OBSERVATIONS ON THE ICE CAPS OF GALINDEZ AND SKUA ISLANDS, ARGENTINE ISLANDS, 1960–66

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ABSTRACT. The accumulation and ablation of snow and ice were measured on the ice cap of Galindez Island, Argentine Islands, during the 1965–66 budget year. A dense pattern of stakes was used to measure snow-surface height and snow density which were representative of the whole ice cap. Frequent observations were made so that the mass budget could be accurately determined. The movement of the ice cap was investigated in detail and the specific wastage due to irregular calving was calculated. Both the mass-budget and the movement studies were linked to previous investigations (1960–62) to give long-term averages.

Accumulation and ablation studies were also made on the Skua Island ice cap so that a comparison with the nearby Galindez Island ice cap could be made.

Meteorological and solar-radiation data were collected and summarized to investigate their relationship to the observed snow ablation. Snow- and ice-temperature profiles have been used to demonstrate the effect of the climate on the interior of the ice cap.

THE Argentine Islands are a small group of islands which lie 7 km. west of the Antarctic Peninsula in lat. 65°15′S., long. 64°17′W. (Fig. 1). One of these, Galindez Island, supports a dome-shaped ice cap (Fig. 2) whilst Skua Island, 1 km. farther south-west, has an undulating ice cap. These two ice caps, with respective areas of $15 \cdot 1 \times 10^4$ and $20 \cdot 9 \times 10^4$ m.^{2}, were studied during the 1965–66 budget year. Galindez Island represents a typical small detached ice cap in the Argentine Islands, whereas Skua Island possesses the largest ice cap and it has a substantially different topography.

All the larger members of the Argentine Islands support ice caps, whilst most of the smaller ones have an ice foot and the ice cover is thick in comparison with the amount of rock above sea-level (Fig. 3; Thomas, 1963, fig. 3). The majority of the ice caps are in the lee of exposed rocks on the north ends of the islands and they are symmetrical about a north-north-east to south-south-west axis. The ice caps rise to gently rounded summits and terminate at their southern ends in ice cliffs up to 50 m. high. These cliffs are generally undermined by caves and the ice rests on rock at about sea-level. On Galindez and Skua Islands the permanent ice covers 40 and 50 per cent of their respective total areas.

The ice caps of the Argentine Islands are similar in many respects to the Puffball Islands in southern Marguerite Bay (Fuchs, 1951) and the Wauwermans Islands south of Anvers Island (Gourdon, 1908). Both of these other island groups have little exposed rock and their ice cover is distinctly orientated.

The present studies are based on 13 months' field work which was intended to continue and expand Thomas's (1963) glaciological studies. Mass-budget determination required measurements of snow-surface height and snow density, ice movement, and snow and ice temperatures. Also, the climate was recorded by synoptic meteorological observations and solar-radiation measurements so that its effect on the snow cover could be evaluated.

PREVIOUS WORK

The first glaciological work in the Antarctic Peninsula was carried out by Arçtowski (1900), who described the Moureaux Islands in Flanders Bay as being low and completely covered with a cap of ice except on the perimeter. Several scientists working under Charcot in two expeditions made general glaciological observations (Gourdon, 1908) and regular meteorological observations whilst wintering at Booth Island and Petermann Island. The British Imperial Expedition found that the weather on the Danco Coast during 1921–22 was "almost identical to that experienced by Charcot 10 years previously" (Lester, 1923). Holtedahl (1929, p. 122) observed dome-shaped ice masses on small islands in the Palmer Archipelago but he thought that the underlying rock was dome-shaped and that the phenomenon was of no consequence.

The British Graham Land Expedition made meteorological observations at the Argentine Islands for 11 months during 1935–36 (Fleming and others, 1938), and Fleming (1940) studied the glaciology of the western seaboard of Graham Land. He concluded that the present island

Fig. 1. Map of the Argentine Islands showing the main survey stations.

Fig. 2. Panorama of the Galindez Island ice cap from the eastern extremity of the island. (Photograph by J. A. Thoday.)

Fig. 3. The southern ice cliffs of Galindez Island viewed from the summit of Winter Island (May 1966). (Photograph by P. D. Morgan.)

ice caps and coastal "fringing" glaciers were relics of a formerly extensive ice sheet which is now reduced to several minor ice shelves in Beascochea and Marguerite Bays. Fleming observed snow giving way to old hard ice during three successive summers at the Argentine Islands and hence believed that there was a marked excess of ablation over accumulation. He therefore concluded that the relict ice caps and glaciers were out of proportion in the present climate and would disappear in "a few years". It is now thought that part of the winter's snow accumulation becomes superimposed ice even during a warm summer (Roe, 1960, p. 4), and Thomas (1963, p. 36–38) has shown that there has been no great change since 1935. An example of the viability of drift deposits in the lee of obstructions has occurred at Marina Point, Galindez Island. Here the construction of a new hut led in 10 years to the build-up of a 10 m. high and 50 m. long mass to the south-west in spite of the enhanced ablation caused by human habitation.

The Falkland Islands Dependencies Survey set up a scientific station on Winter Island in the Argentine Islands in 1947 and this was replaced by one on the north-western extremity of Galindez Island in 1954. Continuous meteorological records have been kept from 1947 to the present time, whilst solar-radiation records commenced in 1957 and are still continuing. Roe (1960) measured snow-surface height and dug pits for density observations on the summits of Galindez, Winter and Uruguay Islands. He concluded that ice accumulated at a rate of about 6 cm. yr.$^{-1}$ and that the positive budget for June 1958 to February 1960 was atypical. On Winter Island he measured ice movement of about 20–50 cm. yr.$^{-1}$ over a 5-month period with a line of stakes 30 m. from the edge of the ice cliff.

From August 1960 to January 1962 more detailed glaciological observations were made by Thomas (1963) on Galindez Island. He set up a rectangular stake pattern at which he measured snow depth and snow density every few months. A. J. Schärer continued some of the work from January 1962 to March 1963. From these measurements, snow depths over a 2-yr. period were calculated and the mean annual net accumulation for 1958–63 was found to be

+20 cm. of water at one site. These same stakes were surveyed three times at yearly intervals and a very small movement was derived for stakes more than 50 m. from the edge of the southern ice cliffs of Galindez Island.

Snow-level Studies on Galindez Island

1965–66 budget year

Snow-level recording

The depths of snow which had fallen at any time during the budget year and the consequent level of the ice cap were recorded frequently by means of a network of stakes. The normal method, which uses the exposed part of the stake as a yardstick, was supplemented by readings of the depth from the snow surface to the ice layers. These readings were obtained by probing with a ski-stick. Intrinsically, ablation can be measured more accurately by a bore hole than by a stake but, because there is some accumulation in the ablation season, bore holes are impractical at the Argentine Islands.

The stakes remaining from a previous rectangular pattern, which sampled the ice cap at 100 m. intervals (Thomas, 1963), were an adequate basis for the present work. These stakes were identified from Thomas's (1963, p. 28) map of Galindez Island and the missing ones were replaced in the usual manner. They were visited on skis and the readings were taken with a measuring stick and recorded on a Perspex sheet with a chinagraph pencil. Readings were transferred to a permanent record book in the main hut of the station. Frequent visits were made to record how the ice cap reacted to all meteorological conditions.

The start of the budget year was 31 March 1965, because the lowest surface levels occurred mainly then, and the snow level relative to the stake on that date was taken as the datum for transforming the stake readings into heights of snow accumulated. These heights were then immediately comparable with those determined by the ski-stick method and thus gross error was eliminated. Whenever a stake was lengthened, a new datum was calculated and used as long as the extra stake remained in place.

Fig. 4 shows the detailed changes in snow level at four representative stakes and they were

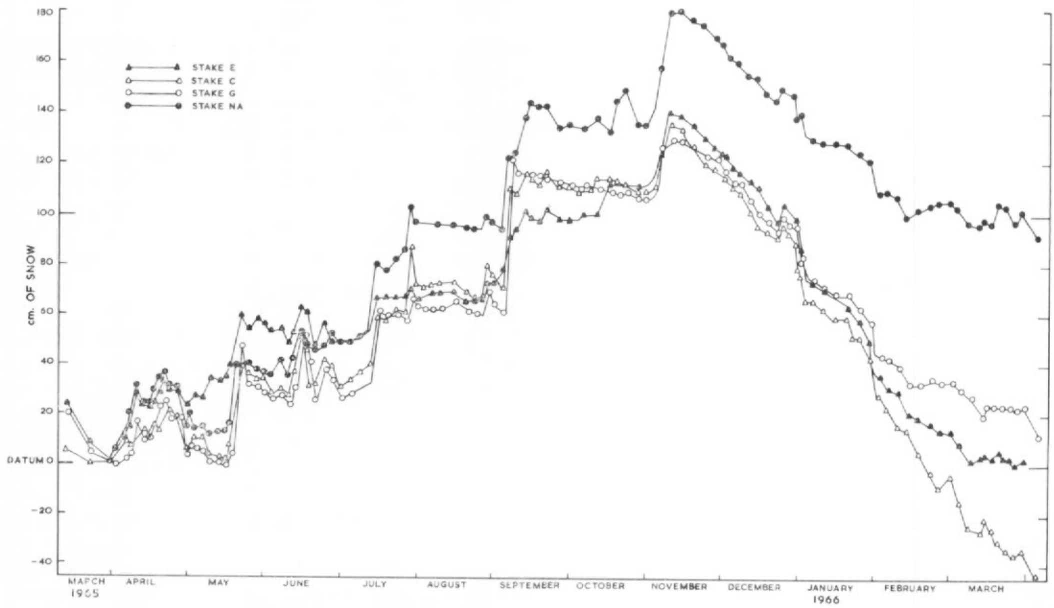

Fig. 4. Heights of snow accumulation for 1965–66 relative to 31 March 1965 at four selected stakes on Galindez Island. Changes in gradient between observations are made by reference to other stakes and weather conditions.

similar to each other until mid-July. The snow-surface height continued to increase until 10 November and the southernmost part of the ice cap (e.g. stake NA) attained a much greater height than the remainder (maximum 275 cm. at stake P and minimum 105 cm. at stake F). The decrease in snow-surface height during the ablation season was very regular at all sites.

During the first half of the ablation season, surface heights were still similar except at stake NA. However, during the second half of this season more rock was exposed so that the snow to the north of Woozle Hill (e.g. stake C) ablated more than that on the ice cap proper (e.g. stage G). Temperatures also rose to their highest for the year (Table V) and run-off occurred at stakes such as C and E.

Snow-level parameters

Certain interesting parameters were derived from the stake heights measured on Galindez Island. An overall mean of heights (Σh) measured on any day was computed. A comparison between these values and the true means (see below) shows that the error introduced by omitting a few stakes was quite small during the accumulation season.

Parameter e is the mean height at nine stakes, which represent approximately area for area the whole of the ice cap proper. Missing values are estimated so that the means are unbiased. The nine stakes were chosen because their sites had a slope of less than 10° (Fig. 11) and the least number of missing observations. e reached a maximum (Fig. 5) of 154 cm. on 10 November 1965 and diminished to 50 cm. on 13 March 1966. As the situation would suggest, this final snow height was considerably greater than that for the mean of all stakes.

The dates when the accumulation and ablation seasons began each year, from 1958 onwards, are given in Table I. This shows that the accumulation season most often commences in mid-March whilst the ablation season usually starts in mid-November.

TABLE I. ACCUMULATION AND ABLATION SEASON DATES

Budget year	*Start of accumulation*	*Start of ablation*
1958–59	13 March 1958	23 November 1958
1959–60	30 January 1959*	5 December 1959
1960–61	19 March 1960	2 November 1960
1961–62	17 March 1961	26 October 1961*
1962–63	23 March 1962	16 November 1962
1963–64	16 February 1963*	30 November 1963*
1964–65	—	—
1965–66	31 March 1965	10 November 1965
1966–67	5 April 1966	November 1966*

* Approximate dates.

Profiles

A series of profiles was drawn to illustrate the variation of accumulation and ablation along the north–south axis of the Galindez Island ice cap (Figs. 6 and 11) during 1965–66. The line of stakes G to GB was chosen for this purpose, the southernmost point being designated GE (the mean of GC and FC). The heights above sea-level are also shown for comparison. The accumulation was comparatively steady over three-quarters of the ice cap with a tremendous increase to the south of stake GB.

Comparisons

Previous work

The preceding detailed results for one budget year were compared with data at 13 stakes over a 5-yr. period. The difference in snow-surface height between 12 August 1960 and 15 August 1965 had a mean rate of change of 28 cm. of snow per year with a range on the ice cap proper of 22 to 40 cm. of snow per year (Fig. 7). The net accumulation at stakes GA and GB of 27 and 23 cm. of snow per year, respectively, is directly comparable with 31 cm. of snow per year for 1958–63 (Thomas, 1963, p. 38, table II). The mean for April 1958 to August 1965 on the top of the ice cap was thus 26 cm. of snow per year. A comparison between the 1960–65 figures and the 1965–66 budget year showed that the latter had a much lower net snow accumulation than average, but the relative snow accumulation between the 13 stakes was strikingly constant. A plot of the 5-yr. mean net snow-accumulation figures was made (Fig. 7) with tentative contours on the ice cap proper.

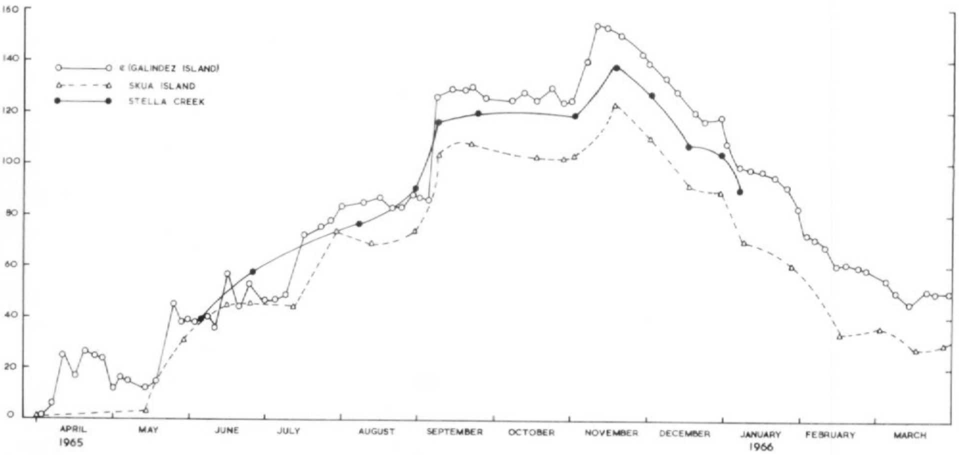

Fig. 5. Mean snow-surface heights for 1965–66 on the Galindez and Skua Islands ice caps and the sea ice of Stella Creek. The sea-ice readings ceased on 6 January 1966 when it became unsafe.

Skua Island and sea ice

A comparison between the heights of snow accumulation on the Galindez Island and Skua Island (p. 39) ice caps has also been made. The mean snow heights on Skua Island followed the same pattern throughout the year as those on Galindez Island but with a consistently lower magnitude (Fig. 5). The ratio of the height on Galindez Island (Σh) to the height on Skua Island on the same day was then evaluated (Sadler, 1967, table XI). The mean height ratio was 1·25 during both the ablation and accumulation seasons. This indicates that the level of the Skua Island ice cap changed by one-quarter less than that on Galindez Island. A comparison with the mean for Galindez Island (e) showed a constant height ratio during the accumulation season of $1 \cdot 20 \pm 0 \cdot 05$ and a rate of ablation very similar to that of e until the snow cover gave way to solid ice in places.

Snow-surface height readings were made at a stake sited on the sea ice in Stella Creek during the period 3 June 1965 to 6 January 1966. A datum height of 39 cm., equal to e, has been assumed for the first date and this gives snow-surface heights (Fig. 5) which are broadly similar to e.

Snow-density Studies on Galindez Island

The amount of time available for density measurements governed the methods used. The author realized the advantages of sampling all constituent parts of a snow column to derive

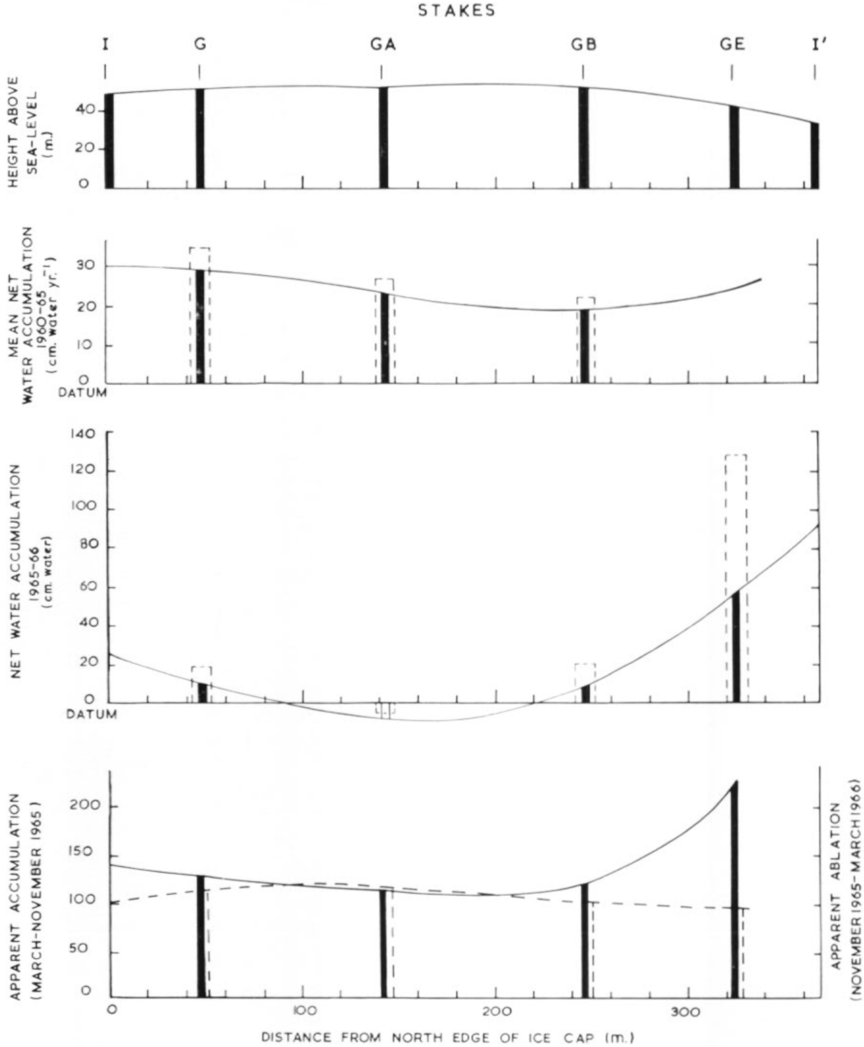

Fig. 6. Accumulation and ablation profiles along the axis of Galindez Island. For the location of these profiles see Fig. 11. In each of the profiles the height of the solid columns represents centimetres of water, whilst the height of the dashed-line columns represents centimetres of snow.

its true mean density. However, it was necessary to rely on sample columns taken *in toto* and supplemented by constituent densities when possible. This method is further necessary because the variation in snow cover from one point to another suggests a variable snow mass. Hence several sites near accumulation stakes are required to give both a mean figure and the probable variation.

The basic method was to sample the whole vertical column above a fixed datum. A cylindrical sample of constant cross-section was obtained by pushing an aluminium density tube (length 1 m., cross-section 12 cm.^{2}) into the snow. The cross-section of the snow-density tube was determined with a pair of vernier calipers. The exact sampling site was chosen within a 5 m. radius of the relevant stake but in a different position from previous density sampling during that budget year.

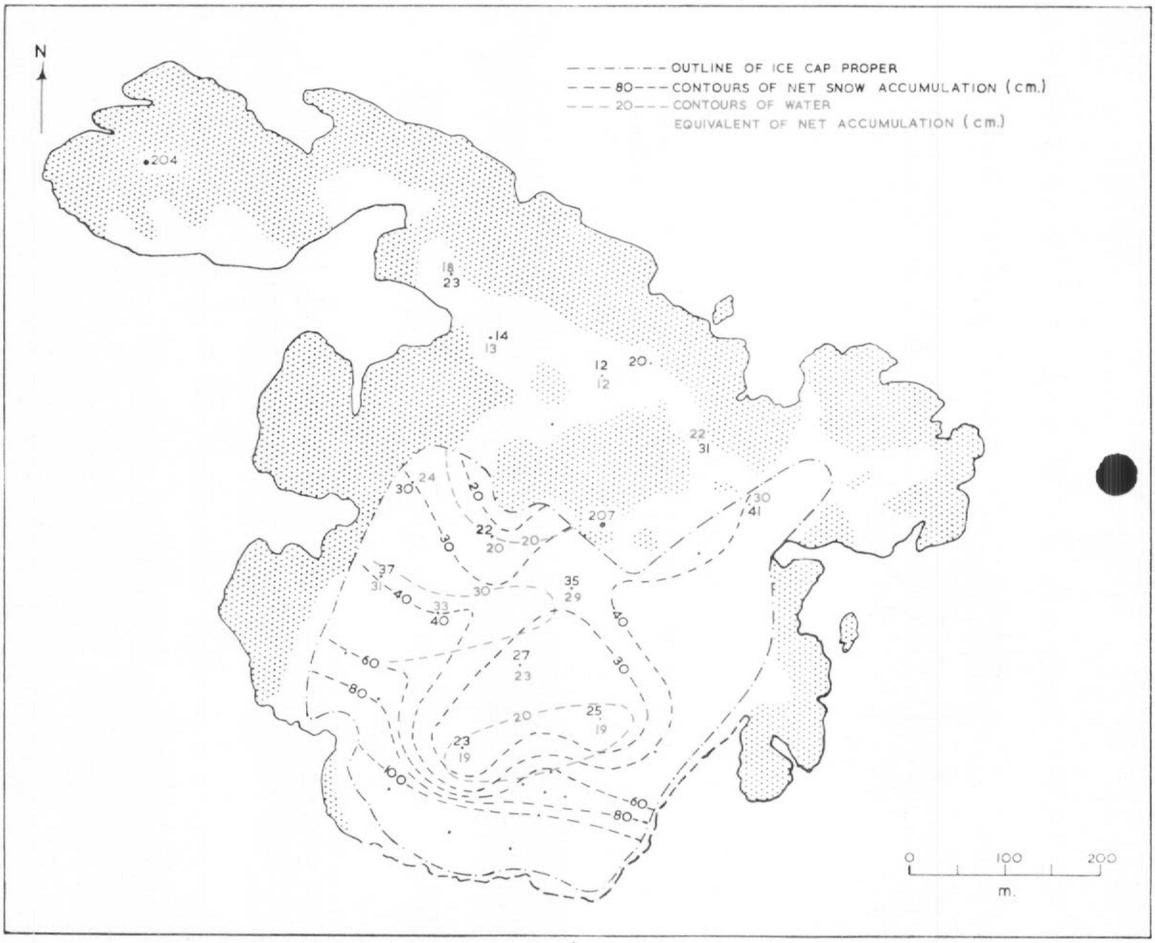

Fig. 7. Mean annual depths in centimetres of net snow accumulation (black) and water equivalent of net accumulation (red) over a 5 yr. period on Galindez Island.

There are many errors inherent in the method used. The considerable variation in density between samples taken a few centimetres apart was ascribed partly to natural micro-variation. This kind of variation has been noted previously by glaciologists and it appears to be as large as 10 per cent in some cases. A minimum of two samples was taken to define and reduce the natural errors. Other errors involve uncertainties in the length (magnitude 1–3 per cent), cross-section and mass (magnitude 2 per cent) of the sample.

Another method of snow-density determination, involving cutting, measuring and weighing a rectangular block, has a very large standard error in the volume (8 per cent at 1,000 cm.^{3}) and hence it was seldom used.

1965–66 budget year

Routine column densities

The density of each snow sample was calculated and tabulated according to site and depth. Comparison amongst densities helped to eliminate mistakes and enabled calculation of a mean density for the whole column representing the present budget year (Sadler, 1967, table XIII). Knowing the height of the column, the mass of snow per unit area throughout the year was derived for each sample site (Fig. 8).

Stakes C, E, G and NA were chosen as density sites because Thomas (1963, p. 30, fig. 5) used them and they represented different areas. Stake C was on the slopes to the north of Woozle Hill and stake E was on a steep gradient on the west side of the ice cap, whilst stakes G and NA represented low- and high-accumulation areas, respectively, on the crest of the ice cap.

In spite of this diversity of sites, the snow mass (Fig. 8) at three of the sites (stakes C, E and G) was of comparable magnitude for most of the budget year. The fourth site, stake NA, experienced both far higher accumulation and less ablation than any of the other sites.

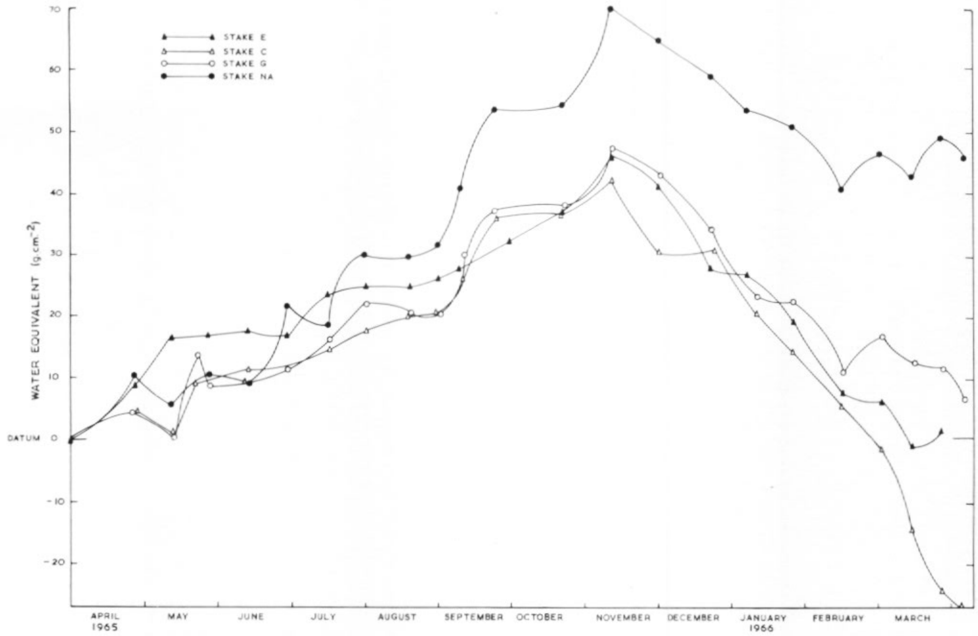

Fig. 8. Water equivalent of snow accumulated at four sites on Galindez Island throughout 1965–66 relative to 31 March 1965.

This agreement of snow masses, combined with the trend of all densities to increase at the end of the ablation season, made it possible to estimate fairly accurately the snow mass at any stake at any time. This estimation was therefore carried out for all stakes for 5 April 1966, the end of the budget year which started on 31 March 1965. The thickness of superimposed or ablated ice was obtained by readings at the beginning and the end of the period down to the ice/snow interface, and the weight of this ice was calculated using a density of 0·87 g. cm.$^{-3}$. From these data the water equivalent of the net accumulation was derived and plotted on the map of the ice cap (Fig. 9). A pattern substantially different from that for the net snow-surface heights (Fig. 7) emerged. There was still a preponderance of accumulation at the southern end of the ice cap and the extra accumulation on the western margin relative to the eastern margin was clearly shown. However, there was a large area of lower accumulation, in fact net ablation during this budget year, which extended from the north-west to the centre of the ice-cap crest.

The mean net accumulation for 1965–66 at the nine selected ice-cap stakes (*e*; p. 25) was 18·7 cm. of water over the ice cap proper.

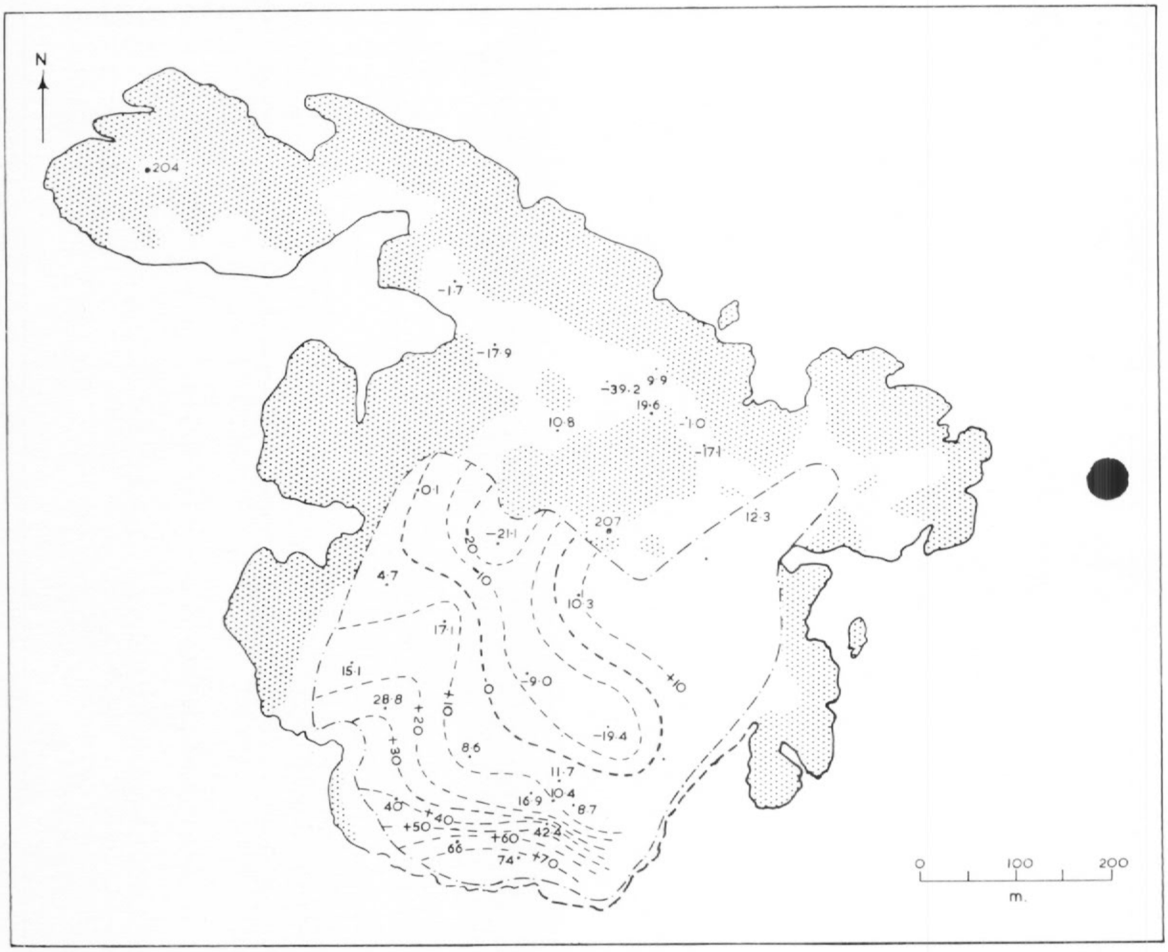

Fig. 9. Variation of net water accumulation (cm.) over the Galindez Island ice cap during the 1965–66 budget year. The contour interval is 10 cm.

Pit profiles

Density-profile pits were dug during the 1965–66 season adjacent to two of the column-density sites. The first was dug near stake G on 25 October 1965, just before the end of the accumulation season. Snow densities were measured by means of horizontal cores, and these were supplemented by cut blocks in the denser sections, every 5 cm. down to ice at 114 cm. below the snow surface. The depths and thicknesses of the ice layers encountered were also noted.

Similar observations were made in a second pit, which was excavated near stake NA on 7 December 1965, shortly after the start of the ablation season. In this case, observations were made down to coarse-grained firn at 165 cm. and probing showed that this continued to an impenetrable surface (? bubbly ice) at a depth of 204 cm. Fig. 10 shows the results obtained from both pits and a tentative correlation between most of the ice layers. The thick ice layers, 107 and 155 cm. below the surface at pits 1 and 2 respectively, represent the end of the previous ablation season, 31 March 1965.

At pit 1 the average density of the 1965 snowfall (i.e. to a depth of 107 cm. on 25 October) was $0 \cdot 291 \pm 0 \cdot 009$ g. cm.$^{-3}$ or a total of $31 \cdot 2 \pm 1 \cdot 0$ g. per unit area. Within this 107 cm., solid ice layers added 2·0±0·5 cm. (1·7 g.), and below there were 7 cm. of firn (average density 0·47 g. cm.$^{-3}$) before bubbly ice was reached. Hence the total water equivalent down to ice was 36·2±1·6 g. per unit area. This can be directly compared with the column densities measured at stake G on 21 October and estimated to be 114 cm. (down to ice) at an average density of 0·350±0·025 g. cm.$^{-3}$ on 25 October. The water equivalent of this column is 39·9±2·9 g., which agrees, within the calculated errors, with the pit-profile value. This is a useful justification of the column method of measuring densities rapidly without undue loss of accuracy.

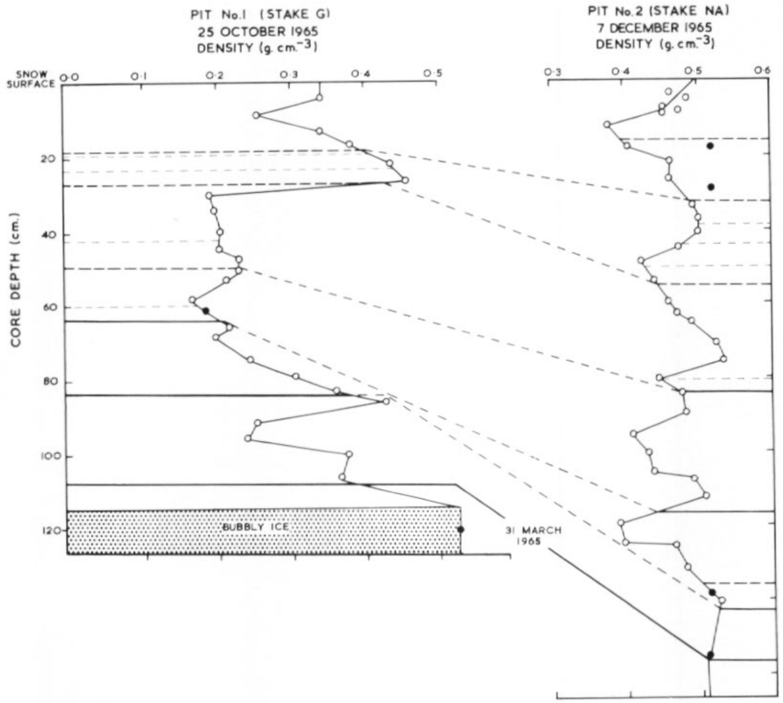

Fig. 10. Density profiles at two sites on Galindez Island. Circles represent observations, of which the solid ones are less accurate than the open ones. Horizontal lines represent ice layers and dashed lines are narrow or discontinuous layers.

At pit 2 the corresponding average density of the 1965 snowfall was 0·468±0·014 g. cm.$^{-3}$, which represents 72·5±2·2 g. per unit area. Within this, solid ice layers added 3·5±0·5 cm. (3·0 g.) to give a total water equivalent of 75·5±2·6 g. per unit area. The column measured on 30 November at stake NA (about 20 m. away) was estimated to be 159 cm. to the same (31 March 1965) layer at an average density of 0·395±0·030 g. cm.$^{-3}$ on 7 December. The water equivalent of this column is 62·8±4·8 g. per unit area and this is considerably lower than the pit value. This difference can be attributed to the rapid changes in accumulation in this area (Figs. 7 and 9), and it is unlikely to be due to the measuring techniques as this would have affected the results in the first pit equally.

Comparisons

1960–65

It was possible, by reference to Thomas's unpublished data, to calculate the change in snow mass over a 5-yr. period (1960–65) at 13 stakes. The month of August was chosen for the ends of the period because there were no sudden changes in accumulation. The ice horizon rose by between 114 and 215 cm. during this period and this rise agreed with Thomas's (1963, p. 40, fig. 11) measurements of superimposed ice at stakes C and G but it was rather more than his other results.

The snow mass was considerably lower in 1965 but the change in ice mass outweighed that of the snow and this caused an overall increase in mass ranging from 12 g. yr.$^{-1}$ at stake AD to 33 g. yr.$^{-1}$ at stake FA (Fig. 7).

These snow-mass changes for 1960–65 are also illustrated in Fig. 6. The profile along the axis of Galindez Island shows a slight decrease in mean net water accumulation from stake G southwards to stake GB. However, the comparable profile for 1965–66 shows a rapid increase south of stake GB and it is thought that long-term measurements would also show this increase if they were available. The 1965–66 profile has a minimum near stake GA (net ablation) and the net accumulation is similar at stakes G and GB. The comparable snow-height profiles (Fig. 6, dotted outlines) confirm Thomas's (1963, p. 29) suggestion that snow-height measurements alone, over a period of years, give a reasonably accurate picture of the budget state.

Thomas (1963, p. 38) found that the mean net accumulation at the summit of the Galindez Island ice cap was +19·6 cm. of water equivalent for the period 1958–63. Individual annual values vary from −13 to +57 cm. of water, which suggests that the more detailed studies in the present work refer to a typical budget year.

Other ice caps

No ice caps truly comparable with those of the Argentine Islands have been studied. The only other ice-cap accumulation figures available for the Antarctic Peninsula are those of Bryan (1965, p. 55–56) for various sites on Adelaide Island during 1962–63. He found tentative net annual accumulations of 84 and 27 cm. of water at two sites at altitudes of 372 and 250 m. respectively, but he did not derive the budget for the whole "ice cap".

The Barnes Ice Cap on Baffin Island (lat. 69°N.) has a similar type of net accumulation (mainly superimposed ice) to that of the Galindez Island ice cap but the corresponding level of net accumulation does not occur until almost 1,000 m. above sea-level (Baird and others, 1952). The Sukkertoppen ice cap (lat. 66°N.) in south-west Greenland had a mean net accumulation of 31·3 g. cm.$^{-2}$ over a period of 11 years (1953–63) from pit measurements at four sites (Rundle, 1965). This ice cap is separate from the Greenland ice sheet but it is surrounded by ice-free ground rather than by water and hence it has a different climate to the Argentine Islands. The Ongul Islands (lat. 69°S., long. 37°E.) had a net accumulation of 57·4 cm. of water from stake measurements during 1961 (Seino and others, 1963). However, these are low islands with little snow cover and again they are quite different from the Argentine Islands. Within the Argentine Islands, the accumulation on the Galindez and Skua Islands ice caps is compared on p. 26.

Movement Studies on Galindez Island

The stake pattern which was used for budget studies on Galindez Island also served as a set of movement markers. Triangulation of the stakes was accomplished with a Tavistock theodolite from a series of known rock survey stations (Murray, 1962), supplemented by resected and intersected stations where necessary. A large number of stations was required because the terrain had steep gradients and rock outcrops were scarce (Fig. 11). Partial surveys were carried out during March–April and September 1965, with a complete survey in March 1966. One resected station was sited in the centre of the Galindez Island ice cap. This was chosen because from it many important stakes were visible, particularly those which could be seen from few rock stations. At this station the tripod was prevented from settling in the snow by using special feet.

The rectangular coordinates of the four rock survey stations previously occupied by Falkland Islands Dependencies Survey surveyors were obtained from the Directorate of Overseas Surveys. One of the stations (207), at the northern end of the Galindez Island ice cap, was chosen as the origin for the whole survey and all distances were resolved into rectangular coordinates relative to it. The true bearing of a second station (204), at the western extremity

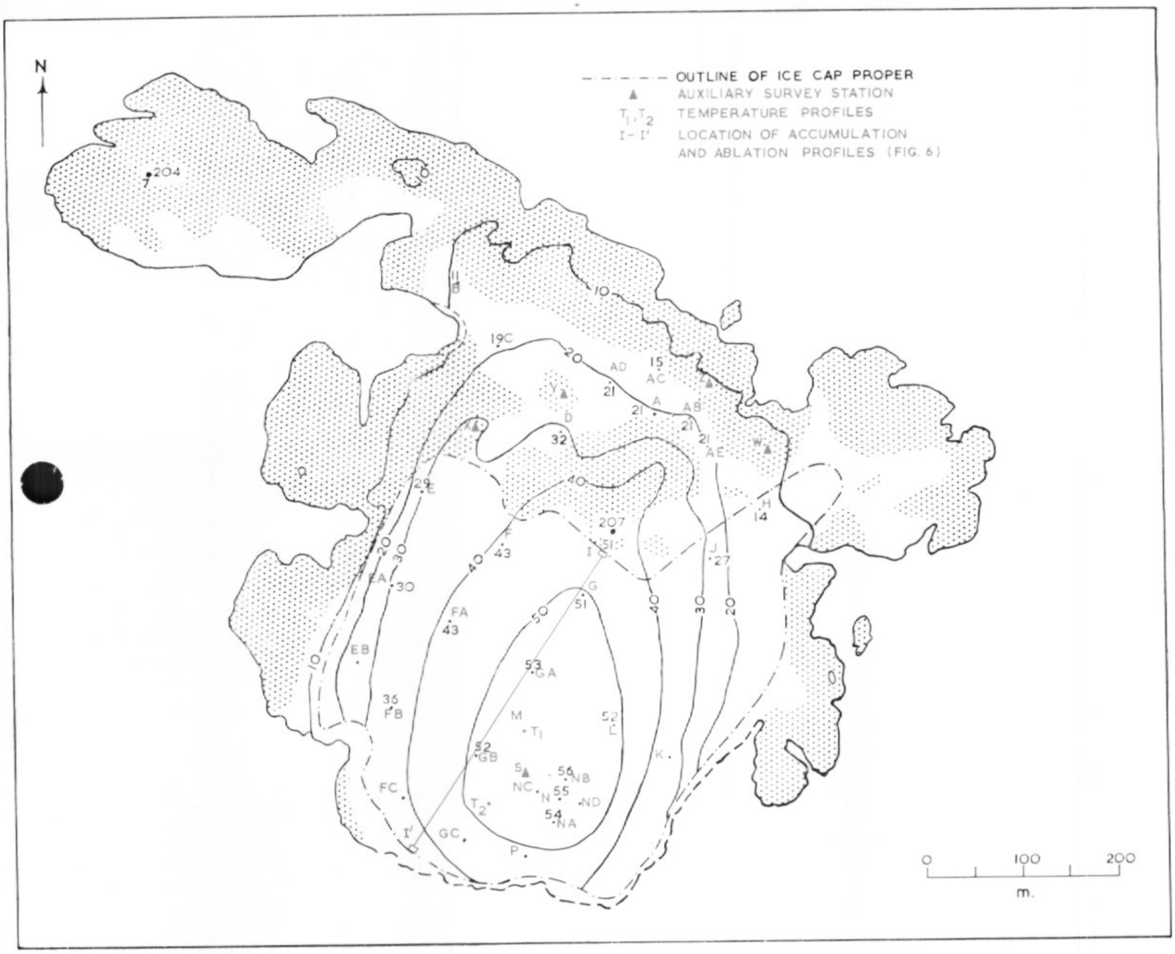

Fig. 11. Map of Galindez Island showing spot heights, approximate contours above sea-level (in m.) and stake nomenclature (red). Areas of land without permanent snow cover are stippled and the dashed part of the coastline is formed by ice cliffs. The snow-surface gradients at budget stakes were:

Stake	B	C	D	A	AB	AC	AD	AE	E	EA	EB
Gradient (degrees)	4·8	8·8	7·0	7·2	12·5	10·6	7·0	10·9	17·5	15·6	16·3

Stake	F	FA	FB	FC	G	GA	GB	GC	L	NB
Gradient (degrees)	6·6	6·0	14·5	9·0	4·3	3·3	6·2	7·3	7·7	2·2

Stake	N	NA	NC	ND	P	H	J	K
Gradient (degrees)	2·4	3·4	5·8	5·8	7·0	9·3	17·2	20·5

of Galindez Island, relative to station 207 was found to be 308° 33′ 54″±3″. All other true bearings were calculated from this by using the observed angles.

Before the field data could be utilized, the angles for each survey were averaged, corrected for closure errors and tabulated. Maximum errors of observation were estimated wherever possible and tabulated adjacent to the angles. Thereafter errors were estimated whenever further calculations were made. Means were taken for angles between fixed points determined several times and weight was given inversely as the probable error in the angle. These angles included only four fully observed triangles which were adjusted until they were consistent. The positions of four intersected auxiliary survey stations (X, Y, T and S_1) were calculated by several "routes" and the resulting values were averaged (Table II). Positions of the resected stations (S and T_1) were determined by the "Collins point method" (Ministry of Defence, 1965, p. 148).

TABLE II. SURVEY STATION POSITIONS

Survey station	*Rectangular coordinates* (m.)			
	x	*Error*	*y*	*Error*
207	000·0		000·0	
204	−476·6	±0·05	+380·0	±0·05
277	−141·8	±0·05	+649·2	±0·05
25	−1,050·0	±0·05	−242·8	±0·05
X	−148·8	±0·05	+128·0	±0·04
Y	−046·6	±0·14	+141·2	±0·09
T	−673·3	±0·40	+122·0	±0·45
S_1	−748·7	±0·08	−331·1	±0·04
S(1966)*	−096·7	±0·50	−248·4	±0·50
T_1	−097·6	±0·30	−209·5	±0·30

* The position of station S(1965) has not been calculated.

The stations are on Galindez Island (Fig. 11), except 25 and S_1 on Skua Island, 277 on Grotto Island and T on Winter Island (Fig. 1). Coordinates are relative to station 207 reckoning north and east as positive.

Positions of movement stakes

The polar coordinates given by Thomas (1963, p. 31) were resolved into rectangular coordinates. The positions of the stakes were then determined, using the best triangles available both in the 1966 and in the earlier surveys where possible. From these positions several values of the movement over different periods were obtained and compared (Table III). The less important stakes were investigated by considering the changes in subtended angles at the various available survey points. Often the changes were so small that the movement was manifestly nil. Larger changes were converted into motions of the stake perpendicular to the line of sight. The observed movement of the stake was then found by resolving the calculated values in several directions to give a resultant magnitude and direction.

The low values of movement found by Thomas (1963) led the author to disregard the splay of dates within the three surveys (13 March–25 April, 2–28 September 1965 and 9–19 March 1966). Data have been evaluated as if continuous linear movement was expected. This assumes that seasonal and annual variations of movement would be much less than the total movement and hence not detected by the present techniques.

Discussion of movement values

Most of the stakes to the north of Woozle Hill and not on the ice cap proper (stakes A, AC, AD, C and D) were stationary within an error of ±2 cm. yr.$^{-1}$. Thomas recorded small movements of stakes C, D and AC during 1 year but his errors were large. The other three stakes north of Woozle Hill are B, AB and AE. No firm result was possible for stake B but the

TABLE III. MOVEMENT VALUES FOR GALINDEZ ISLAND

Stake	*Present determinations* (1) Total movement (cm. ± m.d.)		(2) Total movement (cm. ± m.d.)		(3) Total movement (cm. ± m.d.)		*Thomas's determinations** (1) Total movement (cm. ± m.d.)		(2)	*Mean of all movement values* (cm. yr.$^{-1}$ ± m.d.)
	Total movement (cm. ± m.d.)	*Movement* (cm. yr.$^{-1}$ ± m.d.)	*Total movement* (cm. ± m.d.)	*Movement* (cm. yr.$^{-1}$ ± m.d.)	*Total movement* (cm. ± m.d.)	*Movement* (cm. yr.$^{-1}$ ± m.d.)	*Total movement* (cm. ± m.d.)	*Movement* (cm. yr.$^{-1}$ ± m.d.)	*Movement in 1 yr.* (cm. ± m.d.)	
B	**17 ± 7**	**3·5 ± 1·5**	0	0			0 ± 5	0 ± 7		1 ± 3
C	**0 ± 2**	**0 ± 0·5**	**9·5 ± 13**	**2 ± 2·5**			4 ± 3	5 ± 4		2 ± 3
D	**1 ± 5**	**0 ± 1**	1 ± 2	1 ± 2			7 ± 9	9 ± 12		1 ± 2
A	2·5 ± 5	0·5 ± 1					0	0		0 ± 1
AB	12·5 ± 8	12·5 ± 8					7 ± 4	9 ± 5		
AC	**8 ± 4**	**1·5 ± 1**					2 ± 1·5	3 ± 2		2 ± 1·5
AD	**5 ± 6**	**1 ± 1**					0 ± 6	0 ± 8		1 ± 1
AE	**17 ± 10**	**3·5 ± 2**					1 ± 3	1 ± 4		2·5 ± 2
G	**1 ± 9**	**0 ± 2**	**02 ± 9**	**0·5 ± 2**	0 ± 3	0 ± 3	2 ± 3·5	3 ± 4·5		0 ± 2
GA	**23 ± 13**	**4·5 ± 2·5**	**11 ± 4**	**2 ± 1**	**8 ± 10**	**1·5 ± 2**	3·5 ± 6	4·5 ± 8	2·5 ± 2	3 ± 1·5
GB	**32·5 ± 4**	**6·5 ± 1**	**34 ± 15**	**7 ± 3**			10 ± 4·5	13 ± 6	9 ± 3	8 ± 2
FA	**21 ± 5**	**4 ± 1**	**26 ± 7**	**5 ± 1·5**			3 ± 4·5	4 ± 6	2 ± 1	4 ± 1
FB	49 ± 10	49 ± 10	**542 ± 26**	**108 ± 5**	**580**	**116**	64·5 ± 7	86 ± 9		
FC	17·5 ± 16·5	17·5 ± 16·5	(5·5) ± (5·5)	(11) ± (11)						14 ± 11
E	**5 ± 2**	**1 ± 0·5**					6·5 ± 4	8·5 ± 5		1 ± 0·5
EA	**25 ± 2·5**	**5 ± 0·5**					8 ± 4	11 ± 5	3·5 ± 1	5 ± 2
NB	**28 ± 10**	**5·5 ± 2**	**44 ± 12**	**9 ± 2·5**			2 ± 5·5	3 ± 7·5	7 ± 8	6·5 ± 2
N	**103 ± 11**	**20·5 ± 2**	**88 ± 10**	**18 ± 2**						
N	7† ± 3	14 ± 5	**54†**	**17**	6† ± 3	13 ± 5	17 ± 7	23 ± 9	23 ± 6	18 ± 3
NA	69‡ ± 3	93 ± 5	73‡ ± 3	91 ± 8			76·5 ± 5·5	102 ± 7·5		95 ± 5
P	226§ ± 12	350 ± 18								

Bold figures are derived from observations over a 5 yr. period, but others from a 1 yr. period. The figures in brackets are derived from a 0·5 yr. period and Thomas's first determinations from a 0·75 yr. period.

m.d. Maximum deviation.
* Re-evaluated in 1967.
† Relative to stake NB.
‡ Relative to stake N.
§ Relative to stake NA.

[*face page 34*

movement was no more than 3 cm. $yr.^{-1}$. For stake AB, the present derivation gave movement in the opposite direction to Thomas's measurement (Table III). Finally, there was some indication that stake AE moved south towards the windscoop, against the surface slope.

On the ice cap proper, consider first the line of stakes G, GA and GB down the crest. The measurements show that stake G was stationary, whilst the movement at stake GA was very little, $3 \pm 1 \cdot 5$ cm. $yr.^{-1}$. The movement at stake GB was greater, 7 cm. $yr.^{-1}$. Thomas's value of 13 cm. $yr.^{-1}$ has not been maintained over the longer interval.

In the line of stakes F, FA and FB, stake F has been omitted as it was not vertical and almost buried. Stake FA gave a clear picture of movement over 5 years at 5 cm. $yr.^{-1}$, verifying Thomas's previous conclusion. Stake FB has been changed with consequent errors of the order of 30 cm. in the 5-yr. figures. However, the general movement was 50–100 cm. $yr.^{-1}$, possibly varying from year to year. Thomas's figures gave 86 ± 9 cm. $yr.^{-1}$ for the movement of stake FB. The new stake FC moved about 14 cm. $yr.^{-1}$ measured in the direction north-east to south-west.

In the line of stakes E, EA and EB, the new stake EB has not moved from north to south (towards the ice cliff) but there is no check on its east to west movement. The 5-yr. figures suggest that stake E was virtually stationary (1 cm. $yr.^{-1}$) in contrast with Thomas's previous measurements. Stake EA had a clear movement of 5 cm. $yr.^{-1}$ as shown by measurement every year during the period 1961–66, except 1964. There is poor agreement with Thomas's figure for 1961.

On the east side of the ice cap, no further linear movement has been measured for stake L, whilst Thomas's figures are inaccurate.

Relative movement from tape measurements

Five stakes in the form of a cross (N to ND) were placed just north of the ice cliff which forms the southern end of Galindez Island. Here Thomas (1963) found considerable movement. In addition to the angles on to the various stakes, the distances between them were taped in May 1965, March 1966 (by the author) and March 1967 (by J. A. Thoday) (Table IV). Stake NB was the slowest moving of the group with $6 \cdot 5 \pm 2$ cm. $yr.^{-1}$. The central stake (N) moved 18 ± 3 cm. $yr.^{-1}$. This value takes account of tape measurements relative to stake NB, as well as Thomas's and the present survey results.

TABLE IV. TAPED DISTANCES BETWEEN "CROSS" OF STAKES

Distance	*Observed length* (m.)			*Difference* (cm. ± m.d.)	
	(1) May 1965	(2) March 1966	(3) March 1967	(2)−(1)	(3)−(2)
NB–N	21·21	21·28	21·34	7±3	6±3
N–NA*	22·63	23·32	24·05	69±3	73±3
NC–N	23·07	23·22	23·29	15±3	7±3
N–ND	22·82	22·91	22·96	9±3	5±3
NB–NC	31·55	31·78	31·83	23±6	5±6
ND–NA*	32·46	32·69	33·17	204±6	48±6
NA–P*	46·18	48·44	—	226±6	—
NB–ND	30·91	30·96	31·07	5±6	11±6
NC–NA*	32·08	32·79	33·58	71±6	79±6

* Line crosses known crevasse.

Stake NA moved faster than the others in the group but unfortunately Thomas's stake in this position had disappeared by March 1965. Measurements on the new stake gave a very similar rate of movement (92 ± 5 cm. yr.$^{-1}$) to that recorded by Thomas (102 ± 7 cm. yr.$^{-1}$). There was a small crevasse between stakes N and NA but it appeared to be inactive during the period 1965–66 and therefore it does not account for the movement attributed to stake NA. No evaluation of the true movement of stakes NC and ND was possible but Table IV gives their relative movements.

Tape measurements at a new stake (P), sited still nearer to the edge of the ice cliff, showed that the distance from stake NA to stake P increased by 2·26 m. in 10½ months. This "true" movement rate of 3·5 m. yr.$^{-1}$ was not due to continuous flow. A crack opened to the north of stake P on 26 February 1966 and it quickly widened to a definite crevasse. Measurements during March showed that this crevasse was at least 30 m. deep (cf. Thomas, 1963, p. 41) and the ice to the south calved during May 1966 (Fig. 12). This was the first time that the ice cliff had calved for several years and it took place during a late period of high temperatures accompanied by high winds and snowfall.

Fig. 12. The result of calving along the southern ice cliff of Galindez Island during May 1966. (Photograph by J. A. Thoday.)

Wastage due to calving

The wastage due to calving takes place over a 500 m. perimeter of the ice cap proper, which has an average height of 38 m. above sea-level (range 17 to 47 m.). Over the whole of this perimeter the ice/rock interface is quite near to sea-level, and the average height of ice (h_i) and firn (h_f) calving is therefore assumed to be 38 m. The density is assumed to be 0·9 g. cm.$^{-3}$ (ρ_i) over height h_i and an average of 0·7 g. cm.$^{-3}$ (ρ_f) over the 8 m. of firn.

Movement measurements (Table III), the form of the ice cap and the type of gravity-assisted calving all point to radial flow of ice. Calving occurs at random intervals of several years and hence the actual calving during any budget year gives a false picture. Instead, the rate of flow during several years over a line on the ice cap (the 30 cm. net accumulation contour in Fig. 9) is estimated and all ice which has passed this line is considered to be lost from the ice cap. The rate of flow (r) over this line was about 1·0 m. yr.$^{-1}$, though there are conclusive measurements at only two stakes (Table III) to derive it (cf. Thomas, 1963, p. 42). It is assumed that the ice-cap surface is approximately parallel to the underlying rock surface (Thomas, 1963, fig. 12). Also, the active ice-cap perimeter is reduced to about 400 m. (p) at the 30 cm. net-accumulation line. Let the average mass of ice and firn calved per year be M kg. Then $M = (h_i\rho_i + h_f\rho_f)rp = 1{\cdot}3 \times 10^7$ kg.

Mass Budget of Galindez Island

For the purpose of determining the mass budget, the area of the Galindez Island ice cap was that defined in Fig. 11 and found to be $(15{\cdot}14 \pm 0{\cdot}01) \times 10^4$ m.^{2}. The mean net accumulation over this ice cap proper for the 1965–66 budget year was 18·7 cm. of water (p. 29). This represents a gain of $2{\cdot}82 \times 10^4$ m.^{3} of water equivalent during a specific budget year which may be broken down into its constituent parts. It is found empirically that the mean net accumulation of 17·6 cm. of water at stakes E, G and NA (Fig. 9) compares closely with the mean for the ice cap given already (p. 29). Consequently, the mean of the data at these three stakes can be used to represent the whole of the ice cap proper.

By definition:

$$\text{Net accumulation} = (\text{Gross accumulation}) - (\text{Total ablation}). \qquad (1)$$

There was no run-off of melt water at site NA, and this had much less ablation than the other sites (Fig. 8). Therefore, run-off made the major contribution to ablation on the ice cap. There was no significant melt-water run-off during the accumulation season. Hence, to a first approximation:

$$\text{Gross accumulation} = (\text{Apparent accumulation at the end of the accumulation season}) + (\text{Accumulation during the ablation season}). \qquad (2)$$

The sums of individual apparent accumulation values observed during the accumulation season at stakes E, G and NA were 222, 264 and 297 cm. of snow, respectively (Sadler, 1967, table XXIII). Under the previous assumption of negligible ablation during the accumulation season:

$$\text{Average density of apparent snowfall} = \frac{I}{\text{Total apparent snowfall}},$$

where I is the increase in water equivalent during the accumulation season. This average was approximately 0·2 g. cm.$^{-3}$ and it is used to convert the apparent snow accumulation during the ablation season (stakes E, 12; G, 14; and NA, 27 cm. of snow) into its water equivalent (stakes E, 2·5; G, 2·5; and NA, 6·4 cm. of water). Thus the mean accumulation during the ablation season was 3·8 cm. of water. Therefore, using equation (2):

$$\begin{aligned}\text{Mean gross accumulation} &= \tfrac{1}{3}(69{\cdot}9 + 47{\cdot}3 + 46{\cdot}0) + 3{\cdot}8 \\ &= 58 \text{ cm. of water.}\end{aligned}$$

This figure can be compared with the approximate total precipitation at the summit of the ice cap during the budget year (38 cm. of water; Table VI).

Using this gross-accumulation value in equation (1), total ablation $= 58 - 19 = 39$ cm. of water. Thus the total ablation removes two-thirds of the gross accumulation. The total ablation comprises:

i. Melt-water run-off, which is difficult to measure accurately, and no attempt to do so has been made in the present work. However, the situation at stake C probably represents the greatest run-off at any point on the ice cap because it was in the path of a run-off stream for several weeks. At stake C, 22 cm. (19 g. cm.$^{-2}$) of ablation occurred in 26 days (March 1966) at a rate of 0·7 g. day^{-1}.

ii. Evaporation, which is not thought to be an important factor since the relative humidity at the Argentine Islands (Table V) is almost uniformly high with an annual mean of 78 per cent.

iii. There is ablation at any geographical position due to horizontal movement if less ice reaches the point than passes it during any time interval. Over most of the ice cap there is no differential movement but in the main movement zone (p. 35) differential movement of the order of 1 cm. yr.$^{-1}$ m.$^{-1}$ occurs. This causes both overall ablation when the ice eventually calves, and the observed crevasse system. The average annual ablation due to calving from the Galindez Island ice cap is estimated to be $1 \cdot 3 \times 10^7$ kg. (p. 37), which represents 8·6 g. per unit area (9 cm. of water equivalent) and 22 per cent of the estimated total ablation.

iv. The drifting of uncompacted snow when the wind speed exceeds 8–10 m. sec.$^{-1}$, and this can be an agent of either accumulation or ablation at any particular site. In practice, the topography of the Argentine Islands assists the prevailing wind to remove snow and more snow is lost to the sea and the sea ice than is gained.

Snow Studies on Skua Island

Snow studies were undertaken on the Skua Island ice cap in 1965–66 for the first time as a complement to those on the ice cap of Galindez Island, because the topography is substantially different on each. Skua Island was less accessible and hence the programme was much less intensive than that of Galindez Island.

A preliminary investigation showed that the Skua Island ice cap consists of two main ridges trending north–south (Fig. 13) divided by a low valley. The snow-surface gradients were much less than those encountered on Galindez Island. In May 1965, when most of the snowfall since the start of the 1965–66 budget year had been blown away, a line of stakes was erected along each ridge and joined by a perpendicular line across the valley. The surface was bubbly ice over most of the island and the stakes were set 50 cm. into the ice. Tension was apparent in some of the ice layers encountered, since they cracked audibly when pierced at stakes SA and SD.

Snow level and snow density on Skua Island were recorded in the same manner as on

Fig. 13. The Skua Island ice cap (in the distance) viewed from Galindez Island. (Photograph by P. D. Morgan.)

Galindez Island (p. 24, 27). Approximate positions of the stakes were obtained by graphical intersection using angles observed during the Galindez Island movement survey (p. 32).

Snow-level and snow-density values

The snow level at each stake on Skua Island was estimated for 31 March 1965 and it was used to derive the snow-surface height throughout the budget year. A mean snow-surface height was calculated over the available stakes, excluding stake SE which occupied a very exposed position and had readings entirely different from the other stakes. This mean was used (p. 26) to compare the snow-surface heights between the Galindez and Skua Island ice caps. The thickness of snow accumulated on any given date was more constant over Skua Island than over Galindez Island. In the absence of frequent density measurements, the variation of net snow accumulation over the ice cap due to the 1965–66 budget year was plotted (Fig. 14) and the mean over all the stakes was 30 cm. of snow.

Snow densities were measured on five occasions throughout the budget year near stakes QA, SC and RA, which represented each of the ridges and the central valley, respectively. The variations in water equivalent of accumulation derived from these measurements (Fig. 15) are comparable with Fig. 8 which gives water equivalents on Galindez Island. The trends in each case are similar but the magnitudes on Skua Island are considerably less than those on Galindez Island. Snow accumulated at stakes QA and RA in the same manner as at stakes E and G, and all have a small net accumulation. The accumulation was much higher at stake SC, as at stake NA, and both had a large net accumulation.

Climate and its Effect on Snow Cover

Meteorological factors

From the surface synoptic meteorological observations, which were made every 3 hr. at the Argentine Islands, several parameters were calculated for the period January 1965 to March 1966 (Table V). The mean temperature, wind speed and relative humidity are self-explanatory, whilst the monthly mean wind direction (not tabulated) is invariably within the north to north-east sector. The meteorological variables (*A*, *B*, *C and D*) discussed by Thomas (1963, p. 34–35) have been calculated for 1965–66 (Table V). The mean duration of sunshine recorded corresponds to variable *D*, and *B* is the percentage of each $\frac{1}{2}$ month with temperatures above 0° C and most of the sky covered with low stratiform cloud. *C* is the average of the temperatures above 0° C recorded during each $\frac{1}{2}$ month. The parameters of high temperature (*B* and *C*) both have maxima in January to March and minima in May to August. They are similar to Thomas's (1963, fig. 8) 1960–61 data but with maxima later in the year. The rate of net accumulation (Thomas's variable *A*) in 1965–66 (gradient of the curves in Fig. 8) was positive from April to early November with a maximum towards the end of this period. There was then an abrupt change to a rapid rate of net ablation which did not diminish until February and March and which was in contrast to Thomas's curve A for 1960–61.

Solid precipitation was approximately measured (Table VI) on the summit of the Galindez Island ice cap using a snow gauge constructed by A. J. Schärer. This comprised a large metal can (of the rain-gauge type) mounted above the level of drifting snow and surrounded by a vertical cylindrical baffle which gave the air stream a greater downward motion. Oil was added during the summer months to prevent evaporation and "anti-freeze" during the winter months.

Solar radiation

Total, diffuse and reflected solar radiation and the radiation balance were measured at the Argentine Islands by means of Moll-Gorczynski solarimeters, a Kew pattern mark IV ventilated flux-plate radiometer and an Ångström compensation pyrheliometer. Two solarimeters recorded total (global) and diffuse short-wave radiation, respectively (Fig. 16). A third solarimeter measured the short-wave radiation which was reflected by the snow surface. Both this solarimeter and the radiometer, which measured the long-wave radiation balance, were

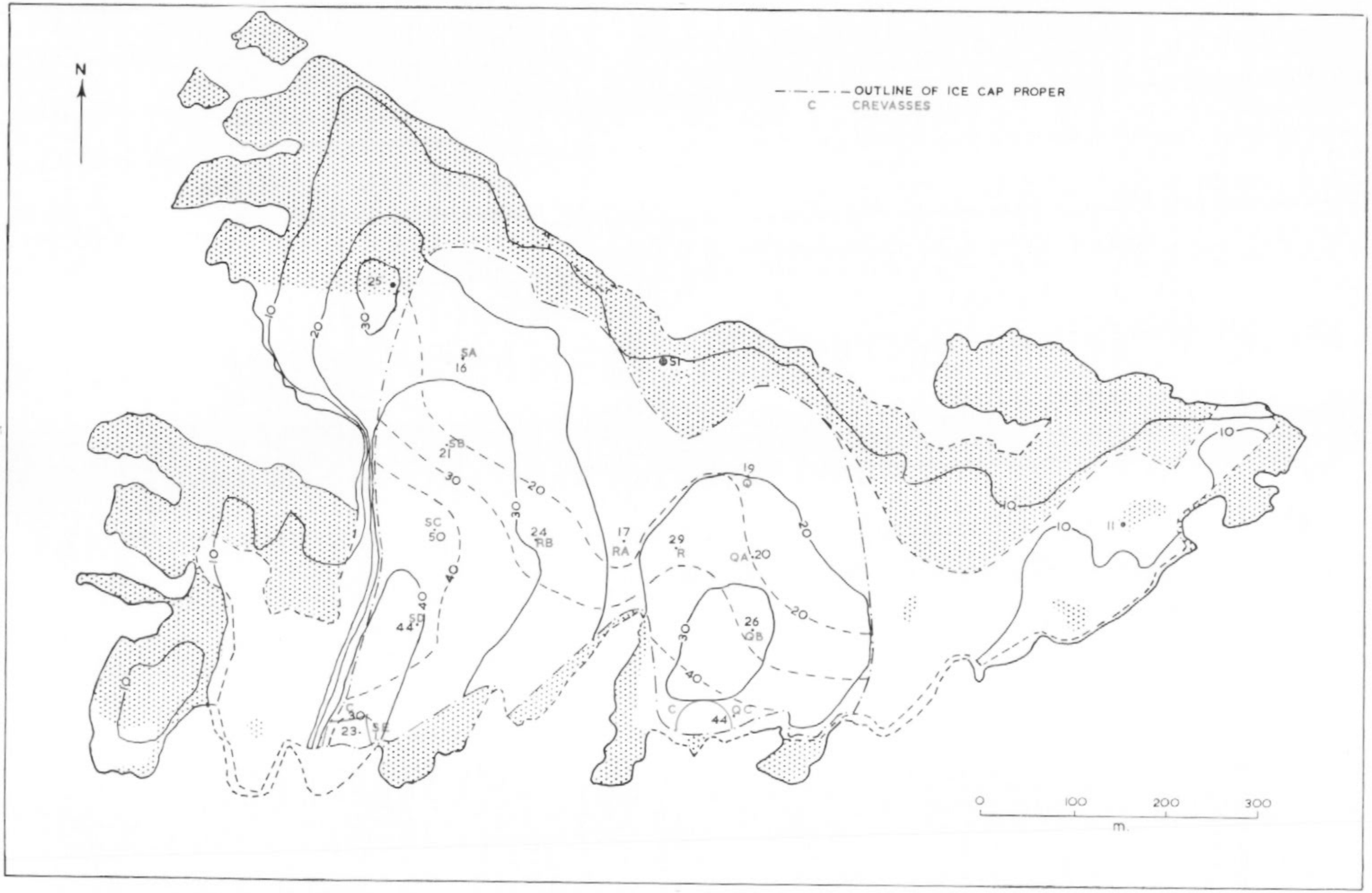

Fig. 14. Map of Skua Island showing variation of net snow accumulation (cm.) during the 1965–66 budget year (contours as dashed lines). Contours of approximate height (m.) above sea-level are also shown as continuous lines. Stake nomenclature and crevasse systems (c) are overprinted in red. The solid coastline is rock and [illegible] dashed coastline is ice. Areas of land without permanent sn[illegible]cover are stippled.

mounted on posts several feet high over flat patches of snow. The solarimeters were very stable in use whilst the pyrheliometer was a sub-standard instrument (for calibrations). In contrast, the sensitive radiometer surface weathered rapidly under certain conditions, and as much as 30 per cent during a season. The radiometer was rotated to face down-wind whenever the wind direction changed so that the ventilation was not anulled. During precipitation, a careful note was kept of the times when the sensitive surface was wet because this invalidated the record. Regular sensitivity and resistance tests were carried out on all radiation instruments

TABLE V. HALF-MONTHLY SUMMARY OF WEATHER OBSERVATIONS

Date	*Monthly mean temperature* (°C)	*Mean wind speed* (m. sec.$^{-1}$)	*Mean relative humidity* (per cent)	*B** (per cent)	*C** (°C)	*Mean duration of sunshine* (hr. day^{-1})
1965 January	+0·4	1·85 2·68	—	22 73	0·5 1·3	4·0
February	+0·9	3·19 0·62	—	66 36	1·6 0·7	2·7
March	+0·9	3·35 5·46	86	57 61	1·8 1·0	2·2
April	−3·1	2·93 2·57	84	3 14	0·0 0·2	1·0
May	−3·0	2·11 4·74	79	1 13	0·0 0·6	0·9
June	−6·0	5·15 4·43	79	16 4	0·2 0·1	0·2
July	−11·5	1·80 3·86	80	0 9	0·0 0·3	0·9
August	−13·3	0·70 3·14	71	0 13	0·0 0·1	2·5
September	−6·2	5·30 4·69	74	23 19	0·1 0·2	1·7
October	−8·4	3·76 5·05	71	5 10	0·1 0·1	3·3
November	−2·0	6·90 2·06	79	31 26	0·3 0·5	2·8
December	−0·6	1·60 3·35	69	8 28	0·5 0·5	5·1
1966 January	+0·3	2·99 2·94	83	46 30	0·7 1·0	3·6
February	−0·5	2·88 1·29	81	29 3	0·6 0·1	6·4
March	−0·7	3·14 2·42	75	52 10	0·9 0·2	1·6
Mean for 1965	−4·3	3·40	78†	22	0·5	2·3

* For definitions see p. 39.
† Mean of April 1965 to March 1966.

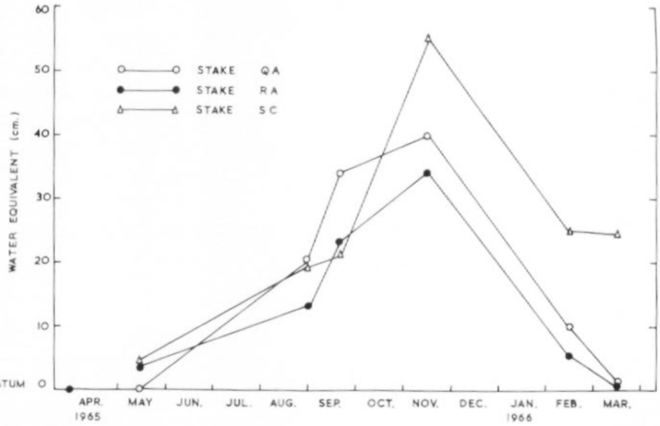

Fig. 15. Water equivalent of snow accumulated at three sites on Skua Island during 1965–66.

and the radiometer was compared with a spare radiometer every month in the apparatus shown in Fig. 17.

Evaluation of the chart records for 1965 and January 1966 was carried out by F. Stacey and T. P. Jones at Edinburgh. All four radiation components were measured as hourly values, from which daily means were calculated. The absolute accuracy of the data is ±5 per cent. For the present work weekly (i.e. quarter-monthly) averages of total and reflected short-wave radiation

TABLE VI. APPROXIMATE TOTAL PRECIPITATION

Month	*Precipitation* (cm. of water)
1965 March	2·4
April	5·9
May	3·3
June	1·5
July	2·0
August	2·0
September	2·3
October	2·4
November	3·2
December	4·5
1966 January	3·5
February	3·9
March	3·6
Annual total (April 1965–March 1966)	38·1

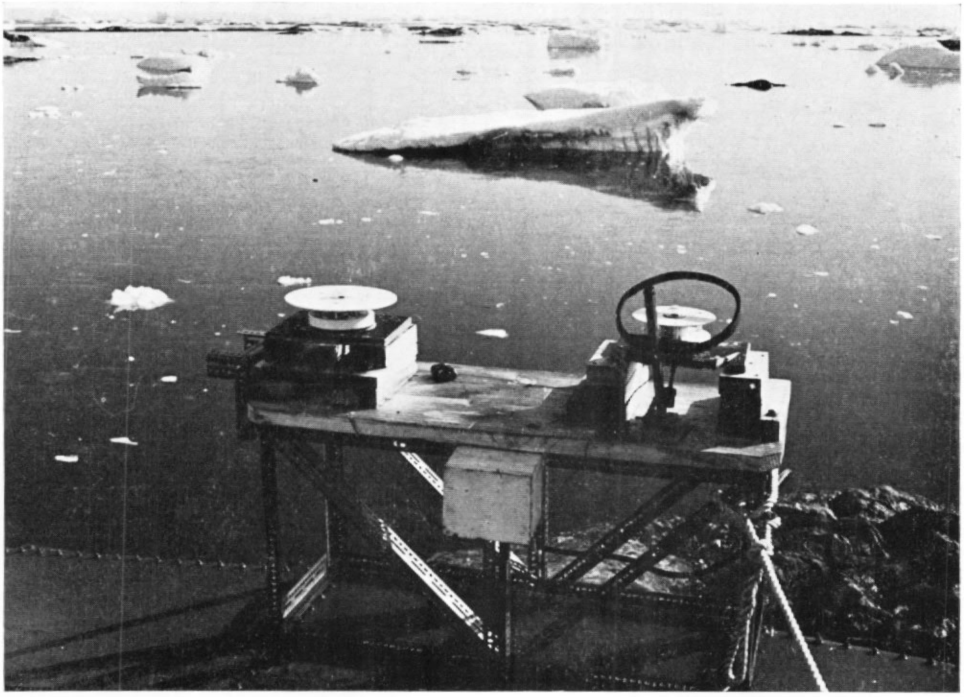

Fig. 16. Total (left) and diffuse (right) solarimeters mounted on top of the fuel tank at the Argentine Islands scientific station.

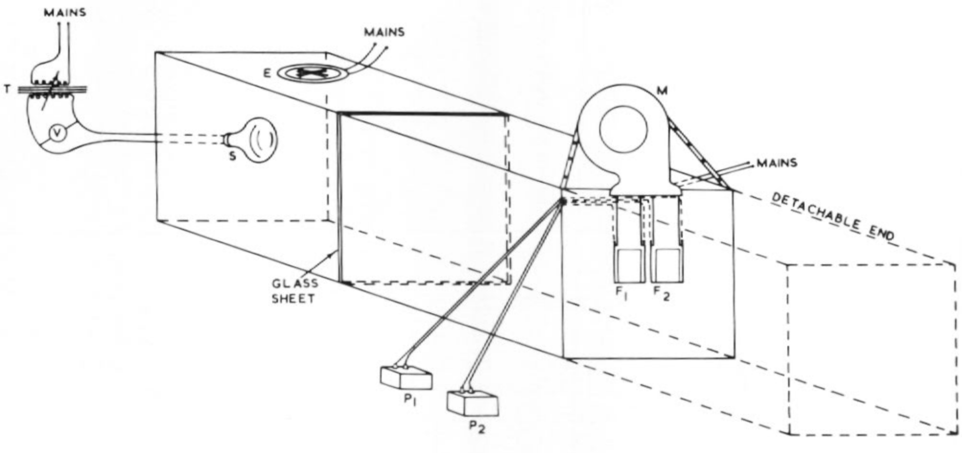

Fig. 17. Schematic diagram of radiation tunnel and associated circuitry. *T* variable transformer; *V* voltmeter; *S* standard lamp; *E* extractor fan; *M* flux-plate ventilator motor; F_1 and F_2 the two flux plates being compared; P_1 and P_2 two potentiometers.

were calculated (figures 1–4 in Table VII). The corresponding average radiation absorbed by a horizontal surface (total minus reflected radiation) was calculated (Fig. 18). There were occasional large variations in the absorbed radiation but more often there was a steady change as the solar declination changed. Weekly averages were also calculated for the long-wave radiation balance (Fig. 18) and these were very variable at all times of the year. The most noticeable feature was a sudden drop from +50 to −40 mW. hr. cm.$^{-2}$ day^{-1} at the end of March 1965. The corresponding rise in net long-wave radiation at the beginning of November was less marked.

TABLE VII. WEEKLY AVERAGE SOLAR RADIATION
(mW. hr. cm.$^{-2}$ day^{-1})

Date		*Short-wave*		*Date*		*Short-wave*	
		Total	*Reflected*			*Total*	*Reflected*
1965				*1965*			
Month	*Week*			*Month*	*Week*		
January	1	744	510	August	1	33	26
	2	530	365		2	49	41
	3	423	279		3	67	54
	4	410	272		4	110	84
February	1	328	185	September	1	122	98
	2	329	159		2	135	116
	3	439	194		3	207	173
	4	197	124		4	280	221
March	1	329	170	October	1	316	257
	2	169	63		2	356	291
	3	90	49		3	427	351
	4	106	49		4	452	357
April	1	111	72	November	1	423	362
	2	102	76		2	522	434
	3	45	36		3	573	460
	4	39	29		4	673	522
May	1	35	24	December	1	651	484
	2	22	12		2	691	510
	3	9	7		3	681	510
	4	8	6		4	406	347
June	1	4	3	*1966*			
	2	3	2	January	1	393	287
	3	3	3		2	449	333
	4	3	2		3	575	396
					4	369	250
July	1	8	5				
	2	9	6				
	3	13	11				
	4	15	12				

Factors controlling ablation

Solar radiation is thought to be the most important energy source for ablation in many areas of the world (e.g. Mayo and Péwé, 1963). Hence an attempt has been made to correlate ablation with absorbed radiation on Galindez Island for the period October 1965 to January 1966. The mean of the ablation at stakes E, G and NA over each period measured (Fig. 8) has been plotted in the centre of the period (Fig. 19). The situation at these three stakes was used to represent the ice cap proper (cf. p. 37) but half weight was given to the measurements at stake E because they were less accurate (Sadler, 1967, p. 57) and the snow-surface gradient at this site was considerable (17°). The average amounts of long- and short-wave radiation

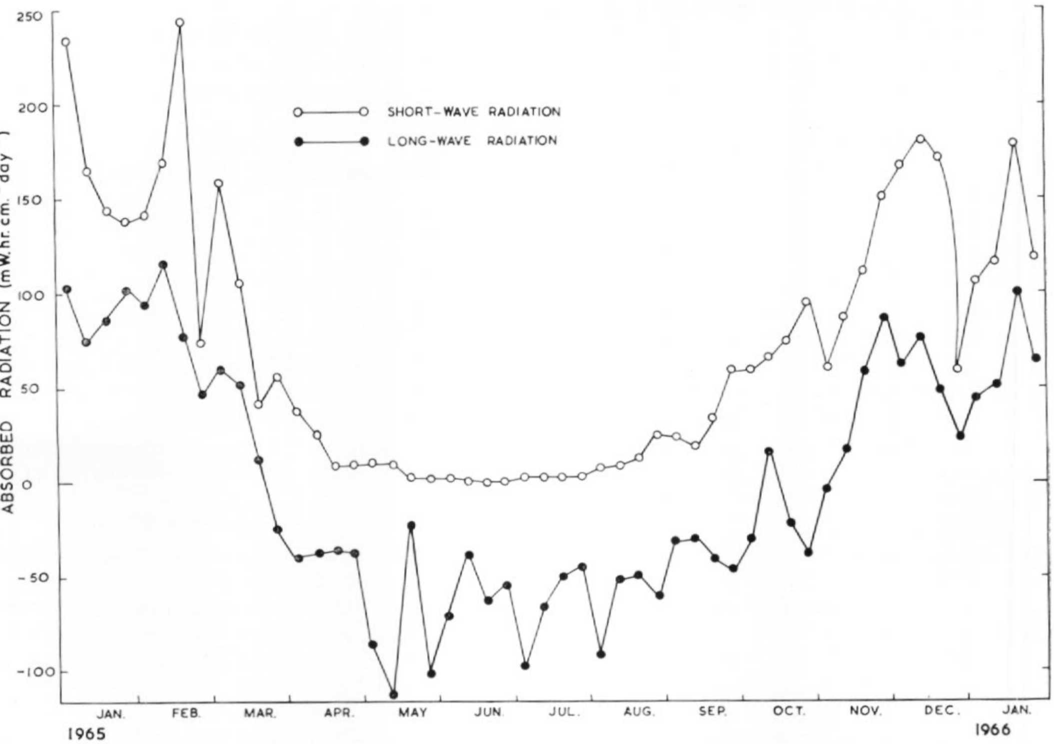

Fig. 18. Average absorption of long- and short-wave radiation for the period January 1965–January 1966.

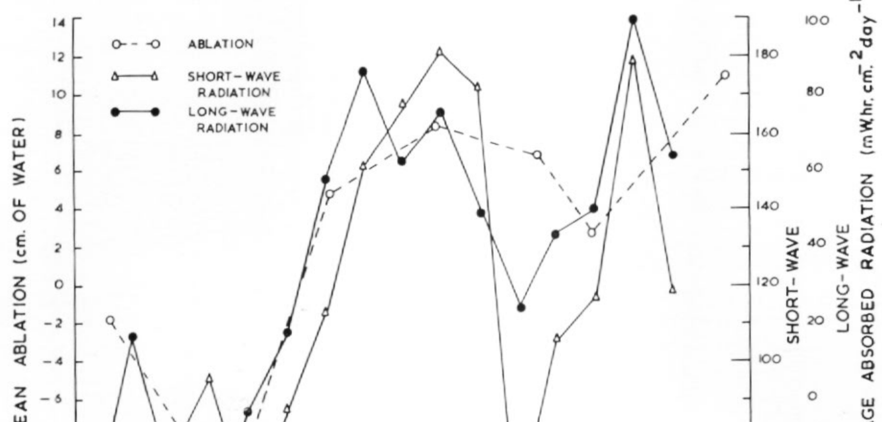

Fig. 19. Comparison between mean ablation (dashed line) and average absorbed radiation (solid lines) at Galindez Island for the period October 1965–February 1966.

absorbed (from Fig. 18) are also shown on Fig. 19. The expected lack of correlation between the curves in Fig. 19 in October changes to good agreement between all three curves at the start of the ablation season (November and early December). This breaks down in late December and January when the average daily temperature rises above 0° C (Table V) and falling rain changes the energy balance.

No correlation was found between the net accumulation at any point on the Galindez Island ice cap (Fig. 9) and its height above sea-level, snow-surface gradient (Fig. 11) and aspect.

Snow- and ice-temperature profiles

Thermistor profiles

Two sets of thermistors (Thomas, 1963) were read at intervals of 2 weeks during 1965–66 to give comparable snow-temperature profiles. One set was originally embedded in bubbly ice and one in firn (T_1 and T_2, Fig. 11). Access to the junction box at T_2 in the winter was via a shaft which, it is estimated, disturbed between one-sixth of the flux at the uppermost thermistor and 1/700 at the lowest one. The measuring technique was quite normal, using calibrated, portable Wheatstone bridges. A nearby stake gave the height of the snow surface relative to the thermistors and a Rototherm thermometer gave an immediate reading of the snow-surface temperature.

The initial calibration of the thermistors used in the snow-temperature profiles was carried out by Thomas (1963, p. 32) in 1961. It was necessary to use the resultant calibration curves for the thermistor readings during 1965–66, because an attempt made in March 1966 to recover at least one the thermistors at profile T_1 was unsuccessful. It was therefore necessary to assume that there was no change in calibration between 1961 and 1965–66. Fortunately thermistors are known to retain their calibration unless they are subjected to abnormally high temperatures after calibration and this has not happened in the present case (but see below).

The resultant temperature/depth profiles for the period April 1965 to March 1966 are plotted in Fig. 20. The depths shown were correct when the thermistors were installed in 1961 but they are now nominal because there has been continual change in snow-surface height. This change tended to be somewhat cyclic at profile T_1 so that the level in March 1965 was only about 1·8 m. higher than in 1961. The change has been cumulative at profile T_2 and it is thought to amount to several metres since 1961.

The temperature profile at T_1 (Fig. 20) shows the degree of penetration of the winter cold-wave diminishing as the depth increases. At a nominal depth of 8 m. there is less than 0·5° C change in temperature over the whole year. The profile at T_2 shows a similar form but the positive temperatures plotted for January and February 1966 are not possible. Thomas (1963, fig. 6) has shown a similar feature on his curve and he suggested that it was due to melt water re-freezing at depth. However, this could not cause positive temperatures and it is concluded that either the thermistor calibration was in error, or it has changed since 1961.

Rototherm thermometer measurements

Rototherm thermometers were used to measure temperatures in the *névé* because they could be adapted more easily than thermistors to the depths and positions required. As their readings were very varied, the thermometers were completely re-calibrated in the refrigerators of the Department of Physics, University of Birmingham. This showed that each thermometer had both a large zero error and a temperature-dependent error not exceeding 1° C over the range used (Sadler, 1967, fig. 17). This result was accepted because the thermometers were only read to ±0·2° C and the readings were corrected accordingly.

The temperatures in the snow near thermistor profile T_2 show a greater annual variation than the nominal 0·5 m. deep thermistor, confirming that this thermistor is now considerably deeper. The air temperature on the top of the ice cap was compared with the dry-bulb temperature 0·5 km. away and 40 m. lower (Table V). There was good correlation in the winter when the ice-cap temperature tended to be about 1·5° C warmer than the dry-bulb temperature but this was not so in the summer because the Rototherm thermometer was not ventilated correctly.

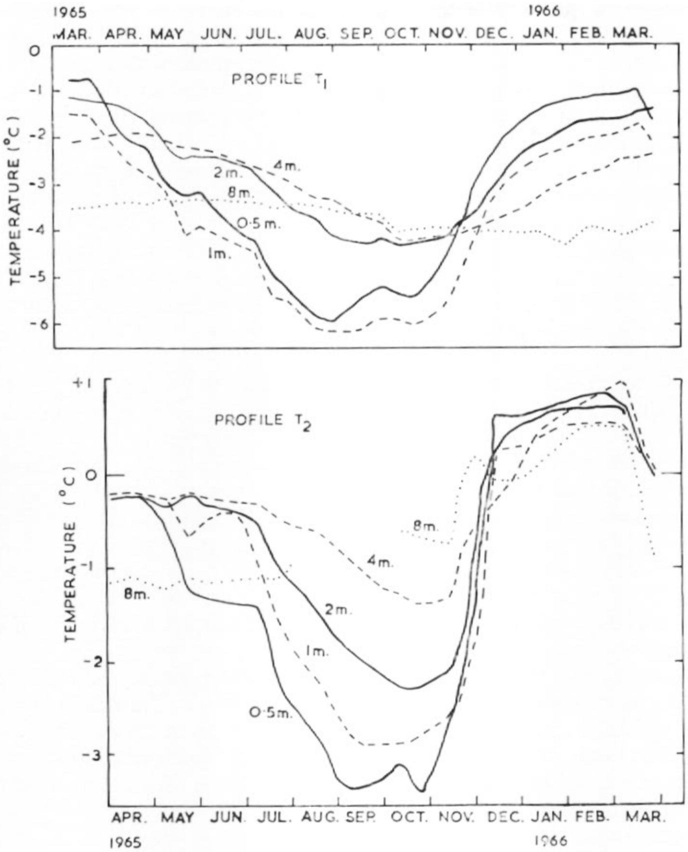

Fig. 20. Temperature/depth profiles at two sites (T_1 and T_2, Fig. 11) on the Galindez Island ice cap for the period March 1965–March 1966. The depths shown are nominal.

Conclusions

From the snow-level studies on Galindez Island (p. 24), it has been shown that snow-level changes are intermittent during the accumulation season and regular in the ablation season. Table I shows that the dates on which these seasons start and end do not vary by more than a few weeks from year to year, and hence the budget year is about 12 months long every year. The fact that, on the Galindez Island ice cap, the mean height at all stakes and the mean height at nine selected stakes, *e*, agreed throughout the accumulation season (Fig. 5) gives validity to these parameters and to the use of *e* on p. 29 to give the mean net accumulation for the ice cap proper.

The mean rate of change of snow-surface height on the Galindez Island ice cap over a 5-yr. period was close to Thomas's figure for the previous 5 years. Therefore, the average rate of change of snow-surface height over any long period is likely to be close to the quoted mean, although any individual year may differ widely from the norm.

The observations on the Skua Island ice cap (p. 38) help to set the detailed work on the Galindez Island ice cap in its true perspective. The weather patterns which envelop the Argentine Islands evidently affect each ice cap in a similar manner, but the magnitude of the effect varies considerably. It is not known whether the long-term effects are similar on each island but a comparison between net accumulation values on the two islands studied (Figs. 9 and 15) suggests short-term similarity.

Studies on Galindez Island (Fig. 8) yielded the interesting result that the snow mass accumulated was of similar magnitude at three apparently diverse sites for most of the 1965–66 budget year. This agrees with the result (p. 46) that accumulation does not vary significantly with height above sea-level, gradient or aspect. This correlation of snow masses makes the estimation of the net accumulation of the ice cap proper during 1965–66 worthwhile (p. 29).

The 1965 snow masses are linked to those measured by Thomas (1963) at the same stakes in 1960 to give representative measurements of net accumulation over a 5-yr. period. There are insufficient data to give a 5-yr. average measurement balanced over the ice cap proper but this would probably be higher than the 19 cm. of water equivalent for 1965–66, whilst less than the rate of change in snow-surface height (28 cm. $yr.^{-1}$; p. 26). These snow-surface height measurements gave a fairly accurate picture of the ice-cap budget over a period of years (p. 32) because much of the change was due to superimposed ice. This analysis gives results which are completely contrary to Fleming's (1940) theory that the ice caps of the Argentine Islands are wasting away rapidly.

A comparison between data for the Argentine Islands' ice caps and other published data emphasizes the unique form of these small islands. Their similarity to other small ice caps on islands off the west coast of the Antarctic Peninsula (p. 21) needs to be investigated more fully.

Linking movement measurements over a 5-yr. period (Table III) has confirmed Thomas's (1963, p. 41) conclusion that the greater part of the Galindez Island ice cap has a negligible movement. At the same time, further investigations of the interesting movement zone (Table IV) gave an estimate of the average annual calving of the ice cap: 9 cm. of water equivalent per unit area (p. 38). However, this was only part of the total ablation since two-thirds of the gross accumulation (58 cm. of water equivalent; p. 37) was lost by the end of the 1965–66 budget year. The remainder of the ablation consisted mainly of water run-off and the drifting of uncompacted snow.

The present studies of the effect of the climate of the Argentine Islands on the prevailing snow cover do little more than point the way for future work. Thomas's correlation between net accumulation and high temperature with low cloud cover is not generally valid but it may be true for part of the time. The variation of ablation with absorbed radiation also appears to be true over a limited part of the budget year but future observations must be carried out on a day-to-day basis to verify this.

Snow- and ice-temperature profiles show that the annual variation in mean monthly air temperature of about 14° C was damped down to about 5° C by 2 m. of snow and to less than 1° C by 10 m. of snow and ice cover.

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