ERRORS IN ABLATION MEASUREMENTS FROM SETTLEMENT AND SUB-SURFACE MELTING*

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Abstract. Both long and short-term snow ablation measurements usually contain errors when made with a simple ablation stake. Ablations measured over long periods for glacier regimen studies are subject to a settlement error in even dense snow, corrections for which may be made by simultaneous measurements with stakes of different lengths. For observation periods in the order of twenty-four hours or less, both mass loss and ice melt are often poorly represented by the simple product of mean bulk density and change in surface level. These quantities may be measured directly by successive determinations of bulk density and ice density profiles in the surface snow layer. Under certain favorable conditions, they may also be derived by observing directly the total and ice mass changes in a sampled area of the snow surface.

Résumé. Le mesurage de l'ablation de la neige pendant de longues et courtes périodes comporte en général des erreurs lorsque ce mesurage s'effectue à l'aide d'un simple piquet d'ablation. Les mesures de l'ablation étalées sur une longue période au cours de l'étude du régime des glaciers sont sujettes à des erreurs par suite du tassement de la neige, même quand il s'agit d'une neige dense. Des mesures simultanées prises sur des piquets de longueurs variées permettent de corriger ces erreurs. Pour des périodes d'observation de l'ordre de vingt-quatre heures ou plus courtes encore, les pertes de masse et la fusion de la glace se trouvent souvent mal indiquées par le produit simple de la densité moyenne de la couche de neige et des changements de niveau de la surface. On peut mesurer ces quantités directement par le moyen d'observations successives des profils de la densité totale et de la densité de la glace dans la couche superficielle de la neige. Sous certaines conditions favorables on peut obtenir des mesures par l'observation directe des changements qui se produisent dans la masse totale et dans la masse de glace dans un échantillon de la surface de la neige.

Zusammenfassung. Sowohl kurze als auch langfristige Ablationsmessungen enthalten gewöhnlich Fehler, wenn sie mit einfachen Ablationsstäben ausgeführt werden. Misst man, etwa zum Studium des Gesamtgletscher-Verhaltens, die Ablation für eine lange Zeitperiode, so können Fehler durch Zusammensinken des Schnees selbst in dichtem Schnee entstehen; diese Fehler kann man durch gleichzeitige Verwendung von verschieden langen Stäben korrigieren. Für vierundzwanzig-stündige oder geringere Beobachtungszeiten werden oft sowohl der Masseverlust als auch die Eisschmelze schlecht durch das einfache Produkt aus Gesamtdichte und Niveausenkung der Oberfläche wiedergegeben. Diese Grössen kann man direkt durch aufeinanderfolgende Bestimmungen der Gesamtdichte und der Eisdichte der Profile in den oberen Schneeschichten messen. Unter gewissen günstigen Bedingungen können sie auch von direkten Beobachtungen der Änderungen der totalen Masse und der Eismasse in untersuchten Proben nahe der Oberfläche hergeleitet werden.

Definitions

h = *thickness*, cm. Between the snow surface and a sub-surface reference point.
Δh = *surface depression*, cm. Taken as positive when h decreases.
W = *surface wastage*, cm. That component of Δh due to the agents of ablation (evaporation, deflation and melting).
A = *ablation*, g./cm.². Loss of water in all phases from a glacier.
A' = *ablation*, g./cm.². Loss of water in all phases from a surface snow layer of given thickness, h.
I = *ice melt*, g./cm.². Water in the surface snow layer converted from a solid to liquid state.
u = *settlement*, cm. The vertical component of shrinkage in a snow layer due to compression and internal metamorphic changes.
ρ = *bulk density of snow*, g./cm.³.
ρ_i = *ice density of snow*, g./cm.³.

Introduction

The problems of accurately measuring snow ablation have been the object of especial concern in conjunction with the precise measurement of heat transfer at a melting snow

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surface through techniques of micrometeorology. Hubley [1] has discussed these problems analytically and formulated basic expressions describing surface and sub-surface mass loss and change of state. The purpose of this present paper is to extend the theoretical discussion of Hubley to the practical application of ablation measurements in the field, clarifying the terminology, describing techniques by which mass loss and ice melt in the surface snow layer have been successfully measured, and noting the relation of these to glacier ablation.

In the ordinary course of glaciological investigations, particularly in the measurement of the annual mass exchange on a snow-covered glacier, the broad assumption is sometimes made that the following is valid:

$$A = A' = \rho W = \rho \Delta h = I. \qquad (1)$$

It is a thesis of the present discussion that this equality, or any part of it, is valid only under certain restricting conditions. If the restricting conditions cannot be demonstrated to hold for a given set of circumstances on a given glacier, then it must be the ordinary assumption that the series of equalities given in (1) are invalid, and individual parameters such as A' and I must be measured directly, rather than inferred from observation of Δh.

Glacier Ablation

The validity of the relation $A = A'$ depends on the assumption that water substance lost from the surface snow (or ice) layer actually departs from the body of the glacier. In the case of a thermally temperate glacier in the middle of the ablation season, when melt-water channels are thoroughly established, this assumption may be reasonably accurate, though the time lag, t_1, between departure of a given element of water from the surface and its departure from the glacier proper must be considered. This time lag will vary for elements of melt water originating in different parts of the glacier. At any given instant the rate of snow ablation dA'/dt normally will not equal the rate of glacier ablation dA/dt. Thus surface ablation can equal glacier ablation only when these represent quantities equivalent to the integration of their respective rates over a time period, t, which is long in respect to the time lag of melt-water run-off. ($t \gg t_1$.)

If sub-freezing temperatures exist within the glacier, part or all of the melt water may be refrozen and retained within the glacier. When sub-freezing temperatures exist near the surface of the annual accumulated snow layer, the refrozen melt water may again be remelted later in the summer as the zone of redeposition later becomes exposed to melting processes. In this case the same mass of water may appear twice in one season under the guise of A', though actually departing from the glacier only once as A, thus introducing a source of error in glacier ablation measurements. If cold layers exist at greater depths within the glacier, as in the case of a thermally polar glacier, the refrozen melt water is all or in part permanently retained, and does not appear in A. The sub-surface retention of melt water as liquid in the temperate glacier through storage in internal cavities or reservoirs must also be considered, but data on this are few. The relation between A and A' is complicated by many such factors; these deserve a more thorough field investigation, discussion of which falls beyond the scope of this paper.

The Measurement of Δh and W

If conventional measurements of snow wastage with the aid of ablation stakes are to furnish accurate data for determination of a glacier mass budget, the assumption $A' = \bar{\rho}_1 W = \bar{\rho}_2 \Delta h$ must be valid. The conditions of validity are dependent upon settlement processes in the surface snow layers, and the time interval over which the measurements of Δh are made. It is assumed here that ρ is either constant with depth, or else $\rho(h)$ is known. Ordinarily $\rho(h)$ can be determined by direct measurement of the density profile in the surface snow layers, and this is the usual step preliminary to measurement of Δh. Snow density ordinarily is not invariant with time, and changes in ρ for the surface snow layers during the period of measurement for Δh must be considered. Density decrease near the surface due to melting by transmitted radiation is an important consideration in short-term ablation measurements, and its measurement is discussed in more detail below in connexion with the direct measurement of I. Where measured values of Δh greatly exceed the depth to which sub-surface melting normally occurs (15-20 cm.), the local density decrease can ordinarily be neglected.

In general, the surface depression is the sum of wastage and settlement

$$\Delta h = W + u, \tag{2}$$

so

$$W = \Delta h - u. \tag{2a}$$

Now the measurement of Δh is normally made with a stake set into the snow to some depth h, the change in snow level from t_0 to t_1 being observed in reference to a mark on the stake (see Fig. 1). The bottom of the stake is assumed to remain fixed in the snow during the observation period. From (2) it is seen that this measurement involves the settlement which takes place within layer h. Settlement below this layer affects both stake (the reference) and snow surface alike, and does not appear in Δh.

If two adjacent ablation stakes are implanted to different depths h and h' ($h > h'$), and the surface depression observed over time t,

for the first stake
$$\Delta h = W_t + u_t, \tag{3}$$
and for the second stake
$$\Delta h' = W'_t + u'_t. \tag{4}$$

But, because the two stakes are adjacent and measuring wastage of the same snow surface, it follows that

$$W_t = W'_t, \tag{5}$$

therefore

$$\Delta h - u_t = \Delta h' - u'_t, \tag{6}$$

$$u_t - u'_t = \Delta h - \Delta h' \tag{7}$$

$$= \text{settlement within layer } h - h'.$$

If two or more stakes, 1, 2, 3, . . . , are implanted to successively greater depths, h_1, h_2, h_3, . . . , and the corresponding values of surface depression, Δh_1, Δh_2, Δh_3, . . . are obtained over a given time interval, then Δh may be plotted as a function of h. The resulting curve, if extrapolated back to h_0, will intersect that ordinate at a value of Δh for which $u = 0$. From (2) this is also the value of W (see Fig. 2). An example of the Δh vs h plot taken from actual field observations is presented in Fig. 3. These observations were made in summer snow remaining from a dense, strongly metamorphosed winter snow cover deposited in a highly maritime climate. The initial density ranged from 0·52 to 0·55 g./cm.^{2} when Δh records were started. These conditions suggest that settlement would be small, but it actually made a measurable contribution to the total value of Δh during this period. Direct measurement of u with a resistance wire settlement gauge immediately adjacent to the Δh observation site confirmed the magnitude of settlement in this snow. The influence of u on Δh may be expected to increase as the initial snow density is lower and the snow less metamorphosed.

It is thus seen that settlement cannot be neglected during long-period ablation measurements even in very dense snow, and may contribute a substantial error in less metamorphosed snow.

The Relation of ρW to A' and I

Assuming that ρ has been determined and accurate values of W deduced from Δh and u, the next problem is to determine under what circumstances $\rho W = A' = I$.

For long-period ablation observations to determine glacier regimens, this relationship is assumed valid for an isothermal, melting snow cover. Here the value of h is large, often equal to the total thickness of the annual snow cover, and the total amount of water substance removed from the snow cover by evaporation and melt-water percolation is given directly by the product of density and wastage. Time variations of retention capacity for free water in the lower layers can affect the simple relationship $\rho W = A'$, but such influences are very small in relation to the large mass of water removed by weeks or months of ablation, and may be regarded as a negligible source of error.

Strictly speaking, $A' = I$ under the same circumstances only when the snow does not contain free water at the start of the observation period. If liquid water is entrapped among the snow grains, it is released when the grains melt, and departs from the snow cover without changing state.

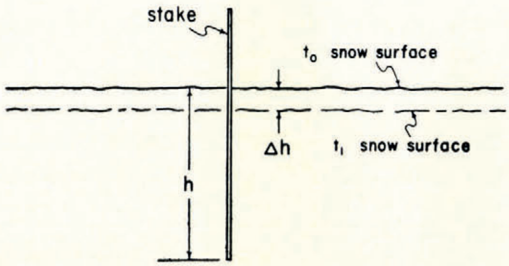

Fig. 1. The simple ablation stake

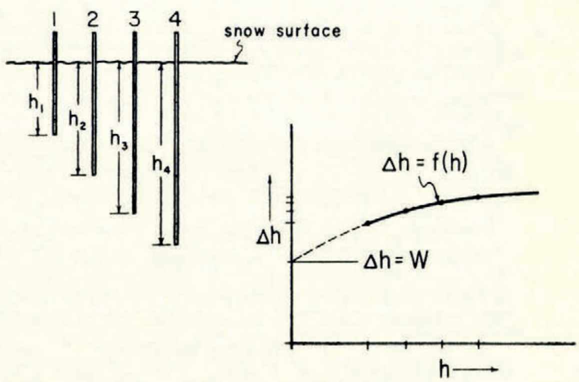

Fig. 2. The dependence of observed surface depression on length of the ablation stake

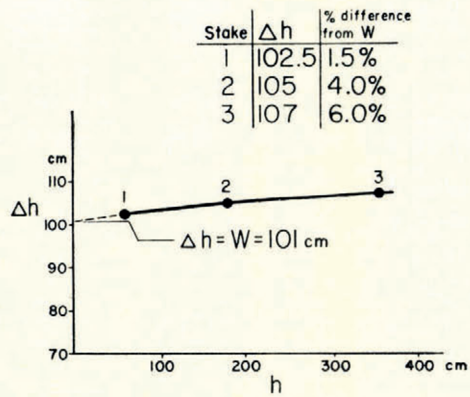

Fig. 3. An actual field example of surface depression dependence on ablation stake length, as observed in highly metamorphosed summer firn

When observation periods are short—generally 24 hours or less—the assumption that $\rho W = A'$ becomes quite uncertain. In some circumstances it may be accurate; periods of warm, stormy weather which maintain a more or less constant melt rate day and night are likely to establish a continuous flow of percolating melt water which drains away water substance from the surface snow layer as fast as it is melted. In other circumstances, departure of liquid run-off from the surface snow layer obviously is not an immediate consequence of wastage. Such a condition may occur during clear weather following the formation of a strong nocturnal crust, wastage at the surface in the morning hours being accompanied by refreezing of melt water in the crust below. Even when no sub-freezing temperatures develop, the temporary retention of melt water by ice layers in the snow can alter the relationship of ρW and A' for short periods. These effects lead to values of A' which are less than of ρW for the same period. An error of the opposite sign also occurs which arises from the sub-surface melting by transmitted solar radiation.

If all the ablating agents were to act only at the snow surface, the problem of measuring ablation and ice melt would be greatly simplified. The penetration of solar radiation into the snow cover introduces complications which cannot be disregarded, for ice melt, and often consequent ablation of the surface snow layer, is then able to take place below the surface. This leads to a sub-surface melt and run-off which is not necessarily reflected by a measurable wastage at the surface. These differences between ρW and A tend to cancel out over long time periods, but for short-term measurements in the order of a few hours they can assume a significant size.

The deviation of I from ρW for short periods is even more marked than that of A'. During periods of heavy insolation the actual amount of ice melt which takes place is always greater than indicated by observed values of Δh or W. If heavy insolation is followed by a period of low insolation and warm winds, W then indicates an ice melt rate higher than actually takes place, for wastage at the surface proceeds in snow whose ice density has been lowered by the previous insolation. When insolation falls on a snow crust formed by refreezing of melt water entrapped between the ice grains, a significant amount of ice melt can occur below the surface while W remains zero. Variation between observed values of W and actual ice melt is great when strong sub-surface melting takes place while low air temperature keeps the snow surface frozen. There then forms over the snow surface a thin ice film (*Firnspiegel*), underneath which melting can locally reduce ice and bulk density to zero as cavities are formed to depths as great as 3 or 4 centimeters. The original position of the snow surface, represented by the ice film, remains practically unchanged.

The phenomena discussed here are primarily confined to the first ten to fifteen centimeters below the snow surface. It is thus seen that when measurements of ice melt or snow ablation are required over a short period for micrometeorological studies, the use of W values obtained from an ablation stake or other reference are apt to lead to error. In such situations A' and I must be measured directly.

The Direct Measurement of Mass Loss from the Surface Snow Layer

The fundamental problem is illustrated in Fig. 4. When the observation interval begins (t_0), there exists a snow layer of thickness h_0, with a given, measurable, vertical distribution of bulk snow density, $\rho(h,t_0)$. After this interval (t_1-t_0), the snow has a thickness reduced by Δh and a new density distribution, $\rho(h,t_1)$. If $\rho(h,t_0)=\rho(h,t_1)$ then the loss (ablation) is given directly by $\bar{\rho}\Delta h$, where $\bar{\rho}$ is the mean bulk density of the wasted layer, Δh. Ordinarily ρ will not remain constant with time close to the snow surface, and such changes will occur as the reduction in sub-surface density illustrated in Fig. 4. When these do occur, the loss (or gain) in the snow layer h_0 is given by

$$A' = \int_0^{h_0} \rho(h, t_0)\, dh - \int_0^{h_0} \rho(h, t_1)\, dh, \qquad (8)$$

where, of course, $\rho(t_1)=0$ for the Δh layer. Analytically, this is the expression for the area enclosed by the two density curves in Fig. 4. It is obvious that a direct determination of A' may be made by observing and plotting vertical density distributions in the snow at the beginning and end of the period, and actually measuring the enclosed area. Field experience has demonstrated this to be a sound technique when there exists a reasonable homogeneity of the snow which permits delineation of the density profiles from a limited number of samples. Density sample tubes of small diameter (2 cm. or less) are required. This limits the method's usefulness in very coarse-grained snow, when accurate sampling of small volumes becomes difficult. An example of A'-determination from an actual field observation is presented in

Fig. 5, with only the curved parts of the density functions plotted. This gives the mass loss for a period when strong solar radiation followed a night of warm wind with significant evaporation, and the discrepancy introduced by sub-surface melting is large. Here it is seen that this sub-surface loss, unreflected in W, amounts to very nearly one-quarter of the total loss for the 24-hour period. In these measurements u is considered to be negligible for the small values of h and t involved.

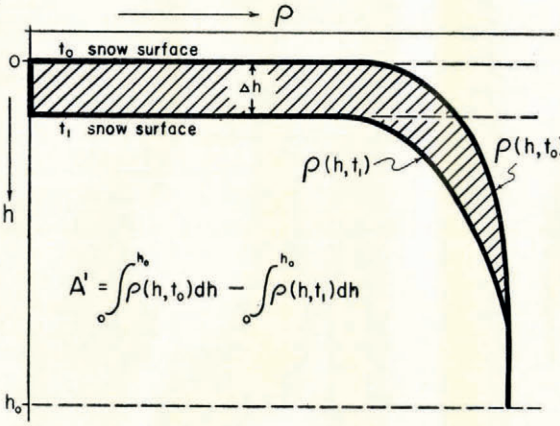

Fig. 4. The direct determination of mass loss due to ablation by the successive determinations of $\rho(h)$

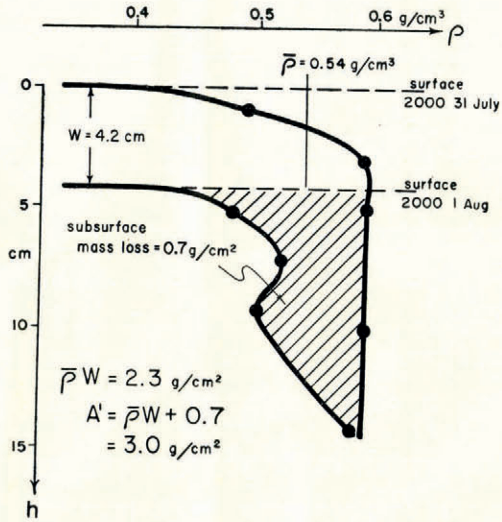

Fig. 5. An actual example of direct mass loss measurement taken from 1958 field work on the Blue Glacier

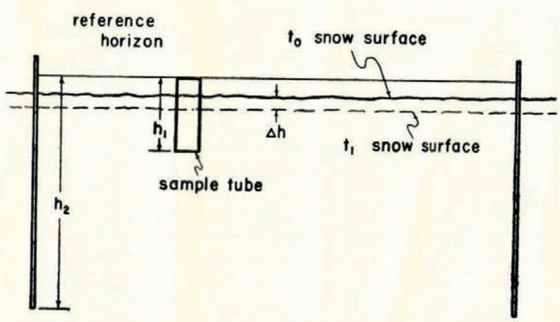

Fig. 6. An alternate method for the direct measurement of mass loss at a melting snow surface

The direct determination of A' from successive measurements of density profiles is difficult in non-homogeneous snow or under conditions where accurate collection of small samples cannot be made. In such circumstances an alternate method of mass loss measurement may be applied which permits direct measurement of A' in the field, although this method, too, suffers limitations. Required is the direct measurement of mass per unit area in a snow layer of given initial thickness at two successive times t_0 and t_1. This is achieved as follows (see Fig. 6):

1. At the beginning of each observation period a reference horizon is established within 5 cm. above the snow surface by means of string stretched between two stakes implanted to a depth h_2.

2. Standard 500 cm.^{3} snow sample tubes 19 cm. long are driven vertically into the snow until their upper ends are level with the reference horizon. The tubes, with their enclosed snow cores, are then dug out carefully and weighed.

3. At the end of the observation period snow cores are again collected and weighed in the same manner, the tubes being driven level with the same reference horizon.

The total loss in weight between beginning and end of the observation period, divided by total cross-section of the sample tubes, is taken as the mass loss per unit area from layer h. It is necessary to introduce a correction for any snow settlement which takes place between the bottom of layer h_1 and the bottom of the stakes supporting the reference horizon. Settlement within h_1 causes no change in the measured mass loss.

Let M_0 = total mass of collected sample at time t_0, grams,
M_1 = total mass of collected sample at time t_1, grams,
$u_{(2-1)}$ = settlement within layer h_2-h_1, cm. (See Equation 6),
ρ_h = bulk density of snow at bottom of layer h_1, g./cm.^{3},
S = total sampled area, cm.^{2}.

Then

$$A' = \frac{M_0-M_1}{S} - \rho_h u_{(2-1)}. \tag{9}$$

This technique is primarily limited by such snow-surface irregularities as sun cups. With a smooth snow surface, only a conveniently small number of samples are required at each observation, but when the snow surface becomes irregular the extensive sampling required to average out the variations of h_1 becomes very unwieldy. Even so, application of this method in the field has shown [2] that it consistently yields mass-loss data which are more nearly in accord with values calculated from heat exchange than are the data obtained from measurements only of ρ and W. For short observation intervals of a few hours, the mass loss thus measured often departs widely from calculated ice melt, but for long periods it tends to approach more closely the actual ice melt value than do mass loss measurements based on ρW. The discrepancies between mass loss and ice melt for short periods, especially during clear weather, require the independent measurement of I.

The Direct Measurement of Ice Melt

The basic problem of measuring ice melt is analogous to that of measuring mass loss, as displayed in Fig. 4, except that the vertical distribution of ice density is required instead of that for bulk density. If the initial ice density profile is designated by the relation $\rho_i(h,t_0)$, and the subsequent profile by $\rho_i(h,t_1)$, then the ice melt during the interval is given by

$$I = \int_0^{h_0} \rho_i(h, t_0)\, dh - \int_0^{h_0} \rho_i(h, t_1)\, dh. \tag{10}$$

As in the case of A', solution to the problem is reached by actually measuring the ice density profile at two successive intervals, plotting these, and determining the enclosed area. Field experience to date has shown this to be the most satisfactory method of measuring short-term ice melt; the data are generally consistent with observed heat exchange at the snow surface, and sufficient sensitivity exists to follow, under favorable conditions, such small ice density changes as those associated with nocturnal crust formation. Figs. 7, 8 and 9 display actual ice melt determinations in the field by this method. Fig. 7 is for the same period as the mass loss measurement in Fig. 5, but here the vertical profiles are of ice density instead of bulk density. Attention is called to the difference in the values obtained for direct ice melt, direct mass loss, and ρW for this period, confirmation that these three must be obtained independently under such conditions. In contrast is the condition shown in Fig. 8. Here a large amount of melt has resulted from a period of strong wind and condensation, with solar radiation playing a much reduced rôle. Ablation and ice melt are very nearly represented by ρW in these circumstances. Fig. 9 shows a nocturnal crust had started to form at the time of the terminal observation,

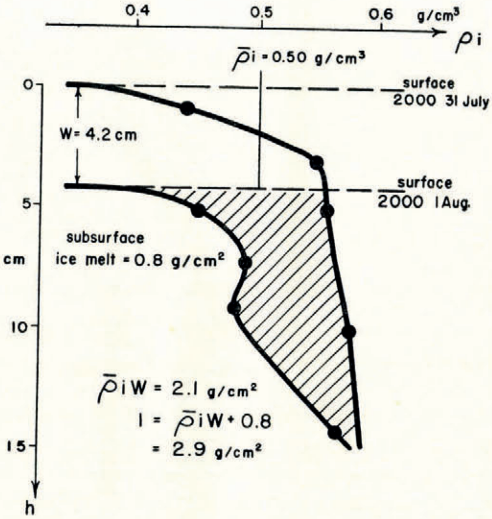

Fig. 7. The direct measurement of ice melt in surface snow layers, taken from field observations during a period of strong insolation on the Blue Glacier

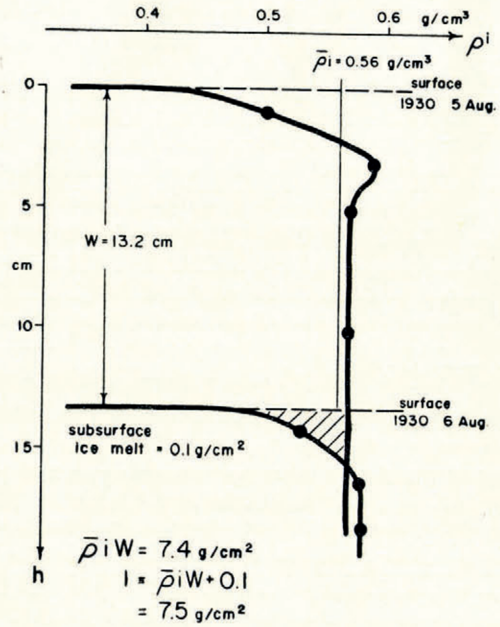

Fig. 8. The direct measurement of ice melt in surface snow layers on the Blue Glacier during a period of low insolation and strong melt by eddy conduction

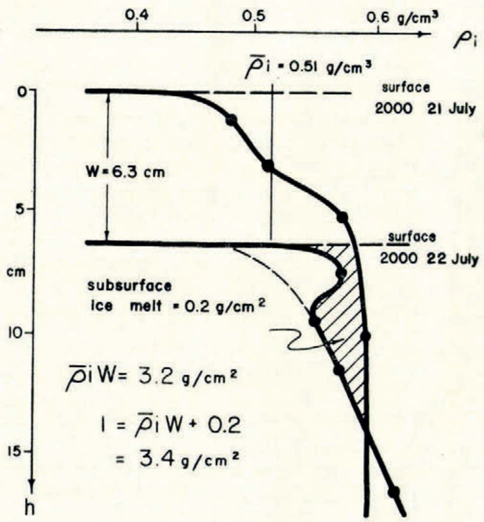

Fig. 9. The direct measurement of ice melt in surface snow layers. The formation of a nocturnal crust at the snow surface is clearly shown

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with the surface increase in ice density clearly shown. Here the area between the two curves represents ice *loss*, a quantity smaller than the actual total *melt* by the amount of refreezing which has taken place.

An alternate method directly to measure ice melt may be derived from the second method for mass loss previously described. If, in addition to the measurements for mass loss, the free-water content of layer h is determined, the ice melt from t_0 to t_1 can be calculated.

If e_0=free-water content of layer h_1 at t_0, decimal fraction,

e_1=free-water content of layer h_1 at t_1, decimal fraction,

then

$$I = \frac{M_0(1-e_0)-(M_1+S\rho_h u_{(2-1)})(1-e_1)}{S}. \qquad (11)$$

Equation 11 is invalid when sub-freezing temperatures exist within layer h_1.

Again, this method cannot easily be applied when there exist large-scale irregularities in the snow surface, requiring an inordinate amount of sampling.

Both methods for the direct determination of I require a rapid and reliable method of measuring ice density in the field. Practically, this limits the measurement of ρ_i to the indirect method of measuring bulk density and free-water content. Time limitations require the centrifugal extraction of free water from the melting snow [3]; calorimetric methods are often too slow, using a large portion of the total ice melt observation period just for a single set of ice densities required to plot $\rho_i(h)$. In the examples presented in Figs. 7, 8 and 9, bulk density was measured at four different levels below the snow surface with 50 cm.^{3} sample tubes, and free-water content simultaneously measured at the same levels with a hand-operated centrifuge. These observations can be performed by two men in less than fifteen minutes. The consistency with surface energy exchange of ice melt measurements made in this way attests to the reasonable accuracy of the free-water extractions, as do hundreds of determinations with the aid of this centrifuge during recent field seasons.

Summary

1. Mass loss from a surface snow layer may be considered mass loss from the glacier only when no sub-freezing temperatures exist within the glacier and the interval of measurement is long compared with the time lag of melt-water run-off.

2. Surface depression of melting snow normally differs from surface wastage by the amount of settlement which takes place. This settlement cannot be neglected for long-term ablation measurements even in dense and highly metamorphosed snow. Its magnitude can be measured by comparing surface depression values from ablation stakes implanted to different depths.

3. For long periods of measurement, mass loss from the surface snow layer may be expected to equal the product of surface wastage and the mean bulk density of the wasted layer. These quantities are equal to ice melt for the same period only if no free water existed in the snow at the start of that period. For observation periods of 24 hours or less, particularly in clear weather, mass loss, ice melt and the product of bulk snow density and surface wastage will differ from one another, and each must be measured separately.

4. Direct values of mass loss may be obtained by the successive measurement of bulk density profiles in the surface snow layer. This may also be accomplished by measuring the mass change in a surface snow layer of given initial thickness.

5. Direct values of ice melt follow from the successive measurement of ice density profiles near the surface. The second method for mass loss may also be applied to ice melt if the free-water content of the surface snow layer is also measured. With either method, the determination of free water by centrifugal extraction is required to keep the measurement time a sufficiently small part of the observation interval.

In theory these methods are simple. In practice their application in the field is beset with numerous difficulties, such as the presence of ice layers, and both horizontal and vertical irregularities of density and free water content in the snow. Accurate measurement of ice melt in a surface snow layer is not a task to be undertaken lightly.

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