OBSERVATIONS ON SNOW ACCUMULATION PATTERNS AT ADELAIDE ISLAND

By Rorke Bryan

Abstract. On the west coast of Adelaide Island there is an ice piedmont approximately 1,400 km.^{2} in area which rises from near sea-level to 870 m. a.s.l. Gross snow accumulation as high as 203·2 cm. of water equivalent in 8 months has been recorded here. The amount of accumulation decreases from north to south, becoming almost negligible on the lee slope at the southern coast of Adelaide Island. Most of the island lies above the firn line, which is at 190 m. a.s.l. on the west coast and tentatively below 77 m. a.s.l. on the east coast.

The formation of rime deposits is common and thicknesses up to 2·5 cm. have been known to form in 12 hr. on a horizontal surface. Rime deposits are of great importance in the regime of the ice piedmont, which is now thought to be positive after a long period of negative regime.

During the winters of 1962 and 1963 observations were made on accumulation rates at various sites on Adelaide Island. The observations were centred on the British Antarctic Survey station at the southern tip of the island (lat. 67°46′S., long. 68°55′W.).

Physiography

Adelaide Island lies off the west coast of Graham Land, extending for a distance of approximately 144 km. between lat. 66°37′ and 67°46′S. A high mountain chain, rising in places to an altitude of 2,800 m. a.s.l., extends for about two-thirds of this distance along the east coast of the island. The western part of Adelaide Island is formed by the Fuchs Ice Piedmont, which covers the whole length of the island and varies in width from 3 to 16 km. This gives an approximate area of 1,400 km.^{2} for the ice piedmont. To the south, west and north, the ice piedmont is bounded by vertical ice cliffs varying in height from 20 to 50 m. There is only one easily accessible approach on these coasts: at the south-western tip of the island. The ice cliffs are generally backed by a heavily crevassed area, varying in width from 0·5 to 5 km. This is in contrast to the main body of the ice piedmont which shows little crevassing. From the ice cliffs the surface of the ice piedmont rises in a gentle convex slope to an average altitude of 600 m. near the mountain chain, but it rises locally to 870 m. in the vicinity of the Mount Bouvier massif.

In the area north of the main mountain chain, the use of the term "ice piedmont" is questionable. The ice forms a broad dome, the surface of which is penetrated by four nunataks: Mount Machatschek, Blümcke Knoll, Visser Hill and Mount Vélain. For convenience the term "ice piedmont" is retained for the whole formation. The east coast of the island in this sector is formed by steep, heavily crevassed slopes which border Hanusse Bay.

Southward from Hanusse Bay, the mountain chain is unbroken, except by Shambles Glacier, which forms a 16 km. wide breach in the chain. Through this gap the east coast of the island can be reached at Square Peninsula. This peninsula is a small ice piedmont which calves directly into Laubeuf Fjord, and it also feeds Crumbles Glacier which enters Ryder Bay. The east coast of Adelaide Island is formed by the steep slopes of the main mountain chain, which nourish numerous small fringing glaciers ending in ice cliffs 30-40 m. high. Calving from these fringing glaciers and avalanching from the mountain slopes are active throughout the year.

The Fuchs Ice Piedmont is nourished by valley glaciers from the mountain chain, by avalanching from the mountain slopes and by accumulation on the surface of the ice piedmont. Mass removal from the ice piedmont is by wind ablation, evaporation, run-off of melt water and calving. The movement of the ice piedmont is basically radial, but only on the south, west and north coasts is it unrestricted. On these coasts calving is directly into the sea; it is localized into numerous ice streams which are governed by the underlying topography. To the east, ice movement is restricted by the mountain chain, but release is via Shambles Glacier into Laubeuf Fjord and directly into Hanusse Bay.

Climate

A meteorological station has been in operation on Adelaide Island only for two winters (1962 and 1963), so no climatic means are available. For most of the year the island lies in a cyclonic belt, characterized by the passage of frontal depressions and associated disturbed weather. Only during August, and for short spells in July and September, does the polar anticyclone extend over Adelaide Island.

A comparison with meteorological records from neighbouring stations at Horseshoe and Stonington Islands indicates that the winter of 1962 was one of the warmest on record for the area, and that of 1963 was one of the coldest. During the summer months (November, December and January), the temperature varies around freezing point and melt conditions are widespread. One of the characteristics of the temperature patterns is the sudden rise in temperature which accompanies northerly winds. On one occasion this reached a maximum of 44° C in 24 hr. (August 1963).

Northerly and north-westerly winds are dominant at Adelaide Island throughout the year. The bias is towards north-westerly in summer and northerly in winter. Throughout the year east–south-easterly winds are prominent and are associated with cold clear weather. During east–south-easterly winds a föhn bank commonly lies along the western foot of the Adelaide Island mountain chain at an altitude of about 600 m. High wind averages are recorded and gusts of 45 m./sec. are common.

Since most of the precipitation occurs during northerly and north-westerly blizzards when there is heavy drifting, it is impossible to measure the exact amount of precipitation. Using the figures available, an average of 22 days of precipitation per month has been calculated. No information is available on the amount of precipitation during any given day. Because most of Adelaide Island lies above 200 m., it is consequently cloud-covered for a large part of the year. As a result of this, rime deposits are of great importance.

Methods of Studying Accumulation

The following three methods were used to study accumulation:

i. *Stakes.* Triangular patterns of 14 and 12 stakes, respectively, were set out on the southern end of the ice piedmont near the British Antarctic Survey station during the winters of 1962 and 1963.

ii. *Pits.* A total of 13 pits was dug on Adelaide Island during the two winters, thus giving a reasonable coverage of the Fuchs Ice Piedmont.

iii. *Information from depot sites.* During the winters of 1962 and 1963 numerous sledge parties travelled on Adelaide Island, and much information on accumulation at depot sites is available. This can be a useful guide in areas where information from pits or stakes is not available.

Accumulation Observations during the Winter of 1962*

In March 1962 a depot was laid by aircraft at Blümcke Knoll (site A; Fig. 1) at an altitude of 248 m. This depot was fixed by compass resection and marked by a 3·15 m. pole. When the site was re-visited in August 1962 the depot could not be re-located, which suggested exceptionally high accumulation. The site was subsequently visited at the beginning of October 1962 and a pit was dug (Fig. 2) which supplied further evidence for extremely high accumulation.

Fig. 2 shows the profiles of pits dug during the winter of 1962 and the summer of 1962–63. The pit at site A was dug to a depth of 5·25 m. and at a depth of 4·85 m. a pronounced layer of clear ice was reached. This was underlain by highly crystalline firn which appeared to have been metamorphosed by percolating melt water. This ice layer was interpreted as representing the 1961–62 summer melt layer, the overlying accumulation representing a period of approximately 7 months and an equivalent of 196·5 cm. of water. The thin ice bands which occur in the upper part of the profile (above 2·50 m.) probably represent rime accumulation layers.

* The terminology used in this section is that defined by Koerner (1964).

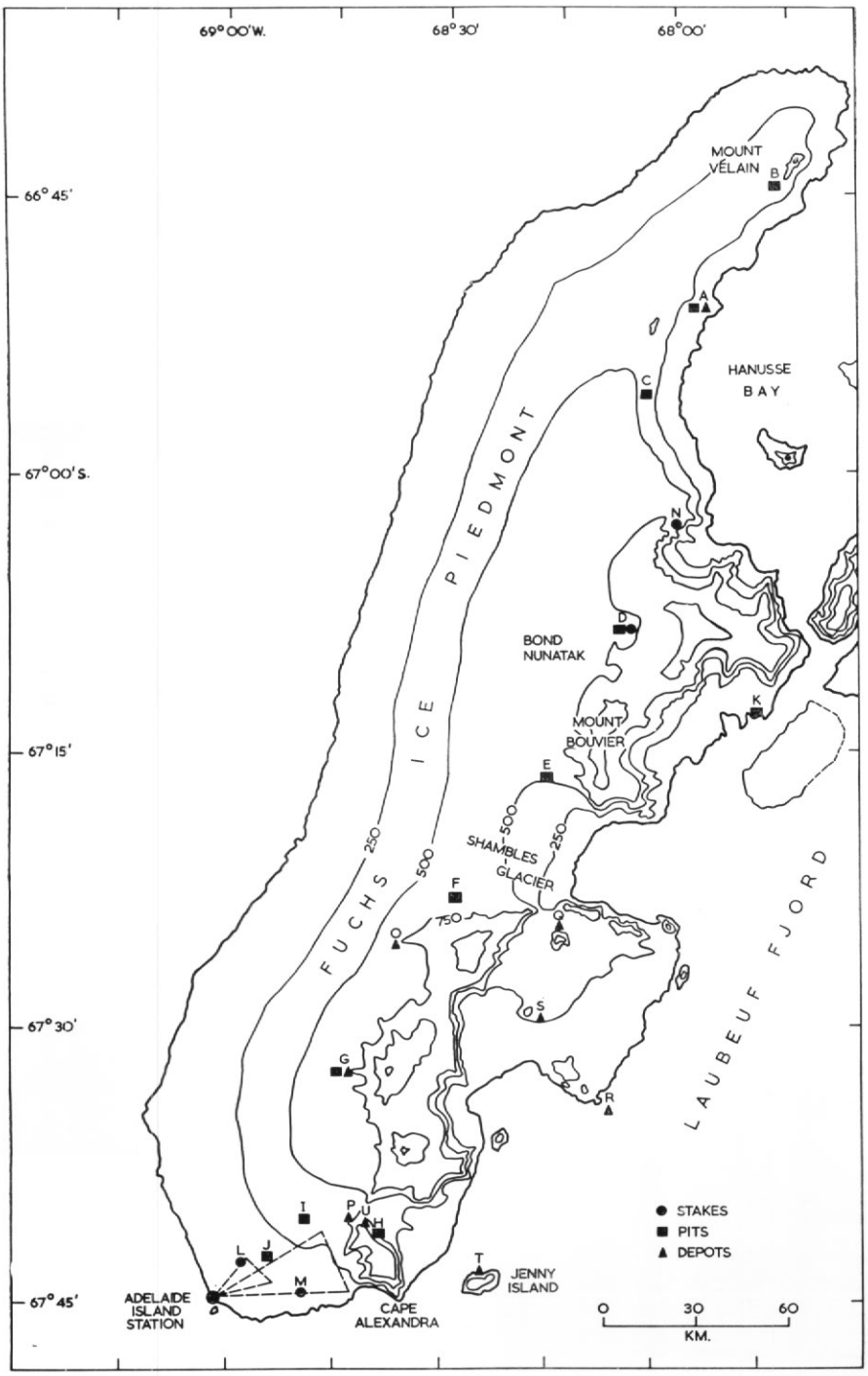

Fig. 1. Sketch map of Adelaide Island showing pit, stake and depot sites used for accumulation studies. The form lines are at 250 m. intervals up to 750 m. and at 750 m. intervals above.

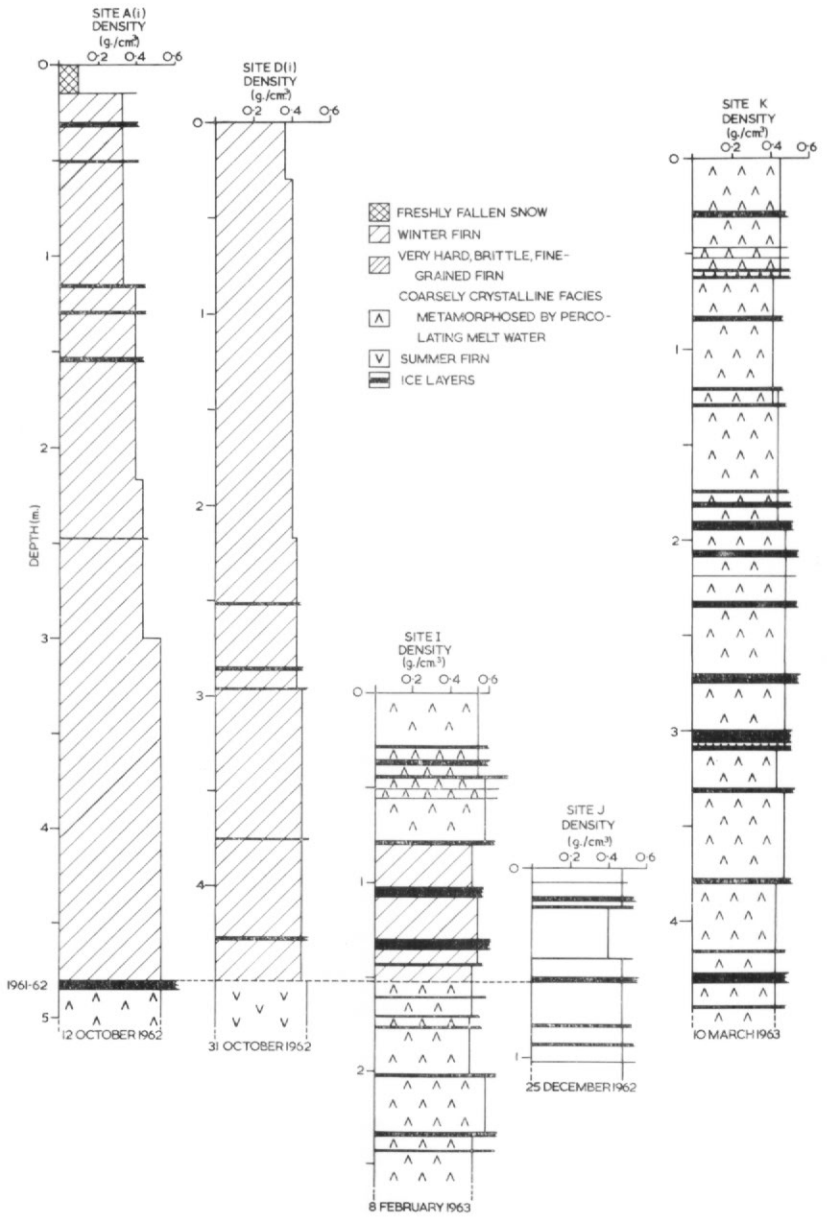

Fig. 2. Profiles of 5 pits dug during the 1962 winter and the 1962–63 summer. The positions of the sites are given in Fig. 1.

Site D, at an altitude of 870 m., is situated at the highest point of the Fuchs Ice Piedmont, where it is joined by glaciers flowing from the Mount Bouvier–Mount Reeves massif. At this site an 8-month accumulation of 203·2 cm. of water equivalent was found, which agreed closely with that at site A. No pronounced ice layer was found which could be interpreted as a melt horizon. However, at a depth of 4·50 m. there was an horizon of firn which consisted of very large crystals, and this was interpreted as representing the end of the 1961–62 summer

firn. There was no evidence of melting or percolation of melt water. This is thought to be due to the greater altitude, and it is possible that this site is representative of the area above the dry snow line. One interesting comparison with site A is in the stratigraphy of the rime deposits. At site A all rime deposits lie between the surface and a depth of 2·50 m., but at site D all the rime deposits lie below 2·50 m. The only horizons which can be tentatively correlated are those at 2·45 m. at site A and 2·55 m. at site D.

Site N, at an altitude of 840 m., lies in the area between sites A and D. The situation is on a snow and ice platform at the northern tip of the mountain chain, overlooking Hanusse Bay. Observations from a survey pole at this site indicate an accumulation of 530 cm. of snow between early June 1962 and late January 1963. This suggests a higher accumulation than at site A or D, which is probably due to a local increase in orographic precipitation at the windward foot of a mountain barrier.

Between sites D and I only depot information is available for 1962. Site O, which has been the site of the main central depot on Adelaide Island for three winters, is on a snow ridge extending westwards from the mountain chain to Lincoln Nunatak, at an altitude of 808 m. The ridge is very exposed and the crest is several hundred metres above the surrounding ice piedmont. Between the end of December 1961 and the beginning of September 1962 an accumulation of 372·5 cm. of snow was recorded. There was no steady accumulation throughout the 8-month period and the final figure includes long periods of no accumulation or of active ablation. This site is subject to very severe wind ablation and is atypical of the Fuchs Ice Piedmont.

A depot was laid in March 1962 at site G (769 m.). Between 21 March 1962 and 25 November 1962 an accumulation of 647·5 cm. of snow was recorded. This site is at the confluence of several valleys down which winds are funnelled and it is subject to exceptionally heavy drifting, so that accumulation figures are probably higher than they would be for the adjacent ice piedmont where there is less topographic influence.

Site P lies at the foot of a glacier which descends from the plateau between Mounts Ditte and Liotard to the Fuchs Ice Piedmont. Associated with this glacier are strong katabatic easterly winds but the site itself is protected from ablation by a prominent step in the surface of the glacier. Between March and June 1962 there was snow accumulation of at least 250 cm. at this site. This is in strong contrast to site U, 300 m. higher up, which is on a ridge connecting the plateau between Mounts Ditte and Liotard with one of the scarp bluffs overlooking the Fuchs Ice Piedmont. At site U, between April and December 1962, 15 cm. of snow accumulated, which is attributable solely to drifting around a depot. The ridge on which this depot is sited is subject to severe wind-scouring throughout the year and bare ice is commonly exposed at the surface.

Site I is on the lee slope of the Fuchs Ice Piedmont at an altitude of 372 m. The profile of the pit dug there (Fig. 2) probably covers a period of more than one calendar year. The first 0·75 m. beneath the surface were soaked by percolating melt water of the 1962–63 summer. At that depth there was an horizon of compacted winter firn, which was apparently unaffected by percolating melt water. As at other pit sites, the winter firn was interbedded with rime deposits and a few very thin bands of clear ice that were thought to represent freezing rain deposits. The only correlation which can be made with pits in the northern part of the Fuchs Ice Piedmont is the termination of horizons affected by the 1961–62 summer melt, which was reached at a depth of 1·50 m. The water equivalent for the accumulation in the budget year was 84·27 cm., which suggests a much lower accumulation than at sites A, N and D.

The pattern of stakes set out on the ice piedmont in March 1962 (Fig. 3) forms site L. The pattern extended to 4 km. from the British Antarctic Survey station and reached an altitude of 200 m. The observations made at these stakes are shown in Fig. 4. It is thought that some of the figures for December are unreliable, because some of the stakes had started to melt downwards due to conduction. Of the 14 stakes in the pattern, stakes 9, 10, 11 and 12 are at the same altitude, and within 50 m. of one another.

The two marked features of the observations are a general sharp rise in surface level during August and general ablation in September. August had one of the lower precipitation rates for the year, so the sharp increase in the surface level is probably a reflection of the relatively

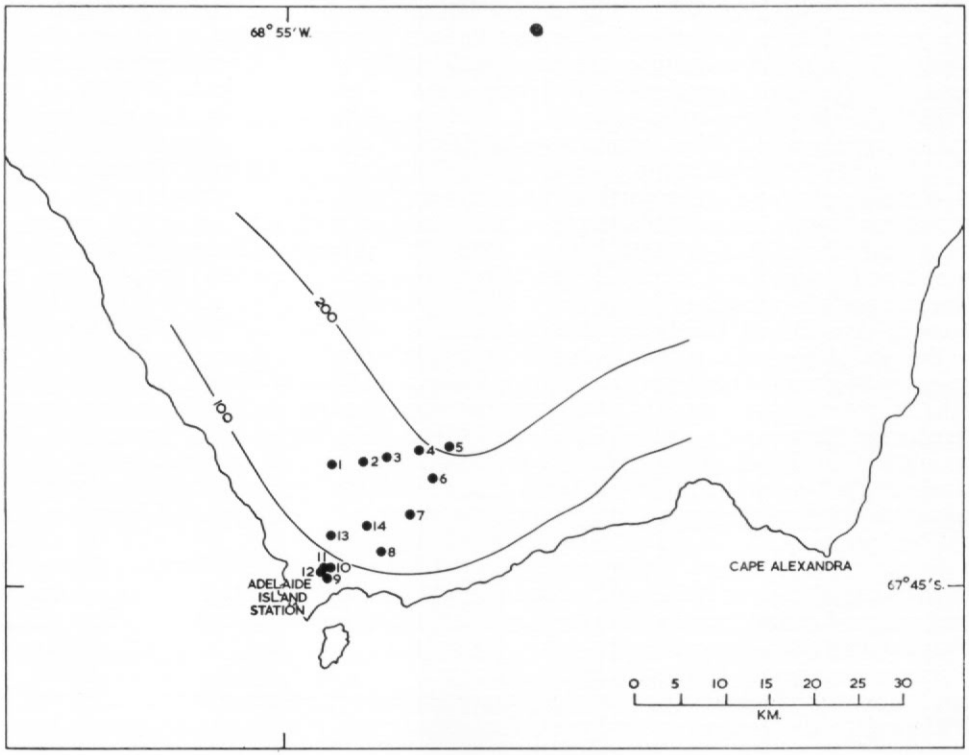

Fig. 3. Sketch map showing the stake pattern set out on the southern part of the Fuchs Ice Piedmont in March 1962.

slow compaction rates due mainly to long periods of cold calm weather. Wind ablation was also relatively low during this month.

At two stakes no ablation was recorded during September but the ablation at the other stakes varied between 1 and 12 cm. during the month. This pronounced ablation can be attributed to the high average wind velocity of 11 m./sec. for September, which was the highest average recorded during 1962. The prevailing wind was northerly during the month, which brought high snowfalls to the windward parts of the island during the period. (This is based on a report from a sledge party at site A.)

No accurate ablation measurements were obtained during the 1962–63 summer, because by January a number of the lower stakes had melted out and large melt pools up to a depth of 15 cm. lay on the surface near stake 9 at an altitude of 90 m. During the 1962–63 summer the firn line was at 190 m. at this site.

The fourth profile in Fig. 2 is of a pit dug at site J, 5·6 km. north of the British Antarctic Survey station and at an altitude of approximately 250 m. The pit was dug to a box deposited there in July 1961. The accumulation over the 16-month period was only 49·78 cm. of water equivalent. It is possible that the ice layer at a depth of 0·65 m. represents the 1961–62 summer melt, which would give a figure of 26·9 cm. of water equivalent for the last budget year.

The last profile in Fig. 2 is of a pit at site K, on the east side of the mountain chain at an altitude of 77 m. This profile differs from those of the other pits because all the exposed firn had been metamorphosed by percolating melt water. Although numerous ice layers were found, it was not possible to establish a direct stratigraphic correlation with other pits because of the firn metamorphism. The firn line was considered to be below this pit, whereas the saturation line was above it, and melt water percolated through more than a complete budget year's accumulation.

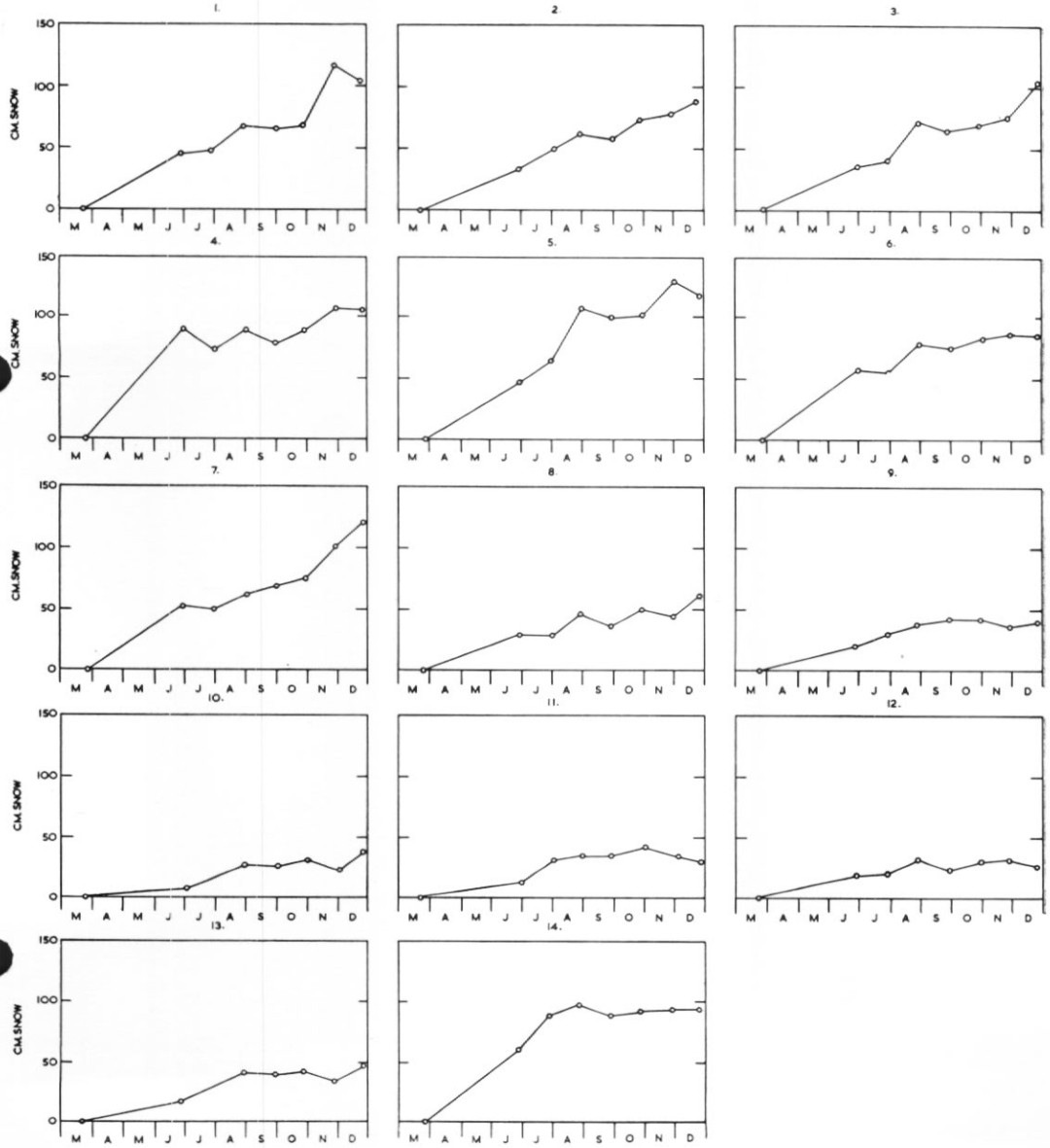

Fig. 4. Graphs showing snow accumulation trends at stakes 1–14 set out on the southern part of the Fuchs Ice Piedmont in March 1962.

Other information from the east side of the mountain chain is sparse. Site Q, on the summit of McCallum Pass at an altitude of 620 m., showed an accumulation of 75 cm. of snow in the 5 months between May and October 1962. Site S, at an altitude of about 600 m., had an accumulation of 165 cm. of snow between the end of May and the end of August 1962. Depots laid at heights of 6 m. a.s.l. at site T on Jenny Island and site R at Rothera Point remained free of snow throughout the 1962 winter.

Accumulation Observations during the Winter of 1963

Fig. 5 shows the profiles of two pits dug during the early part of the 1963 winter. In the first pit, at site A, there was uniform winter firn down to a depth of 1·65 m., where there was a prominent layer of clear ice underlain by highly crystalline firn apparently metamorphosed by percolating melt water. This was interpreted as representing the melt of the 1962–63 summer. The accumulation over a period of approximately 2 months was 65·9 cm. of water equivalent, which agrees closely with information from a depot 30 m. away; this was laid at the beginning of March 1963 and was dug out at the end of April to a depth of 1·65 m. This also agrees in amount and in the absence of rime deposits with the corresponding part of the 1962 profile at the same site (Fig. 2). However, it shows lower densities than in the corresponding part of the 1962 profile, which are attributable to the greater compaction of the latter.

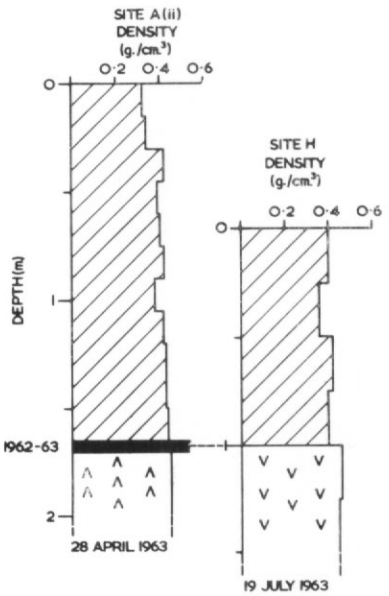

Fig. 5. Profiles of 2 pits dug during the early part of the 1963 winter. The positions of the sites are given in Fig. 1 and the key to the symbols used is given in Fig. 2.

At site N 255 cm. of snow accumulation was observed between the end of January and the end of April 1963. As in 1962 this was somewhat larger than the accumulation for adjacent sites.

The second profile in Fig. 5 is of a pit at site H (930 m.) on the plateau between Mount Liotard and Mount Ditte, and in the lee shadow of Mount Liotard. No ice layers were found in this pit but at a depth of 1·00 m. an horizon of firn with large crystals was encountered. This was interpreted to be firn of the 1962–63 summer. This firn did not appear to have been metamorphosed by percolating melt water and the pit is probably in the area above the dry snow line. The accumulation for a period of 4 months was 62·25 cm. of water equivalent.

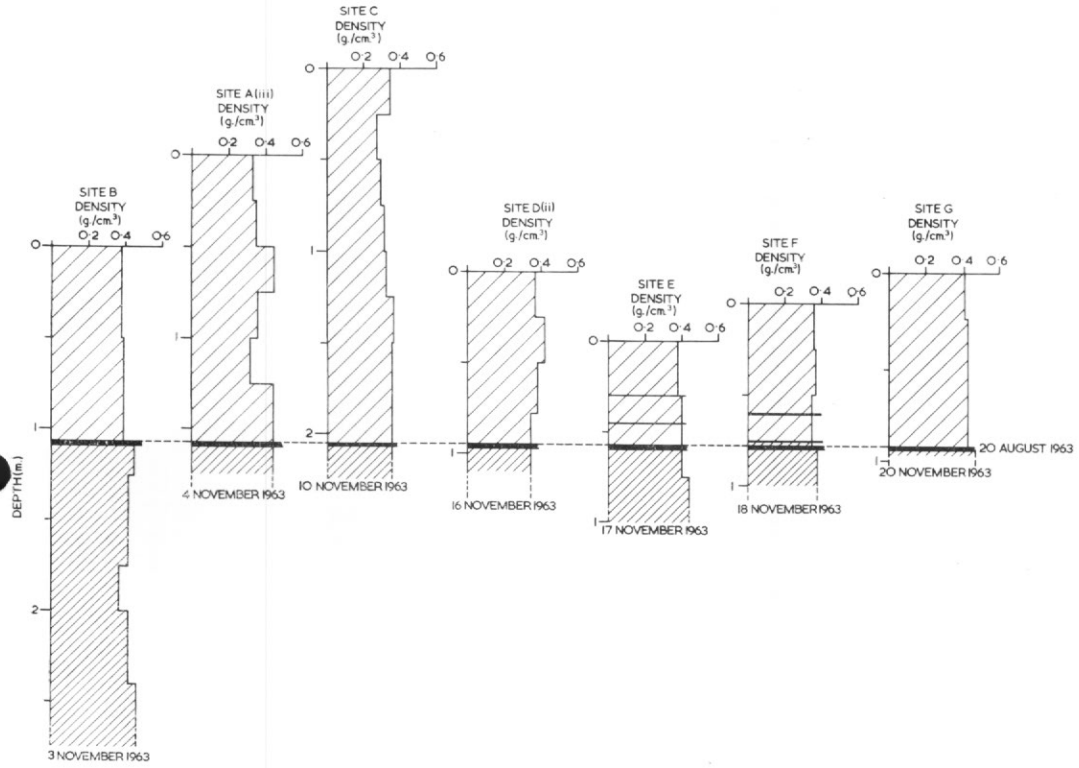

Fig. 6. Profiles of 7 pits dug during November 1963. The positions of the sites are given in Fig. 1 and the key to the symbols used is given in Fig. 2.

Fig. 6 shows the profiles of seven pits which were dug on Adelaide Island during November 1963. The reference datum for stratigraphic correlation between these profiles is a very pronounced rime ice layer which is thought to have accumulated over most of Adelaide Island about 20 August 1963. The conditions which gave rise to its formation were a period of very cold weather culminating in a minimum temperature of —44° C, and followed by a rise to 0° C within 24 hr. This sharp rise in temperature was accompanied by the influx of stratoform clouds over Adelaide Island, with a cloud base at 150–300 m. This situation of a relatively warm water vapour cloud being brought into contact with a very cold surface under calm conditions provided perfect conditions for the deposition of rime over a wide area (Pepper, 1954). In all pit profiles the rime deposit was underlain by very hard firn which must have been subjected to the same low temperatures.

The period of time represented by the accumulation above the August rime ice layer increases from $2\frac{1}{2}$ months at site B to 3 months at site G. Sites A, D and G show typical snow accumulations but the pattern at the other sites is partially obscured by local topographic effects. The accumulation at site B is rather low for a site on the northern part of the Fuchs Ice Piedmont, and this is probably due to being on the lee side of Mount Vélain, which rises 500 m. above the general ice level. The accumulation at site A is probably representative of the northern part of the ice piedmont but is somewhat lower than during a comparable period at the same site earlier in the winter. This could be due to the lower wind velocity earlier in the winter. The respective average wind speeds for the relevant period are 7·4 and 12·28 m./sec. The accumulation at site C is larger than would be expected, probably because of its situation in a broad depression where the ice piedmont starts to feed into Hanusse Bay.

Even allowing for a general southward decrease in accumulation, the observations for sites E and F are lower than expected. This is probably due to local severe wind ablation, as both sites are exposed to strong easterly winds funnelled up Shambles Glacier. Both of these sites have rime deposits above the August horizon, and these do not occur in any of the other profiles. It is thought that the deposition of rime in this area is more frequent than elsewhere on the island and this is due to condensation when air is funnelled up the 600 m. rise of Shambles Glacier. When the rest of the island is cloud-free, it is common to find a cloud bank over the lower parts of this glacier.

During June 1963 a triangular pattern of 12 stakes was set out to form site M at the southern end of the Fuchs Ice Piedmont (Fig. 7). This extended 8 km. from the British Antarctic Survey station and reached an altitude of 288 m. The observations at these stakes are given in Fig. 8. Most of the stakes showed steady accumulation until the middle of October but thereafter a sharp decrease in accumulation or active ablation. The ablation figures for December 1963 are unreliable because conduction had caused some of the stakes to melt into the ice. During the 1963–64 summer the lower stakes melted out completely; ice was exposed and melt water flowed on the surface. In places, particularly in artificial channels formed by tractor tracks, slush flow was observed and small-scale slushers formed.

At no stage during the 1963–64 summer did the total accumulation disappear from the vicinity of stakes 3, 4, 5, 6, 7, 8, and 9. The firn line for this summer was at 202 m., which is somewhat higher than for the preceding summer. The 1963–64 summer was unusually warm and melting in the vicinity of the British Antarctic Survey station was widespread. It seems that the height of the 1962–63 firn line at 190 m. is more normal in this area.

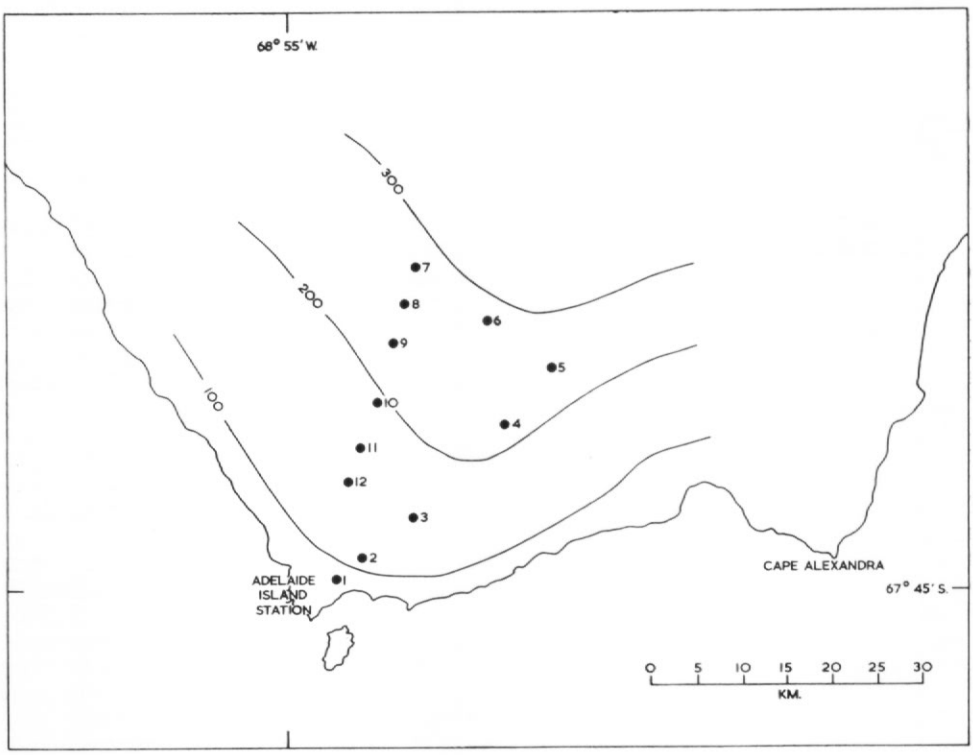

Fig. 7. Sketch map showing the stake pattern set out on the southern part of the Fuchs Ice Piedmont in June 1963.

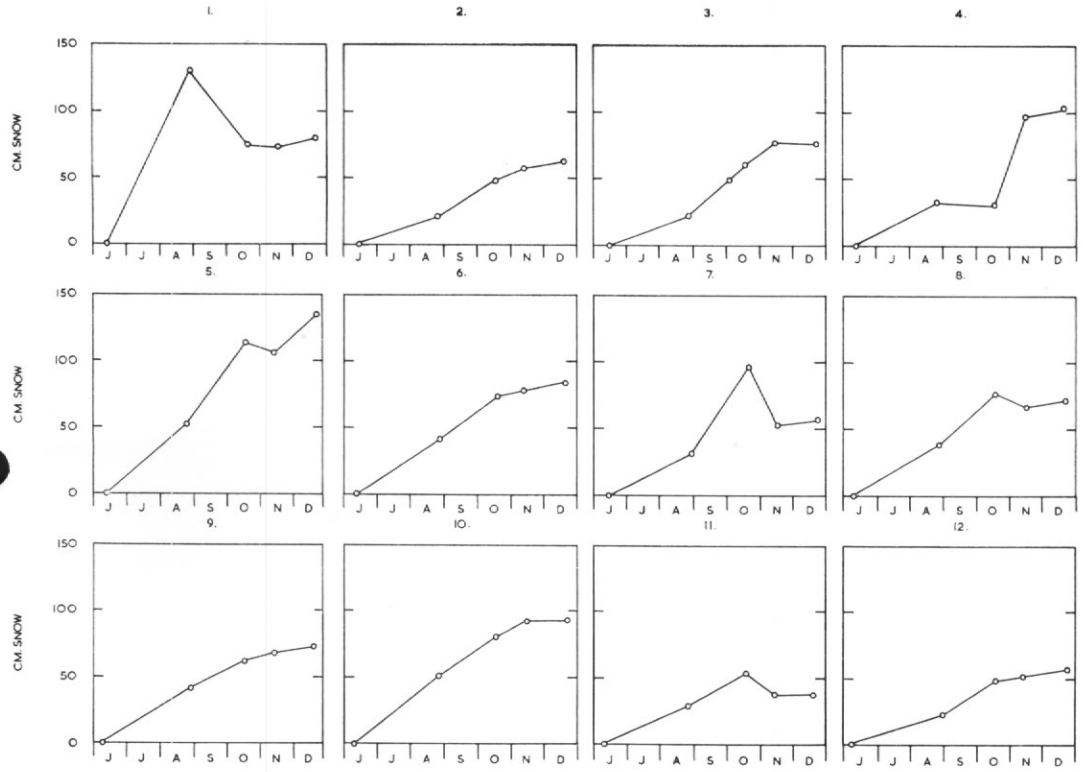

Fig. 8. Graphs showing snow accumulation trends at stakes 1–12 set out on the southern part of the Fuchs Ice Piedmont in June 1963.

Discussion

The outstanding feature of the accumulation pattern at Adelaide Island is the very large amount in the northern part of the island. Although there are no observations covering a complete budget year, accumulation figures of up to 203·2 cm. of water equivalent in 8 months were observed. This extremely high accumulation is considered to be due to a combination of cyclonic and orographic precipitation on windward slopes. Most of the precipitation occurs during periods of northerly and north-westerly winds in association with depressions passing south of Adelaide Island. These winds prevail throughout the year and in some months they represent more than 50 per cent of the total winds recorded. Accumulation reaches a maximum in the northern area between Blümcke Knoll and Bond Nunatak, where the surface level rises from 248 to 870 m. in a distance of 48 km. Southward from Bond Nunatak the accumulation decreases gradually on the lee slope of the island, until at the south coast there is almost negligible accumulation throughout the year.

At present there is insufficient evidence to enable any comparison of accumulation to be made between the east and west sides of the Adelaide Island mountain chain. The little available information suggests that accumulation on the east side of the mountain chain is appreciably lower than on the west side.

Accumulation is generally high throughout the winter but it appears to reach a maximum during May, June and July. Much of the precipitation occurs during periods of high wind, so that the greater part of the gross accumulation is in fact removed as drift. This is particularly important during September when average wind speeds of 11·0 and 12·3 m./sec. were recorded for the 1962 and 1963 winters.

Rime deposits are of considerable importance on Adelaide Island. Most of the island lies above 200 m. and many of the sledge party reports indicate that conditions suitable for rime formation occur during 60 per cent of the year. This agrees closely with observations by Koerner (1964) on the west side of Trinity Peninsula and Joinville Island. On many occasions heavy rime deposits have been observed and in one instance a deposit of 2·5 cm. formed on a horizontal surface in 12 hr. Apart from the actual accumulation, rime deposits are important because they protect underlying firn from wind ablation. Well-formed rime lobes have been reported from the summits of all the peaks climbed in the Adelaide Island mountain chain. As in Trinity Peninsula, these probably make a significant contribution to the mass accumulation (Koerner, 1964).

On the west side of the island, the firn line is at 190 m. in a normal year but on the east side it is below 77 m. Most of the island, therefore, lies within the accumulation zone. The only figure available for annual net accumulation (near the southern end of the island) is 84·27 cm. of water equivalent, where the annual gross accumulation is less than 50 per cent of that at the north end. The saturation line is below 370 m., so a large part of the Fuchs Ice Piedmont lies between the saturation line and the dry snow line. The dry snow line is tentatively placed at a height of 850 m.

The limited observations available suggest that accumulation on the Fuchs Ice Piedmont far exceeds ablation by wind, evaporation and run-off. So far no accurate estimate of calving has been attempted but it is known that numerous localized ice streams within the body of the ice piedmont are calving actively. It appears probable that the regime of the ice piedmont is either slightly positive or in equilibrium. This is in contrast with Fleming's (1940) observations of 30 yr. ago, when he stated that the island ice caps of Graham Land were ephemeral features that would disappear completely in a few years if the then existing climatic conditions continued. It is possible that a southward migration of depression tracks over Graham Land has resulted in greatly increased precipitation on Adelaide Island. This seems to have restored a positive regime after a long period of negative regime which resulted in extensive evidence of "temporary" deglaciation in the Marguerite Bay area. This suggestion of a recently restored positive regime is indeed supported by the development of semi-permanent sea ice into a low ice shelf in parts of Hanusse Bay.

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REFERENCES

FLEMING, W. L. S. 1940. Relic Glacial Forms on the Western Seaboard of Graham Land. *Geogr. J.*, **96**, No. 2, 93–100.

KOERNER, R. M. 1964. Glaciological Observations in Trinity Peninsula and the Islands in Prince Gustav Channel, Graham Land, 1958–60. *British Antarctic Survey Scientific Reports*, No. 42, 45 pp.

PEPPER, J. 1954. *The Meteorology of the Falkland Islands and Dependencies, 1944–1950*. London, Falkland Islands and Dependencies Meteorological Service.