Fig. 2. The Hodges Glacier which occupies the south-facing cirque of Petrel Peak. Photograph taken 4 February 1957

Fig. 6. View of the Hamberg Glacier from the east coast of Moraine Fjord. Photograph taken 2 February 1957 *(see p. 707–14)*

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Fig. 7. View of the Harker Glacier from 304 m. (1,000 ft.) a.s.l. on the east coast of Moraine Fjord. Photograph taken 2 February 1957 (see p. 711)

Fig. 8. Moraines in the Hamberg Lakes, indicating the former extent of the small glacier now occupying the head of the valley, viewed from Mount Duse at 320 m. (1,050 ft.). Photograph taken 7 March 1958 (see p. 713)

GLACIER PROBLEMS IN SOUTH GEORGIA*

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Abstract. This paper is a synopsis of *Falkland Islands Dependencies Survey Scientific Report* No. 29. Glaciological and climatic investigations carried out in South Georgia during the International Geophysical Year are described. The budgets of the Hodges and Hamberg Glaciers for 1957-58 are given and discussed in relation to climatic factors. Temperature measurements indicate that the Hodges Glacier, and probably all ice in South Georgia below an altitude of 1,000 m., is geophysically temperate. The fluctuations of South Georgian glaciers during relatively recent times are briefly discussed.

Résumé. Cette communication résume *Falkland Islands Dependencies Survey Scientific Report* No. 29. On décrit des enquêtes poursuivies dans la Georgie du Sud pendant l'Année Géophysique Internationale. Les bilans des glaciers Hodges et Hamberg pendant 1957-58 sont exposés, et on discute les rapports de ceux-ci avec les facteurs climatiques. Les températures observées semblent indiquer que le Hodges Glacier, et probablement toute la glace de la Georgie du Sud située à une altitude inférieure à 1000 m, sont tempérés. On discute les oscillations des glaciers de la Georgie du Sud pendant une époque relativement récente.

Zusammenfassung. Der nachfolgende Aufsatz ist eine Zusammenfassung des *Falkland Islands Dependencies Survey Scientific Report* Nr. 29. Gletscherkundliche und klimatische Untersuchungen, die im Laufe des Internationalen Geophysikalischen Jahres in Süd-Georgien vorgenommen wurden, werden beschrieben. Der Haushalt für den Hodges- und den Hamberg-Gletscher für die Jahre 1957/58 wird angegeben und dessen Beziehung zu klimatischen Faktoren besprochen. Temperaturmessungen deuten darauf hin, dass der Hodges-Gletscher und vermutlich das ganze unter 1000 m liegende Eis in Süd-Georgien geophysikalisch gemässigt ist. Gletscherschwankungen in relativ rezenter Zeit in Süd-Georgien werden besprochen.

Introduction

About 2,000 kilometres east of Cape Horn and the same distance from the coast of Antarctica is the mountainous island of South Georgia (lat. 54-55° S., long. 36-38° W.). It is the largest island in the Scotia Arc, being about 170 km. long by 30 km. broad (Fig. 1). Its highest point is Mount Paget (2,934 m.). The climate is cool, wet and windy on account of its position south of the Antarctic Convergence and within the sub-antarctic cyclonic zone; the mean annual temperature at Grytviken, the principal settlement, is +1·7° C., and the mean annual precipitation is 1,395 mm. 58 per cent of South Georgia is covered by ice, making it one of the most extensively glacierized sub-antarctic islands. During the International Geophysical Year, 1957-58, it was chosen by the Royal Society as a centre for glaciological studies. The complete results of this work will be published shortly as *Falkland Islands Dependencies Survey Scientific Report* No. 29,[1] of which this paper is a summary.

The scanty literature on the glaciology of South Georgia is mainly descriptive, and has arisen from the visits of expeditions whose principal interests were in other fields.[2, 3, 4] Consequently, a broad programme of glaciological and climatological investigations suggested itself for the I.G.Y. Following Ahlmann's classical work around the North Atlantic coasts,[5] the activities of several glaciers and their climatological interrelationships were studied on three time-scales. First, the daily and monthly changes in mass which comprise one budget year were related to synoptic meteorological events. Secondly, the oscillations in the positions of glacier snouts over the past century were compared with concurrent climatic records. Finally, the later Quaternary climatic variations were studied by examining moraines and other evidence of changes in glacierization.

Two glaciers were selected for detailed budget observations. One, the Hodges Glacier, is a cirque glacier near Grytviken and the other, the Hamberg Glacier, is a mountain valley glacier draining from the principal mountain range (the Allardyce Range) of the island.

* Substance of a lecture given to the British Glaciological Society at Birmingham, 23 October 1958, and at Cambridge, 24 October 1958.

THE HODGES GLACIER

The Hodges Glacier, of which a photograph is shown in Figure 2 (p. 705) and a map in Figure 3, occupies the south-facing cirque of Petrel Peak (634 m.). It is roughly oval in shape, 0·27 km.^{2} in area, has an average surface slope of 22 degrees and ranges in altitude from 600 to 280 m. The firn limit is at an altitude of 460 m. Twelve stakes were erected in January

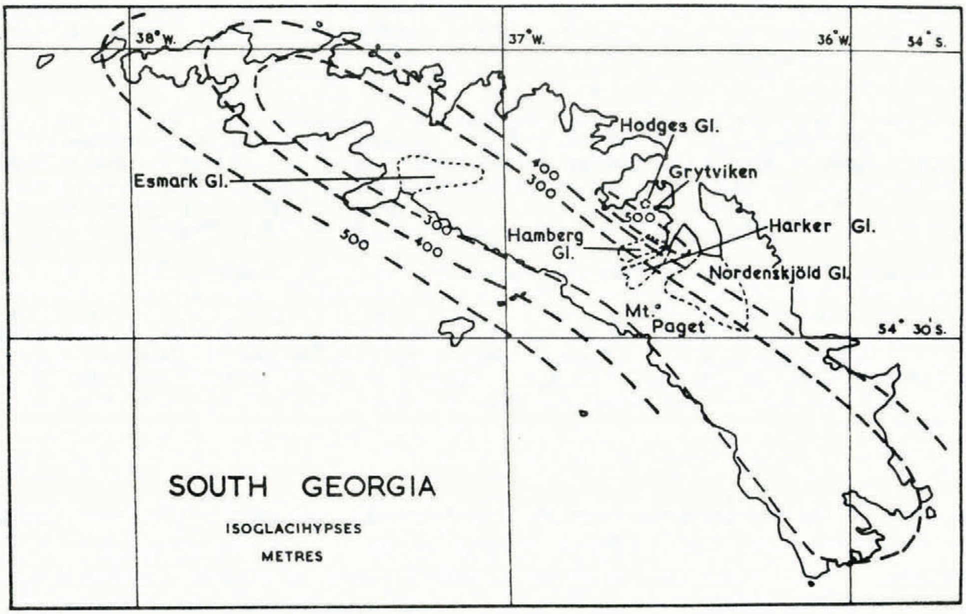

Fig. 1. Sketch map of South Georgia, showing localities of glaciers investigated and isoglacihypses in metres

1957 for budget measurements, and these had been visited 62 times by April 1958. The 1957 accumulation season started on 15 April and lasted until 25 October, whereas the succeeding ablation season lasted until 14 April 1958. A synopsis of the 1957-58 budget is given in Table I; it is also illustrated in Figure 3 by means of lines of equal net accumulation or ablation.

TABLE I. BUDGET OF THE HODGES GLACIER, 1957-58

Gross accumulation	$+494\times10^3$ m.^{3} water
Gross ablation	-535×10^3 m.^{3} water
Net accumulation of accumulation region	$+\ 34\times10^3$ m.^{3} water
Net ablation of ablation region	$-\ 73\times10^3$ m.^{3} water
Internal and basal melting	$-\ 2\times10^3$ m.^{3} water
Budget	$-\ 41\times10^3$ m.^{3} water $=-15\cdot0$ cm./unit area of glacier

Heavy accumulation in winter and strong melting in summer are characteristic of glaciers in the cyclonic climatic zones. In South Georgia the accumulation was found to result predominantly from precipitation, additions of ice by the freezing of rain and melt water being comparatively small. The heat exchange which results in ablation was calculated

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for a point approximately 100 m. below the firn limit (Table II) using the formula and empirical relationships of Sverdrup,[6] Wallén[7] and Kimball.[8] Evidently the meteorological factors, convection and condensation, have important rôles in comparison with radiation which accounts for only 35 per cent of ablation.

TABLE II. CAUSES OF ACCUMULATION AND ABLATION ON THE HODGES GLACIER

Accumulation		*Ablation*	
Solid precipitation	79%	Radiation	35%
Drifting	16%	Convection	35%
Freezing of rain	5%	Condensation	30%
Rime	<1%		

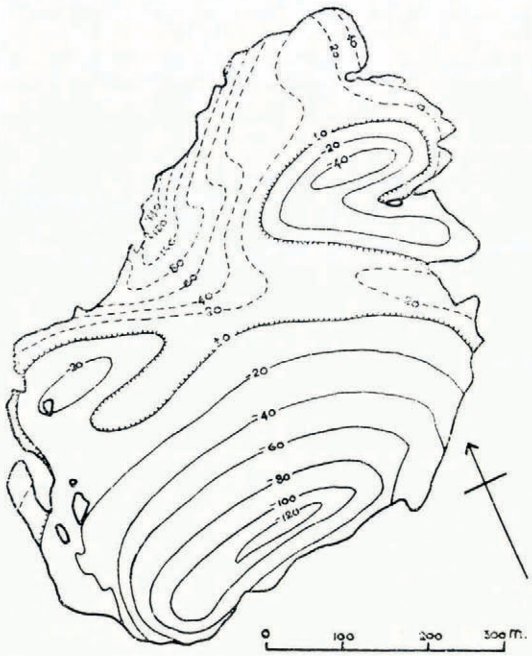

Fig. 3. Sketch map of the Hodges Glacier showing lines of equal accumulation (pecked; in cm. of snow) and ablation (solid; in cm. of ice)

The Hodges Glacier is geophysically temperate as, probably, is all the ice in South Georgia below an altitude of 1,000 m. The cold wave reached about 20 m. below the surface and lasted for 152 days at an altitude of 345 m., but at 524 m. it lasted for 213 days (Fig. 4). It was eliminated rapidly at the onset of the ablation season by the latent heat liberated by the re-freezing of melt water. As a result a layer of superimposed ice, between 6 and 22 cm. in thickness, formed at the base of the 1957 accumulation.

The precise meteorological factors causing glacier fluctuations are not always known. Ablation is affected by changes in cloudiness, temperature, wind velocity or humidity, while accumulation is affected by changes in precipitation, wind velocity and temperature. In Table III, Column 1, have been calculated the changes in five factors necessary to increase the ablation of the Hodges Glacier by 22 cm. or 10 per cent of the ablation during the 1957-58 season. In Column 2 the changes are expressed as percentages of the variabilities actually experienced during the period 1944-58. A high percentage in Column 2 indicates that the change in that factor required to decrease the budget by the given amount is large in comparison with the variability actually experienced. Consequently, that factor is less critical in causing variations in the budget from year to year. Temperature, therefore, is the most influential factor, and cloudiness the least, while precipitation, wind velocity and humidity

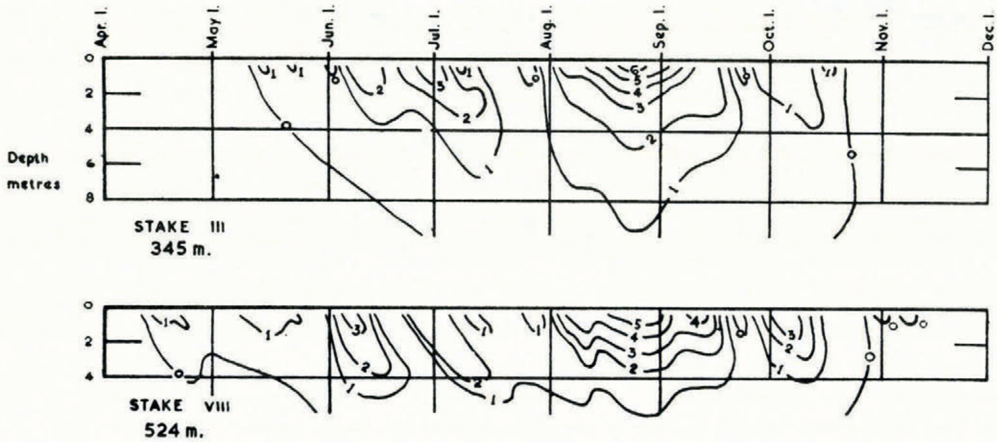

Fig. 4. Isotherms at stakes III (345 m.) and VIII (524 m.) on the Hodges Glacier for the period 1 April to 1 December 1957. Temperatures are given in negative ° C.

have a moderate influence on the regime of the Hodges Glacier. From this, and considering the relatively simple synoptic climatology of South Georgia, it is concluded that an enlargement of the Hodges Glacier would most probably be caused by a northerly shift of the average track of depressions across the Scotia Sea, which, in turn, would result from a northerly extension of the Antarctic pack ice.

TABLE III. RELATIVE IMPORTANCE OF METEOROLOGICAL FACTORS UPON THE BUDGET OF THE HODGES GLACIER

Factor and units	*1. Change required to reduce budget by 22 cm.*	*2. As percentage of standard deviation from mean 1944-58*
Cloudiness (tenths)	−1·35	300
Temperature (° C.)	+0·14	36
Wind velocity (cm./sec.)	+88	137
Humidity (mm. mercury)	+0·19	95
Precipitation (cm.)	−18	75

Relating the recent changes in activity of the Hodges Glacier to climatic records at Grytviken depended upon discovering the temperature gradients between various points on the glacier and sea-level at Grytviken. A thermograph screen was erected on the glacier at an altitude of 345 m., and the 115 days' records obtained during the 1957-58 ablation season showed that the mean lapse-rate between this point and Grytviken is 0·98° C./100 m., or practically the dry adiabatic lapse-rate. Over the surface of the glacier an indication of the temperature gradient was obtained by relating the daily ablation rate, da/dT, at four selected stakes to the mean daily temperature at Grytviken, θ, to give a relationship

$$\frac{da}{dT} = (\theta - c)b \text{ cm./day.}$$

b is an empirical constant with the dimensions cm./day ° C. and c is the minimum temperature at Grytviken at which ablation takes place at the altitude under consideration. The latter value was found to change with altitude by 0·30° C./100 m. which, therefore, is the temperature lapse-rate over the surface of the glacier.

The temperature structure of the Hodges Glacier is illustrated in Figure 5. Between

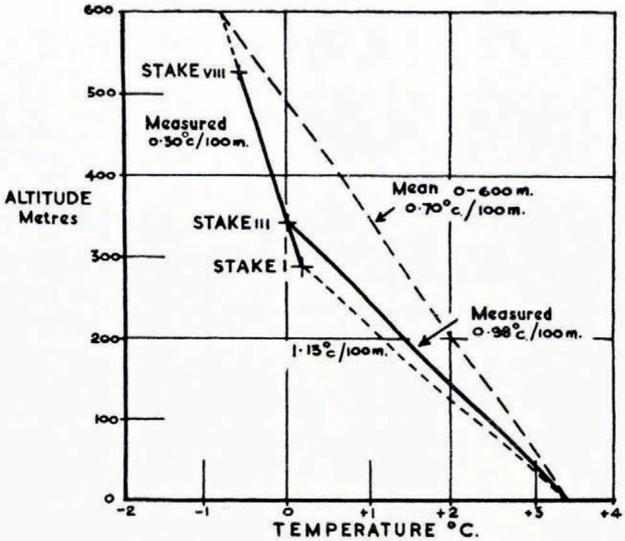

Fig. 5. Graphical representation of the temperature structure of the Hodges Glacier

Grytviken (at sea-level) and the foot of the glacier the temperature gradient is 1·13° C./100 m.; over the glacier it is 0·30° C./100 m., while between sea-level and 600 m., the overall gradient is 0·70° C./100 m. This phenomenon is thought to result from the subsidence of cold air over the smooth glacier surface.

The Hamberg Glacier

Fifteen kilometres south-west of Grytviken is the Allardyce Range, which forms the island's watershed and contains its highest summits. All the ice draining from the north-eastern side of the Allardyce Range reaches Cumberland Bay by six large mountain valley glaciers. Three of these, the Hamberg (Fig. 6, p. 705), Harker (Fig. 7, p. 706) and Nordenskjöld Glaciers, were visited from time to time and, in response to the emphasis placed on the estimation of budgets by I.G.Y. observers, the data obtained from these glaciers have been combined in order to obtain the 1957-58 budget of the Hamberg Glacier (Table IV).

The Hamberg Glacier is 7·45 km. long and 11·4 km.^{2} in area. Its altitude range is 2,000 m. and the firn limit is at about 500 m. above sea-level. It calves into Moraine Fjord and, during the budget year 1957-58, the ice cliffs receded an average distance of 80 m. The net loss of $2 \cdot 9 \times 10^6$ m.^{3} is of the same order as the measured recession of the ice cliffs, $4 \cdot 5 \times 10^6$ m.^{3}.

TABLE IV. BUDGET OF THE HAMBERG GLACIER × 10^6 m.³ WATER

Month	*Accumulation*	*Ablation*	
		Melting	*Calving*
April 1957	+3·1	−1·6	−1·4
May	+2·5	−0·9	−0·9
June	+3·3	0·0	−1·5
July	+4·2	0·0	−1·5
August	+2·2	0·0	−0·5
September	+4·5	−0·1	−1·1
October	+4·1	−0·4	−0·9
November	+0·5	−3·1	−0·5
December	+0·8	−2·9	−0·5
January 1958	+0·6	−4·5	−0·7
February	+2·7	−1·9	−2·8
March	+1·3	−2·5	−2·5
Total	+29·8	−17·9	−14·8

Budget −2·9 × 10^6 m.³ water

One of the problems arising in estimating the budget of the Hamberg Glacier was the determination of the amount of ice lost by calving. Two observations were made periodically: a plane-table survey of the terminal ice cliffs which enabled the change in area to be measured, and a photograph of the ice fall, 2·5 km. from the terminus, from which the surface velocity could be estimated. In addition, the thickness of ice at the terminus was found by sounding the depth of the fjord and measuring by Indian clinometer the height of ice cliffs. The cross-section of the glacier at the site of the movement observations was estimated by extrapolating the valley walls into a suitable U-shape.

The mean axial velocity in the ice fall was 2·3 m./day during the 1957-58 ablation season and the marginal velocity was approximately 10 per cent of this. Assuming parabolic velocity gradients both laterally and vertically, a basal shear equal to the marginal shear,[9] and that in winter the glacier flows at 90 per cent of the summer velocity,[10] a graphical integration gave a discharge through the ice fall of 2·7 × 10^6 m.³/month from November to April, and 2·3 × 10^6 m.³/month between May and October. From these values were subtracted the amounts of ice ablated each month beneath the ice fall, to give the discharge through the terminal ice cliffs. Finally, the gain or loss of volume at the terminus, measured by plane-table, were respectively subtracted from or added to the discharge through the ice cliffs to give the actual loss of ice by calving.

THE NORDENSKJÖLD GLACIER

At the end of August 1957 a journey was made on the Nordenskjöld Glacier in order to study the winter accumulation at various altitudes. Pits were dug in the firn at 130, 390, 670 and 940 m. above sea-level, and in each of these it was possible to recognize the sequence of snowfalls and thaws which characterized the winter snow of the Hodges Glacier. A comparison of the accumulation on the two glaciers shows that, at similar altitudes, accumulation commences sooner on the Nordenskjöld Glacier and is approximately 30 per cent greater than on the Hodges Glacier.

THE ESMARK GLACIER

The south-western coast of South Georgia is not so well known as the north-eastern coast but reports suggest that it is the more extensively glacierized.[2, 3, 11] This is illustrated in Figure 1, where the isoglacihypses (lines of equal altitude of the climatic firn limit) show that the firn limit is about 150 m. lower on the south-western than on the north-eastern coast.

This is found to be due to the more severe climatic conditions on the south-western coast, the climate of the north-eastern coast being modified by föhn and rain-shadow effects. The Esmark Glacier was visited in September 1957, and accumulation was found to be 50 to 100 per cent greater on this south-west coast glacier than at comparable altitudes on the Nordenskjöld Glacier. An interesting observation on the Esmark Glacier was that at approximately equal altitudes and depths the firn was warmer than on the Hodges Glacier. Furthermore, the winter accumulation was composed principally of medium- and coarse-grained firn, whereas on the Hodges and Nordenskjöld Glaciers it was predominantly fine-grained firn. The condensation of rime is considerable on the south-western side of South Georgia. All rock faces above 500 m. were entirely encrusted during our visit and it is thought that the latent heats of vaporization and fusion, liberated during the accretion of rime, warm the firn. If its temperature rises to 0° C. further condensation is in the form of water which percolates through the firn and increases its grain size.

Historical Studies

Historical studies of South Georgian glaciers show that recently they have been in their most advanced positions for several thousands of years. The culmination of this glacial advance preceded the meteorological records at Grytviken, but by using climatic [12, 13] and glaciological [14] records from South America, it is tentatively dated at about 1875. More recently, a deterioration in the climate at Grytviken started in 1924 and the responses by a number of glaciers have been studied with the aid of photographs taken from time to time by visiting expeditions. The large sea-calving glaciers had completed their advances between 2 and 5 yr. from this date; but, in the case of a cirque glacier with a land terminus, the delay was between 4 and 12 yr.

Before 1875 there was a long period when the climate was as warm as, or warmer than, at present. The youngest Pleistocene moraines have a mature carpet of the climax vegetation but a very angular micro-relief. They are tentatively correlated with the post-Allerød moraines of northern Europe. Three older series of moraines (see Fig. 8, p. 706) are present and, judging by their state of preservation, they are relatively close to each other in age. In accordance with Caldenius's [15] work in the southern Andes, they are referred to the three phases of the Würm glaciation. There is also evidence for an older and more extensive glaciation in South Georgia but its moraines are not well preserved.

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