POLISH POLAR RESEARCH
vol. 27, no. 3, pp. 243–258, 2006

A meteorological study of the ablation process on Hans Glacier, SW Spitsbergen

Krzysztof MIGAŁA[1], Bogumiła A. PIWOWAR[2] and Dariusz PUCZKO[3]

[1] *Instytut Geografii i Rozwoju Regionalnego, Uniwersytet Wrocławski, Kosiby 6/8, 51-670 Wrocław, Poland*
<migalak@meteo.uni.wroc.pl>

[2] *Wydział Nauk o Ziemi, Uniwersytet Śląski, Będzińska 60, 41-200 Sosnowiec, Poland*
<bpiwowar@wnoz.us.edu.pl>

[3] *Instytut Geofizyki, Polska Akademia Nauk, Księcia Janusza 64, 01-452 Warszawa, Poland*
<dp@igf.edu.pl>

Abstract: The ablation of glaciers is an important factor in energy exchange between the atmosphere and land ice masses. The dynamics of ablation closely reflects climate changes and is important for the estimation of the outflow of meltwater, which, having penetrated a glacier to bedrock, stimulates its velocity by increasing basal sliding. More detailed studies using automatic weather stations (AWS) and the calculation of the energy budget are rarely conducted on small glaciers. The mass balance of the Hans Glacier has been monitored since 1989. Its intensified monitoring using AWS began in 2003. The results show that ablation depends more evidently on the daily mean and maximum air temperature and wind speed than on total and net radiation. Ablation, both that controlled by sonic height ranger and that measured manually on stakes, was compared with the values calculated on the basis of energy flux formulas applied by Oerlemans (2000). The statistical results allowed us to construct empirical equations, which in turn enabled us to compute the course and total ablation during the summer seasons. It can be described on the basis of two primary meteorological elements (air temperature and wind speed), as recorded in the station representing the regional area (Hornsund) or measured *in situ* on the glacier. Standard measurements of ablation from the years 1989–2004 were used to verify empirical model. The computed mean value of summer ablation for 1989–2004 was calculated at 1.35 m, differing from real measurements by only 10% (with $SD = 0.18$). The results obtained illustrate that an empirical equation can be applied in time series analyses. A regional ablation model enables us to investigate the mass-balance history of glaciers on the basis of meteorological data.

Key words: Arctic, Spitsbergen, Hans Glacier, energy budget of ablation.

Introduction

Ablation and accumulation occur with variable intensity during the whole balance year and also in multi-annual periods. The relation between ablation and climatic factors depends on the meteorological conditions above the glacier and the physical conditions of the ice (Röthlisberger and Lang 1987; Oerlemans 1988; Braithwaite and Olesen 1989; Laumann and Reeh 1993; Braithwaite 1995; Johannesson *et al*. 1995; Hock 1998, 1999). The importance of these processes is different in relation to different glaciers. Baranowski (1977) showed that in South Spitsbergen the ablation process is mainly determined by positive air temperatures, whereas the processes of condensation and evaporation are least important. The transport of heat by turbulence exchange depends on the wind speed. The influence of individual meteorological parameters on ablation is variable and depends not only on weather conditions in a given season, but also on the topoclimatic changes of a given area. A proper evaluation of ablation is the basis for estimating the amount of meltwater which reaches the glacier's substratum, affecting the speed of basal slip and influencing the release of the active phase of a glacier surge. These processes are favoured by the thermal structure of a glacier, which enables meltwater to penetrate glacier shafts in the ablation zone (Jania *et al*. 1996; Jania 1997).

The main aim of this research was to determine daily and seasonal ablation using certain empirical formulas. Secondly, to verify the usefulness of individual meteorological parameters obtained from two meteorological stations (one located in a tundra area in Hornsund, and one AWS located on the glacier) for ablation estimating. Other tasks included the evaluation and comparison of the ablation data so-obtained with that derived from direct measurements.

Study area

Research was carried out on the Hans Glacier and near the Polish Polar Station (PPS) of the Polish Academy of Sciences, located in South Spitsbergen, on Wedel Jarlsberg Land (Fig. 1). Hans Glacier (Hansbreen) is a typical valley glacier, which terminates in a 50 m-high cliff in the sea. It is 16 km long and on average 2.5–3 km wide. Its area is *c*. 56 km^2 and its thickness reaches *c*. 400 m (Jania *et al*. 1996; Moore *et al*. 1999). The mean slope angle of the glacier is 1.5°. The lateral parts of the glacier snout terminate on land. Hans Glacier is a polythermal glacier, *i.e*. it has a complex thermal structure. The upper part of the glacier's tongue in the ablation zone contains a layer of cold ice which is 40–100 m thick (*i.e*. ice at a temperature clearly below the pressure melting point). For the glaciers of South Spitsbergen, the thickness of this layer varies over a range of 80–100 m (Jania *et al*. 1996).

Methods

Meteorological measurements on the glacier, together with the ablation dynamics were carried out during two seasons; from 19 July to 15 October 2003 and

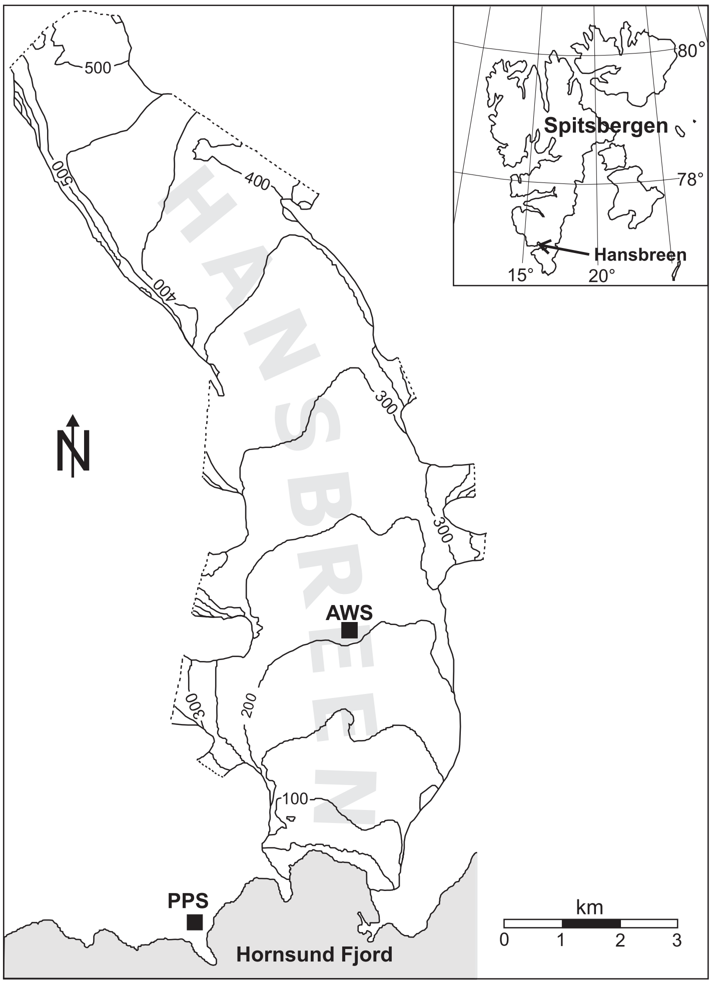

Fig. 1. Location of the Polish Polar Station (PPS) of the Polish Academy of Sciences in Hornsund and the automatic weather station (AWS) on Hans Glacier (Hansbreen).

from 8 May to 28 September 2004. An AWS with Campbell CR7 (Fig. 2a) was placed at the height of 201 m a.s.l. to record hourly values of surface ablation, air temperature and humidity, wind speed and direction, total short-wave radiation, and the balance of net radiation including long-wave radiation. The comparison data comes from the coastal meteorological synoptic station of the PPS, at Hornsund (international code 01003).

In this paper, the terms "surface ablation" and "real ablation" are used. Surface ablation shows a change of the thickness of snow/ice layer and it is measured by a sonic height ranger with sensor type Campbell SR50 (Fig. 2b). Real ablation shows the water equivalent (w.e.) of the melted layer of snow/ice (height of water column). This value represents surface ablation rectified by a value of snow/ice density.

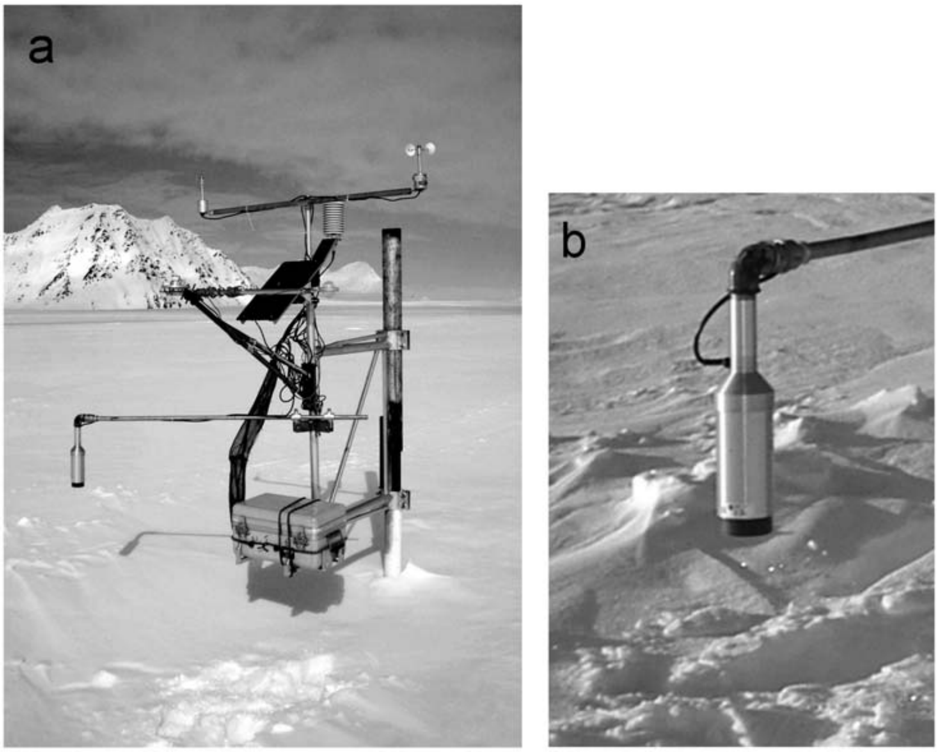

Fig. 2. The automatic weather station (AWS) with Campbell CR7 on Hans Glacier (a) and sonic height ranger with a sensor type Campbell SR50 (b).

Real ablation was calculated using two methods. The first was a correction of daily values of surface ablation by snow and ice thickness. It was assumed that melting snow cover has a density of 500 kg m^{-3}, representing a "mature" state of a temperature of 0°C and has a supplied deficit of liquid water (Eagleson 1978). For melting glacier ice, a mean density of 900 kg m^{-3} was assumed.

In the second method a formula of energy balance (F) was applied:

$$F = Q_{net} + H_{se} + H_{la}$$

where,

Q_{net} – net radiation,
H_{se} – turbulent sensible heat flux,
H_{la} – turbulent latent heat flux.

The values H_{se} and H_{la} were approximated using thermodynamic formulas and meteorological values recorded on the glacier. This made it possible to estimate the contribution of the constituents of energy balance and the final calculation of the water equivalent of ablation using a mass balance formula (M) (Oerlemans 2000):

$$M = - F L_m^{-1} + H_{la} L_v^{-1}$$

where,
F – energy balance,
H_{la} – turbulent latent heat flux,
L_m, L_v – potential heat of melting and evaporation/condensation process.

Results

Relationship between surface ablation and meteorological conditions. — Table 1 shows general characteristics of meteorological conditions in both ablation seasons. In the first season 2003, the mean daily ablation rate was 2.0 cm per day. The largest ablation rate, from 5.2 to 6.7 cm per day, was recorded from 28 to 31 July. This was a period when the area of SW Spitsbergen was influenced by the advection of warm air masses with intensive precipitation (from 3.7 to 8.2 mm) and strong wind. Maximum ablation (6.7 cm per day) was observed on 28 July,

Table 1

Weather conditions on Hans Glacier (AWS) and Polish Polar Station (PPS) in both ablation seasons

Location	AWS, 200 m a.s.l.							PPS, 10 m a.s.l.			
Parameter	Ab [cm/d]	U [%]	T [°C]	T_{max} [°C]	W [m/s]	It [W/m²]	Q_{net} [W/m²]	T [°C]	T_{max} [°C]	SS [Σ h]	R [Σ mm]
Meteorological data from the period 20th July to 10th September 2003 (days 201–253)											
Total	106.7									219.1	113.5
Mean	2.0	89.8	1.9	3.3	2.3	118.9	47.0	4.5	6.6	4.1	
Maximum	6.7	98.4	4.7	6.7	5.7	298.5	84.7	6.3	11.0	19.4	14.2
Minimum	0.0	74.3	–2.0	–0.2	1.1	15.5	2.4	1.1	3.3	0.0	
Meteorological data from the period 13th June to 6th September 2004 (days 165–250)											
Total	278.8									339.1	247.8
Mean	3.2	90.4	2.5	4.5	2.7	147.2	50.5	3.7	6.0	3.9	
Maximum	14.6	99.0	6.6	12.2	7.5	346.7	124.7	7.4	12.1	16.4	32.4
Minimum	0.0	72.1	–1.3	–0.1	0.4	9.5	–13.2	0.9	1.9	0.0	

Ab – daily mean of surface ablation
U – daily mean of relative humidity
T – daily mean of air temperature
T_{max} – daily maximum of air temperature
W – daily mean of wind speed
It – daily mean intensity of total radiation
Q_{net} – daily mean of net balance radiation
SS – daily sum of sunshine duration
R – daily sum of precipitation

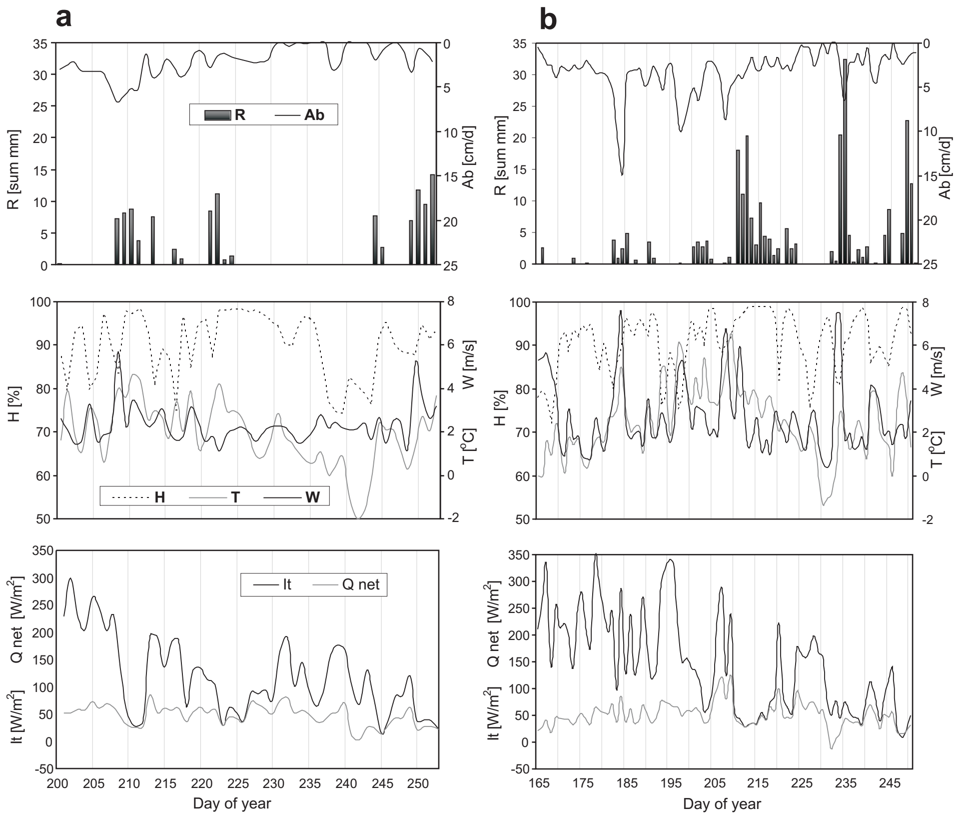

Fig. 3. Daily ablation and meteorological elements on Hans Glacier for two periods: (a) 20 July to 10 September 2003 (days 201–253) and (b) 13 June to 6 September 2004 (days 165–250). Abbreviations: Ab – ablation, R – precipitation, H – humidity at 2 m height above surface, T – air temperature at 2 m, W – wind speed at 2.5 m, It – total radiation and Q_{net} – net balance radiation at 1.5 m.

when the daily precipitation total was 7.2 mm. It was the warmest and the windiest day in the whole period, with a mean daily air temperature of 4.7°C and mean daily wind speed of 5.7 m/s. It should be emphasised that on 21 July, when the intensity of solar radiation was greatest (298.5 W/m^2) and with the largest duration of insolation recorded in the PPS (19.4 hours), the daily surface ablation was very close to average and amounted to 2.6 cm per day (Fig. 3a).

In 2004, the ablation was recorded over the whole season (13 June to 6 September 2004), the mean value being 3.2 cm per day. The largest rate of ablation (11.4–14.6 cm per day) was recorded on 1 and 2 July, when the strongest wind velocities were recorded. The second peak of daily ablation in this season was 9.9 cm, on the warmest day (15 July), when the mean daily air temperature at PPS was 7.4°C, whereas, on the glacier at AWS, the temperature reached 6.1°C. It was the warmest day in the whole region. On the glacier, the warmest day was 27 July, when owing to a thermal inversion it was colder at PPS by 1.7°C. The ablation rate

Table 2

Statistical relationship between ablation and some meteorological parameters

Parameters	Pearson's correlation coefficient (*R*)	Significance level (*p*)
Daily mean of air temperature (at AWS)	0.58	0.000
Daily maximum air temperature (at AWS)	0.59	0.000
Daily mean of wind speed (at AWS)	0.56	0.000
Daily mean intensity of total radiation (at AWS)	0.29	0.001
Daily mean of net radiation (at AWS)	0.28	0.001
Daily mean of relative humidity (at AWS)	–0.15	0.075
Daily mean of air temperature (at PPS)	0.36	0.000
Daily maximum air temperature (at PPS)	0.42	0.000
Daily sum of sunshine duration (at PPS)	0.09	0.309
Daily sum of precipitation (at PPS)	0.11	0.208

was only modest at that time, reaching a value of 4.4 cm per day. On the day with the greatest intensity of solar radiation (346.7 W/m^2) and the longest sunshine duration (16.4 hours), the daily surface ablation was 3.5 cm *i.e.* close to the mean values, similarly as in the previous season. A clear reaction to energy influx from solar radiation was observed only between 10 and 15 July and then, again on 25 July and 28 August (Fig. 3b).

Statistical analysis showed a significant correlation between ablation and air temperature on AWS (especially maximum daily temperature) and mean daily wind velocity (Table 2). Also, the relationship with the maximum air temperature recorded at the PPS is significant. The influence of radiation balance and precipitation on the average seasonal ablation is less important; however, these values are quite significant in episodes of an extreme nature. The weak correlation between ablation and net radiation displays the considerable role of other contributions to the ablation energy balance, *i.e.* turbulent sensible and latent heat flux. Their influence is indirectly shown by the clear correlation between temperature and air temperature as well as wind velocity, which can be explained by detailed structure of energy balance. In the case of precipitation as a result of advection melting, the amount of heat proportional to the mass of rain precipitation and supplied to snow should be taken into account.

Real ablation and energy balance. — Using measurements carried out in 2004 for the whole ablation period, daily values of measured ablation and ablation estimated from the surface energy balance were compared, according to the method proposed by Oerlemens (2000). The results are shown in Fig. 4. It should be emphasised that the cumulative (seasonal) value of real ablation, corrected by

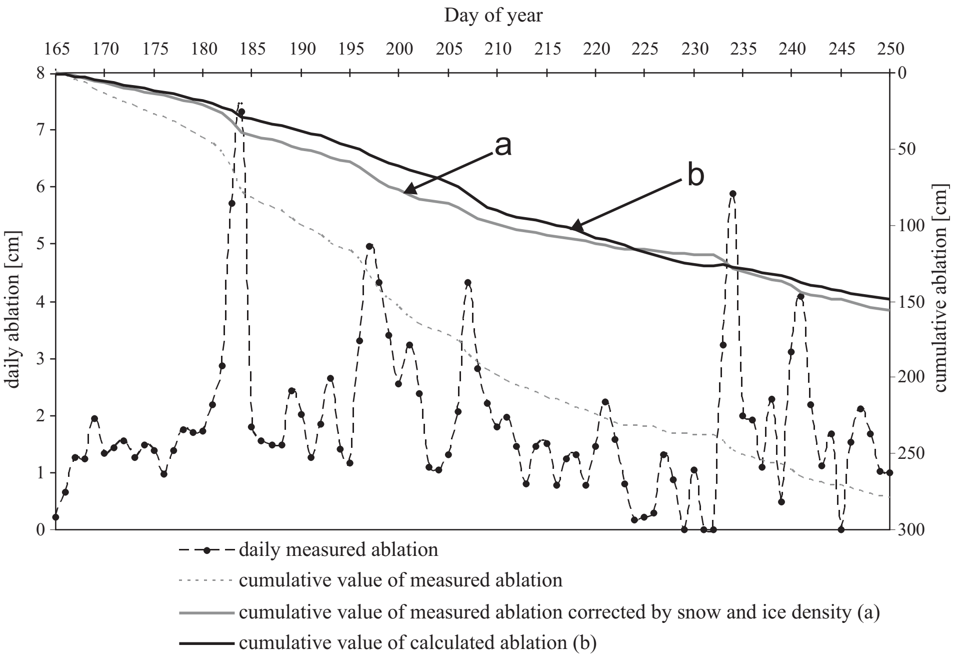

Fig. 4. Surface ablation, calculated and measured on Hans Glacier for the period 13 June to 6 September 2004 (days 165–250).

snow and ice density (a), is similar to the value calculated from energy balance data (b) by choosing an optimal value of the turbulent exchange coefficient.

The water equivalent of ablation for the whole season using both methods was 1.56 m w.e. and 1.49 m w.e. respectively. The results obtained are very similar to a value obtained using traditional means (direct measurement of ablation stick), according to which the ablation value was 1.49 m w.e.

The accuracy of the applied methods makes it possible to evaluate daily mass loss and the increase of meltwater penetrating the glacial shafts in the ablation zone. In 2004, the melting of glacier mass occurred at an average rate of 1.8 cm w.e. per day. However, changing weather conditions caused five major episodes with daily ablation from 4.1 to 7.3 cm per day resulting in a water discharge of 40–70 l from each square meter of the surface of the ablation zone during 24 hours. In the energy balance of ablation, the heat resulting from the radiation balance of the surface contributed on average 76% (from 100% to losses in over 90%). The turbulent sensible heat flux represented on average 18.2% of energy (from income in 67% to losses in about 60%). The contribution of the latent heat flux was only 5.7% fluctuating from 26% of income to 58% of losses (Table 3, Fig. 5).

The relationship between air temperature and ablation. — A correct evaluation of the ablation rate is often problematic because of the paucity of meteorological measurements on a glacier. Therefore, an evaluation in five-day periods is

Table 3

The energy balance of ablation (F) in the year 2004

		F	Q_{net}	H_{se}	H_{la}
Energy flux	Mean [Wm^{-2}]	66.5	50.5	12.1	3.8
	Maximum [Wm^{-2}]	178.4	124.7	59.7	29.1
	Minimum [Wm^{-2}]	–14.2	–13.2	–1.2	–16.4
Percentage	Mean [%]		76.1	18.2	5.7
	Maximum share [%]		100.0	67.0	26.0
	Maximum waste [%]		–93.0	–60.0	–58.0

$F = Q_{net} + H_{se} + H_{la}$
where,
Q_{net} – net balance radiation,
H_{se} – sensible heat flux,
H_{la} – turbulent latent heat flux.

usually used and also a method based on the model, which includes totals of positive daily air temperatures (Krenke and Khodakov 1966; Braithwaite 1995).

The relationship between ablation and meteorological parameters in five-day periods was studied. For the whole series of data (two seasons), it was found that the relation between ablation and five-day period totals of air temperature revealed a more significant relation than in the case of daily values, especially in the case of maximum temperatures (Table 2). This enabled to construct an empirical formula (equation 1), which requires only information about air temperature from the AWS and makes it possible to estimate five-day period values of surface ablation on glacier (Fig. 6).

$$(1)\ Ab_5 = 0.764\ \Sigma T_{max5} - 1.296$$

with $R = 0.697$, $F\ (1.25) = 23.625$, $p < 0.00005$; error of standard estimation at 6.5610
where,
Ab_5 – five-day period values of surface ablation,
ΣT_{max5} – five-day periods total of daily maximum air temperatures from the AWS.

The use of cumulative values for the whole ablation season (daily ablation and totals of positive air temperature) gives satisfactory results, even if only data from the PPS are included. This station is located in an area of maritime tundra, where the correlation coefficient (R) between the values of mean daily temperature and maximum temperature on AWS and PPS was 0.80 and 0.74 respectively. As a result, differences between cumulative values of ablation and air temperature totals for the whole season are very high. They were described using a second degree polynomial formulas (equations 2–5) and defined by a correlation coefficient close to 1 (Fig. 7).

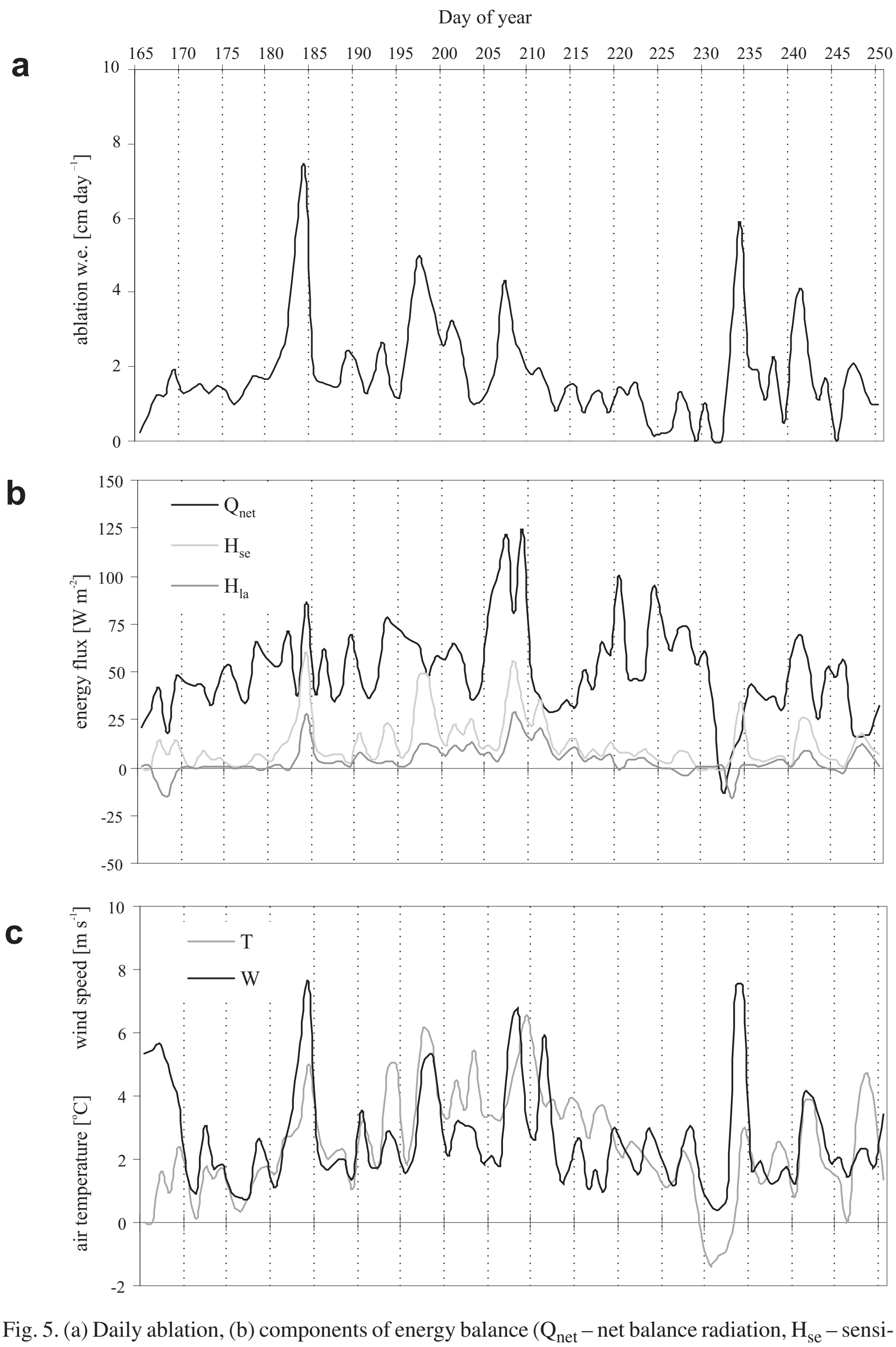

Fig. 5. (a) Daily ablation, (b) components of energy balance (Q_{net} – net balance radiation, H_{se} – sensible heat flux, H_{la} – turbulent latent heat flux) and (c) air temperature (T) and wind speed (W) for the period 13 June to 6 September 2004 (days 165–250).

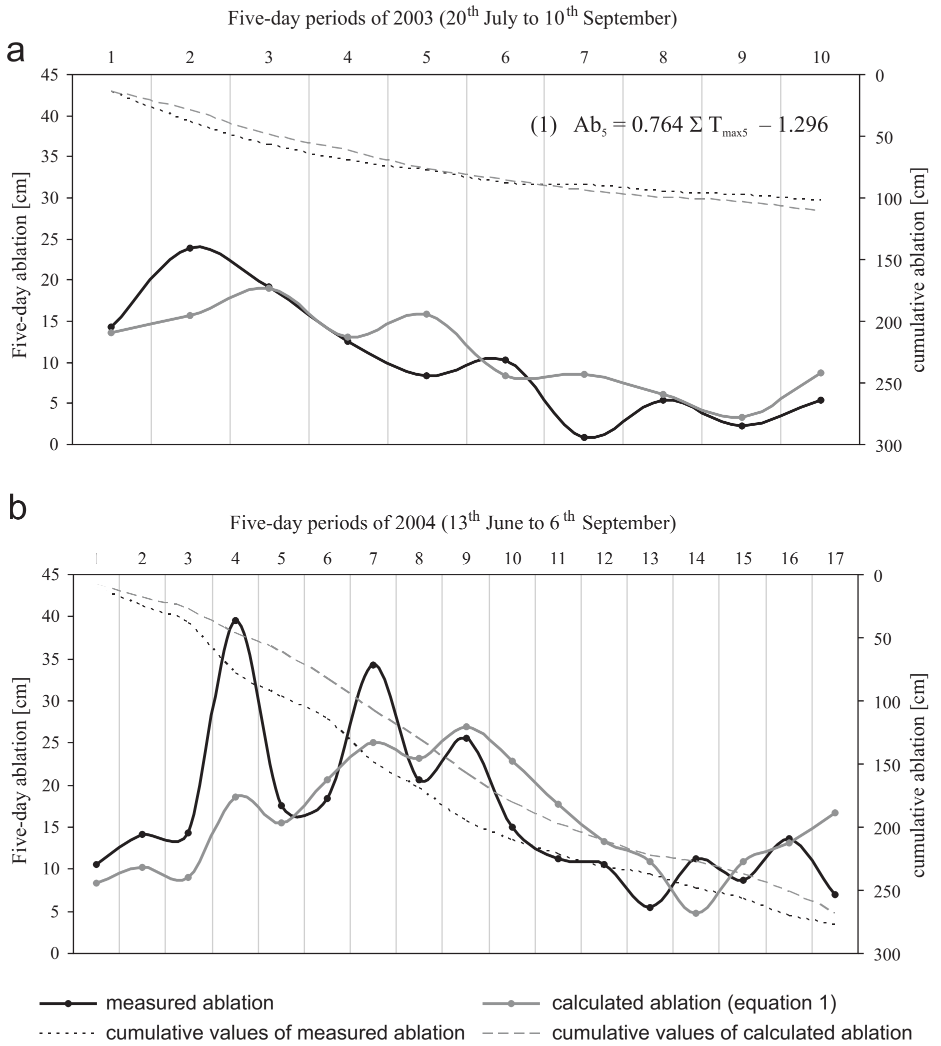

Fig. 6. Five-day and cumulative values of measured and calculated ablation, according to equation 1, in 2003 (a) and 2004 (b).

(2) $Ab_T = -0.0032\ (\Sigma T_p AWS)^2 + 1.911\ \Sigma T_p AWS + 9.1976$, with $R = 0.99$

(3) $Ab_T = -0.0019\ (\Sigma T_p PPS)^2 + 1.477\ \Sigma T_p PPS - 2.5045$, with $R = 0.99$

(4) $Ab_T = -0.001\ (\Sigma T_{max} AWS)^2 + 1.0996\ \Sigma T_{max} AWS - 0.8796$, with $R = 0.99$

(5) $Ab_T = -0.0006\ (\Sigma T_{max} PPS)^2 + 0.8788\ \Sigma T_{max} PPS - 5.7278$, with $R = 0.99$

where,

Ab_T – total ablation of a season [cm],

ΣT_p – sums of positive values of mean daily air temperature on AWS or PPS,

ΣT_{max} – sums of positive values of daily maximum air temperature on AWS or PPS.

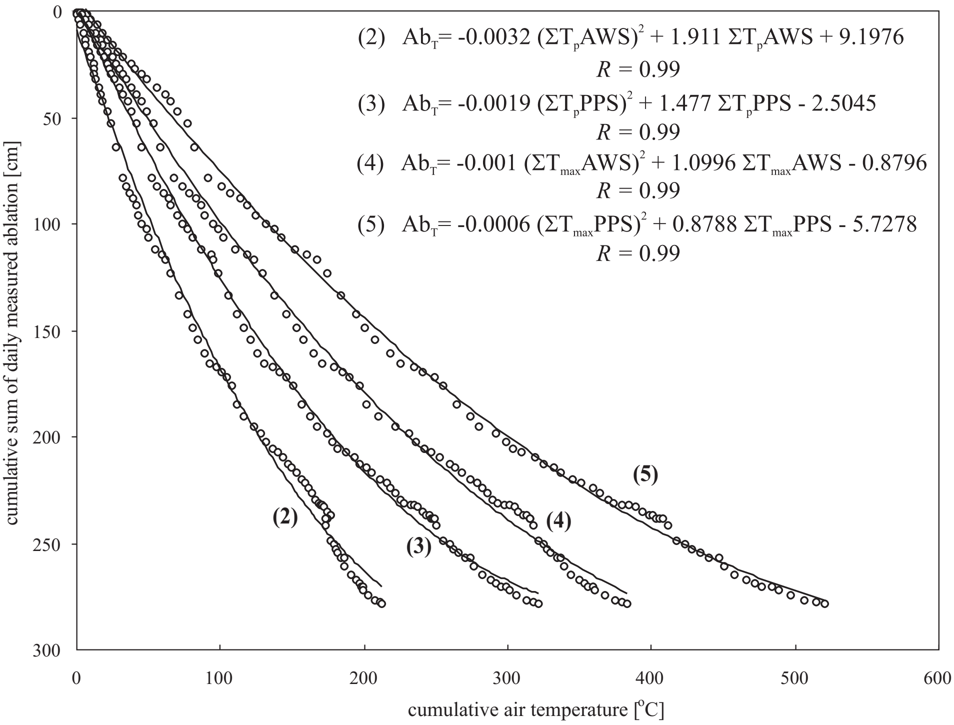

Fig. 7. Cumulative values of daily measured ablation as a function depend on sum of positive values of mean daily air temperature on AWS (2) or PPS (3) and the maximum daily air temperature on AWS (4) or PPS (5).

By taking into account the time of melting of the snow cover and ice and their densities (500 kg m^{-3} and 900 kg m^{-3}) in cumulative values, it was possible finally to verify the relationship between cumulative values of ablation water equivalent and air temperature totals for the whole season and to compare them with traditional measurements from the period 1989–2004 (Figs 8 and 9). In comparison with multi-annual data obtained by traditional means, a formulas was applied which takes into account the cumulative totals of daily values of maximum air temperatures from AWS (equation 6) or PPS (equation 7).

(6) $Ab_{T\,w.e.} = -0.0002\,(\Sigma T_{max}AWS)^2 + 0.4791\,\Sigma T_{max}AWS + 2.1723$, with $R = 0.99$
(7) $Ab_{T\,w.e.} = -0.0002\,(\Sigma T_{max}PPS)^2 + 0.3873\,\Sigma T_{max}PPS - 0.2698$, with $R = 0.99$

where,
$Ab_{T\,w.e.}$ – cumulative values daily ablation expressed in water equivalent.

It should be noted that the time changeability of ablation values measured by traditional means and that calculated from the applied method shows a similar character. The decrease in values for some years (*e.g.* 1991, 1993, 1999) may indicate the influence of precipitation on ablation in these seasons.

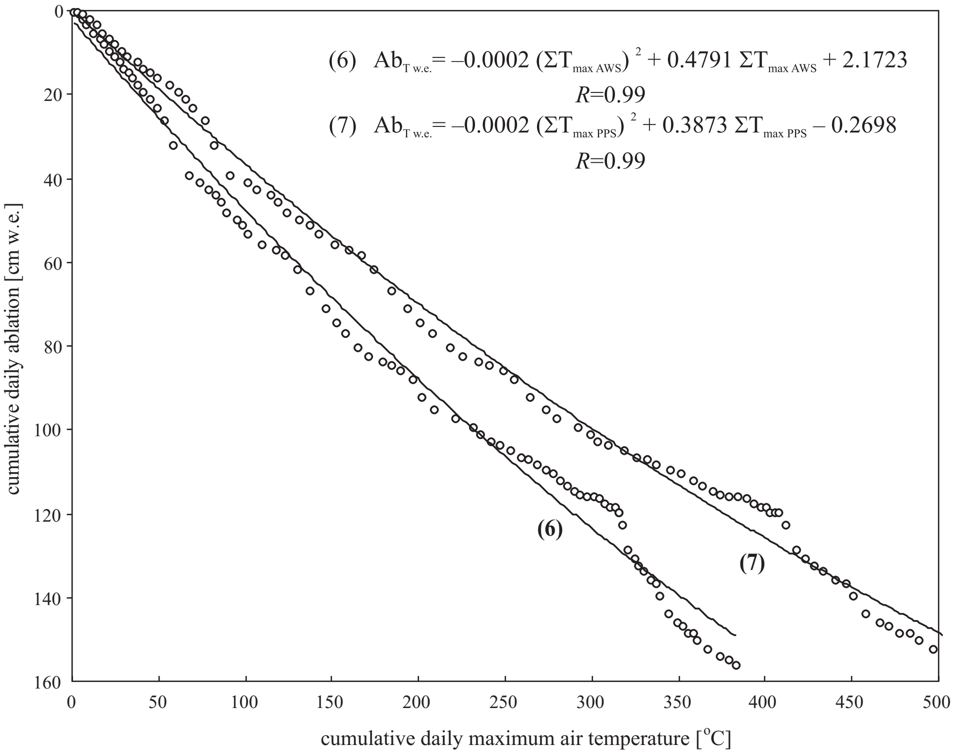

Fig. 8. Cumulative values daily ablation expresses in water equivalent as a function of daily maximum air temperature on AWS (6) and PPS (7).

Summary and conclusions

The investigations carried out in 2003 and 2004 made it possible to (i) evaluate weather conditions/complexes which influence ablation rate; (ii) determine, in detail, daily values of surface ablation, which show the loss of the snow/ice layer thickness and real (effective) ablation, which is shown in water equivalent per surface unit; (iii) estimate the share of constituents of energy balance in the ablation process based on thermodynamic formulas; (iv) construct empirical formulas, which make it possible to determine ablation dynamics based on daily values of air temperature and wind velocities; and (v) evaluate ablation size in the period 1989–2004.

Radiation balance, despite the large contribution of energy income, does not appear to have a direct influence on ablation dynamics. These dynamics depend mainly on anemological conditions, which indicate simultaneously the significant role of the other constituents of ablation energy balance *i.e.* turbulent sensible heat flux, and potential heat of evaporation and condensation. Their contribu-

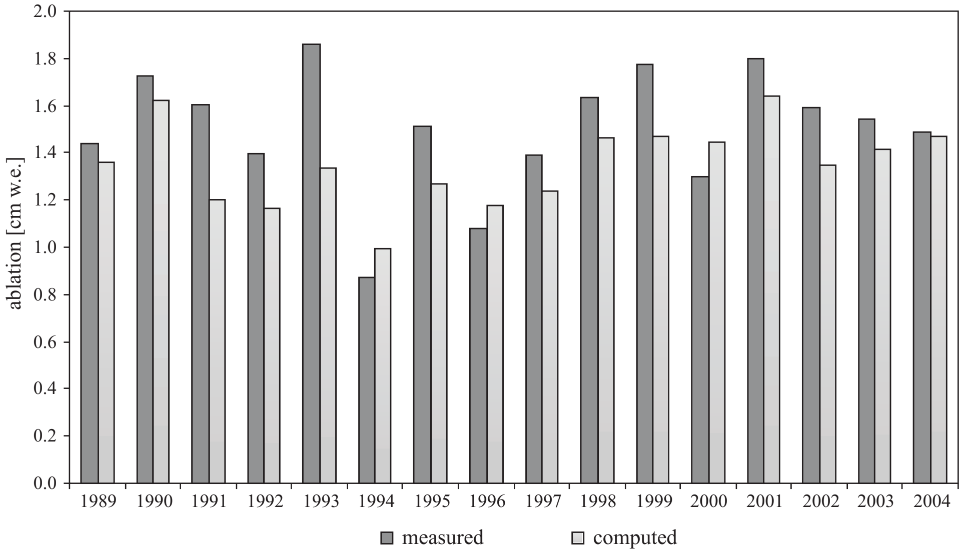

Fig. 9. Computed and measured ablation in the zone of 200–220 m a.s.l. between 1989 and 2004.

tion may be indirectly shown by the clear relation of ablation with air temperature and wind velocity. In the case of precipitation as a result of advection melting, the amount of heat proportional to the mass of rain precipitation and the amount of heat supplied to snow should be also considered. Warm advections with fronts, precipitation and an increase of wind velocity represent episodes of increased ablation with large contribution of perceptible heat that is carried with precipitation mass.

The applied methods of real ablation calculation are assumed to be equally reliable. They are based on surface ablation, corrected by snow and ice density, and according to energy balance. The accuracy of the methods makes it possible to evaluate mass loss and increase of meltwater in the ablation zone. In 2004, the melting of glacier mass took place at an average rate of 1.8 cm w.e. per day, but with occasional weather conditions causing water discharge in the range from 40–70 l from each square meter of the ablation zone surface over a 24 hour-period.

In the energy balance, ablation heat resulting from surface radiation balance represented on average 76%. The turbulent sensible heat flux was 18.2% of energy, whereas the contribution of the latent heat flux was only 5.7%. A significant statistical relationship between ablation and basic values has made it possible to construct formula which describe a daily value of the process or its distribution in five-day periods. This formula ($Ab_5 = 0.764\ \Sigma T_{max5} - 1.296$) require only information about daily maximum air temperature from AWS.

The application of cumulative values of daily ablation and totals of positive air temperature for the whole ablation season revealed a significant correlation between both values even in case of data from PPS. This relationship was described by a second degree polynomial function, which made it possible to compare the calculations with manual measurements of ablation for the period 1989–2004. The calculation for this period mean value of ablation is 1.35 m and it is different by 10% (standard deviation 0.18) from the result obtained from traditional methods, with a character similar to the intra-seasonal changes.

The results obtained illustrate that a regional ablation model can both be used to investigate mass-balance history of glaciers and also may be applied in future studies of climate – glacier interactions.

Acknowledgements. — The authors would like to thank Dr P. Głowacki from the Institute of Geophysics of the Polish Academy of Sciences and colleagues from XXVI and XXVII Polar Expeditions to Polish Polar Station on Spitsbergen for providing data. We are grateful to Professor J. Jania (University of Silesia) for critical remarks as well as Professors J.O. Hagen, J. Oerlemans and P.T. Walsh for their helpful reviews. This work was supported by the Committee on Scientific Research, Poland under the terms of research grant No. 6-PO4E-014-21.

References

BARANOWSKI S. 1977. Subpolarne lodowce Spitsbergenu na tle klimatu tego regionu. *Acta Universitatis Wratislaviensis* 393: 157 pp (in Polish).

BRAITHWAITE R.J. 1995. Positive degree-day factors for ablation on the Greenland ice sheet studied by energy-balance modeling. *Journal of Glaciology* 41 (137): 153–160.

BRAITHWAITE R.J. and OLESEN O.B. 1989. Calculation of glacier ablation from air temperature, West Greenland. *In*: J. Oerlemans (ed.) *Glacier Fluctuations and Climatic Change*. Kluwer Academic Publishers, Dordrecht: 219–233.

EAGLESON P.S. 1978. *Hydrologia dynamiczna*. PWN, Warszawa: 501 pp. (in Polish).

HOCK R. 1998. Modeling of glacier melt and discharge. *Züricher Geographische Schriften* 70: 1–126.

HOCK R. 1999. A distributed temperature-index ice- and snowmelt model including potential direct solar radiation. *Journal of Glaciology* 45 (149): 101–111.

JANIA J. 1997. *Glacjologia.* PWN, Warszawa: 360 pp. (in Polish).

JANIA J., MOCHNACKI D. and GĄDEK B. 1996. The thermal structure of Hansbreen, a tidewater glacier in southern Spitsbergen, Svalbard. *Polar Research* 15 (1): 53–66.

JOHANNESSON T., SIGURDSSON O., LAUMANN T. and KENNETT M. 1995. Degree-day glacier mass-balance modeling with applications to glaciers in Iceland, Norway and Greenland. *Journal of Glaciology* 41 (138): 345–358.

KRENKE A.N. and KHODAKOV V.G. 1966. O svyasi povercknostnogo tayaniya lednikov s temperaturoy vozdukha (On the relationship between melt of glaciers and air temperature). *Materialy Glyatsiologicheskikh Issledovaniy* 12: 153–163 (in Russian).

LAUMANN T. and REEH N. 1993. Sensitivity to climate change of the mass balance of glaciers in Southern Norway. *Journal of Glaciology* 39 (133): 656–665.

MOORE J.C., PÄLLI A., LUDWIG F., BLATTER H., JANIA J., GĄDEK B., GŁOWACKI P., MOCHNACKI D. and ISAKSSON E. 1999. High-resolution hydrothermal structure of Hansbreen, Spitsbergen, mapped by ground-penetrating radar. *Journal of Glaciology* 45 (151): 524–532.

OERLEMANS J. 1988. Simulation of historic glacier variations with a simple climate-glacier model. *Journal of Glaciology* 34 (118): 333–341.

OERLEMANS J. 2000. Analysis of a 3 year meteorological record from the ablation zone of Morteratschgletscher, Switzerland: energy and mass balance. *Journal of Glaciology* 46 (155): 571–579.

RÖTHLISBERGER H. and LANG H. 1987. Glacial Hydrology *In*: A.M. Gurnell and M.J. Clark (eds) *Glacio-fluvial sediment transfer. An alpine perspective*. J. Wiley and Sons Ltd., London: 207–284.

Received 3 March 2006
Accepted 31 July 2006