HYDROLOGICAL BUDGET STUDIES ON GEOPHYSICALLY TEMPERATE GLACIERS*

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ABSTRACT

Glaciology is defined as the study of the origin, composition, distribution and physics of snow and ice. The glacier itself forms a surface for the interaction of energy and mass, which represents the budget approach to climatology and hydrology.

The paper outlines the techniques and results of budget studies in a maritime-polar glacial environment. It refers particularly to the influence of meteorological parameters on the glacial hydrology and describes actual budget measurements together with englacial temperature structures and surface velocity patterns. The paper emphasizes the great need in New Zealand for similar snow and ice research and outlines the aims of a proposed I.H.D. project.

INTRODUCTION

During 1961 and 1962 the writer completed glaciological research on the Orwell Glacier at Signy Island in British Antarctic Territory (Fig. 1). The research project was designed as a contribution towards the clarification of the critical relationship between subantarctic glacial hydrology and meteorological parameters. The hydrological budget of the glacier was measured, particularly the changes in glacier mass associated with water movement on to, within and from the glacier.

TERMINOLOGY

Névé — snow accumulation deposited in a current budget year (density 0.36 g/cm^3).

Firn — at the end of the summer season the previous winter's névé is obliterated by new snow deposition to become true firn (density 0.55 g/cm^3).

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Ablation — wastage of ice and snow by melting, evaporation, deflation and iceberg calving.

Firn line — the highest elevation on a glacier where the entire névé accumulation is removed by ablation. At the end of the ablation season the area below the firn line is composed of bare glacier ice, while above it some of the winter névé remains.

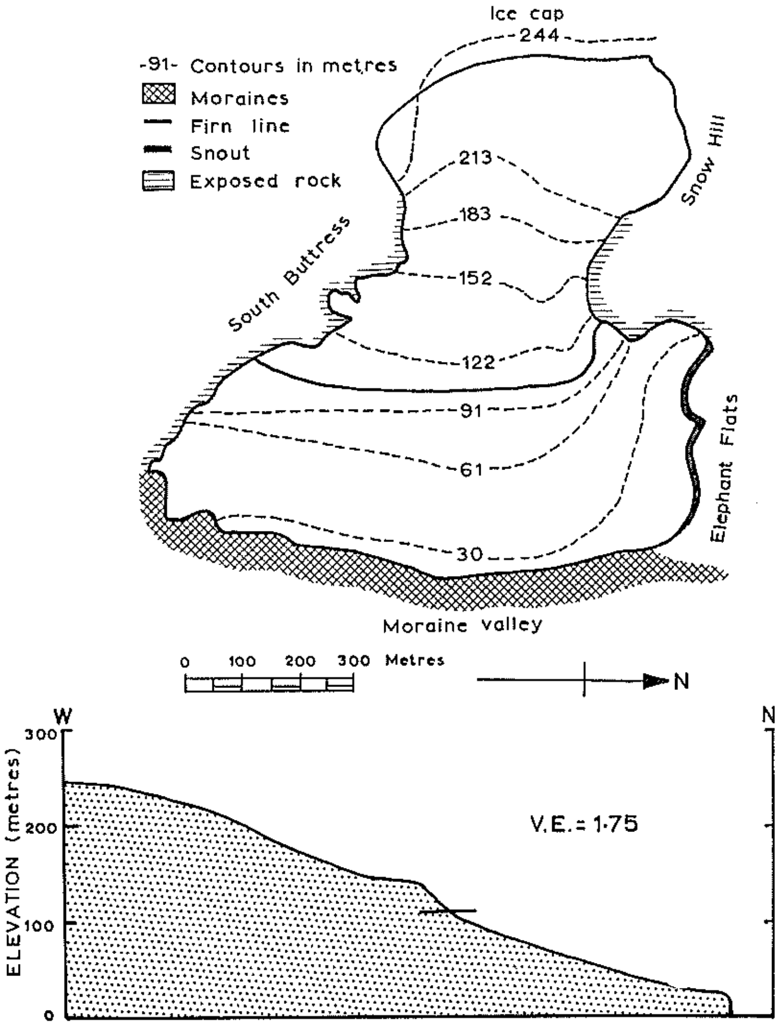

Fig. 1 — The Orwell Glacier — contours and medial cross section.

METHODOLOGY

The meteorological-hydrological relationships were measured on a macro- and microscopic scale. The former analysis involved the evaluation of glacier fluctuations in terms of available and easily measured synoptic parameters. The micro-investigations were concerned with the energy-transfer processes and the actual energy exchange at the glacier surface.

Budget computations involved the measurement of accumulation and ablation by means of closely distributed stakes; the density/water equivalent of the accumulation was determined by pit excavations at the end of the season. Density measurements in the névé remaining above the firn line at the end of the ablation season indicated the actual amount of surface meltwater refrozen in the névé as part of the firnification process (i.e. net ablation).

The geophysical condition of the glacier was determined by F 22-type thermistors which measured the penetration of the winter cold wave down to 16 metres depth in the glacier ice.

The surface velocity of the glacier was measured by triangulation from theodolite stations at either end of a base line and the position of each stake was plotted by rectangular coordinates.

REGIONAL AND LOCAL ENVIRONMENTS

Signy Island (60° 43′ S, 45° 36′ W) is situated about 1300 kilometres south-east of Cape Horn and is one of the smallest islands in the South Orkney group. The position is dominated by the Scotia Sea zone of moisture and warmth to the north (southern maritime air masses) and the Weddell Sea ice reservoir to the south which represents a zone of dry, cold, stable polar continental air masses.

The South Orkneys project into the circumpolar low-pressure trough of the Southern Ocean, a cyclogenetic region where wave depressions develop and migrate eastwards. The maritime airstreams and dynamic perturbation of these disturbances encourage an active hydrological budget with significant ablation and accumulation. Ablation is accentuated by the location of mountainous Coronation Island some three kilometres to the north, which introduces foehn heating with the northerly airstreams before the warm front. Such conditions were evident in January 1961 when 43,000 m^3 water of glacier ice (20% of the season's wastage) were ablated at the colossal rate of 1,800 m^3 per hour.

Blocking anticyclones extend from the semi-permanent high-pressure belts to the north and south, and the associated dynamic subsidence terminates glacial activity in the form of accumulation or ablation. The extension is especially common in winter when a low frequency of northerly airstreams facilitates sea-ice consolidation and continentality.

The Orwell Glacier is an outlet-type glacier where the Signy ice cap spills through a col and cascades some 240 metres to sea level. It is situated on the eastern side of the ice cap where lee waves and helm winds in the prevailing westerly airstream concentrate snow deposition in the sheltered col between 116 and 168 metres.

The areal coverage of the glacier was approximately 500,000 m^2, of which some 50% was below the firn line (110 metres in 1962) to represent a considerable area experiencing ablation of névé and ice.

RELATIONSHIP BETWEEN METEOROLOGICAL ELEMENTS AND GLACIAL HYDROLOGY

Ablation

The energy transfers involved in the ablation process are as follows:

Radiative — the effectiveness of solar radiation and the absorption of insolation are kept to a minimum by the high degree of cloudiness (mean 7.1 octas) and the albedo of the glacier surface (70% reflectivity).

Sensible heat — conduction between the glacier surface and the overriding 'warm' southern maritime airstream, which is accelerated by atmospheric turbulence (eddy diffusion) removing the chilled stable air and renewing the supply of warmer air in contact with the glacier.

Latent heat — condensation of water vapour on to the glacier surface when moist air is chilled below the dew point, releasing 600 calories per gram of water. Again, this transfer process is prolonged when atmospheric turbulence renews the supply of moist air.

The effectiveness of the heat transfers decreases with increasing altitude and the temperature lapse rate. Continentality limits the role of these ablation components since the ocean is the source of warmth and moisture.

The percentage contribution of the energy-transfer mechanism was dominated by the latent and sensible heat transfers (73% of ablation) and this represents a typical maritime situation at low elevations where frontal disturbances are common. The southern maritime airstream was responsible for the heat transfers and, during the ablation season, the months with significant ablation rates were related to those with the highest frequency of vigorous warm, moist northerly airstreams.

Accumulation

Névé deposition was attributed to the following factors: snow 82%, rime ice 16% and freezing rain 2%. The contribution of rime increased with altitude (40% of the ice-cap accumulation) and helm-wind deposition concentrated snow accumulation in the sheltered col above 116 metres. The accumulation of névé on the Orwell depends on a high frequency of wave depressions, with associated dynamic/frontal instability and moist airstreams, and the months with abundant snow deposition were those with the highest frequency of polar maritime airstreams.

HYDROLOGICAL BUDGET STUDIES

Accumulation

The water-equivalent measurements in the Orwell névé revealed that the density decreased with depth, to emphasize the influence of percolating and refreezing meltwater in névé densification. During the winter season on the Orwell, surface meltwater is associated with the passage of warm southern maritime airstreams. This water, however, percolates into the permeable cold névé and refreezes close to the surface; for example, meltwater infiltration was measured as 0.2 ml per hour but became frozen at about 15 cm depth where the névé temperature was −6.0°C. The pit excavations also indicated numerous ice bands in the névé which represented refrozen melt crusts, rime ice and freezing rain deposition. These impervious layers encouraged the lateral channelling of the meltwater and concentrated the refreezing near to the surface.

At the end of the accumulation season the névé density averaged 0.36 g/cm^3 and the 10% increase during the season was associated with the refreezing of 26,000 m^3 of percolating surface meltwater. The total accumulation equalled 182,000 m^3 water and 50% of this total was concentrated in the sheltered col.

Ablation

A characteristic feature of the Orwell ablation was the severe wastage of ice below the firn line in 1961 (202,000 m^3 water) and in 1962 (162,000 m^3). The greater ablation in the former year was due to more pronounced eddy diffusion with increased atmospheric turbulence. The glacier ice surface was lowered by more than one metre in successive ablation seasons and this rapid thinning appears to be a normal trend.

The net ablation below the firn line includes the entire winter névé deposition plus a considerable proportion of glacier ice, whereas above the line only part of the névé is ablated. The actual net ablation in the latter zone included the addition of percolating meltwater, especially at the end of the ablation season with the gradual destruction of the isothermal condition (the névé density had subsequently increased to 0.55 g/cm^3).

The total volume of net ablation was 287,000 m^3 water, and 80% of this total was ablated from below the firn line. It is interesting to note that the area just above the firn line lost 90% of its winter névé deposition; only 5,000 m^3 water of névé remained at the end of the summer season. The 1960 firn would have been exposed with a 13% extension in the length of the ablation season, or with mean increases of 0.2°C temperature and 0.3 knot wind speed during March 1962.

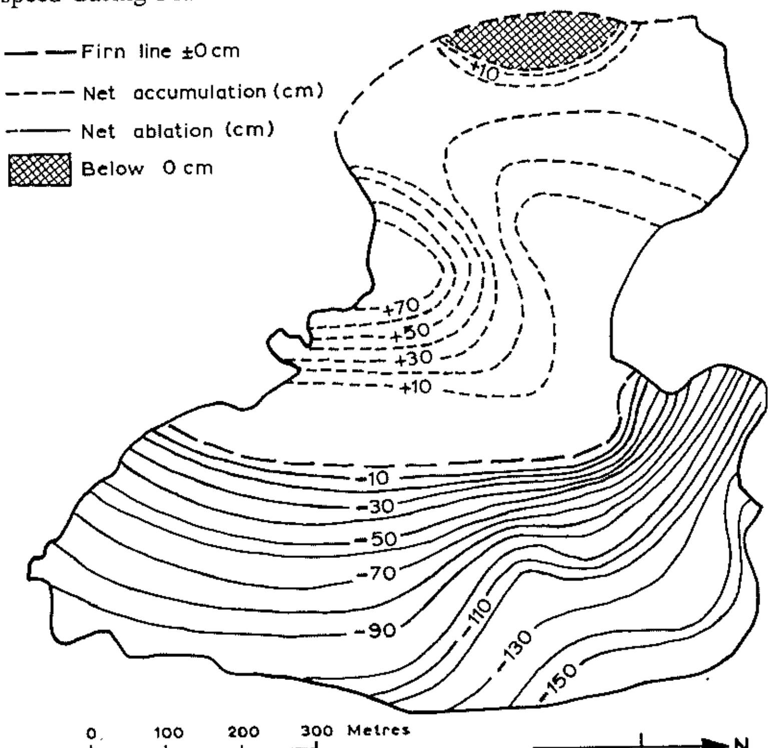

Fig. 2 — The Orwell Glacier — lines of equal net ablation and net accumulation, 1961 to 1962 budget year.

Budget Computations

The Orwell Glacier had a seriously negative budget of −105,000 m^3 water between 29/3/61 and 29/3/62. If the budget year considered is a normal climatological period then this outstanding deficit must eventually lead to severe shrinkage of the glacier.

Probability analyses of critical meteorological parameters indicated that, during the budget year considered, the rate of ablation was well below normal and the rate of accumulation was well above normal. Consequently the budget deficit of $-105{,}000\ m^3$ water is a very conservative estimate and glacial shrinkage will be accelerated under more normal meteorological conditions. The estimated length of 'survival' of the glacier ice below the firn line was calculated as approximately 50 years. By the early 21st century the glacial recession would have continued up to the firn line (110 metres) with considerable thinning in the areas above this limit.

GLACIOTHERMAL STUDIES

The geophysical investigations revealed that the glacier was temperate and influenced by the 'warm' maritime environment, being chilled by winter cold-wave penetration to a depth of 16

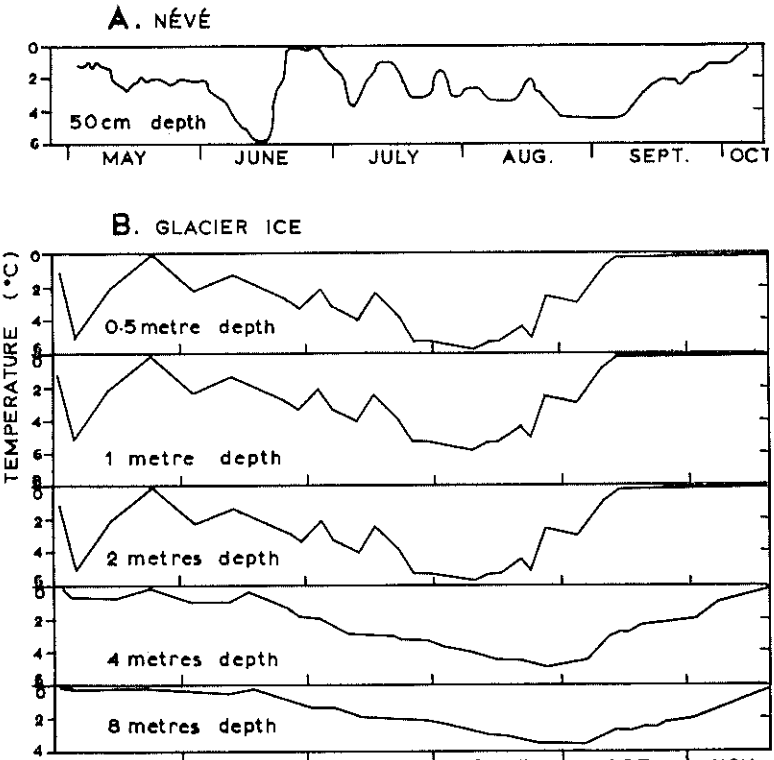

Fig. 3 — Thermal variations at depth in the Orwell Glacier during the winter chilling, 1961.

metres. Below this depth the glacier remained isothermal with englacial temperatures close to pressure-melting point. The magnitude and duration of the winter chilling was influenced by the migration of contrasting airstreams during the early accumulation season. The associated temperature variations were reflected sharply in the surface layers of the glacier but the penetration of these fluctuations into the basal layers of the ice was characterized by a considerable time lag and a markedly reduced amplitude of change (Fig. 3). Both these characteristics are related to the very low coefficient of heat conductivity in ice and névé.

Temperature changes were more rapid in the névé when associated with the percolation of surface meltwater during warm frontal conditions, and with the release of latent heat on refreezing. For example, in mid June 1961 the névé temperature at 50 cm depth increased by 6°C in four days following a meltwater flush in an abnormal midwinter foehn-thaw.

During periods of anticyclonic stability, glacier chilling by the slow conduction process continued without interruption so that at eight metres depth the maximum chilling was recorded some 25 days after the maximum at one metre (Table 1).

TABLE 1 — Magnitude of maximum chilling, Orwell Glacier 1961.

Englacial level (metres)	*Date of max. chilling*	*Maximum chilling (°C)*	*No. of days to reach max.*
½	7 Sept.	−5.7	99
1	7 Sept.	−7.3	99
2	13 Sept.	−5.2	105
4	24 Sept.	−4.8	116
8	2 Oct.	−3.7	124

After early September, renewed frontal activity and increasing insolation resulted in the general dissipation of the winter chilling and a gradual return to a completely isothermal condition. The amelioration was of course more rapid in the surface layers of the ice, and the isothermal return was 41 days later at a depth of eight metres compared with half a metre (Table 2).

TABLE 2 — The attainment of isothermal conditions, Orwell Glacier 1961.

Englacial level (metres)	*Date of return to pressure-melting point*	*Duration of cold-wave penetration (days)*	*No. of days of dissipation from max. chilling*
½	12 Oct.	122	23
1	5 Nov.	158	57
2	8 Nov.	161	56
4	16 Nov.	169	53
8	21 Nov.	172	48

GLACIER MOVEMENT

The surface velocity during the budget year was determined primarily as an indicator of the budget trends of the glacier in preceding years.

The transverse velocity curves indicated that the movement was greater near the centre of the glacier where the frictional retardation of the rocky peripheral zones is least and where the ice is thickest. The movement was modified by the slope of the underlying rock floor and the greatest distance of movement (15 metres) was recorded near the ice-cap 'spill over'. Generally the area above the firn line represented the zone of greatest movement, and this is associated with the zone of greatest accumulation.

The rate of flow of a glacier indicates the condition of the glacial regime; positive hydrological budgets represent an increasing load of firn and ice, and this is reflected eventually in significant glacier advance. For the Orwell Glacier as a whole the mean movement was quite negligible (466 cm between 18/4/61 and 21/3/62 or 1.5 cm per day) and this virtual stagnation must be related to negative budgets in recent years.

In 1949 the Orwell movement was found to be 468 cm or 1.4 cm per day, and the remarkably close similarity between the rates of movement emphasizes the stagnant characteristics of the glacier and the similarity between hydrological budgets in the years preceding both observations. This must be associated with consistently negative budgets and pronounced glacial thinning over at least the last two decades.

GLACIOLOGICAL RESEARCH ON NEW ZEALAND GLACIERS

The Orwell results have been outlined at some length because the writer considers that the programme of work could be readily adapted to geophysically temperate glaciers in New Zealand, where glacio-meteorological relationships are similar to those of the sub-antarctic maritime environment.

Despite the great potential for snow and ice research in this country and the increasing use of glacial meltwater for the nation's hydro-electric power development, hydrological budget studies involving glacier-climate relationships have been largely neglected on New Zealand glaciers.

There is a great need for the establishment of an active snow and ice research group in this country, composed of researchers from the Department of Scientific and Industrial Research, the Ministry of Works, the Meteorological Service and the Universities.

Such a group should be formed immediately to initiate and execute continuous, integrated glacio-meteorological projects from Mt Ruapehu through the Southern Alps to the Ross Dependency Territory.

The proposed project represents a five-year plan for glaciological investigations on selected New Zealand glaciers, and has been designed as an advanced continuation of the Orwell research programme outlined earlier. The aims of the project are as follows:

(1) To study the critical relationship between glacial hydrology and meteorological parameters on a macro- and microscopic scale. The latter investigations will be concerned with the energy-transfer processes (i.e. radiative, sensible heat and latent heat transfers) and with actual energy exchange at the glacier surface. The macro-study will concentrate on the influence of synoptic/dynamic climatology on the mass balance of the glaciers.

(2) To measure the hydrological budget of the glaciers in terms of net accumulation and net ablation of snow and ice. Stratigraphical investigations will determine the degree of moisture fluxes within the glacier and will also examine névé crystallography. The excavation of pits will indicate the density and water equivalent of the névé at the end of both the accumulation and the ablation seasons, and will reveal the role of refreezing percolating meltwater in névé/firn augmentation. The actual rate of percolation of surface water will be measured to assess its significance in the firnification process and in the superimposition of ice on the surface of the glacier. The run-off in meltwater streams will be measured at stream-gauging sites at the snout of the glacier, where the sediment transfer will also be analysed.

The excavation of tunnels and the drilling of cores in the firn and glacial ice will indicate the net accumulation over time, and measurements of the depth and density of the glacial strata will determine the water equivalent of past budget years. The normality of the current budget year will also be determined by statistical analyses of critical meteorological data.

(3) To determine the geophysical condition of the glacier in terms of being temperate ('warm' maritime environment) or polar ('cold' continental environment). Thermistors drilled to 16 metres depth will measure the glaciothermal 'regime' of New Zealand glaciers and will probably confirm their suspected temperate condition (dominated by warm moist airstreams at all seasons). Investigations will indicate the penetration of the winter cold wave into the glacier ice, especially during periods of anticyclonic stability, and the eventual return to an isothermal condition during the summer season. The proximity of the melting point above the firn line will lead to the percolation of surface meltwater and discharge into meltwater streams.

(4) To measure the horizontal and vertical components of velocity on the glacier. This will indicate the actual mechanics of motion and the glacial budget trends during preceding years. (Advancing glaciers will have active positive budgets with a high frequency of moist airstreams and pronounced dynamic instability.)

The project would represent a significant contribution to the New Zealand I.H.D. programme, especially in terms of hydro-electric potential and flood mitigation in areas affected by the run-off of glacial meltwater. The project would also clarify the neglected interaction of glacial development and synchronous climatic fluctuations in New Zealand.

Initially the project is directed at the accessible north- and south-facing glaciers on Mt Ruapehu with the help of under-graduate and postgraduate geographers from Massey University. But, with increased support, it will be extended to the Southern Alps and Ross Dependency Territory during 1969.