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ENERGY EXCHANGE AT A GLACIER SURFACE: AN ALTERNATIVE TO AERODYNAMIC METHODS OF MEASUREMENT

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ABSTRACT. Analysis of wind-speed measurements made over a six-month period on an Antarctic glacier showed that conditions near the surface were dominated by gravity winds flowing downhill. In such conditions there is no satisfactory method of calculating the amount of energy exchanged between the glacier and the atmosphere. It is also difficult to extrapolate satisfactorily energy changes measured at a single point to the whole glacier. Moreover the loss of five days' meteorological records may cause an error as large as the total change in energy content of the glacier during a year. In view of these difficulties it is more fruitful to measure the changes in energy content of the glacier directly. This can be done by accurate measurements of ice temperature and density near the surface. By defining the total energy content of a glacier as the heat required to melt it, fractional changes in the energy content and mass occurring over a year are equal and indicate the probable lifetime of the glacier. Estimates based on data from an Antarctic glacier suggest that the long-term change of energy of the glacier (≈ 1.5 W/m^2) could be measured with an accuracy of 10% within a year.

RÉSUMÉ. *Échanges d'energie à la surface d'un glacier: une alternative aux méthodes aérodynamiques de mesure.* L'analyse des mesures de vitesse de vent réalisées pendant une période de six mois sur un glacier Antarctique a montré que les conditions près de la surface étaient dominées par les vents de gravité s'écoulant de haut en bas. Dans de telles conditions, il n'y a pas de méthode satisfaisante pour calculer la quantité d'énergie échangée entre le glacier et l'atmosphère. Il est également difficile d'extrapoler sur toute l'étendue d'un glacier de manière satisfaisante les échanges d'énergie mesurés en un point particulier. Bien plus, la perte de cinq jours de données météorologiques peut entraîner une erreur aussi grande que le bilan énergétique total du glacier pendant un an. En raison de ces difficultés, il est plus fructueux de mesurer directement le bilan énergétique du glacier. Ceci peut se faire par des mesures précises de température de la glace et de densité près de la surface. En définissant le contenu énergétique total d'un glacier comme la chaleur qu'il faudrait lui fournir pour le faire fondre, les changements partiels du contenu énergétique et de masse survenant au cours d'une année sont égaux et donnent une idée de la durée de vie probable du glacier. Des estimations basées sur des données recueillies sur un glacier d'Antarctique font penser que le bilan énergétique à long terme d'un glacier (de l'ordre de 1,5 W/m^2) pourrait être mesuré avec une précision de 10% en une année.

ZUSAMMENFASSUNG. *Energieaustausch an einer Gletscher-Oberfläche: Eine Alternative zu aerodynamischen Messmethoden.* Eine Analyse von Messungen der Windgeschwindigkeit während einer Periode von 6 Monaten auf einem antarktischen Gletscher zeigt, dass die Verhältnisse an der Oberfläche durch abwärts wehende Schwerkraftwinde beherrscht sind. Unter solchen Bedingungen gibt es keine befriedigende Methode zur Berechnung der zwischen dem Gletscher und der Atmosphäre ausgetauschten Energie. Ebenso ist es schwierig, die an einem Punkt gemessenen Energieumsätze auf den ganzen Gletscher zufriedenstellend zu extrapolieren. Ausserdem kann der Verlust der meteorologischen Aufzeichnungen über 5 Tage einen Fehler verursachen, dessen Grössenordnung der Änderung des Energiegehaltes des Gletschers während eines ganzen Jahres entspricht. Im Hinblick auf diese Schwierigkeiten ist es vernünftiger, die Änderungen im Energiegehalt des Gletschers direkt zu messen. Dies kann durch genaue Messung der Eistemperatur und -dichte nahe der Oberfläche geschehen. Definiert man den gesamten Energiegehalt eines Gletschers als die Wärme, die zu seinem Abschmelzen nötig ist, so entsprechen sich teilweise Änderungen im Energiegehalt und in der Masse im Verlauf eines Jahres und geben einen Hinweis auf die wahrscheinliche Lebensdauer des Gletschers. Abschätzungen, die auf Daten von einem antarktischem Gletscher beruhen, lassen erwarten, dass langzeitige Änderungen der Energie (1,5 W/cm^2) des Gletschers mit einer Genauigkeit von 10% innerhalb eines Jahres gemessen werden können.

INTRODUCTION

One of the agreed objectives of the International Hydrological Decade 1965–74 was to determine the ice, water and energy balances of glaciers in many parts of the world (UNESCO/IASH, 1970, 1973).

The exchanges of energy and mass between a glacier and its surroundings are related as follows:

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Conservation of energy implies that the sources of energy available to a glacier are equal to the resulting changes in the energy of the glacier, i.e.

$$F_r + F_c + F_l + F_g = F_f + F_t \qquad (1)$$

where F_r is the radiative heat flux, F_c the sensible heat flux, F_l the latent heat flux from condensation and evaporation, F_g is a small amount of energy derived from geothermal heat, bottom friction and internal deformation, F_f is the change in energy content of the glacier due to latent heat associated with changes in the mass of snow and ice and F_t the change in energy content of the glacier due to changes in temperature of the snow/ice mass.

Conservation of mass of ice implies that

$$I_p + I_l + I_r + I_f = I_m \qquad (2)$$

where I_p is the precipitation in the solid phase, I_l the condensation/evaporation of ice, I_r the change of mass of ice and snow due to calving, snow-drift, avalanches, etc., I_f the change in mass of ice due to ice/water phase changes, and I_m the change in total ice mass.

Between 1969 and 1974 we studied Spartan Glacier in Alexander Island, the most southerly of an internationally selected chain of glaciers extending from Alaska through the Americas to the Antarctic Peninsula. We measured wind speed, temperature and humidity at several levels (Jamieson and Wager, in press) and have analysed data covering the period from September 1973 to January 1974. Measurements of wind speed indicated that conditions near the glacier surface were dominated by gravity winds flowing down the glacier. In such circumstances the method developed by Deacon (1949) to calculate sensible and latent heat fluxes (F_c and F_l in Equation (1)) could not be used. Holmgren (1971), who studied these conditions in great detail, was also unable to derive a satisfactory theoretical treatment. A further difficulty with the aerodynamic method of estimating energy changes over the glacier was that measurements could only be made at a single point because of the work involved. It was very difficult to extrapolate these measurements satisfactorily to the whole glacier because meteorological conditions were affected by altitude and topography.

Yet another drawback to the aerodynamic method of obtaining the annual energy change was that radiative, sensible and latent heat fluxes had to be measured continuously for the whole year. These quantities had first to be measured, then extrapolated over the glacier, and finally summed for the whole year. Estimates made at Spartan Glacier showed that the mean rate of energy exchange was 1.5 W/m². The energy gain in summer was about 100 W/m², and the energy loss in winter was about 50 W/m². The loss of five days' records in summer or ten days' records in winter could have caused an error of the same size as the total change in energy content of the glacier during the whole year.

Although aerodynamic methods can reveal the relative energy contributions from different atmospheric sources, we do not believe that they can be used to determine accurately the total energy change of an entire glacier. Radiation measurements can be made to an acceptable accuracy, although in polar regions much of the incoming radiation is reflected and the energy supplied by turbulent transfer is generally of the same order of magnitude as the net radiation (Liljequist, 1957, p. 292; Dalrymple and others, 1966, p. 55). For these reasons alternative methods should be considered in order to determine accurately changes in the total energy content of a glacier.

The energy content of a glacier E may usefully be defined as the total energy required to melt it.

$$E = \iiint_V (c\theta - L)\, \rho \, \mathrm{d}V \qquad (3)$$

where c is the specific heat capacity of ice, θ is the Celsius ice temperature, L is the latent heat of fusion of ice, ρ is the density of ice, and V is the volume of the glacier.

The corresponding definition of the total mass of the glacier M is

$$M = \iiint_V \rho \, dV.$$

Because the energy $F_r + F_c + F_l + F_g$ (Equation (1)) must be supplied from sources external to the glacier, it is logical to treat the energy content E as negative. It also follows from the definition of E that the heat content of water at 0°C is zero.

From Equation (1), $F_t + F_f$ ($= \Delta E$) is the change in energy content of the glacier. The predicted lifetime of the glacier λ is

$$\lambda = \frac{E}{\Delta E} = \frac{M}{\Delta M}$$

where ΔE and ΔM are the measured changes in energy and mass in one year and E and M are the total energy and mass of the glacier. If the glacier is decreasing then λ is the length of time until it vanishes. If the glacier has been increasing continuously, then it is the length of time for which it has been in existence.

Direct determination of energy and mass changes

Theoretical considerations

Consider a valley glacier (Fig. 1). The line $z = z_0$ represents a surface below which there is very little heat conducted from the atmosphere during the study period. The energy content of the volume below this surface is changed slightly by deformation, by friction on the bed, by geothermal heat and by the heat δ required to melt the small volume lost at the snout.

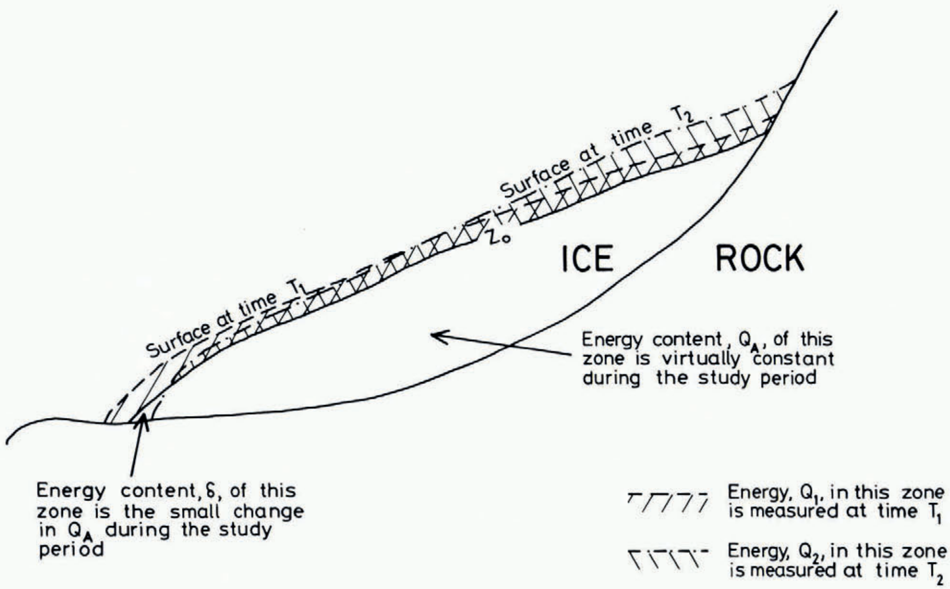

Fig. 1. Longitudinal section of a valley glacier showing zones with their associated energy content.

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We use the following notation:

Q measured heat content of the volume between the surface $z = z_0$ and the glacier surface;

δ heat content of the volume of the glacier below the surface $z = z_0$ which is lost by melting at the snout;

D energy supplied to the glacier by internal deformation (negligible near the surface);

R energy supplied by friction at the bed of the glacier;

G energy supplied as geothermal heat.

At time T_1 the heat content of the glacier is $Q_A + Q_1$ where Q_A is the heat content of the volume below the surface $z = z_0$ and Q_1 is measured at time T_1. At time T_2 the heat content of the glacier is

$$Q_A + Q_2 + \delta + D + R + G$$

where Q_2 is measured at time T_2.

The change in heat content of the entire glacier is therefore

$$\Delta E = Q_2 - Q_1 + \delta + D + R + G. \tag{4}$$

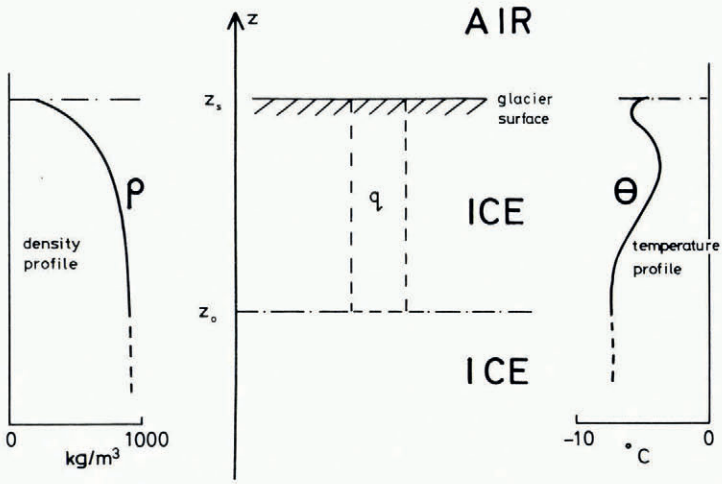

Fig. 2. Vertical section near the glacier surface. q is the energy content of the prism bounded by pecked lines. It is calculated from the profiles of ρ and θ.

Consider a prism extending through the glacier (Fig. 2). The heat required to melt the ice in the prism down to the $z = z_0$ surface is

$$q = c \int_{z_0}^{z_s} \theta \rho \, \mathrm{d}z - L \int_{z_0}^{z_s} \rho \, \mathrm{d}z \tag{5}$$

The total heat content Q of the volume above the surface $z = z_0$ is the surface integral of q over the glacier.

$$Q = \iint_A q \, \mathrm{d}A$$

where A is the area of the glacier.

The change of heat content of the surface layers $Q_2 - Q_1$ is given by

$$\Delta Q = (Q_2 - Q_1) = \iint_A \Delta q \, \mathrm{d}A$$

where

$$\Delta q = q_2 - q_1.$$

Similarly the change in mass of the glacier is

$$I_{\mathrm{m}} = M_2 - M_1 + \Gamma$$

where M_1 and M_2 are the masses of ice above the surface $z = z_0$ at times T_1 and T_2, Γ is the aggregate of mass changes below the surface $z = z_0$ caused by bottom melting, by ablation at the snout, and by freezing of water in crevasses.

$$\Delta M = (M_2 - M_1) = \iint_A \Delta m \, \mathrm{d}A$$

where

$$\Delta m = m_2 - m_1$$

and

$$m = \int_{z_0}^{z_s} \rho \, \mathrm{d}z$$

Location of the z_0 surface

Measurements are referred to a z_0 surface, which must be used again for subsequent measurements. The z_0 surface should be chosen below the level at which there is significant heat flow even at the end of the study period. It may be chosen at a shallower depth in the accumulation area than in the ablation area.

Since the z_0 surface can be relocated only by reference to stakes drilled into the glacier, it is essential that the stakes remain in place for the entire study period. This may prevent the method being used on glaciers with extensive ablation areas where the stakes cannot be planted deeply enough to remain in place through several ablation seasons. In the accumulation area, the settling of stakes relative to the z_0 surface must be taken into account.

Practical considerations

In principle ρ and θ can be measured at any point in the glacier. It is sufficient to consider the volume above the z_0 surface because Q_{A} is almost constant.

To perform the surface integral for Q we need values of Δq over the glacier surface. In practice, we must interpolate between sampled points. The required density of points depends on the complexity of the accumulation pattern. We must determine the temperature and density profiles down to the z_0 surface at each point. The integral for Δq can then be calculated numerically.

Temperature profiles

The most reliable way to maintain a datum for ice temperatures is to bond sensors to a stake made of an insulating material drilled into the z_0 surface. The choice between chromel/constantan thermocouples and platinum resistance thermometers depends on cost, sensitivity, stability, and ease of measurement.

Density profiles

Densities obtained at Spartan Glacier by weighing blocks of snow were not sufficiently precise. The blocks crumbled easily because they contained a large amount of superimposed ice. Even on glaciers where the block method is more accurate, gamma-ray transmission measurements (Smith and others, 1965) would be preferable in that they can determine the densities of a 1 cm layer to an accuracy of 1%.

Evaluation of heat content at sample points

We can now obtain the value of Δq $(= q_2 - q_1)$ from Equation (5). Functional forms of ρ and θ may be obtained by fitting suitable curves to the measured values. The integral may then be calculated by numerical methods.

Evaluation of the surface integral

To evaluate the surface integral of Δq we use an array of equally spaced points covering the glacier. At each array point, we derive a value of Δq by interpolation between the measured values.

The interpolation can be performed by computer programme (Dudnik, 1971). The surface integral becomes

$$\frac{A}{J}\sum_{j=1}^{J} \Delta q_j$$

where A is the surface area of the glacier, Δq_j is the jth value of Δq in the array of J points.

Discussion

Energy changes at Spartan Glacier

From Equation (4) the change in energy content of the glacier is

$$\Delta E = \Delta Q + \delta + D + R + G.$$

We have made estimates of the terms using data from Spartan Glacier. The estimates are expressed as energy input per unit time over the whole glacier divided by the surface area of the glacier.

(i) $\Delta E \approx 1.5\ \text{W/m}^2$ derived from the mass balance, assuming steady temperature conditions in the glacier.

(ii) $\delta \approx 0.1\ \text{W/m}^2$ derived from estimates of flow and thickness near the snout.

(iii) $(D+R) \approx 0.02\ \text{W/m}^2$. All the potential energy gained by the fall of the glacier appears as these two terms. [Mean velocity 25 mm/d (Jamieson and Wager, in press); mean bottom slope 4° (Wager, in press); total mass 700×10^9 kg (Jamieson and Wager, in press).]

(iv) $G \approx 0.04\ \text{W/m}^2$ (Runcorn, 1967). Because $(D+R+G)$ must be small for any glacier, the change in energy content of the glacier becomes

$$\Delta E \approx \Delta Q + \delta$$

(v) $\Delta Q \approx 1.4\ \text{W/m}^2$ from the above equation.

Accuracy of determination of ΔQ

The integral for Δq consists of two parts

$$(1) \qquad c\int_{z_0}^{z_s} \rho\theta \, dz$$

in which the smallest detectable energy change is about 10^6 J/m². This is the result of a temperature change of 0.1 deg at the surface. We assumed the z_0 surface to be 10 m deep.

$$(2) \qquad L\int_{z_0}^{z_s} \rho \, dz$$

and the smallest detectable energy change is again about 10^6 J/m². This is the result of a 1 cm change in the surface level z_s, assuming a density near the surface of 250 kg/m³.

10^6 J/m² would be transferred in 8 d at 1.5 W/m², the average energy input at Spartan Glacier. It should therefore be possible to measure the change in energy content per year to within 3% averaged over the glacier. Uncertainties in the surface integral increase this error. However, it is likely that ΔQ can be determined to within 10% in one year.

A series of measurements of ΔE ($= \Delta Q + \delta$) for, say, 10 years would establish the trend and the variation from year to year. Approximate values of ΔE at Spartan Glacier were calculated from the mass balance by assuming steady-state temperature conditions. The results are shown in Table I.

TABLE I. ANNUAL CHANGE IN ENERGY OF SPARTAN GLACIER

Year	*Increase in total energy* ΔE $J \times 10^{14}$
1970	5.0
1971	5.6
1972	7.8
1973	4.6

Free water

Free water in the layers above the z_0 surface produces errors in both integrals in Equation (5). The specific heat capacity of water is twice that of ice and the heat content is, by our definition, zero. Therefore q must be determined at times when there is no free water in the surface layers, preferably at the end of the accumulation season. The heat content of the glacier is then at a minimum.

Crevasses

Water flowing into crevasses which penetrate the z_0 surface has zero energy content by our definition and therefore Q_A is not changed. However, the corresponding mass, M_A, is changed and an error is introduced into the calculation of change of mass of the glacier.

Temperate glaciers

A simplification of Equation (3) is possible for temperate glaciers. The temperature of the whole ice mass is very close to the melting point at the end of the ablation season.

$$c\iiint_V \rho\theta \, dV$$

is therefore zero and

$$E = L \iiint_V \rho \, dV = LM$$

and

$$\Delta E = L \Delta M.$$

Changes in energy are due solely to the latent heat associated with changes in mass of ice.

Other ice masses

Although we have discussed a valley glacier the same considerations may be applied to some other ice masses. The method cannot be applied to ice shelves because of the practical difficulties in determining the energy exchange beneath them.

A simple and probably fruitful extension is to large ice sheets (Fig. 3a). No ice flows into a sector bounded by the ice divide and two flow lines (Fig. 3b). The analysis for this volume exactly corresponds with that for the valley glacier.

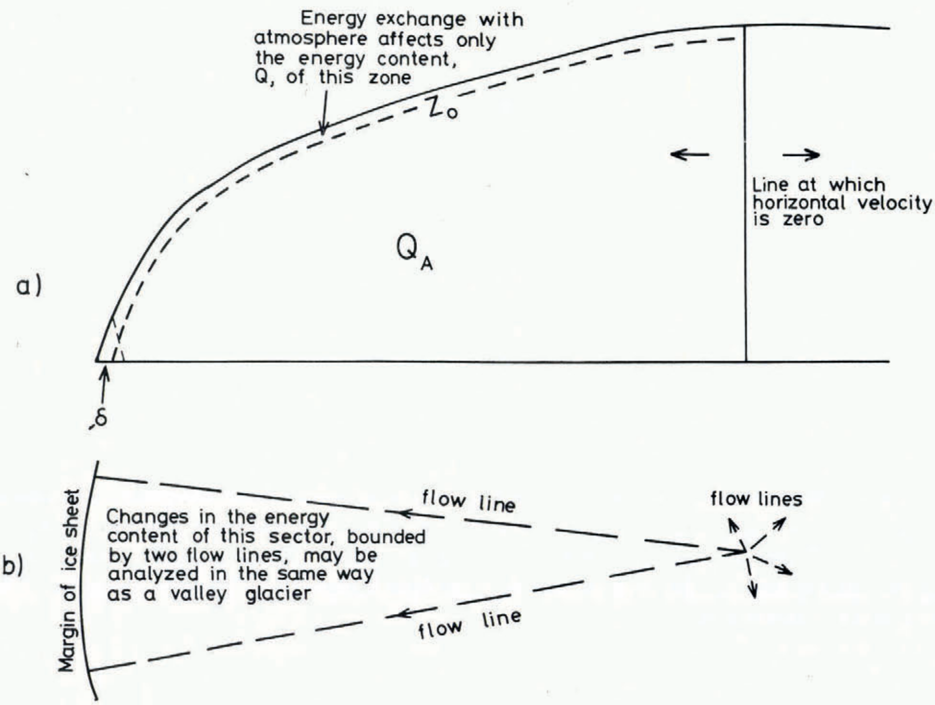

Fig. 3. Cross-section of an ice sheet showing zones corresponding to those in a valley glacier.

Conclusions

In the past, emphasis has been laid on determining the components of the energy exchange. These are difficult to measure accurately over sufficiently long periods to give useful information about the long-term behaviour of the glacier. We believe that direct methods should be used to determine accurately changes in the energy and mass of glaciers. Only then should attempts be made to relate these changes to meteorological parameters.

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