THE WHAKAPAPANUI GLACIER:

HYDROLOGICAL BUDGET STUDIES AND ASSOCIATED ASPECTS OF ITS GLACIOMETEOROLOGY

A THESIS PRESENTED IN PARTIAL FULFILMENT OF THE REQUIREMENTS
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PREFACE

This thesis represents an attempt to analyse some of the causes and effects of climate/glacier interaction on the Whakapapanui Glacier. Climate/glacier studies encompass a wide range of relationships all of which are interrelated. Meier has developed a system which expresses the manner in which the various aspects of this interrelationship are linked.

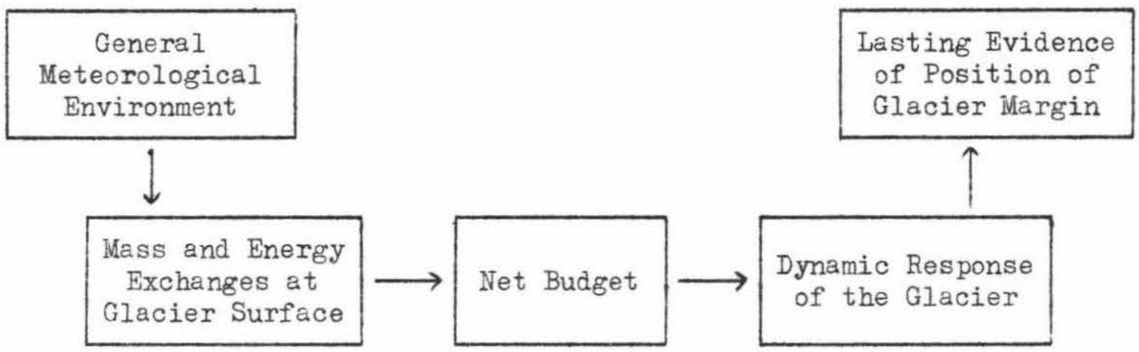

FIG.1

From "Glaciers and Climate", M.F. Meier. In The Quaternary of the United States, 1965, 795.

The writer was concerned principally with the first three stages of this system, those which dealt with "the size to which a glacier grows, its state of health, its degree of activity, its life span and its history" (Sharp, 1960). All these aspects are controlled by meteorological factors and the discipline of glaciometeorology has grown up to deal with them.

Part I introduces the background, setting, instrumentation, methodology and problems encountered in the technique of hydrological budget studies. Part II is essentially a study of the 1968/9 budget year using the methodology described in Part I, together with an indication of the state of health of the glacier. Part III examines the normality of the 1968/9 climatic year, suggests future trends in the state of health of the glacier, and postulates its length of survival. Finally, Part IV is a comparison with selected glaciers and contains the general conclusions.

The thesis is not intended as a complete exposé of climate/glacier relationships on the Whakapapanui Glacier, it represents rather a method for showing how a simplified glaciometeorological technique can contribute to an understanding of this general problem. There are two prominent and readily observable avenues which are known to reflect the character of climate/glacier relationships. First, there is the budget approach which is concerned with the alteration in balance or imbalance between annual accumulation and annual ablation. Second, there is the approach which examines the response of the glacier to these alterations. "Whereas the former approach registers the finite adjustments of glaciers in the year-to-year fluctuations in weather conditions, the latter because the response is less immediate registers long term climatic trends." (Komb, 1964) This latter technique is an expansion of glacier dynamics while the former aspect is a problem of meteorology.

Aims and Objectives

The principal aim was to develop a simple and relatively inexpensive method for measuring the hydrological budget. The second aim was to analyse the causes and effects of easily measured meteorological parameters on the fluctuations in glacier behaviour. Consequently the research has been conducted using, principally, the meso- and macroscopic scales to examine the relationship between synchronous meteorological parameters and the regime of the glacier. Emphasis was placed on the meteorology of the glacier budget, but it was lack of essential hydrological equipment that prevented the use of the true hydrological approach (i.e. calculating the water potential of a glacier through catchment and runoff measurements) as a complementary technique.

ACKNOWLEDGEMENTS

For the emergence of this thesis I am greatly indebted to my supervisor, Mr R.D. Thompson, for introducing me to this field of research. Through his active interest in the field of glaciometeorology, his patience and dedication to this cause, what was originally just an idea and a hope has culminated in a documented piece of research and a continuing interest in the subject. Second, for the typing of the thesis in its various stages, for unfailing assistance in proof reading and for the typing of the final copy, I am eternally grateful to my wife, Geraldine.

From the inception of the project to its final production in bound form there are a number of people to whom I owe my thanks. For their enthusiasm and assistance I am grateful to Messrs W.A. Buckman, R.B. LeHeron, B. Stafford-Bush and P.J. Liddell, and Miss R.A. Hunt. Special thanks are due to Warwick for acting as guide on several occasions, to Pat for his technical assistance and to Royce for acting as camp dietician on several occasions. For making certain items of equipment available on loan from the Zoology Department at Massey University and for his technical assistance, my grateful thanks to Mr M. Mannering. I am also indebted to various staff members and other student geographers at Massey University for their assistance during field excursions.

Throughout the project close cooperation was maintained with the Tongariro National Park Board Rangers, who assisted in every way possible. Records were readily made available, rangers visited the meteorological station and changed charts whenever they were in the vicinity of the glacier, and Park Board accommodation was made available at our request. Many thanks to Messrs J. Mazey (Chief Ranger), W. Cooper and B. Jeffries for their support.

For historical evidence and qualitative records I am grateful to Mr L.O. Krenek who made his full collection of photographs available for my use. Thanks also to the Lands and Survey Department and the R.N.Z.A.F. base, Ohakea, for providing useful photographs and to the Massey University photographer, Miss D. Scott, for five further aerial photographs.

Finally, I am greatly indebted to the University Grants Committee and Massey University for financial assistance which covered the cost of instrumentation and operational logistics.

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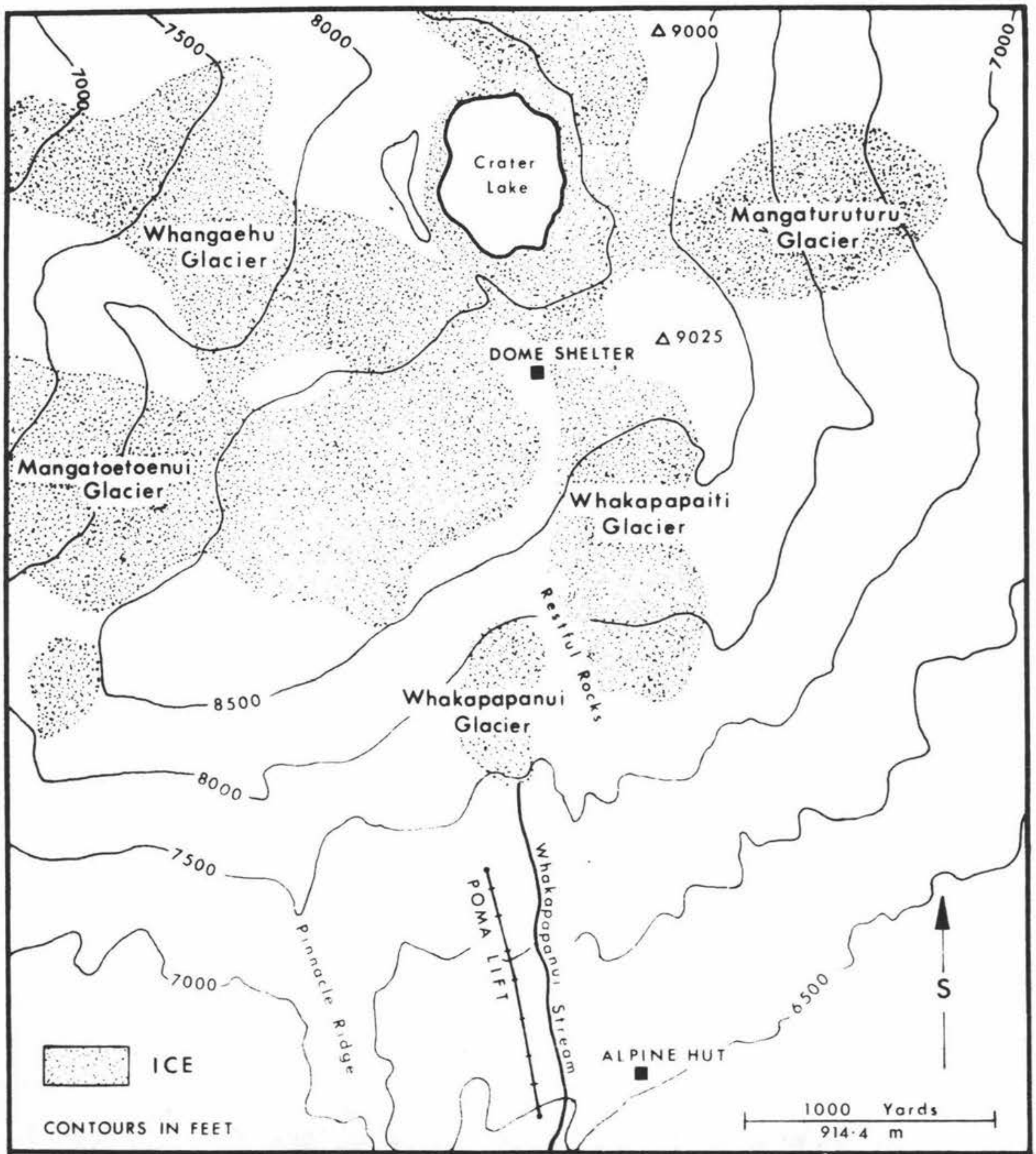
LOCATION AND REGIONAL CHARACTERISTICS

In the centre of the North Island of New Zealand, almost equidistant from the Tasman Sea and Pacific Ocean, is situated a volcanic plateau which is dominated by a complex of three mountains aligned in a south-easterly/north-westerly direction. To the east of this complex, forming the eastern periphery of the plateau, is a cordillera consisting of the Hauhangaroa, Kaimanawa and Kaweka Ranges, while to the south aligned along an almost north/south axis is the Ruahine Range. The only barrier impeding the advance of the prevailing westerly and south-westerly weather is the now extinct volcanic cone of Mt Egmont (2,517 m) on the west coast of the North Island. Of the expanse ringed by these mountainous barriers a 170,000-acre area has been claimed as the Tongariro National Park. This extensive native reserve—the original 6,500 acres of which was bequeathed to the New Zealand Government in 1887 by the Maori chief Te Heuheu Tukino—takes its name from the extinct and northernmost member of the central volcanic complex, Mt Tongariro (1,969 m). Immediately south-east of Mt Tongariro is Mt Ngauruhoe (2,291 m), a young and still very active peak forming an almost perfect cone. South of this again is Mt Ruapehu which, at 2,797 m, is the highest peak in the North Island.

The Whakapapanui is one of seven glaciers on the upper slopes of very extensive Mt Ruapehu. At latitude 39°16'S and longitude 175°33'E it faces almost due north. The Whakapapanui and the north-westerly facing Whakapapaiti are the only two of the seven glaciers which are no longer connected to the summit ice plateau (see Fig.2). Moving around the mountain in an anti-clockwise direction, the other five glaciers are: Mangaturuturu, Mangaehuehu, Wahianoa, Whangaehuehu and Mangatoetoenui. This unusual situation of glacier ice on an active volcano underlines the



DISTRIBUTION OF GLACIER ICE

NORTHERN SLOPES MOUNT RUAPEHU

FIG. 2

exceptional nature of their location (especially since Mt Egmont is completely devoid of glacier ice), while at the same time it accentuates the precarious nature of their existence. They appear to exist, however, not because of the tabu which Te Heuheu, chief of the Taupo tribes, is said to have put on the area, but more likely as a result of the combined effects of topography, altitude, climate and regional setting.

Setting

The Whakapapanui is a small glacier, nestled under a protective rock buttress in the upper reaches of an asymmetrical valley. This rock buttress, rising more than 15 m vertically above the western periphery of the glacier, is the uppermost extremity of Restful Rocks (see Plate 1), a ridge forming the western bank of the Whakapapanui Valley. The slopes to the east of the glacier are much more gentle and form part of the cuesta-like slope which drops down into Te Heu Heu Valley on the steep scarp side. These debris-strewn slopes show strong evidence of glacio-fluvial erosion. Large boulders strewn indeterminately over the lower slopes are testimony of glacial activity while the smaller rounded material and fine debris indicate the extent of erosion caused by meltwater and runoff.

The scene on the upper portion of Mt Ruapehu (see Plate 2) is one of sharp peaks, precipitous ridges, hard volcanic rock and strongly eroded, deglaciated slopes covered with debris and boulders. All in all it is a rather inhospitable landscape, devoid of all vegetation (except mosses and lichens), and exposed to whatever ravages nature can muster. The once U-shaped valley leading into "The Gut" (see Plate 3) is now strewn with large boulders up to 2 m high on which exfoliation and nivation have been at work, giving rise to slated surfaces. Despoliation characterises the valley sides and everywhere there is the look of utter uselessness and

Plate 1. The northern slopes of Mt Ruapehu showing Pinnacle Ridge in the left foreground and the highest peak, Tahurangi (2,797 m), in the right background. In the lower middle and lower right foregrounds are three crescent-like depressions believed to have been occupied by cirque glaciers. The one in the lower right foreground is "The Amphitheatre", while the uppermost one is "The Cirque" and the other "The Staircase".

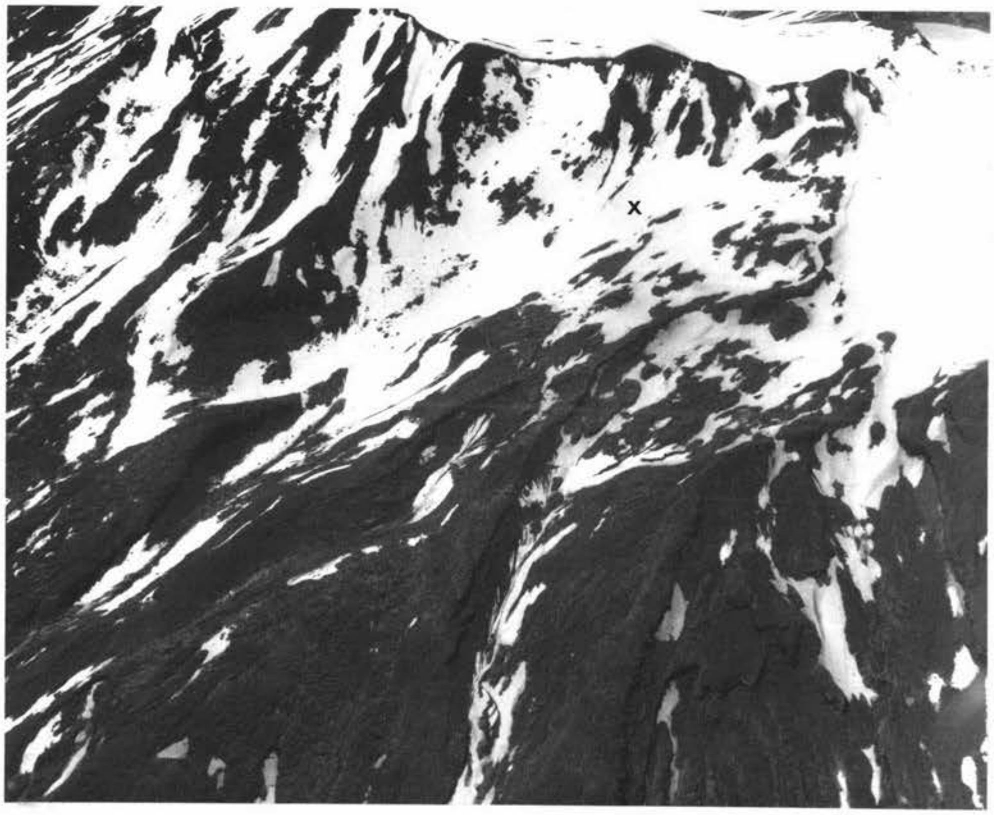


Plate 2. A close-up of the region of the northern slopes above 2,100 m. Knoll Ridge is distinguishable in the middle left foreground with the Whakapapanui Stream barely visible in the valley immediately below. It issues from the snow-covered region in the centre foreground, which is the site of the Whakapapanui Glacier (marked with an "X"). On the extreme right is a large snow-covered depression which is partially occupied by the Whakapapaiti Glacier.

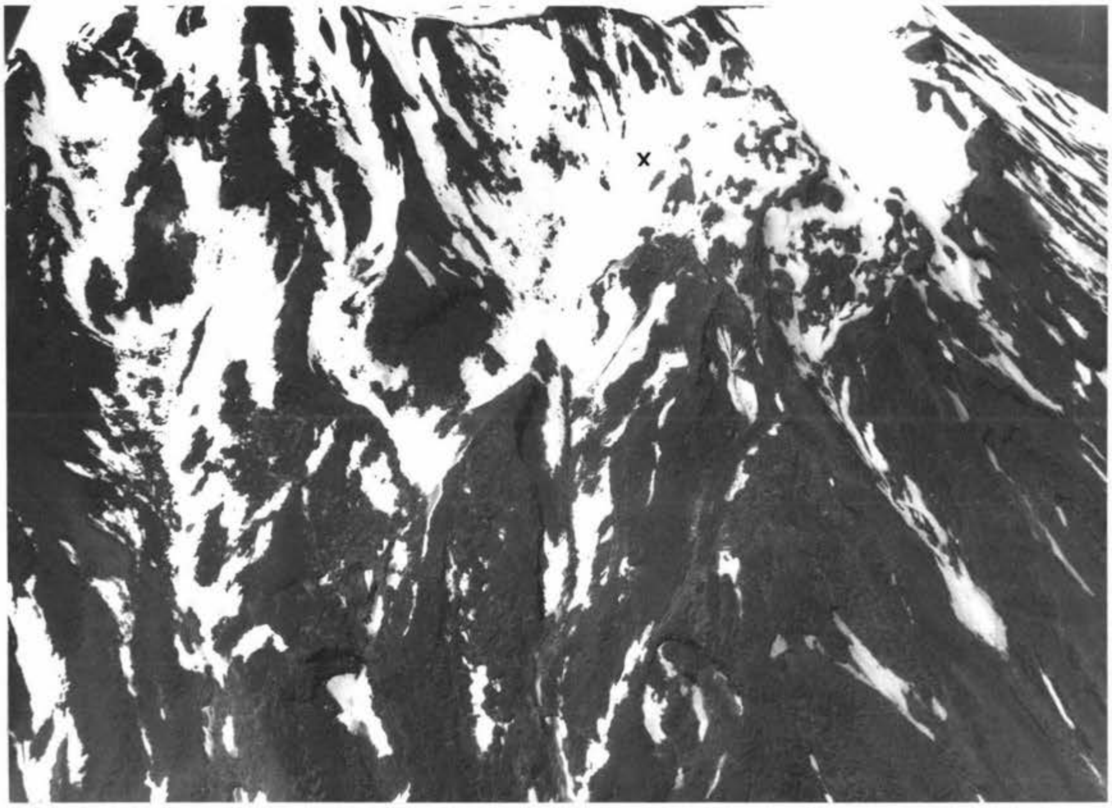


Plate 3. View directly up the Whakapapanui Stream in the centre foreground. "The Cirque" and "The Staircase" are again visible in the lower middle foreground. The area immediately between these two features is known as "The Gut". In the upper middle foreground an "X" marks the position of the Whakapapanui Glacier.

barren infertility (see Plates 4 and 5). Despite its raw and uninviting appearance, in winter when snow covers the landscape down to about 1,500 m it sports tantalisingly superb ski slopes and the mountain becomes alive with ski enthusiasts.

Climate

Two aspects of Mt Ruapehu's climate, which are universal to the whole of New Zealand, are (i) its changeability and (ii) the importance of wind systems in determining the type of weather. The direction of the airflows is fairly predictable: generally speaking, south-westerlies follow cold fronts, north-westerlies follow anticyclones and precede cold fronts, and easterlies are associated with the southern sector of depressions moving along the west coast of New Zealand. Of these airflows the southerly is the most common and its characteristics are readily discernible: cold and often snowy weather is a common feature with the precipitation often falling in the wake of cold fronts. The northerly, on the contrary, usually gives rise to less vigorous winds and mild, but somewhat muggy, weather.

Despite its changeability there is a certain amount of predictability in the weather. This results from the regular weather cycle over New Zealand taking from 6 to 10 days, during which time winds from almost every corner of the compass are experienced to a greater or lesser extent and, likewise, weather of almost every nature. Seldom is the same weather experienced for more than two consecutive days so that variability is the keynote (Garnier, 1957).

Its maritime position means that rainfall is substantial but not outstandingly high, while the fairly clear skies result in abundant sunshine and considerable solar radiation. All in all it has a temperate

Plate 4. The Upper Whakapapanui Valley. In the left foreground is The Knoll, marking the point where the left arm of the original Whakapapa Glacier bifurcated. The Whakapapanui Glacier is demarcated by the dotted line.

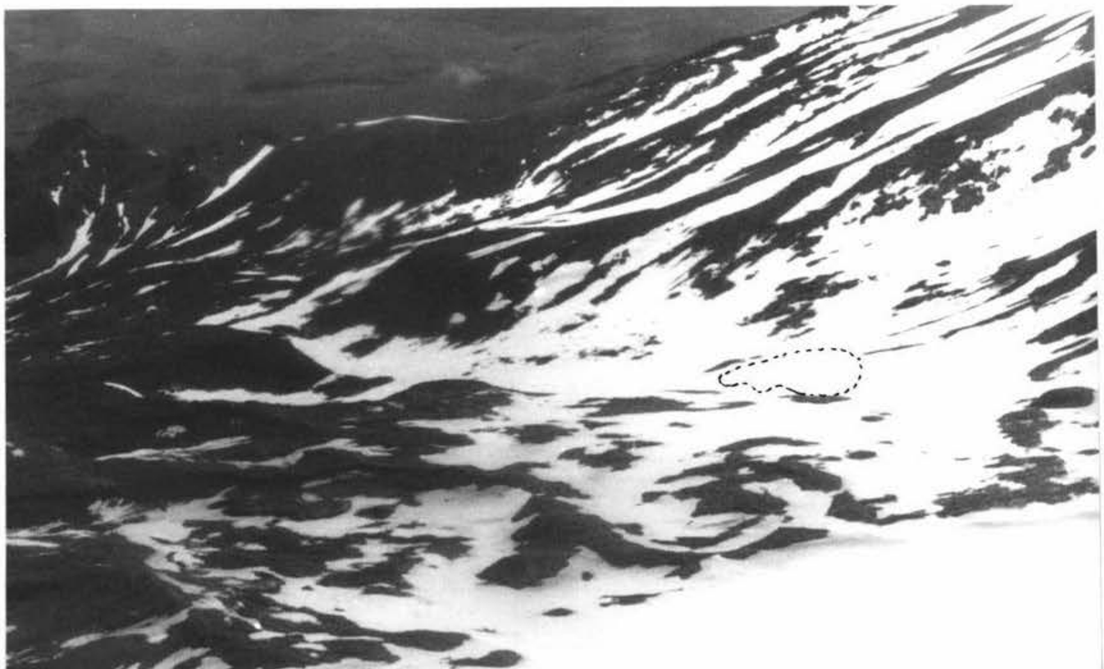


Plate 5. View looking north-east across the Whakapapanui Glacier, with the outline of Pinnacle Ridge just visible in the upper left foreground. The Glacier is demarcated by the dotted line.

maritime climate bordering on the region of the "roaring forties".

Systems of Glacier Classification

Due to its location the Whakapapanui is a thermally temperate glacier in that the pressure melting temperature of the ice is attained throughout the glacier during the ablation season. Geophysically it is also classed as temperate in that "it consists of crystalline ice formed by fairly rapid recrystallisation of the annual surplus of solid precipitation due to great quantities of fluid water" (Ahlmann, 1949). Morphologically it is a "cut-off" lobe of ice for it is now separated from the ice plateau from which it originally extended as an outlet glacier. Finally, in terms of both climatic and dynamic classifications it is known as dead ice. In the first place it is dead because it is no longer connected to a year-round source of ice and snow, while the lack of movement within the ice, resulting from a complete lack of transfer of materials from a regular source, has accounted for its dynamically dead state.

PROBLEMS

The project outline and the preparation for all the field work were carried out at Massey University in Palmerston North. To implement the project it was necessary to travel 225 km by road to the Top o' the Bruce (1,630 m), the closest vehicle access to the glacier. A distance of approximately 2.8 km, and a climb of 655 m, separated the glacier from the Top o' the Bruce. Most of the field work was conducted from the Ski Patrol Headquarters (1,752 m), although the New Zealand Alpine Club made their Ruapehu hut (2,006 m) available on the last two occasions (see Fig.3). Operational logistics within the area were facilitated by chair lifts from the Top o' the Bruce to an elevation of 2,001 m, about 365 m east of the Alpine Club hut. The rather high winds, which were funnelled through the Whakapapanui Valley and over The Waterfall, often made the chairs swing dangerously, however, and sometimes prevented their use. This problem of logistics continues to be largely unresolved and is one of the major problems facing future researchers in this area. Wood (1963), from his experiences in the Canadian high Arctic, has stipulated that "in the recipe for efficient fieldwork, the essential ingredient is the solution of logistic problems, both of access to the area and of operations and mobility within it. If this ingredient is lacking or present only in moderation the pudding will not gell, no matter how tasteful and beneficial the other ingredients."

The second major set of problems was associated with the pioneering of instruments, techniques and procedures associated with a project which was new to both the area in particular and New Zealand in general. The problem of introducing science into a recreational area such as the Tongariro National Park, which involves systematic and regular measurements

MT RUAPEHU : NORTHERN SLOPES

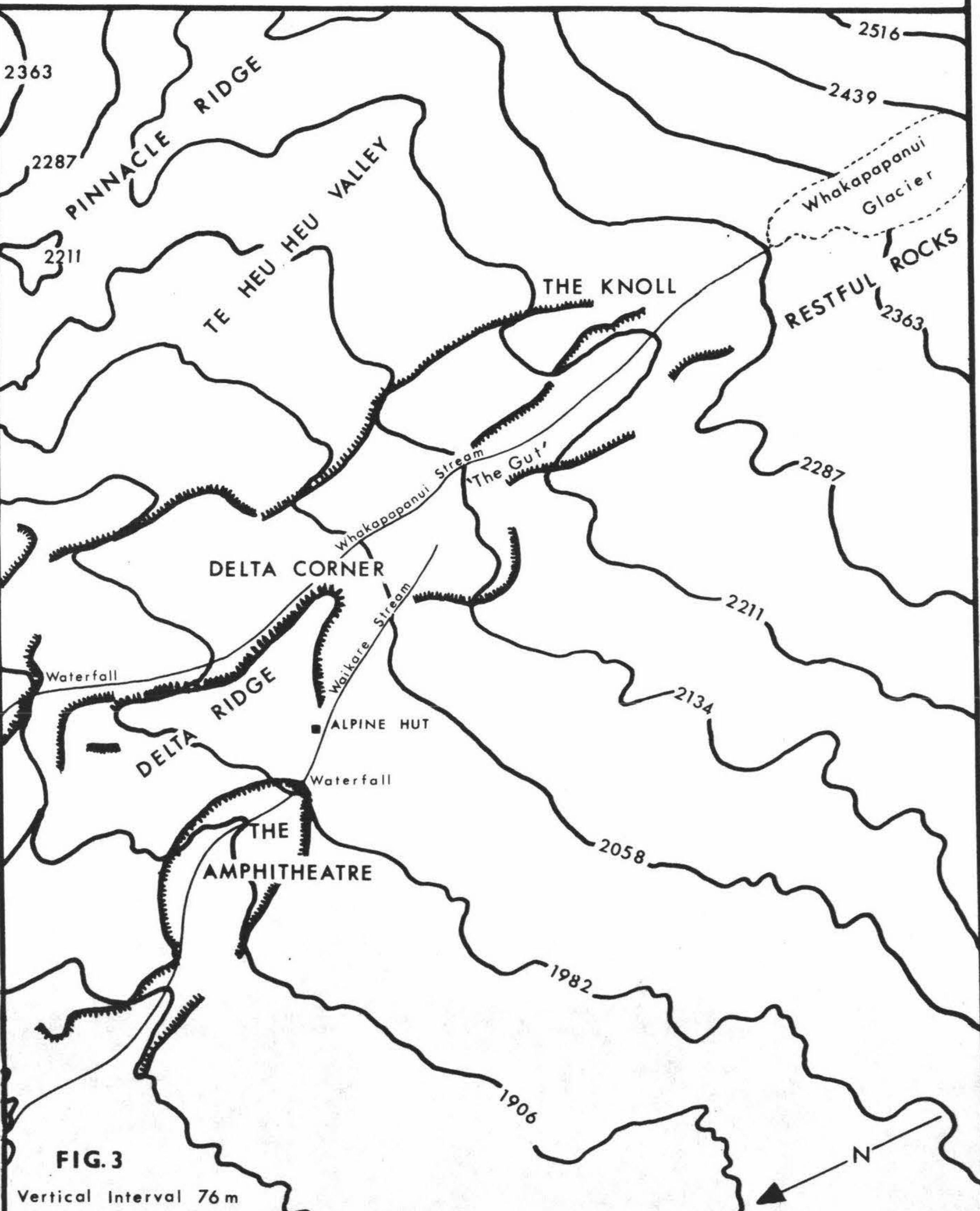


FIG. 3
Vertical Interval 76 m
SCALE 1:10,000

and recordings, brought with it a number of difficulties. First, there was the problem of broken and intermittent daily meteorological recordings resulting either from the deployment of Park Rangers on matters of human safety, or as a result of broken equipment. In the ski season, time and lack of personnel trained in meteorological techniques led to inconsistent and often irregular recordings of the daily weather and snow conditions. A more comprehensive and synchronised programme of recordings on the three ski fields, which face in three different directions, could lead to worthwhile and interesting results. A capital grant, or the training of personnel in techniques of glaciology, may secure a more regular and organised approach besides providing a more efficient basis for snow and weather reports on all three ski fields.

Some of the problems associated with the equipment have been dealt with in the section on instrumentation but two factors deserve attention. First, there were the long delays involved in acquiring equipment and even after an order had been placed it was up to twelve months before the equipment arrived. This necessitates detailed planning well in advance of the inauguration of any project. Second, very few of the commercially-produced tools for use in glaciology had been tested in conditions akin to those on Mt Ruapehu. Initially, excavation tools, which had proven suitable for Antarctic conditions, were tried on the Whakapapanui Glacier without success. Tools of a sturdier and more robust nature were found to be necessary even though it usually resulted in increased weight. On the whole, simple and relatively unsophisticated remote recording portable equipment, which is both reliable and sensitive, is required for these conditions.

Acting on Park Board recommendations the writer was never alone on the mountain and, while it was sometimes a problem to recruit sufficient personnel, on more than one occasion the writer was grateful that he was accompanied by experienced trampers and/or a part-time ranger. In winter the continuous snow cover and the changeability of the weather often led to a complete loss of any sense of direction. In such a landscape this can be particularly dangerous and the writer advises that future researchers in this area always undertake a reconnaissance of the area before the winter, and that they be accompanied, whenever possible, by experienced climbers.

Finally, finance was one of the biggest problems and the difficulties involved in acquiring a capital grant at the outset led to delays in the arrival of equipment which necessarily limited the scope of the project.

FIELD PROCEDURE

May 4 - 9, 1968

An uninitiated six member reconnaissance party, equipped with a strange assembly of tools and equipment, made a three-hour ascent to the glacier in perfect weather on the morning of May 5. Dry and wet bulb readings were taken at regular intervals throughout the climb and, together with similar watch-synchronised recordings at The Chateau, provided an opportunity to work out the environmental lapse rate.

Heavy snowfalls in April had left a fairly extensive snow cover above 2,000 m so that the glacier ice was obscured. Attempts to locate the ice and drill in some ablation stakes using a soil auger proved futile and completely ineffective. The location later in the day of two meltwater/subsidence holes was the highlight of the trip. This enabled some micro-meteorological measurements, using the Telemax Telethermometer to record temperatures above and below the surface of the glacier. Recordings were made of the ice thickness and samples of ash were removed for carbon-dating. Before leaving, a meltwater gauge was inserted into the side of the melt-water hole.

A cold south-easterly wind and accompanying mist, which sprang up about 3.00 p.m., discouraged further work and sent the party on the journey back down the mountain in pursuit of the comforts of camp. A subpolar low and accompanying high winds, low temperatures and driving rain, prevented later attempts to reach the glacier.

September 22 - 24, 1968

On arriving at the glacier a four-man party began work immediately on the excavation of two pits. Progress was slow and difficult after finding that snow shovels were too light and brittle for the hard icy névé.

Once below shovelling depth the one and only spade was also abandoned leaving only ice axes to loosen the névé and a hearth shovel to transfer the loosened material into a bucket, which was then lifted to the top and emptied. Because of the cramped and difficult operating conditions it was necessary to abandon the top pit after a day and concentrate all our energies on the remaining pit. Even with regular changeovers by a four-man team, the excavation process was slow and laborious. Eventually, after two days of digging (part of which was spent in cleaning out the large build-up of snow which had accumulated over night), a tired and exhausted party had to terminate its activities and return to Palmerston North. Before leaving, however, a few temperature recordings were made and dye was then sprinkled in the base of the pit. Metal poles were also inserted at various levels in the filling. This meant that the pit was marked for re-excavation at a later date.

November 5 - 7, 1968

This was a visit by a four-man party to make a check on the depth of gross accumulation. The September pits, located by means of the ablation poles, were re-excavated. Only about 25 cm of the uppermost pole was exposed (see Plate 6), indicating that the maximum depth of gross accumulation occurred considerably later than the end of September. Reports from the National Park Board Rangers indicated that the maximum height of accumulation had probably occurred only a few days before the party arrived. Before excavations had proceeded very far the dye, which had been spread around the pit top in September, was located and depth/density recordings were made in the névé above it. One by one the remaining ablation poles were uncovered and before long the dye in the bottom of the pit was exposed. A hand ice-boring corer was then used to determine the remaining depth of

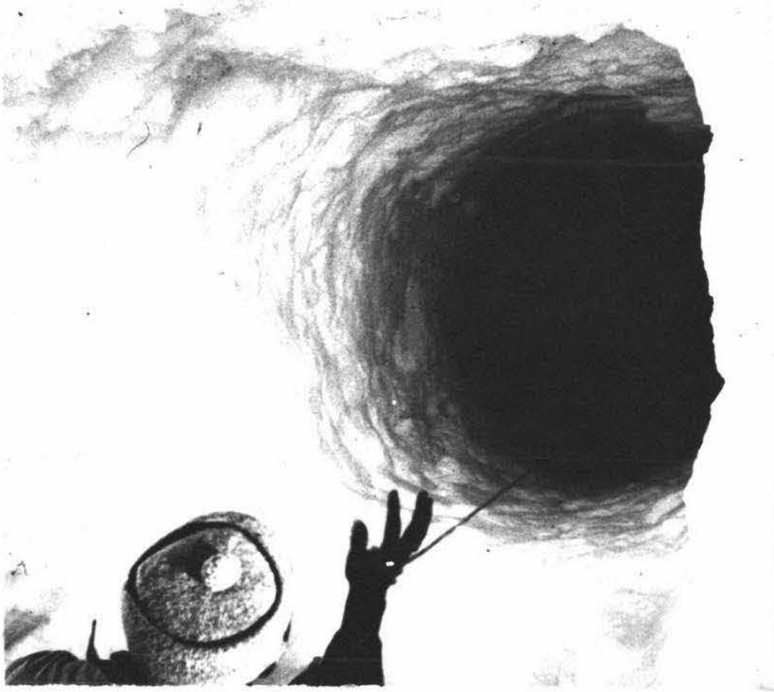


Photo: W.A. Buckman

Plate 6. View down a névé pit excavated at the height of the gross accumulation season on the Whakapapanui Glacier in late September, 1968. Although the hole was over 11 m deep, pit props were not necessary because of the very dense nature of the névé.

Plate 7. "Whiteout" conditions on the Glacier, September 1968. The rime ice encasing the ablation stakes was formed in less than 24 hours. The wind-blown nature of its formation is evidenced by the encrusting largely on the upper or windward side of the stakes.

névé. Under clear skies and slowly dropping temperatures the party started back down to camp at about 6.30 p.m., after spending over eight hours on the glacier.

January 18 - 19, 1969

The prime object of this trip was the installation of a meteorological station. Built by the writer, the weather screen (see Plate 17) was essentially a wooden box large enough to house a thermohygrograph and rigid enough to withstand strong gales. Two ends of the box contained sliding metal louvres and, together with holes in the top and bottom, these provided the ventilation. On one of the solid walls a maximum/minimum thermometer was attached. Finally, a cup anemometer was attached to the outside of the screen, down the side of the four-legged metal frame to which the screen was bolted. The screen stood a little less than one metre above the ground.

A rock outcrop was found about 10 m above the glacier surface and about 7 or 8 m to the west, this being the closest snow-free area to the glacier. The screen was eventually secured with wire threaded through rock pins and a metal ring on the top of the screen. Access to the instruments was by way of the louvres which could be removed on one side.

May 11 - 17, 1969

The principal object of this visit was to measure the net accumulation. New snow on the glacier, varying in thickness from 10 to 30 cm, indicated that the 1968/9 net budget was at an end and that the 1969/70 season had already begun (see Plate 8). The large student labour force undertaking field work on the glacier, as part of their course requirements, provided an opportunity to measure the area of the glacier, as well as conduct surface gradient measurements. Pits were excavated and snow cores

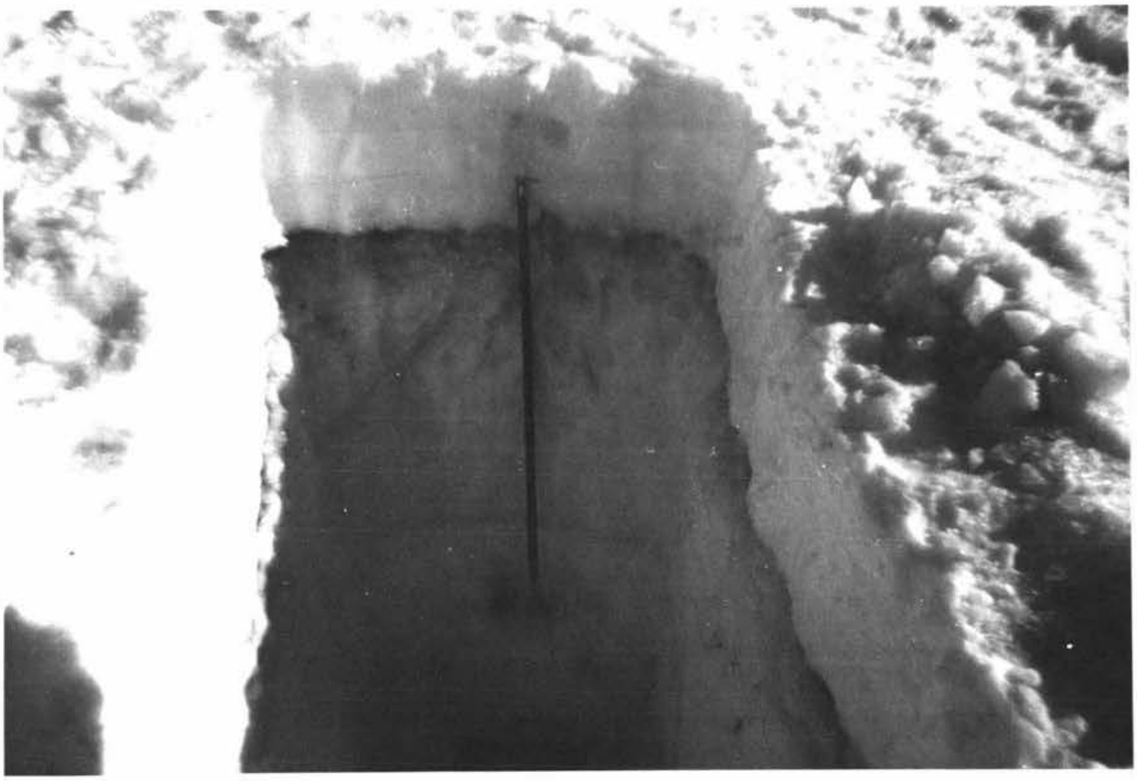


Plate 8. A pit excavated in May, 1969, showing two distinct horizons. The upper horizon is the first accumulation of the 1969/70 budget year showing only névé while the lower horizon is the firn from the 1968/9 budget year. Bands of ice are apparent about half-way down this horizon. The summer surface which separates the two horizons is immediately apparent by the discolouration resulting from waterborne debris being washed off the slopes. It is this debris that becomes embedded in the ablation surface which facilitates the rapid melting late in the ablation season as a result of the greatly reduced surface albedo.

were made in many places over the glacier surface. At the same time micro-meteorological measurements were made in one pit while regular recordings were also conducted at the weather screen on the ridge overlooking the glacier.

Once again a meltwater/subsidence hole was discovered, enabling further examination of dirt samples from dirt bands and the ice/rock interface. The presence of dirt bands at various depths in the glacier ice is probably testimony to earlier eruptions of Mt Ruapehu.

June 26 - 28, 1969

A visit was made to assess the extent and effects of the June 22 eruption of Mt Ruapehu. Atrocious weather conditions prohibited organised field work and prevented an extensive appraisal of the mud and ash flow covering the glacier. Apart from determining the depth of the mud and ash in a few places, and recording on film the effects of the eruption on the densification of the névé (see Plate 9), the only other evidence of value to emerge from this trip was the manifestation that a north-easterly blizzard could deposit up to 115 cm of new snow on the glacier in only three days.

November 25 - 28, 1969

This was an excursion to undertake heat budget studies. The three weeks preceding this trip were characterised by perfectly fine, dry weather. In the weekend immediately prior to leaving, a cold front moved on to the country, bringing heavy snowfalls and leaving Mt Ruapehu covered by a blanket of snow down to 1,800 m. In anticipation of the good weather that an anticyclone, migrating across the Tasman Sea on Sunday, would bring during the remainder of the week, a party of eight set off in a mini-bus loaded with expensive micro-meteorological equipment. Among this equipment, some of which had arrived only a few weeks before departure, was a

Photo: K.A. Ross

Plate 9. A shallow pit excavated one week after the June 22nd eruption of Mt Ruapehu. The eruption poured out mostly andesitic ash and fine mud suspended in hot water. From the photo it appears as though this torrent of mud and ash melted a considerable amount of fresh snow which percolated down through the névé and refroze as bands of ice. This is suggested by the dirty colour of these ice bands. Approximately 0.6 m below the layer of mud the névé is not discoloured and much less dense than the névé which lies immediately below the mud layer.

CSIRO net radiometer, a clockwork psychrometer, an instantaneous wind speed recorder, a monthly thermograph, a rainfall gauge and a Telemax Telethermometer, together with a maximum/minimum thermometer and a cup anemometer for the recording station.

Almost continuous cold, wet and windy weather, together with low cloud and hailstorms (on the first day), prevented the programme from being put into operation. Equipment was set up for a while on November 26 but rain and generally unpleasant conditions forced the abandonment of the station within an hour of beginning measurements. Next morning similar conditions were encountered and, with an outlook of continuing cold wet weather, it was decided to terminate the programme and move the equipment back to the Alpine Club hut. When the morning of November 28 brought little change in the weather, it was decided to make a trip to the Crater Lake in the hope that the weather might improve later in the day. Bad weather continued, however, forcing the complete abandonment of the project, for the hut had to be vacated that night.

INSTRUMENTATION

While the procedural techniques utilised in field measurements have been outlined earlier, a more detailed description of some of the equipment utilised may be useful for future researchers in this field.

Snow Sampler

In the initial depth/density recordings the snow sampler was merely a brass alloy cylindrical tube, open at both ends, with an arm attached on the outside for weighing purposes. It was soon found to be inadequate because of the difficulty involved in extracting samples from the very dense and compacted névé. A mallet was needed to force the sampler into the profile and it was rarely full when first removed. Two and sometimes three attempts were necessary before a full sample was obtained. This technique was not likely to enhance the accuracy of the measurements. The sampler was full when a knife, used to trim and even the ends of the sample, only just shaved the contents without removing any surplus.

On later visits an improved version was used. In its assembled form this sampler was open at one end only, whilst a lid was attached to the other, preventing the sample from being pushed right through. The lid was attached simply by pushing on and twisting it so that two lugs engaged in sockets at one end of the cylinder. Screwed to the centre of the lid was a 6 mm diameter piece of steel and a thick brass bush was slid along this handle acting like a pile driver on the lid.

For weighing purposes an elastic band was placed around the middle of the cylinder, the lid was removed and a spring balance was then hooked into the elastic. Despite the rudimentary technique, this method of measuring the water content, which necessitated depth measurements of each stratum, was believed to have been as accurate or possibly even more accurate than measurements using a specially designed snow sampler, where a standard error of 3 percent was obtained by only the most proficient operators.

Ice Corer

A corer 2.5 cm in diameter, approximately 25 cm in length and of standard design was used in later attempts to set the depth of accumulation at various points over the glacier surface. Teething problems were also encountered with this instrument. At first the corer failed to penetrate the névé by more than 10 or 12 cm. Added to this was the difficulty of extracting the sample from the corer. This was, in spite of strategically placed incisions down the length of the tube, designed to allow the insertion of an L-shaped steel lever so that the core could be worked out. These problems were counteracted after some experimentation and the best results were obtained with the following modifications. First, the teeth on the cutting edge of the corer were set in such a way that the outer teeth loosened the névé while the inner teeth cut down parallel with the inner edge of the corer. In this way the corer was always filled, while the slight concave surface of the inner teeth prevented the sample from slipping out, but at the same time allowed for easy removal of the core. With the original set there was a tendency for the névé, loosened by the cutting edge, to freeze and expand so blocking the end of the corer and preventing its easy passage down through the névé. Second, several coatings of teflon were painted on the inner surface of the corer and this helped to prevent the névé from freezing against the interior of the cutting edge.

The corer was screwed down through the surface using a hand-operated brace to which extension rods were attached. The addition of successive rods allowed cores to be extracted down to a depth of 10 m.

Of the remaining instruments only a brief mention will be made of the Telemax Telethermometer. This consisted merely of a control box with a meter calibrated in $\frac{1}{10}^{\circ}$C intervals from -20° up to $+50^{\circ}$C, and a feeder box into which all the probes and sensors were fed. As the distribution box, it also housed the terminals to which the probes and sensors were connected. A selector dial on the recording box enabled recordings of each sensor and probe in an almost simultaneous manner.

Pre-testing in the laboratory indicated a degree of accuracy of between $\pm 0.5^{\circ}$C, which is somewhat low for this type of recording work where finite differences in temperature are often significant.

METHODOLOGY

Water Equivalent Measurements of Gross and Net Accumulation

Both the gross and net accumulation quantities were determined using the method of pit excavation, from which samples of the various accumulated strata were extracted using a cylindrical snow sampler of the following dimensions: diameter 6.3 cm and depth 6.3 cm, to represent a volume of 200 cm^3. From these samples the water equivalent of each pit was calculated, using the following formula and method:

$$\text{Density} = \frac{\text{Mass}}{\text{Volume}}$$

Volume = $\pi r^2 h$ where r = 3.15 cm (the radius of the sampler) and h = 6.3 cm (the depth of the sampler).

$$\begin{aligned} \log \pi \ (3.142) &= 0.4971 \\ \log r \ (3.15) &= 0.4983 \\ \log r \ (3.15) &= 0.4983 \\ \log h \ (6.3) &= \underline{0.7993} \\ \text{Log of Volume} &= \underline{2.2930} \end{aligned}$$

Mass = weight of material, e.g. névé at 100 gm.

$$\text{Log } 100 = 2.0000$$

The Density of this névé sample was obtained by subtracting the log of the volume from the log of the mass, thus:

$$\begin{aligned} \log 100 &= 2.0000 \text{ (mass)} \\ \log \text{volume} &= \underline{2.2930} \\ &= \underline{\bar{1}.7070} \end{aligned}$$

The anti-log of this figure gave the névé density of 0.5093 g/cm^3.

This method was repeated throughout the pit depth to determine the density/water equivalent of all the different strata. The following calculation was for a 30.5 cm stratum of névé having a density of

0.5093 g/cm^3.

$$\text{Volume of water} = \text{depth x density}$$
$$= \log 30.5 + \log 0.5093.$$

$$\text{Now} \quad \log 30.5 = 1.4843$$
$$\text{and} \quad \log 0.5083 = \bar{1}.7070$$
$$= 1.1913$$

The anti-log of this figure = 15.53 cm, which was the volume of water in that stratum.

This procedure was repeated for each stratum which had a differing density, and the addition of the resulting figures gave the total specific water equivalent of each pit. Since each pit represented a particular area of the glacier, according to certain outlined characteristics, the total water equivalent of this part of the glacier was obtained by multiplying the specific water equivalent of each pit by the area it represented, e.g. Pit 1, in the gross accumulation season, had a water equivalent depth of almost 7 m and was taken as representing an area of 19,700 m^2.

The total water equivalent of the area represented by Pit 1

$$= \text{area } (m^2) \text{ x water equivalent depth } (m)$$
$$= 19{,}700 \text{ m}^2 \text{ x } 7 \text{ m}$$
$$= 137{,}800 \text{ m}^3.$$

When the water equivalents of all the areas were added together they gave the total gross accumulation of the glacier. In the same manner the net accumulation was calculated and the difference between the two water equivalent totals was the net budget.

An alternative method was to determine the specific mass flux at a point on the glacier. This would have been achieved by excavating the gross and net accumulation pits at exactly the same spot and then by calculating the water equivalent for the pit in each season. By subtracting the net accumulation total from the gross accumulation total, the specific net flux would have been computed. When multiplied by the area which the pit represented this would have given the net budget of the glacier.

Areal Computations

By a system of trial-and-error borings using an ice corer, the extremities of the glacier were located and marked with flagged poles. The perimeter of the glacier was next located on a map by traversing a line of poles which marked off various lengths up the middle of the glacier. From these poles the marker flags at the extremities of the glacier were located by "intersection" (effected through use of a compass) and "offset" (a technique involving both tape and compass). Thus a sketch map was produced showing the distance between the poles on the traverse, as well as the bearings from one pole to another, and the angles of the intersections from these poles to the marker flags on the extremities. The glacier was plotted as a map and the area was then calculated using a planimeter.

This course of action was necessitated by the presence of a continuous snow cover on the glacier from April 10, 1968 until well into the summer of 1969/70. At no stage during this period was the glacier ice exposed, so that the exact margins of the ice were at no time visible.

Gradient Calculations

The poles used in marking the traverse for the tape and compass measurements were placed in such a way that they marked the approximate extremities of uniform surface slopes. An aneroid altimeter was used to record the altitude of these poles. The gradient of each slope was then calculated using the formula

$$\text{Gradient} = \frac{\text{V.I.}}{\text{H.E.}}$$

where V.I. is the vertical interval and H.E. the horizontal equivalent.

The difference in elevation between the poles was the vertical interval, while the horizontal equivalent approximated the surface distance between the poles. When calculating the gradient as an angular measurement, the error, introduced by the slope as a result of the substitution of longitudinal distance for the horizontal equivalent, was remedied by recording the sine of the angle made by the slope where it met the horizontal. Normally the tangent of this angle would have been read. The calculation procedure is outlined below.

Vertical distance between Stake 6 (7,980') and Stake 7 (7,910') = 70 ft.
Longitudinal distance between these stakes was 200 ft.

$$\text{The slope expressed as a ratio} = \frac{\text{200 ft (longitudinal distance)}}{\text{70 ft (vertical interval)}}$$

giving a slope of 1 ft up for every 2.857 ft along.

$$\text{Expressed as an angle this gave a gradient of } \frac{\text{70 ft}}{\text{200 ft}}$$

$$= 0.3500.$$

Normally the tangent of this figure would have given the gradient, but in this particular case the angle was best represented by sine 0.3500,

which = $\underline{20^{\circ}29'}$.

Glaciothermal Measurements

Measurements of the ambient air temperature and the depth of cold wave penetration were made by using a remote recording Telemax Telethermometer with eight sensors and three probes. The sensors were attached to the windward side of a pole at various intervals above the glacier surface, while the probes were inserted at intervals into the vertical face of the pit profile. This enabled synchronous measurements at regular time intervals throughout the day, from which temperature gradients were constructed.

Note

All field measurements, except those necessary for the calculation of the water budget, were made in British Standard Units and converted to Metric Units using standard techniques. In all cases the calculations were made in British Standard Units and only the final results were converted to Metric Units, thus minimising the errors introduced through conversion.

All measurements of temperature, except those made with the Telemax Telethermometer, were made in degrees Fahrenheit. Telemax measurements were made in degrees Centigrade.

TERMS AND TECHNIQUES

The regime or budget of a glacier can be measured in a number of different ways, the two most common methods being (a) direct measurement of the mass budget quantities at different points on the glacier surface using pits and stakes (glaciological method), and (b) the measurement of precipitation runoff, evaporation condensation and other quantities in the hydrologic equation (hydrologic method). These methods are often used in a complementary fashion, especially in attempts to relate changes in the mass of a glacier to its dynamic responses, for it enables a cross-check of the results. Where only the mass budget of the glacier has to be measured either one of these methods may be used, although the data would be more accurate and reliable if supplementary measurements were made.

Despite the allusion made in the title to the hydrological aspect of budget studies, the so-called hydrologic method was not employed on the Whakapapanui Glacier. Rather it was the glaciological method which was used. The apparent confusion of terminology resulted from the basic concept of the hydrologic cycle. The hydrologic cycle explains the transfer of water (as a flow resource, through its various phases) from the earth's surface to the atmosphere and back to the earth's surface. The specific flux represents a measure of the gain or loss of water over a specific time period at any one point on the earth's surface and, when measured in units of grams per cubic centimetre, it is known as the specific mass flux. The water equivalent mass of a glacier is not homogeneous as its density varies considerably from basal to uppermost layers. Consequently, the mass or weight of a known volume of glacial material is expressed relative to the weight of water in its unfrozen state which has a value of 1.0 compared with new snow which has a value of 0.2 water equivalents. Therefore, glacial hydrologic budget studies refer to the actual specific mass flux at the surface of the glacier over a particular period.

Thus, while the hydrologic concept still refers to the mass flux, it avoids confusion incurred by the use of the term mass balance which requires that the kind of mass be specified, i.e. whether it is ice or snow. By mass balance or regime of a glacier is meant its total accumulation volume during one accumulation season and its total gross ablation volume during the following ablation season. Since accumulation is the income and ablation is the removal of snow and ice, together they make up the glacier's balance sheet.

The problem of terminology is further accentuated by the system of measurement of the accumulation and ablation parameters. In 1968 the International Commission of Snow and Ice, in a series of Technical Papers in Hydrology, singled out two basic systems of measurement and the terminology differs according to the system used. First, there is the stratigraphic system which involves identification of a summer surface as the means of determining the end of the budget year; and second, there is the fixed date system in which measurements are made regularly on fixed days each year. In the former system the parameters to be measured are the total or gross accumulation and the gross ablation, while in the latter the annual accumulation and annual ablation are measured.

These are the standard systems of measurement but they are both dependent upon the existence of a firn or equilibrium line on the glacier. This is the line above which is the accumulation area and below which is the ablation area, and it connects points on the glacier where the net balance is zero at the end of the budget year. It was earlier established (Introduction) that the Whakapapanui Glacier was characterised by a climatically "dead" condition in that it was a "cut-off" lobe of ice lying well below the normal snow line limit (which is actually above the highest elevation on Mt Ruapehu, 2780 m). Consequently the firn line was currently above the summit level so that thinning and recession characterised the ice cover of the Mt Ruapehu glaciers. Budget measurements as a result would refer to the net ablation of snow and ice. As will be established later, the 1968/9 budget year was exceptional in that the "ice-cap" and glaciers were covered by névé at the end of the ablation season. A tongue of firn extended to the snout of the Whakapapanui Glacier and this "abnormal" extension meant that the budget was measured in gross and net accumulation quantities. The consequence of these conditions was that the actual firn line was never evident on the glacier and the standard budget technique of analysing net accumulation and net ablation in the areas respectively above and below the firn line could not be employed.

Despite these problems of terminology the stratigraphic system was used to determine the beginning and end of the 1968/9 budget year. The budget year is defined as that period of time which commences when new névé accumulation exceeds the ablation of ice and/or névé and continues to the close of the ablation season in the following year. The break between budget years on the Whakapapanui Glacier normally occurs in April but it is a transitional period related to the frequency of significant storm activity in late autumn. The 1968/9 budget year, for instance, commenced on April 10, 1968 with the deposition of 2.5 m of névé on the glacier ice during the vigorous uplift of air in the "Wahine" Cyclone. The year ended in late April, 1969 when light snowfalls accompanied the turbulence along an active cold front.

Terminology

Accumulation: all the processes by which snow and ice are added to a glacier.

Gross accumulation: the maximum amount of snow and ice existing on the glacier at any time during the budget year.

Net accumulation: the snow and ice remaining at the end of the ablation season.

Ablation: the wastage or removal of snow and ice.

Gross ablation: the total amount of snow and ice consumed during the budget year (snow and ice which is melted may percolate downwards and refreeze again as superimposed ice).

Net ablation: the total amount of snow and ice actually lost from the glacier during the budget year.

Budget year: one complete accumulation and ablation season (not necessarily equal to one calendar year).

Névé: snow deposited in a current budget year.

Firn: the previous winter's névé obscured at the end of the ablation season by new snow deposition, to become true firn.

Firn line: The highest position reached by névé recession during the ablation season which represents the point on the glacier where the net budget is zero.

P A R T I I

HYDROLOGICAL BUDGET STUDIES, 1968/9

Gross Accumulation

Net Accumulation

Ablation

Net Budgets

CHAPTER 1

GROSS ACCUMULATION

Sharp (1951) has aptly described accumulation as "the life-blood of a glacier" so that the accumulation season is the period in the budget year when the glacier experiences a net gain over loss of mass. Gross accumulation has been chosen as the title of this chapter not merely because it contains a discussion of the ways in which the glacier builds up its mass, but also because the "accumulation season", like the "ablation season", was difficult to define in terms of time. Both accumulation and ablation take place continually so that one season differs from the other principally in the degree to which one or other of these elements was dominant.

This difficulty in defining periods and relationships within a period of the budget year highlights the basic problem of climate/glacier relationships itself. It is a problem of both time and space and since they are independent variables this makes attempts to relate elements of climate and mass budgets valid for a specific period in time only. The task of describing gross accumulation was necessarily limited by this problem to a fixed period of time, and its validity was dependent upon the nature and extent of the information available.

The information used in this section was obtained by field surveys and examinations of meteorological records. Measurement of the spatial distribution of gross accumulation has been outlined in the Introduction. The temporal distribution of accumulation was based on precipitation records at The Chateau Meteorological Station (1,118 m), approximately 10 km directly north-west of the glacier, together with weather reports for the Whakapapa Ski Field recorded at the Ski Patrol

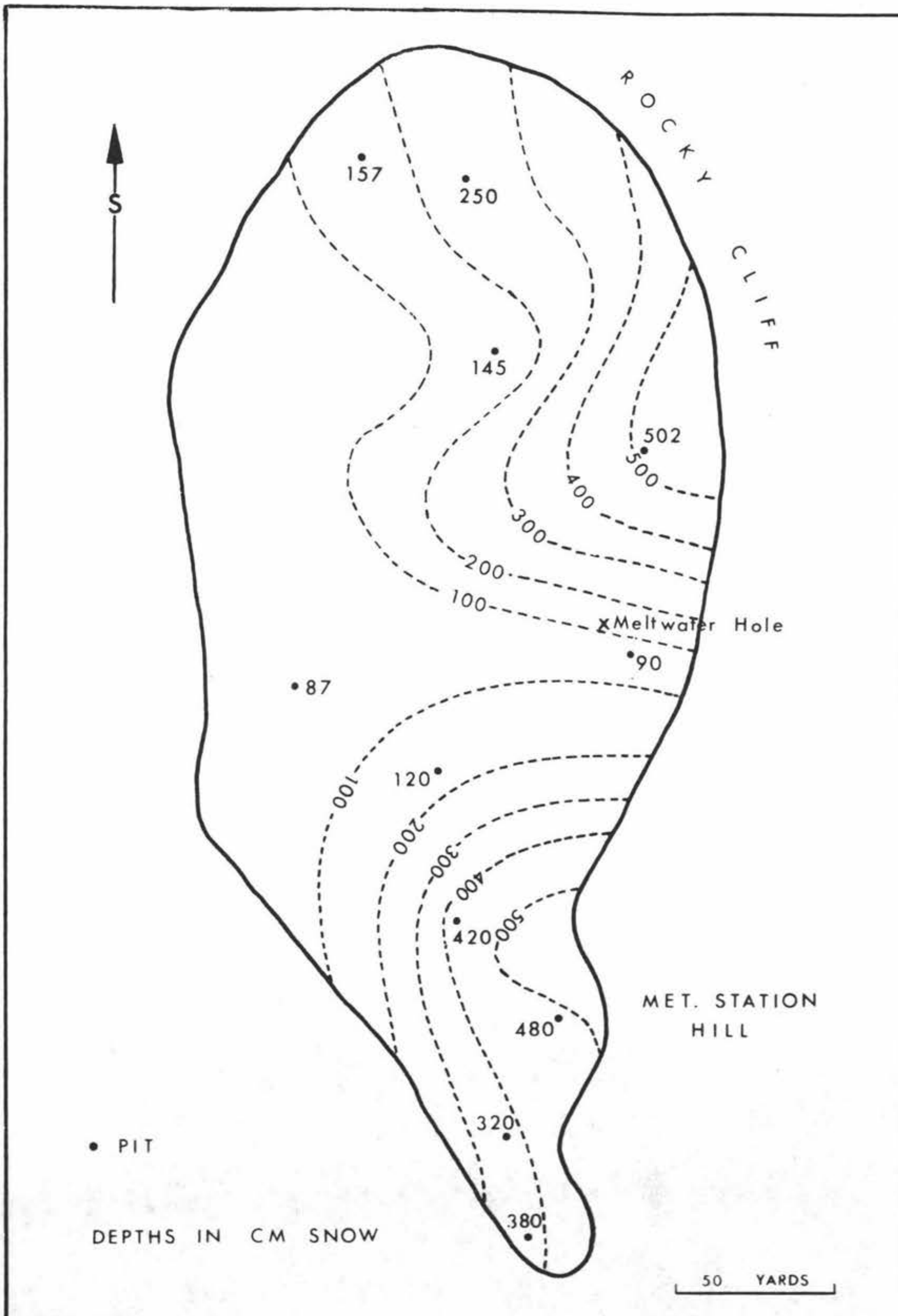


FIG. 3a

WHAKAPAPANUI GLACIER – NET ACCUMULATION

Headquarters (1,752 m), approximately 2 km from the snout of the glacier. The mean environmental lapse rate of 0.53°C/100 m was calculated and employed as a rough measure of snow frequency on the glacier. It was assumed that snow had fallen on the glacier when the daily mean air temperature at The Chateau (approximately 1,168 m below the glacier) was 7°C or less, and that more than 0.25 mm of rain had been recorded during the day.

Problems of logistics prevented regular daily recordings of the accumulation patterns on the glacier. Observations of the nature and magnitude of accumulation were based principally on the analyses of pit profiles (see Plate 6). Postulations on the frequency, duration and types of accumulation were based on two principal sources of information: (i) observations by Ski Patrol and Park Board personnel as recorded in the Park Board Snow and Weather Reports at the Ski Patrol Headquarters; and (ii) the writer's own experience of the weather and snow conditions while on excursions to the glacier. The latter, inevitably, are rather qualitative.

Sources of Accumulation

Accumulation was derived from two main sources which have been labelled primary and secondary, but both of these can be further subdivided.

1. Primary Sources

(a) The principal source of accumulation was considered to be precipitation in the form of snow, accompanying cold fronts and unstable air masses. Using the system of frequency of snowfalls worked out above it was calculated that snow had fallen on 123 out of a possible 244 days during the 1968/9 accumulation season, i.e. about 50 percent of total days.

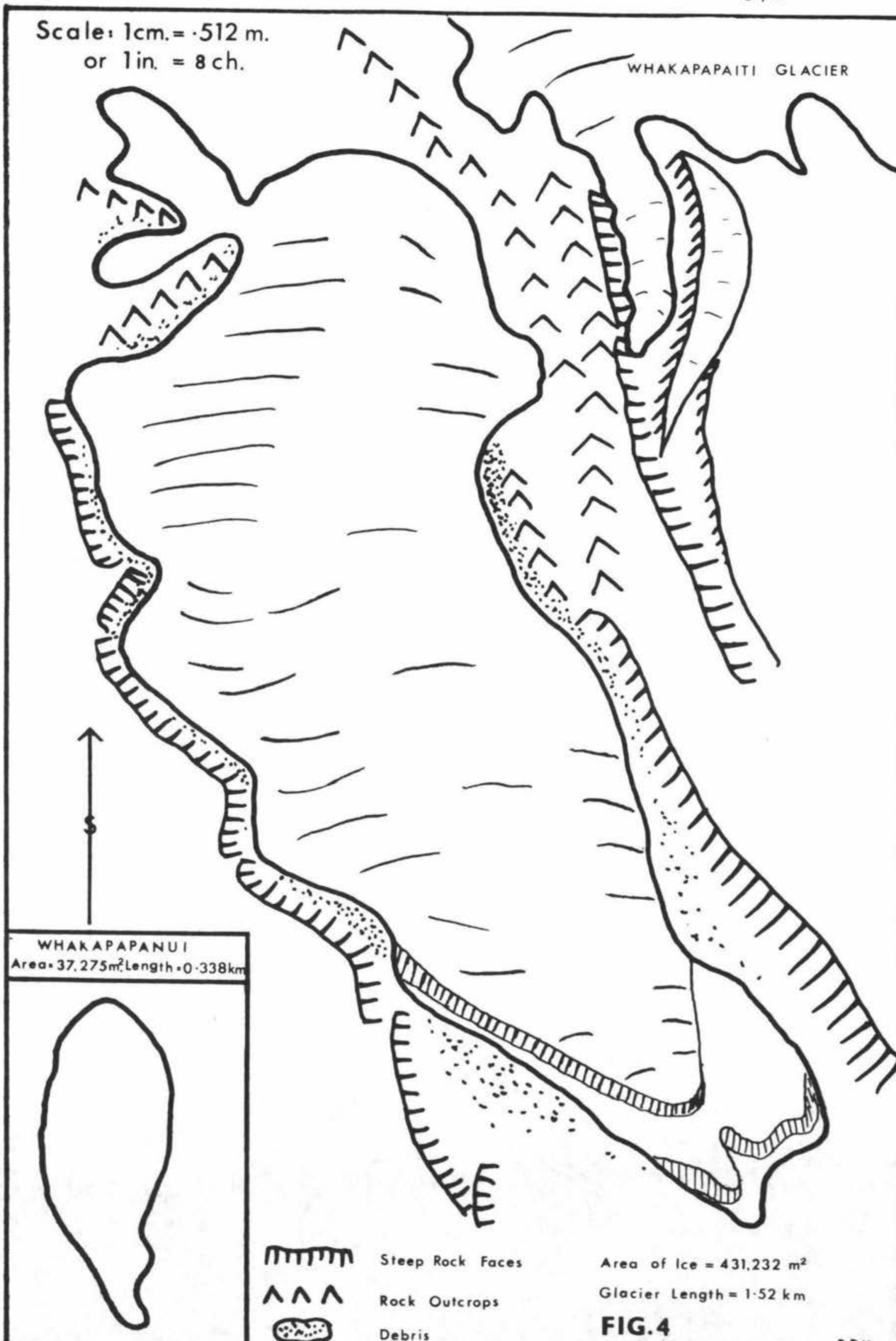


FIG.4

WHAKAPAPANUI GLACIER: MARCH 9, 1955; INSET: MAY 12, 1969.

Table I gives a breakdown of frequency of snowfalls per month in the accumulation season.

Table I

Snowfalls in 1968/9 Budget Year

Month		Days
April	1968	9
May	"	8
June	"	17
July	"	15
August	"	15
September	"	23
October	"	23
November	"	13
Total		123

September and October, with approximately 23 snow days each, had the highest frequencies. The most significant aspect of this table, however, was the relatively high frequency of snowfalls in November, a month which was usually regarded as the beginning of the ablation season. It was only when looked at in conjunction with Figures 9 to 16, however, that the full significance of Table I was appreciated. These figures illustrated the recorded daily skiable level and snow line for the Whakapapa Ski Field, of which the Whakapapanui Glacier was a part. Compiled from Ski Patrol Accident and Snow Records, together with records from The Chateau Meteorological Station, these provided a useful if somewhat qualitative indication of the intensity of snowfalls in the various months. When Figure 16 was compared with the other figures, it was apparent that the 1968/9 winter ski season was of longer duration than any of the other ski seasons from 1962 onwards. In 1968 the skiable level on

THE WHAKAPAPANUI GLACIER : (a) HORIZONTAL (b) LONGITUDINAL (c) CROSS-SECTIONAL VIEWS

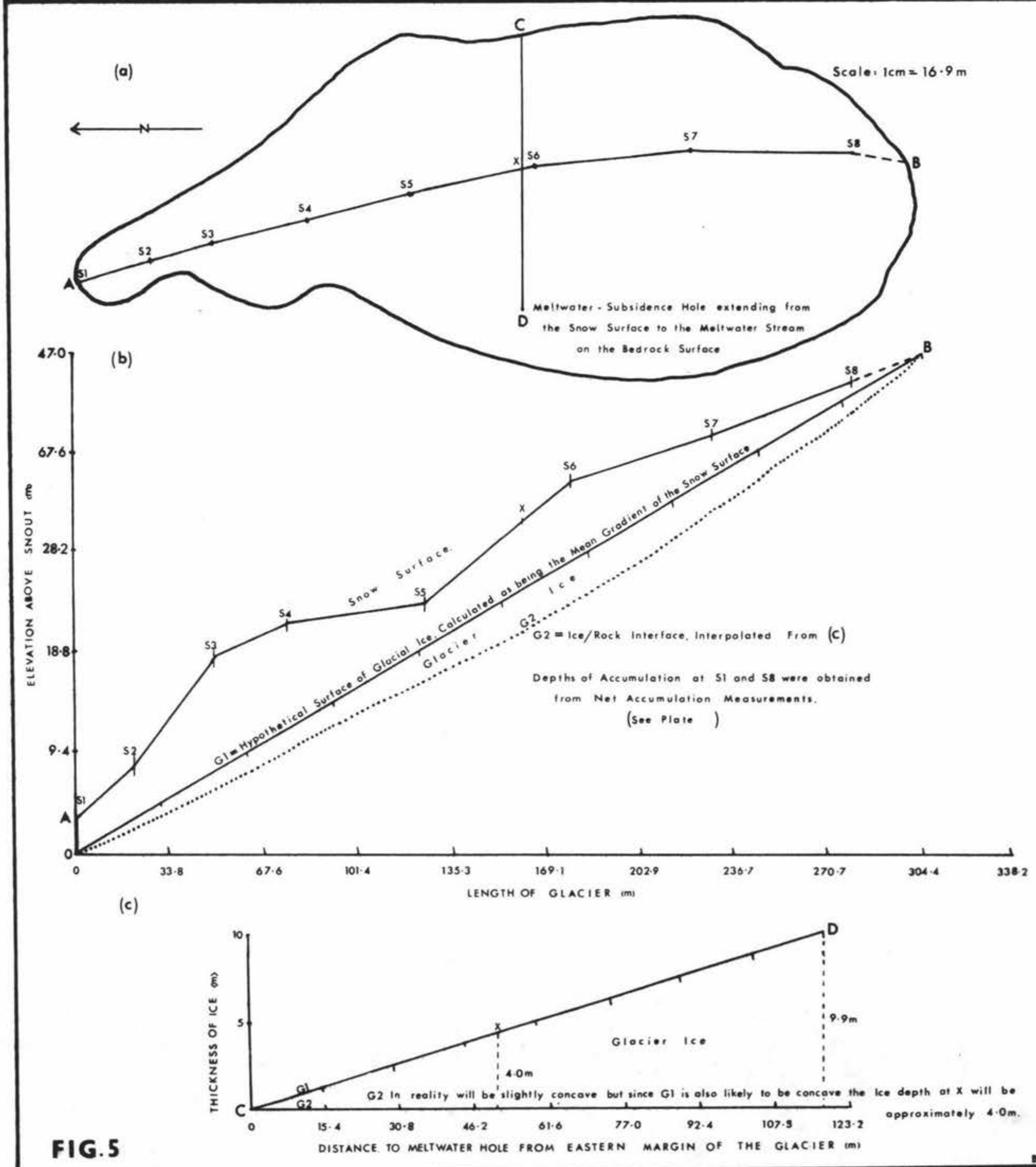


FIG.5

October 28 was about 1,300 m above sea level, and by the end of November it had receded to only about 1,400 m a.s.l. In all other recorded years the rate of recession of the skiable level had become so rapid that conditions had not warranted the continuance of a regular ski patrol service beyond the end of October. The November snowfalls, moreover, were of sufficient intensity to have brought the snow line down to 800 m or less on at least two occasions.

While the amount of snow required to raise these respective snow levels was not measured, after careful consideration of ski reports the writer believed that approximately 0.6 m of snow was required to lower the skiable level 30 m from 1220 m a.s.l. to 1,190 m a.s.l. It was considered that snowfalls in the order of 10 cm on every second or third day would be necessary to maintain the skiable level at or near 1,350 m a.s.l. through most of November. Consequently accumulation in the order of 6 to 8 m must have existed on the glacier to support a skiable level of 1,220 m.[1] This meant that, as a result of the frequency and intensity of snowfalls in November, that month actually had a net gain over loss of mass.

(b) Arien Deposits

Less significant aspects of the regime were the so-called arien deposits, resulting from the direct freezing or sublimation of water vapour during mists, as rime and hoarfrost. It was often difficult to distinguish between the two although hoar is "an ice-crystal deposit formed by the sublimation of water vapour on to a solid body at temperatures below freezing" (A.D.T.I.C. U.S. Air Force, 1966), and as such is less dense than true rime which is defined as "an opaque ice coating on exposed surfaces formed by freezing of very small water droplets immediately upon contact" (A.D.T.I.C. U.S. Air Force, 1966). Riming was found to freeze up the ventilations on the weather screen and act as a cement around hollow aluminium ablation poles (see Plate 7) which had been left out overnight in adverse weather conditions of strong winds, low temperatures, low cloud and mist. On the actual snow surface a combination of both hoar and rime was often found with the sparse leaflets and tufts of crystals, characterising hoar, being interspersed with tufts of plate crystals having a more regular structure. Ice formed in this manner, as a result of the interaction of the two processes, was found to be less dense than ice resulting from refreezing of meltwater, for the former contained a much greater proportion of air bubbles. Rime and hoar, between them, accounted for only a small proportion of the accumulation, being confined in the main to thin layers on the snow surface. During the course of the accumulation season, however, several such layers may have existed as buried surfaces in the accumulation profile.

As a result of the mechanisms by which they were formed, this combination of rime ice and hoarfrost was called sedimentary ice and its density was found to vary between 0.815 and 0.846 g/cm^3 (see Figs.6 to 8). Ice formed as a result of pressure and melting was called metamorphic ice and, according to Hattersley-Smith (1963), varied in density between 0.84 and 0.9170 g/cm^3.

Conditions which favoured the formation of sedimentary ice occurred quite frequently on Mt Ruapehu. They were best described as "white out" conditions (see Plate 7) and occurred in almost any season so long as there was a continuous snow cover. A "white out" is said to have existed when the sky was overcast or foggy with a rather uniform cloud cover occurring over parts of the mountain where there was an unbroken snow cover. On occasions when the cloud cover is very low "incoming light is scattered and reflected many times causing a complete lack of visual contrast between the sky and snow surface. This results in poor depth perception, reduced visibility and an apparent lack of surface features." (Hicks, 1965) This condition was made so much the worse by fog and blowing snow which reduced visibility to less than a metre. Mt Ruapehu was renowned for its windy conditions and blizzards were a not too infrequent occurrence. The winds, however, were generally more of a gusty nature than sustained gales (see Chapter 3). Owing to its position in a somewhat sheltered valley on the northern slopes of Mt Ruapehu (see Plate 27), the glacier's regime was considerably augmented by wind-blown snow. The importance of this sheltered aspect to the regime of this glacier will be emphasised later.

2. Secondary Sources

The secondary sources of accumulation played a considerable role in the densification of the névé. Rain was considered to have been a source of accumulation as long as it had fallen on snow at sub-freezing temperatures for, like meltwater—the other secondary source—it became frozen as it percolated downward. Rain accompanying south and south-westerly airstreams, which had their origins in the polar and subpolar latitudes, was more likely to have augmented the accumulation than rain which was associated with airstreams from the northerly quarters. The latter, being of subhumid origin, were warmer and more likely to act as potential agents of ablation. Airflows from the east and south-easterly quarters tended to be more stable since, in passing over the land, most of their moisture had been precipitated as they were forced to rise over the broad mountain belt comprising the Ruahine and Kaimanawa Ranges. From the writer's experiences of this climate, temperatures during the passage of these latter airflows were usually cooler than temperatures during prevailing westerlies, so that the south-easterly airstreams were more likely to have caused the meltwaters to have frozen on the glacier.

Meltwater, which developed on sunny days with clear skies and/or with the passage of warm, moist airstreams (particularly those from the north-west), was frozen as it percolated downward into the material chilled by the winter cold wave penetration. The winter cold wave was associated with the passage of cold fronts or, alternatively, with continued nocturnal chilling. The latter condition arose as a result of the clear nights which accompanied the migration of anticyclones across the country from west to east, and accounted for the icy crystalline surfaces in the mornings. It may also have contributed to the formation of ice bands and ice pipes in the upper few centimetres of the snow profile. Ice bands at depths below this were, in most cases, buried surface melt-surfaces, or had resulted from the refreezing of percolating meltwater due to cold wave penetration. A rather weak temperature gradient in the névé profile (see Fig.28) suggested that ice bands in profiles of the gross accumulation had arisen principally as buried surface meltsurfaces (see Plate 8). Nevertheless, the passage of a cold front was likely to have caused chilling to a certain depth. For it to have penetrated 10 or 11 m right to the glacier ice would have required a particularly rapid transfer before dissipation of the cold wave and the return to pressure-melting conditions. This would have been brought about by the advance of the weather cycle bringing improved weather conditions. A transfer of this nature could have occurred in rather dense névé (see Fig.6) with a minimal amount of insulating air molecules, for it has been demonstrated by

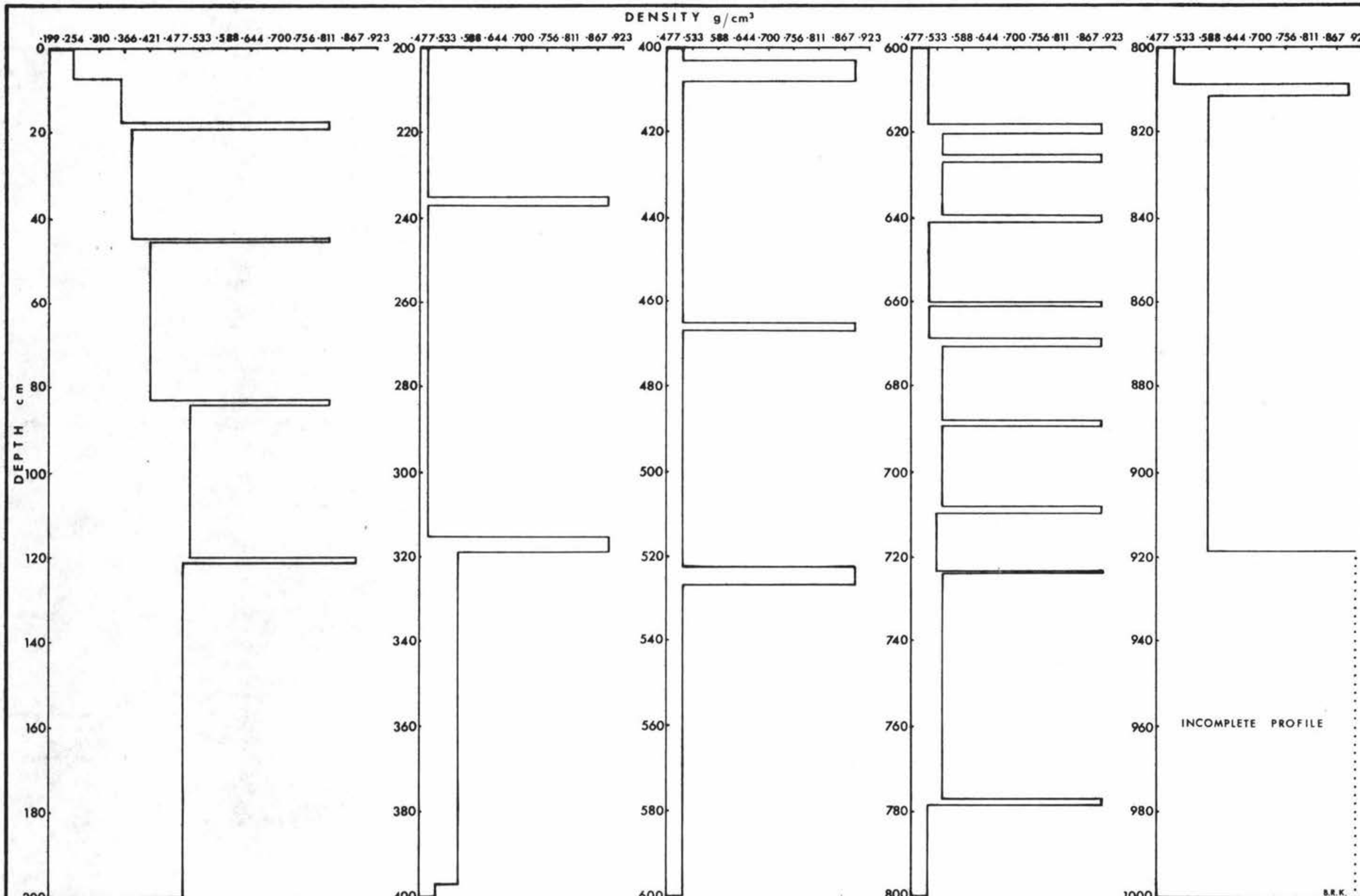


FIG.6 GROSS ACCUMULATION PIT SHOWING DEPTH/DENSITY RELATIONSHIPS

Yin Chao-Yen (1966) that "the thermal diffusivity of snow is greatest where the snow is densest". Hence the cold air which came in contact with the surface may have been conducted to lower levels causing the rapid refreezing of percolating meltwater into ice.

The likelihood of depth hoar crystals being formed on the glacier was enhanced by the presence of hard snow which was quite resistant to mechanical deformation (e.g. lack of distortion of pit walls). The very large size (between 1 and 5 mm in diameter) and rounded shape of the crystals, which made up the névé, were believed to have favoured the presence of cavities and pores, where the water vapour necessary for the formation of hoar crystals could collect. The water vapour could not, however, have been formed without some activating force. The presence of an inverted temperature gradient below the 2 m level (see Fig.28) may in fact have been the activating force on the Whakapapanui Glacier. The vapour could have developed where the temperature was warmer and migrated upwards by capillary action, through the cavities formed by the rounded crystals, into cooler regions. This process may have helped to account for the variations in the progressive increase of density with depth (see Fig.6).

The presence of ice throughout the pit profiles could thus have been the result of one or all of three processes: (i) the deposition of sedimentary ice such as rime and hoar (0.825 g/cm^3); (ii) the rapid refreezing of percolating meltwater (0.8859 g/cm^3); and (iii) from the process of metamorphosis (0.9170 g/cm^3). The ice resulting from the latter process—the true glacier ice—was transformed from névé through the procedure of <u>firnification</u>.

Association of Airflow Types with Accumulation

A further problem concerning the analysis of gross accumulation was associated with attempts to designate the type of weather conditions during which snow was most likely to have fallen. In Chapter 2, Part II, a system of airflow types associated with characteristic weather patterns was devised, on the basis of Lamb's classification system, for use in attempts to ascertain the climatic normality of the 1968/9 budget year. This same system has been used in attempts to relate days of snowfall to weather patterns. The four different weather types accompanying the airflows were as follows:

Airflow 1—convergence of air from the SE, E, N and NE sectors of the compass associated with troughs or fronts to the north of Mt Ruapehu.

Airflow 2—convergence of air from the SW, W, S and NW sectors of the compass associated with troughs or fronts to the south of Mt Ruapehu.

Airflow 3—subsidence of air from the NW, W, S and SW sectors of the compass associated with the migration of anticyclones to the north of Mt Ruapehu.

Airflow 4—subsidence of air from the N, NE, E and SE sectors, together with the calm air, associated with the migration of anticyclones to the south of Mt Ruapehu.

These four airflow types were associated with snow days as shown in Table II.

Table II illustrates that Airflow 2 had the highest frequency of snow days with 50 percent of the occurrences, while Airflow 3, with only 24.4 percent, had the second highest association with snow days. While these two between them accounted for almost 75 percent of the snow days, their actual contribution to the total accumulation on the glacier could not have been indicated without some knowledge of the intensity of the snowfalls. This has been dealt with in Chapter 2, Part III.

Table II

Association of Airflow Types with Snowfall, 1968/9

Airflow Type	No. of Days with Snow	Proportion of the Days with Snow	
A_1 (CSE, CE, CN, CNE)	12	9.8%	61.8%
A_2 (CSW, CW, CNW, CS)	64	52.0%	
A_3 (ANW, AW, AS, ASW)	30	24.4%	38.2%
A_4 (AN, ANE, AE, ASE, A)	17	13.8%	

In the meantime it appears that orographic augmentation was most likely to have arisen from the westerly airstreams. Since the south and south-westerly airflows were modified maritime polar airstreams with dewpoints of between 1°C and 7°C (based on Shields' observations of maritime polar air over South Australia), their dewpoints were likely to have been reached earlier than those for air of subpolar maritime or tropical maritime origins. The subpolar maritime air with dewpoints of between 18°C and 24°C (according to Shields, 1965) included the north-westerly airflows while the tropical maritime air with dewpoints of between 7°C and 15°C included the straight westerlies. On this basis alone the south-westerlies with their rather low moisture retaining capacities and accelerated dewpoints were expected to have contributed the greatest overall accumulation. This did not, of course, take into account the precipitation resulting from cyclogenesis and frontogenesis.

Densification Processes

According to Embleton and King (1967) the transformation of snow to ice by firnification takes place in three phases and the rate and extent to which they operate is important to the density of the gross accumulation. Quervain (1963) has stated that the initial process is the compaction of ice crystals forcing them closer together so that a thermodynamic instability is induced which leads to a general rounding of the crystals. This is the so-called destructive phase of metamorphism. The second phase is the constructive metamorphism in which there is an enlargement of crystals. Essentially it results from temperature and vapour concentrations and the resultant gradients lead to vapour transfers from warm layers to colder layers. Finally, the third phase involves successive melting and refreezing under the pressure of the snow blanket and it is known appropriately as melting metamorphism.

According to Quervain (1963), there are a number of pre-requisite conditions which govern the operation of each of these phases. The first stage of densification is dependent essentially on spatial factors. In its driest state, when temperatures are well below freezing, the snow crystals are very fine and diagenesis is very slow. On the Whakapapanui Glacier, while there was considerable nocturnal cooling, daily temperatures were seldom much below freezing point (see Table III) and, as a consequence, surface temperatures were usually at or near freezing point. These conditions were conducive to fairly wet snow which greatly facilitated the rounding of the snow crystals into a more granular texture.

With the exceptionally large falls of snow the processes of packing and cohesion operated fairly rapidly so that within 24 hours of falling, new snow, with a density of between 0.1 and 0.3 g/cm^3 (Meier, 1964), had increased to 0.35 g/cm^3. This represents a percentage increase in pressure of between 15 and 70 percent. Within 48 hours of falling, the snow had increased in pressure by a further 10 to 20 percent to a density of between 0.40 and 0.45 g/cm^3.

Table III

Mean Air Temperatures on the Glacier, 1968/9

Month	Mean Temperature °C*
April	3.4
May	1.0
June	-1.9
July	-3.5
August	-2.0
September	-2.2
October	-0.8
November	1.1

* Temperatures were obtained from The Chateau Meteorological Station and reduced to parity using the Lapse Rate of 0.53°C/100 m.

Meteorological conditions other than air temperature had some bearing on this initial process. The number of sunshine hours was an important factor in surface melting and, whilst there were no figures for sunshine hours available, the glacier's location on the northern adrêt slopes and its rather considerable average surface gradient[2] of 30.5° (see Fig.5) meant that even in winter the insulation was quite concentrated and must have induced a considerable amount of surface melting (see Plate 10). Moreover, the cyclic pattern of New Zealand's weather, with the high pressure stagnation, would have combined with the glacier's aspect to give a fairly high frequency of sunshine days, even in winter.

There was considerable spatial variation in accumulation over the glacier, resulting from two principal factors. First was the topography of the glacier valley. The glacier occupied a setting whereby it avoided the full unimpeded force of the prevailing westerly winds. A small spur or knoll jutting out into "The Gut" hindered the passage of the

Plate 10. View looking due north from the snout of the Whakapapanui Glacier. In the lower left foreground is The Knoll, while in the middle foreground are the three pinnacles of Pinnacle Ridge. The two summits projecting above the cloud ceiling are volcanic peaks which, together with Mt Ruapehu (2,797 m), make up the core of the Volcanic Plateau in the centre of the North Island of New Zealand. Furtherest away is Mt Tongariro (1,969 m) whilst in the centre is the young and still very active Mt Ngauruhoe (2,291 m) forming an almost perfect cone.

wind as it was funnelled up through "The Gut" (see Plate 28). Such a phenomenon was likely to have caused an increased accumulation on the upper side of the barrier, for studies in Australia have shown that deposition in the lee of a barrier have been up to three times greater than on the windward side. This meant that the glacier stood to gain more mass than the more exposed regions above and below it, e.g. the Whakapapaiti Glacier. The Whakapapanui Glacier also was nestled at the foot of the south-easterly/north-westerly aligned extremity of Restful Rocks. As such it was in a particularly favourable position for the receipt of accumulation accompanying airflows from the southern and south-easterly quarters. Topography then appeared to have been instrumental in the preservation of the glacier ice. In particular the glacier's position immediately beneath the 15 m high rock wall—the eastern fringe of Restful Rocks—appeared to have been particularly important. Also the very uneven accumulation over the glacier surface in 1968/9 was due in part to the higher than normal frequency of snowfalls accompanying A_1 and A_3 airflow types associated with the decreasing significance of A_2 airflows (see Table II) and led to a concentration of snow in the lee of the rock wall (see Fig.3).

The second factor which contributed to this spatial variation was the local wind, since the prevalence of easterly and southerly winds had not been entirely responsible for the build-up of snow on the glacier. In fact the deflation accompanying these airflow types probably contributed quite considerably to the existence of an "inverted" firn line, a phenomenon recorded by Krenek in 1954 and 1955. Winds blowing over the rim of the old crater had, in many places, exposed the glacier ice in what was normally the upper accumulation area of the glacier. These winds undoubtedly contributed to the ablation and ultimate recession downhill of the upper extremities of the original glacier.

It was more likely to have been the existence of lee wave/helm wind deposition associated with the two separate rock outcrops, "Met. Station Hill" and "Rocky Cliff", which led to an uneven distribution of snow over the glacier. In passing over these rock outcrops the wind was induced into a circular motion resulting in eddies which eventually dissipated depositing the wind-borne snow in the lee of the outcrops. Conversely, deflation took place on the more exposed parts, especially in the topographic "funnel" created by the gap between "Met. Station Hill" and "Rocky Cliff" (see Fig.3).

The two remaining phases of metamorphosis relied largely on time-dependent mechanisms and have been dealt with in the chapter on net accumulation. The rest of this chapter is devoted to the calculation of the size of the gross accumulation.

The Water Equivalent of Gross Accumulation

Using the procedure outlined in the methodology, the specific gross accumulation was calculated at two pits, aligned along the middle of the valley depression, with the upper pit coinciding with S.7 on Fig.5(a) and the lower about mid-way between S.4 and S.5. As a result of their rather exposed positions in the valley depression the water equivalent value for the gross accumulation was likely to have been quite conservative. The upper pit was assumed to have been representative of an area 19,690 m^2, whilst the lower pit represented an area of 17,320 m^2. This gave a total area of accumulation of 37,280 m^2 which corresponded with the actual area of the glacier ice. In reality the area of gross accumulation was difficult to define because the glacier occupied only a very small portion of the valley which, at the height of accumulation, was little more than an elongated trough-shaped depression. Consequently the zone of gross accumulation has been taken as that area immediately above the glacier ice.

The density of the névé at each of the pits was calculated from depth/density recordings and the mean value of the névé was computed as 0.5713 g/cm^3. The depth of accumulation over the entire glacier averaged 11.4 m and when multiplied by the mean density, indicated a mean specific gross accumulation of 6.8 m of water. When this figure was multiplied by the entire area of the glacier the result was the total gross accumulation of 253,000 m^3.

Footnotes

1. This estimate was based upon the depth of accumulation on the glacier on days when the skiable level of the Whakapapa Ski Field was also known.
2. The slope of the glacier surface varied from 54°34' near the snout down to 8°38' in the middle section, increasing again to 40°33' before tapering off at the upper terminus to about 20°.

CHAPTER 2

NET ACCUMULATION

The net accumulation was the volume of water remaining in storage on the glacier, as ice and névé, at the end of the budget year. Like the gross accumulation the actual quantity did not mean much in itself. What was more important was (a) its size relative to the gross accumulation, and (b) the similarities and differences in the nature of the mass, as measured at those particular times of the budget year.

The time that had elapsed between the measuring of the gross and net accumulation quantities was in the order of five to six months so that time dependent mechanisms were likely to have engineered the greatest changes in the nature and the quantity of the mass remaining at the end of the budget year.

Densification Processes

Densification of the gross accumulation involved the mechanisms by which the hexagonal snow crystals were transformed into granular névé, largely by the temperature dependent diagenetic processes of sublimation (evaporation-condensation). However, diffusion and a general aggregation of grains—the processes which operated up to the stage of net accumulation—were concerned more with the growth of crystals. The mechanisms of readjustment and packing were also quite prevalent as a result of the exceptionally large gross accumulation, while melt metamorphism was also pronounced. The existence of meltwater permitted not only close packing of grains but also filled the pore spaces forcing the air out as it did.

The mediums on which the metamorphic processes were operative during the accumulation season were both snow and névé, whilst it was mostly névé which was present in the period between the measurement of the gross and net accumulation quantities. Snow was generally termed névé when "as a result of compaction, a critical density is reached beyond which densification is possible only through molecular diffusion (and the processes which produce a) change of state" (Anderson and Benson, 1963). By the end of the budget year the density of the névé ranged from 0.60 g/cm^3 at the surface to 0.76 g/cm^3 in the basal layers (see Figs.7 and 8), while in the gross accumulation profiles the densities ranged from only 0.35 g/cm^3 in the upper layers to 0.58 g/cm^3 in the basal layers (see Fig.6).

Table IV

Mean Air Temperatures, December 1968 - April 1969

Month	Mean Temperature at Glacier °C*
December	4.56
January	6.12
February	6.66
March	4.50
April	1.07

* These were calculated using the mean lapse rate.

The time period elapsing between the measurement of the gross and net accumulation quantities—a period of approximately five months—coincided with the spring and summer thaw, when the densification processes were likely to have been accelerated by high temperatures. No month had a temperature less than 1°C, while the estimated lowest daily average temperature recorded during the whole period was -3.9°C on April 28.[1] It was on April 9, with a temperature of -2.4°C, however, that the first snow for 1970 was deposited and it was followed by more snow on April 10,

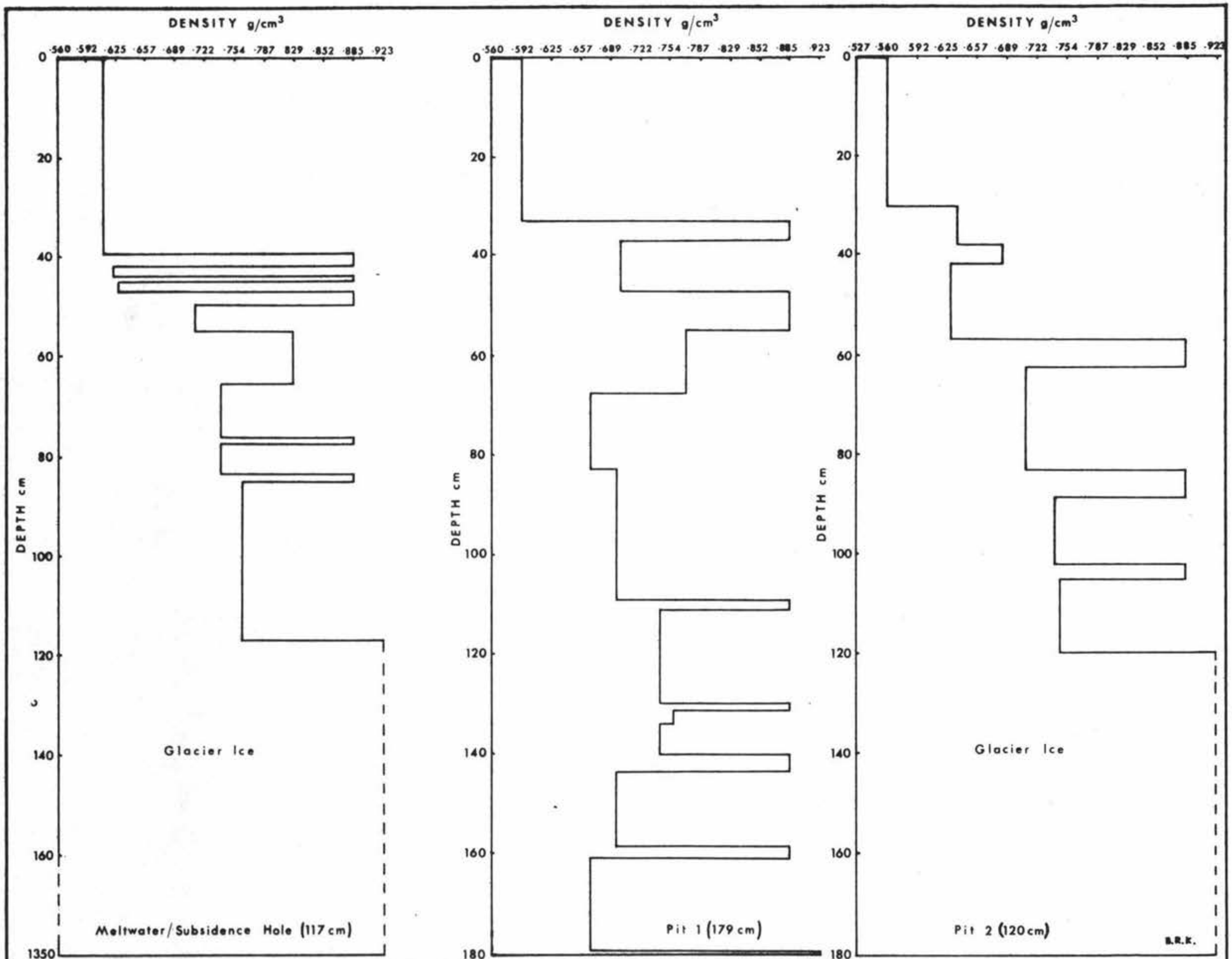


FIG. 7 NET ACCUMULATION PITS SHOWING DEPTH/DENSITY RELATIONSHIPS

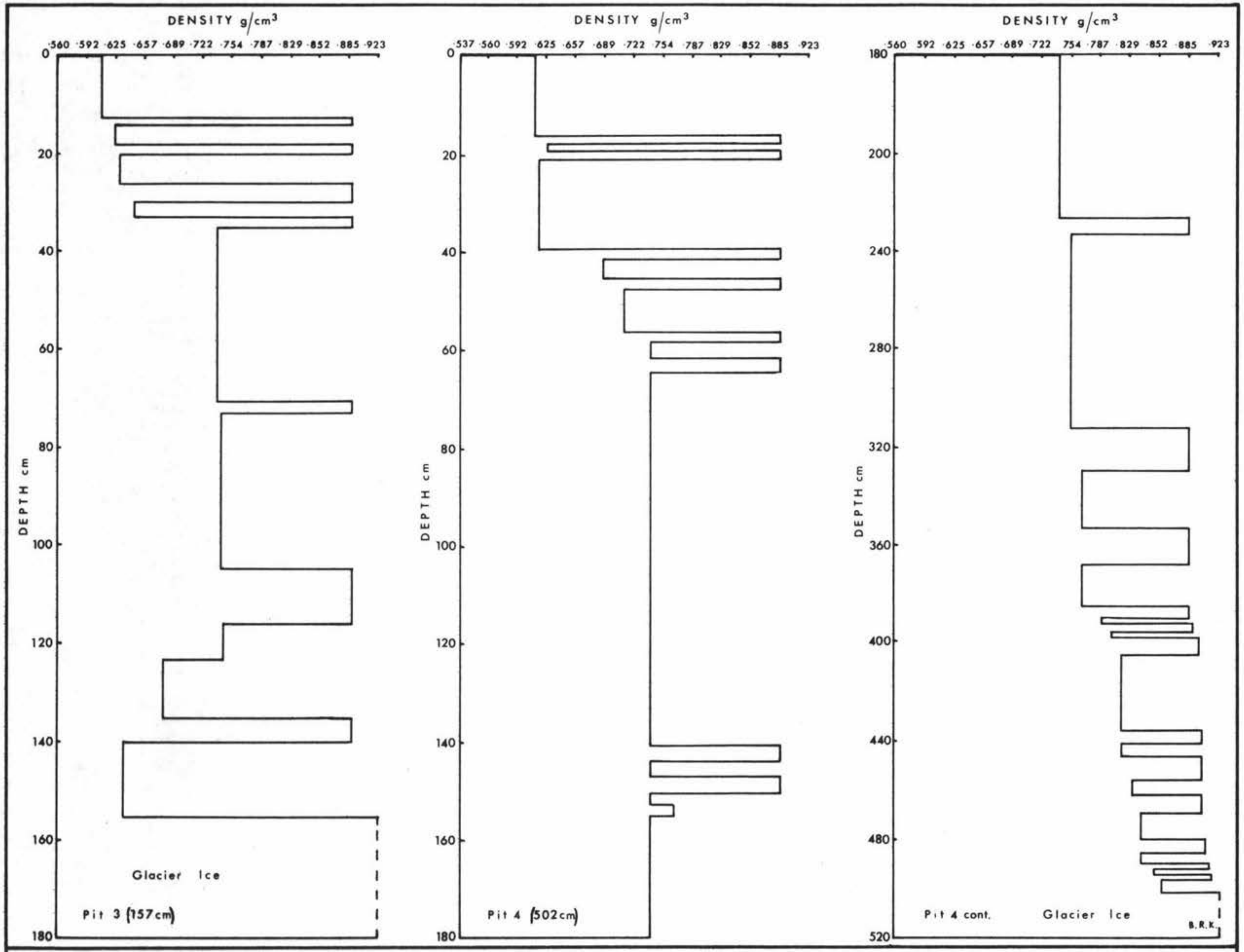


FIG. 8 NET ACCUMULATION PITS SHOWING DEPTH/DENSITY RELATIONSHIPS (cont.)

11, 14, 17, 18 and 27. April 9, 1969 thus marked the end of the 1968/9 budget year and the beginning of the 1969/70 budget year.

These above-freezing temperatures were accentuated by the considerable elevation of the glacier (2,360 m) and its maritime mid-latitude position, which meant that the sensible heat transfer and the radiative energy had induced considerable surface melting. This meltwater percolated downward and on refreezing liberated latent heat, part of which was used to dissipate the winter cold wave and part of which was used in recrystallisation. Although no systematic study of the crystallography was undertaken, grains in the upper 20 to 30 cm of névé had diameters of between 3 and 5 mm. Together with the high densities in the basal layers, this indicated that the process of firnification was particularly rapid on the Whakapapanui Glacier. The phases of constructive and melt metamorphosis were obviously accelerated and intensified by the high temperatures, as well as the effective system of communicating pores between the large grains which increased the air permeability so allowing vapour transfer. Together these processes maintained the névé at or near pressure melting point.

Stratigraphy

Five pit profiles for the net accumulation, in which depth was plotted against density, are displayed in Figures 7 and 8. A characteristic feature of all the profiles was the prevalence of ice bands, particularly in the upper 20 to 30 cm. Ranging in thickness from 1 to 7.5 cm these bands were often so close as to make density measurements extremely difficult. In such cases the névé was extracted from the pit face using a small cutting tool and then transferred into the sampler.

Whilst slight inaccuracies may have occurred as a result of this transfer, it was considered that a very close approximation was possible for the névé was so hard and dense that it was unlikely to be further compressed as a result of packing. Excavation tools needed to be particularly sharp and rigid to penetrate the névé for even the upper layers were dense and brittle. Only the very upper stratum—the new season's névé—was less than 0.63 g/cm^3. Below this the layers of firn gradually increased in density with depth though the rate of increase was neither uniforn nor regular. Irregularities occurred as a result of the differing rates of densification accompanying the varying weather types. Under anticyclonic conditions surface melting was rapid during the day but the meltwater became frozen at night with nocturnal chilling. The passage of warm fronts and troughs produced somewhat different conditions, especially if accompanied by rain. Under warm humid conditions, Mayo and Péwé (1963) have found that rain percolates down through the firn and as it refreezes it releases latent heat which further raises the temperature of the névé and this facilitates further recrystallisation. As a result of the cloudy skies accompanying such conditions, the heat loss at night was not considered to be very pronounced and this may have prevented the degree of cooling necessary for the formation of ice. These variations in the weather must have accounted for the differing thicknesses of the firn strata on the Whakapapanui Glacier.

Two processes in particular contribute to the gradual increase in density with depth. The first of these, described by Müller and Keeler (1969) as internal ablation, occurs as a result of the differential absorption of radiative energy along grain boundaries and especially where the névé has been discoloured, for this greatly decreases the albedo with a concomitant increase in the absorptivity and transmissivity. Radiation of short wave length normally penetrates quite deeply into the snow whereas "radiation of longer wavelengths is almost entirely absorbed in the first few thousandths of an inch" (Edgar, 1966). Absorption of long wave terrestrial radiation leads to slow internal melting and as this refreezes with downwards percolation, it liberates a certain amount of latent heat (when water changes from a liquid to a solid it releases 80 cals/gm of water sufficient to raise the temperature by $1^{\circ}C$) ← (NO) (La Chapelle, 1959a). The latent heat then produces more liquid which in turn vaporises, further facilitating the process of crystallisation which forces the air out of the pores and increases the density of the névé. The second important process of densification is percolating meltwater.

The Role of Refreezing Percolating Meltwater in Névé Densification

The importance of meltwater in the role of densification of the névé can be found merely by subtracting the average density of the net accumulation ($0.57\ g/cm^3$) from the average density of the gross accumulation ($0.79\ g/cm^3$). The difference of $0.22\ g/cm^3$ was then expressed as a fraction of the gross accumulation to give an increase in density of 38.5 percent. This should have corresponded with the volume of water remaining in the net accumulation ($77,000\ m^3$) when expressed as a percentage of the gross accumulation volume of $253,000\ m^3$. In fact the result was only a 59.6 percent reduction in volume or a net volume of 30.4 percent, indicating a disparity of 8.2 percent between the net density and the net volume. It was quite possible that this difference may have been the result of superimposition of ice on the glacier surface. This would have accounted for the reduced depth of so-called névé existing above the glacier ice, for the net accumulation average water equivalent depth of 2.1 m was only 30.6 percent of the gross accumulation average water equivalent depth of 6.8 m. A water equivalent depth of 2.6 m would have been required to bring the water equivalent depth of net accumulation to 38.5 percent of the gross accumulation. If this difference in depth of 0.54 m were made up entirely of superimposed ice, it would have averaged about 0.5 m over the entire surface, assuming an average density of 0.90 g/cm^3. This amount was bound to vary over the glacier with variations in the surface gradient, nevertheless it did appear to be a rather large average depth, especially in view of the lateral runoff which had taken place. However, the combined effects of fairly dense and relatively impermeable basal layers, together with a fairly low average surface gradient, must have acted to retard the lateral runoff of meltwater. The mechanism by which this meltwater became frozen as ice was very much a matter of conjecture. It may have been formed by continued nocturnal chilling as a result of the high frequency of cloudless skies (see Chapter 4), which would have facilitated the convection of terrestrial radiation away from the glacier. Whether such chilling could have penetrated through the considerable depth of accumulation (in excess of 2 m) was not ascertained and it remains for subsequent researchers to clarify. It is possible though rather unlikely that the cold wave at the ice surface was not dissipated until late in the budget year, and this facilitated the formation of superimposed ice. The large volume of refreezing percolating meltwater which had greatly contributed to the high densities of the basal layers was likely to have liberated sufficient latent heat to maintain an isothermal condition and prevent such a build-up of superimposed ice. Measurements are needed to confirm or refute these claims. In the meantime the most acceptable solution seems to be that the downward conduction of cold nocturnal air, together with outwards radiation during anticyclonic conditions, accounted for this large build-up of superimposed ice.

It is possible that the measurements from which the depth of ice was calculated were in error, although this could not discount the actual existence of superimposed ice, for a depth of at least 10 cm was observed around the opening of the meltwater subsidence hole. Since the boundary between glacial ice and superimposed ice was rather transitory, it was difficult to establish the exact depth of superimposed ice, although superimposed ice generally has a much greater proportion of air bubbles trapped in it.

It appeared, then, that metamorphosis was rapidly progressing in the five months from November 1968 to April 1969, during which time two essential mechanisms were dominant. First, the aggregation and cohesion of crystals which resulted from constructive metamorphism, and second, the accretion and bonding of grains which eventually produced a material which was almost impervious to water.[2] A further examination of the profiles in Figures 7 and 8 showed that the basal layers had attained a density of around 0.76 g/cm^3, indicating that the process of firnification of snow into ice was almost complete at the end of one budget year. Any névé which survived the summer to become "firn" (in the sense that it was the "last winter's snow") would doubtless have been metamorphosed into glacier ice by the end of the following winter. This would result from the enormous pressure exerted by the extremely large gross accumulation, combined with melting and further displacement of air.

Glaciothermal Measurements

The extent of the glaciothermal measurements is indicated by reference to Tables V and VI, together with Figure 28. Apart from the two telemax recordings in September 1968, the remaining measurements were confined to the ends of the 1967/8 and 1968/9 seasons respectively. Because of the paucity and limited extent of this data, the analysis was rather superficial.

Table V

Telemax Telethermometer Recordings in Meltwater Hole

Date: 6 May 1968 Hours N.Z.S.T.

Depth of Sensors (m)	1300	1330	1400	1430	1500
-9.75*	-0.4	-0.6	-0.5	-1.0	-1.2
-0.75	-1.0	-1.0	-0.9	-0.8	-0.8
-0.35	-0.6	-1.0	-0.8	-0.7	-0.7
-0.07	-0.5	-0.4	-0.2	-0.5	-0.1
+0.31	0.9	2.0	1.8	1.0	-0.6
+0.63	0.1	1.6	1.0	0.4	-1.3
+0.94	1.0	1.4	0.4	0.2	-1.4
+1.25	0.9	2.5	1.0	1.0	-1.5
+1.52	0.3	1.5	0.3	0.4	-1.7
+1.82	0.6	1.7	0.3	0.8	-1.3
+2.15	-0.4	1.2	1.0	0.6	-1.3

* Bottom of the glacier ice. The surface opening of the hole was approximately 1 m in diameter.

In Table V the sensors in the ambient air reflect the warming associated with sunny conditions, up until 1400 hrs. At about this time cloud began to move in from the west and surround the mountain, while the wind freshened considerably. By 1500 hrs the weather had changed from fine and warm conditions to cold, windy conditions with greatly reduced visibility. In all the recordings, except those taken at 1500 hrs, an inversion was distinctly apparent in the lower air where a reversal of the downward trend of temperatures, above the 0.9 m level, culminated in warmer temperatures at about the 1.25 m level. Above this level the normal lapse rate resumed once again. The height of this skin of warmer air, about 1 m above the glacier surface, was a surprising anomaly which was difficult to explain with the limited evidence available. It seemed likely, however, that it may have been advected aloft by the undermining of katabatic winds at ground level. The slight inversion recorded in the first 0.3 m above the surface, however, was more likely to have resulted from molecular diffusion which led to chilling of the air immediately adjacent to the glacier surface. A slight temperature gradient in the upper 0.75 m of the névé and firn, which had induced the conduction away from the surface, was probably the result of nocturnal chilling or the beginnings of the cold wave penetration, which was initiated in April by the cold southerly on the western periphery of the "Wahine" Cyclone. Being confined to the upper metre or so of the snowpack, it was more likely to be the result of nocturnal chilling. This was supported by lack of significant cooling at the very bottom of the meltwater hole in the early afternoon, with a progressive lowering of temperatures at this level in the late afternoon, as a result of the circulation of colder air down the hole.

Displayed in Tables VI to VIII are similar recordings taken just over one year later. On the first day the relative humidity was around 50 percent with ground level temperatures between 4.5°C and 6.0°C, while the speed of the predominantly south-easterly wind averaged about 10.5 m.p.h. The névé, as indicated by measurements in the upper 1.25 m, was isothermal and just above freezing. Relative humidities on the second day varied mostly between 20 and 30 percent, with wind speeds gusting in the region of 20 to 30 m.p.h. Air temperatures on the average were a few points higher than on May 13 and this may have resulted partly from the change in wind direction from south-easterly to south-westerly.

Table VI

Telemax Telethermometer Recordings in Net Accumulation Pit (°C)

Date: 13 May 1969 Hours N.Z.S.T.

Depth of Sensors (m)	1145	1200	1215	1230	1245	1300	1315	1330	1345	1400	1415
-1.25	0.5	0.5	0.5	0.5		0.5	0.5	0.5			0.5
-0.75	0.6	0.5	0.5	0.5		0.5	0.5	0.5			0.5
-0.11	0.5	0.5	0.5	0.5		0.5	0.5	0.5			0.5
+0.10	4.5	4.5	5.5	6.5		5.0	6.0	5.0			6.0
+0.25	4.9	5.0	6.0	6.0		5.0	5.0	5.0			6.0
+0.55	5.4	5.5	5.5	6.0		5.5	5.0	5.0			6.0
+0.86	5.8	6.0	5.5	6.0		5.5	5.0	5.0			6.0
+1.16	5.8	6.0	5.5	6.0		5.5	5.0	5.0			6.0
+2.05	6.3	6.0	6.0	6.5		6.0	6.0	6.0			7.0
% R.H.*	36	51	55	56		63	58	44	35	49	33
Wind Speed+		8		15		16		11		9	
Direction		SE		SE		SE		SE		SE	

* Dry and wet bulb recordings used in the calculation of the relative humidity were obtained from a hand psychrometer operated about 1.5 m above the glacier surface.

+ The wind speed, calculated from a cup anemometer, allowed the average for half hourly periods to be recorded (see Plate 17).

(These two footnotes apply to the following two tables also.)

Testimony of the nocturnal chilling was apparent in the mid-morning névé temperatures on May 14, with a gradual warming as the angle of incidence of the sun's rays increased later in the day. On both these days (13 and 14) a slight temperature inversion was registered in the

Table VII

Telemax Telethermometer Recordings in Net Accumulation Pit (^{o}C)

Date: 14 May 1969 Hours N.Z.S.T.

Depth of Sensors (m)	1100	1115	1130	1145	1200	1215	1230	1245	1300
-1.25	-0.1	-0.1	0	0.1	0.2	0.3		0.2	0.3
-0.75	0	0	0	0	0.2	0.3		0.2	0.3
-0.11	-0.1	0.1	0.1	0.2	0.2	0.4		0.3	0.3
+0.10	5.1	5.6	5.9	5.9	6.3	6.4		6.9	7.0
+0.25	4.9	5.2	5.2	5.9	6.1	6.3		7.0	7.0
+0.55	5.5	6.0	6.0	6.5	6.9	7.0		6.9	6.9
+0.86	6.3	6.1	6.0	6.5	6.9	7.0		7.0	7.0
+1.16	5.9	6.2	6.1	6.8	7.0	7.1		7.1	7.0
+2.05	6.0	6.6	6.8	7.1	7.8	7.8		8.0	8.0
% R.H.*	27	24	23	16	20	18		22	22
Wind Speed+			25		25		27		25
Direction			S		S		S		S

Depth of Sensors (m)	1315	1330	1345	1400	1415	1430	1445	1500
-1.25	0.3	0.3	0.3	0.1	0.1	0.1	0.3	0.2
-0.75	0.3	0.3	0.3	0.1	0.1	0.1	0.2	0.2
-0.11	0.3	0.3	0.3	0.1	0.1	0.1	0.1	0.1
+0.10	7.0	7.1	7.1	7.1	7.0	7.0	5.5	6.5
+0.25	7.0	7.1	7.1	7.1	7.1	5.9	6.0	7.1
+0.55	6.9	7.0	7.0	6.9	6.2	6.9	6.3	6.0
+0.86	7.0	7.0	7.0	7.0	6.0	7.0	7.0	7.0
+1.16	7.0	7.0	7.0	7.0	6.9	7.0	6.9	7.0
+2.05	7.2	7.8	8.0	8.0	8.0	8.0	8.0	8.0
% R.H.*	18	29	16	15	42	40	24	28
Wind Speed+		26		19		16		
Direction		S		S		S		

mid-morning ambient air temperatures. This had usually dissipated by the afternoon although on the afternoon of May 14 the emergence of an elevated inversion was beginning to show through at approximately the same elevation above the surface as it did in the previous May's recordings.

Table VIII

Telemax Telethermometer Recordings in Net Accumulation Pit (°C)

Date: 15 May 1969 Hours N.Z.S.T.

Depth of Sensors (m)	1030	1045	1100	1115	1130	1145	1200	1215	1230	1245	1300	1315
-1.25	-0.4		-0.5		-0.2	-0.2	-0.2	-0.2	-0.2	-0.2	0	0
-0.75	-1.0		-1.0		-1.0	-1.0	-0.5	-0.5	-0.5	-0.3	-0.3	-0.5
-0.11	-2.0		-2.5		-2.0	-2.0	-1.9	-2.0	-1.9	-1.9	-1.8	-0.5
+0.10	3.0		2.0		3.0	2.8	2.5	2.5	2.0	3.0	2.5	2.9
+0.25	2.4		2.4		2.5	2.0	2.1	2.0	1.2	2.9	2.1	2.1
+0.55	3.0		2.9		1.0	2.0	2.1	2.1	2.0	2.8	2.2	2.2
+0.86	2.6		2.8		2.6	2.0	2.1	2.0	2.0	2.5	2.1	2.2
+1.16	2.6		2.9		2.8	2.0	2.1	2.0	1.2	2.5	2.1	2.3
+2.05	2.5		2.8		2.5	2.0	2.1	2.1	2.0	2.6	2.2	3.0
% R.H.*	74		72		72	52	68	68	65	63	70	30
Wind Speed+			13		19		20		18		21	
Direction			NE		NE		NE		NE		NE	

Both the névé and the ambient air temperatures on May 15 were evidence of the deterioration in the weather with the development of frontogenesis over the mountain in the late evening of May 14. By mid-morning of May 15 this subpolar front had migrated northwards and the accompanying rainfall and perturbation had abated somewhat. The associated sub-freezing temperatures were by this stage confined to only the upper few centimetres and by early afternoon this cold wave had considerably dissipated with a return to near isothermal conditions. Air temperatures remained fairly low, however, and this was reflected in the high relative humidity. The prolonged duration of cool temperatures, despite the passing of the front, was believed to have resulted principally from the persistence of a cold north-easterly airstream accentuated by steady winds which seldom dropped below 20 m.p.h. Along with these conditions there was a return to the normal lapse rate in the ambient air.

Calculation of Net Accumulation Value

The net accumulation quantity was calculated with a fairly high degree of accuracy since a total of five pits were used in the computations of the mean specific gravity, while seven additional net accumulation depths were measured using a snow corer. This meant that a much greater consideration was given to spatial variations in the firn cover than in the gross accumulation calculations. Such factors as gradient and differential albedo were considered in the positioning of the pits (see Figs.3a and 5).

From the five pits the mean density of 0.78 g/cm^3 was calculated, while all twelve depth recordings were used to obtain the average firn depth of 2.6 m. These two figures were multiplied together and provided the mean water equivalent depth of 2.08 m, which was the mean specific net accumulation. The total net accumulation of 76,830 m^3 was obtained when the mean specific accumulation was multiplied by the area of the glacier.

Footnotes

1. The daily temperatures at the glacier were calculated using the lapse rate of 0.53°C/100 m. This value was derived from recordings at the Ski Patrol Headquarters (1,752 m) in conjunction with the daily recordings at The Chateau Meteorological Station (1,118 m). Both of these stations were maintained by National Park Rangers, but recordings at the Ski Patrol Headquarters were available for only the winter ski season. Since the daily meteorological recordings were not mandatory, the number of days on which there were recordings from which valid lapse rates could be calculated was rather minimal. An added drawback of the resulting lapse rate was that it had been calculated for only the most severe winter months, so that it included a reasonable number of inversions. The summer lapse rate was likely to have been somewhat greater, as a result of the reduced number of inversions, though it was considered highly probable that maximum temperatures on the glacier were likely to have been somewhat higher than those calculated from The Chateau records. This was associated with the greatly increased insolation at the higher elevation. Garnier (1957) has calculated a summer lapse rate for elevations above 610 m of 0.6°C/100 m. However, even if Garnier's value was used in the calculation of air temperatures on the glacier, they would on the average be only 0.84°C lower than indicated.

2. It is commonly accepted that névé becomes impermeable at a density of about 0.84 g/cm^3, while Hattersley-Smith (1963) is of the opinion that the transition to ice is also complete at this stage.

CHAPTER 3

ABLATION

Frequent reference has been made to the word ablation in the past few chapters but, apart from briefly indicating that it is the wastage of snow and ice, no attempt has yet been made to accurately define it. Hubley (1963), in attempts to define ablation, states that the "melting of snow, ice or firn in a glacier is not a process of ablation. Ablation is the loss of mass whereas melting is a change of mass from solid to liquid." The two, however, operate in a complementary fashion in that melting makes water available for the ablation processes of runoff, evaporation etc. In summary, then, melting often initiates ablation while melting itself is caused by the energy transfer processes of radiation, condensation, conduction and convection. Thus it would appear that the mass and energy budgets are inextricably linked and that consideration of the one necessarily implies consideration of the other.

Unfortunately few ablation season measurements were available since attempts to establish the relative importance of the various heat transfer mechanisms in the 1968/9 mass transfer rate were prevented by a lack of equipment. Attempts to analyse the significance of these various parameters through detailed and comprehensive micro-meteorology in late November, 1969 were thwarted by persistently adverse weather. Insufficient time prevented subsequent attempts to undertake these measurements in the 1969/70 ablation season.

The total gross ablation of 176,300 m^3 was calculated simply by subtracting the net accumulation from the gross accumulation. This quantity, representing 70 percent of the total gross accumulation, was the net loss from the glacier in the 1968/9 budget year as well as being the amount of water which was returned to the atmosphere, either directly through evaporation or indirectly through the process of runoff. According to Müller and Keeler (1969), these processes operate internally as well as on the surface of the névé and this often causes problems in their measurement.

Ablation Processes

1. Runoff

The efficiency with which the process of lateral removal of snow and ice occurred was greatly dependent upon the state of the medium, both in terms of its density and temperature, together with the effectiveness of the various energy transfer mechanisms in initiating melting. From the size of the glacial streams in the height of the accumulation season it appeared that runoff was likely to be one of the most significant ablation processes (see Plate 12). Although no stream gauging measurements have ever been made on these streams, the turbulence was itself sufficient to suggest that the rate of removal of snow and ice, as water, was of quite large proportions. Even in early May of the 1968/9 and 1969/70 seasons, when the depth of accumulation of the respective winters was already greater than 10 cm, a fairly turbulent glacial stream flowed beneath the glacier ice. This stream was fed from melting at the ice/rock interface, together with meltwater which had percolated down through the névé. The existence of caves, zig-zagging downwards to the bedrock in May of both 1968 and 1969, suggested that subsidence of the rather thin remnant of glacier ice probably occurred as a result of fracture under the weight of the overlying névé, as well as through basal

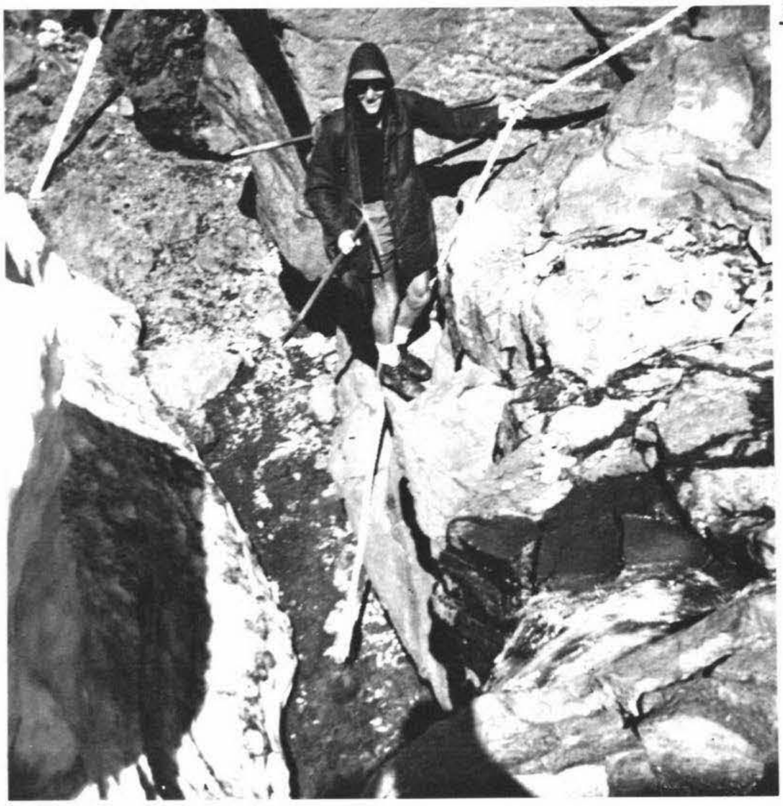


Plate 11. Radiation type troughs or randklufts formed where the terrain is very broken. This particular trough, near the waterfall on the Whakapapanui Stream, resulted initially from melting of the snow lying immediately adjacent to the steep rock faces. As further melting of the snow lying above the waterfall took place, the meltwater percolated down between the ice/rock interface accentuating the lateral melting of the face of the compacted snow.

Plate 12. Waterfall on the Upper Whakapapanui Stream, January 1969. At this level the stream is fed entirely by meltwater from the catchment in and around the Glacier valley. It is obvious that in the height of the ablation season a considerable volume of fast-moving water moves off the mountain eroding areas that were originally believed to have been occupied by the Glacier. This would account for the absence of depositional features marking the limits of glaciation on this side of the mountain.

erosion of the ice by the underground stream. Once it had been weakened, surface meltwater percolated through and enlarged the original breakpoint.

Erosion of new snow or of the less dense névé took place in a somewhat different manner. Rain and hail were particularly noteworthy ablation agents of this material. They played a role which was usually more dramatic than lasting and was most effective when the air temperature was above freezing and at or near dewpoint. Frequently accompanied by strong if not gale-force winds, such conditions were best described as "stormy". On the average they prevailed about five or six times during the winter and frequently about the end of the accumulation season. A classic example which extended from October 8 - 10, 1968 is recorded in Figure 25, showing winter conditions on the Turoa Ski Field. On the first two days a depth of approximately 46 cm of snow was eroded by warm (average air temperature 5°C), heavy rain from north to north-westerly quarters, accompanied by winds of about 30 kts and corn snow. As a result the skiable level was raised from 1,200 m to about 1,300 m. In the following 18 hours there was continuous rain during which over 30 cm of snow was lost, raising the skiable level by a further 70 m to about 1,370 m.

A further examination of Figure 25 suggested that moist north to north-westerly winds were particularly conducive to ablation when the temperature minimum was above freezing point and the diurnal temperature range was in the order of about 3°C. If the temperatures dropped below freezing point during the evening the surface froze, preventing further melting by latent heat of condensation.

2. Wind Erosion

A pre-requisite for erosion by this method is the existence of fairly dry powdery snow which is light and easily transportable. Where such snow fell it did not stay that way for long (see Chapter 1), for it was very soon metamorphosed into a much more dense and less transportable medium. Observations by Park Board personnel showed that snow driven by wind, especially if it was the corn or hard granular type, favoured the downhill erosion of deposited snow and, while actual blizzard conditions, in which this sort of erosion was at its maximum, have lasted up to two days, they occurred only about three or four times in a season. Situated on one of the more exposed parts of Mt Ruapehu, the glacier was likely to have encountered winds of a much greater velocity than any observed at either the Ski Patrol Headquarters or The Chateau Meteorological Station.

It was not surprising that a considerable amount of new snow was lost from the glacier through deflation. While winds commonly reached a velocity of between 60 and 80 kts, steady gales were a rather infrequent phenomenon being recorded about three times per winter.[1] Variable winds were more commonplace and gusts of 30 to 60 kts were quite a regular feature of the climate. The exposed eastern side of the glacial accumulation was continually savaged by both ascending and descending winds with the latter being more dominant, especially since "southerly" winds were much more prevalent. As a consequence deflation was more pronounced on this side and it helped account for the uneven accumulation pattern (see Fig.3a).

3. Mass Wasting

While avalanches are not an unknown feature of Mt Ruapehu, few, if any, have been observed in the immediate vicinity of the Whakapapanui Glacier. This is because (a) the terrain was not sufficiently steep and broken, and (b) metamorphism was much too rapid to have allowed much internal movement of the névé. Slopes in excess of 40° and very rough ground are pre-requisites for even the smallest movement (in der Gand and Zuparĉiĉ, 1966) and, since the terrain surrounding the glacier was generally fairly rounded with even slopes, there was hardly any chance of ablation of this nature. Nevertheless a type of snow gliding did occur just below the present limits of the glacier where the sides of the glacier valley were broken and almost vertical in places. The presence of sickle-shaped crevices in the névé (see Plate 16), which extended to the base rock, were testimony of this type of ablation. These crevices are known as glide cracks and open "as a result of tensile failures during rapid gliding" (in der Gand and Zuparĉiĉ, 1966). They also indicated that not all the meltwater from the glacier finds its way into the glacier stream, for according to the previous authors a "pre-requisite for gliding is a wet snow/earth interface formed by melting, or the intrusion of meltwater flowing along the ground". Thus, while conditions were favourable to the slow creepage of dense névé off the glacier, the movement was imperceptible and it was not thought to have been of much consequence in the overall ablation.

Melting

Quantitatively, melting appeared to be the most significant element in the weathering of snow and ice on the Whakapapanui Glacier. There are four essential parameters involved in melting and the following principles are based on a report by Hoinkes (1964), unless otherwise stated. Figures 9 to 17 show the effects of melting on the snow level of the Mt Ruapehu Ski Fields between 1962 and 1968.

1. Radiative Energy

The effectiveness of the glacier surface in the absorption of solar radiation was influenced by the degree of cloudiness and the albedo of the surface. A frequent comment of National Park Board Rangers, in describing the winter weather conditions on the Whakapapa Ski Field, was "clear skies and visibility unlimited". To give some indication of the frequency with which fine weather occurred during the winter months, a table has been prepared below.

Table IX

Days on which Weather was Described as Fine and/or Clear, 1968

Month	Days on which Fine Weather was Recorded	Monthly Total	Overcast Conditions* No. Days
June	9, 10, 12, 17, 18, 19 (record incomplete)	6	5
July	2, 4, 5, 9, 12-15, 17-21, 26-28	16	8
August	1, 6-11, 14-16, 19-21, 26-28	16	3
September	3, 4, 13, 14, 19, 20, 29, 30	8	5
October	1, 4, 7, 13, 28, 29	6	5
Total		52	26

* Overcast is here used to mean cloudy conditions without rain or snow. Sun often appeared for short periods on such days while snow often accompanied overcast conditions.

Some of the days on which fine weather was recorded were particularly cold so that very little melting would have taken place. This very cold, fine weather, the type that accompanied stable anticyclonic conditions, was recorded on no more than 10 percent of the days with fine weather. Since fine days occurred on 34 percent of the 153 days from

WHAKAPAPA SKI FIELD: WINTER SNOW LEVELS, 1962.

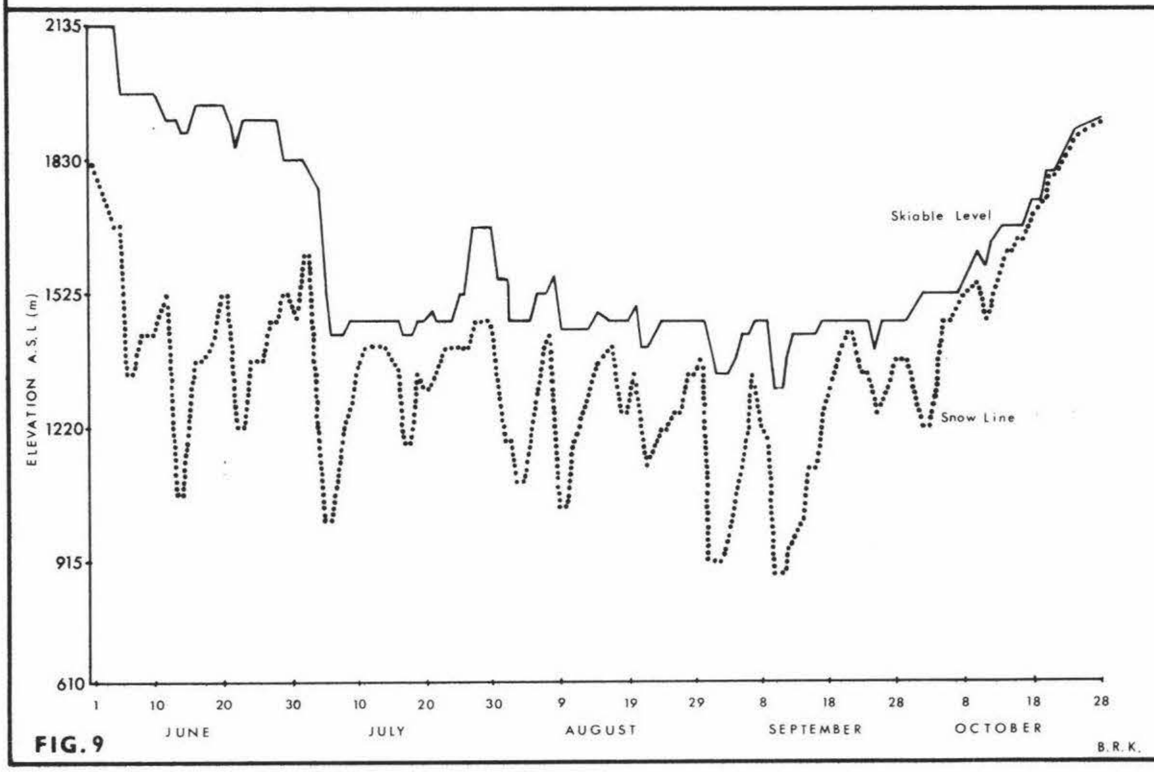


FIG. 9

WHAKAPAPA SKI FIELD: WINTER SNOW LEVELS, 1963.

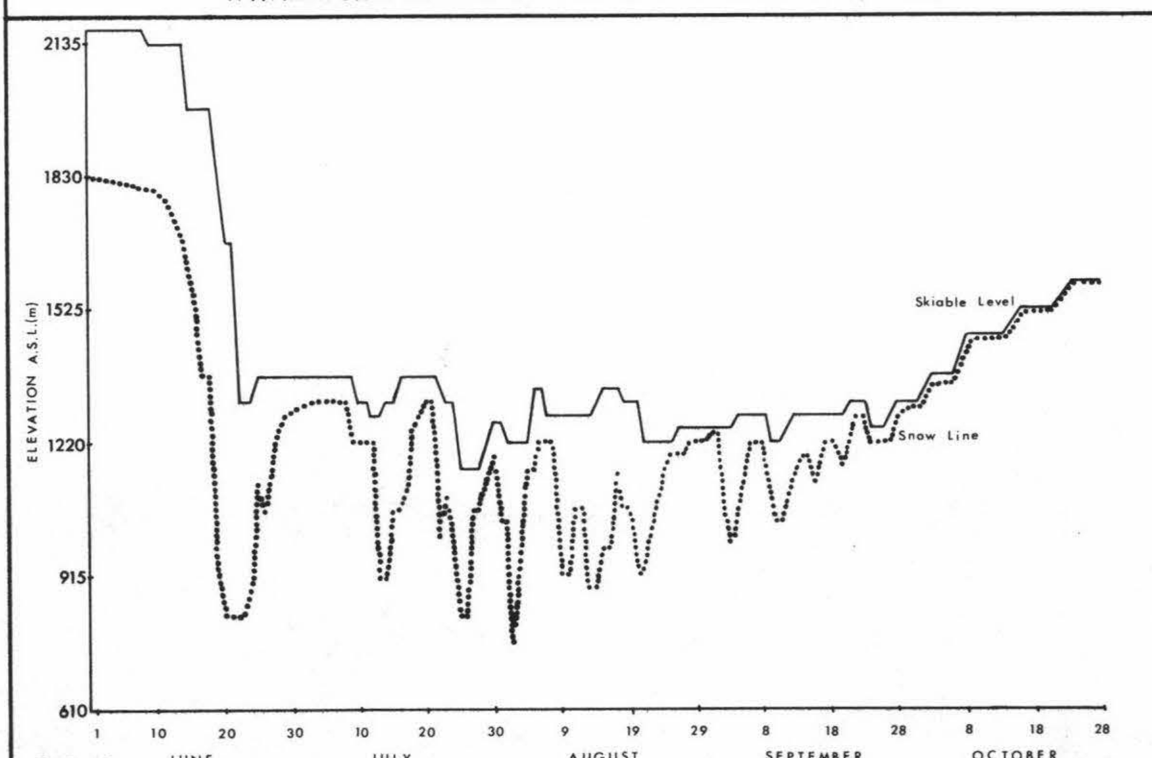


FIG. 10

June to the end of October, the importance of radiation to the melting in winter was readily apparent. On many occasions during which cloudy skies were recorded at the Ski Patrol Headquarters (1,752 m) the skies above the glacier, which lay between 2,273 m and 2,424 m, were cloud free (see Plate 10).

A further 17 percent of these 153 winter days experienced overcast conditions in which the effectiveness of short wave radiation was greatly reduced. However, as the air temperatures remained above freezing point, it was highly probable that the existence of a cloud cover—especially a low-lying cloud "blanket"—prohibited excessive terrestrial radiation and gave rise to a "greenhouse effect" with considerable warming of the air adjacent to the glacier surface. Conditions favourable for melting by radiative energy, as a result of the high prevalence of these conditions, were assumed to exist on no less than 45 percent of the winter days. Radiative energy would have been much more effective for melting in the summer months when the mean air temperatures were all above freezing point (see Table XI). While the amount of solar radiation which was available for melting snow and ice remained highly dependent on the temperature of the air immediately above it, it would also have been affected to some extent by the aspect of the glacier, its latitude and the surface albedo, according to evidence presented by Hoinkes (1964).

Albedo: Gabites (1959) has calculated values for the amount of solar radiation reaching the surface at various southern latitudes. The Whakapapanui Glacier was situated at approximately 40^{o}S and from Gabites' calculations this provided a very generalised solar heating rate of about 60 cals/cm^2/hr. To determine the effectiveness of this energy it was necessary to know the surface albedo (reflectivity). This, of course,

WHAKAPAPA SKI FIELD: WINTER SNOW LEVELS, 1964.

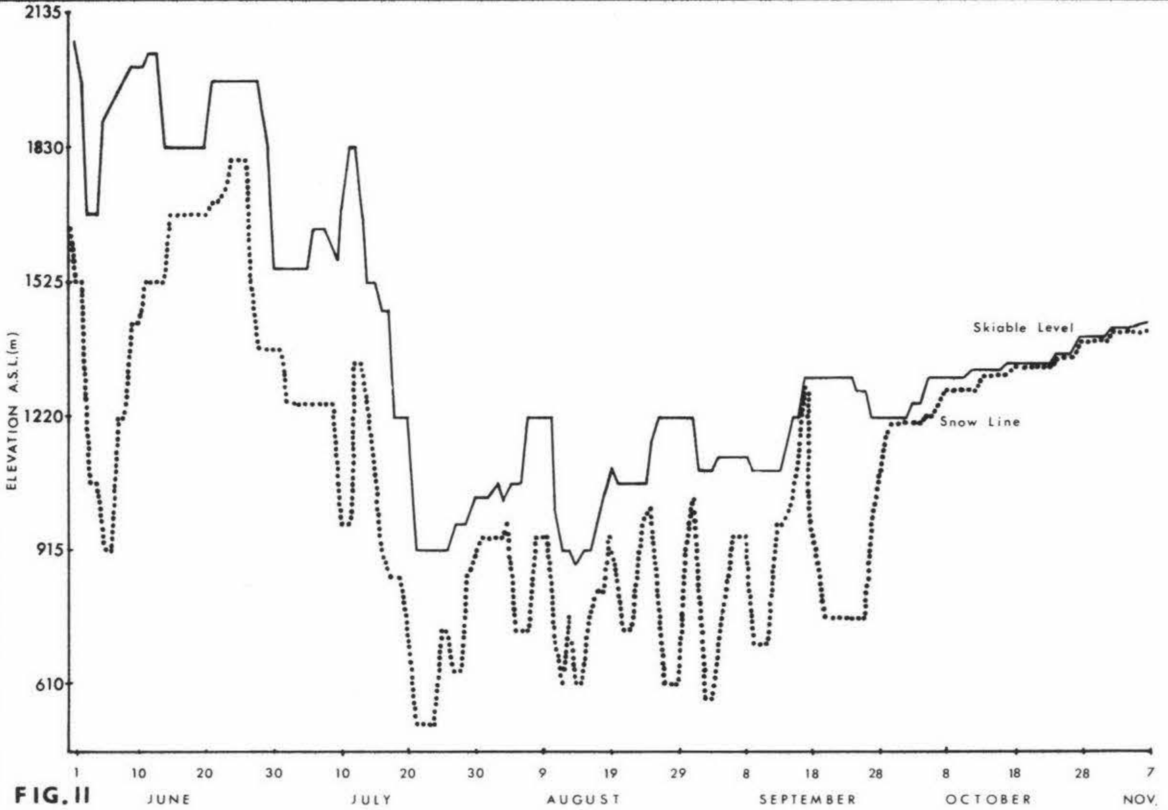


FIG.11

B.R.K.

WHAKAPAPA SKI FIELD: WINTER SNOW LEVELS, 1965.

FIG.12

B.R.K.

varied with the state of the surface (see Plate 11). The albedo of new snow in Antarctica is known to be as high as 93 percent (Hoinkes, 1964), while a dirty surface at the end of the ablation season on the Greenland Ice Cap had a reflectivity of only 36 percent (Hoinkes, 1964). The presence of meltwater on the glacier surface also greatly reduces the albedo and, all other factors excluded, Arai (1966) has demonstrated that, in controlled experiments, "the albedo value increases inversely proportional to the density of the snow". Consequently radiation was likely to have been much more effective at the end of the ablation season than at the beginning. Although there are large variations in albedo with respect to time and locality, in the firn basin of the Fedchenko Glacier the annual albedo averaged 76 percent, which seems to be typical of high snowfields of mountain glaciers (Hoinkes, 1964).

Situated approximately 39°N and 4,900 m above sea level, the Fedchenko Glacier was about 1,300 km from the sea. While the Whakapapanui was only about 104 km from the sea and situated approximately 2,800 m above sea level, it qualified as a high mountain glacier of the temperate latitudes. It was not unreasonable to assume, therefore, that an average albedo value similar to that for the Fedchenko would have existed on the Whakapapanui Glacier. On the basis of Gabites' measurements, this would have meant that approximately 15 cals/cm^2/hr would have been left to supply the outward radiation and to have caused melting on the Whakapapanui Glacier. Furthermore, from Gabites' (1959) figures the actual amount of solar radiation available for melting increased on the average about 2 to 3 cals/cm^2/hr with every 5° rise in temperature from -5°C to 10°C. Although these figures were only very average values subject to great variations, they do show just how many variables had to

WHAKAPAPA SKI FIELD: WINTER SNOW LEVELS, 1966.

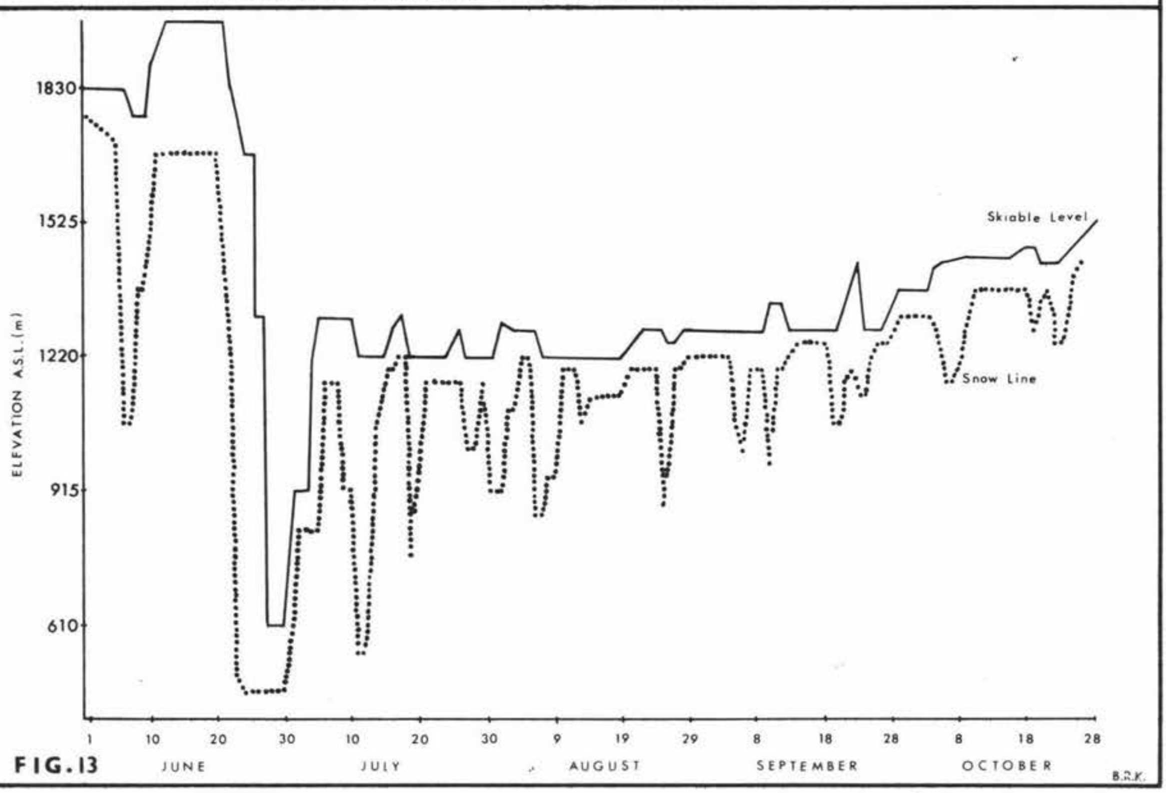


FIG.13

WHAKAPAPA SKI FIELD: WINTER SNOW LEVELS, 1967.

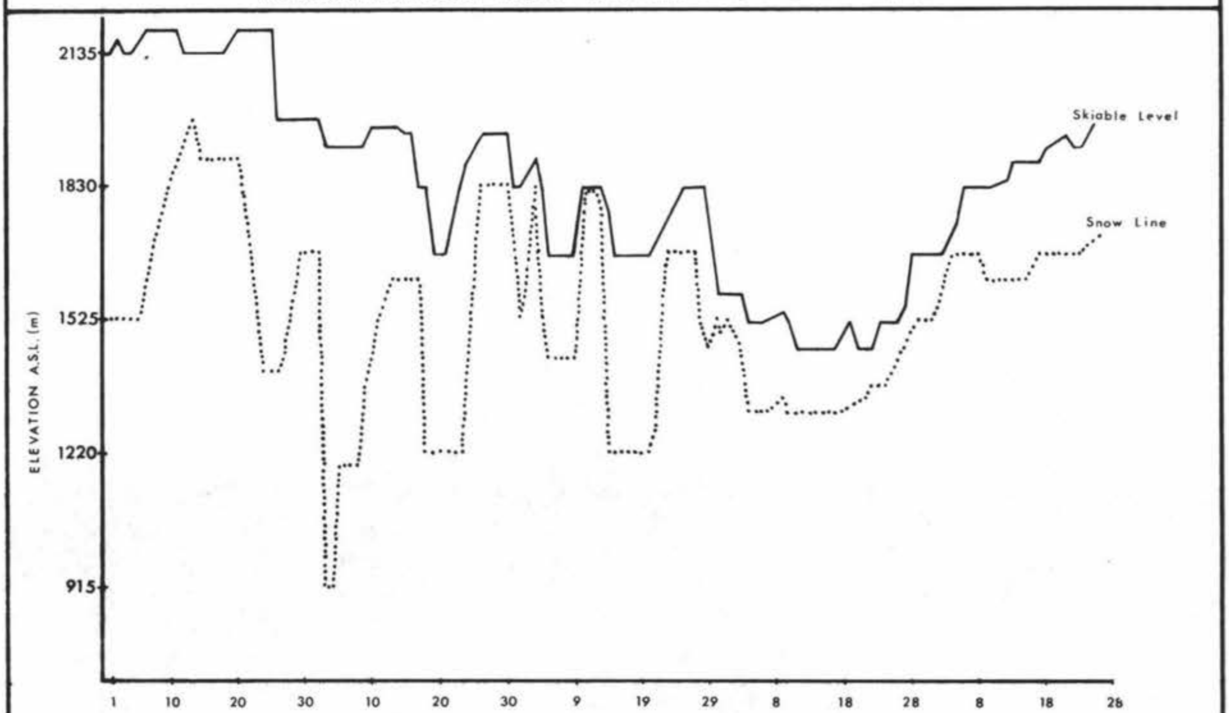


FIG.14

be calculated in order to appreciate the effectiveness of radiation in melting.

Most of the following principles of ablation are based on Hoinkes' (1964) publication and heat balance studies of Sorbreen (Dibben, 1965). Whilst radiation is considered to be important as a source of heat for melting of the snow and ice, it is less important in the heat loss. Despite a considerable amount of nocturnal re-radiation under clear skies, both Hoinkes and Dibben have established that cooling by radiation involves only the upper few centimetres of the névé, whereas short wave insolation usually penetrates to much greater depths. The principal controlling factor in the net radiation of a glacier during the melting season, when radiation from the surface remains fairly constant, is thought to be the albedo.

2. Sensible Heat Transfer

Transfer of thermal energy directly from the overlying air takes place by two principal mechanisms, both of which are dependent upon a reasonably high temperature gradient and a considerable wind speed.

(a) Conduction. This process is often referred to as turbulent heat transfer (Shumskii et al., 1964) when there is strong advection, or eddy conduction when characterised by perturbation. Conduction usually operates most successfully when there is a warm overriding airstream which is not too close to dewpoint. The northerly airstreams best fulfil these conditions for, having blown across the land for approximately 100 km, they are generally drier than the westerly airstreams. Molecular diffusion of warm air down into the névé is greatly accelerated by atmospheric turbulence which removes the chilled stable air and replaces it with a

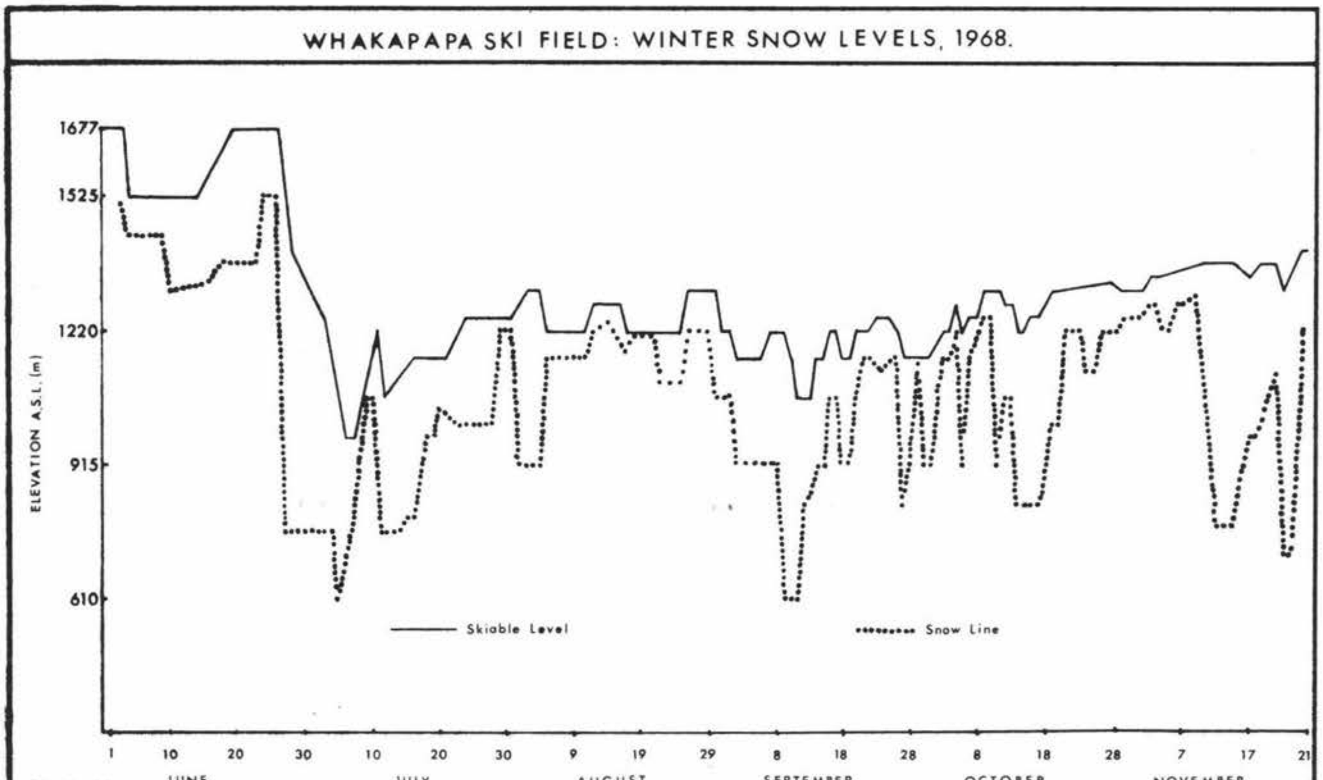

WHAKAPAPA SKI FIELD: WINTER SNOW LEVELS, 1968.
ELEVATION A.S.L. (m)
1677
1525
1220
915
610
Skiable Level
Snow Line
1
10
20
30
10
20
30
9
19
29
8
18
28
8
18
28
7
17
21
JUNE
JULY
AUGUST
SEPTEMBER
OCTOBER
NOVEMBER
B.R.K.

FIG. 16

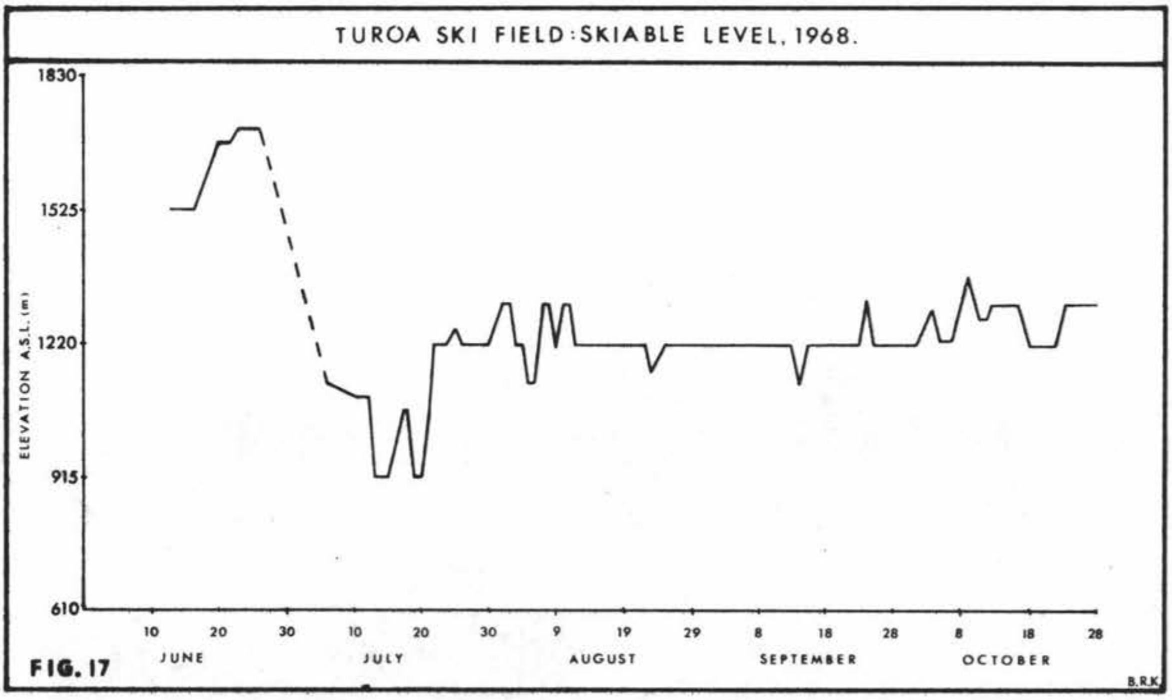

TUROA SKI FIELD: SKIABLE LEVEL, 1968.
ELEVATION A.S.L. (m)
1830
1525
1220
915
610
10
20
30
10
20
30
9
19
29
8
18
28
8
18
28
JUNE
JULY
AUGUST
SEPTEMBER
OCTOBER
B.R.K.

FIG. 17

supply of warmer air. It was only in the winter, when there was sufficient cold wave penetration to give rise to a temperature gradient within the névé, that this process was found to be effective on the Whakapapanui for, in the spring and summer, the névé was isothermal (see Tables V to VIII) preventing the transfer of energy by conduction.

(b) Convection. Once again high winds are an essential pre-requisite, but this process is also greatly dependent on the permeability of the snow to air. In Chapter 2 it was established that only in the true accumulation season, when the diffusivity of the névé was quite high, was there likely to be an effective transfer of heat from the air to the glacier ice. Even then, according to evidence from Hoinkes (1964), it is dependent on above freezing temperatures for, when the free air is several degrees below freezing, convection tends to cool the snow and prevent the solar heat which is not reflected from being used in melting. This combination of conditions favourable for convective melting was usually confined to brief periods on the glacier in winter, before the metamorphosis of new snow had proceeded very far. The existence of inverse temperature gradients in the ambient air above the glacier surface acted to retard convection (see Table VI).

Convective transfer of energy, on the other hand, appeared to be an important source of heat loss during the evenings as indicated by the persistently frozen surfaces on winter mornings. These frosty surfaces were thought to have arisen when the air above the glacier cooled very rapidly under cloudless night skies. Outward transfer of energy must have set up strong temperature gradients at the snow/air interface (see Tables V to VIII) leading to the sublimation and deposition of ice crystals on the surface.

3. Latent Heat of Fusion

This is heat released when there is a change of state, from either a vapour to a liquid or a liquid to a solid. Consequently, latent energy is a source of considerable heat in the accumulation season, when there is a large build-up of snow and ice. After the winter chill has dissipated, however, a temperate glacier serves as a heat sink absorbing latent heat from its environment without any appreciable change in temperature. Much of this heat is used in the melt of snow and ice.

Condensation was probably the most significant supplier of latent heat. The tropical maritime airstreams from the north-east, east and north-west, with dewpoints of between 18° and 24°C (Shields, 1965), would have had a much greater specific heat than dry polar maritime airstreams from the south and hence have a much greater melting capacity. The general mechanism considered to apply under these conditions is that when the airstreams come in contact with the cold glacier surface, they are often chilled to dewpoint so that the water vapour condenses on to the surface, with a concomitant release of latent heat. La Chapelle (1959) has calculated that for every gram of water condensed on to the surface, 600 cals of energy is liberated, sufficient, in fact, to melt 7.5 gm of ice or snow at 0°C. This process was prolonged when atmospheric turbulence renewed the supply of moist air to the glacier surface.

Rain is a much less effective method of energy transfer, especially when it falls on to an isothermal snowpack, for the absence of the freezing process means there is very little release of latent heat. In fact at 10°C rain has a heat content sufficient only to melt about 3 mm of ice. By the same token the contribution of evaporation to the energy transfer is only very slight, for it requires 680 cals of energy to evaporate 1 gm of ice at $0^{o}C$, compared with only 80 cals needed to melt the same amount (La Chapelle, 1959a). Only when the relative humidity of air is so low that when in contact with the snow it does not reach dew-point, is there any significant evaporation. Even in Greenland, where it is proportionately a most significant factor in the ablation, it accounts for only 2.5 percent of the wastage.

Relative Significance of Heat Transfer Mechanisms

The effectiveness of the two heat transfer mechanisms decreased with increasing altitude (due to the temperature lapse rate) and with continentality. This limits the role of these components since the ocean is the source of warmth and moisture. The importance of net radiation, however, increases with altitude and latitude. The same can be said of evaporation, while there is general agreement with Ahlmann's statement of 1953, that "the greater the elevation the greater the reduction in convection and condensation in contributing toward ablation". Consequently, in summer the radiative transfers should be the most effective on the Whakapapanui Glacier with its high elevation (above 2,273 m), temperate latitude ($39^{o}17$'S) and inland location (104 km from the sea).

The pattern of ablation on the glacier appeared to emphasise the radiation fluctuations associated with significant variations in the albedo of the névé surface (see Plates 13 and 14). For example, ablation was more effective on the eastern margins of the glacier where the dirt deposition (and absorption of solar radiation) was much more prevalent compared with the western peripheral zones. The eastern valley sides were composed of unconsolidated material which was readily transported by runoff from melting snow and rain wash. The asymmetrical valley profile

Photo: L.O. Krenek

Plate 13. The Upper Whakapapanui Glacier, Easter 1956. The terraced-like surface is a result of differential ablation caused by the appearance of volcanic ash which was deposited during an earlier eruption of Mt Ruapehu in 1945, and possibly even from eruptions of Mt Ngauruhoe in 1949 and 1954. In most places this ash layer appears to have been less than the critical thickness of three decimeters so that the ablation has been accelerated on most of the ash-covered portions, giving rise to troughs between the uncovered ridges. Cones have formed where the layer of ash exceeded the critical depth of three decimeters and has acted instead as a protective cap reducing the amount of ablation through radiation.

Plate 14. A dirt cone on the Whakapapanui Glacier, March 1969. Much larger than the cones shown in Plate 13, this dirt cone is believed to be of fluvial origin. It probably formed as a result of water-borne debris percolating down a meltwater hole in the gross accumulation surface, and then refreezing with the debris still in suspension. As some of this frozen mound has melted it has washed away some of the debris which has been deposited lower down on the Glacier in an uneven manner. This has led to a ridge-and-depression topography as a result of the differential albedo of the surface.

Plate 15. A close-up view of the dirt cone shown in Plate 14. The dirt covering has been scraped off in places exposing the ice.

Plate 16. Glide cracks below the Glacier snout, January 1969. These sickle-shaped crevices in the snow cover result from tensile failures during downhill gliding of the entire snow cover. Gliding can only take place where there is a wet basal layer of snow, but the movement is generally imperceptible. Once the cracks have formed, the intrusion of meltwater makes them an avalanche danger. Most of these cracks appear where the underlying terrain is broken and very uneven, which is presently below the limits of the Glacier.

tended to concentrate the runoff over the eastern periphery of the glacier, which was subsequently covered with a layer of debris early in the ablation season. When the dirt deposition was less than 3 decimetres thick, the surface albedo was reduced considerably and more insolation was absorbed from the névé than on the debris-free surface (see Plate 14). It should be noted (Plate 15) that when the debris cover exceeded this critical thickness, it acted as an insulator and reduced the amount of insolation absorbed by the névé surface. The volcanic eruption of June 22, 1969 caused a thick layer of mud and ash to be deposited on the centre of the glacier from the uppermost reaches to the snout, as part of the 1969 gross accumulation. However, it could be exposed by ablation in the 1969/70 summer season and, because of its thickness (see Plate 9), would insulate the central reaches and retard ablation. A subsequent visit to the glacier in March 1970 showed that a ridge of névé with a protective mud capping developed on the centre of the glacier, while the dust coating on the peripheral areas was thin enough to accelerate ablation. The discharge of meltwater transported some of the mud off the glacier surface but not before the differential ablation rate had operated for some time.

The varying dirt deposition over the glacier surface influenced the transfer of radiative energy on the eastern margins and this was reflected in the micro ridge-depression topography over the glacier surface. The crests were 60 cm higher than the floor of the depressions and represented parts of the glacier where the dirt insulated the underlying névé. In comparison, the western periphery was comparatively free of debris and the glacier surface was more uniform.

Footnote

1. These figures were based on an analysis of the last seven years of the winter weather reports for the Whakapapa Ski Field, prepared by the Tongariro National Park Board.

CHAPTER 4

NET BUDGETS

While the major consideration of this thesis has been the hydrological or mass budget, because of the relationship between mass and energy the energy budget will also be calculated.

Energy Budget

Most of the energy transfer on the Whakapapanui Glacier was of thermal origin in that it came from extra-terrestrial sources, the sun and the troposphere. Such energy exchange took place at the surface of the glacier by the mediums of long and short wave and terrestrial radiation. Another possible source could have been kinetic energy resulting from movement of the glacier along the basal rock (frictional energy) or from expansion or contraction of the periphery of the glacier.
La Chapelle (1959) recognised the existence of such an energy supply on the Blue Glacier in Washington. Generated from below this was said to be a source of terrestrial energy. Since the Whakapapanui Glacier had remained in a fairly stagnant state for some years, this kind of energy was not likely to have been of much significance in the overall energy budget. Although the glacier was in a potentially active state at the end of the 1968/9 season with its strong positive budget, a negative budget in 1969/70 completely nullified any movement in this year.
Potential energy which resulted from the glacier's position on the side of Mt Ruapehu was likely to have been of some consequence in the heat loss for it was propagated through water. Since meltwater runoff was quite considerable, potential energy was likely to have amounted to the second most important heat source. A weather screen (see Plate 17) was

Plate 17. Meteorological Station at altitude 2,362 m on the ridge to the west of the Whakapapanui Glacier. The screen does not conform to the standard design of the Stevenson Screen, there being less ventilation in this home-made version, and consequently the temperatures on the average were about 1°C higher, the difference varying according to a graduated scale. Without air transport to carry in standard equipment, however, it was necessary to build a screen of proportions which would make it easily transportable in a car and easily carried on one's shoulders, whilst maintaining most of the qualities of the Stevenson Screen. It is impossible to maintain a permanent meteorological station directly on the Glacier because of the tremendous depth of accumulation in the winter.

installed to aid in the measurement of the heat budget (micro-meteorology), but unsatisfactory operational logistics thwarted this attempt.

These conclusions point to the fact that the energy gain of a glacier was related to the change of state of water during the ablation season. While the accumulation season led to an energy deficit the ablation season, with reduced albedo, led to an energy gain. Like the mass budget the net budget greatly depended on the net loss or gain of energy during the ablation season. On this basis the 1968/9 heat budget has been calculated.

The equation for calculating the heat budget from the mass budget is shown below:

$$\Delta E = -k\Delta m \text{ (La Chapelle, 1959a)}$$

where k, the heat of fusion, is a constant 80 cals of energy.

From this equation, where the specific gross mass accumulation equalled 6.79 m of water, the mean specific energy loss for the 1968/9 budget year was:

$$\begin{aligned}\Delta E &= -679 \text{ g/cm}^2 \times 80 \text{ cals/gm} \\ &= -5.43 \times 10^4 \text{ cals.}\end{aligned}$$

By the same token the specific mass ablation equalled 4.71 m of water and the mean specific energy gain was:

$$\begin{aligned}\Delta E &= 471 \text{ g/cm}^2 \times 80 \text{ cals/gm} \\ &= 3.76 \times 10^4 \text{ cals/cm}^2.\end{aligned}$$

As a consequence there was a total energy deficit for the year of

$$3.76 \times 10^4 \text{ cals/cm}^2 - (-5.43 \times 10^4 \text{ cals/gm}^2)$$

$$= -1.66 \times 10^4 \text{ cals/gm}^2.$$

This gave a total energy budget for the 1968/9 year of

1.66 x area of glacier

$$= 1.66 \text{ cals/cm}^2 \times 37{,}275 \text{ m}^2$$
$$= \underline{-6.2 \times 10^2 \text{ cals}}.$$

Hydrological Net Budget (Mass Budget)

In the 1968/9 hydrological year on the Whakapapanui Glacier there was a net accumulation of 76,800 m^3 water. This figure also represented the net budget of the glacier since it was the amount of water remaining on the glacier immediately prior to the 1969/70 accumulation season. The net ablation, on the other hand, was the estimated total of 176,300 m^3 water. This quantity was not measured—it was simply calculated as the difference between the gross accumulation total of 253,000 m^3 water and the net accumulation quantity of 76,800 m^3 water.

A positive budget therefore characterised the glacier for the budget year under review, and this was the first significant net gain of material in at least 15 years. With an energy deficit of 6.2×10^{12} cals for the 1968/9 budget year and a net gain of 76,800 m^3 water, this meant, therefore, that for every cubic metre net gain of water by the glacier there had been an average heat loss to the atmosphere of approximately 1.2×10^9 cals.

Conclusion

As Meier (1965) has concluded, it is because glaciers and climate are essentially consequences of energy and mass exchanges between the surface and the atmosphere that there is a definite relationship between the two. That they are not related in a simple cause and effect manner on the Whakapapanui Glacier appeared to be the result of other considerations such as relief and the state of the glacier itself, for these factors in determining the supply of non-thermal energy introduced other variables into the climate/glacier relationship.

PART III

NORMALITY OF 1968/9 BUDGET YEAR

Normality of the Whakapapanui Glacier 1968/9, in Terms of Glacier Behaviour

Statistical Normality of the 1968/9 Climatic Year

Trends and Tendencies

CHAPTER 1

NORMALITY OF THE WHAKAPAPANUI GLACIER, 1968/9, IN TERMS OF GLACIER BEHAVIOUR

In order to compare the 1968/9 budget with past trends of glacial behaviour on Mt Ruapehu, it is convenient, at this stage, to examine the glacier largely from the point of view of its temporal characteristics leaving detailed consideration of its relation to the wider spatial pattern for a later chapter.

Glacial Periods

While it is generally agreed (Gage, 1965) that New Zealand has experienced at least four and possibly six major glacial periods distributed throughout the Pleistocene period, the maximum glaciation was thought to have occurred in the early or mid-Pleistocene, while "the last three glaciations (Porika, Waimaunga and Otira successively) were without doubt major events" (Gage and Suggate, 1958). These glacial periods were held to be in fairly close agreement with similar events in other countries, in fact Gage (1965) goes so far as to say that "examples of sequences from different geographical situations show a generally accordant pattern of glacial events, regardless of correlation, throughout most or all of the Pleistocene". The same author recognises, however, that the general accordance of glacial sequences throughout the world does not necessarily imply that climatic variations were in fact synchronous, but believes instead that such a condition was only likely to have occurred "for a small fraction of late Pleistocene time" (Gage, 1965). This meant, in effect, that the Otiran Glaciation was likely to have occurred between 37,000 and 32,000 years ago with renewed advances possibly as late as 14,500 years ago (Fair, 1968) over all New Zealand, with similar occurrences throughout the world. Since the synchronous climatic variations applied equally as well to the inter-glacial periods of climatic optimum conditions, the practice of drawing on world-wide examples to substantiate evidence of glacial variations in New Zealand between 30,000 and 10,000 years ago, did not therefore violate any established principles of glacial chronology. In the last 10,000 years, however, we can at best draw only on other examples in the Southern Hemisphere to substantiate local glacier variations.

According to O'Shea (1954) the present glaciers on Mt Ruapehu may have formed as a result of an "ice age" some 4,000 years ago. Several other writers have attempted to assess the onset of this last "ice age". In the United States botanical methods are being used extensively to assess its approximate limits. One method utilises the approximate time taken for certain plant species to re-establish themselves after an ice age and, from the growth rings in the trunks of some species and the life cycles of others, it is possible to determine the limits of the various ice ages. A botanist at Canterbury University, Dr C. Burrows, has employed the technique of lichen-dating, in which the maximum diameters of the lichen thalli which encrust rocks, are measured, and from it has been able to set the limits of the ice ages in the Canterbury region. On the whole he has found local evidence to support Gage's postulation and from these he estimated that the oldest glacier advance, one of considerable magnitude and extent, ended about 15,000 years before the present (B.P.). Subsequent advances have apparently not always manifested themselves in the same way with considerable variations in glaciers lying in close proximity to one another, for example the

Mueller and Tasman Glaciers which are only four miles apart have not always displayed synchronous behaviour. Differing aspects may reinforce trends on one glacier and mitigate the same trends on another, in which case it was quite possible that the glaciers on Mt Ruapehu have not always displayed like behaviour. Burrows (pers. comm.) believes that another advance took place about 9,520 years B.P. with likely further advances at about 2,000 year intervals until approximately 2,000 years B.P. Much more precise and accurate evidence is available for the last 2,000 years.

Moraines near the Cameron Glacier in Canterbury have been lichen-dated at 1580, 1645 and 1670 years A.D. respectively (pers. comm.) whilst outwash moraine was C^{14} dated at 1413 A.D. A further minor advance has been lichen-dated at 1750 A.D. whilst even more recent advances recorded in historical records and substantiated by lichen-dating have been set at 1750, 1890 and 1920 A.D. respectively.

Age of Glaciers on Mt Ruapehu

It seems then that the minor advances in the last 1,000 to 300 years have been both irregular and localised with considerable disharmony in both range and extent. This makes it very difficult to postulate from one area to another without first having undertaken some amount of field study in the area concerned. Nevertheless, in a conservative estimate, Burrows maintains that the ice in the Whakapapanui Glacier "would be no older than a few hundred years" (pers. comm.) which is considerably within O'Shea's estimate. Attempts to confirm these dates, through the technique of radio-carbon dating of ash debris samples extracted from the ice/rock interface of the Whakapapanui Glacier, have proved unsuccessful since the samples contained insufficient carbonaceous material, but consisted largely of andesitic ash.

Other Methods of Glacier Dating

Another recent investigator in this field is D.B. Lawrence. In a paper entitled "Recent Variations in Glaciers and Closed-Basin Lakes, Indicators of Climatic Change" (1969), Lawrence attempted to establish a relationship between the levels of closed-basin lakes (for example Lakes Rotomahana, Rotorua and Rotoiti) and glacier behaviour. From the results he postulated the approximate times of the major climatic changes in New Zealand. In his studies to date, the author has established that the lakes in the Rotorua area rose to drown Maori villages on their shores some time between 1715 and 1790 A.D. concurrently with the growth of glaciers to maximum size in the South Island of New Zealand. This method implies that the lowering of closed-basin lakes and glacier advances are similar consequences of a common cause; namely, energy and mass exchange between the atmosphere and the surface. Being more sensitive to changes in the precipitation/evaporation regime, the responses of closed-basin lakes to climatic changes are likely to precede the response of glaciers and hence may act as indicators of subsequent changes in glaciers.

Through dendrochronological studies in the South Island, supported by similar studies on the glaciers in the southern Andes of South America, Lawrence has set the limits of maximum glacier advance in New Zealand between 1600 and 1750 A.D. In the succeeding two centuries, however, the glaciers were characterised by drastic recession (as was the case in the Northern Hemisphere). It is only since the late nineteenth century, however, that anything has been written about the glaciers of

Mt Ruapehu in particular. Friedlander (1898), writing on the formation of Mt Ruapehu's summit, described it as "a vast oblong almost level plain covered with névé". This would tend to suggest that the summit was covered by névé throughout the year, although he gives no evidence to support this statement. On the basis of this assumption it seems likely that the firn line at the end of the nineteenth century was below the summit of the mountain (2,796 m). Not until the 1950s was further material written on the state of Mt Ruapehu's glaciers.

Behaviour of Glaciers on Mt Ruapehu

In describing the Tangiwai disaster of Christmas eve, 1953, O'Shea (1954) referred to the Whakapapanui Glacier as "a remnant of the Whakapapa Glacier, one of the six original glacier tongues which extended from the ice field". This was the first evidence to suggest that glacier melt had taken place on Mt Ruapehu. Krenek (1959), writing on the condition of the glaciers on Mt Ruapehu in 1955, was the first to establish any trends in glacier behaviour. Between 1941 and 1954 he was able to measure the retreat of the Whangaehu Glacier as approximately 120 m with a consequent loss in area of about 7.2 acres (1.8 ha.). On all the glaciers except the Whakapapa, morainic evidence was apparent, suggesting that all five glaciers had retreated considerably from their original extent (Krenek, 1959). This evidence was particularly noticeable on the Mangaehuehu, the southern facing glacier, while on the others it was apparent to a lesser extent. Krenek attributed this complete lack of moraine along the Whakapapa Glacier to its somewhat irregular basin shape. Unlike the normal glacier valley, this valley was asymmetrical with only the rim of the crater to mark its eastern edge and rather low walls forming its western extremity (see Plate 27). Only near what was thought to have been its original terminus were there obstructions of sufficient magnitude to have allowed the formation of terminal moraine, which must since have been obliterated by the runoff and glacier meltwater stream.

By comparing the morainic evidence on Mt Ruapehu with similar evidence in South Island glacier basins, Krenek believed that the moraines on Mt Ruapehu were probably formed as early as the mid-eighteenth or as late as the end of the nineteenth century, the actual time being conditional upon the individual glacier fluctuations. Whilst the rate of recession of the individual glaciers had obviously varied considerably (Krenek, 1959), they had all suffered some recession (see Plate 21) though to varying extents, and it appeared likely that this trend continued right up until the mid-1930s. Since then there has been much more reliable evidence, documenting the rate of retreat of the individual glaciers (see Plate 18) and, in particular, the Whakapapa Glacier since it was the most accessible of all the glaciers.

In the 25 years from the early 1930s up until the mid-1950s, the Whakapapa Glacier "was more or less stationary.... There were minor fluctuations but no major retreat up to 1955." (Krenek, 1959) It appears that 1955 marked the turning point in the behaviour of the Whakapapa Glacier, since its initial recession in the nineteenth and early twentieth centuries (see Plates 19 and 20). Since 1952 the measurement of the rate of recession has been carried out by Krenek, from 1954 to 1958, and Heine, from 1960. Whilst both writers initially based their observations on successive photographs taken each year from fixed rock cairns, they have subsequently supplemented these records with

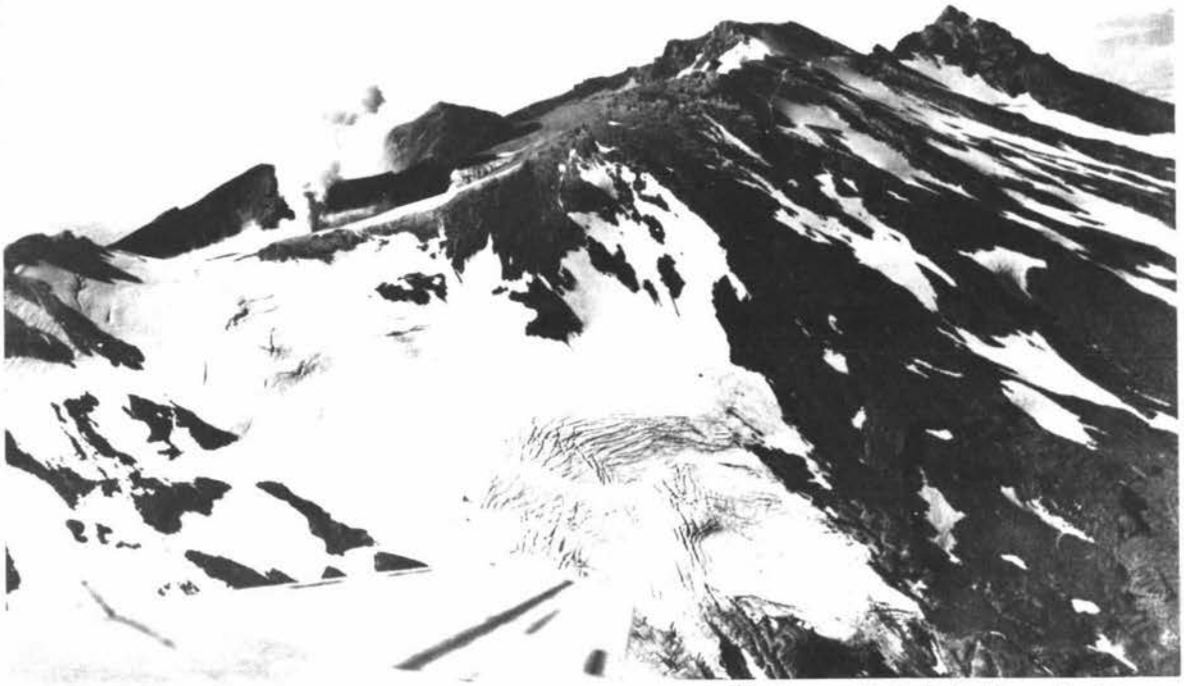


Photo: R.N.Z.A.F., Ohakea

Plate 18. Aerial view of the Wahianoa Glacier on the south-easterly slopes of Mt Ruapehu, 1947. This Glacier, like the glaciers on the south-facing slopes, has in general a much steeper surface gradient than those on the northern slopes. Clinging almost tenaciously to the rim of the Crater Lake, shown emitting steam almost two years after the 1945 eruption, the Wahianoa Glacier displays a very crevassed surface which usually indicates motion of either an advancing or recessional nature. It is impossible to establish which of these conditions the Glacier displays, however, without instrumental measurements. Thus isolated photographs such as this, unaccompanied by actual measurements, cannot on their own be used to support theories of advance or retreat. Nevertheless, the extensively crevassed surface not only at the snout but over most of the surface is probably a result of a period of shrinkage prior to and perhaps during the year in which the photo was taken.

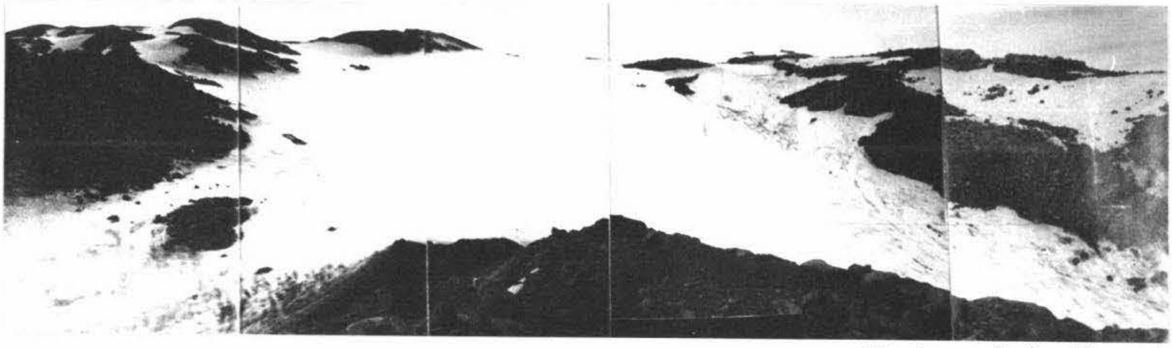


Photo: L.O. Krenek

Plate 19. The eastern section of the Whakapapa Glacier (now the Whakapapanui), Summer 1954, showing The Knoll in the middle foreground. It is at this point that the bifurcation of the lower terminus of the Glacier takes place. An examination of the morphology of the area indicates that the western arm probably extended originally down as far as Delta Corner where it in turn branched, with one fork veering west down what is now the upper Waikare Stream, while the other fork followed the present course of the upper Whakapapanui Stream down beyond The Gut. Both these extensions of the western arm are believed to have extended at least as far down as the present waterfalls (1,985 m and 1,906 m respectively) on the two streams and it seems quite likely that ice falls may have allowed the extension of the glacier ice down into The Amphitheatre on one side and on to an area now known to skiers as "The Staircase" on the other. Meanwhile the eastern arm which branched off from the main trunk at The Knoll is likely to have continued only a short distance before ending in a steep drop into Te Heu Heu Valley.

Photo: L.O. Krenek

Plate 20. The Lower Whakapapa Glacier, March 1955, after a particularly severe ablation season in which the Glacier shrunk, lengthwise, by over 200 m. A close examination of the snout shows that the glacier ice is quite thick, though randklufts are already apparent along the western margin.

measurements of a more empirical nature.

Measurements from rock cairns revealed that the snout of the Whakapapanui Glacier was relatively stationary from 1952-54 with possibly an overall advance of 2 m. In 1955 when the glacier was a little over 1.7 km long it experienced recession of quite fantastic proportions. By the end of the 1954/5 budget year the snout of the glacier had receded 94 m, leaving the glacier only 1.52 km in length on March 9, 1955 (see Plate 22). In 1955/6 and 1956/7, with recessions of 65 m and 6 m respectively, the glacier had shrunk by quite a considerable amount. Length, however, is only one dimension and Krenek showed that reductions in areal extent and thickness of the glacial ice were even more remarkable. Shrinkage in width was evidenced by the "wide randklufts (radiation troughs)" (Krenek, 1959) separating the margins of the glacier ice from the rock shoulders on either side (see Plate 20). Vertical downwasting in 1954/5 alone was equivalent to about 10 m over the entire glacier surface which is equal in magnitude to "16 years of downwasting in the European Alps" (Krenek, 1959). It was quite clear from the very crevassed nature of its surface that the Whakapapa Glacier was no longer being fed from the permanent ice field surrounding the Crater Lake and that it was instead rapidly becoming a "cut-off" lobe of ice.

In 1955 aerial photographs of the Whakapapa Glacier revealed that it had been split into two distinct parts: the eastern portion or Whakapapanui and the western portion or Whakapapaiti (see Plate 22). Although these were originally misnomers (see Plate 19) with the Whakapapaiti being the larger of the two, the names have subsequently proven to be most appropriate for the Whakapapaiti is now reputedly the smaller of the two. Both, however, are regarded as "dead ice" in that they are

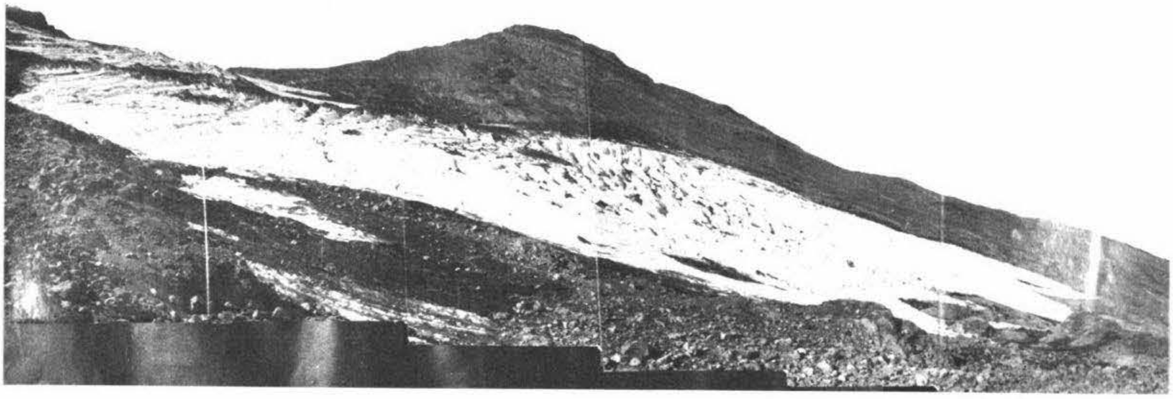


Photo: L.O. Krenek

Plate 21. The Mangaturuturu Glacier on the western slopes of Mt Ruapehu. Taken in 1955, the photo shows a considerably crevassed surface which suggests that this Glacier, like the Whakapapa, was in a state of shrinkage at this time.

Plate 22. The Whakapapanui Glacier, March 9, 1955, showing the divide (the northern extremity of Restful Rocks) which separates this Glacier from the Whakapapaiti to the west. The terraced-like appearance of the snout is indicative of upward recession.

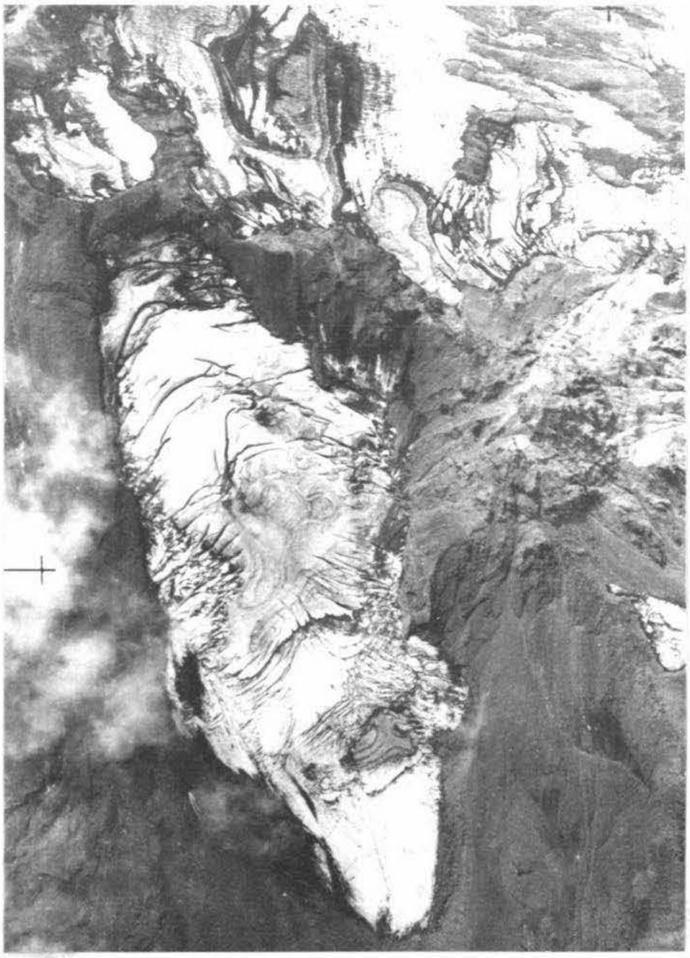


Photo: Dept. Lands and Survey

no longer being fed from the permanent ice field. Whilst the separation arose as the result of the areal recession of both lobes, the Whakapapaiti resulted principally from recession of the glacier terminus up the mountain, while the Whakapapanui resulted from corresponding recession of the upper extremities, downslope. This rather curious phenomenon was noted by Krenek (1959) and confirmed by Odell (1955) as early as 1954. However, neither of these authors was able to measure the rate of recession downhill by the Whakapapanui. Assuming that both upward and downward recession of the snout were resultant only upon glacier downwasting, then they were likely to have taken place at comparable rates. Available evidence (Krenek, 1959) indicates, however, that this recession consequent upon downwasting may have been complemented by marginal erosion, as a result of meltwater runoff, similar in fact to that which took place on the upper extremities of the Whakapapaiti.

The intensity of glacier downwasting in the 1954/5 ablation season was further evidenced by the appearance of "dirt cones" (small snow domes left projecting above the surrounding snow surface as a result of a protective dirt cap) as early as February, 1955 (see Plate 13). The dirt forming these cones was believed to have been part of an ash layer deposited on the glacier during the 1945 eruption of Mt Ruapehu (Krenek, 1959), possibly even augmented by the 1949 and 1954 eruptions of Mt Ngauruhoe. This further illustrated that between 1945 and 1955 some of the névé falling on the glacier must have remained to have become firn or even glacial ice, so preserving the volcanic ash. Moreover it indicated that the wave of recession inaugurated in 1954/5, and continuing through into the 1960s, was initiated by climatic optimum conditions, favourable to glacier recession (see Plates 23 to 25). By

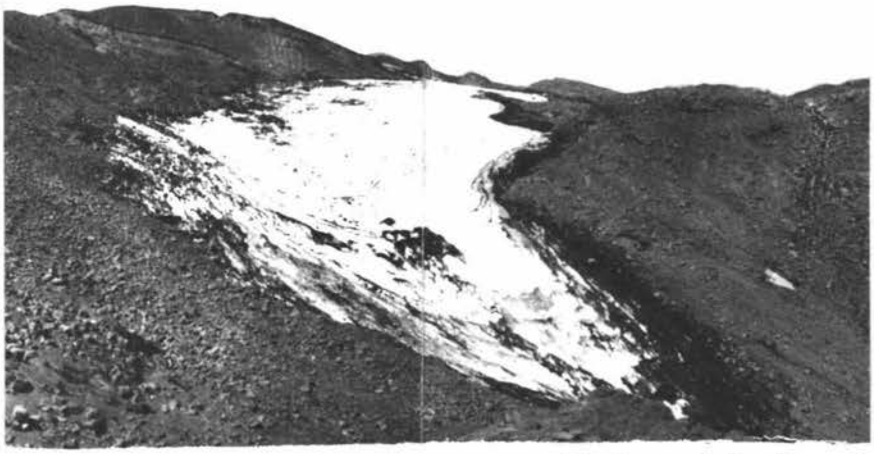


Photo: L.O. Krenek

Plate 23. The Whakapapanui Glacier, Easter 1956. Whilst the Glacier has not receded a great deal during the 1956 ablation season, downwasting had certainly been taking place, as evidenced by the emergence of several rock outcrops.

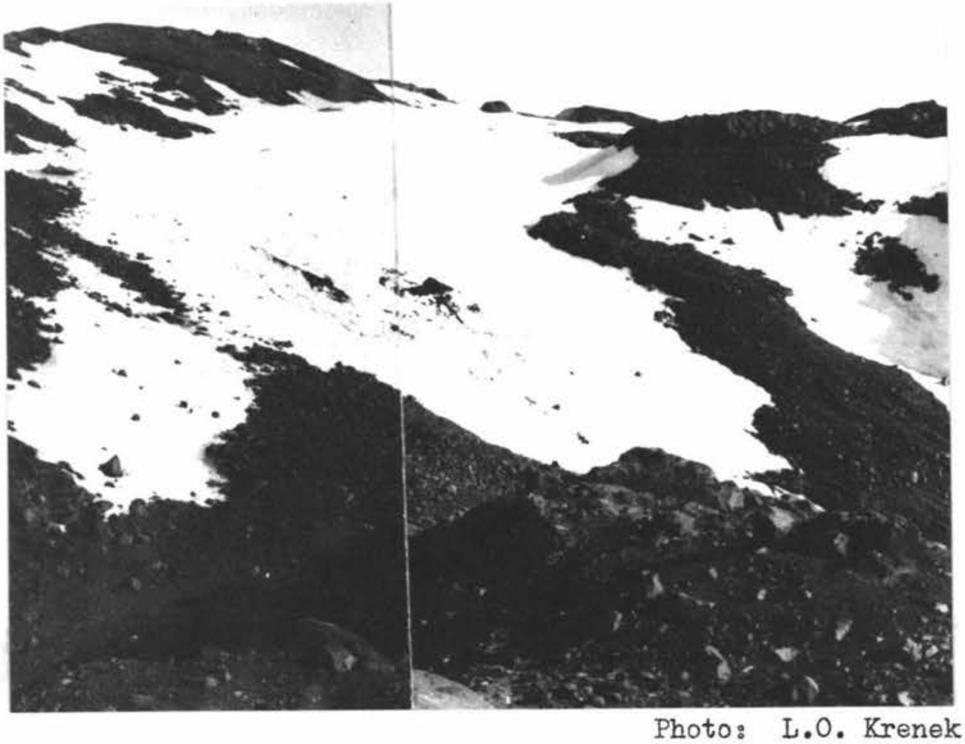


Photo: L.O. Krenek

Plate 24. The Whakapapanui Glacier, Easter 1957. More névé is lying about than at a similar time in the previous two years, making it difficult to observe any great changes in the extent of the glacier ice. However, from the rock outcrops it would appear that further downwasting has taken place since the previous photo was taken. It is from the lowermost of these outcrops that Plate 27 was taken.

1960 it was apparent that the firn line had receded beyond the highest point on the mountain (Heine, 1962).

In the years from 1959/60 to 1967/8 the glacier was characterised by a steady decline in ice area, but in a much less dramatic manner than in the mid-1950s. On March 30, 1962, at a little over 0.8 km in length and 0.3 km in width (Heine, 1962), the Whakapapanui had receded to an extent whereby the glacier terminus lay about 2,256 m above sea level (see Fig.4). With the conclusion of the 1959/60 ablation season all the névé and firn which had hitherto existed on the glacier had been removed and, along with it, much of the glacier ice. This condition was to be repeated frequently in the years up to 1967/8 in which year much of the glacier ice was lost, leaving many of the basal rocks protruding through the remaining ice (see Plate 26). Only in 1964/5, when near equilibrium conditions were experienced, was this process of yearly removal of glacier ice interrupted. In February, 1968 the glacier ice was only about 10 m thick in its thickest part so that the true glacier ice was then only a thin veneer over the rock base (see Plates 27 and 28).

The 1968/9 budget year saw the occurrence of the first positive budget that the Whakapapanui Glacier had experienced in its total existence, as a distinct and separate glacier, of almost a decade and a half. This unusual turn of events in retrospect appears almost to have been a final bid to save the glacier from extinction. Even so it seemed that this large positive budget would be followed in 1969/70 by another negative budget unless the thick mud and ash layer deposited on the glacier by the eruption of Mt Ruapehu on June 22, 1969 acted as an insulator helping to preserve the last remains. Nature has some unusual ways of preserving its relics and this may well have been one of them.

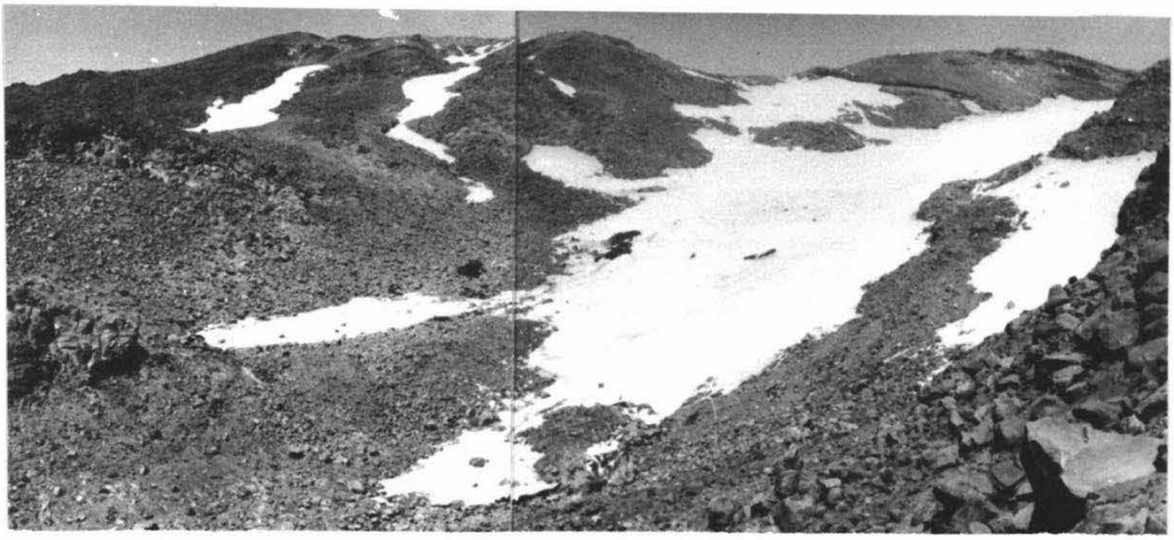


Photo: L.O. Krenek

Plate 25. The Whakapapanui Glacier, Easter 1958, taken this time from the western bank of the valley, showing The Knoll in the left foreground. Again the presence of névé makes it difficult to recognise any changes, but the very existence of névé at this time suggests that budgets are likely to be less strongly negative than in the mid-1950's.

Photo: Tongariro National Park Board

Plate 26. The Whakapapanui Glacier, January 1968. Whilst the margins of the Glacier are not clearly delineated, the main purpose of this Plate is to show the surface topography of the Glacier. There appears to be almost as much rock exposed through the ice as there is of true glacier ice. This is evidence of the severe downwasting which has taken place since 1958.

In the next chapter these trends and tendencies will be looked at in terms of the climatic patterns over the past twelve years. Prior to a consideration of the climatic normality of the 1968/9 year in detail, however, it may well be an opportune place to reflect once more upon Lawrence's observations on the recent levels of the closed-basin lakes in the Rotorua area to see how they correlate with the behaviour of the Whakapapanui Glacier over the past forty years.

Validity of Lawrence's Postulations Concerning Glacier Behaviour for the Whakapapanui

Lawrence has reported that in the late 1950s and early 1960s water levels of the closed-basin lakes in both the Rotorua district and the West Argentine, have risen above previous levels. Such changes may be taken as indicative of increasing yearly precipitation which should, according to his theory, be reflected in a tendency towards positive budgets. The last 15 years, however, have seen marked variations in the budget of the Whakapapanui Glacier with the only large positive budget appearing in the 1968/9 budget year. Despite these trends, when the individual years were considered in detail, there appeared to be a much closer agreement with Lawrence's findings.

In Part II it was established that firnification of snow into ice would take no more than two years on the Whakapapanui Glacier. According to Lawrence's latest report, the lakes in the Rotorua district "have grown from low stages in the mid-1930s to crest levels early in 1963.... Since 1956 they have fluctuated slightly and then late in 1968 rose 2 feet (0.6 m) higher than the crests of 1963." (Lawrence, 1969)

As stated earlier, the Whakapapanui Glacier experienced almost equilibrium conditions in 1964/5 and a substantial positive budget in

Photo: R.I. Robert

Plate 27. The Whakapapanui Glacier, May 1969. The asymmetrical nature of the valley can be seen here. In the upper left background is the end of Te Heu Heu Ridge which joins the end of Restful Rocks almost at right angles. The basin-like nature of the Glacier is immediately obvious with the greater accumulation in the lee of the steep-walled portion of the finger-like extension of Restful Rocks. The party in the foreground is working close by some of the debris cones shown in Plates 14 and 15.

Plate 28. The Upper Whakapapanui Valley which the western arm of the Glacier is believed to have occupied some years ago. This once cleanly glaciated valley has since been strongly eroded, making it difficult to distinguish between fluvial and glacial features. In the middle left foreground is The Knoll with the Glacier lying on the upper side of the knoll in the middle foreground.

1968/9, which tended to substantiate Lawrence's theory that the glacier was in fact reflecting the response in lake levels which had taken place one year before the positive budget, and two years before the equilibrium conditions. Furthermore, it appeared that the 1969/70 budget year would in no way approach that of 1968/9 and, to coincide with this, Lawrence reported that in the summer of 1968/9 the lake levels declined by about 2 feet (0.6 m).

Lawrence's records, therefore, show considerable agreement with the records for the Whakapapanui Glacier and, since it is rather unlikely that both are in error, it is quite possible that Lawrence's theory holds true in this particular situation, at least insofar as the extremes of precipitation are concerned. More important to the writer, however, was the fact that this particular case had been tested against a theory with the result that the 1968/9 budget computations did not pose an exception. In fact, it appeared that the climatic conditions which triggered this positive budget were of a scale sufficient to affect the South Island glaciers. In 1968 the Tasman Glacier experienced heavy winter snowfalls raising the névé landing fields for light aircraft 100 feet (30.4 m) higher than in the winter of 1967 (Lawrence, 1969).

A more detailed treatise of the separate climatic seasons will be made in the following chapter. Before moving on to this consideration, however, the general dynamic responses of the Whakapapanui Glacier have been outlined below.

Summary

From the records available there appear to have been three distinct phases in the recent history of the glacier.

1. From the end of the nineteenth century up until the early 1950s it seemed as though the glacier—then known as the Whakapapa Glacier, one of six outlet glaciers—displayed a fairly steady state of health, for it exhibited no great net gain of mass. Instead it existed in a state of near equilibrium conditions where nourishment from the permanent ice field surrounding the Crater Lake was barely sufficient to satisfy the wastage, especially since the 1930s when the move towards climatic optimum conditions became more obvious. In such a condition the glacier could be said to have been climatically alive but leading a fairly passive existence in terms of behaviour (Embleton and King, 1968), perhaps even displaying minor shrinkage.

2. During the period from 1954 to 1960, when the glacier was in a state of marked retreat as a result of strong negative budgets, much of the glacier ice was lost. The beginning of this period was highlighted by the appearance of two distinct glaciers from the original outlet glacier. In this period the glacier became both climatically and dynamically dead or static. It was defined as climatically dead when the glacier became disconnected from the ice plateau and hence its life-line. Because of this the glacier ice could no longer extend its frontiers by way of the kinematic waves which are known to conduct the precipitation away from the ice plateau (Nye, 1963). It could, however, have expanded or contracted its margins if positive budgets had prevailed for two or more years, or it may have moved as a result of earthquakes or volcanic vibrations since its base was lubricated by the meltwater stream.

3. The years from 1960 to 1969 constituted a period of variable regimes with negative budgets prevailing, though with occasional years when equilibrium or near equilibrium conditions were believed to have

existed, for example 1965/6. In 1968/9, when a strong positive budget was displayed, the glacier was in a state of potential growth manifested in the marked increase of nourishment over wastage. In 1968/9, as a "cut-off" lobe of ice, the glacier relied upon self-sufficiency to maintain a healthy condition. Because of the time period involved in the firnification of this snow into glacier ice, the effects of the positive budget may be attenuated somewhat or may never even become apparent. Hence the glacier is said to have been in a potentially active state in 1968/9, but usually two successive positive budgets are necessary before any lengthening or movement becomes apparent. Since it appeared as though the 1969/70 budget would be negative, it seemed unlikely that the positive budget would be registered in a dynamic response.

On this evidence the glacier may be said to have attained old age since it displayed the traits commensurate with such a condition; namely wasting, a generally unhealthy condition and a tendency towards extinction.

CHAPTER 2

STATISTICAL NORMALITY OF THE 1968/9 CLIMATIC YEAR

In the previous chapter use was made of qualitative evidence to establish the general dynamic state of the Whakapapanui Glacier. On its own such evidence had limited application in any attempt to relate the dynamic condition of the glacier to the general meteorological environment. Apart from broad generalisations as to the nature of the climatic environment—whether a period of cooler climates prevailed or whether there had been a trend to warmer and drier conditions. Thus, apart from enabling a fairly elementary reconstruction of past climates, this sort of evidence did little to enhance our understanding of the way in which the glacier and climate were related.

One method of establishing the degree of normalcy of the 1968/9 climatic year is to consider a number of climatic parameters over a longitudinal time period. The longer the period of time and the greater the number of climatic parameters, the more reliable would be the relationships evolved. Thus a consideration of temperature and precipitation data over a period of twelve years from 1957/8 to 1968/9 should help in our understanding of the meso-dimension of the glaciometeorology on the Whakapapanui Glacier, which was essentially the glacier/weather relationship. The meso-scale provided the connecting link between the macro-dimension of glacier/climate relationships, or the dynamic state of the glacier, and the micro-dimension, namely the heat budget. The importance of the two meso-scale parameters of rainfall and temperature were assessed in relation to changes in the mass budget of the glacier. An attempt has been made to ascertain the ways in which these two parameters characterised the heat budget, but it was necessarily limited by the absence of true micro-meteorological measurements. Nevertheless what has been achieved should improve our knowledge of the climate/glacier relationships characterising the Whakapapanui Glacier.

The object of this chapter, therefore, was to account for the large positive budget in 1968/9 against a background of essentially negative or equilibrium budgets, in terms of rainfall and temperature, and to establish the normalcy of the 1968/9 hydrological year. Three factors influenced the choice of these two parameters: (i) available records for other parameters were often incomplete or were available for shorter periods only; and (ii) Hoinkes (1954) has stated that "air temperature has frequently been used as a very rough indication of the heat budget because it can be easily reduced to glacierised altitudes". This, however, does not overlook the complex manner in which temperature is related to the mass balance. It does, however, lend substance to the belief that heat transfer mechanisms of latent and sensible heat, as well as the radiative energy transfer, were influenced by the ambient air temperature.

Hoinkes, Howarka and Schneider (1968) found that daily observations of temperature, at some distance from the Hintereisferner Glacier, were useful in deducing ablation conditions on the glacier. In their own words, "temperature is merely a substitute for radiation". However, they caution that "if temperature is used as an indication of radiation, the existence of fresh snow on the glacier has to be considered as well" for fresh snow prevents ablation. On the Whakapapanui where ablation was a continuing process, effectively taking place throughout the year to a greater or lesser degree, the use of temperature as an indication of ablation was all the more justified. The third factor relates to precipitation and Hoinkes, Howarka and Schneider (1968) have found that it was very closely associated with the mass budget of the glacier in years of extremes of accumulation and ablation. All that is known of the relationship within these thresholds is that it varies in time and space, but this should not prevent the use of precipitation as a climatic indicator on the Whakapapanui Glacier.

Rainfall and temperature data were considered in terms of the entire hydrological budget year and, to ensure that valid comparisons were made, a fixed period of the calendar year was assigned to the two seasons, known as the potential accumulation and ablation seasons. The accumulation season was taken as extending from May to October inclusive while the ablation season was from November to the following April inclusive.

Precipitation

With regard to the total rainfall for the hydrological years it was obvious that the 2,923 mm deposition in 1968/9 was not abnormally high. In fact the total was exceeded on four occasions in the last twelve years, the highest total falling in 1964/5 when there was 3,789 mm. This figure of 2,923 mm was, however, almost 8 percent above the average for the twelve years from 1957/8 to 1968/9 of 2,713 mm. Furthermore, it was just over 6 percent above the average taken over the period 1921 to 1950, of 2,748 mm.

Thus the twelve-year period from 1957/8 to 1968/9, in terms of annual rainfall, was only 1.2 percent below the average for the period from 1921 to 1950 and hence could be assumed to have been a fairly representative sample. In the last seven years of this twelve-year period the average rainfall of 2,713 mm was exceeded on no less than five occasions with only 1966/7 and 1967/8 recording totals below this average with 2,574 mm and 2,550 mm respectively (see Table X). On both these latter occasions the glacier experienced rather strong negative budgets. Nevertheless, these totals were considerably above the yearly values when compared with the values for the period from 1957/8 to 1962/3 where the rainfall totals varied between 1,930 mm and 2,521 mm. These below average totals in the late 1950s and early 1960s coincided with a period of fairly rapid recession by the glacier. On their own, however, they were not sufficient to indicate the sign or magnitude of the net budget for in the 1964/5 budget year, when there was a 39 percent above average total rainfall of 3,789 mm, the glacier experienced only about equilibrium conditions. In the 1968/9 budget year, however, when an 8 percent above average rainfall total of 2,923 mm was recorded at The Chateau, the glacier experienced a strong positive net budget.

Reference to Table X also indicates that in terms of percentage contribution to the annual rainfall by the accumulation and ablation seasons, the 1964/5 season had a 57:43 ratio in favour of the accumulation season. This differed from the twelve-year average ratio of 52:48 by only 5 percent, while in the 1968/9 season, with a 60:40 ratio in favour of the accumulation season, the difference was 8 percent. In this respect the 1968/9 season was exceeded by the 1962/3 season only, which displayed a 61:39 ratio in favour of the accumulation season. It would appear from the above that the temporal distribution of precipitation may have been more important than the magnitude, at least above certain threshold values.

Closer examination of the monthly rainfall totals indicated that the May 1968 rainfall of 365 mm, while only 2 percent above the 1959/60

Table X

Monthly Rainfall Totals and Means

(a) Accumulation Seasons—Rainfall (mm)

Month	57/8	58/9	59/60	60/1	61/2	62/3	63/4	64/5	65/6	66/7	67/8	68/9	Means
May	230.6	350.5	361.4	262.6	85.8	213.1	272.0	190.2	203.9	106.6	186.1	364.9	236.7
June	125.4	94.9	154.1	218.6	170.1	442.9	326.1	180.8	261.3	351.2	171.7	386.0	236.2
July	160.5	248.6	285.2	322.3	331.2	263.3	249.4	590.2	257.3	315.4	138.6	189.4	277.1
August	99.0	169.1	84.3	220.4	190.2	337.5	276.3	408.9	248.6	170.1	476.2	272.7	245.8
September	65.5	31.4	191.0	293.3	232.9	209.5	293.1	502.4	179.5	175.7	198.6	224.7	216.4
October	224.2	144.5	229.6	136.9	145.5	438.9	103.3	301.2	226.0	144.0	217.6	335.5	220.7
Total	905.5	1039.3	2321.8	1302.0	1138.1	1918.2	1520.4	2173.9	1376.9	1263.3	1389.1	1773.6	
Mean	150.8	173.2	217.6	242.3	197.1	319.5	253.4	278.3	229.6	210.5	231.6	295.6	
% of Yearly Total	46.92	41.04	55.40	51.63	42.75	61.00	52.37	57.38	44.69	49.08	54.46	60.67	

Average for 12 years = 52.08 percent

(b) Ablation Seasons—Rainfall (mm)

Month	57/8	58/9	59/60	60/1	61/2	62/3	63/4	64/5	65/6	66/7	67/8	68/9	Means
November	288.2	70.8	224.0	190.2	185.1	382.0	239.0	211.3	450.5	282.9	360.6	238.7	260.3
December	261.8	553.2	145.2	75.6	115.0	198.3	186.1	348.9	331.9	343.6	292.3	274.3	251.9
January	142.2	258.5	173.7	228.6	400.0	125.7	335.2	215.9	207.2	155.7	124.2	117.3	207.0
February	171.1	186.6	287.0	150.1	123.9	305.3	158.2	316.4	250.9	214.8	51.5	186.4	200.1
March	99.0	152.9	158.2	198.8	263.3	122.4	320.5	267.9	128.5	198.6	78.9	84.0	172.7
April	61.7	223.2	63.5	223.5	232.6	93.4	144.0	231.9	334.2	114.8	253.4	248.9	186.9
Total	1024.3	1445.5	1051.8	1067.0	1320.5	1227.3	1383.2	1612.3	1703.5	1310.6	1161.2	1149.8	
Mean	170.6	240.7	175.2	177.8	219.9	204.4	230.6	268.7	283.9	218.4	193.5	191.5	
% of Yearly Total	53.18	58.96	44.60	48.37	57.25	39.00	47.63	42.62	55.31	50.91	46.54	39.33	

Average for 12 years = 47.91 percent

(c) Hydrological Year—Total Rainfall (mm)

1930.1 2484.1 2357.1 2521.4 2306.0 3144.5 2903.2 3788.9 3080.5 2574.0 2550.4 2923.5

12 year average total for full Hydrological Years = 2713.4 mm

Annual average for 1921 to 1950 = 2748.5 mm total of 361 mm, was 54 percent above the twelve-year average and, as such, was the highest May total in the last twelve years. Furthermore, the June total of 386 mm in 1968/9 was exceeded by only the 1962/3 June total of 443 mm and was over 63 percent above the twelve-year average. The monthly total of July was 46 percent below average, while August and September, with totals 11 percent and 4 percent respectively above their averages, were exceeded on a number of occasions. October, with 336 mm of rain, was 52 percent above the twelve-year October mean, and was only exceeded by October 1962/3 which, with 439 mm, was almost 100 percent above the mean. Insofar as the magnitude of accumulation was concerned, May, June and October appeared to have been exceptional months.

In the ablation season the reverse was the case: January of 1968/9 was on record as having the lowest rainfall of any January in the past twelve years and, with only 117 mm, it was 44 percent below the mean of 207 mm. March of 1968/9, with 84 mm, had the second lowest of the March totals next to March of 1958/9, with 79 mm. With only 5 mm more rainfall it was 51 percent lower than the twelve-year March average of 173 mm. The 1968/9 ablation season was particularly dry with a total rainfall of 1,150 mm being the lowest for the past eight years and the fourth lowest in the last twelve years. More important to the regime of the glacier, however, was the rather minimal amount of rainfall in the months when the temperatures were warmest (see Table XI b), which meant that the contribution of latent heat to the ablation process in these months was particularly low. By comparison the total precipitation in the 1964/5 ablation season of 1,612 mm, with the exception of the 1965/6 season, was the largest ablation season total on record for the last twelve years and yet, in 1964/5, the glacier maintained a state of equilibrium.

Table XI

Mean Monthly Temperatures (^{o}C)

(a) Accumulation Seasons

Month	57/8	58/9	59/60	60/1	61/2	62.3	63/4	64/5	65/6	66/7	67/8	68/9	Means
May	10.3	9.7	2.7	6.2	4.8	7.8		4.5	5.3	4.6	5.3	6.2	6.1
June	8.1	7.0	2.6	3.6		4.0		3.3	3.1	2.6	3.2	3.5	4.1
July	5.7	6.2	2.3	2.7	1.5	3.7		3.3	1.2	2.0	2.7	1.7	2.9
Aug.	8.1	7.8	4.0	2.5	2.7	3.5	2.2	2.5	3.2	2.8	4.3	3.3	3.9
Sept.	9.0	8.2	5.0	5.3	4.5	4.4	4.5	4.0	4.7	4.6	3.8	3.1	5.1
Oct.	10.0	14.0	6.2	7.0	8.6	7.8	7.3	6.0	5.1	5.8	8.1	4.5	7.5
Means	8.5	8.8	3.8	4.6	4.5	5.2	4.7	3.9	3.8	3.7	4.6	3.7	

(b) Ablation Seasons

Nov.	12.6	13.7	8.5	8.0	8.4	8.6	6.8	7.4	6.5	7.1	8.4	6.4	8.5
Dec.	7.4	16.2	11.7	10.0	12.4	10.2	9.9	10.2	9.7	9.3	10.2	10.1	11.1
Jan.	15.2	14.1	11.8	12.5	13.3	12.3	9.2	12.6	12.0	11.2		11.5	12.2
Feb.	18.1	11.9	12.7	12.5	12.3	13.1	11.5	9.8	13.9	11.7	12.0	12.0	12.6
March	16.4	11.3	9.6	9.8	10.7	10.3	9.4	10.3	11.5	11.7	13.8	9.6	11.2
April	10.7	8.0	8.0	7.8	9.8	7.5	8.3	7.5	7.6	7.8	8.3	6.0	8.1
Means	14.3	12.6	10.4	10.1	11.2	10.3	9.2	9.6	10.2	9.8	10.6	9.2	

The net result of these precipitation patterns was a particularly intense accumulation season (see Fig.16) in the 1968/9 budget year and in all probability a much less effective ablation season, owing to the high albedo of new snow. The intensity of the accumulation season as shown in Table X a was reflected in the maintenance of the snow level below 1,220 m a.s.l. during most of the winter (see Fig.16). These graphs have been constructed from Snow Reports issued during the ski season by the Tongariro National Park Board. The snow line is defined by them as "the lowest general level at which people can use toboggans in gulleys or at which there is a reasonable depth of snow"[1], whilst the skiable level is defined as "the lowest level to which an average skier of intermediate standard can get a continuous run without having to jump or climb over rocks".[2] Figure 16 shows that both the snow line and the skiable level during the 1968/9 accumulation season were at abnormally low elevations at the beginning of November, reflecting a longer than normal accumulation season. The weather patterns which acted to produce the snowfalls in November, also reduced the actual length of the potential ablation season. As a result the true onset of the ablation season was delayed because of the high albedo of fresh snow which must have effectively reduced the amount of melting that resulted from radiation. Since the 1969/70 accumulation season began on April 9, 1969, the duration of the ablation season was also reduced. This, together with the reduced effectiveness of the ablation season, must have contributed substantially to the positive net budget in 1968/9.

Temperature

The validity of the temperature data was somewhat suspect since there were gaps in some months from either broken equipment or more urgent duties for the Park Board personnel who maintain the meteorological station. The Meteorological Office has, however, produced a continuous record of mean monthly temperatures with the exception of three months in the 1963/4 year and a month each in 1961/2 and 1967/8. Certain conclusions can be made from these values.

From observation of the accumulation season records (see Table XI), September and October of 1968/9 had the lowest temperatures of any similar month in the last twelve years. The September value of 3.1°C was 2°C lower than the overall September mean of 5.1°C, while the October value of 4.5°C was 3°C below the twelve-year October mean of 7.5°C. Of the monthly average temperatures in the accumulation season, only May experienced average temperatures. The remaining months from June to October experienced monthly averages between 0.6°C and 3.0°C below their respective twelve-year mean temperatures. This could have meant either one or both of two things: (i) the amount of ablation occurring in the accumulation season was considerably reduced so that less snow than normal was lost as meltwater runoff; or (ii) a greater than normal frequency of airflows with accelerated dewpoints, all things being equal, may have led to a greater than normal percentage of the precipitation falling as snow. Hence it would appear that many factors combined to produce this exceptional budget year.

Average temperatures for the months of the ablation season were all below their respective twelve-year means. November, at 6.4°C, and April at 6.0°C were both 2.1°C below their means and, as such, were the lowest November and April means in the twelve-year period. February at 12.0°C had the closest to average conditions of any of the months in the ablation season, for it was only 0.6°C below average. December at 1.0°C below the average of 11.1°C and March at 1.6°C below the average of 11.2°C were, however, significantly below normal. The net result of these differences could have been that the radiative energy and heat transfer mechanisms operated with much reduced efficiency in the 1968/9 ablation season.

To ascertain whether in fact these differences were sufficiently great to give rise to mathematically significant differences from the mean, a parametric test was applied to them (see Table XII). It was with certain reservations that these data were tested in such a way, however,

Table XII

T-Test on the Mean Temperature Data

Period Tested	Mean for 1968/9 $(\bar{x})^{o}C$	Mean for 1957/8 - 67/8 $(\bar{X})^{o}C$	Difference $(\bar{X}-\bar{x})^{o}C$	t	1968/9 $\sigma^{o}C$	n*	Significance+
Full Year	6.5	8.0	1.5	0.400	3.7	9	N.S.
Accum. Season	3.7	5.1	1.4	1.450	0.9	10	N.S.
Ablation Season	9.2	10.7	1.5	0.527	2.7	10	N.S.
May	6.2	6.1	-0.1	0.161	2.3	9	N.S.
June	3.5	4.1	0.6	0.581	1.3	8	N.S.
July	1.7	3.1	1.4	0.471	2.7	9	N.S.
August	3.3	4.0	0.7	0.448	1.5	10	N.S.
September	3.1	5.2	2.1	3.367	0.6	10	S.
October	4.5	7.8	3.3	1.824	1.7	10	N.S.
November	6.4	8.7	2.3	1.926	2.8	10	N.S.
December	10.1	11.1	1.0	0.235	4.1	10	N.S.
January	11.5	12.4	0.9	0.949	0.9	9	N.S.
February	12.0	12.7	0.7	0.488	1.4	10	N.S.
March	9.6	11.3	1.7	0.801	2.1	10	N.S.
April	6.0	8.3	2.3	0.413	5.4	10	N.S.

* n = Degrees of Freedom

\+ Significance Level is set at 5% Probability
when $n = 10$, $t \geq 2.228$ to be significant
when $n = 9$, $t \geq 2.262$ to be significant
when $n = 8$, $t \geq 2.306$ to be significant

for none of the samples completely fulfilled the pre-requisites set down for a parametric test. First, there were insufficient values in most of the samples to allow any real distribution patterns to emerge, let alone normal distributions. Second, the samples could not be taken as representative of the "population" from which they were drawn since they were not randomly selected. Despite the above-mentioned shortcomings of the data, the realisation that climatological data pose special problems when used in statistical tests, satisfied the writer that the use of the T-test was justified in that any differences which did appear were likely to have been particularly significant.

When the T-test of variance was applied to these fifteen sets of data (see Table XII), only one difference emerged as being significant above the 5 percent level, this being the September value which was statistically significant at the 1 percent level and hence very meaningful. The fact that all the other differences did not show up in this test meant ideally that none of the other apparent differences were mathematically significant and should therefore be discounted. The fact remains, however, that the 1968/9 regime was greatly different from any other year in the twelve-year period and it appeared most likely that the abnormal monthly temperature values were of sufficient magnitude to have contributed in some way to this condition. That these differences did not show up in the variance test was more likely to have been a reflection of the inadequacies of the data and the consequent large standard deviations, than it was of any real lack of change in the climatic elements.

It was at least noteworthy that September 1968/9 experienced a mean temperature statistically different from that of the remaining Septembers in the eleven-year period tested. September was, however, recorded as having a mean monthly temperature only 2°C below the twelve-year mean. This difference was equalled by November and April, and surpassed by October with a monthly mean 3°C below the average of 7.5°C.

That neither of these last three months emerged as having statistically significant differences from their respective means was not particularly paramount for the limitations of statistical tests, when applied to climatological data, are widely acknowledged. In this case the particularly large standard deviations of the temperatures in November, April and October must have over-shadowed the apparent differences between their respective means.

On the whole the picture emerging from this treatise of mean temperature data reinforced the pattern established earlier when dealing with total rainfall figures; namely, that the crucial months at the end of the accumulation season and beginning of the ablation season experienced weather which acted to prolong the accumulation season and delay the beginning of the ablation season. First, new snow as late as November 28, together with the below normal temperatures in the ablation season, must have combined to reduce the effectiveness of solar radiation as a factor in the ablation process. Second, the probable reduction in latent heat, resulting from reduced precipitation, together with the delayed beginning of the ablation season, must have combined with the above factors to have minimised the amount of melting which took place, so allowing ablation to have continued at a much slower rate.

These differences in the duration of the accumulation and ablation seasons, together with their abnormal characteristics of rainfall and temperature, must have been connected with the frequency of an abnormal synoptic situation characterising the form and sequence of the weather in the immediate vicinity of the glacier. We will now consider the synoptic situation and analyse its relationship with certain climatic elements.

Meso-Scale Weather

Lamb's system of classification of airflow types was employed to distinguish the major weather types[3] characterising the general meteorologic environment over Mt Ruapehu. Basically there were four main types of synoptic situations which brought differing weather types to the area, and these arose from the two main types of pressure systems with a secondary classification according to the position of these systems in relation to Mt Ruapehu. Airflow 1 encompassed the CN, CE, CSE and CNE airflows which resulted from cyclogenesis or frontogenesis to the north of Mt Ruapehu. Airflow 2 was made up of the CSW, CW, CNW and CS airflows which resulted from convergence as a result of trough depressions and fronts to the south of Mt Ruapehu. Airflow 3 was a composite of diverging airflows which resulted from anticyclones migrating to the north of Mt Ruapehu. It encompassed the ANW, AW, AS and ASW airflow types, while Airflow 4 was made up of the AN, ANE, ASE, AE and A airflows which originated from anticyclonic conditions to the south of Mt Ruapehu. As a result of New Zealand's insular nature and oceanic position in the mid-latitudes, its weather is influenced by the dominant pressure system (low pressure convergence or high pressure divergence) and the source of origin and modification en route of the airstream motivated by the pressure pattern (Garnier, 1957).

Both A_1 and A_2 airflow types were associated either with the passage of tropical cyclones which form over the Coral Sea during the summer months, or from depressions which develop in the south Tasman Sea and migrate in a north-easterly direction across New Zealand, steered by the zone of westerly winds. In winter in particular, frontogenesis also occurs over New Zealand with the penetration of warm, moist north-westerly air by polar maritime air from the south-west. These cold fronts frequently undercut the warm, moist unstable north-westerly or westerly air and force it to rise. The resulting uplift leads to cloudy and windy weather, generally cool temperatures and rain (Garnier, 1957). The tropical cyclones are associated with warm, humid air and when they migrate over the extensive Pacific Ocean they intensify and form a huge vortex of moist, unstable air circulating in a clockwise direction. Air flows on to New Zealand from the westerly quadrants veering south-west when, as is sometimes the case (e.g. the "Wahine" Cyclone), it moves beyond Cook Strait and it has a great potential for the release of sensible and latent heat (Thompson, unpublished research).

Complex situations often develop from the above conditions, with depressions often accompanying the fronts and prolonging the duration of this weather from the average of three up to five or more days, particularly in winter. The position of these pressure systems, as recorded at 0000 hrs N.Z.S.T., determined whether the weather was classified as type one or type two. If the pressure system was lying north of Mt Ruapehu, the resulting airflows were classified as A_1, while A_2 airflows originated from low pressure systems to the south of Mt Ruapehu. Such a system did, of course, have its limitations particularly as a result of the speed at which some of these systems pass across New Zealand. It is quite possible for a cold front or subpolar low to pass through the area at such a speed that, in the space of one evening, a completely different weather type may pass through leaving the dynamic situation the next morning the same as it had been on the previous evening, with only the wind direction changed. Consequently, a weather pattern based on only one daily recording had its shortcomings, though a more suitable substitute has yet to be found.

As mentioned earlier, Airflows 3 and 4 were associated with the procession of anticyclones across from the Australian Bight from west to east, and across the Tasman Sea to New Zealand, steered by the subtropical jet stream flow (Thompson, unpublished research). In winter they pass mostly across northern New Zealand (Garnier, 1957), while in summer they move across at about the centre of the country in the vicinity of Cook Strait. Air from the south to south-westerly quadrant of the anticyclones to the south of Mt Ruapehu was generally of a cold maritime nature, being of Antarctic origin, while easterly flowing air, characterised by subsidence, was usually fairly stable and somewhat cooler than the prevailing westerly air.

Over a 2,191 day period from May 1, 1963 to April 30, 1969, these four airflows were found to occur in the following proportions in the vicinity of Mt Ruapehu (see Appendix I):

Airflow 1	(CN, CE, CSE, CNE)	=	14.0%	47.0%
Airflow 2	(CSW, CW, CNW, CS)	=	33.0%	
Airflow 3	(ANW, AW, AS, ASW)	=	31.5%	53.0%
Airflow 4	(AN, ANE, ASE, AE, A)	=	21.5%	

These figures indicated that for the last six hydrological years the weather pattern was dominated by (i) converging airstreams originating as a result of cyclogenesis or frontogenesis to the south of Mt Ruapehu, and (ii) anticyclonic systems migrating across to the north of Mt Ruapehu with resultant unstable airflows from the south-westerly quadrant of the compass. This can be seen, generally speaking, as a reflection of the cyclic pattern of New Zealand's weather with alternating lows and highs.

The frequency occurrence of each of the major airflow types in the 1968/9 year has been compared with the mean frequencies in the period from 1963/4 to 1967/8 in Table XIII. The purpose of this exercise was to establish whether the measured abnormalities in the two meso-meteorological parameters of rainfall and temperature were also measureable in the meso-scale weather.

Table XIII

Percentage Frequency Occurrences of Airflow Types

(Hydrological Years)

Airflow Type	1963/4 - 1967/8 (X)	1968/9 (x)	Difference (X - x)
A_1	14.29	12.32	+1.97
A_2	31.66	39.73	-8.07
A_3	31.87	29.59	+2.28
A_4	22.18	18.16	+4.02

While there were slight reductions in the proportion of A_1, A_3 and A_4 airflow types in the 1968/9 year as compared with the five-year period mean, the 8 percent increase in the proportion of A_2 (CSW, CW, CNW, CS) airflows prompted the writer to test whether the frequency distribution of airflow types in 1968/9 was mathematically significant from the distributions for the period from 1963/4 to 1967/8 (see Table XIV).

With a Chi-Squared value of 9.349 the difference between the 1968/9 frequency distribution in the four major airflow types, and that for the previous five-year period, was said to be statistically proven at the 2.5 percent level, but this did not indicate where the difference existed. (For the calculation of X^2 values see Appendix II.) Not all the "observed" frequencies for the airflow types differed from the "expected" values by the same amount, however. In Airflow 2 there was a frequency difference of 24.5 and this increased frequency in the 1968/9 year appeared to be the main reason for the significant difference between the two periods.

Table XIV

X^2-Test on the Frequency Occurrence of the Major Airflow Types in 1968/9, as compared with the period 1963/4 - 1967/8

Airflow Type	Observed Frequency 1963/4 - 1967/8	Expected Frequency 1963/4 - 1967/8	Observed Frequency 1968/9	Expected Frequency 1968/9	Observed-Expected Frequencies 1963/4 - 1967/8	Observed-Expected Frequencies 1968/9
A_1	261	255.1	45	50.9	5.9	- 5.9
A_2	578	602.5	145	120.5	-24.5	24.5
A_3	582	575.1	108	114.9	6.9	- 6.9
A_4	412	393.4	67	78.6	11.6	-11.6

$X^2 = 9.349$

Degrees of Freedom = 3

Value of X^2 for difference to be significant at 5% level ≥ 7.815

Table XIV confirmed that the frequency occurrence of airflow types in 1968/9 was significantly different from the pattern for 1963/4 to 1967/8, but it did not indicate where the greatest difference lay. An examination of Table XVI, however, indicated that for the overall hydrological year the greatest difference in frequency occurrence was in airflow type A_1, in which there was a reduced frequency of airflows without rain. This confirmed somewhat the pattern as shown in Table XV, where the average intensity of rainfall associated with A_1 airflows was about 1 mm lower than that for the previous five-year mean.

The pattern for the hydrological year did not, however, confirm the suggested frequency difference in A_2 airflows as shown in Table XIII. As a consequence it was decided to examine the accumulation seasons and ablation seasons separately. Table XVII demonstrated that there was a significant difference in the frequency occurrence of A_4 airflows in the

Table XV

Intensity of Rainfall Associated with Airflow Types—Comparison Between 1968/9 and 1963 - 1969

(a) Full Hydrological Years

Air-flow Type	1963 - 1969	Mean R.F. (mm)	Air-flow Type	1968/9	Mean R.F. (mm)
A_2	CSW, CW, CNW, CS	9.90	A_2	CSW, CW, CNW, CS	8.89
A_1	CN, CE, CSE, CNE	8.63	A_1	CN, CE, CSE, CNE	7.87
A_3	ANW, AW, AS, ASW	4.57	A_3	ANW, AW, AS, ASW	6.09
A_4	AN, ANE, ASE, AE, A	4.31	A_4	AN, ANE, ASE, AE A	4.82

(b) Accumulation Season

A_2	CSW, CW, CNW, CS	11.43	A_2	CSW, CW, CNW, CS	11.93
A_1	CN, CE, CSE, CNE	5.84	A_3	ANW, AW, ASW, AS	9.39
A_3	ANW, AW, AS, ASW	5.33	A_1	CN, CE, CSE, CNE	6.60
A_4	AN, ANE, ASE, AE, A	3.55	A_4	AN, ANE, AE, ASE, A	5.84

(c) Ablation Season

A_1	CN, CE, CSE, CNE	11.93	A_1	CN, CE, CSE, CNE	9.39
A_2	CSW, CW, CNE, CS	8.63	A_2	CSW, CW, CNW, CS	4.57
A_3	ANW, AW, AS, ASW	4.32	A_3	ANW, AW, AS, ASW	4.06
A_4	AN, ANE, ASE, AE, A	2.79	A_4	AN, ANE, ASE, AE, A	3.30

two periods with the 1968/9 accumulation season having an increased frequency of airflows which were associated with rainfall. Meantime, Table XVIII for the ablation season demonstrated a significant difference in the frequencies of A_2 airflows. In 1968/9 there was an increased frequency of A_2 airflows associated with non-rain days, when compared with the average frequencies for the 1963/4 to 1967/8 period. Table XV, which shows the intensity of precipitation associated with the airflow types in each of the seasons, confirmed the above results, but in the accumulation season the increase in the intensity of A_4 airflows in 1968/9, when

Table XVI

Chi-Squared Test of Difference in Frequency Distribution Between 1963 - 1968 and 1968/9

(Hydrological Years)

Air-flow	Rainfall* (mm)	"Observed" Frequencies 1963-8	"Observed" Frequencies 1968/9	"Expected" Frequencies 1963-8	"Expected" Frequencies 1968/9	X^2 Value	n^+	Significance[±]
A_1	0	102	14	99	17			
	0.10-6.34	58	17	64	11	7.880	3	< 5%
	6.35-12.69	34	8	36	6			
	> 12.70	67	6	62	11			
A_2	0	157	49	165	41			
	0.10-6.34	161	42	162	41			
	6.35-12.69	79	13	74	18			
	12.70-19.04	54	11	52	13	4.950	6	N.S.
	19.05-25.39	38	9	38	9			
	25.40-38.09	59	12	57	14			
	> 38.10	30	9	31	8			
A_3	0	318	60	319	58			
	0.10-6.34	125	19	122	22			
	6.35-12.69	42	7	41	8			
	12.70-19.04	29	8	31	6	3.128	5	N.S.
	19.05-25.39	21	6	23	4			
	> 25.40	50	7	48	9			
A_4	0	260	37	255	42			
	0.10-6.34	63	12	64	11			
	6.35-12.69	20	6	22	4	2.971	4	N.S.
	12.70-25.39	33	7	34	6			
	> 25.40	29	5	29	5			

± Significance Level is 5% or less

+ n = Degrees of Freedom

* The class interval of 6.34 mm has been doubled in some instances in order to obtain sufficient frequencies for testing

when n = 3 $X^2 \geq 7.815$

when n = 4 $X^2 \geq 9.488$

when n = 5 $X^2 \geq 11.070$

when n = 6 $X^2 \geq 12.592$

$$X^2 = \sum \frac{(o - e)^2}{e}$$

where o = observed frequencies

e = expected frequencies

Table XVII

Chi-Squared Test of Difference in Frequency Distribution

Between 1963 - 1968 and 1968/9

(Accumulation Seasons)

Air-flow	Rainfall* (mm)	"Observed" Frequencies 1963-8	"Observed" Frequencies 1968/9	"Expected" Frequencies 1963-8	"Expected" Frequencies 1968/9	X^2 Value	n⁺	Significance±
A_1	0	60	8	57	11	3.017	3	N.S.
	0.10-6.34	34	9	36	7			
	6.35-12.69	16	5	18	3			
	> 12.70	29	4	28	5			
A_2	0	76	19	73	19	3.329	5	N.S.
	0.10-6.34	83	22	83	22			
	6.35-12.69	52	10	49	13			
	12.70-19.04	27	10	29	8			
	19.05-31.74	52	10	49	13			
	> 31.75	30	11	33	8			
A_3	0	136	21	134	23	3.446	3	N.S.
	0.10-6.34	59	10	59	10			
	6.35-19.04	28	9	32	5			
	> 19.05	40	5	38	7			
A_4	0	121	15	117	19	8.900	3	< 2%
	0.10-6.34	36	4	35	5			
	6.35-12.69	12	5	15	2			
	> 12.70	31	8	34	5			

± Significance Level is 5% or less

⁺ n = Degrees of Freedom

* The class interval of 6.34 mm has been doubled in some instances in order to obtain sufficient frequencies for testing

when n = 2 $X^2 \doteq 5.991$ when n = 3 $X^2 \doteq 7.815$

when n = 4 $X^2 \doteq 9.488$ when n = 5 $X^2 \doteq 11.070$

compared with the mean for the period from 1963 to 1969, was not as great as the difference in intensity between the A_1 airflows in the respective periods, of 3.6 mm. Nevertheless, the ablation season figures of rainfall intensity, in Table XV, most definitely confirmed the difference between the A_2 frequencies in the two periods. The 1968/9 intensity of

Table XVIII

Chi-Squared Test of Difference in Frequency Distribution

Between 1963 - 1968 and 1968/9

(Ablation Seasons)

Air-flow	Rainfall* (mm)	"Observed" Frequencies 1963-8	"Observed" Frequencies 1968/9	"Expected" Frequencies 1963-8	"Expected" Frequencies 1968/9	X^2 Value	n^+	Sig-nifi-cance‡
A_1	0	42	6	42	6			
	0.10-6.34	24	8	28	4	6.700	3	N.S.
	6.35-25.39	38	3	35	6			
	> 25.40	18	2	17	3			
A_2	0	83	30	91	22			
	0.10-6.34	78	20	79	19			
	6.35-19.04	54	4	47	11	10.54	4	< 5%
	19.05-25.39	13	4	14	3			
	> 25.40	32	5	30	7			
A_3	0	184	39	187	36			
	0.10-6.34	66	9	63	12			
	6.35-12.69	27	4	26	5	2.744	4	N.S.
	12.70-25.39	22	6	24	4			
	> 25.40	26	4	25	5			
A_4	0	139	22	137	24			
	0.10-6.34	27	8	30	5	2.399	2	N.S.
	> 6.35	39	5	38	6			

‡ Significance Level is 5% or less

+ n = Degrees of Freedom

* The class interval of 6.34 mm has been doubled in some instances in order to obtain sufficient frequencies for testing

when n = 2 $X^2 \geq 5.991$ when n = 3 $X^2 \geq 7.815$

when n = 4 $X^2 \geq 9.488$ when n = 5 $X^2 \geq 11.070$

4.6 mm was just over half as intense as the precipitation of 8.6 mm associated with the A_2 airflows in the overall period from 1963 to 1969.

From the above it appears quite certain that one of the principal reasons for the prolonged and intensified accumulation season in 1968/9 was an increased amount of precipitation accompanying divergent airflows from the north, north-east, east and south-easterly quadrants. These normally fairly stable airflows must have had accelerated dewpoints as a result of lower than normal temperatures in several months of the accumulation season. The snowfall from the east and south-easterly quadrants in particular, as indicated in Chapter 2, Part II, would have led to a greater accumulation than would normally have been precipitated by airflows from the direction of the prevailing winds.

The reduced effectiveness of the ablation season appeared to have been the result principally of an increase in the frequency of south, south-westerly, westerly and north-westerly airflows, which were not associated with rain (see Table XVIII). A reduction in precipitation from the west and north-westerly quadrants could be explained by a decreased frequency of tropical cyclones and this would have led to a reduction in the contribution of latent and sensible heat.

Before going further into an explanation of the results of the above observations, it was deemed necessary to indicate which airflow types had the greatest association with rainfall in both the accumulation and ablation seasons. As in the previous tables, where precipitation has been correlated with airflow types, the daily precipitation at The Chateau, as recorded on the standard Meteorological Office form, was associated with the surface level synoptic conditions read from micro-filmed charts prepared by the Commonwealth Bureau of Meteorology in Australia at 1100 hrs G.M.T. This time corresponded with 0000 hrs N.Z.S.T., approximately three hours before the time at which the rainfall was recorded at The Chateau Meteorological Station. For the analysis of the frequency and intensity of rainfall associated with the major airflow types see Appendix I.

Table XIX

Association of Airflows with and without Rainfall for the Accumulation Seasons 1963 - 1969

Air-flow	"Observed" Days With Rain	"Observed" Days Without Rain	"Expected" Days With Rain	"Expected" Days Without Rain	X^2 Value	Significance Level	Coeff. of Contingency (C)	Rank Based on Diff. Between Airflow Pairs
A_1	97	68	118	49	18.94	< .1%	0.180	2
A_2	307	92	286	113				
A_1	97	68	86	79	4.11	< 5%	0.092	5
A_3	151	157	162	146				
A_1	97	68	80	85	11.72	< .1%	0.169	3
A_4	96	136	113	119				
A_2	307	92	259	140	59.31	< .1%	0.278	1
A_3	151	157	199	109				
A_2	307	92	255	144	80.49	< .1%	0.113	4
A_4	96	136	148	84				
A_3	151	157	141	167	3.07	N.S.	0.075	6
A_4	96	136	106	126				

Table XIX indicated that for the six-year period from 1963 to 1969, for the accumulation season, the differences in frequency and intensity of rainfall between the airflow types was greatest between A_2 and A_3. That is, A_2 airflows had a much higher association with rain than A_3, while the difference between A_1 and A_2 airflow types, though somewhat less pronounced, was nevertheless mathematically significant when tested by the Chi-Squared Test. The only airflows which were not associated with rain and non-rain days in a manner which allowed them to be considered as significantly different and distinctly separate were the A_3 and A_4 airflows. All the other airflow types showed associations

Table XX

Association of Airflows with and without Rainfall for the Ablation Seasons 1963 - 1969

	"Observed" Days		"Expected" Days					
Air-flow	With Rain	With-out Rain	With Rain	With-out Rain	X^2 Value	Sig-nifi-cance Level	Coeff. of Contin-gency (C)	Rank Based on Diff. Between Airflow Pairs
A_1	92	48	91	49	0.02	N.S.	0.006	6
A_2	210	113	211	112				
A_1	92	48	68	72	23.03	< .1%	0.204	3
A_3	162	223	186	199				
A_1	92	48	63	77	38.43	< .1%	0.300	1
A_4	79	161	108	132				
A_2	210	113	170	153	37.08	< .1%	0.220	2
A_3	162	223	202	183				
A_2	210	113	166	157	56.79	< .1%	0.200	4
A_4	79	161	123	117				
A_3	162	223	149	236	5.20	2.5%	0.090	5
A_4	79	161	92	148				

n = 1 in all cases (Degrees of Freedom)

when n = 1, X^2 value ≥ 3.841 to be significant

$$C = \sqrt{\frac{X^2}{N + X^2}}$$ Contingency Coefficient

(These values of n and the formula for C, apply to Table XIX also.)

with rainfall and non-rainfall days which were significant enough to warrant their treatment as separate weather types.

For the ablation season A_1 and A_4 airflow types on the Coefficiency Contingency Test had the most significantly different association with rain and non-rain days of the six possible combinations of airflow types (see Table XX). Only airflow types A_1 and A_2 were shown to exhibit insufficient mathematical difference to warrant consideration as separate airflow types. This meant, in effect, that with regard to precipitation in the ablation season, the treatment of A_1 and A_2 airflows as separate weather types was not justified. Likewise A_3 and A_4 in the accumulation season, for the purposes of intensity and frequency association with precipitation, were not sufficiently different to warrant consideration as separate synoptic weather types.

The analysis of the meso-scale weather has indicated that even with the broad weather types used in this classification significant differences in the pattern of these weather types emerged between the normal pattern (as displayed by the 1963/4 to 1967/8 period) and that for 1968/9.

The analysis of the meso-scale weather has shown that, when 1968/9 was compared with the years from 1963/4 to 1967/8, significant differences emerged which indicated that the broad weather types selected were sufficiently different for all but two sets of categories (A_3 and A_4 in the accumulation season, and A_1 and A_2 in the ablation season) to record statistically significant differences in application of the Chi-Squared Test. The failure of any significant difference to have appeared between these two sets of airflows appeared to have been the result of abnormal frequencies and intensities of rainfall associated with the A_4 and A_2 airflow types in the 1968/9 budget year. In the accumulation season of 1968/9, A_4 airflows were shown in Table XVII to have had abnormal associations with and without rain. These were sufficiently large to have given rise to a statistically significant difference from the normal association pattern in the period from 1963/4 to 1967/8. Likewise, in the 1968/9 ablation season (see Table XVIII), the A_2 airflows were associated with rain and non-rain days in a manner which was significantly different from the norm for the five-year period from 1963/4 to 1967/8.

Conclusions

As suspected, variations in the accumulation season pattern were also registered in the ablation season. The accumulation season contributed to a greater than normal mass input and hence an abnormally high operating margin. The principal factor contributing to this abnormal condition seems to have been an increased proportion of subsiding airflows originating from high pressure systems to the south of Mt Ruapehu. The lower than normal temperatures in the latter months of the accumulation season must have led to accelerated dewpoints and a consequent increase in the proportion of the precipitation falling as snow.

The abnormally large accumulation in 1968/9 and the exceptionally long accumulation season, operated to delay the onset of the ablation season and reduce its normal intensity. This condition was accentuated by the reduced frequency of rain-bearing airflows originating from cyclonic conditions to the south of Mt Ruapehu in the ablation season. The effect of this latter condition was to reduce the importance of latent and sensible heat in the ablation process. Furthermore, the increased conditions of low cloud, unaccompanied by rain (see Table XVIII, airflow type A_2 showing differences between "observed" and "expected" frequencies with "No Rain" and in the 6.35 - 25.39 mm rainfall groups), must have acted to reduce the amount of effective insolation available, thus mitigating the role of radiant energy as a factor in the heat budget.

The net result of all these factors must have been: (i) a decrease in the normal rate at which the large reserve of in situ névé was abladed; (ii) a reduction in the amount of gross ablation of the névé; and (iii) because of the greater than normal amount of névé available for ablation much of the névé was preserved and remained to become firn.

Footnotes

1. and 2. Defined by the Tongariro National Park Board in instructions to Park Board personnel on the presentation of winter snow reports.

3. Lamb's system of classification, in giving prominence to the direction of the windstream, takes account of the singularly most important factor in local weather; namely orography. Reference to the position of the pressure systems and their paths relates the weather types to the atmospheric circulatory pattern. Finally, the use of a small overall number of weather types gives a large number of samples for each type of condition, which is essential in statistical considerations.

CHAPTER 3

TRENDS AND TENDENCIES

In the previous two chapters the abnormality of the 1968/9 glacier regime was established, in terms of both behaviour and climate. In this chapter the future of the glacier is examined in terms of the trends and tendencies in its state of health. This was best accomplished by examining past and present trends in easily measured meteorological parameters and analysing them in terms of probable climatic cycles. The first aim was to establish climatic means and assess the deviation of yearly values from these means; and the second aim was to calculate regression lines so that overall trends could be established, along with the percentage variations of the individual years about these trends. For all these analyses, data covering the twelve-year period from 1957/8 to 1968/9 were examined.

Deviations from Means

The first feature to emerge from a consideration of the deviations of total yearly rainfalls from the twelve-year mean was a general upward trend (see Fig.18a), though with marked fluctuations from year to year towards increased rainfall, reaching a peak in 1964/5. After this year there was a general but far from consistent reduction of rainfall totals, up to 1967/8. Against this latter trend there was the above normal 2,923 mm of precipitation in 1968/9, which caused the tail of the graph to bend upwards. The patterns for the accumulation and ablation seasons, taken separately, were fairly closely reflected in the graph for the yearly figures, but did not completely mirror it. First, in the accumulation seasons the highest rainfall total occurred in the 1964/5

NORMALITY OF HYDROLOGICAL YEARS IN TERMS OF RAINFALL AND TEMPERATURE

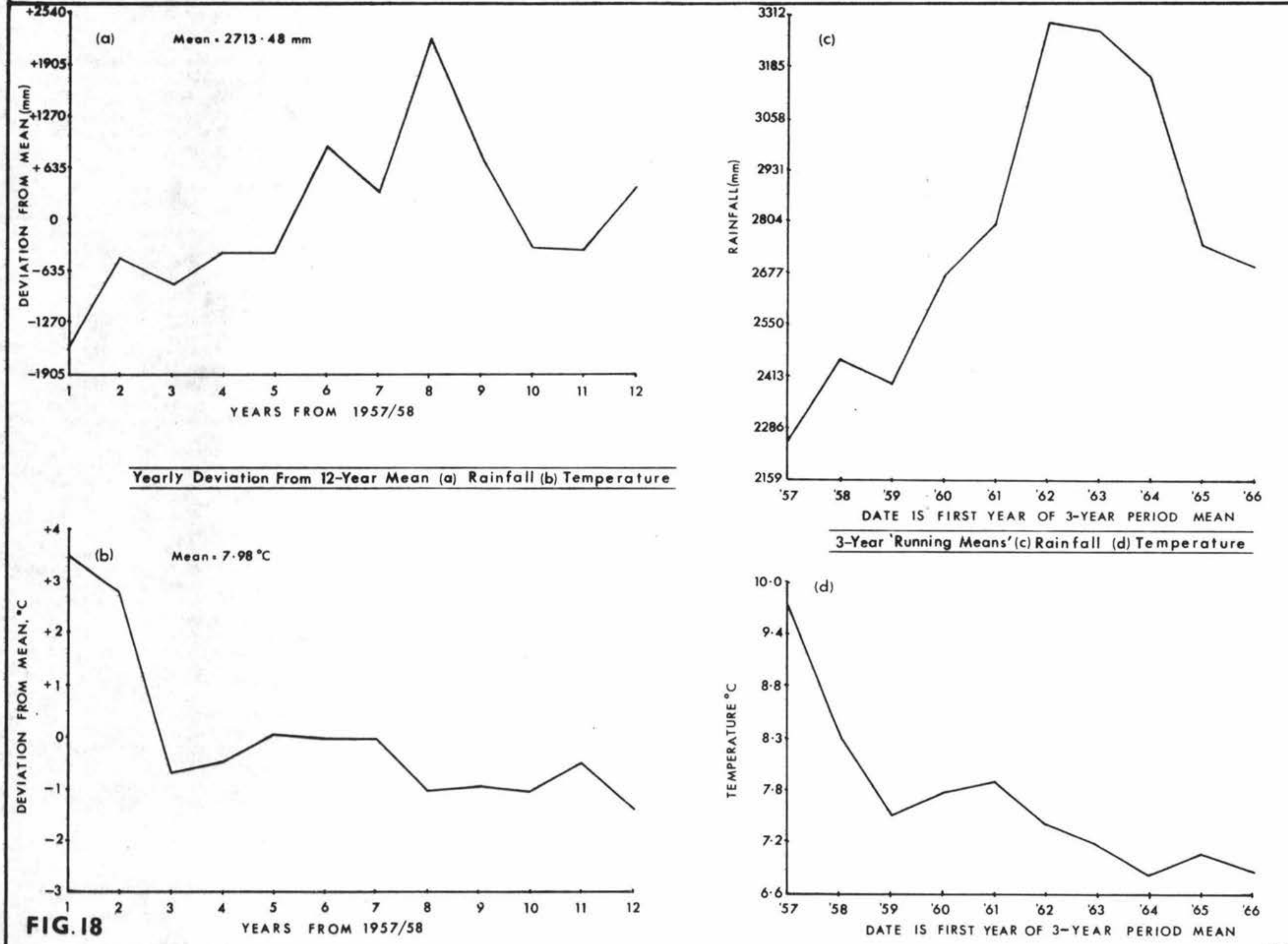


FIG. 18

hydrological year which was the same as for the full hydrological year totals, but the highest rainfall total of the twelve ablation seasons occurred in 1965/6 (see Table XXI c). While in all three time intervals (hydrological year, accumulation season and ablation season) a period of well above average figures was recorded in the mid-1960s (see Table XXI a, b and c), there was considerable disharmony in the duration and year of inauguration of this period. From the graph showing full hydrological year rainfalls (see Fig.18a) it can be seen that above average years were registered from 1962/3 to 1965/6, while totals of comparable significance in the accumulation seasons extended from only 1962/3 to 1964/5. The ablation season figures illustrated an even greater deviation. Above average figures occurred in 1958/9 and again in 1961/2 before a sustained period of above average figures lasting from 1963/4 until 1966/7. This period of four consecutive greater-than-average years began and terminated one year later than the period of above average years for the full hydrological year totals (see Table XXI a and c).

With regard to average temperatures, the relationship between the three sets of figures appeared to be much more integrated and the graph showing the average temperatures for the full hydrological years (see Fig.18b) was fairly representative of conditions in both the accumulation and ablation seasons. The trends, however, were not nearly so clear as in the pattern for total rainfalls. In the case of mean temperatures the exceptional years of 1957/8 and 1958/9 were clearly apparent and, after a rapid drop towards below average conditions, the graph recovered to about average conditions for three years from 1961/2 to 1963/4, before dropping again, with rather large below average

Table XXI

Yearly Variations about Means—Rainfall and Temperature

(a) Full Hydrological Years

Year	R.F. (mm) (a)	Running Mean (3 yr)	$(\bar{X}-a)$	$\sum(\bar{X}-a)$	Av. Temp. °C (b)	Running Mean (3 yr)	$(\bar{x}-b)$	$\sum(\bar{x}-b)$
1957/58	1929.9	2257.0	- 783.6	- 783.6	11.4	9.7	+3.5	+3.5
1958/59	2484.1	2454.1	- 229.4	-1013.0	10.7	8.3	+2.8	+6.3
1959/60	2357.1	2403.3	- 356.4	-1369.4	7.1	7.5	-0.7	+5.6
1960/61	2521.4	2657.3	- 192.1	-1561.5	7.4	7.7	-0.5	+5.1
1961/62	2306.0	2784.6	- 407.5	-1969.0	8.1	7.8	+0.2	+5.3
1962/63	3144.5	3257.5	+ 431.0	-1538.0	7.8	7.4	0	+5.3
1963/64	2903.2	3020.7	+ 189.7	-1348.3	6.9	7.2	-0.9	+4.3
1964/65	3788.9	3147.8	+1075.4	- 272.9	6.8	6.9	-1.0	+3.3
1965/66	3080.5	2734.8	+ 367.0	+ 94.1	7.0	7.1	-0.8	+2.4
1966/67	2574.0	2682.5	- 139.5	- 45.4	6.8	7.0	-1.0	+1.3
1967/68	2550.4		- 163.1	- 208.5	7.4		-0.5	+0.8
1968/69	2923.5		+ 209.5	+ 1.0	6.5		-1.4	-0.5

Mean R.F. $(\bar{X})$ = 2713.5 mm   Mean Temp. $(\bar{x})$ = 7.8°C

(b) Accumulation Seasons

Year	R.F. (mm) (a)	Running Mean (3 yr)	$(\bar{X}-a)$	$\sum(\bar{X}-a)$	Av. Temp. °C (b)	Running Mean (3 yr)	$(\bar{x}-b)$	$\sum(\bar{x}-b)$
1957/58	905.5	1083.5	- 519.9	- 519.9	8.5	7.0	+3.5	+3.5
1958/59	1039.3	1215.6	- 386.0	- 906.0	8.9	5.8	+3.8	+7.3
1959/60	1305.8	1248.6	- 119.6	-1025.6	3.9	4.1	-1.1	+6.2
1960/61	1302.0	1452.6	- 123.4	-1149.0	4.5	4.7	-0.4	+5.7
1961/62	1138.1	1525.5	- 287.7	-1436.3	4.4	4.8	-0.5	+5.2
1962/63	1918.2	1870.7	+ 492.7	- 943.6	5.3	4.7	+0.2	+5.4
1963/64	1520.4	1690.3	+ 94.9	- 848.6	4.7	4.1	-0.3	+5.1
1964/65	2173.9	1604.7	+ 788.5	- 100.0	3.9	3.9	-1.0	+4.1
1965/66	1376.9	1343.1	- 48.5	- 148.6	3.8	4.1	-1.2	+2.9
1966/67	1263.4	1475.2	- 162.0	- 310.6	3.8	4.0	-1.2	+1.7
1967/68	1389.1		- 36.3	- 346.9	4.6		-0.4	+1.3
1968/69	1773.6		+ 348.2	+ 1.2	3.7		-1.2	0

Mean R.F. $(\bar{X})$ = 1425.4 mm   Mean Temp. $(\bar{x})$ = 5.0°C

(c) Ablation Seasons

Year	R.F. (mm) (a)	Running Mean (3 yr)	$(\bar{X}-a)$	$\sum(\bar{X}-a)$	Av. Temp. °C (b)	Running Mean (3 yr)	$(\bar{x}-b)$	$\sum(\bar{x}-b)$
1957/58	1024.3	1173.7	- 261.6	- 261.6	14.3	12.5	+3.7	+3.7
1958/59	1445.5	1187.9	+ 159.5	- 102.1	12.5	10.9	+1.9	+5.6
1959/60	1051.8	1146.3	- 234.1	- 336.3	10.4	10.6	-0.3	+5.3
1960/61	1067.0	1204.7	- 218.9	- 555.2	10.2	10.6	-0.4	+4.9
1961/62	1320.3	1310.1	+ 34.3	- 520.9	11.2	10.3	+0.5	+5.4
1962/63	1227.3	1407.6	- 58.6	- 579.6	10.3	9.7	-0.4	+5.0
1963/64	1383.2	1566.4	+ 97.2	- 482.3	9.2	9.7	-1.5	+3.5
1964/65	1612.4	1542.0	+ 326.3	- 155.9	9.6	9.9	-1.0	+2.5
1965/66	1703.5	1391.6	+ 417.5	+ 261.6	10.3	10.3	-0.4	+2.1
1966/67	1310.6	1207.2	+ 24.6	+ 286.2	9.8	9.9	-0.8	+1.3
1967/68	1161.2		- 124.7	+ 212.3	10.7		0	+1.3
1968/69	1149.0		- 136.1	+ 76.2	9.2		-1.4	0

Mean R.F. $(\bar{X})$ = 1288.0 mm   Mean Temp. $(\bar{x})$ = 10.7°C deviations from 1964/5 to 1966/7. This slight downward trend was interrupted by only average, or near average, conditions in 1967/8.

"Running" Means

The trends and relationships portrayed by Figure 18c and d and Table XXI, showing deviations from the means, were not nearly as explicit as those in which the three-year "running" means were plotted, for the fluctuations in the graphs of these figures were not nearly as pronounced as those showing straight deviations, and this made for much easier comparisons. Figure 18c, showing the three-year "running" means for total annual rainfall, illustrated an almost cyclic trend. From a trough in 1957/8 the graph showed a steady, and at times rapid, rise (except for 1959/60), reaching a peak in 1962/3. Since then the trend has been once more in a downward direction. Apart from displacements of the peak value to 1963/4 for the ablation seasons (see Table XXIc) the pattern was pretty much as displayed in Figure 18c for the full hydrological year rainfall totals.

"Running" means for temperature data showed a much lesser degree of harmony. The pattern for the accumulation seasons showed decreasing temperatures up to 1960/1 when an inverted "V", depicting a superimposed crest, interrupted the pattern which continued on its downward trend after 1964/5 (see Fig.18d). While the superimposed crest in the temperature data for the hydrological years spanned only two years from 1960/1 to 1961/2, the pattern otherwise displayed trends similar to those in the accumulation seasons (see Table XXIb). Once again it was the pattern for the ablation seasons which showed the greatest disparities. Apart from the occasional levelling off, the trend in mean temperatures was downwards until 1964/5, when the superimposed crest showed a short upward tendency before dropping again to the 1964/5 value.

Cumulative Deviations

It appeared that, with regard to both of these climatic elements, the pattern which was displayed in the accumulation season was reflected a full year later in the ablation season. The overall pattern, however, as depicted in the data for the full hydrological years, more closely resembled the pattern for the accumulation seasons than that for the ablation seasons. This relationship appeared again in the graphs showing the cumulative deviations from the mean. Parts (a) and (b) of Figure 20, depicting the cumulative deviations from the mean by the accumulation seasons, showed a much closer resemblance to their counterparts in Figure 19 for the full hydrological years than did the ablation seasons (Fig.20 c and d). In both these figures above average values were indicated by an upward trend of the graph while below average figures were illustrated in a downward trend. The steepness of the curve indicated how much faster or slower the trend was occurring, from one year to the next.

In terms of the rainfall in the ablation seasons, then, the most rapid increases appear to have occurred between 1962/3 and 1964/5. A similar trend was apparent in the accumulation seasons and hydrological years, although the increase was registered in both cases between 1961/2 and 1965/6, i.e. over five years instead of only three as in the ablation seasons. While the increasing rainfalls were pronounced in all three periods, the accumulation season and hydrological year patterns were the most similar. After 1964/5 the trend in ablation season rainfall totals

CUMULATIVE DEVIATIONS FROM MEANS

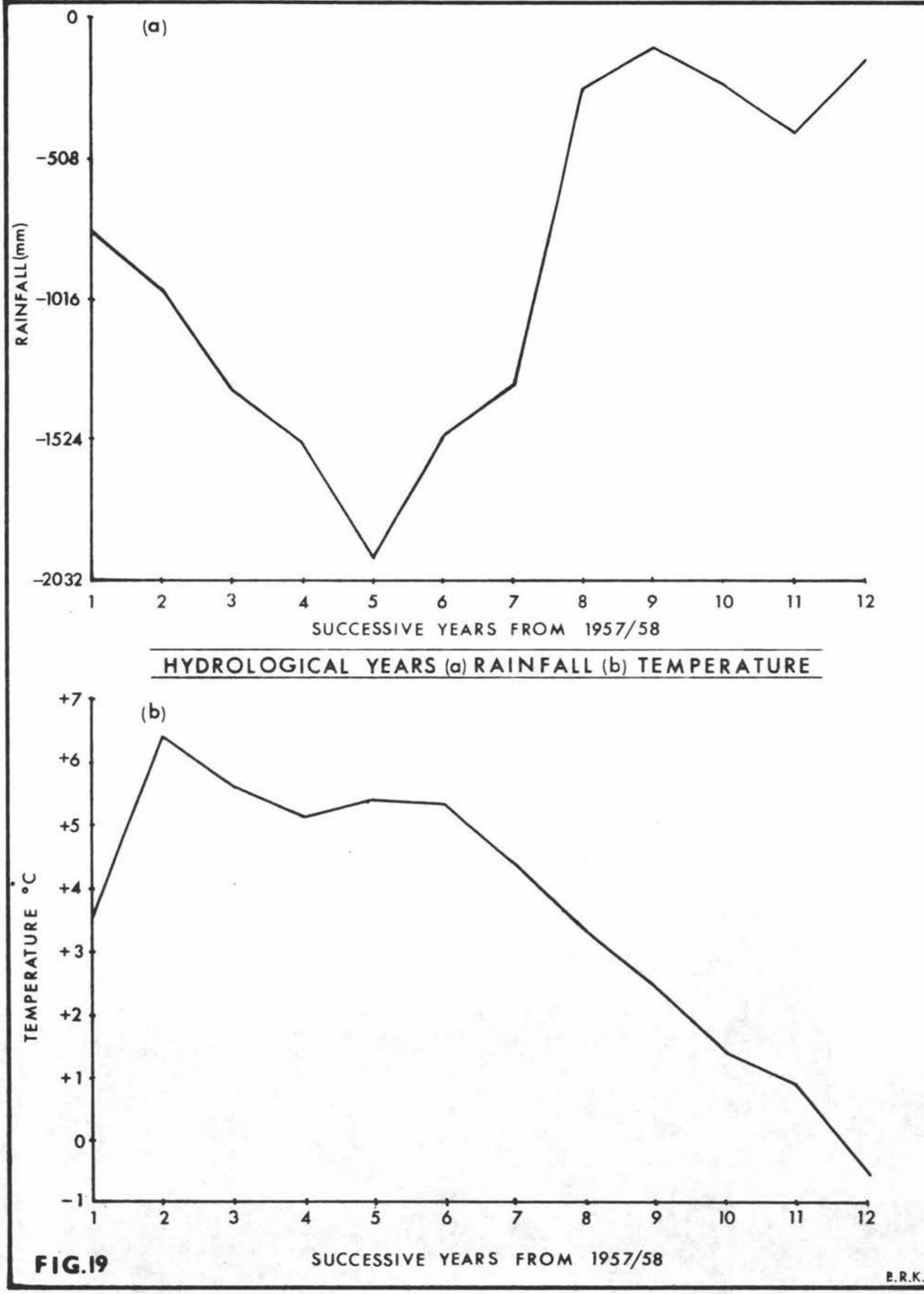


FIG.19

towards below average conditions was much less pronounced. It was significant that in both the accumulation season and hydrological year graphs of total rainfall, there was a sharp upward trend in 1968/9, indicating above average conditions, while the ablation season graph equally as well depicted the markedly below average tendency in 1967/8.

The graphs of mean temperature for the accumulation and ablation seasons (see Fig.20) did not exemplify the same degree of difference between the periods, as did those for rainfall. While the accumulation season graph again most closely depicted the picture for the complete hydrological year, it was not greatly different from the pattern for the ablation season. Perhaps most noticeable was the consistency of the downward trend in average temperatures, at least after 1962/3. On the basis of temperature, then, the immediate future seemed likely to bring further cooling and a trend towards colder conditions but, since these graphs considered only the relative trends and not the absolute values for each year, it was impossible to indicate just how rapidly this trend was occurring.

Regression Coefficients

For a true indication of trends and the yearly fluctuations from such a trend, regression lines were constructed. In all cases the regression was a straight line regression of one variable—either temperature or rainfall—over a period of twelve years. The great advantage of these lines was that they expressed the overall trend throughout the period and allowed the yearly degree of fluctuations about the trends to be calculated. In all the examples presented the assumption was that the regression line gave the closest approximation to the

ABSOLUTE CUMULATIVE DEVIATIONS FROM 12-YEAR MEANS

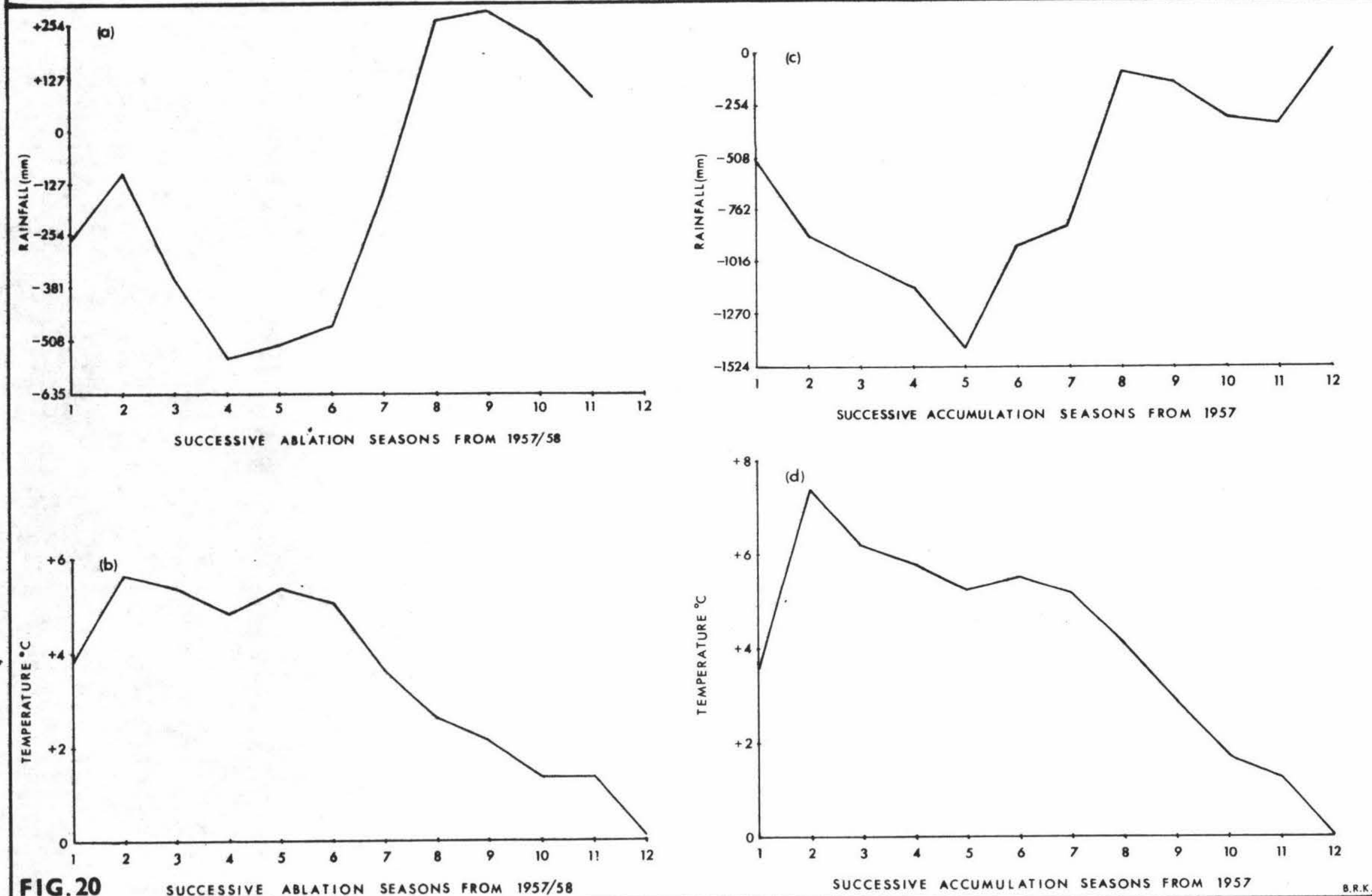


FIG. 20

relationship that would occur in each successive year if a regular relationship existed between the climatic element being tested and the time period over which the study was made. (See Appendix III for the calculation of these values.)

An examination of the regression lines for the full hydrological years (see Fig.21), which contained the values most closely related to the regime of the glacier, showed that for every year change there would be a change of +70.10 mm in rainfall and a -0.31°C change in temperature. In terms of accumulation seasons the pattern was similar with a temperature change each year of 0.30°C and a change in rainfall of +46.2 mm (see Fig.22). In the ablation seasons, however, the trends, though in similar directions, were of quite different magnitudes (see Fig.23). Rainfall showed a yearly change of +7.28 mm while temperature changed by -0.517°C. In as much as the past, as recorded in these graphs, was of only a very limited duration (twelve years), postulations as to the future could only be suggested along very general lines and then only in terms of the experiences of the past twelve years. The best indication of the reliability of any such postulations was the "best estimate" of the Coefficient of Variation of the sample, from the regression line. These values were obtained by calculating the difference between the observed values and the expected values (see Appendix IIIb).

In Table XXII the variability was likely to have been introduced as a result of local variations in climate and also as a result of the influence of the glacier upon its own climate. These were much greater in respect to rainfall totals than in the corresponding periods for temperature, hence postulations regarding future temperature trends, based on the regression lines, should be more reliable than similar

HYDROLOGICAL YEAR TRENDS IN RAINFALL AND TEMPERATURE

(a) Rainfall Totals (b) Overall Mean Temperatures

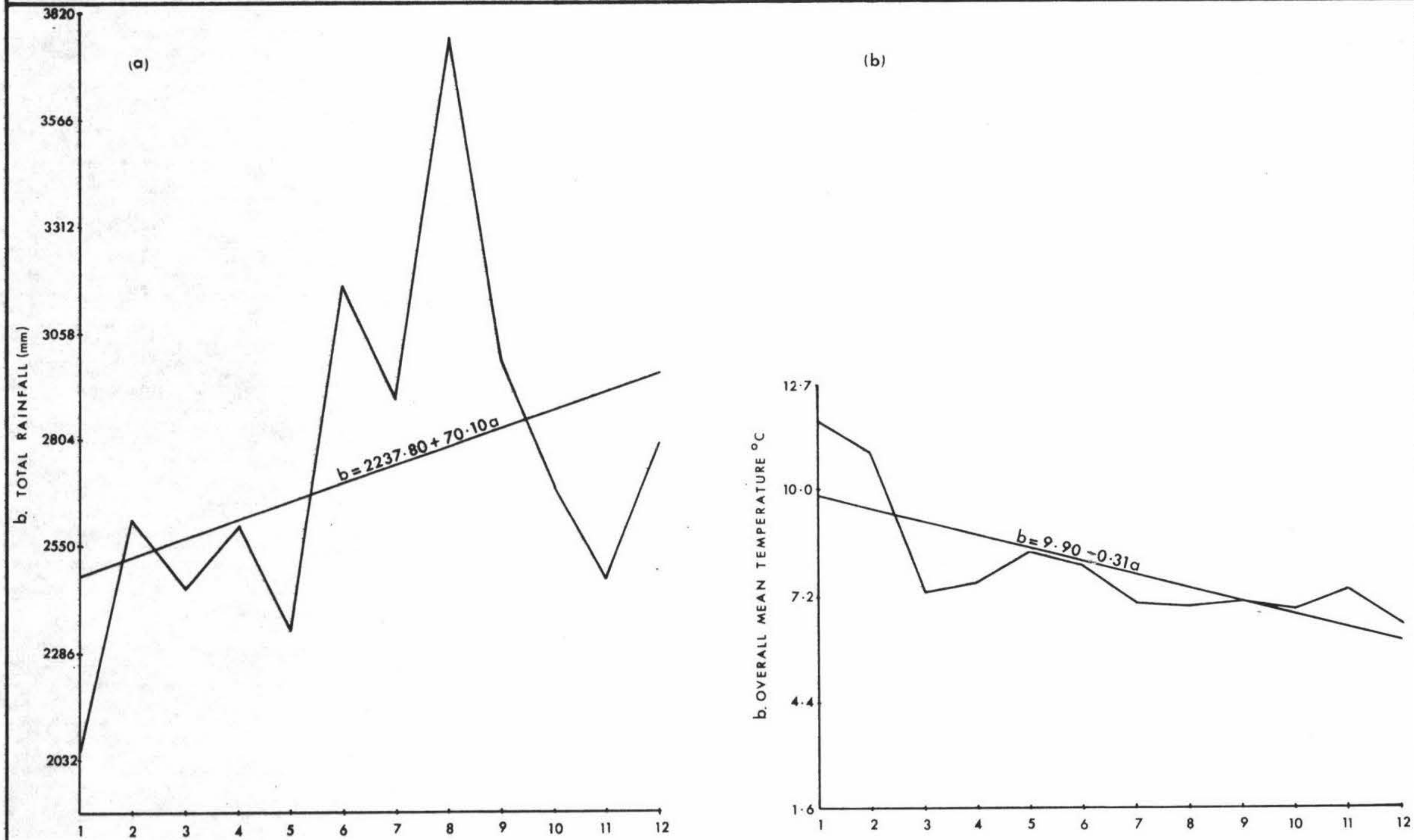


FIG. 21 a. SUCCESSIVE HDROLOGICAL YEARS BEGINNING 1957/58 a. SUCCESSIVE HDROLOGICAL YEARS BEGINNING 1957/58

B.R.K.

Table XXII

Variability of Rainfall and Temperature, 1968/9

Period	% Variation of Rainfall	% Variation of Temperature
Full Hydrological Years	46.21	4.21
Accumulation Seasons	69.60	7.64
Ablation Seasons	52.34	3.58

postulations about rainfall. Since the percentage deviations in the accumulation season were much greater than in either of the other two periods, it was likely that the effect of the glacier upon the local climate was more pronounced in this season than in either the ablation seasons or the hydrological years seen as a whole.

Correlation Between Rainfall and Temperature

All the graphs demonstrating rainfall and temperature trends have added substance to the belief that in most climates these two parameters are in some way related. The extent to which one of these elements was likely to have produced an effect in the other would doubtless have been increased by a knowledge of the degree of correlation existing between them. It is to this end that the following workings are directed.

The degree of correlation between rainfall and temperature was obtained by substituting the values from Appendix IIIa in the Product Moment Correlation Coefficient Formula. This gives the value

$$r = \frac{\frac{1}{12}(-322.11)}{2.935 \times 18.363}$$
$$= -0.513.$$

This figure indicated that there was a negative correlation between the rainfall and temperature data over the period

ACCUMULATION SEASON TRENDS IN RAINFALL AND TEMPERATURE

(a) Rainfall Totals (b) Overall Mean Temperatures

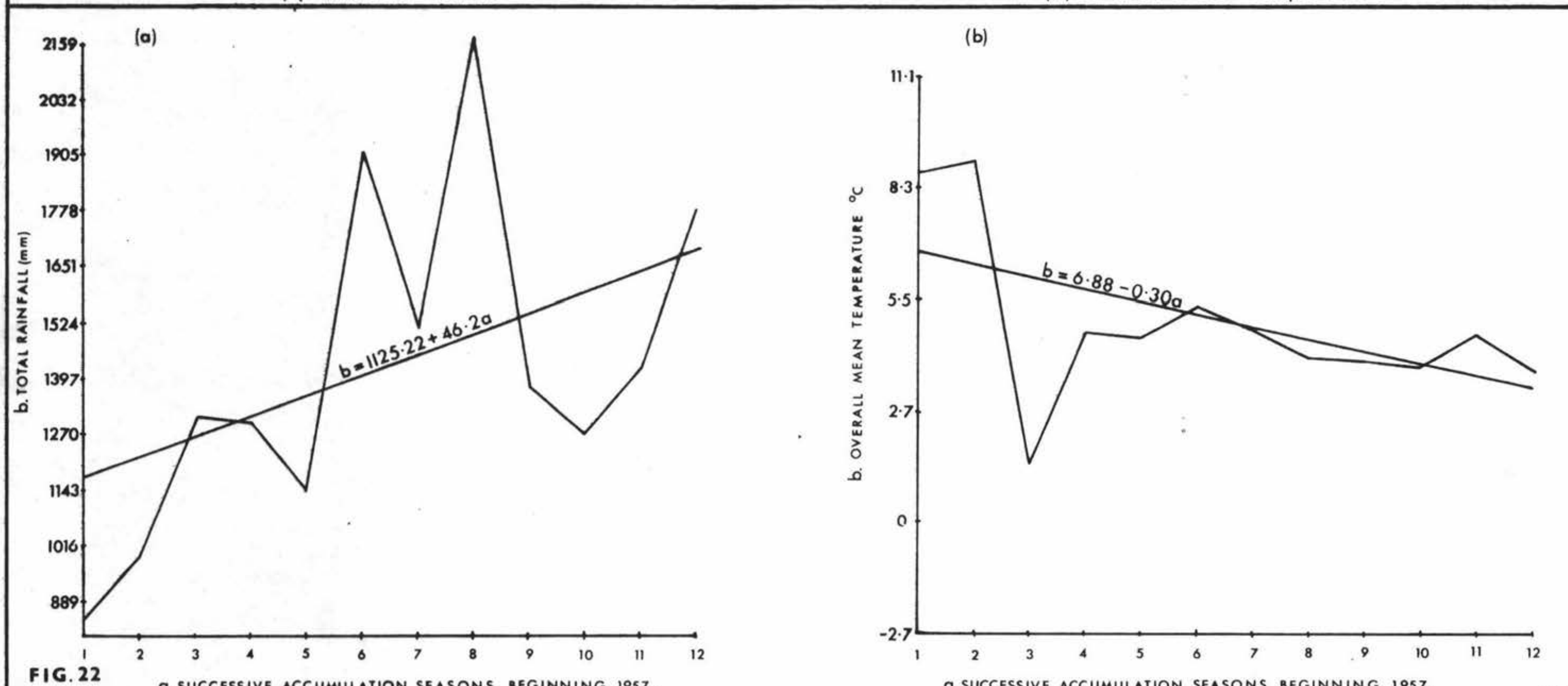


FIG. 22

ABLATION SEASON TRENDS IN RAINFALL AND TEMPERATURE

(a) Rainfall Totals (b) Overall Mean Temperatures

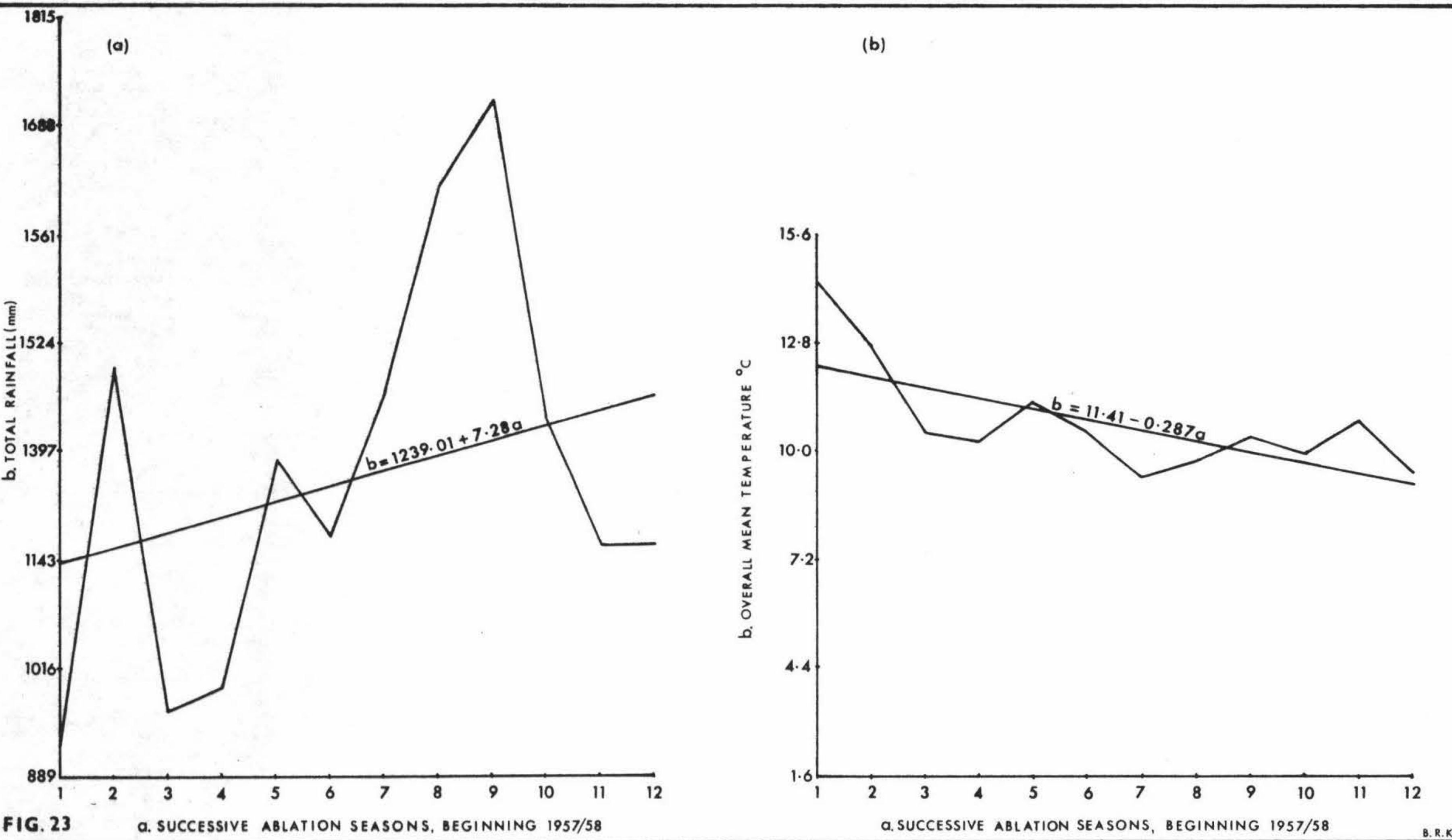


FIG. 23

from 1957/8 to 1968/9. It signified, moreover, that 26.314 percent of the variations in rainfall data can be explained from temperature data. This value is known as the Coefficient of Determination and is calculated using the formula in Appendix IIIc. Then, substituting in this formula

$$t = \frac{-0.513\sqrt{10-2}}{\sqrt{1-(-0.513)^2}}$$

$$= \frac{-1.622}{\sqrt{0.74}}$$

$$= 1.8856.$$

The value of t is significant just outside the 5 percent level which means that there was a fairly low probability that more than 26 percent of the variations in rainfall could be explained from the available temperature data for the same period.

Apart from suggesting the accuracy with which future trends in rainfall and temperature could be predicted, this chapter has demonstrated one other salient feature which may be mentioned in conclusion. It appears from the available evidence that there was a stronger association between the accumulation patterns and the overall pattern for the full hydrological years than there was between the latter and the ablation seasons. An opposite association was, however, reported by Hoinkes (1968) after consideration of the behaviour of European glaciers from the late eighteenth century up to the present. He believed that emphasis should be put "on weather conditions during the ablation season because they are considered more important for glacier welfare than weather conditions during the accumulation season", although every writer agrees with Sharp's contention that "accumulation is the life-blood of a glacier" (1960). Apparently the Whakapapanui Glacier, in 1968/9, was much like the glaciers on the Pacific Coast of North America, which have had active regimens for most of the 1960s.

PART IV

CONCLUSIONS

Comparison of the Whakapapanui Glacier with Selected World Glaciers

Effect of Aspect on Glaciometeorology

Stratigraphy, Crystallography and Cold Wave Penetration

General Conclusions

COMPARISON OF THE WHAKAPAPANUI WITH SELECTED WORLD GLACIERS

In this section an attempt has been made to demonstrate the similarities and differences that exist between the Whakapapanui and other glaciers, particularly those with similar locational characteristics.

Climatic Inferences from Location

Table XXIII contains the location and associated characteristics of ten glaciers ranging in extent from polar to temperate climates. The Whakapapanui was very small by comparison with these glaciers, only one of which, the Fedchenko, had a similar latitudinal location. The fact that it was situated in the Northern Hemisphere in the middle of the Asian Continent meant that the latitudinal parallels had little bearing on the types of climates characterising the two glaciers. Continental land masses set up climatic extremes and these frequently destroy latitudinal surface level analogies between the climates of the two hemispheres. More significant was the relative proximity of the glaciers to the sea, for this factor, together with the direction of the prevailing airstreams, greatly influenced the "continentality" of the respective climates. The climate of Mt Ruapehu was conditioned by a number of quasi-continental characteristics such as its inland location and considerable elevation, but these were attenuated somewhat by Mt Ruapehu's exposure to the prevailing maritime westerlies. Like the Blue Glacier, which is dominated by a temperate maritime climate (La Chapelle, 1959), the Whakapapanui had a very high mass turnover with a large income and a rapid wastage of mass.

As mountain glaciers, both the Blue Glacier and the Whakapapanui Glacier could expect fairly low rates of evaporation, an aspect of climate which is related to the lapse rate and the resulting rather cool temperatures. The Blue Glacier was, however, larger in area by a factor of 10^2 and while this may have meant that the influence of the glacier on its own climate was somewhat greater than for the Whakapapanui, it was believed to have been less important than the differences in elevation above sea level.

Table XXIII

Geographic Position, Area and Elevation of Selected Glaciers

Glacier	Approx. Location	Approx. Area km^2	Approx. Elevation Snout (m) a.s.l.	Equilibrium line Altitude (m) 1958	Distance from Sea (km)
Blue	48°N 124°W	4.2	2050	1700	50
South Cascade	48°N 121°W	2.6		2090	
Gilman	80°N 75°W	481		1200	0
Fedchenko	39°N 72°E			4900	1,300
Hodges	54°S 37°W	0.27	360	500	1
Whakapapanui	39°S 175°E	0.037	2273	>2797	104
Orwell	61°S 46°W	0.475	20	110	0.4
Salmon	56°N 130°W		1700		320
Barnes	70°N 72°E		865		150
Sveanor	79°N 18°E		5		6

Although the Blue Glacier extended over a greater elevation, being over twelve times longer than the Whakapapanui, a considerably greater portion was below 2,200 m than above it (based on the elevation of the firn line and the net budgets of the Blue Glacier). This difference in areal distribution was likely to have resulted in the reduced importance of net radiation in the ablation on the Blue Glacier.

Table XXIV, which contains a breakdown of the relative importance of the various heat sources to the ablation, shows radiation as accounting for 69 percent of the ablation on the Blue Glacier. When

Table XXIV

Importance of Radiation to the Ablation of Selected Glaciers

Glacier	Radiation	Conduction and Convection	Condensation
Blue	69%	25%	6%
Salmon	75%	15%	10%
Barnes	68%	20%	12%
Hodges	35%	35%	30%
Sveanor	24%	58%	18%

this table was interpreted in conjunction with Table XXIII it was apparent that the importance of radiation increased with an increase in elevation above sea level, together with its distance from the sea. This reduced the amount of incident radiation at the glacier surface to low levels for long periods of time, while the albedo of fresh snow under these conditions of diffuse illumination was generally about 0.9, which meant that the effectiveness of the radiation was greatly reduced (La Chapelle, 1961). While winter hailstorms occurred in the wake of cold fronts, the Whakapapanui Glacier did not experience an excess of such conditions nor did it experience the same degree of cloud as did The Chateau. Garnier (1957) set the winter average for The Chateau at less than 100 hours of cloud per month, but since a large proportion of this total was low stratus cloud, the skies above the Whakapapanui Glacier were frequently cloud free (see Plate 10). Rather high mid-day temperatures (10^{o} to $15^{o}C$) were recorded even during the winter season at this elevation (2,273 m). While snowfalls were quite frequent on the glacier, melting of the surface and densification of the névé was rapid, and this acted to lower the albedo and increase the absorption of solar radiation. On the Blue Glacier, however, the energy available from solar radiation during the mid-winter months was negligible (La Chapelle, 1961). Under fair weather conditions during the summer months, however, condensation prevailed during the day and evaporation at night.

The role of latent heat in the ablation process was quite pronounced on the Whakapapanui, especially since the ablation season accounted for approximately 50 percent of the annual precipitation recorded at The Chateau. In view of the above conditions it seemed likely that solar radiation and condensation may have accounted for a higher proportion of the ablation on the Whakapapanui Glacier than recorded on the Blue Glacier, while the role of sensible heat, by the same token, must have been proportionately less significant.

The Fedchenko Glacier, which had a very similar latitudinal location as the Whakapapanui (except that it was located in the northern hemisphere), appeared to have a radiation regime akin, in many ways, to the Whakapapanui Glacier. In the 1958/9 budget year it was characterised by a huge meltwater runoff and very marked seasonal fluctuations in the river volume. Situated at the western end of the European Alps on Mt Stalina, it was over 1,300 km from the sea and with a firn line about 5,000 m a.s.l. radiation was likely to have played a very dominant role in the ablation.

Aspect

One other factor was likely to have affected the suggested difference in the importance of radiation to the ablation of the Whakapapanui and Blue Glaciers; namely, the differing aspects of the slopes which they occupied.

Situated on the north-eastern slopes of Mt Olympus, north-western

Washington, the Blue Glacier is classed morphologically as a valley glacier. Not only, therefore, was it on the ubac slope, but for much of the time it must have been in the shadows created by the valley sides. Such a position was likely to have contributed to the diminished importance of net radiation in the ablation of the Blue Glacier.

By comparison the Whakapapanui Glacier was situated on the northern adrêt slopes of Mt Ruapehu. The absence of high valley walls, and its fairly exposed position, moreover, should have increased the effectiveness of solar radiation; while the reduced cloud thickness was likely to have increased the significance of long wave radiation. The reduced incidence and effectiveness of long wave radiation on the Blue Glacier meant that its influence on the radiation regime was almost negligible (La Chapelle, 1961). Net radiation on the Whakapapanui Glacier was, as a consequence, likely to have been considerably more significant than on the Blue Glacier.

Influence of Location on Glacio-Meteorology

It was difficult to isolate any one locational factor and attempt to ascertain its effect on the regime of a glacier. However, by selecting two ski fields at similar latitudes, elevations and distance from the sea, an attempt was made to establish the influence of aspect on features of the glacio-meteorology of Mt Ruapehu. The Whakapapa Ski Field, which was the upper part of the Iwikau Ski Field, faced due north while the Turoa Ski Field occupied the south-western slopes of Mt Ruapehu and hence was more on the ubac side of the mountain.

Figures 24 to 27, showing winter conditions on the two ski fields for selected periods, exemplify the difficulties in interpretation.

PREFACE TO FIGURES 24,25,26,27.

WIND SPEED, DIRECTION AND CLOUD CONDITIONS

STATION MODEL

A TAIL ATTACHED TO THE MODEL INDICATES THE DIRECTION FROM WHICH THE WIND IS BLOWING.

THE NUMBER AND LENGTH OF THE FEATHERS ATTACHED TO THE TAIL INDICATES THE WIND SPEED :
ONE FULL FEATHER EQUALS 10 kts
ONE HALF " " 5 kts

A WIND OF 50kts FROM THE WEST

CLOUD AMOUNT, MEASURED IN OCTAS (N/8), IS INDICATED BY THE LINES WITHIN THE STATION MODEL. HORIZONTAL LINES INDICATE ODD FRACTIONS, WHILE VERTICAL LINES INDICATE EVEN FRACTIONS. THE EXAMPLE SHOWS 3/8 CLOUD COVER.

CALM CONDITIONS INDICATED BY OUTER CIRCLE

WEATHER CONDITIONS

COLD AND BLEAK
OVERCAST
FINE AND SUNNY
CORN SNOW FALLING (PELLETS)
POWDERY SNOW FALLING
WET SNOW FALLING
SLEET
SHOWERS
DRIZZLE
RAIN
FOG
THUNDERSTORM
WIND BLOWN DUST AND DEBRIS

PRESSURE SYSTEMS

H ANTICYCLONIC
C DEPRESSION
CF COLD FRONT
SF STATIONARY FRONT
WF WARM FRONT

ELEVATIONS AT WHICH THE RECORDINGS WERE MADE

TUROA 1752 m a.s.l.
WHAKAPAPA 1755 m a.s.l.

SNOW SURFACE CONDITIONS

COMPACTED SNOW
CRUSTY SURFACE
MELTING SURFACE
HARD WET SURFACE
ICEY SURFACE
SLUSHY SURFACE
SOFT POWDERY SURFACE

TEMPERATURES

THE DAILY RANGE IS INDICATED BY THE MAX. AND THE MIN. READ AT 0900 hrs N.Z.S.T.

B.R.K.

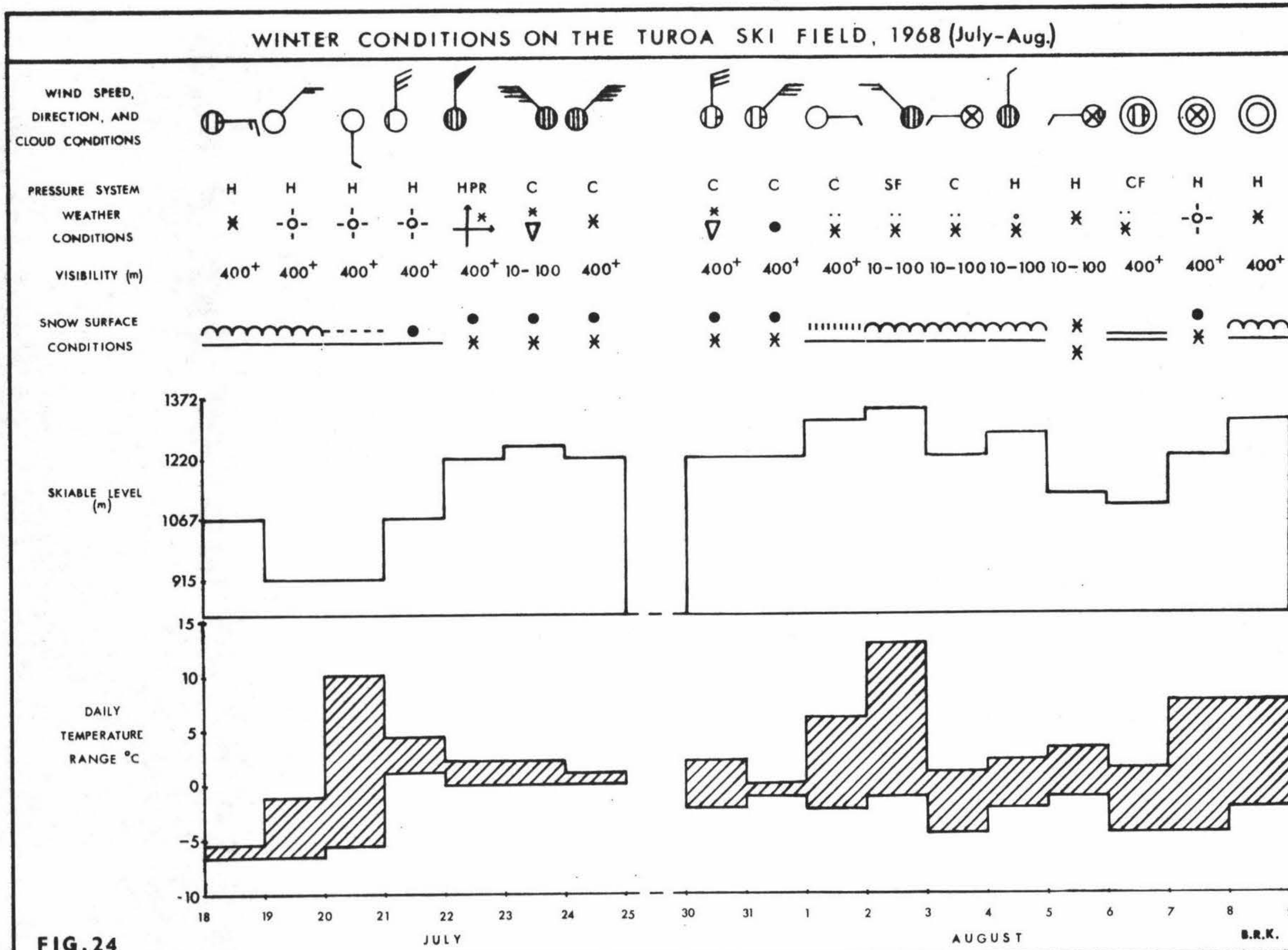

WINTER CONDITIONS ON THE TUROA SKI FIELD, 1968 (July-Aug.)
WIND SPEED, DIRECTION, AND CLOUD CONDITIONS
PRESSURE SYSTEM
H H H H HPR C C C C C SF C H H CF H H
WEATHER CONDITIONS
VISIBILITY (m)
400+ 400+ 400+ 400+ 400+ 10-100 400+ 400+ 400+ 400+ 10-100 10-100 10-100 10-100 400+ 400+ 400+
SNOW SURFACE CONDITIONS
SKIABLE LEVEL (m)
1372
1220
1067
915
DAILY TEMPERATURE RANGE °C
15
10
5
0
-5
-10
18 19 20 21 22 23 24 25
JULY
30 31 1 2 3 4 5 6 7 8 9
AUGUST
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FIG. 24

WINTER CONDITIONS ON THE TUROA SKI FIELD, 1968 (Sept.– Oct.)

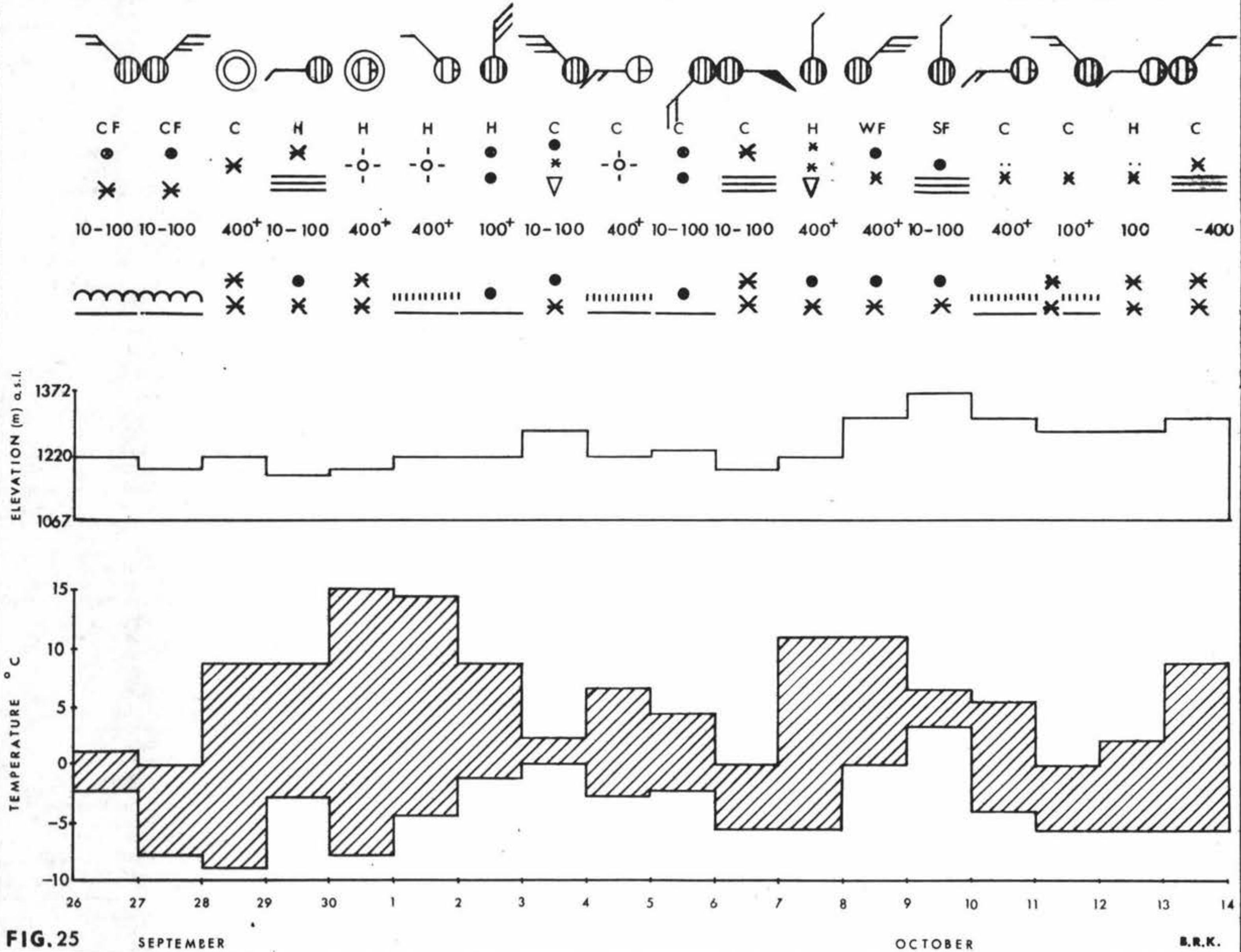


FIG. 25

Unfortunately temperatures on the Whakapapa Ski Field were interpolated from The Chateau records using the lapse rate and, as a consequence, were likely to have been mitigated somewhat. For instance maximum temperatures in July and August were generally higher on the Turoa Ski Field (see Figs.24 and 26), while a similar pattern emerged when the two ski fields were compared in September and October (see Figs.25 and 27). Apart from giving a somewhat misleading relationship between the maximum temperatures and the state of the surface, this disparity was not thought to have been of much consequence. In the overall differences, the temperature range did, however, demonstrate the diurnal temperature range associated with the various weather conditions. The most obvious conclusion from these figures was that the temperature range on both the ubac and adrêt slopes were higher under anticyclonic conditions than under cyclonic conditions. On the ubac slopes these conditions did not appear to have been associated with a rise in the skiable level to the same extent as on the adrêt slopes. Further investigations showed that this was partly due to the increased cloud cover over the ubac field.

Similarly the influence of condensation on melting appeared to have been greater on the Turoa Ski Field, e.g. October 7 to 10, 1968, when, under conditions of high winds and warm rain, the skiable level was raised over 170 m (see Chapter 3, Part II). Surface conditions seemed to have been affected in a similar manner. Low cloud and associated fog conditions on the Turoa Ski Field frequently led to harder surfaces, while the influence of strong westerly winds often led to white out conditions and crystalline surfaces. Such surfaces are particularly fast for skiing. When clear weather prevailed, nocturnal cooling took place, but minimum temperatures appeared to be persistently lower under such

WINTER CONDITIONS : WHAKAPAPA SKI FIELD, 1968 (July – Aug.)

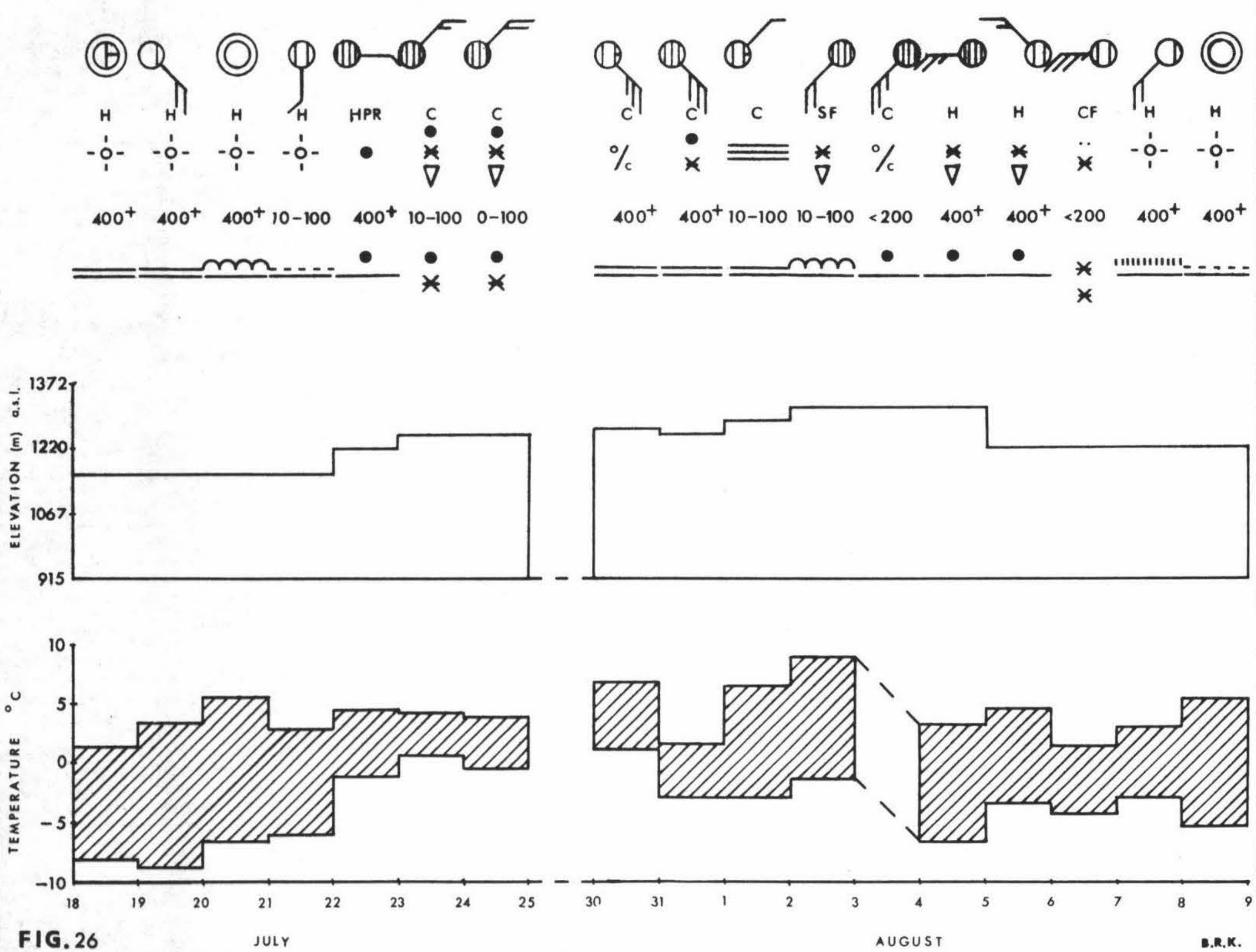


FIG. 26

WINTER CONDITIONS : WHAKAPAPA SKI FIELD, 1968 (Sept.-Oct.)

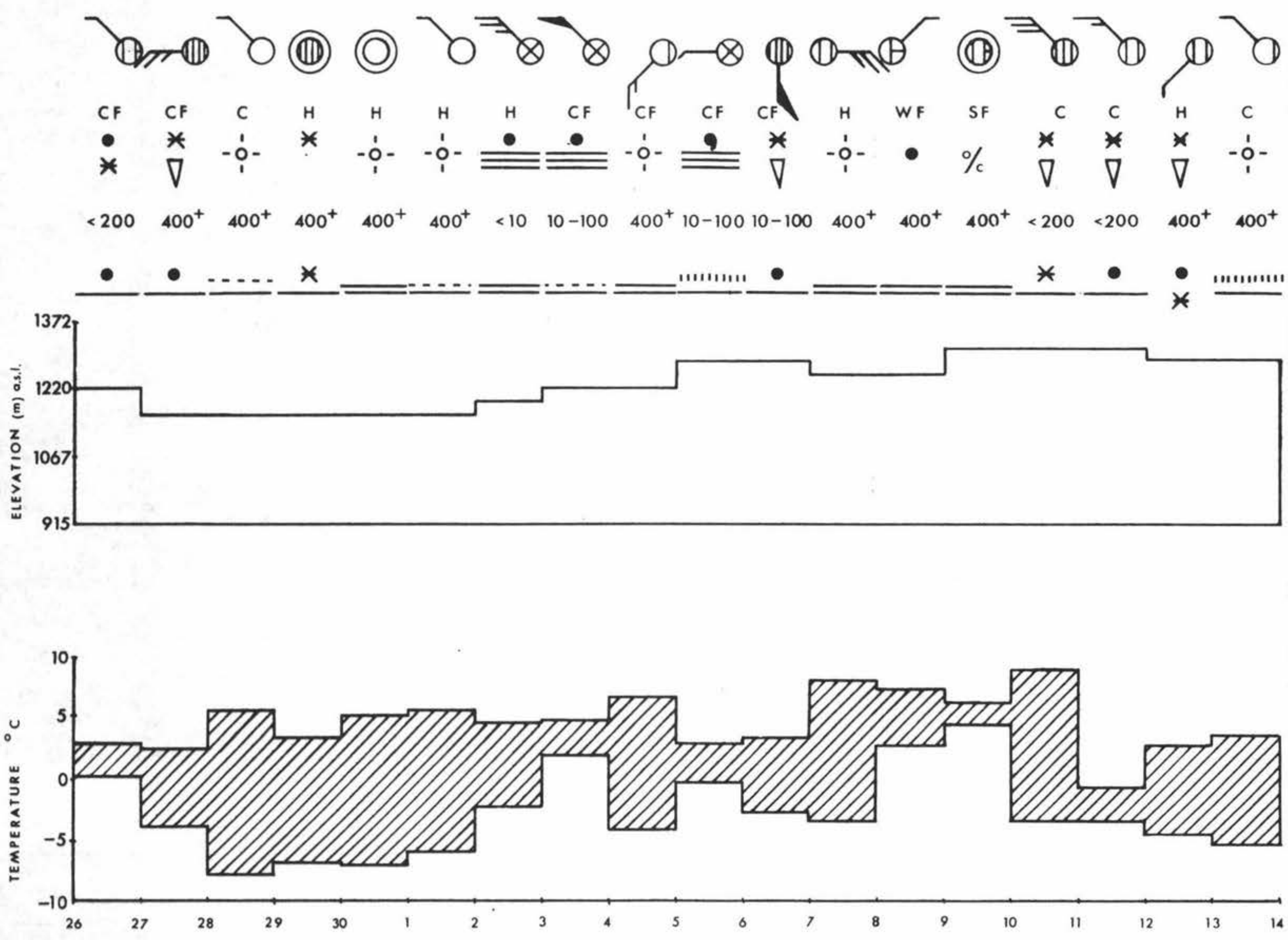


FIG. 27

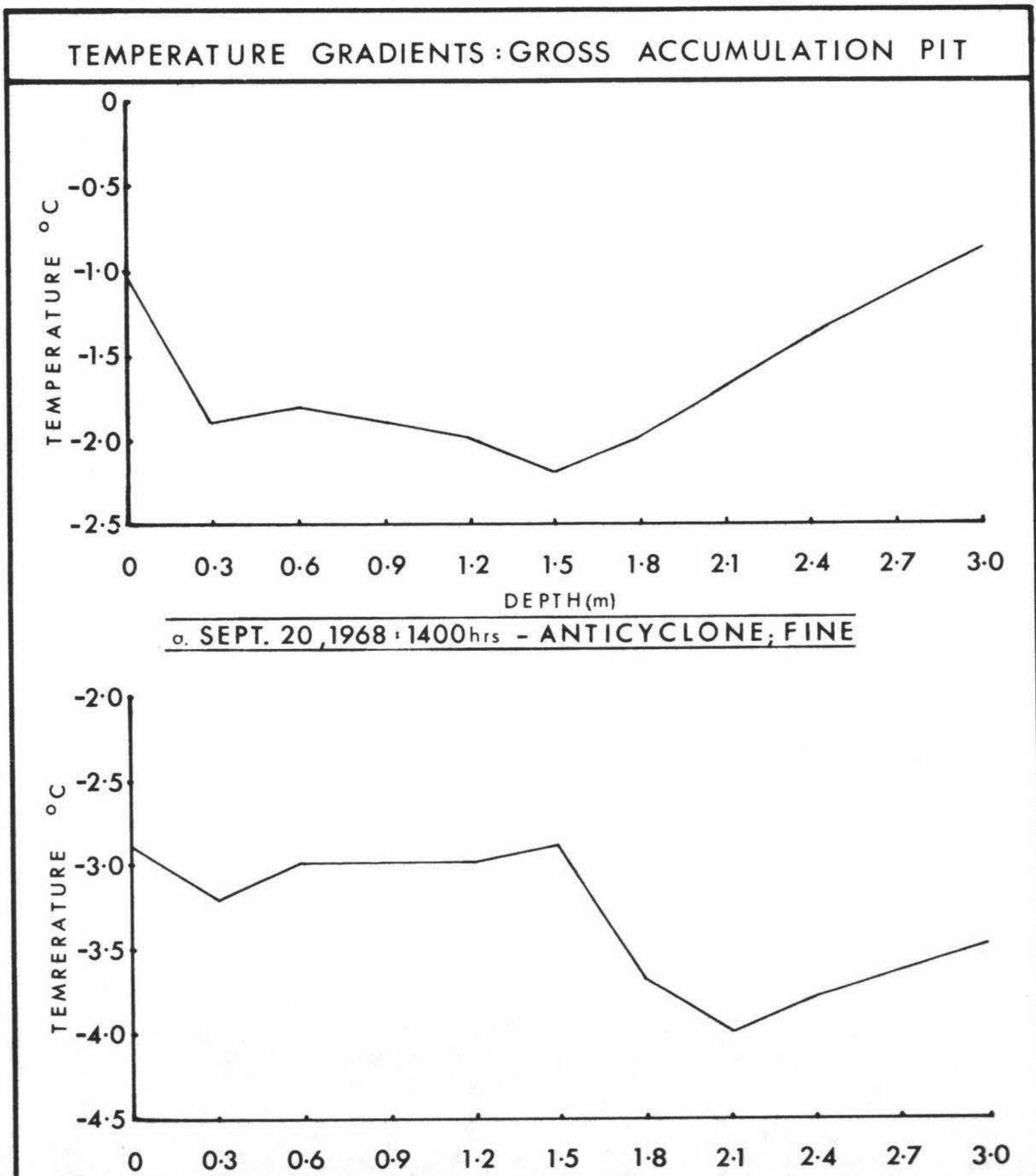
conditions on the Whakapapa Ski Field.

A further notable difference was that metamorphosis, resulting from the above factors, was somewhat slower on the Turoa Ski Field so that surface névé densities were likely to have been lower than on the Whakapapa Ski Field. This would have meant that the albedo was slightly higher, a situation which would have contributed to reduced ablation under anticyclonic conditions. As a result the skiable level was often lower on the Turoa Ski Field.

Stratigraphy and Crystallography and Cold Wave Penetration

La Chapelle's experiences on the Blue Glacier in the 1960s have shown that conditions of low cloud and fog during the winter imposed a uniform temperature regime at the snow surface and on the adjacent air and atmospheric moisture. Under such conditions long wave radiation was greatly reduced and riming and hoarfrost formations were prevalent.

Like the Blue Glacier, winter snowfalls on the Whakapapanui normally occurred at temperatures between 0^{o} and $-5^{o}C$. La Chapelle (1961) reported that "the relatively warm character of the accumulated snow cover (on the Blue Glacier), plus the insulating effect of the thickness attained by this cover in early winter, prevent any strong cooling of the underlying firn or ice." These factors, together with the downwards percolation of meltwater and rain, hindered the formation of deep temperature gradients (see Fig.28). Measurements in 1957/8, taken at the Snowdrome micro-meteorological station on the Blue Glacier, indicated that sub-freezing temperatures penetrated to a maximum depth of 4 m into the firn. Névé densities on the Blue Glacier varied from approximately 0.15 g/cm^3 in the upper layers up to 0.50 g/cm^3 in the basal



a. SEPT. 20, 1968 : 1400hrs – ANTICYCLONE; FINE

b. SEPT. 22, 1968 : 1500hrs – CYCLOGENESIS; WHITEOUT

FIG. 28

layers and contained fewer ice bands (Sharp, 1960), indicating that a much greater proportion of air was trapped in this névé than on the Whakapapanui Glacier. On the latter, névé densities varied between 0.35 g/cm^3 in the upper layers and 0.58 g/cm^3 in the basal layers. The reduced proportion of air in the névé meant that it acted as a better conductor and hence could have been expected to have conducted the cold wave to greater depths. The presence of ice bands down to depths of 10 m or more on the Whakapapanui did not necessarily confirm the penetration of the cold wave to these depths, for these ice bands may have been only buried surface meltsurfaces.

The importance of meltwater in the densification of the Whakapapanui can be seen in a comparison with the Greenland Ice Cap. Lying beyond the 60° parallel in the Northern Hemisphere, its grain structure, as a result of reduced melting and a slower rate of recrystallisation, was much smaller. On the surface the order of magnitude of individual snow grains was only 0.1 mm across, while at 14 m depth they increased to 2 mm (Benson, 1961) compared with 2.5 to 5 mm grains in the upper 30 cm of firn on the Whakapapanui.

From ice cores taken on the Gilman Glacier at elevation 1,040 m a.s.l. densities and grain sizes were found to vary according to the degree of soaking of the snowpack. With partial soaking of the snowpack, crystals varied from 1 to 5 mm in diameter and ice had a density of 0.82 g/cm^3, while at the other extreme superimposed ice (0.87 g/cm^3) crystals varied from 1 to 10 mm. The condition of the snowpack at the 1,450 m level was similar in many respects to the Whakapapanui at 2,273 m. By the end of summer the névé on the Gilman Glacier had become completely soaked and was transformed into a basal ice layer overlain by coarse grained firn (Hattersley-Smith, 1963). Despite these similarities the firn stratigraphy on the Gilman Glacier was characterised by an almost complete absence of ice layers below 9.5 m, indicating that there was virtually no melting beyond this depth, whereas melting existed at least down to 11 m on the Whakapapanui Glacier.

Net Budgets

Valid comparisons between net budgets of glaciers were not possible for measurements were not available for synchronous budget years.

GENERAL CONCLUSIONS

Short term projections have been made concerning the future of the Whakapapanui Glacier, but no overall assessment of its pending state of health has yet been made.

The state of the glacier prior to the 1968/9 budget year led to the belief that the glacier was nearing the end of its existence. The magnitude of the positive budget in 1968/9, however, together with the trends toward increased precipitation and decreased temperature, could have meant that a rejuvenation of glacial activity on Mt Ruapehu was imminent. Whether this tendency would be sustained or not depended essentially on the position of the firn line. Not until the firn line was again lowered to the present level of the snout of the Whakapapanui Glacier (2,273 m), around the entire mountain, would there have been any significant resurgence of glacial activity. In the light of the evidence presented, this did not appear to be completely out of the question, but its length of survival seemed to depend on just how soon this would occur. If, however, downwasting comparable in rate to the mid- and late 1950s were to resume, then the glacier would be unlikely to survive more than a few years.

In assessing the merits of hydrological budget studies it must be remembered that only about 1 percent of the total ice on earth is stored in snow and glaciers, even though most of this is stored in mountain glaciers (Hoinkes, 1968). With 99 percent of the world's ice in polar regions, we cannot expect to discern the nature and causes of glaciers from such localised and remote measurements as performed on the Whakapapanui Glacier. Nevertheless, consideration of the water budget and its relationship with the meteorologic environment has, in the writer's opinion, led to an increased understanding of the mechanics of the water cycle as it affects and is affected by the glacier.

While the size of the glacier was somewhat prohibitive to experiments intended to relate the general meteorologic environment to its dynamic responses, it did favour other forms of climate/glacier studies. In particular it was a most suitable laboratory for analysing the interaction of the atmosphere with the state of the glacier. Almost the full range of surface conditions were encountered in the space of one budget year, while the density and albedo of the medium with which the atmosphere interacted varied throughout the year from one extreme to the other. This makes the Whakapapanui Glacier a logical site for glacio-meteorologic experimentation on all three scales—micro-, meso- and macroscopic—for the complete effects of such experiments would be readily apparent after only a relatively short period of time.

NOTE

Owing to the occurrence of the longest and driest summer on record (Meteorological Office Broadcast) during the 1969/70 budget year, the glacier experienced a negative net budget losing not only the firn which had remained at the end of the 1968/9 budget year, but a considerable volume of true glacier ice as well.

A visit to the glacier on March 6, 1970 revealed that a yellowish sediment-embedded layer of ice was uppermost on the surface of the glacier. Ice corings taken in May 1969 indicated that this yellowish band had been overlain by a clear band of ice. It varied in thickness from approximately 3.0 m on the upper eastern margin of the glacier to 1.0 m on the lower eastern margin, while it increased to 4.6 m at the Meltwater Hole. Assuming that an average depth of 2.9 m of ice of density 0.90 g/cm^3 had been lost, over the entire glacier, during the 1969/70 ablation season, this would have given a total water loss resulting from ice melt of 37,280 m^2 x 2.61 m = 778,800 m^3. This was without taking into account the loss of ice resulting from the formation of numerous meltwater subsidence holes extending right to the base rock. However, the existence of a layer of andesitic mud and ash (resulting from the June 22, 1969 eruption of Mt Ruapehu) thick enough to retard ablation and preserve the ice on much of the eastern and central portions of the glacier, was likely to have cancelled out the loss of water resulting from the formation of numerous meltwater subsidence holes.

The total water loss during the 1969/70 ablation season would have been equal to the volume of firn remaining at the end of the 1968/9 budget year (76,800 m^3 water), together with the volume of névé lost (estimated value = 150,000 m^3), plus the volume of ice (778,800 m^3 water), which equalled 855,600 m^3 water. This value would have been somewhat conservative, for the ablation season continued until about the middle of March before the first snowfalls of the 1970/1 accumulation season. This is evidenced by the 135 m recession of the glacier snout in the seven weeks between February 26 and April 18, 1970 (based on actual measurements on these two dates). By the end of the 1969/70 budget year, therefore, the glacier had been reduced to a state of fragmentation consisting of little more than an aggregation of ice pockets separated by huge meltwater holes and being completely beyond rejuvenation.

All this indicates that a climatic change, which may be mathematically insignificant, could be sufficient to engender profound changes in the climate/glacier relationship.

APPENDICES

APPENDIX I

ANALYSIS OF AIRFLOW TYPES

(Full Hydrological Years)

Weather Type: Cyclogenesis to the North

Airstreams: CN, CSE, CE, CNE

Years	1963-9		1963/4		1964/5		1965/6		1966/7		1967/8		1968/9	
R.F. (mm)	f	%f	f	%f	f	%f	f	%f	f	%f	f	%f	f	%f
0	116	37.9	9	30.0	12	28.6	11	25.0	40	50.0	30	45.4	14	31.1
.005-.24	75	24.5	3	10.0	11	26.2	11	25.0	20	25.0	13	19.7	17	37.8
.25-.49	42	13.7	6	20.0	8	19.0	7	15.9	7	8.7	6	9.0	8	17.8
.50-.74	28		5		6		5		4		7		1	
.75-.99	10		2		3	26.2	1		2		2			
1.00-1.24	8		1		1		2		3			25.8	1	
1.25-1.49	7		1		1		2		1		1		1	
1.50-1.74	8						2				4		2	
1.75-1.99	2		1								1			
2.00-2.24	1						1	34.1						13.3
2.25-2.49	2		1								1			
2.50-2.74	1			40.0							1			
2.75-2.99	1								1					
3.00-3.24	1	23.9					1			16.3				
3.25-3.49	1						1							
3.50-3.74	1								1					
3.75-3.99	1													
4.00-4.24													1	
4.25-4.49			1											
4.50-4.74														
4.75-4.99														
5.00-5.24														
5.25-5.49	1								1					
Total	306		30		42		44		80		66		45	
$\overline{x}$	0.34		0.57		0.26		0.42		0.22		0.31		0.31	
f < $\overline{x}$	220		22		27		228		58		47		36	
%f < $\overline{x}$	71.9		73.3		64.3		63.6		73.4		71.2		80.0	

Weather Type: Cyclogenesis to the South

Airstreams: CSW, CW, CNW, CS

Years	1963-9		1963/4		1964/5		1965/6		1966/7		1967/8		1968/9	
R.F. (mm)	f	%f	f	%f	f	%f	f	%f	f	%f	f	%f	f	%f
0	206	28.5	35	27.3	32	20.0	36	30.0	23	28.7	31	34.4	49	33.8
.005-.24	203	28.1	39	30.5	40	25.0	33	27.5	20	25.0	29	32.2	42	29.0
.25-.49	92	12.7	15	11.7	24	15.0	15	12.5	19	23.8	6	6.7	13	9.0
.50-.74	65	9.0	16	12.5	17	10.8	9	7.5	7	8.8	5	5.6	11	7.6
.75-.99	47	6.5	8	6.3	12	7.5	11	9.2	2	2.5	5	5.6	9	6.1
1.00-1.24	42)	9.8	4)	4.7	17)	8.2	7)	9.2	3)	8.7	5)	13.3	6)	8.3
1.25-1.49	29)		2)		6)		4)		4)		7)		6)	
1.50-1.74	13	↑	3	↑	2	↑	1	↑	1	↑	2	2.2	4	↑
1.75-1.99	5		1		2		1						1	6.2
2.00-2.24	6		1		2		1			2.5			2	
2.25-2.49	5		1		2								2	↓
2.50-2.74	2		1	7.0				4.1	1	↓				
2.75-2.99	2		1		1									
3.00-3.24	2	5.4			1	7.5	1							
3.25-3.49	1				1									
3.50-3.74	2		1	↓			1	↓						
3.75-3.99														
4.00-4.24														
4.25-4.49	1	↓			1	↓								
4.50-4.74														
4.75-4.99														
5.00-5.24														
5.25-5.49														
Total	723		128		160		120		80		90		145	
$\bar{x}$	0.39		0.40		0.54		0.39		0.31		0.30		0.35	
f < $\bar{x}$	482		86		108		81		55		64		100	
%f < $\bar{x}$	66.7		67.2		67.5		67.5		68.7		71.1		69.0	

Weather Type: Anticyclones to the North

Airstreams: ANW, AW, AS, ASW

Years / R.F. (mm)	1963-9 f	1963-9 %f	1963/4 f	1963/4 %f	1964/5 f	1964/5 %f	1965/6 f	1965/6 %f	1966/7 f	1966/7 %f	1967/8 f	1967/8 %f	1968/9 f	1968/9 %f
0	378	54.7	79	60.2	58	56.9	65	50.4	52	46.0	64	57.7	60	56.1
.005-.24	144	20.8	26	20.5	16	15.7	33	25.6	27	23.9	23	20.7	19	17.8
.25-.49	49	7.1	6	4.6	4	3.9	13	10.1	11	9.7	8	7.2	7	6.5
.50-.74	37	5.3	6	4.6	5	4.9	10	7.7	4	3.6	4	3.6	8	7.5
.75-.99	27	3.9	6	4.6	5	4.9	1	0.8	5	4.4	4	3.6	6	5.6
1.00-1.24	11	↑	1	↑	3	↑	2	↑	3	↑	1	↑	1	↑
1.25-1.49	16				4		4		3		4		1	
1.50-1.74	8		3	5.5	1	13.7			1		1		2	
1.75-1.99	7		1		2			5.4	2	12.4	1		1	
2.00-2.24	9		2	↓	3				3				1	
2.25-2.49	1	8.2			1	↓						7.2		6.5
2.50-2.74	1								1					
2.75-2.99	2						1	↓	1	↓				
3.00-3.24														
3.25-3.49														
3.50-3.74														
3.75-3.99	2	↓									1	↓	1	↓
4.00-4.24														
4.25-4.49														
4.50-4.74														
4.75-4.99														
5.00-5.24														
5.25-5.49														
Total	690		127		102		129		113		111		107	
$\overline{x}$	0.18		0.12		0.25		0.14		0.28		0.12		0.24	
f < $\overline{x}$	486		92		76		84		85		76		79	
%f < $\overline{x}$	70.4		72.4		74.5		67.2		75.2		68.5		73.8	

Weather Type: Anticyclones to the South

Airstreams: AN, ANE, ASE, AE, A

Years / R.F. (mm)	1963-9 f	%f	1963/4 f	%f	1964/5 f	%f	1965/6 f	%f	1966/7 f	%f	1967/8 f	%f	1968/9 f	%f
0	297	62.9	54	69.2	32	52.5	41	56.1	65	69.9	68	68.0	37	55.2
.005-.24	75	15.9	11	14.1	14	22.9	11	15.1	10	10.7	17	17.0	12	17.9
.25-.49	26	5.5	3	3.9	3	4.9	5	6.9	5	5.4	4	4.0	6	8.9
.50-.74	26)	8.5	1)	1.3	5)	13.1	7)	12.3	4)	9.7	5)	6.0	4)	10.5
.75-.99	14)		0)		3)		2)		5)		1)		3)	
1.00-1.24	7		2		2				1				2	
1.25-1.49	13		5		1		5		1		1			
1.50-1.74	5			11.5		6.6	1		1	4.3	1	5.0	2	
1.75-1.99	1		1											7.5
2.00-2.24	3	7.2			1			9.6			2			
2.25-2.49	3		1						1		1			
2.50-2.74														
2.75-2.99	1												1	
3.00-3.24														
3.25-3.49	1						1							
3.50-3.74														
3.75-3.99														
4.00-4.24														
4.25-4.49														
4.50-4.74														
4.75-4.99														
5.00-5.24														
5.25-5.49														

	1963-9	1963/4	1964/5	1965/6	1966/7	1967/8	1968/9
Total	472	78	61	73	93	100	67
$\overline{x}$	0.17	0.13	0.16	0.21	0.07	0.09	0.19
$f < \overline{x}$	350	60	41	51	68	74	46
$\%f < \overline{x}$	74.2	76.9	67.2	69.9	73.1	74.0	68.7

$$\overline{x} = xd + \left(\frac{\sum fx}{N}\right) \times i$$

where xd = assumed mean, i = class interval and N = total no. of frequencies.

$f < \overline{x}$ indicates the degree of normalcy of the distribution.

$f < \overline{x}$ = $\sum f$ below lower limit of class with $\overline{x}$ + $\overline{x}$/upper limit of class with $\overline{x}$ x f in class containing the $\overline{x}$.

e.g. $f < \overline{x}(1963-9) = 297 + \frac{0.17}{0.24} \times 75$

$= 297 + 53$

$= 350.$

The abnormal frequency distributions in these tables show that it is unwise to base any comparisons between years on the mean value alone. It is necessary to conduct a Chi-Squared Test to establish whether there are any significant differences between the different years and where they lie.

[The same pattern was repeated for the accumulation and ablation seasons taken separately.]

APPENDIX II

CALCULATION OF CHI-SQUARED VALUES

Chi-Squared (X^2) values were calculated using the formula

$$X^2 = \sum \frac{(o - e)^2}{e}$$

where o = observed frequencies, and e = expected frequencies.

The Degrees of Freedom values (n) were calculated using the formula

$$n = (n_1 - 1)(n_2 - 1)$$

where n_1 is the number of items in one column of frequencies and n_2 is the number of items in one line of frequencies.

APPENDIX III

(a) REGRESSION COEFFICIENTS

Calculation of Regression Coefficients and the equations for the Regression Lines of Total Rainfall and Mean Monthly Temperatures over the six years from 1963/4 to 1968/9 are set out below.

First, it was necessary to calculate the deviation of each value from the mean of each set of data. The two sets of figures (q and t) obtained from these calculations were then multiplied together for each year to give the values (qt). These were then summed to give a total deviation which was in turn divided by the number of pairs of data to give the Co-Variance. The Product Moment Correlation Coefficient (r) was calculated using the formula

$$r = \frac{\frac{1}{n}\sum(a - \bar{a})(b - \bar{b})}{\sigma a.\sigma b} \qquad \text{or } r = \frac{\frac{\sum ab}{n} - \bar{a}.\bar{b}}{\sigma a.\sigma b}$$

where σa and σb were the standard deviations of the two sets of data a and b about their respective means, calculated from the formula

$$\sigma = \sqrt{\frac{\sum x^2}{n} - \bar{x}^2}.$$

(b) COEFFICIENT OF VARIATION

To obtain the "best estimate" of the Coefficient of Variation the hypothetical b values (see p. 185) were subtracted from the actual recorded values of b. This difference was expressed as a percentage of the expected values, all of which were then summed and squared. From the resulting values the "best estimate" of the percentage variance was obtained after dividing by n - 1. Lastly, the square root of the variance gave the "best estimate" of the percentage standard deviation. This final figure was the variability which occurred due to "factors other than those producing the overall patterns" (Gregory, 1968).

(c) COEFFICIENT OF DETERMINATION AND CORRELATION SIGNIFICANCE TEST

The Coefficient of Determination = $r^2 \times 100$.

This formula demonstrates that almost 74 percent of the rainfall variations can not be explained from the corresponding temperature data, for the Coefficient of Determination value was only 26 percent. This figure of 26 percent is considered to be reliable, having been ascertained as valid using the Correlation Significance Test:

$$t = \frac{r.\sqrt{n - 2}}{\sqrt{1 - r^2}}$$

when $r = -0.513$ and $n = 12$.

Hydrological Year Mean Temperature Trends

Average Values: $\overline{a} = \overline{q}$ + assumed mean of a $\quad \overline{b} = \overline{t}$ + assumed mean of b

$= 6.5 \quad\quad = 46.21$

Regression Coefficient of t on q

$Y = -0.57$

Base Constant $= \overline{b}$ - Regress.Coeff. $\overline{a}$

where $\overline{b} = 46.21$ and $\overline{a} = 6.5$

then substituting

Base Constant $= 46.125 - (-0.57 \times 6.5)$

$= 49.82^{\circ}F.$

The Equation for the Regression Line is

$b = 49.82 - 0.57.a$

Metric Equivalent (mm) $\quad b = 9.90 - 0.31.a$

Regression Line Formulae for the Accumulation and Ablation Seasons

The Regression Line Equation for the Accumulation Season Rainfall Totals is

$b = 44.30 + 1.819.a$

Metric Equivalent (mm) $\quad b = 1125.22 + 46.2.a$

The Regression Line Equation for the Accumulation Season Mean Temperatures is

$b = 44.38 - 0.54.a$

Metric Equivalent (mm) $\quad b = 6.88 - 0.30.a$

The Regression Line Equation for the Ablation Season Rainfall Totals is

$b = 48.78 + 0.287.a$

Metric Equivalent (mm) $\quad b = 1239.01 + 7.28.a$

The Regression Line Equation for the Ablation Season Mean Temperatures is

$b = 54.55 - 0.517.a$

Metric Equivalent (mm) $\quad b = 11.41 - 0.278.a$

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