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The ice mass loss in the front zone of the Werenskiold Glacier from 1957 to 1978 determined using terrestrial photogrammetry*

ABSTRACT. This paper contains the result of the comparison of photogrammetric records of the state of the front zone of the Werenskiold Glacier over the period 1957–1978. Two 1:5000 maps were compared. The ice volume loss at 20 m altitude intervals (only as far up as 200 m over the sea level) and changes in the ice thickness were analysed with a network of basic squares with a 50 m side in the field, using an Odra 1305 computer. This permitted a map of the altitude changes in the glacier front to be plotted with isolines every 2.5 m. The results of the photogrammetric investigations were compared with ablation observations using ablations stakes. Taking account of the motion of the lobe the total and the mean annual ice volume loss in the front zone of the Werenskiold Glacier was evaluated for the period in question.

Key words: Arctic, Spitsbergen, photogrammetry, glaciology, mass loss.

1. Introduction

The Werenskiold Glacier on the Wedel-Jarlsberg Land (S Spitsbergen) has for a long time been the object of glaciological investigation. Its extended characterization has been given by Kosiba (1960), Baranowski (1975, 1977) and Pulina et al. (this issue). Investigations of this glacier were commenced by A. Kosiba (1960) in 1956 and continued by some younger scientists from Wrocław University (Pereyma 1981) and Silesian University (Pulina 1981, Pulina et al.—this issue; Jania, Kolondra 1982).

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The aim of this paper is to determine the changes in the relief of the front part of the tongue of the Werenskiold Glacier over 21 years and on this basis to attempt to draw conclusions as to the magnitude of the ice mass loss. This work has been made possible by the surveys by the method of terrestrial photogrammetry of the front part of this glacier in 1975 (Lipert 1958, 1961) and the repetition of this investigation in 1978 (Mechliński 1979). Terrestrial photogrammetric measurements of this glacier were also taken in 1973 (Żyszkowski 1982) and 1982 (Jania, Kolondra 1982); the data obtained from these investigations, however, are still undergoing elaboration. In view of this, the results presented in this paper are fragmentary and should therefore be regarded as preliminary. Nevertheless, they lead to some interesting observations and conclusions.

2. Photogrammetric investigations

Polish photogrammetric measurements on the Werenskiold Glacier were related to the glaciological programme of A. Kosiba mentioned above. A team of photogrammetrists headed by C. Lipert worked on a detailed mapping of this glacier in three summer seasons: 1957, 1958 and 1959. In the first year of these investigations 294 measurements were taken at 119 points which formed 65 photogrammetric bases. In the successive years measurements of the so called "dead fields" and geodetic measurements were complemented. More than 42 km^2 of the area was mapped. The points and photopoints were linked to the Norwegian geodetic network with three resections. Also three traverse sequences with two nodal points and one linking sequence were set (Lipert 1958). The measurements were taken by a Photheo 1318/19 phototheodolite with the focal length f = 197.76 mm and the geodetic measurements by a Th II theodolite (in 1957) and by a Theo 030 device (in the successive years)—all manufactured by C. Zeiss Jena (GDR).

On the basis of these measurements a 1:5000 topographic map was made on the A7 plotter—manufactured by the Wild Company, Heerbrugg (Switzerland). Two of the projected three sheets have been published so far in colour version. They cover 28.2 km^2 of the area, including the terminal zone of the glacier and the marginal zone with a complicated relief of the terminal moraines with the ice core (Lipert 1961). The frame of the two sheets shows the systems of geographical coordinates and of the rectangular coordinates of the Gauss-Kruger projection Contour line cutus were used at intervals of 1.25 m on land and 2.5 m on the tongue of the glacier.

In the summer of 1978, the expedition of the Polish Academy of Sciences resumed photogrammetric mapping of the front part of the Werenskiold Glacier and part of the marginal zone between the terminal moraines

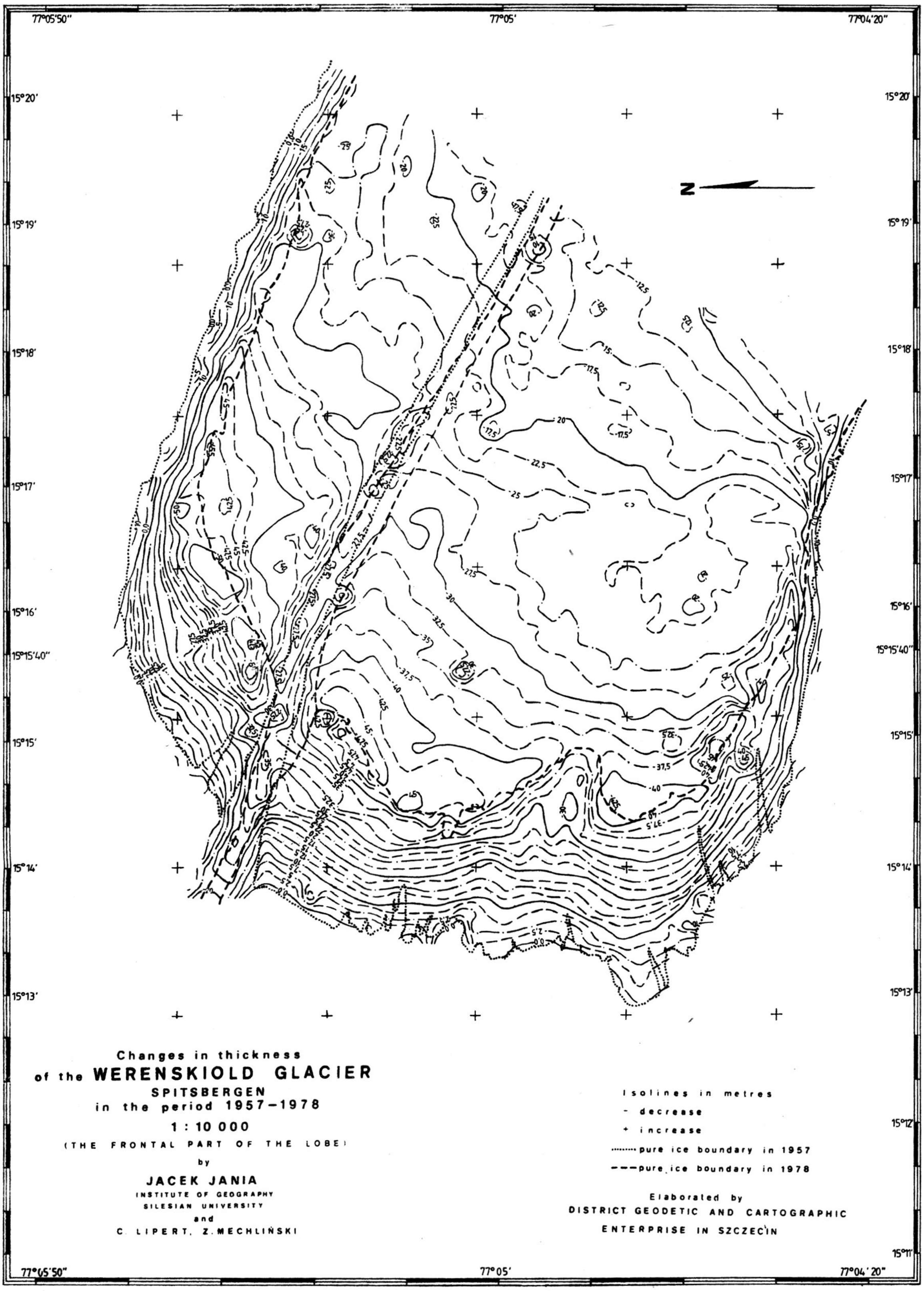

Fig. 1. A map of changes in thickness of the Werenskiold Glacier from 1957—1978. Reduction twice time

and the glacier. The work was carried out in August and in favourable weather and due to the large effort of the two-person photogrammetric team, lasted only two weeks. 80 measurements were taken at 25 photogrammetric bases. The geodetic net formed a central eleven-sided figure whose main point lay near the centre of the area being mapped, by the edge of the glacier 20 photopoints were used; they were marked in the field by white 60×80 cm aluminium plates and their geodetic coordinates were determined. The local geodetic net was linked by a resection with the Norwegian triangulation network (the same points as those in 1957—1959 were used). Measurements were taken by the same phototheodolite type, while geodetic measurements by a Theo 010A theodolite (C. Zeiss Jena, GDR).

The abridged version was made on the Topokart B plotter manufactured by C. Zeiss Jena. A. 1:5000 map with a contour interval of 2.5 m on land and the glacier was produced. The map was published in two colour sheets; it covered about 12 km^2 of the area (Mechliński 1979). It showed the range of the glacier in 1957. On the frame there was the geographic coordinate system. The two maps were made in the Gauss-Kruger projection with the reference meridian $\lambda_0 = 15°$E.

The measurements in 1978 were not taken at the same points as those in 1957. In contrast to the previous measurements which were taken for glaciological purposes, in 1978 the aim of the mapping was to determine accurately the relief of the marginal zone between the terminal moraine and the glacier, in order to define the changes which had taken place (Szupryczyński 1980). For this reason the range of measurements was not very far up the glacier, only up to about 200 m over the sea level.

3. Comparison of the states of the glacier in 1957 and 1978

It was possible to compare two detailed topographic maps of the front of the Werenskiold Glacier by referring them to the same geographic coordinate system. Thus, it was not difficult at all to superimpose the 1978 map on that from 1957; particularly in view of the same contour line intervals on the glacier.

Calculation of changes in the height and volume of the glacier by superimposing the contour lines of maps from different periods was begun by Finsterwalder (1954) and improved by Hofmann (1957) and Konecny (1964). These methods consist in the calculation of the area between the corresponding contour lines in two maps and between the neigbouring lines. Results are obtained for particular altitude zones of the glacier.

These data are not sufficient for any detailed changes in the relief of the glacier. An analysis with a network of basic fields is usually used to show the spatial variation of a phenomenon within a given altitude zone. Changes in the height of the tongue are registered at nodal points of the network. The precision of this method depends on the size of the basic fields assumed. A. Davey (1962) used it to determine changes in the Blue Glacier in the state of Washington, USA.

The investigations on the Werenskiold Glacier were designed in a dense network of 1 cm—sided squares on a 1:5000 map (50 m in the field), based on the geographic coordinates. The initial lines were the meridian 15° 14'E and the parallel 77° 04′ 30″ N. In the map enclosed (Fig. 1) the intersections of every tenth line of the network of the basic fields are marked with crosses.

The District Geodetic and Cartographic Enterprise in Szczecin was asked to elaborate changes in height, volume, area and the resultant map. It was done by M. Lewandowski and P. Madeyski from the Remote Sensing Laboratory.

The heights of the glacier in 1957 and 1978 were read from the intersections of the lines of the basic network. A specification of these heights, when classified in rows and columns, was the base material for further computer processing. In addition, the ranges of the glacier in 1957 and 1978 were recorded (in the system of the basic fields) using a CODIMAT type digitometer. Similarly, the areas of the altitude zones were registered at intervals of 20 m, according to the 1957 map. The data so prepared were processed in an Odra 1305 computer using the NMT — GIPS system programme. This programme serves to make and process a numerical model of the area. One of the important functions of this system is condensation of the basic network, which performs the actual calculation of the numerical model. The large field network is condensed to a network whose basic fields corresponds to the type size of the printer i.e. 2.54×3.175 m in the field. On the basis of the condensed network of the basic fields, the areas of the altitude zones were calculated at intervals of 20 m in 1975 and also the changes in the ice volume within them till 1978 were determined.

The NMT — GIPS system permits visualization—print-out of resultant digital maps according to present parameters. In the case of the Werenskiold Glacier a print-out of the isolines in ice thickness changes was obtained on a 1:2500 scale. After reduction to a 1:10000 scale, it is shown in Fig. 1.

4. Results and discussion

Comparison of the states of the Werenskoild Glacier in 1957 and 1978 permits accurate, quantitative determination of its retreat and of changes in the relief (Fig. 1). The front of the glacier has retreated about 500 m (with a maximum of about 650 m and minimum of about 350 m). This signifies a mean annual recession rate of 23.8 m/year. It is interesting to observe the mean recession rate of this glacier since 1918 (partly after Kosiba, 1960 and Baranowski 1977). From 1918 to 1936 the recession was about 21 m/year from 1936 to 1958 it was 37 m/year, from 1958–1970 about w5 m/year and in 1970–1978 about 24 m/year. It can thus be seen that the intensive retreat from 1936 to 1958 was followed by a period of regular recession at an average rate of 24 m/year. It also shows the differentiation in the ground cover in this retreat by particular parts of the front.

The map in Fig. 1 shows the isolines of the ice thickness changes (the glacier height—dH) in the period under study. Those isolines were plotted at intervals of 2.5 m. The maximum lowering of the surface of the glacier was recorded in the northern part of the tongue in the area of the front limit in 1978 (max. dH = −50 m, i.e. with an average loss of 2.38 m/year). The southern lowered the most close to the median moraine (dH = 47.5 m) and close to the lateral moraine (dH = −45 m). These areas are related to the outlets of large sub- and inglacial chennels and also to superglacial streams. The lowering of the surface of the glacier decreases gradually up the lobe although numerous, slight irregularities occur in the variation of the isolines. The long time interval between the initial and the final registration of the state of the front makes it difficult to interpret the causes in detail.

Another phenomenon, quite conspicuous in Fig. 1, is the decrease in—dh closer to the lower parts of the front. This is shown distinctly by an investigation of the mean rate of the lowering of the surface in the altitude zones at intervals of 20 m. It is illustrated by the diagram in Fig. 2. These data were obtained from the division of the ice volume lost in a given altitude zone by its area. The maximum losses in the ice thickness were found at 80–100 m over the sea level (1.84 m/year). This lowering decreases at 20–10 m over the sea level to as little as 0.26 m/year, whereas as a rule it should increase as ablation increases. In turn, above 100 m over the sea level, the lowering of the front of the glacier decreases gradually) up to the investigation limit), corresponding to the decreasing ablation.

The zone of smaller mean values of — dH occurs at 20–80 m over the sea level and covers a belt 300–500 m wide. In explaining this anomaly it is necessary to exclude protection of the front from thawing by the rubble of the surface and ablation, moraines, which is quite common in the Alpes, for example. The front of this glacier is covered at many places by mineral powder, but its amount is very small, although it enhances the thawing of the ice by as much as 20 per cent, according to Baranowski (1977). The explanation should be sought in the subpolar character of this glacier. Baranowski (1977) established the existence of a zone of cold ice, frozen to the base in the front part. This zone can have a slower derease rate because of the temperature and the emergence of new ice portions related to the motion of the tongue. The cold front blocks the motion of the glacier and the shear planes bend upwards of the cold zone mentioned above.

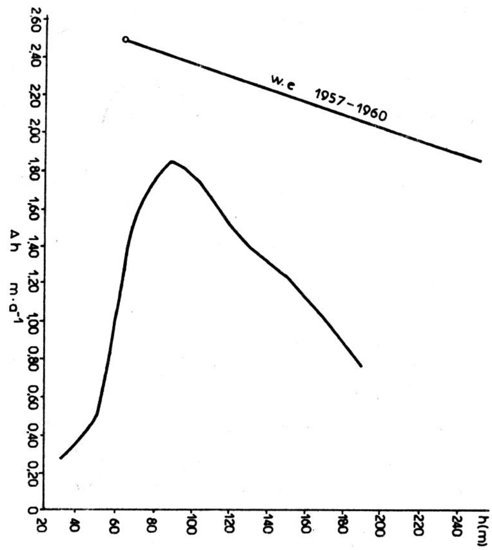

Fig. 2. The mean changes in the ice thickness in the front zone of the Werenskiold Glacier, depending on the altitude over the sea level: — dH — the mean lowering in m/years, +dH — the mean elevation in m/year

Another additional factor related to the lowest parts of the front is the presence of large snow drifts in winter. They cover some fragments of the front. Their formation is largely affected by katabatic and foehn winds blowing from the east along the axis of the glacier. Some thick snow patches survive the ablation season (e.g. in 1982) and affect the accumulaction of superimposed ice in the lowest parts of the glacier.

These phenomena account for the fact that in the course of its retreat the front of the Werenskiold Glacier leaves behind almost flat patches of cold relict ice. It is covered by the moraine material which emerges at the lines of the slide planes in the cold zone near the front and particularly by fluvioglacial sediments. In summary of this part of the results, it can be stated that the present comparison of photogrammetric registrations established the range of the compression zone related to the cold ice at the front of the glacier and also throws new light on the details of the formation of dead ice patches in the base of the internal marginal zone. These problems, however, require more exact investigations in shorter time periods, with consideration given to the vectors of the motion of the tongue and the distribution of shear stresses in the front zone.

The most important problem in photogrammetric investigations of the fluctuation of the glacier is the relation of the results obtained to the ablation measurements by direct or hydrometric methods, and, on a wider scale, to particular elements of the mass balance. It follows from the investigations by Baranowski and Głowicki (1975) of the ablation rate of this glacier versus metereological conditions and from the extrapolation of the results to the whole ablation seasons (Baranowski 1977) that the gradient of full ablation is equal to about 35 cm/100 m upgrade in the water equivalent. Kosiba (1960) showed that in the area of the ablation stake no. 33 (see Fig. 1) the net ablation in 1957–1958 was about 250 in the water equivalent (65 m over the sea level). Photogrammetric investigations showed a mean annual lowering of the surface of the glacier by about 130 cm of ice (corresponding to a water layer of about 116 cm, with the most frequent ice thickness in the front, 0.89 g/cm^3). For the same altitude Baranowski (1977) calculated the net ablation as 280 cm in the ablation season of 1970. These differences can be explained by the fact that photogrammetric registration does not account for the element of motion—the addition of new ice portions to the tongue. Fig. 2 shows the result of Kosiba's observation at the stake no. 33 and the line of the net ablation. The mean lowering of the front in the period under study was also calculated to the water equivalent. These lines are not parallel. The gradient calculated by Baranowski (C) is certainly too steep, as the network of ablation stakes used was not dense enough. The gradient represent by the plot for photogrammetric registration (B) is toot flat, since it only applies up to 200 m over the sea level. It must be steeper upwards of this, since Kosiba and Baranowski found the equilibrium line in the zone of about 380 m over the sea level. It seems, nevertheless that the result achieved photogrammetrically provides a more favourable averaging of results in particular altitude zones. In view of the subpolar glacier type (cold front), it is very difficult to account for the element of motion in the sense of the classical investigations of Meire and Tangborn (1965) and Nye (1965).

It is however, possible to evaluate the total mass loss in 1957–1978 from the part of the tongue of the Werenskiold Glacier under study with consideration given to its flow. A comparison of the maps showed a decrease of 125.8 mln m^3 in the volume of this part over 21 year, with an annual rate of 5.98 mln m^3. Measurements of the surface velocity of the tongue in a cross-section profile in the periods 1956–1959 and 1970–71 (Baranowski 1977, p. 57, Fig. 54) gave results of the order of 2–5 cm/day in the year. The necessary information about the cross-section of the Werenskiold Glacier in this profile was provided by the radio echo-sounding measurements of Czajkowski (1981). These data made it possible to evaluate the increment of ice to the glacier part investigated at about 28 mln m^3 in 1957–1978, i.e. at an average annual rate of 1.33 mln m^3. The total ice volume loss in the front part of the glacier is 7.32 mln m^3/year. Referred to the whole area under investigation this volume represents an ice layer of 1.54 m, i.e. about 1.38 m in the water equivalent. It is the mean, long-term value for the zone in question.

It is interesting to compare this result with the observations of Pulina et all (this issue), who were the first to calculate the mass balance of the Werenskiold Glacier in the hydrological year 1979/1980, measuring the ablation by the hydrological method. This balance is negative. The glacier loses 28.5 mln m^3 of water annually, which corresponds to a water layer of 0.65 m over the whole surface of the glacier. It can be concluded from photogrammetric investigations that the net balance of this glacier has remained negative for a long time. As was stressed above, the results and their discussion are not full. Further investigations are planned at present to explain the rate and direction of the motion of the tongue in the front zone, particularly at the interface of the cold ice with the active "warm" ice of the tongue. The results will become more detailed when the registrations of the state of the front in 1973 (Żyszkowski 1982) and in 1982 (Jania, Kolondra 1982) have been elaborated and compared with the results given here.

5. Резюме

Даны результаты сравнения фотограметрической регистрации состояния краевой части ледника Веренщельда в 1957 и в 1978 годах. Сравнивались две карты в масштабе 1:5000. Анализировалось уменьшение объема льда в высотных зонах через каждые 20 м (только до 200 м н.у.м), и изменения мощности льда при помощи сети основых квадратов со стороной в 50 м в поле с применением вычислительной машины Одра 1305. Это дало возможность составления карты изменений высоты края ледника с изолиниями через 2,5 м. Результаты фотограметрических исследований сравнивались с наблюдениями абляции, проведенными с применением абляционных вешек. Была проведена оценка общего и среднего годового уменьшения массы льда в краевой зоне ледника Веренщельда в исследуемом периоде, причем принималось во внимание движение ледникового языка.

6. Streszczenie

Artykuł zawiera wynik porównania fotogrametrycznych rejestracji stanu czołowej części Lodowca Werenskiolda w okresie 1957—1978. Zestawiono ze sobą dwie mapy w podziałce 1:5000. Analizowano ubytek objętości lodu w strefach wysokościowych co 20 m (tylko do 200 m npm) oraz zmiany miąższości lodu przy pomocy sieci kwadratów podstawowych o boku 50 m w terenie, z zastosowaniem komputera Odra 1305. Pozwoliło to na wykreślenie mapy zmian wysokości czoła z izoliniami co 2,5 m. Wyniki badań fotogrametrycznych

zestawiono z obserwacjami ablacji z użyciem tyczek ablacyjnych. Uwzględniając ruch jęzora oszacowano ogólny i średni roczny ubytek masy lodowej w strefie czołowej Lodowca Werenskiolda w badanym okresie.

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8. Summary.

The aim of this investigation is to determine changes in the ice volume and height of the Werenskiold Glacier (Spitsbergen) in is front zone up to 200 m over the sea level (Fig. 1). Two regiostrations of the state of the front of the glacier taken, in 1957 and 1978, by terrestrial photogrammetry were used. On their basis two 1-5000 maps with contour lines on the glacier at intervals of 2.5 m were made (Lipert 1961, Mechliński 1979). These maps were "suspeimposed" while height changes were analyzed in a network of 1 cm-sided squares (50 m in the field). The effect is a map of changes in the relief of the front of the Werenskiold Glacier over an interval of 21 years on a 1:10000 scale and with height change isolines (dh) at every 2.5 m (Fig. 2). This elaboration was made with an Odra 1305 computer, using the NMP-GIPS programme (numerical terrain model) at the District Geodetic and Cartographic Enterprise in Szczecin.

Volume changes, which are related to the ice mass loss, were calculated for altitude zones at every 20 m. They were also recalculated to the mean annual lowering of these altitude zones, as given in Fig. 2. The total loss of the glacier volume in the part of the tongue investigated from 1957 to 1978(125.8 mln m^3) and the mean annual loss (5.99 mln m^3/year) were also calculated. Taking into account the addition of ice to the front caused by motion of the glacier, the annual loss was determined at about 7.32 mln m^3 of ice. This corresponds to the thawing of a water layer 1.38 m thick. The results obtained were compared with those of the classical ablation investigations performed on this glacier in 1957–1959 by Kosiba (1960), in 1970 and the later years by Baranowski (1977) and in the season 1978/1980 by Pulina (1981).

On the basis of an anomaly in the variation in ice loss in particular altitude zones (Fig. 2), the relation was shown between the presence of dead ice patches in the forefield of the glacier and the smaller ice loss caused by the cold compression zone in the front and the presence of snow drifts.

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