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Changes in the extent and geometry of the Scott Glacier, Spitsbergen

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Abstract: Spitsbergen glaciers react rapidly to changes in the polar environment, which is expressed in differences in extent of their fronts and surface geometry. The Scott Glacier, which is situated in the NW part of Wedel Jarlsberg Land, is an example of the glacier that has undergone almost continuous recession since the Little Ice Age, interrupted by surges. The variations in recession are characterised based on multiannual data with particularly consideration of the period 1990–2005 and the season 2005/2006. Acceleration of front recession and lowering the surface was found only within the tongue up to a height of about 220 m a.s.l. Whereas, in the area situated in the zone of rock steps and above in the ablation zone, the change of glacier surface ablation (Δh) has been recorded compared to the mean annual recession for the period 1990–2005. Moreover, for the upper firn field, the positive surface ablation (ΔhS7 = +0.19 m) was observed. As the result of progressive reduction of the Scott Glacier mass, with the participation of other factors (bedrock relief among others), new surfaces of roche moutonnée are uncovering particularly in the tongue zone.

Key words: Spitsbergen, Scott Glacier, glacier geometry, surface ablation, GIS analysis.

Introduction

Changes in glacier extent and surface geometry reflect their internal dynamics and mass balance (Hagen *et al.* 2005). The rate of glaciers response depends on their size, mass and development of alimentation zones. Moreover, their structures and shapes are affected by reliefs of bedrock beneath the glacier. For many years, observations and measurements of glaciers on Spitsbergen have been conducted using various methods, including ground geodetic and photogrammetric measure-

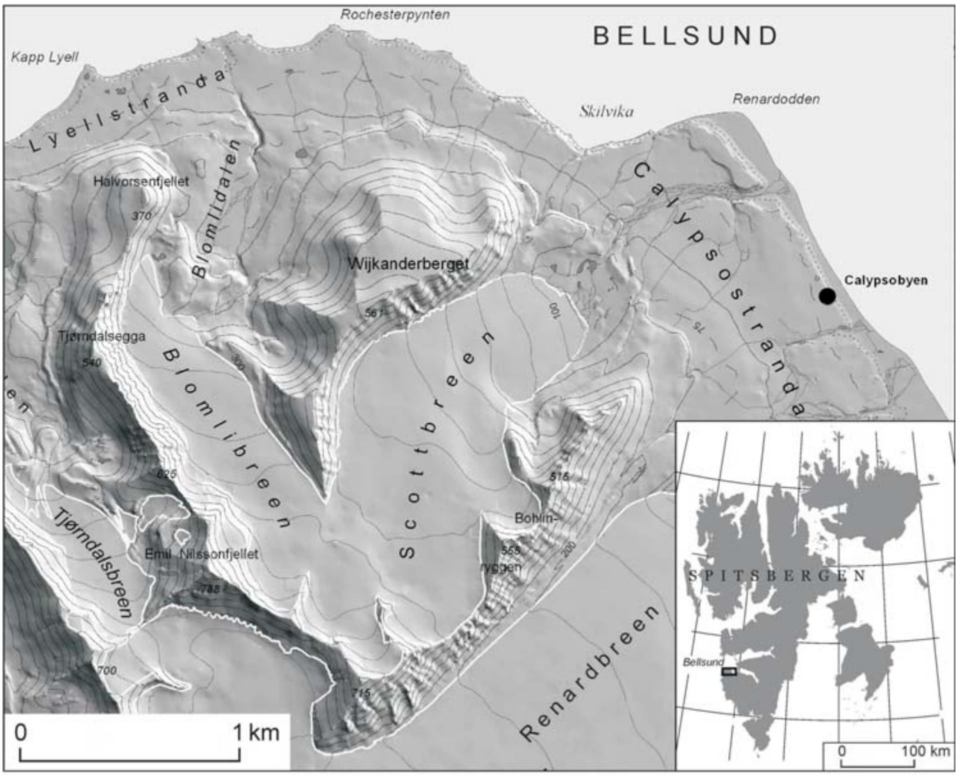

Fig. 1. Location of the study area. The shade map made using the Digital Terrain Model (DTM) obtained from the aerial photograph from 1990 (Zagórski 2002).

ments, analysis of aerial and satellite photos and the latest GPS and laser altimetry measurement techniques (*e.g.* Lipert 1958; Kosiba 1960; Jania *et al.* 1984; Jania 1988; Merta *et al.* 1990; Kolondra and Jania 1998; Ziaja 2001, 2005; Kolondra 2002; Lankauf 2002; Pälli *et al.* 2003; Bartkowiak *et al.* 2004; Řehák *et al.* 2004; Sund and Eiken 2004; Zagórski and Bartoszewski 2004; Bamber *et al.* 2005; Hodgkins *et al.* 2007; Nuth *et al*. 2007; Rachlewicz *et al*. 2007). All these observations confirm the general trend of negative glacier mass balance and progressive recession at different rate (*e.g.* Hagen and Liestøl 1990; Jania and Hagen 1996; Ziaja *et al.* 2007). The monitoring of these changes requires systematic observations. Also in the Bellsund region and at the Polar Station of Maria Curie-Skłodowska University in Calypsobyen, active since 1986, there have been carried out systematic observations of both glacier ablation and the extent of Scott and Renard glaciers (Piasecki 1988; Bartoszewski 1991; Bartoszewski *et al.* 2004; Zagórski and Bartoszewski 2004; Reder and Zagórski 2007a, b) (Fig. 1).

The main aim of this study is the analysis of changes in the Scott Glacier geometry in the season 2005/2006 on the background of multiannual data with particular consideration of period 1990–2005. The term "season 2005/2006" is understood as the time span from 22 August 2005 to 22 August 2006 that covers a full annual cycle of observation. The changes of glacier geometry include the recession of glacier front and change of its surface (covered area, height). The essential part of the present study was the application of the Geographical Information System software (GIS) allowing multidimensional analysis of data and their visualisation. They may provide the starting point for further studies and comparisons.

Method and input data

The extent of Scott Glacier was analysed on the base of archival data and measurements of GPS receivers (Fig. 2):

19th century, so called, Little Ice Age (LIA) – the maximum extent of the Scott Glacier due to a surge took place probably about 1880 (Liestøl 1993). Also in 1927, its front was described as remaining in "hochstadium" or even advancing (Ahlmann 1933). This interpretation was supported by some previous geomorphological studies (Szczęsny *et al.* 1989; Reder 1996) and field observations in summer of 2005 and 2006.

1936 – the Norwegian archival topographical map 1:100 000 scale, scanned and calibrated to the UTM projection using corner points and intersections grid line (B11 Van Keulenfjorden 1952).

1960 – the Photogeological Map made on the base of the Norwegian vertical aerial photos from 1960 (Szczęsny *et al.* 1989; Merta *et al.* 1990), scanned and calibrated to the UTM projection using corner points and intersections grid line.

1987 – The ground photogrammetric measurements made during 2nd Polar Expedition of Maria Curie-Skłodowska University to Spitsbergen (Merta *et al.* 1990). The published cartographic study was only of draft character. Its calibration required additional field observations and GPS measurements performed in 2005 and 2006, as well as study of archive phototographs.

1990 – the orthophotomap (Zagórski 2005), made based on vertical aerial photographs (original resolution 1270 dpi – 20 mm) rendered by the Norwegian Polar Institute and calibrated to the UTM projection using the ground control points measured with GPS – the accuracy of this estimation of glacier front ± 1.5 m.

2000 – the precise measurements with use of the GPS receivers (Leica, Ashtech).

2001, 2002 – the navigation measurements with use of the GPS receiver (Garmin).

2005, 2006 – the precise measurements with use of the GPS receivers (Leica, Ashtech).

The Digital Terrain Model (DTM) and orthophotomap, made on the base of photogrammetric processing of aerial photos from 1990, were the basis for the analysis of multiannual changes of Scott Glacier geometry (Zagórski 2002, 2005).

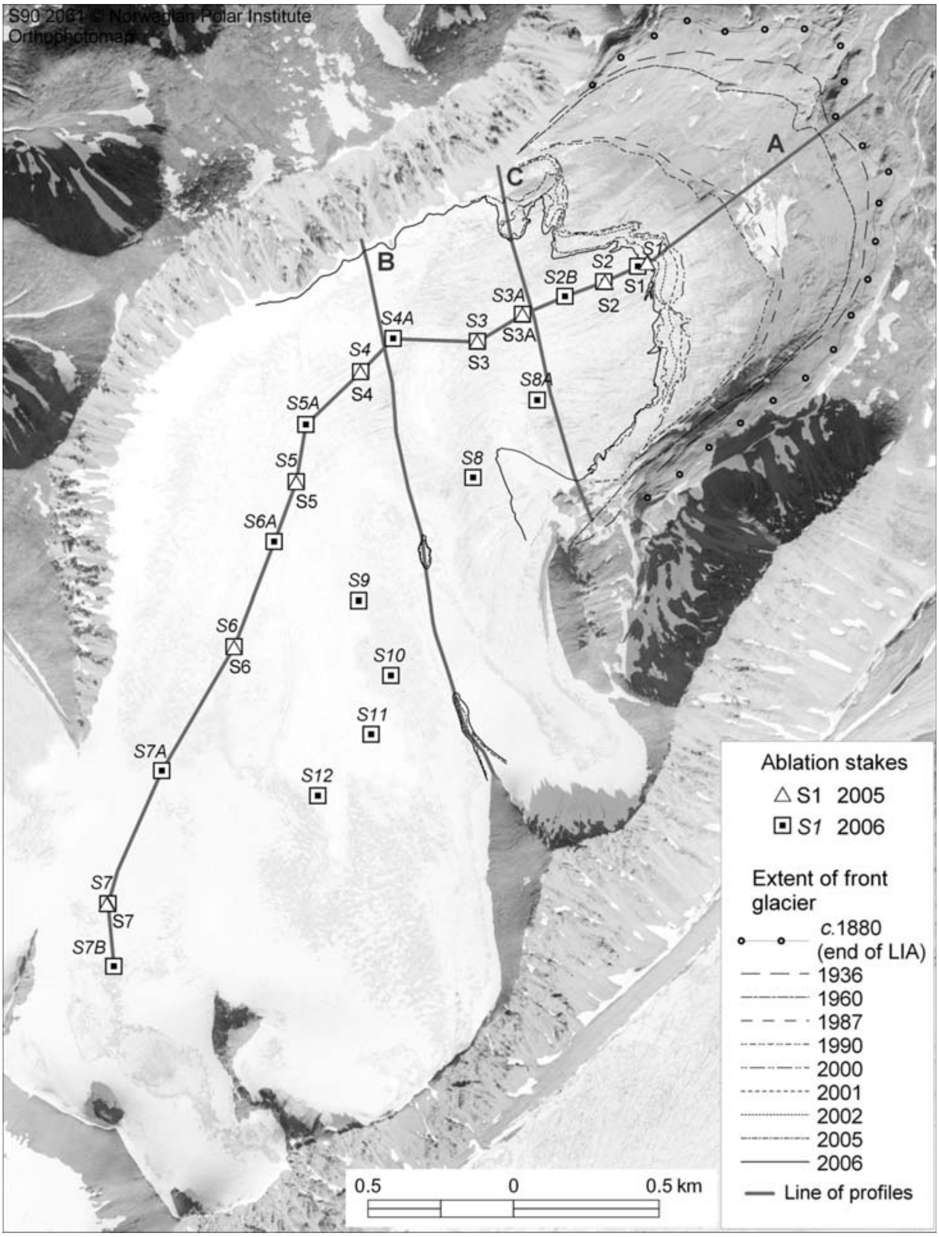

Fig. 2. Changes of Scott Glacier front, location of ablation stakes in the summer of 2005 and 2006 as well as location of line of profiles (orthophotomap, Zagórski 2005).

Direct measurements of the extent of the Scott Glacier front using the GPS receiving began during 16th Polar Expeditions of Maria Curie-Skłodowska University in 2000 (Zagórski and Sękowski 2000). The measurements of this type were repeated in 2001, 2002, 2005 and 2006.

The precise measurements were performed according to the procedures binding in such observations using mainly differential methods (DGPS, postprocessing) – static and “Stop-Go” ones (Lamparski 2001). The observation data were calculated in relation to the reference station point in Calypsobyen (CALY point). Dr Marcin Sękowski from Institute of Geodesy and Cartography (Warsaw, Polish Academy of Science,) determined the point coordinates in 2000. In 2005, the reference station coordinates (CALY point) were corrected to the permanent station IGS on Spitsbergen (ITRF 2000) by Dr Janusz Walo from Warsaw University of Technology. The series of point data were recorded in the cartographical projection UTM, zone 33 on the ellipsoid WGS 84, universal from this region.

One of the problems during marking out the extent of Scott Glacier front was determination of the border between the glacier ice and the moraine material covering some of its parts. Therefore, the area with the visible glacier ice was assumed to be the glacier surface (Rachlewicz *et al.* 2007).

The extent of Scott Glacier fronts in 2000, 2005 and 2006 was determined by differential method (DGPS, precise measurements using the receivers of the Ashtech and Leica SR530 and SR520). The accuracy of this measurements reached 1–2.5 cm. Whereas, in 2001 and 2002 the measurements were made by navigation methods using the GPS Garmin eTrex receiver (Zagórski and Bartoszewski 2004). The precision obtained was about 2–5 m. Therefore, their verification was necessary throughout indirect field observations and measurements of characteristic points and analysis of the available photographic material. All GPS measurements were performed at the end of July or beginning of August to achieve comparable periods of observation: 2000 – 2nd August, 2001 – 30th July, 2002 – 4th August, 2005 – 29th July, 2006 – 1st August.

In the summer of 2005 and 2006, the field work, which aimed to collect the material concerning changes of the extent of the Scott Glacier front and surface geometry, were carried out with the two methods described below. First of them involved the measurement of the extent of Scott Glacier front using the instrumental methods (GPS measurements). The data obtained from the field measurements were compared with the archival data based on the GIS software. There were also some calculations of the average recession (C) performed for the entire length of the Scott Glacier front with the formula:

$$C = \frac{P}{GFa}$$

where: P – is area uncovered in results of recession [m^2];
GFa – is the length of average location of the glacier front [m].

In case of surface (P), successively determined extents of glacier front were compared in the ArcView program, limited to the polygon that was on the uncovered area (Fig. 3). Whereas, the curve GFa, drawn using the ArcView program, is the averaged location of extent of the glacier front, for a given period (*e.g.*

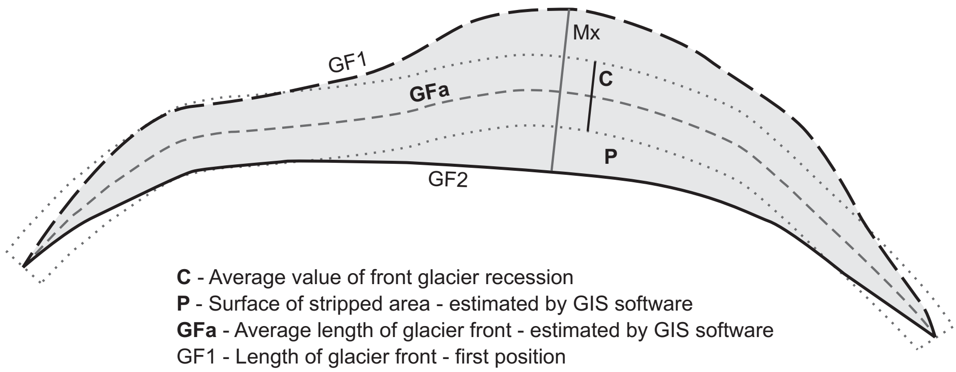

Fig. 3. The methods of determination of average value of glacier front recession (explanation in text).

1990–2005) and divided by the uncovered area into two equal parts. Due to these calculations it was possible to obtain the information about the annual retreat of the glacier front as well as the annual decrease of its area (Tables 1, 2, 4).

Whereas, the second method was related to the registration of glacier surface lowering calculated from longitudinal and transverse profiles with the use of the GPS receiver and based on the data from ablation stakes. In 2005, eight measuring stakes were installed and in 2006 twelve more stakes were added (Fig. 2). This enabled more accurate knowledge about spatial differentiation of surface ablation (Bartoszewski *et al.* 2004). Seven stakes survived the winter of 2005/2006. The point closest to the glacier front (S1) thawed out by the time of ablation season.

Table 1

Change of Scott Glacier area compared with its extent in the end of 19th century (Zagórski and Bartoszewski 2004, corrected and replenished).

Year	Area [km^2]	Decrease of area since the end of 19th century [km^2]	Decrease of area since 19th century [%]
End of 19th (1880)	6.16	–	–
1936	5.98	0.18	2.9
1960	5.83	0.33	5.4
1987	5.37	0.79	12.8
1990	5.32	0.84	13.6
2000	5.04	1.12	18.2
2001	4.99	1.17	19.0
2002	4.95	1.21	19.6
2005	4.82	1.34	21.8
2006	4.75	1.41	22.9

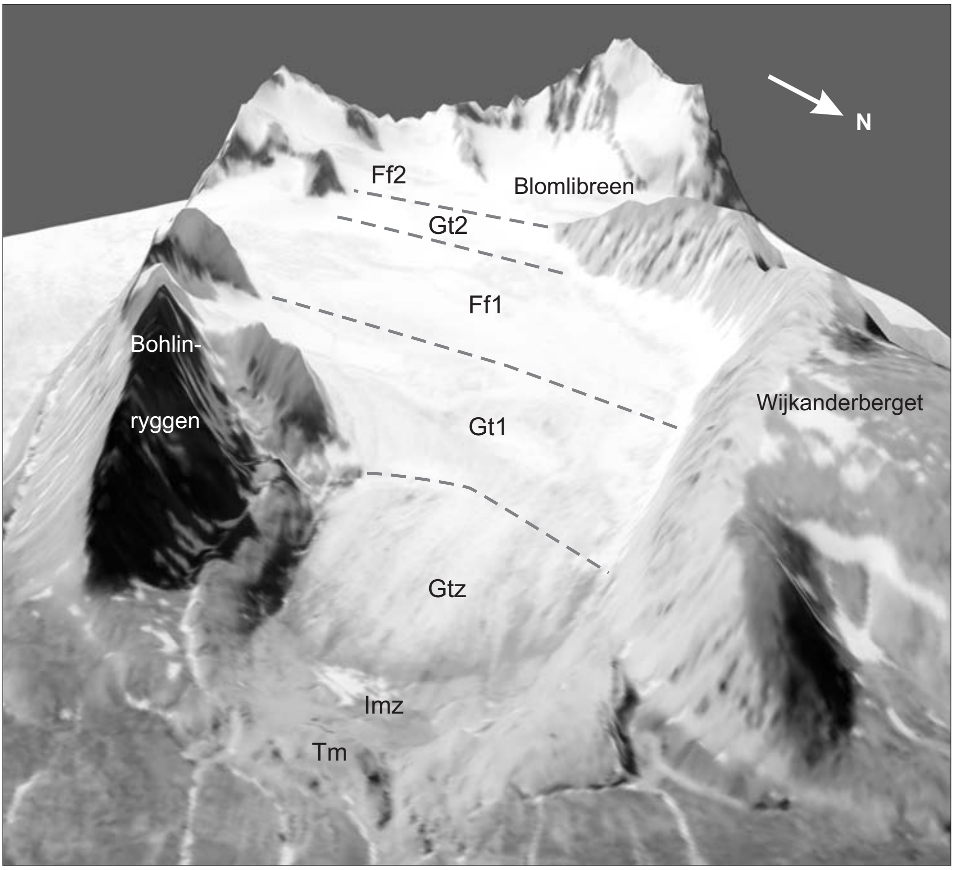

Fig. 4. Zones of Scott Glacier: Tm – terminal ice-cored moraine, Imz – internal marginal zone, Gtz – glacier tongue, Gt – glacier threshold, Ff – firn field. Spatial model of the Scott Glacier made on the basis of combined the Digital Terrain Model with aerial photograph from 1990 (Zagórski 2002).

Object of research

The Scott Glacier is a valley glacier, that is located three kilometres SW of the Polar Station of Maria Curie-Skłodowska University in Calypsobyen (Figs 1, 2). It fills up the valley, which is of NW-SE direction in its lower part and at lower altitudes changes into N-S. From eastern side, it is confined by Bohlinryggen range, from the western side by Wijkanderberget. Form the south eastern side, in the zone of low pass, the Scott Glacier joins the Blomli Glacier (Fig. 4). A valley mouth of the Scott Glacier closes the moraine ridge (ice-core moraine ridge), downcut by gorge connected with outflow of proglacial waters.

During the maximum extent, at the end of LIA, the Scott Glacier covered the area of 6.16 km^2. In this article, that area was assumed as 100%. Progressive accelerated recession since the 1960s’ caused decrease of the area of the Scott Glacier

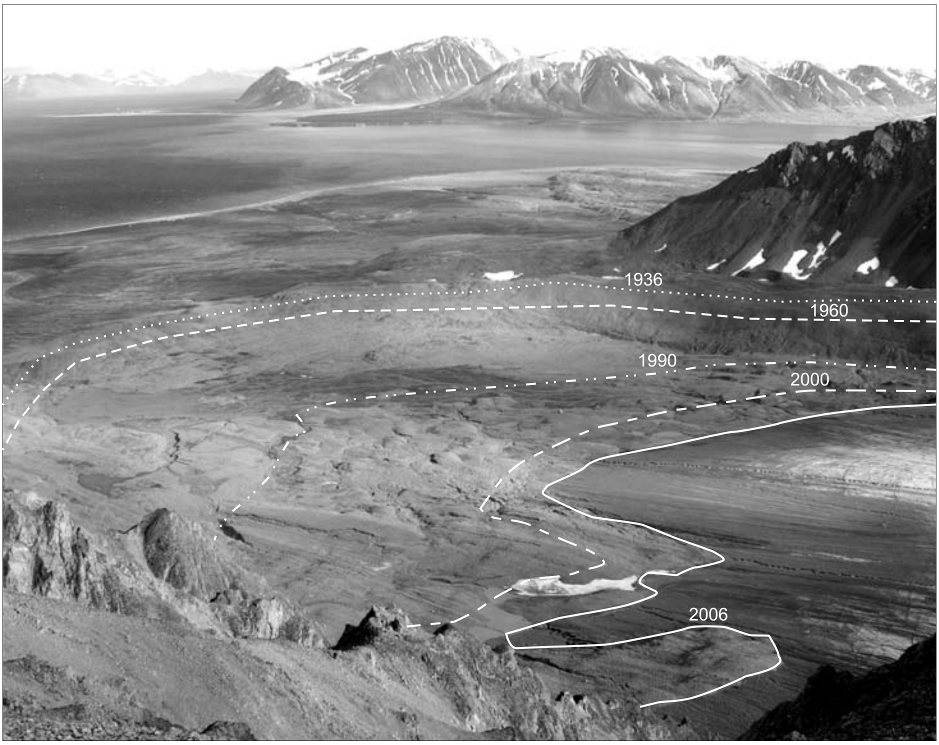

Fig. 5. Changes of the extent of Scott Glacier front. View from Wijkanderberget (Photograph by P. Zagórski 2006).

by 13.6% to 5.32 km^2 only, at the average rate of ~ 7600 m^2 a^{-1} (Table 1). In 2006, it covered only about 4.75 km^2 (Table 1), losing 9.3% comparing to 1990 and almost 23% to the maximum extend at time of LIA. The same year 2006 in the axial part its length was ~3.6 km (in 1990 ~4 km) and width in the lower part exceeded 1 km but in the firn field zone it reached ~1.5 km (Fig. 2).

In relation to bedrock relief and surface morphology, the Scott Glacier can be divided into several sections (Fig. 4). The lowest part is the glacial tongue (Gtz) limited by slantwise coursing of rock steps zone (glacier threshold, Gt1), which position resembles to geology and tectonics of the bedrock (Dallmann *et al*. 1990; Birkenmajer 2004). From the eastern side to the rock steps (Gt1) adheres the lateral hanged glacial cirque. The glacier upper part consists of two firn fields (Ff1, Ff2) divided by the second zone of rock steps (glacier threshold, Gt2).

In the last century, the Scott Glacier passed periods of intensive ablation with the phases of surge (Reder 1996; Reder and Zagórski 2007b). Therefore, it is difficult to determine dynamics of changes of its front extent since the end of LIA (end of 19th century) to the 1960's. After the surge dated to *c.* 1880 (Liestøl 1993), the Scott Glacier covered the whole present internal part of the forefield up to the push moraines (Figs 2, 5).

Table 2

Decrease of Scott Glacier area counted for years as well as values of its glacier front recession in individual periods (Zagórski and Bartoszewski 2004, corrected and replenished)

Period	Decrease of area [$m^2 a^{-1}$]	Average recession of glacier		Maximum recession of glacier [m]
		[m]	[$m a^{-1}$]	
End of 19th 1880–1936*	3 200	57	1.0 (?)	148
1936–1960	6 200	44	1.8	120
1960–1987	17 000	162	6.0	400
1987–1990	16 600	28	9.3	68
1990–2000	28 000	150	15.0	382
2000–2001	50 000	11	11.0	33
2001–2002	40 000	17	17.0	45
2002–2005	43 300	30	10.0	98
2005–2006	70 000	21	21.0	140
1936–1990	12 200	238	4.4	580
1990–2005	33 300	204	13.6	420
1880*–2000	9 500	397	3.3 (?)	1080
1880*–2006	11 200	510	4.0 (?)	1230
1936–2006	17 500	463	6.6	1100
1990–2006	35 600	228	14.3	440
2000–2006	27 300	87	14.5	250

* Accepting after Liestøl (1993), that this was the maximal extent of the Scott Glacier in the final stage of LIA.

From LIA to 1936, the mean recession for the glacier front was 57 m and its maximum was 148 m (Fig. 2, Table 2). However, during the period 1936–1960, the average recession was 44 m (1.8 m a^{-1}) and the maximum was 120 m (Fig. 6). On the photo taken in 1963 (Landvik *et al.* 1992, p. 337), the glacier front had a distinctly larger extent than in the aerial photo from 1960. According to Reder (1998) the surge maximum took place in 1963. Thus from the beginning of the 1960's, the quick recession of the Scott Glacier and uncovering of the internal part of its forefield began (Fig. 5).

During the 1960–1987 period, based on ground photogrammetric measurements, Merta *et al.* (1990) found that the Scott Glacier front retreated about 530 m *i.e.* 20 m a^{-1}. However, according to the latest GPS measurements and data processing with the use of the GIS software, their values were overestimated. The corrected average glacier front recession was 162 m (6 m a^{-1}) and maximum 400 m during those 27 years (Fig. 6, Table 2). The following period of 1987–1990 was characterised by acceleration of the average recession rate of the glacier front up to 28 m (9.3 m a^{-1}) and maximum 68 m (Figs 2, 5, 6, Table 2).

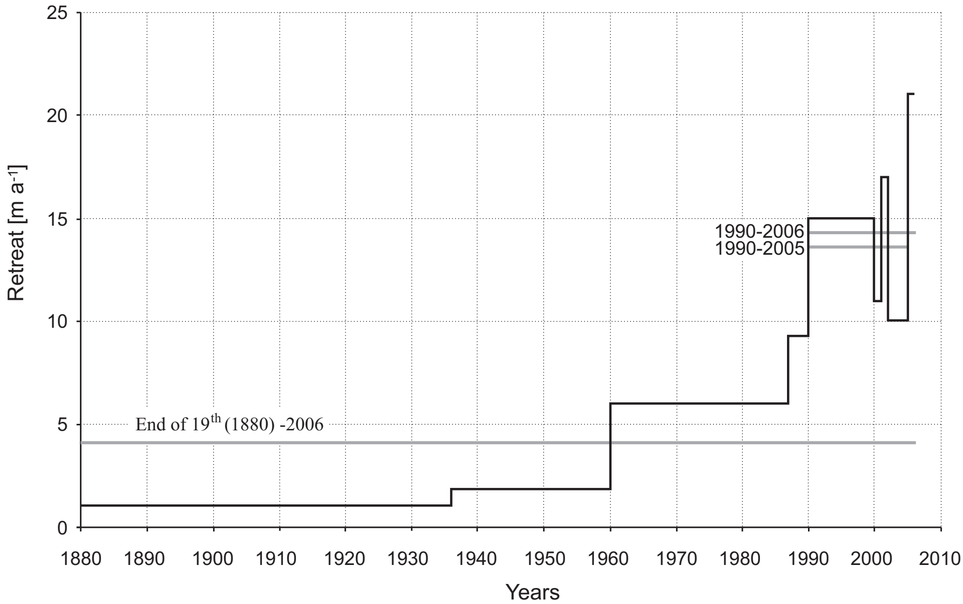

Fig. 6. Average recession rates of Scott Glacier for following periods on the background of periods: end of 19th (1880)–2006, 1990–2005 and 1990–2006.

Results

Observations and systematic measurements of the Scott Glacier indicate that during 1990–2006 its front retreated 228 m on average (14 m a^{-1}) and up to 440 m. The intensity of this process is characterised by large variability in time. The available data allow to distinguish several periods of various recession rates (Fig. 6, Table 2).

The season 2005/2006 is particularly distinct when the average rate of glacier front recession was 21 m per year and the maximum as much as 140 m (Table 2). The main reason for the large differences was the relief of bedrock and small thickness of glacier ice particularly in the zone of rock steps at the foot of Wijkanderberget (Figs 5, 7). Uncovering of these steps continued since the end of the 1990's. In following years, that process went on even more and more intensively. In the summer of 2005, a fragment of bedrock protruded over the glacier ice in the form of roche moutonnée but during the summer of 2006 the rock step was completely exposed (Figs 2, 7). Assuming ablation rates for different periods, it let to various prediction of complete ice tongue melt-out (Table 3).

As a result of the progressive recession of the Scott Glacier in the period 1990–2006, its area diminished by ~0.57 km^2 in an average rate of 0.0356 km^2 a^{-1} (Table 1 and 2). During only 16 years, the glacier area diminished by almost 11%. This value is much larger than that recorded during 1960–1990, when the glacier

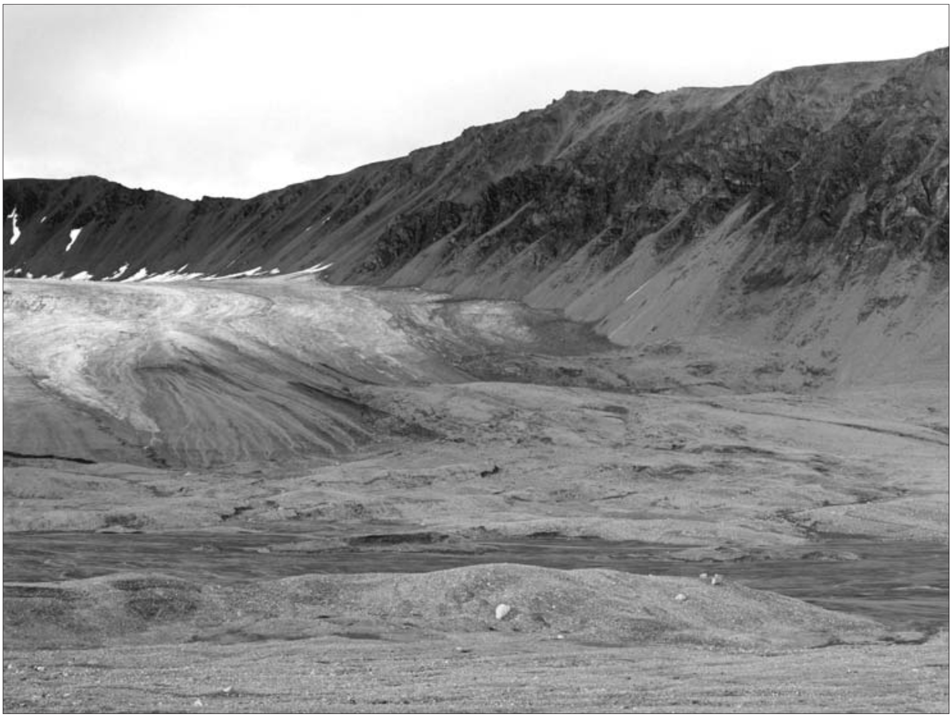

Fig. 7. Marginal zone of Scott Glacier composed of roche moutonnée on the north-western part at the foot of Wijkanderberget (Photograph by P. Zagórski 2006).

area decreased only ~8% (Zagórski and Bartoszewski 2004). This indicates the considerable acceleration of the rate of front recession of the Scott Glacier at the end of the 20th century.

The analysis of surface ablation of the Scott Glacier, based on the archival materials (DTM – 1990) as well as on topographic profiles and readings from ablation stakes in the summer of 2005 and 2006, shows spatio-temporal differentiation of this phenomenon (Fig. 8).

During the summer of 2005 and 2006, similar snow-ice conditions prevailed in the area of Scott Glacier. The glacier tongue zone was subjected to ablation in the lower part of glacial ice that changed upwards into superimposed ice. In the upper

Table 3

The period of time necessary for complete melt out of Scott Glacier tongue

Season/period	Mean annual rate of glacier front recession [m a^{-1}]	Years
2005/2006	21.0	40
1990–2005	14.3	60
1936–2006	6.6	129
1880–2006	4.0	212

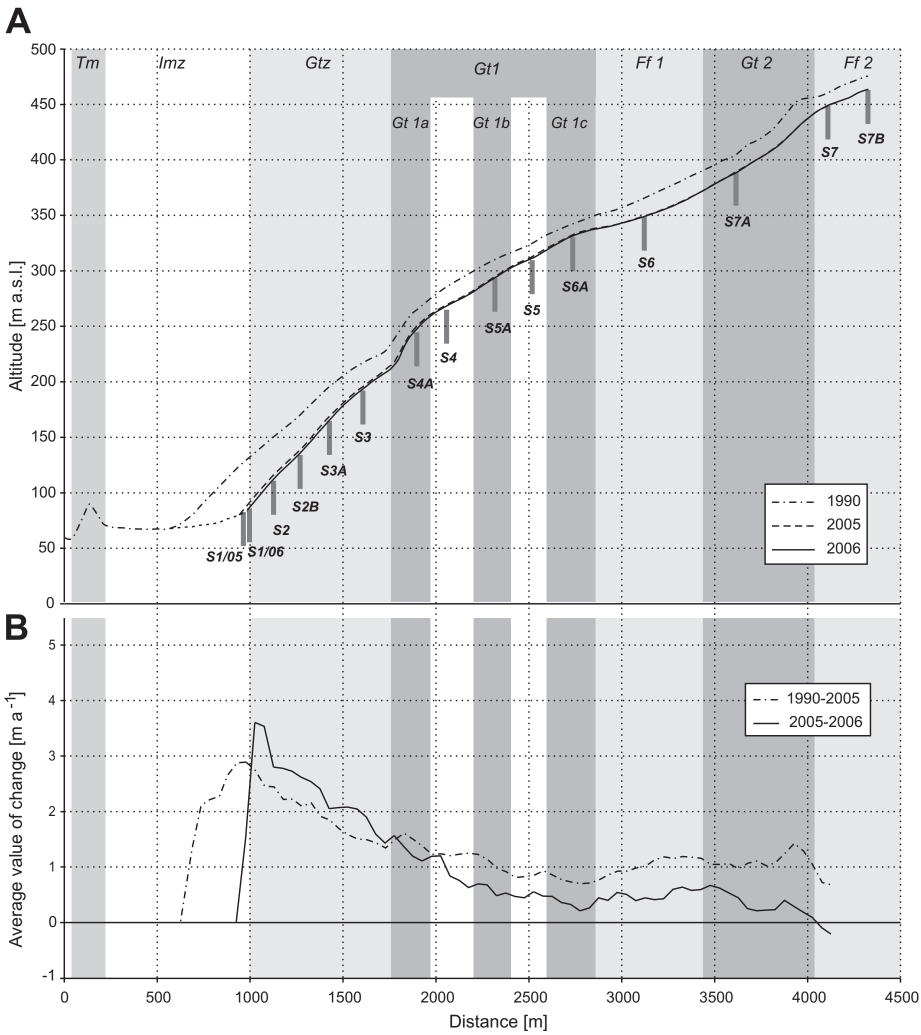

Fig. 8. **A**. Longitudinal profiles along Scott Glacier and location of ablation stakes as well as the zones (explanation on Fig. 4). **B**. Comparison of the average annual rate of changes of height of Scott Glacier surface along profile A (Fig. 2) in periods 1990–2005 and 2005–2006.

part of glacier close to the rock steps (GT1), at first, there was coarse-grained and wet snow which was changing into superimposed ice. On the firn field area (Ff1) and in the bottom part of second zone of rock steps, wet snow and slush occurred during almost the entire observation period. In the highest part of the Scott Glacier (firn field Ff2), only grained snow with ice layers and wet snow was subjected to ablation.

Between years 1990 and 2005 as well as during the season 2005/2006, the lowest part of the glacier *i.e.* the external part of glacier tongue was subjected to the most dynamic changes. In the case of stakes, which survived the winter of 2005/2006 (S2, S3A, S3), the significant lowering of the glacier surface (Δh),

Table 4

Changes in glacier surface level at locations of the ablation stakes in 2006; data from: 1990 – DTM, 2005 – GPS, 2006 – GPS

Ablation stake	1990 h [m a.s.l.]	2005 h [m a.s.l.]	2006 h [m a.s.l.]	Decrease 1990–2005 Δh [m]	Decrease 1990–2006 Δh [m]	Decrease 2005–2006 Δh [m]	Mean value 1990–2005 [m a^{-1}]	Mean value 1990–2006 [m a^{-1}]
S 1*	127.20	81.97	–	45.23	–	–	3.02	–
S 1*	132.23	–	85.97	–	46.26	–	–	2.89
S 2	150.21	113.67	110.86	36.54	39.35	2.81	2.44	2.46
S 2B	170.24	–	134.27	–	35.97	–	–	2.25
S 3A	195.20	167.13	165.17	28.07	30.03	1.96	1.87	1.88
S 3	217.29	194.29	192.89	23.00	24.40	1.40	1.53	1.53
S 4A	264.64	–	244.29	–	20.35	–	–	1.27
S 4	285.51	266.4	265.36	19.11	20.15	1.04	1.27	1.26
S 5A	310.60	–	294.10	–	16.50	–	–	1.03
S 5	324.72	310.59	310.08	14.13	14.64	0.51	0.94	0.91
S 6A	342.48	–	330.28	–	12.20	–	–	0.76
S 6	365.88	349.35	348.87	16.53	17.01	0.48	1.10	1.06
S 7A	404.81	–	389.34	–	15.47	–	–	0.97
S 7	460.62	449.28	449.47	11.34	11.15	**-0.19**	0.76	0.70
S 7B	475.61	–	463.29	–	12.32	–	–	0.77
S 8A	187.45	–	155.07	–	32.38	–	–	2.02
S 8	262.30	–	236.57	–	25.73	–	–	1.61
S 9	353.39	–	338.19	–	15.20	–	–	0.95
S 10	367.54	–	350.38	–	17.16	–	–	1.07
S 11	376.23	–	360.69	–	15.54	–	–	0.97
S 12	388.61	–	371.87	–	16.74	–	–	1.05

* change of location of ablation stake caused by recession of glacial front.

reaching 2.81 m at stake S2, was observed in the lowest part and gradually decreasing upwards to 1.96 m at S3A and 1.40 m at S3. Compared with the average for 1990–2005 (2.44 m for S2, 1.87 m for S3A, and 1.53 m for S3) these values are higher (Table 4). Only in this zone during the season 2005/2006, the ablation was higher than in the period 1990–2005.

In the zone of rock steps (Gt), separating the bottom part of the Scott Glacier (Gtz, above 220 m a.s.l.) from the firn field (Ff1, below 340 m a.s.l.), in 2005, there were located two points of ablation measurements (S4 and S5) and in 2006 six stakes were added (S4A and S8 – Gt1a; S5A – Gt1b; S6A, S9, S10 – Gt1c) (Figs 2, 8). An increase in the number of measurement points will enable better grasp of spatial changeability of surface ablation.

Taking into account annual values during the season 2005/2006, the lowering of glacier surface for the stake S4 was 1.04 m but for the stake S5 almost half of this value *i.e.* 0.51 m (Table 4). However, compared with the data of mean annual sur-

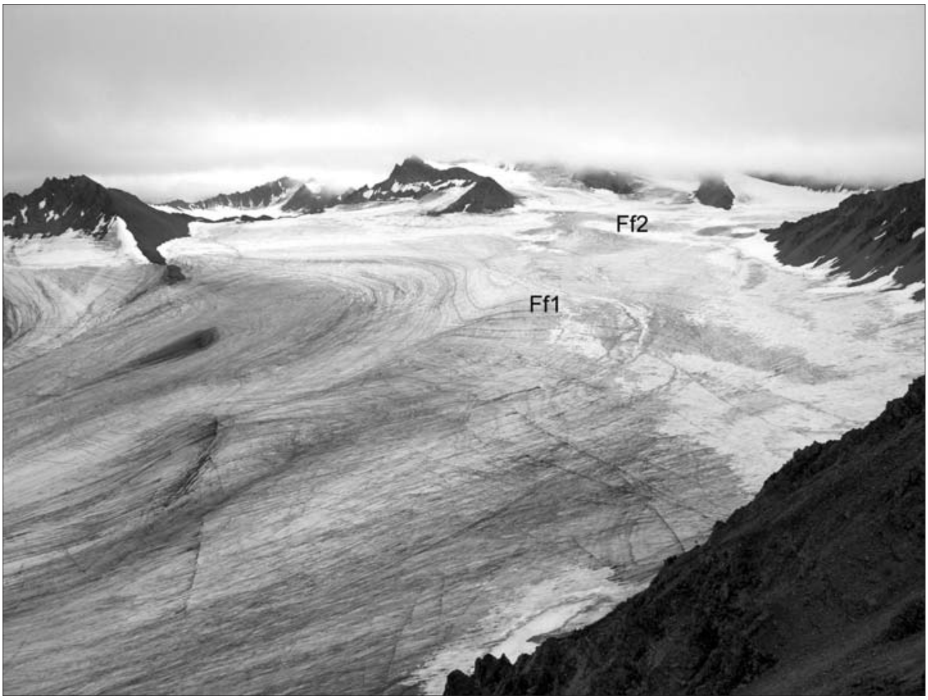

Fig. 9. Middle (Ff1) and upper (Ff2) part of Scott Glacier (Photograph by P. Zagórski 2005).

face lowering for the period 1990–2005, the values are lower: S4 – 1.27 m (0.23 m decrease) and S5 – 0.94 m (0.43 m decrease) (Table 4).

Based on the analysis of the longitudinal topographic profile A (Fig. 2), in the lowest part of glacier threshold zone (Gt), a boundary was found above which during the season 2005/2006 the surface lowering was smaller than the mean annual for the period 1990–2005 (Fig. 8). This boundary was at the high of about 220 m a.s.l. The average values of the surface lowering for years 1990–2005 and the season 2005/2006 differ distinctly. These differences increase with altitude. The smallest occurred in lower part of this zone – Gt1a, the largest in middle and upper parts (Gt1a, Gt1c) (Figs 4, 8). Lowering of the Scott Glacier surface between 1990 and 2006 for the zone of rock steps (Gt) took place in the lower part by ~20 m (S4A) and ~25 m (S8), in the middle part from 16 to 14 m (S5A, S5, S9, S10) and in the upper almost up to 12 m (S6A) (Table 4).

On the border of the rock steps zone (Gt1c) and the firn field (Ff1), the tendency for decreasing the surface lowering with height was halted. This dependence was found both for 15-year period (1990–2005) and the season 2005/2006.

The lower part of the firn field (Ff1) situated between 330 and 380 m a.s.l. is the main alimentation area of the Scott Glacier (Fig. 9). In the summer of 2005, the observation of glacial ablation was made only based on one stake S6, but the next year two more were added (S11, S12) (Figs 2 and 8). During the season 2005/2006, the lowering of the Scott Glacier surface by 0.48 m was found for stake S6. However, this value is almost twice as little as the average annual lowering of glacier surface for the period 1990–2005, which reached 1.06 m. The relative lowering of the Scott Glacier surface in 1990–2005 calculated from topographical profiles (Profile A) in the points of glacial ablation measurement (S6, S11, S12) was 15–17 m (Fig. 8, Table 4).

In the highest zone of the Scott Glacier, above 370 m a.s.l., during 2005, observations were performed based on the stake S7 (firn field – Ff2), whereas in 2006 additionally on stakes S7A (rock steps – Gt2) and S7B (central part of firn field – Ff2) (Figs 2, 4, 8, 9). The surface lowering in these zones was highly variable during the season 2005/2006. According to the topographic profiles, the zone of glacier threshold (Gt 2) was characterised by the lowering of surface but within the firn field (Ff2) the slight aggradation of the glacier surface ($\Delta hS7 = +0.19$ m) was observed (Table 4). It was caused primarily by large snow accumulation during the winter of 2005/2006. This value differs by almost one meter from the average annual surface lowering of the Scott Glacier surface for the period 1990–2005 ($\Delta hS7 = -0.76$ m (Fig. 8, Table 4). Lowering of the glacier surface between 1990 and 2006 for the area of rock steps (Gt2) and the upper firn field (Ff2) varied between 15.47 m in stake 7A, 11.15 m in stake S7 and 12.32 m in stake S7B (Table 4).

Discussion

The relationships described above results from specific climate conditions on both regional (NW part of Wedel Jarlsberg Land) and the regional, Arctic scale. Within the area of Spitsbergen, certain climatic elements show diversity due to microclimatic conditions (Brăzdil *et al.* 1991; Kejna *et al.* 2000; Gluza *et al.* 2004). The main features of climate of NW part of Wedel Jarlsberg Land depend on atmospheric circulation and mutual relations between marine (neighbourhood of wide waters system of Bellsund), glacial (glaciers: Scott, Renard and Recherche) and terrestrial environment (mountain massives free of ice cover *e.g.* Bohlinryggen and Wijkanderberget).

Accessible climatic data from a few polar stations show variable meteorological conditions during the 20th century with distinctive positive and negative trends (Hansen-Bauer and Førland 1998; Hanssen-Bauer 2002; Førland and Hanssen-Bauer 2003). The beginning of the 20th century record was characterised by quick rise of mean annual air temperature till the 1930's. During the following years, the negative trend was marked (especially temperatures of winter months) with the lowest temperatures reached during the middle 1960's. The mean value of front recession of the Scott Glacier for the first half of the 20th century did not exceed 2 m a^{-1} (Fig. 6, Table 2). Since the half of the 1960's up to Recent the progressive rise of warming with the tendencies for further, even more clear increase is registered and expected (Przybylak 2002, 2007).

The acceleration of glaciers recession in Spitsbergen (including the Scott Glacier) during the last 30 years is the result of several changes where the increase of air temperature is the most significant (Marsz and Styszyńska 2007). Its rise is clearly seen during autumn and winter, and less distinctively during the warmest months of year, *i.e.* in July and August: 0.04°C a^{-1} for the period of 1967–2006 and 0.17°C a^{-1} for 1997–2006 (Førland and Hanssen-Bauer 2003).

The rise of annual precipitation especially in summer and autumn and shorter existence of snow-cover is observed. All those factors show the increase of "oceanic climate" of south Spitsbergen in relation to atmospheric circulation (Niedźwiedź 2003; Marsz and Styszyńska 2007). The topography is of essential importance too because it influences the local disturbances of air masses movements and supply of solar energy (slope exposition, height of equilibrium line – ELA), and it may influence spatial variability of glacial conditions (Evans 2006, 2007). Those both factors together determine the value, quality and intensity of either summer precipitation or winter snow accumulation (Grabiec *et al.* 2006).

Higher summer precipitation causes the acceleration of glacier ablation, especially during S and SW cyclone circulations (Niedźwiedź 2003; Marsz and Styszyńska 2007). Such a situation occurred at the end of August 2002 when in Calypsobyen during 3 days over 50 mm of precipitation was recorded (Bartoszewski 2007). As the result, the snow cover was practically removed from the surface of the Scott Glacier. The balance of the whole area of the glacier was negative (ELA at 600 m a.s.l.). In contrast to the example discussed above, there are years which autumn-winter snowfalls could lead to positive balances for the highest parts of the Scott Glacier, for example during season 2005/2006 ($\Delta hS7 = +0.19$ m) (Fig. 8, Table 4). As the consequences, the progressive reduction in the Scott Glacier area and significant acceleration of its recession front 6.0 m a^{-1} (1960/1963–1987), through 9.3 m a^{-1} (1987–1990), and finally to 14.3 m a^{-1} (1990–2006) was observed (Fig. 6, Tables 1, 2).

Similar trends of different intensity were also noted on other glaciers in Svalbard, regardless of their type and size (Lankauf 2002; Rachlewicz *et al.* 2007). In the Table 5, a few examples from different regions of Svalbard are provided; however, they represent similar type and area as the Scott Glacier.

According to hypsographic curve based on DTM for 1990, it seems that 70% of the Scott Glacier area was above 300 m a.s.l., which is its ELA (Liestøl 1993) (Fig. 10) although the mean height according to the same DTM was 362 m a.s.l. However, according the observations during the last years, the position of that line is variable interannually with a rising trend. In the season 2005/2006, it risen to the height of 430–420 m a.s.l. It is consistent with the general trend in Svalbard for numerous glaciers (*e.g.* Jania and Hagen 1996; Pinglot *et al.* 1996; Hagen *et al.* 2003; Bamber *et al.* 2005; Sobota 2005; Hodgkins *et al.* 2007). For example, on Midre Lovén Glacier the ELA height in 1968–1993 varied between 225 and 650 m a.s.l., and the mean for that period was 398 m a.s.l. (Jania and Hagen 1996). During the

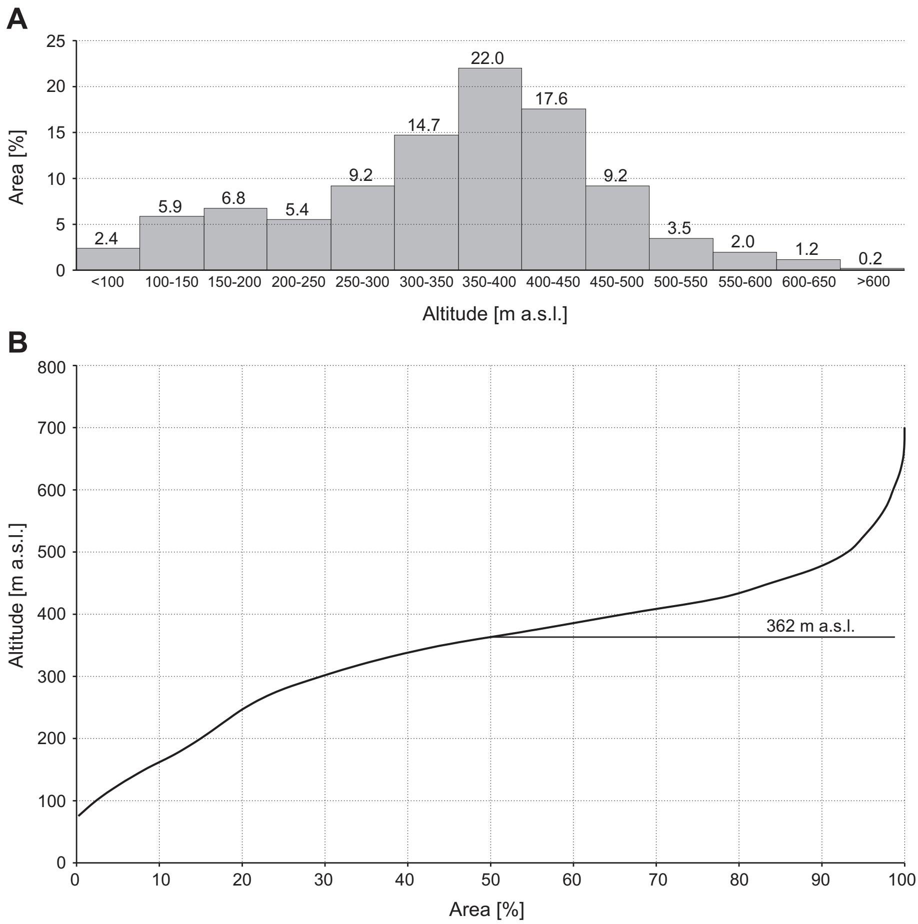

Fig. 10. The Scott Glacier (DTM, 1990). **A**. Percentage proportion of area in particular height sections for 1990. **B**. Hypsographic curve.

following 1994–2003 period, it was between 270 and 517 m a.s.l. and the mean ELA height was at 401 m a.s.l. [IAHS (ICSI)/ UNEP/UNESCO 1996, 1999, 2001, 2003, 2005]. The similar value was indicated for the Irene Glacier, where the ELA was 401 m a.s.l. in 2005 but 420 m a.s.l. in 2006 and it was similar to the mean value from 2002–2006 at 421 m a.s.l. (Sobota 2007a).

The changes of the Scott Glacier parallel transformation that are taking place in polar environment. It is also connected with its thinning. Generally, lowering of the Scott Glacier has been observed in the glacier tongue (Gtz; ΔhS1 = 3.02 m a^{-1}, ΔhS3 = 1.53 m a^{-1}) and firn fields (Ff1; ΔhS6 = 1.1 m a^{-1}), while in rock steps zones it is slower (Gt1 and Gt2; ΔhS5 = 0.94 m a^{-1}) (Figs 2, 8, 11, Table 4). This process took place on the entire width of the glacier as confirmed by topographical transverse profiles (Figs 2, 11 – Profiles B and C). Its intensity is spatially variable. In both cases, large decrease of ice thickness in the lateral parts and rock steps is ob-

Table 5

Examples of glacier from Spitsbergen – the same type and similar area

Glacier	Region	Area [km^2]	Period	Decrease of area [km^2]	Decrease of area [%]	Recession of glacier [m]	Recession of glacier [$m\ a^{-1}$]	Reference
Scott-breen	NW part of Wedel Jarlsberg Land	LIA[1)] – 6.16	LIA–2000	1.12	18.2	397 (1080)	3.3	this paper
		1990 – 5.32	LIA–2006	1.41	22.9	510 (1230)	4.0	
		2000 – 5.04	1990–2006	0.57	9.3	228 (440)	14.3	
		2006 – 4.75	2000–2006	0.29	4.7	87 (250)	14.5	
Waldemar-breen	Kaffiøyra Oscar II Land	XIX – 3.55	XIX–2000	0.89	25.0	651	6.8	Lankauf 2002; Bartkowiak *el al.* 2004; Sobota 2007a, b
		2000 – 2.66	XIX–2006	0.98	27.6			
		2006 – 2.57	2000–2006	0.09	3.6	65 (120)	10.8	
Irena-breen	Kaffiøyra Oscar II Land	1909 – 5.51	1909–2000	1.21	22.0	1 192	13.7	Lankauf 2002; Bartkowiak *el al.* 2004; Sobota 2007a, b
		2000 – 4.30	1909–2006	1.31	23.7			
		2006 – 4.20	2000–2006	0.10	2.4	80[2)]	13.3	
Mc Whae-breen[3)]	Billefjorden Central Spitsbergen	LIA[2)] – 5.63	LIA–1990	0.96	17.0			Rachlewicz *et al.* 2007
		1990 – 4.67	LIA–2002	1.37	24.3	867	9.0	
		2002 – 4.26	1990–2002	0.41	9.6	404	33.6	
Midre Lovén-breen	Kongs-fjorden NW part of Spitsbergen	1936 – 7.20	1936–1962			400	15.4	Liestøl 1971;
		1969 – 6.03	1936–1988	1.7	23.6			Koryakin 1974;
		1977 – 5.90	1936–1995	2.2	30.5			Björnsson *et al.* 1996;
		1988 – 5.50	1936–2005	3.2	44.4			Lankauf 2002;
		1995 – 5.00	1977–1995	0.9	15.2	150	8.3	Rippin *et al.* 2003;
		2005 – 4.00	2003–2005				6.5	Arnold *et al.* 2006

[1)] 1880 – after Liestøl (1993) the maximal extent of Scott Glacier in final stage of LIA,
[2)] 1900 – glacier limit during the end of LIA,
[3)] distance of glacier recession and mean rates of linear retreat – or clean ice border retreat.

served as well as convex profile in the central part starts to be a main zone of ice masses moving out from the firn field area at present.

In the first half of the 20th century, many Svalbard glaciers increased their thickness at the uppermost elevation (Bamber *et al.* 2005; Nuth *et al.* 2007; Ziaja *et al.* 2007). However, in the last three decades of the 20th and at the beginning of the 21st century, the acceleration in thinning of Svalbard glaciers took place especially on its western coast (Lankauf 2002; Kohler *et al.* 2007). The average glacial thinning rates for the Svalbard archipelago is -0.12 ± 0.03 m a^{-1} w.e.; however, for some 16 selected glaciers, its value was as high as -21 m a^{-1} (Hagen *et al.* 2003). For example, the Midre Lovén Glacier mean thinning rate reached 0.52 m a^{-1} for 1995–2003, but for 2003–2005 it reached 0.69 m a^{-1} (Kohler *et al.* 2007).

Conclusions

The course of surface ablation and change of the Scott Glacier front in the season 2005/2006 differ considerably from the period 1990–2005. One of the differences is

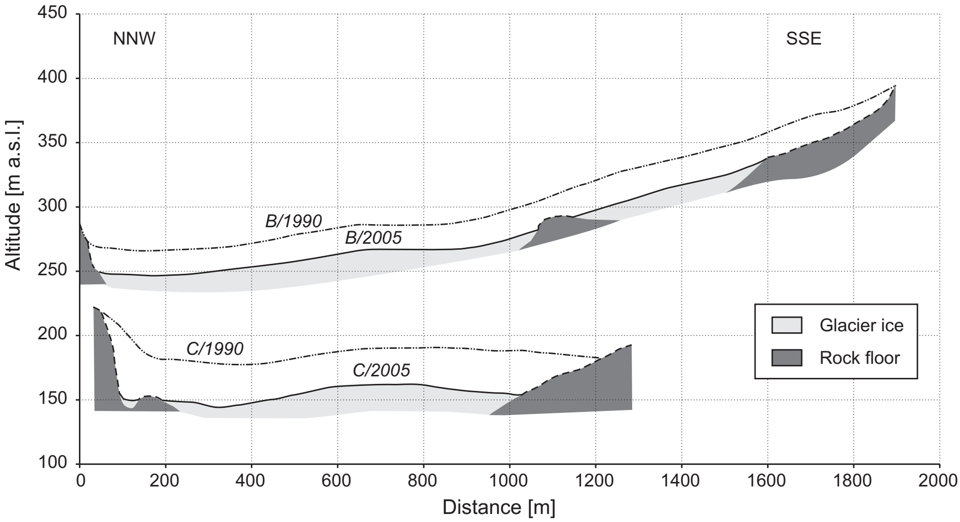

Fig. 11. Transverse profiles across Scott Glacier (location of profiles on Fig. 2).

related to the significant acceleration in recession of the glacier front (21.0 m) compared to the average annual rate from the period 1990–2005 (14.3 m a^{-1}). At the same time, intensity of this phenomenon is characteristic for the end of 20th and beginning of 21th centuries (Tables 1, 2). However, it is not reflected explicitly in surface ablation (change of height of glacier surface) as indicated by the analyses of topographic longitudinal profiles from 1990, 2005 and 2006 and the ablation stakes. Acceleration of glacial surface lowering during the season 2005/2006 took place only in the area of the glacial tongue (Gtz) to the height of about 220 m a.s.l. Starting from the rock steps zone (Gt1) and within the entire upper part of the Scott Glacier, the lower, than the annual average, rate of surface ablation was recorded for the period 1990–2005 (Fig. 8). The season 2005/2006 was characterised by strong winter snow accumulation which resulted in the increase of glacier surface in the area of the upper firn field (Ff2).

Since 1990, the reduction of the Scott Glacier area, its retreat and decrease of thickness particularly on the ice tongue area were observed. Its rate is not only related to climatic fluctuations but also to local conditions such as altitude, exposition and bedrock relief as well as local topoclimatic conditions. Changes in geometry and reduction of the Scott Glacier area are not the only results of its recession. They also occur in the upper parts of the glacier (firn fields – Ff1 and Ff2) as well as in middle zones of rock steps (Gt1) (Fig. 2, 4, 8). Increasing rock areas are uncovered in the form of roche moutonnées (Fig. 7). The progressive change in extent of the glacier surface causes exposition of new rocky elements, as well as narrowing and shorting of the glacial tongue (Fig. 11). This process may lead to complete melt out of the glacier below the rock steps Gt1.

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