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Front of the Werenskiold Glacier (Svalbard) – changes in years 1957–2013

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Abstract. Werenskiold Glacier in the Isle of Spitsbergen is one of the polygons on which evaluation of the rate of glacier recession is performed. Location of the glacier front is precisely presented in the specialist literature since the mid. 30. of 20th century. Article presents results of studies about changes in the position of Werenskiold Glacier based on selected archival data and own research conducted in 2012-2013. The initial location of the glacier front was described by the topographical map in the scale 1:5000 elaborated in the year 1961 on the basis of data from the years 1957-1959 by the Polish Army Topographic Service. Moreover, as comparative data on location of glacier front in the later years there were applied results of photogrammetrical images from the year 1973 and a orthophotomap from 1990. These data together with the author's GPS measurements were transformed into the uniform coordinate system. Thus, prepared data made it possible to evaluate the rate of recession of Werenskiold Glacier front in the three epochs from the years 1957-2013. It was found that during the 56 years the glacier front was moved by ca. 1200 m, which gives the mean recession value of 25 m/year as well as the mean yearly loss of the glacier surface of the order of 5 ha.

1 Introduction

Werenskiold Glacier (Werenskioldbreen) is situated in the south-western part of Spitsbergen which is the largest island of the Svalbard Archipelago belonging to Norway. The Isle of Spitsbergen is situated between 80º48' and 76º28' of northern latitudes and between 10º28' and 28º50' of eastern longitudes. The research area is situated in the south-western part of the island in Wedel Jarlsberg Land, not far from the entrance of Hornsund bay (Fig. 1).

The climate conditions in Spitsbergen are extremely variable and the access to the research area is largely limited in winter. Direct measurements of the glacier front are possible during summer months only. The choice of measurement technology depends on area conditions. Discussion of variations of glacier front course in the periods of 1957 to 1973, in 1990 and also in the period of 2012 to 2013 allowed for precise and quantitative presentation of recession phenomenon of Werenskioldbreen in the above-mentioned

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periods. The linear and spatial values of recession were calculated. Comparison of images in photos taken from the end moraine in the years 1973 and 2013 reveals the scale of glacier recession (Fig. 2) [1, 2].

Similar studies were performed earlier but they did not comprise so vast temporal range. It is also important to note that the analyses concerned only the process of glacier front recession [3].

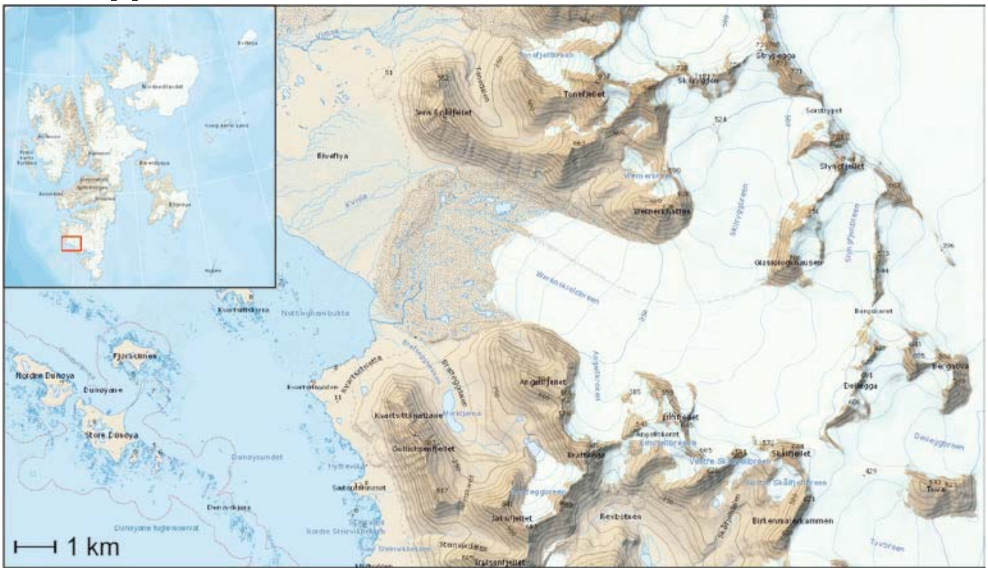

Fig. 1. Location of the research area [4].

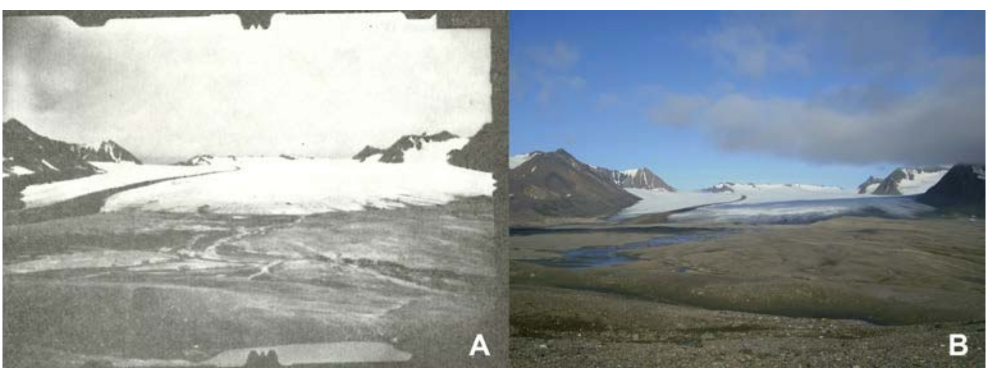

Fig. 2. A) The photo from 1973 [1], with a view of Werenskioldbreen front, and B) the photo from 2013 (K. Grudzińska) from the same position.

2 Werenskioldbreen‘s surroundings and bedrock

Werenskioldbreen is a glacier of valley type with generated structure of connected basins of complex thermics of B type (glacier may have slight cold areas in the zone of dry snow; thickened layer of cold ice down the ablation zone up to thinness freezing front) and with majority of deformations [5]. The total length of glacier is 7 km (state of 1990 - middle of the analyzed area; total length was measured in a straight line to the end of the glacier without side firn fields). Its firn fields are located on the height 350–550 m a.s.l., among the 630–790 m a.s.l. elevations of summits: Wernerknatten, Strypegga, Glasjologerknausen and Deilegga. In its higher parts the glacier is divided into three clearly extending components:

Skilryggbreen (in the north), Slyngfjellbreen (in the east) and Angellisen (in the south). The lower part of glacier extends along the NWW–SEE direction and it is limited by the mountains: Jens-Erikfjellet (576 m a.s.l.) from the north and Angelfjellet (591 m a.s.l.) from the south. In this zone of the glacier area there is a perfectly formed middle moraine separating the ice masses generated in the fields of Skilryggbreen and Slyngfjellbreen. The glacier front is situated at present on the ordinate of ca. 100 m a.s.l. The end moraine is located about 2 km west-wards, its height reaches 90 m a.s.l. Along the slopes of Angelfjellet and Jens-Erikfjellet there are developed lateral moraines.

Until the seventies of 20th century the glacier front was drained in two directions: westwards through the Kvisla river and south-westwards by Werenskioldelva. Later on the first of the two flows broke the barrier of central moraine and therefore presently the total volume of melting water is remitted SW.

3 Source data and methods

The initial material used to determine the change of Werenskioldbreen's scope was a topographical map in the scale 1:5000 as prepared by the Polish Army Topographic Service in 1961 [6] (Fig. 3A). The photos and terrain measurements were performed by C. Lipert with a ground-based photogrametry in the years 1957–1959 with help of Zeiss (Jena) photo-teodolite. The map was elaborated by C. Lipert and M. Bałdyga using analytical plotter Wild-A7 in Gauss-Kruger transformation with central meridian 15°. The print of colour map was executed in the Army Cartographic Plant in 1961. One of the results of polar expedition of Wroclaw University on Spitsbergen in 1973 was elaboration of another map of Werenskioldbreen front (Fig. 3B). The transformation in 1:5000 scale was produced with the use of ground-based photogrammetric measurements also with the use of Zeiss phototheodolite. The author of photographs, analytic elaboration and map editing was J. Żyszkowski. This cartographic elaboration was performed, just as the earlier elaboration, in Gauss-Kruger's transformation with 15° central meridian. The map printout was black and white and formed an Annex to the published article [1]. The next analytical elaboration is a topographic map in 1:25000 scale performed by a staff from the Silesian University in cooperation with the Norwegian Polar Institute in Tromsø, on the basis of aerial photos transformed to the central projection (orthophotomap; Fig. 3C). It was published in 2002 [7] but it was based on photographs from the year 1990. Elaboration of the orthophotomap was based on a series of 14 stereoscopic models calibrated on 7 terrain points determined by GPS technique. The orthophotomap was depicted with Mercators transformation in 33X zone with the 15°central meridian on the ellipsoid WGS 84.

The polar expedition in July 2012 organized by the Faculty of Geoengineering, Mining and Geology of Wrocław University of Science and Technology measured the location of Werenskioldbreen's front with GPS Trimble GeoXT receiver. The measurements were performed in GPS data registration system with latitude and longitude in the global coordinates frame presented on reference ellipsoid WGS 84. The inventory of glacier front comprised 31 measurement points measured within one day (July 18). Supplementation of GPS measurement was a routing map made on the plotting paper in scale 1:5000 and elaborated on the basis of measurements with help of compass and measuring tape. The next expedition organized by the Wrocław University of Science and Technology organized in July 2013 performed the most relevant GPS measurements of glacier front. GNSS Trimble R6 receiver with registered data from satellites GPS and Glonass were used. The measurement was performed similarly as in 2012 in the system of WGS 84 with registration of measurement data with help of Fast Static method. The measurement of the glacier front was performed in July 5 to 7 and comprised 32 measurement points. The data elaboration was made with post-processing method with adjustment of the values of measured coefficients with reference to the GPS station of EUREF network in Ny-Ålesund, located ca. 220 km northwards from the investigated area. This station functions in the continuous mode with stable registration of changes of location in relation to the global reference frame of geocentric coordinates (the data are accessible in the internet page of GPS stations) [8].

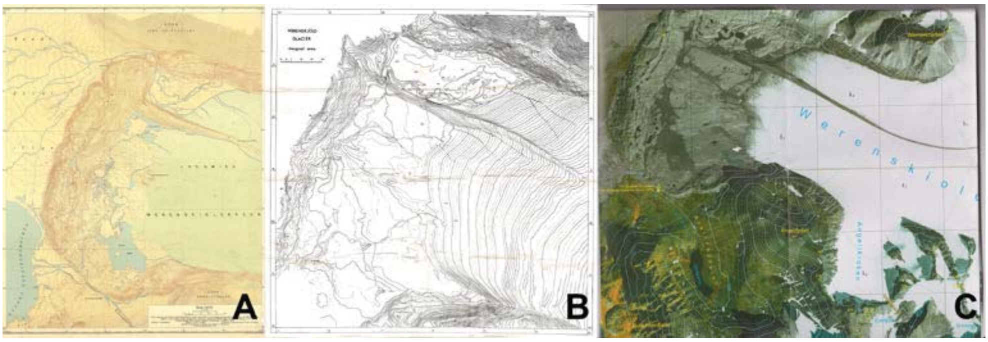

Fig. 3. Source maps for determination of Werenskioldbreen's front: A) Naumienko [6], B) Żyszkowski [1], C) Jania et. al. [7].

4 Elaboration of cartographic and measurement data for analysis of glacier front displacement

Evaluation of velocity of glacier front recession was possible to carry out on the basis of uniform system of coordinates only for all analysed maps and measurement results. Tophographic maps from the years 1957 and 1973 together with the orthophotomap from 1990 were transformed to the single system of coordinates. The system of rectangular coordinates was defined as projection on the surface of reference ellipsoid WGS 84. There was applied crosswise transformation: cylindrical, equiangular projection of Gauss-Kruger's with 15° meridian tangency as applied in Poland projection system "2000" which is used for small scale maps of small areas [9, 10]. Because the investigated surface of glacier covers only few square kilometers, application of the defined projection allows for determination of glacier recession without loss of precision as caused by transformation of coordinate system. The points of accommodation for carrying out transformation were intersection lines of kilometre network and well defined characteristic terrain points such as mountain tops on separate maps. The advantage of the selected projection is its angular fidelity and small deformations of distances on the whole mapping area (7.5 cm in the central part of zone and in the verges of the belt). The geographical longitude and latitude measured with GPS method in 2012 and 2013 was recalculated into the flat system as defined above. The possibility of spatial correlation of all the available archival data and the authors own measurements was obtained as its shown in the resulting map (Fig. 4).

Assessment of the recession of Werenskioldbreen's front was carried out with two methods. The linear values of recession were determined based on analyses of situation on 6 profiles determined generally perpendicularly to the glacier front (Fig. 4). The surfaces by which the glacier was diminished in the analysed time sections also were evaluated.

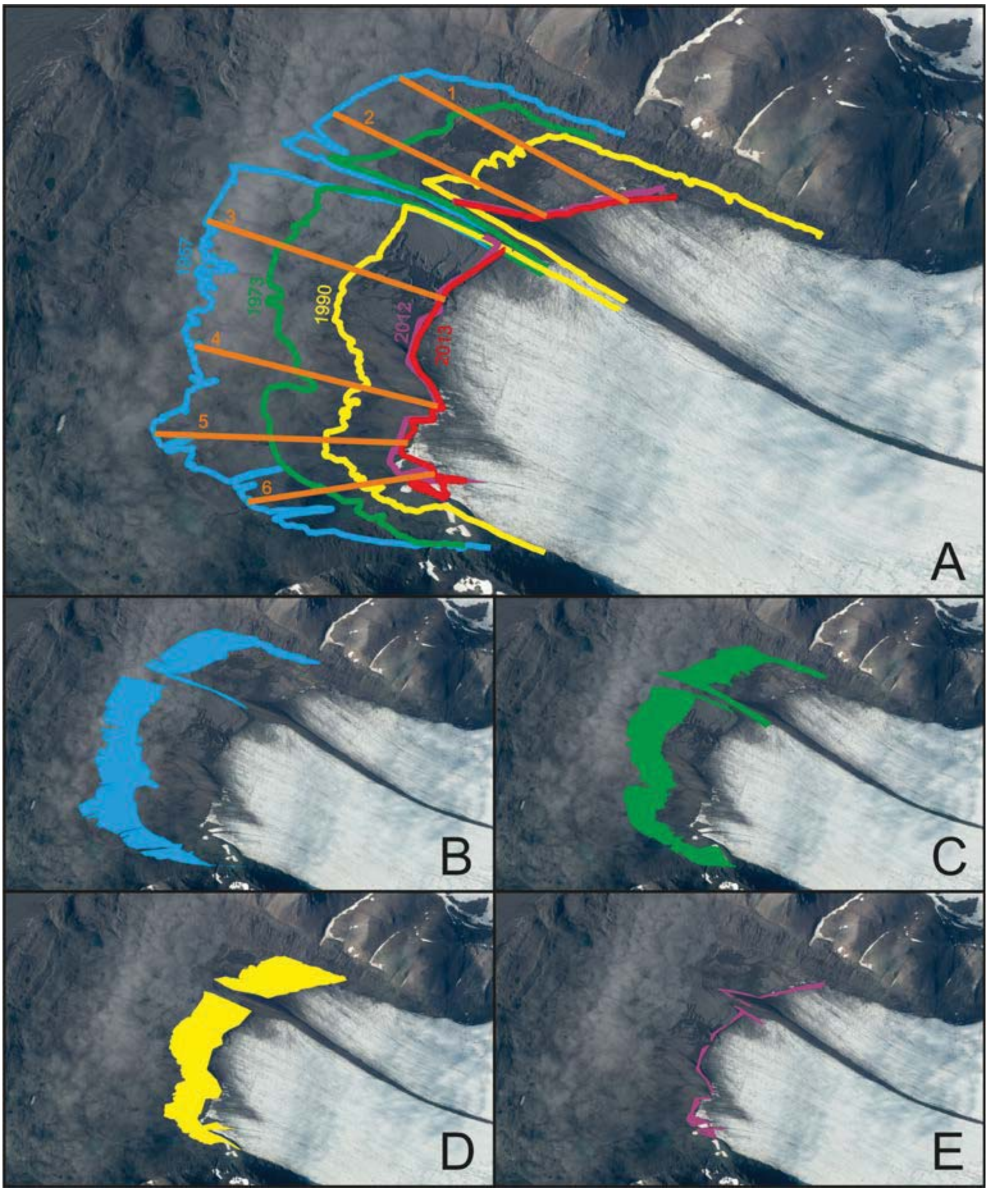

Fig. 4. Location of Werenskioldbreen's front in the years 1957-2013 and longtitudinal profiles where recession was analyzed (A), glacier's surface recession between 1957-1973 (B), glacier's surface recession between 1973-1990 (C), glacier's surface recession between 1990-2012 (D), glacier's surface recession between 2012-2013 (E); background: satellite photos, exemplary, uncalibrated [11].

4.1 The linear method

The linear values of front recession were calculated on the above-mentioned profiles which were determined between the lines of glacier range in the years 1957 and 2013 (Fig. 4). The numeric data concerning the magnitude of the glacier front recession in separate time sections calculated for separate profiles are shown in Tab. 1 and Tab. 2.

Table 1. The values of Werenskioldbreen's front recession in the analysed time sections for separate profiles [m].

Number of profile	**The value of the recession in time intervals**			**Total recession along the profile**	**The average annual recession along the profile**
	1957–1973 (16 years)	1973–1990 (17 years)	1990–2013 (23 years)		
1	375	334	577	1286	23
2	365	300	437	1102	20
3	385	375	443	1203	21
4	528	345	455	1328	24
5	560	270	378	1208	22
6	385	190	360	935	17
Average recession for period	433	302	442	1177	21
Average annual recession for period	27	18	19	21	

Table 2. Mean yearly recession for separates profiles in the analysed time sections [m].

Number of profile	**Average annual recession for the profile in a given period**		
	1957–1973	1973–1990	1990–2013
1	23	20	25
2	22	18	19
3	24	22	19
4	33	20	20
5	35	16	16
6	24	11	16

Elaboration of the rate of glacier recession in detail is possible based on analysis of vertical sections of glacier as shown in Fig. 5. They show approximate form of the glacier front surface in separate years with marked predominance of sections (the ratio of vertical and horizontal scales is 1:2).

The analysis of presented data enables us to show correctness of the observed process of the glacier recession in the period of the last 56 years. The glacier front retreated most spectacularly – by ca. 1300 m – in its southern part, in the area of profile no. 4 (1328 m) and in the northern part, as it is shown in profile no. 1 (1286 m). For maps of each analyzed period also the length of glacier front was determined as its changes also indicate the rate of recession. Simplified field measurements were performed for the sections of glacier rim in the analysed maps and in the measurements data from the glacier valley. The broken lines marking the border of ice from the north moraine to the central moraine and from the central to the southern moraine were measured.

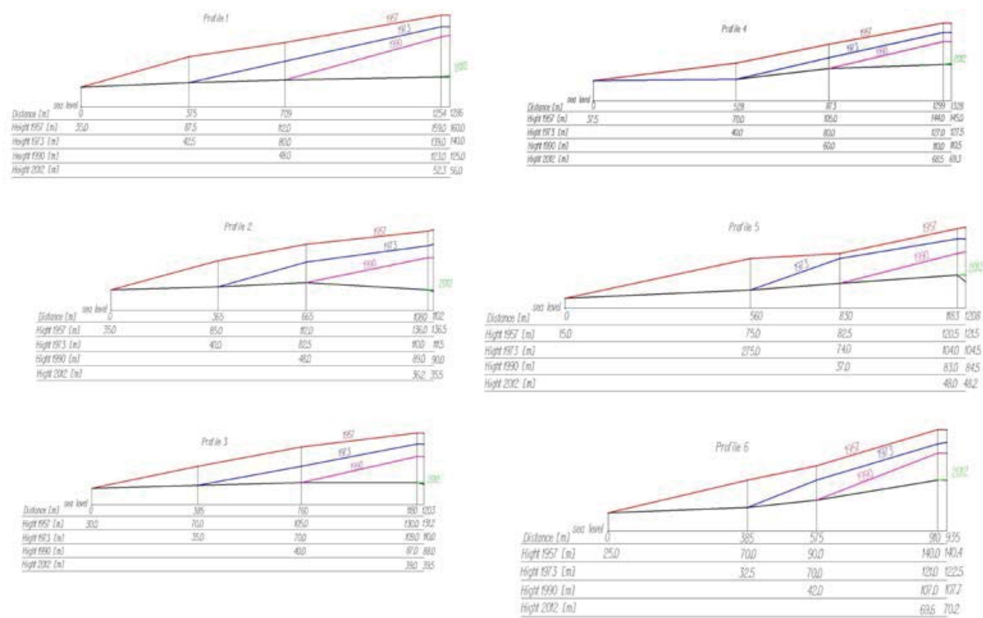

Fig. 5. The cross sections depicting the Werenskioldbreen's recession and front lowering along analyzed profiles (cf. Fig. 4).

The sum of the measured lengths was recognized as the length of glacier front. This value was subject to significant recession – from 6430 m in 1957 to 3480 m in 2013. For the year 1973 this value amounted to 3980 m, whereas for the year 1990 – 3060 m only. This effect is a result of narrowing of the glacier valley to the east and distancing or "escape" of the glacier from the lateral moraines located along the slopes of Angelfjellet and Jens-Erikfjellet.

4.3 The surface method

The second method which was applied, making use of the analysis of changes of the glacier surface, enabled us to determine independently the scale of Werenskioldbreen's recession. In order to obtain this objective with the use of orthophotomap of Werenskioldbreen area the total glacier surface was measured with the Gauss method [7, 12]. The coordinates of the points defining the border of deposition of the ice cover were determined. Based on the determined rectangular coordinates the surfaces of separate discussed areas were calculated. At the first stage the glacier surface in 1990 was calculated because the initial map from 1957 was not the whole glacier which was charted but only its frontal part, which was repeated in 1973. To the surface calculated in 1990 was added the surface between the front lines from the years 1957 and 1990. This way the approximate surface initial for the total glacier in the year 1957 was obtained. The subsequent stages of elaboration consisted in determination of the surfaces of fields between the curves forming the glacier front in the separate measurement periods. The results of these calculations are shown in Tab. 3. The surface is given in hectares and also in percent of the total initial surface of the glacier.

Table 3. The results of calculation of the glacier surface and its recession in different epochs.

Year/period	**Surface of the glacier**		**Decrease of surface**		
	ha	%	ha	average ha/year	average % /year
1957	2960	100			
1957–1973 (16 years)			103	6.4	0.22
1973	2857	96.5			
1973–1990 (17 years)			85	5	0.17
1990	2772	93.7			
1990–2013 (23 years)			79	3.7	0.13
2013	2687	90.8			
2012–2013			6	6	0.20

Based on presented data one can formulate several regularities concerning the glacier recession process and scale of baring of sub-glacier surface. The surface of total glacier in the period of latest 56 years of the research decreased by 279 ha, i.e. 9.2% of the surface determined in the year 1957, which gives the mean yearly loss of the glacier surface of the order of 5 ha, i.e. 0.22% of the initial glacier surface. The greatest loss of surface occurred in the initial period of research in the years 1957–1973 and it amounted to 103 ha, i.e. 3.5% of the initial glacier surface. The smallest loss of the surface occurred in the period 1990–2013 and it amounted to 79 ha, i.e. 2.9% of the initial glacier surface which gives the yearly mean loss about 3.7 ha. In the latest measurement period (2012-2013) the loss of surface increased again to the value of 6 ha, i.e. 0.2% of the total glacier surface. The rate of glacier recession determined by the loss of its surface is variable in time. At the beginning it had value of ca. 6.4 ha per year, and finally it decreased to 3.7 ha per year. We obtain the anomalous value of ca. 6 ha also in the case of application of this research method for the latest year (2012–2013) of research.

5 Discussion

In the result of geometrical analysis of the accessible archival cartographic elaborations together with the results of the author's terrain investigations the process of Werenskioldbreen's recession was showed. It was described with the use of results of linear and surface analyses.

The length of the glacier front was subject to reduction by above 2 km i.e. about 30% of its initial length. This is probably a result of morphologic conditions caused by the eastward narrowing of the glacier valley.

The results of linear analyses of Werenskioldbreen's front recession show the mean value ca. 1200 m during the period of 1957–2013, which corresponds to the rate of recession by ca. 21 m per year. However, the rate of the process is variable in time and space. The rate of recession fell from ca. 27 m per year in the epoch 1957–1973 down to 18–19 m per year later on. Initially the glacier retreated most promptly in the south by 528–560 m, i.e. ca. 34 m per year. In the period of 1973–1990 the melting down had more uniform character along the total glacier front with rather indistinctly drawn maximum in its central part, i.e. 375 m and 22 m per year. In the period of 1990–2013 the recession was distinctly fastest in the northern part of the glacier front - 577 m (25 m per year). From comparison of the results of author's elaboration with the analyses presented by Bukowska-Jania and Jania [13], Grabiec et al. [14], Migała et al. [15] and Ignatiuk et al. [16] one can state that the mean values of speed of the glacier recession (as well as calculation of the glacier surface) are in a high accordance with the values cited from the literature, i.e. with 1 to 2 m difference.

The analysis of the changes of the glacier area shows that during the 56 years long research period it decreased by 279 ha, i.e. 9.2% of the initial surface. It corresponds to the mean yearly loss of surface equal to 5 ha, i.e. 0.22% of the initial surface. The most intensive recession of Werenskioldbreen surface occurred in the first analysed period (1957–1973) when it amounted to 103 ha i.e. 3.5 % of the initial glacier surface, that is 6.4 ha per year. In the two subsequent periods i.e. 1973-1990 and 1990-2013 a systematic rate of slowing of this process to the values of 85 ha and 79 ha was observed. Whereas, during the whole research period the slowing of this process reached only 5 ha in period 1973-1990 and average recession 3.7 ha per year in the years 1990–2013. The changes of glacier's areas and their front recession is observed in whole Svalbard, e.g another valley glacier located in southern Spitsbergen – Ariebreen [17] and others [18].

It should be stressed that the values obtained on the basis of author's terrain research made in the last year considered (2012–2013) are anomalous in comparison to the results of analyses from the years 1957, 1973 and 1990. The mean linear recession along the analysed profiles amounts to 26 m, while the surface recession amounts to 6 ha.

It is also important to emphasize that the factor having a significant impact on the rate of retreat of the glacier is rising average value of annual air temperature [19]. This state is confirmed by a number of published research results, especially when it comes to the West Spitsbergen. The increase in average annual temperatures of air results from an increase in average temperatures for each season. Only during the last twenty years the increase in average annual temperatures was set at 1.0 - 1.2°C. This trend is confirmed by direct instrumental observations as well as statistical increase in number of warm days during the year and decrease in number of cold days, especially during winter seasons [20-25].

6 Conclusions

The most essential observation is recognition of the slowing down or stabilization of the process of melting of the glacier in the total analysed period. This trend is visible in the results obtained with both applied methods of the linear and surface analyses. However, for a credible monitoring of the trend of changes it is necessary to implement regular cyclic observations. Accepted in this elaboration irregular measurement periods result from the character of accessible archival data. The periods of 17 and 23 years long do not allow for creation of complete model of glacier recession. It is possible that in these time intervals there occurred a periodic expansion of the glacier which is a natural phenomenon that often takes place in different parts of Spitsbergen.

There was noticed some differentiation of the rate of glacier recession on separate sections of the glacier front caused by the glacier foundation relief and activity of the glacier rivers. The photogrammetric ground and low-ceiling aerial methods as well as the traditional geodetic measurement methods and the GNSS method can be still applied with consideration of often extreme atmospheric, logistic and economic conditions.

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References

1. J. Żyszkowski, Acta Universitatis Wratislaviensis, **525**, 289-298 (1982)
2. W. Ciężkowski, T. Głowacki, K. Grudzińska, D. Kasza, P. Zagożdżon, 35th Polar Symposium, Diversity and state of polar ecosystems (book of abstracts), 4th-7th June (2014)
3. L. Kolondra, 2003. Problemy fotogrametrycznego pozyskiwania danych w badaniach glacjologicznych (studium metodyczne na przykładzie Spitsbergenu), PhD dissertation, University of Silesia in Katowice (2003)
4. Norwegian Polar Institute, http://toposvalbard.npolar.no/ (2014)
5. J. Jania, *Wyprawy Polarne Uniwersytetu Śląskiego 1980–84*, t. 2, Prace Naukowe Uniwersytetu Śląskiego, 12-47 (1988)
6. T. Naumienko (ed.), Mapa topograficzna czoła lodowca Werenskiodbreen w skali 1:5000,Wojskowe Zakłady Kartograficzne (1961)
7. J. Jania, L. Kolondra, H.F. Aas, Orthophotomap 1:25000, Werenskioldbreen and surrounding area, Uniwersytet Śląski and Norsk Polarinstitutt (2002)
8. website of EUPOS Ny-Ålesund, http://www.epncb.oma.be/_networkdata/ siteinfo4onestation.php?station=NYA1_10317M003 (2014)
9. R. Kadaj, *Polskie układy współrzędnych. Formuły transformacyjne, algorytmy i programy*, AlgoRes-Soft (2002)
10. E. Osada, *Osnowy geodezyjne*, UxLan (2013)
11. satellite photo from Quit Buird, https://browse.digitalglobe.com/imagefinder (2014)
12. W. Kosiński, *Geodezja*, Wydawnictwa Naukowe PWN (2012)
13. E. Bukowska-Jania, J. Jania, W*yprawy Polarne Uniwersytetu Śląskiego 1980–84*, t. 2, Prace Naukowe Uniwersytetu Śląskiego, 65-91 (1988)
14. M. Grabiec, T. Budzik, P. Głowacki, Arctic, Antarctic, and Alpine Research, **44**, No. 2, 164-179 (2012)
15. K. Migała, J. Pereyma, K. Birkenmajer, D. Ignatiuk, C. Kabała, M. Kasprzak, B. Korabiewski, H. Marszałek, J. Matuła, P. Migoń, M. Rysiukiewicz, S. Sikora, S. Staśko, M. Wąsik, A. Witkowski, B.Wojtuń, *Ancient and modern geoecosystems of Spitsbergen*, Z. Zwolinski, A. Kostrzewski, M. Pulina, K. Bogucki (eds.), Wydawnictwo Naukowe, 122-125 (2013)
16. D. Ignatiuk, A. Piechota, M. Ciepły, B. Luks, International Conference of Computational Methods in Sciences and Engineering 2014 (ICCMSE 2014), AIP Conf. Proc. **1618**, 275-280 (2014)
17. J. Lapazaran, M. Petlicki, F. Navarro, F. Machi´o, D.Puczko, P. Glowacki, A. Nawrot, Polar Research **32** (11068), 1-10 (2013)
18. World Glacier Monitoring System, http://wgms.ch/fogbrowser/ (2016)
19. Weather forecast for Longyearbyen (Svalbard), http://www.yr.no/sted/Norge/Svalbard/ Hornsund/ (2016)
20. O. Nordli, Norwegian Meteorological Institute, http://nordicspace.net/2005/01/01/ temperature-variations-at-svalbard-during-the-last-century/ (2005)

21. E. Oseth, *Climate Change in the Norwegian Arctic. Consequences for life in the north*. Norwegian Polar Institute, report series 136 (2011)
22. D. Divine, E. Isaksson, T. Martma, H.A.J. Meijer, J. Moore, V. Pohjola, R.S.W. Van De Wal, F. Godtliebsen, Polar Research **30** (7379), 1-12 (2011)
23. E.J. Forland, R. Benestad, I. Hanssen-Bauer, J.E. Haugen, T.E. Skaugen, Advances in Meteorology, vol. 2011 (2011)
24. O. Nordli, R. Przybylak, A.E.J. Ogilvie, K. Isaksen, Polar Research **33 (**21349), 1-23 (2014)
25. H.M. Gjelten, O. Nordli, K. Isaksen, E.J. Forland, P.N. Sviashchennikov, P. Wyszynski, U.V. Prokhorova, R. Przybylak, B.V. Ivanov, A.V. Urazgildeeva, Polar Research **35** (29878), 1-13 (2016)