II.	0.72	60	404	12.37	–
B.I.	0.75	57	390	12.96_{PDD} 0.07_{U}	84.23 (2. 54)
B.II.	0.79	60	361	14.95_{PDD} 2.45_{U}	113.60 (2. 57)
C.I.	0.89	9	1.39	7.23	–
C.II.	0.93	11	1.05	10.67	–

3. A linear drop of air temperatures and ablation in two models were assumed relative to altitude above sea level. Neither the influence of topographic profile nor local climate was taken into consideration. In reality, the ablation decreases in accordance with multinomial function and then its value depends on the radiation factor (Fig. 4).

For each model two variants of the PDD sums estimation were assumed. For the first, the procedure was mentioned above. In the second, calculations were based on

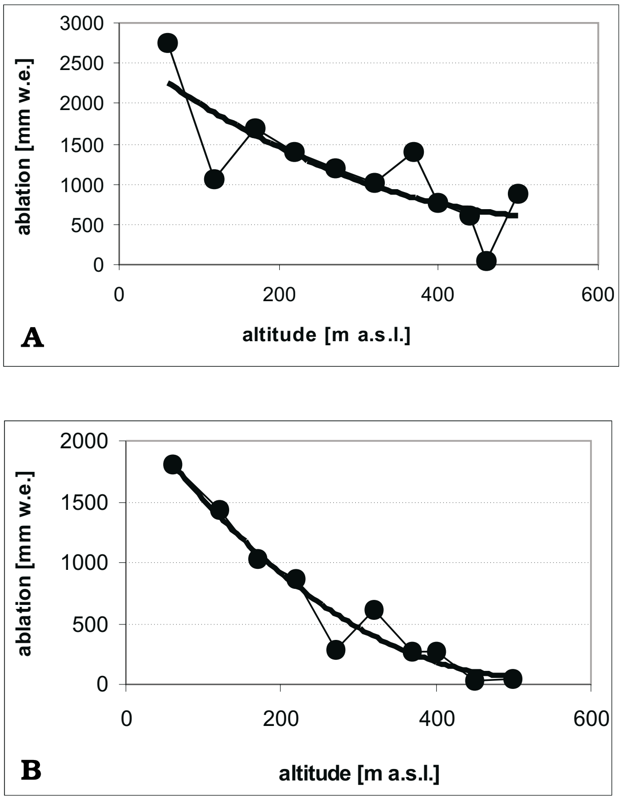

Fig. 4. Comparison the Hansbreen ablation changes with altitude due to: **A**. high sunshine duration (549.4 h) in 1992; **B**. low (278.9 h) in 1994 (data of IGF PAN).

two possible thermal gradients: 0.66°C 100 m for periods with low sunshine duration and 0.91°C 100 m for periods with higher than the average of sunshine.

The **A** Models Group. These consider the relationship of the ablation to the seasonal sums of PDD. The seasonal sums of PDD for each altitude zone were compared with the measured ablation. In this way equations of linear regression were received (Figs 5 and 6).

$$\text{I.}\quad A_{(\mathrm{VI–IX})} = 6.75\ \mathrm{PDD}_{(\mathrm{VI–IX})} - 64.15$$

where: $A_{(\mathrm{VI–IX}^{2})}$ – the seasonal ablation (mm w.e.),
$\mathrm{PDD}_{(\mathrm{VI–IX})}$ – the seasonal sums of temperatures above 0°C.

This equation explains 72% of cases. Shown relationships are statistically significant. Chosen regression statistics show Table 3.

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[2] VI–IX – from June to September.

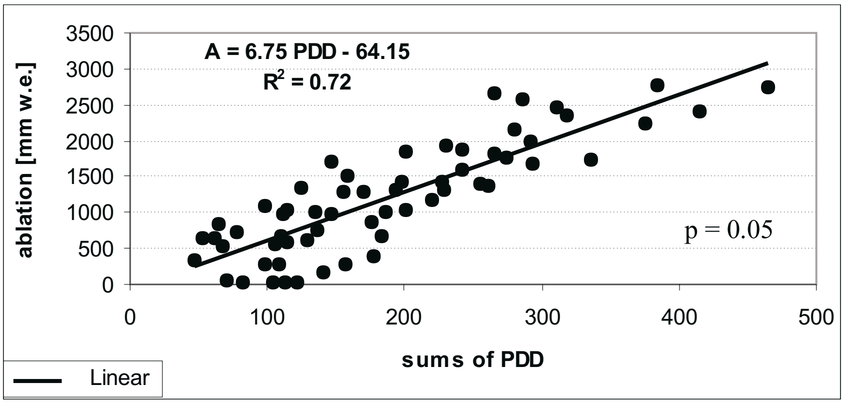

Fig. 5. Relation between the seasonal surface ablation of Hansbreen and seasonal sums of PDD, 1989–1995 (data of IGF PAN and D. Mochnacki, *unpubl.*) – the first variant.

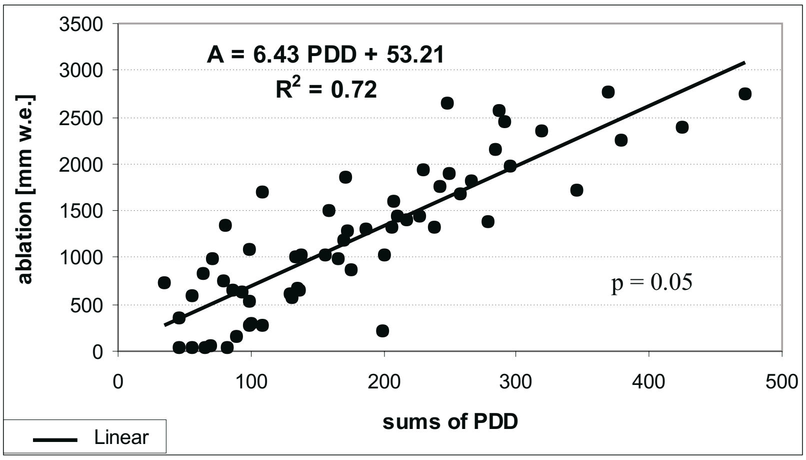

Fig. 6. Relation between the seasonal surface ablation of Hansbreen and seasonal sums of PDD, 1989–1995 (data of IGF PAN and D. Mochnacki, *unpubl.*) – the second variant.

$$\text{II.}\quad A_{(VI–IX)} = 6.43\ PDD_{(VI–IX)} + 53.21$$

$$R^2 = 0.72$$

The **B** Models Group. These consider the relationship of ablation to the PDD and the sunshine duration sums. The surface ablation was calculated on the basis of multiple regression equations.

$$\text{I.}\quad A_{(VI–IX)} = 6.61\ PDD_{(VI–IX)} – 0.03\ U_{(VI–IX)} + 54.29$$

where: $U_{(VI–IX)}$ – the seasonal sums of sunshine duration.

This equation explains 75% of cases. Only sums of PDD are statistically significant at a level of $p = 0.05$ and are necessary for ablation estimation.

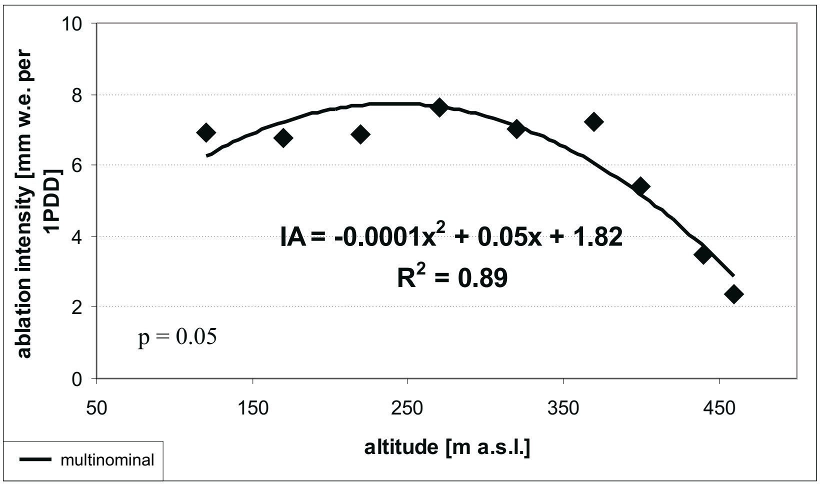

Fig. 7. Relation between the ablation intensity (IA) of Hansbreen and altitude above sea level, 1989–1995 (data of IGF PAN and D. Mochnacki, *unpubl.*) – the first variant.

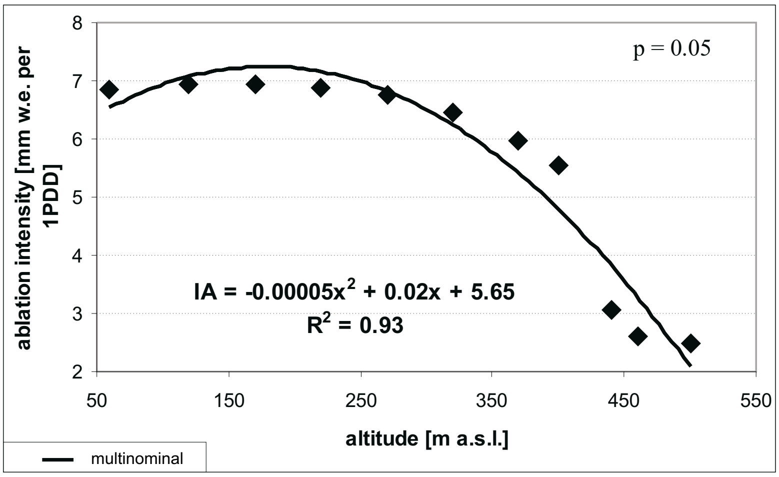

Fig. 8. Relation between the ablation intensity (IA) of Hansbreen and altitude above sea level, 1989–1995 (data of IGF PAN and D. Mochnacki, *unpubl.*) – the second variant.

$$\text{II.}\quad A_{(VI–IX)} = 6.28\ PDD_{(VI–IX)} + 0.93\ U_{(VI–IX)} - 322.86$$

This equation explains 79% of cases. Both components are statistically significant at a level of $p = 0.05$ and are needed to estimate the ablation.

The **C** Models Group. These consider the relationship between the ablation intensity and the altitude above sea level. Ablation intensity is defined as the amount of meltwater (mm) per 1 PDD. It was calculated on the basis of the multinomial regression equations of the 2nd degree (Fig. 7 and Fig. 8).

$$\text{I.}\quad IA = -0.0001\, x^2 + 0.05\, x + 1.82$$

where: IA – the surface ablation intensity (mm w.e. per 1 PDD),
x – the altitude (m a.s.l.).

This equation explains 89% of cases. At a level of $p = 0.05$ the relationships are statistically significant in both variants.

$$\text{II.}\quad IA = -0.00005\, x^2 + 0.02\, x + 5.65$$

$$R^2 = 0.93$$

Testing of the models

The seasonal sums of PDD are available in all of the above models; also, in the case of the B models, the sums of sunshine duration. Thus, the seasonal quantity of surface ablation in mm w.e. for each altitude zone is perceived.

The calculated summer balance (in m w.e.) taken from the period of 1989–2001 was compared with real balance taken from this period (except in respect of 1996 and 1997 because there were insufficient reliable measurements for these years). The error range is shown for each formula (Fig. 9).

The test proves that applied formulae can be used for the years of average thermal and radiation conditions (1989, 1992, 1999). Moreover, they can also find applications in respect of years of relatively high both sunshine duration and temperatures (*e.g.* 1998–2001). They seem to be less useful for the cool years, *e.g.* 1994, 1995 and 1993 – even with higher sunshine duration. It also applies to very warm ablation season (especially with warmer second part of it) but with lower sunshine duration (1990).

Summary and conclusions

In the models erected, the decisive parameters are the sums of positive temperatures in the summer months. This factor was applied to other analyses of other glaciers. In respect of Werenskioldbreen, Baranowski and Głowicki (1975) applied a model which sought to establish the linear relationship of the pentade ablation sums with the pentade PDD sums. Braithwaite and Olesen (1989) considered that there is positive relationship between the annual ablation and the sums of PDD in respect of the glaciers of the Western Greenland.

In this paper, the A, B and C models are all associated with the ablation season (June–September) in which the ablation is most intense. On the basis of the PDD sums for each altitude zone of Hansbreen, they allow us to estimate directly the seasonal ablation. The usefulness of applying PDD sums in studies of the net balance of a glacier was suggested by the work of Lefauconnier and Hagen (1990) in their studies of Brøggerbreen. The positive temperatures of the summer months were also considered to be a decisive factor in this case ($R = -0.89$).

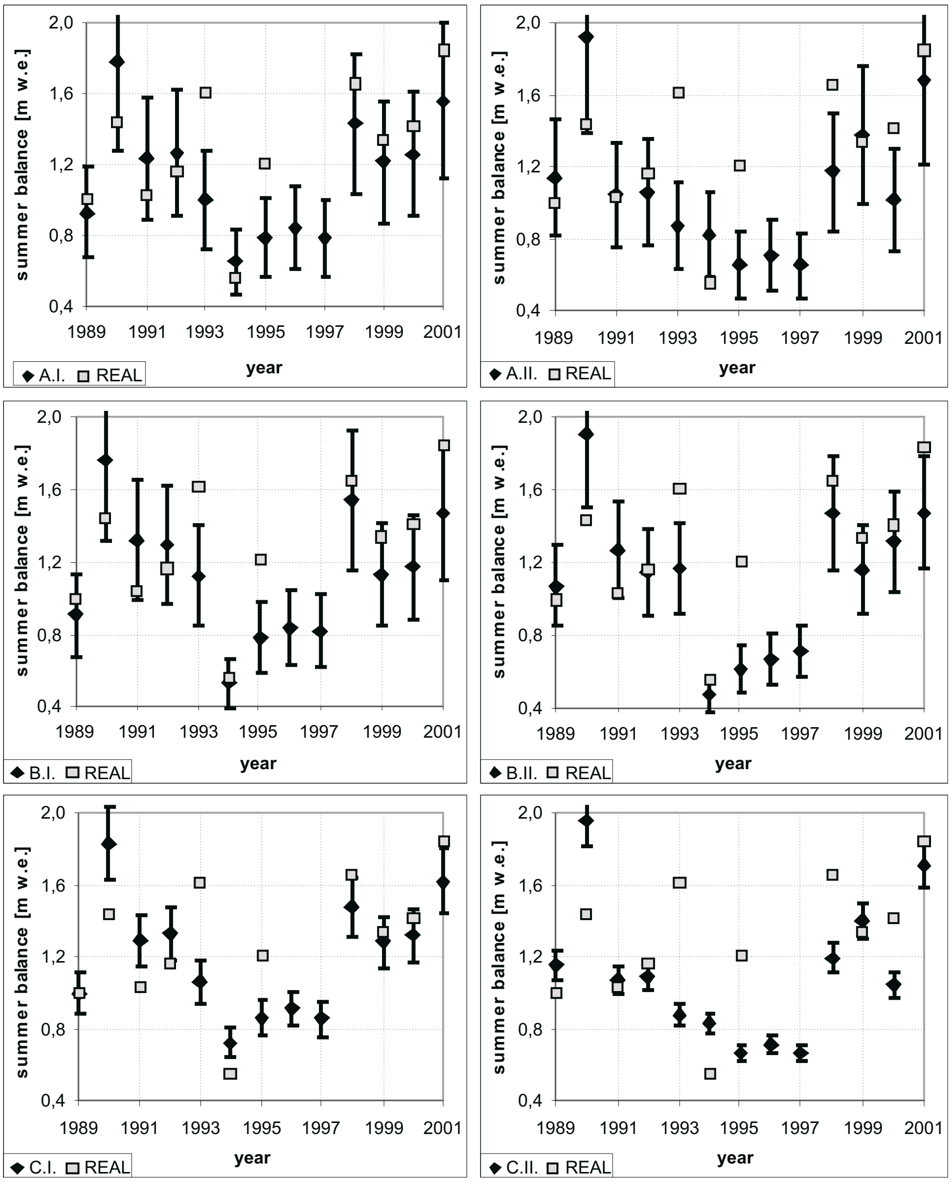

Fig. 9. Comparison of the calculated summer balance of Hansbreen with the real balance for the years 1989–2001 (data of IGF PAN and D. Mochnacki, *unpubl.*). Limits of the error for each formula were respected.

The importance of the sunshine duration factor on general ablation models is not readily apparent, a conclusion also noted by Braithwaite (1995). Its role and that of direct solar radiation, can be very significant in the establishment of thermal gradient along the glacier. This is depicted in Fig. 4. Ablation changes relative to altitude depend on radiation conditions. Hock (1999) suggested that the direct solar radiation factor needs to be applied both in case of observing a diurnal cycle of ablation and its spatial diversity, especially in alpine areas.

The models, as described here, allow us to estimate the surface ablation within error limits of 7–28%. The obtained mean value of the Hansbreen ablation is lowered from 3% (C.I.) to 10% (A.II.) in models with relation to real worth. The best results were obtained when a drop in the ablation intensity due to altitude according to multinomial function (C Models) is taken into account.

These formulae may have a practical application in the calculation of the amount of meltwater which flows into Hansbreen (on average 73.42 × 10^6 m^3 w.e. during the period of 1989–2001 – Table 2). On this basis, the water pressure in the glacier may be estimated and an outline of the nature of any subglacial drainage system present might be discerned (Pälli *et al.*, in preparation). Direct measurements of an outflow are not possible because the glacier empties into Hornsund Fjord. Until now the outflow from Hansbreen was indirectly estimated on the basis of flow measurements of the Glacial River which drains the basin of the wholly terrestrial Werenskioldbreen. The use of these formulae allows us to abbreviate field observations programmes.

An applying of this method allows to take note of other aspect. The reference stakes have been placed for nival research and their location was recognised to be representative for the Hansbreen accumulation measurements (Leszkiewicz and Pulina 1996) but not for ablation. Even in years of similar thermal – radiation conditions the measured values of ablation differ significantly. It is possible that the local factor, namely the topography of Hansbreen surface, may have an important influence on that. Analysis of the topographic map (Jania *et al.* 1994) allows to suppose that some stakes are located in surface depressions where there are also many moulins. It causes a concentration of supraglacial water run-off, especially at times of heavy rain and foehn winds. In upper part of the glacier there also takes place the superimposed ice formation. Unevenness of the glacier surface influences on the ablation spatial diversity and it is reflected in course of the Hansbreen equilibrium line which is asymmetrical (see Fig. 1). Moreover, a shading of surrounding mountain ranges and nunataks can effect on the measurements but on the other hand the meridional course of Hansbreen seems to be a certain convenience.

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