Journal of Glaciology, Vol. 8, No. 52, 1969

ERRORS IN SHORT-TERM ABLATION MEASUREMENTS ON MELTING ICE SURFACES

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ABSTRACT. Rapid changes in time and space in the micro-relief of an ablating glacier surface and radiation-induced melt within the uppermost ice layer, termed the "weathering crust", seriously affect the accuracy of the short-term ablation measurements. The various measuring techniques commonly used (stakes, ablatometers, ablatographs) and some new methods (measurement of discharge from a small supra-glacial drainage basin, and mass loss directly measured on core samples) are critically reviewed and assessed in the light of these phenomena. The implications for studies of heat and mass balance are discussed.

It appears that the direct measurement of mass flux is the most accurate means of assessing short-term ablation rates. The errors in short-term ablation measurements by any method are largely compensatory and consequently do not influence long-period mass-balance estimates.

RÉSUMÉ. *Erreurs des mesures d'ablation à court terme de la surface de glace en fonte.* Des changements rapides dans le temps et l'espace du micro-relief de la surface d'un glacier soumise à l'ablation et la fusion due à la radiation dans la croûte superficielle de la glace, affecte sérieusement la précision des mesures d'ablation à court terme. Les techniques variées utilisées communément (balises, ablatomètres, ablatographes) et quelques méthodes nouvelles (mesure du débit d'un petit bassin de drainage superficiel, et perte de masse mesurée directement sur des carottes) sont revues d'une manière critique à la lumière de ces phénomènes. Les implications pour les études d'énergie et de masse sont discutées.

Il apparaît que la mesure directe du flux de masse est le moyen le plus précis pour éviter l'effet de mesures à court terme de la vitesse d'ablation. Les erreurs de mesures d'ablation à court terme pour chaque méthode se compensent largement et en conséquence n'influence pas les timations du bilan de masse pour une longue période d'observation.

ZUSAMMENFASSUNG. *Fehler in kurzfristigen Ablationsmessungen auf schmelzenden Eisoberflächen.* Rasche Formänderungen im Kleinrelief einer schmelzenden Gletscheroberfläche und strahlungsbedingtes Schmelzen innerhalb der oberflächennahen Schicht, der sog. "Verwitterungskruste", beeinflussen die Genauigkeit kurzfristiger Ablationsmessungen beträchtlich. Die verschiedenen herkömmlichen Messmethoden (Ablationsstangen, Ablatometer oder Ablatographen) und einige neuere Verfahren (Abflussmessungen am Ausgang eines kleinen Einzugsgebietes der Gletscheroberfläche, und direkte Massenverlustbestimmungen an Bohrproben) werden kritisch besprochen und unter spezieller Berücksichtigung der oben genannten Phänomene bewertet. Die Bedeutung der Ergebnisse für Wärme- und Massenhaushaltsstudien wird diskutiert.

Es scheint, dass direkte Massenverlustmessungen die besten kurzfristigen Ablationsdaten liefern. Die Fehler in beliebigen kurzfristigen Ablationsmessungen kompensieren sich grösstenteils und haben daher keinen Einfluss auf langfristige Massenhaushaltsberechnungen.

INTRODUCTION

The chief aim of glacial meteorology is to determine the relationship between the prevailing meteorological situation and the behaviour of glaciers. An important and widely studied aspect of glacial meteorology is the energy balance at melting ice surfaces. Such studies have attempted to determine the important factors in the ablation of ice.

It is common practice in energy-balance studies on melting ice surfaces to compare the heat input with ablation, usually measured by observing changes in surface level relative to some fixed reference. In some cases measured ablation has been used as a known quantity in the computation of the energy balance (e.g. Wallén, 1948; Hubley, 1957). However, it has often been noted that, when the heat sources and sinks are determined by independent methods, there is disagreement between measured and predicted ablation which can be quite significant over short periods (Orvig, 1954; Larsson, 1960; Ambach, 1963[a]; Mayo and Péwé, 1963; Andrews, 1964; Dibben, 1965; Adams, 1966; Platt, 1966). This disagreement appears, in many cases, to be systematic and quite apart from the not inconsiderable instrumental and observational errors.

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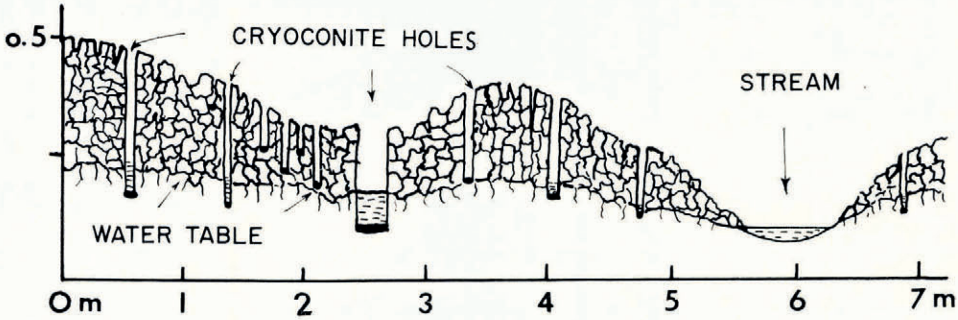

Fig. 1. Schematic profile of the weathering crust at the surface of a glacier.

The surface of a glacier experiencing ablation frequently consists of a layer of porous ice with loosely interlocking crystals, varying in thickness from a few to a few tens of centimetres. Such a layer, referred to as a "weathering crust" (Fig. 1 and 2) is produced by differential absorption of radiant energy along grain boundaries, a process termed internal ablation (*interne Ablation*) by Ambach (1955). Cryoconite action often intensifies this condition. During the period of formation of the weathering crust more ice is being melted than would be apparent from surface lowering measurements. The opposite is true when, during periods of overcast, windy, and warm weather, the weathering crust is ablated away leaving the surface hard and glazed (Fig. 3), as the gross density of the weathering crust which has been melted away is lower than that of normal glacier ice (sometimes as low as 0.5 g cm^{-3}). Therefore measurements of surface lowering may give an erroneous impression of high ablation rates.

Furthermore, the progressive changes in the weathering crust are not uniform, as small differences in the physical properties of the ablating surface cause significant local variations in the development of the weathering crust.

In an attempt to locate and quantify the errors inherent in short-term ablation measurements, field work was carried out on the tongue of the White Glacier (lat. 79° 26′ N., long. 90° 39′ W.), 200 m above sea-level on Axel Heiberg Island, and on the lower part of the Sverdrup Glacier (lat. 75° 43′ N., long. 83° 20′ W.), 300 m above sea-level on Devon Island,

Fig. 2. Glacier surface during a period of prolonged clear weather. Note the numerous cryoconite holes and the lacy texture produced by melting along grain boundaries.

in the Canadian Arctic Archipelago. Both glaciers are medium-sized, sub-polar valley type, and have an ablation period of about three months (early June to end of August).

Energy-balance studies were conducted and ablation measured using both standard and new techniques. Surface run-off from supraglacial drainage basins was also measured to provide a completely independent value of ablation.

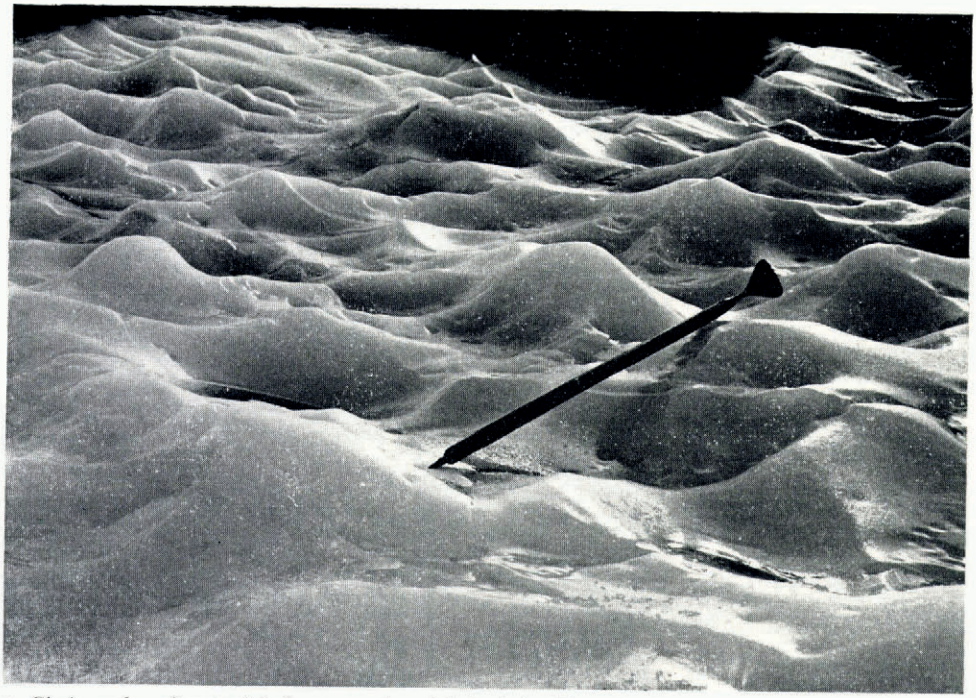

Fig. 3. Glacier surface after a period of overcast, rain and high winds. The surface has become glazed and foliation patterns are exposed.

Energy Balance

The major sources of heat at the freely melting surface of a glacier are incoming solar radiation, incoming long-wave radiation from the atmosphere, latent heat from the freezing of rain, and condensation of vapour and sensible heat transfer from the air. The major causes of heat loss are reflection of radiation, outgoing long-wave radiation, conduction from the surface into the ice or into the air, evaporation, and melt. Such factors as the mechanical energy supplied by running water and cultural disturbances are assumed to be small. The measuring techniques, basic data, and computations used in this study are discussed in detail by Keeler (1964), Havens and others (1965), and Müller (1968).

The radiation balance was determined from measurements of incoming and reflected solar radiation made with Kipp & Zonen solarimeters and from the long-wave radiation estimated using the equation of Hoinkes and Untersteiner (1952). This latter was checked against estimates of cloud-base temperatures and appeared to be valid.

The transfer of sensible and latent heats was computed from wind, temperature, and vapour pressure data gathered at various levels in the first 4 m above the surface. The exchange coefficients were evaluated by assuming a logarithmic wind profile and near neutral stability (such that eddy conductivity is equal to eddy diffusivity and eddy viscosity (Rider and Robinson, 1951)). This assumption may be only partially correct; however, it is supported by the form of the wind profiles, the magnitude of computed Richardson numbers, and by the recent study by Grainger and Lister (1966) which shows the logarithmic law to be the most suitable in near neutral conditions, as expected, and also during inversions.

The amount of energy lost by conduction into the ice (Q_i) in the case of both glaciers was

TABLE I. COMPONENTS OF SHORT-PERIOD HEAT BALANCE CALCULATIONS FOR MELTING ICE SURFACES ON AXEL HEIBERG ISLAND (SUMMERS 1961 AND 1962) AND DEVON ISLAND (SUMMER 1963)

Lower Ice Station, White Glacier, Axel Heiberg Island, 1961

Date	$+Q_r$	$+Q_s$	$+Q_l$	$+Q_p$	$-Q_i$	$=Q_m$	*Ablation* (cm w.e.) A_c	A_m
	ly	ly	ly	ly	ly	ly		
12 June	126	18	−12		76	56	0.7	0.5
15	77	28	29		84	50	0.6	0.6
16	140	125	−79		91	95	1.2	1.2
17	134	25	−28		112	19	0.2	0.2
19	76	2	1		21	58	0.7	0.5
20	129	14	6	1	25	125	1.6	1.1
21	50	23	7		18	62	0.8	1.0
23	214	23	1		55	183	2.3	2.0
24	148	6	3		49	108	1.4	1.2
25	221	47	−31		71	166	2.1	1.3
26	118	107	−115		71	39	0.5	0.5
27	160	18	−2		41	135	1.7	1.3
29	233	38	−15		62	194	2.4	2.0
30	243	17	0		55	205	2.6	2.7
1 July	133	6	2		33	108	1.3	0.7
2	163	53	−20		56	140	1.7	1.1
3	176	147	−19		53	251	3.1	4.8
4	161	100	−5		43	213	2.6	2.3
5	98	99	42	7	39	207	2.6	2.9
6	187	30	22		43	196	2.4	1.3
7	265	25	15		71	234	2.9	2.2
8	198	54	1	1	73	181	2.2	1.6
9	166	21	13		74	126	1.6	1.5
10	71	43	−25		48	41	0.5	0.8
11	132	116	−54		78	116	1.5	2.6
12	107	12	1		38	82	1.0	0.6
13	100	117	39	12	35	233	2.9	3.9
14	75	141	73	3	29	263	3.3	3.4
15	111	189	79	2	26	355	4.4	3.9
16	178	29	19	1	25	202	2.5	1.6
17	91	108	31		24	206	2.3	2.2
18	130	22	14		26	140	1.7	0.9
19	150	69	14		28	205	2.5	1.6
20	59	173	73	3	29	279	3.5	4.5
21	78	94	41		31	182	2.3	2.0
22	203	48	2		41	212	2.6	1.4
23	137	103	43		48	235	2.9	2.2
24	86	34	10		46	84	1.0	1.5
25	148	91	18		47	210	2.6	2.2
26	85	85	50	9	48	181	2.3	3.2
27	39	58	19		33	83	1.0	1.2
28	180	28	−51		42	115	1.4	1.1
29	86	85	−111		30	30	0.4	0.2
30	145	145	−103		50	137	1.7	1.4
31	182	161	−43		48	252	3.1	2.6
1 August	187	477	30		36	658	8.2	9.1
2	164	193	23		33	347	4.3	2.2
3	179	394	19		38	554	6.9	5.3
4	90	412	114		48	568	7.1	6.2
5	132	92	31		50	205	2.5	1.0
6	119	83	30		47	185	2.3	1.5
7	168	447	−31		41	543	6.8	7.2
8	116	85	22		41	182	2.5	2.1
9	11	216	−1		41	185	2.3	4.0
10	94	233	−46		40	241	3.0	2.5
11	128	44	−2		40	130	1.6	1.8
12	108	11	4		39	84	1.0	0.9
13	90	68	0		33	125	1.6	1.0
14	146	61	−1		31	175	2.2	1.2
15	76	67	1		34	110	1.4	1.1
16	35	69	−2		36	66	0.8	1.2
17	20	147	−8		36	123	1.5	1.6
18	63	189	−79		37	136	1.7	2.0
Total	8 115	6 265	59	39	2 867	11 611	144.3	131.4
	Sources: 14 478 ly				Sinks: 14 478 ly			
	56%	43%	0.5%	0.5%	20%	80%		

Lower Ice Station, White Glacier, Axel Heiberg Island, 1962

16–31 July Period no.	*No. of hours*	$+Q_r$	$+Q_s$	$+Q_l$	$+Q_p$	$-Q_i$	$=Q_m$	*Ablation* (cm w.e.) A_c	A_m
		ly	ly	ly	ly	ly	ly		
1	26	311	194	23		44	484	6.1	5.9
2A	24	250	61	40		38	313	3.9	3.2
2B	24	275	103	6		38	346	4.3	3.1
3A	36	327	210	28		57	508	6.4	9.4
3B	36	503	356	29		67	821	10.3	10.9
4	36	139	69	75		69	214	2.7	6.8
5A	48	383	74	61		92	426	5.3	3.2
5B	36	312	28	6		46	300	3.8	3.4
6	48	410	44	9		55	408	5.1	3.4
7	24	114	11	8		28	105	1.3	3.2
8	24	82	153	5		28	212	2.7	6.2
Total	362	3 106	1 303	290		562	4 137	51.9	58.7
		Sources: 4 699 ly				Sinks: 4 699 ly			
		66%	28%	6%		12%	88%		

Sverdrup Glacier, Devon Island, 1963

Date	$+Q_r$	$+Q_s$	$+Q_l$	$+Q_p$	$-Q_i$	$=Q_m$	*Ablation* (cm w.e.) A_c	A_m
	ly	ly	ly	ly	ly	ly		
9 July	74	7	2		27	56	0.7	0.5
10	91	11	6		23	85	1.1	1.5
11	42	17	0		23	36	0.5	0.4
12	71	38	18		30	97	1.2	1.0
13	111	57	24		27	165	2.1	1.0
14	129	39	14		37	145	1.8	0.7
15	111	43	23		37	140	1.8	1.0
16	165	76	29		37	233	2.9	1.4
17	140	87	42		37	232	2.9	1.0
18	148	82	19		42	207	2.3	0.9
19	128	36	9		28	145	1.6	0.8
20	140	8	0		18	130	1.6	0.5
21	130	21	10		18	143	1.8	0.5
22	118	7	0		14	111	1.4	0.9
23	141	24	12		19	158	2.0	1.0
24	109	51	23		19	164	2.0	1.8
25	129	103	31		19	244	3.1	2.4
26	121	112	38		21	250	3.1	2.5
27	136	115	48	7	28	278	3.6	4.4
28	125	86	50		20	241	3.0	5.5
29	33	47	19	4	20	83	1.0	4.3
30	123	38	23	3	20	167	2.1	3.0
31	75	47	53	8	20	163	2.0	4.2
1 August	83	225	146		20	434	5.4	6.1
2	118	161	69		20	328	4.1	5.4
3	123	59	26		20	188	2.4	1.5
4	154	36	15		20	185	2.3	2.0
5	119	17	9		16	129	1.4	1.3
6	12	24	10	2	20	28	0.4	1.1
7	123	40	24		20	167	2.1	3.2
8	69	49	1		13	106	1.3	1.7
9	42	191	112		16	329	4.1	4.8
10	55	165	64		16	268	3.4	4.7
Total	3 488	2 119	969	24	765	5 835	72.5	73.0
	Sources: 6 600 ly				Sinks: 6 600 ly			
	53%	32%	15%	0%	12%	88%		

Notation: Q_r = net radiation
Q_s = sensible heat
Q_l = latent heat
Q_i = heat conduction into ice
Q_p = heat supplied by precipitation
Q_m = heat of melt
A_c = ablation calculated from Q_m
A_m = ablation measured (surface lowering)
ly = langley ≡ cal cm^{-2} = 41.868 kJ m^{-2}

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considerable. Series of thermistors and thermocouples were inserted to a depth of 15 m, with a spacing of 25 cm in the upper third of the profile. These were read periodically and heat conduction computed by integrating between successive depth–temperature curves.

Heat supplied by precipitation was minor. The temperature of the rain was assumed to be the same as the 150-cm air temperature.

Table I summarizes the short-period (usually daily) heat-balance terms obtained on Axel Heiberg Island in 1961 and 1962 and on Devon Island in 1963. The values for calculated melt were found by dividing the available heat by the heat of fusion of ice. These figures are subject to considerable error arising from such factors as type of instrument, low solar angle in the case of radiation, sampling time, deviation from a logarithmic wind structure and operator error. A conservative estimate indicates that there may be as much as a 30 per cent error for any daily value of the heat sources. Therefore some caution should be exercised in using these figures.

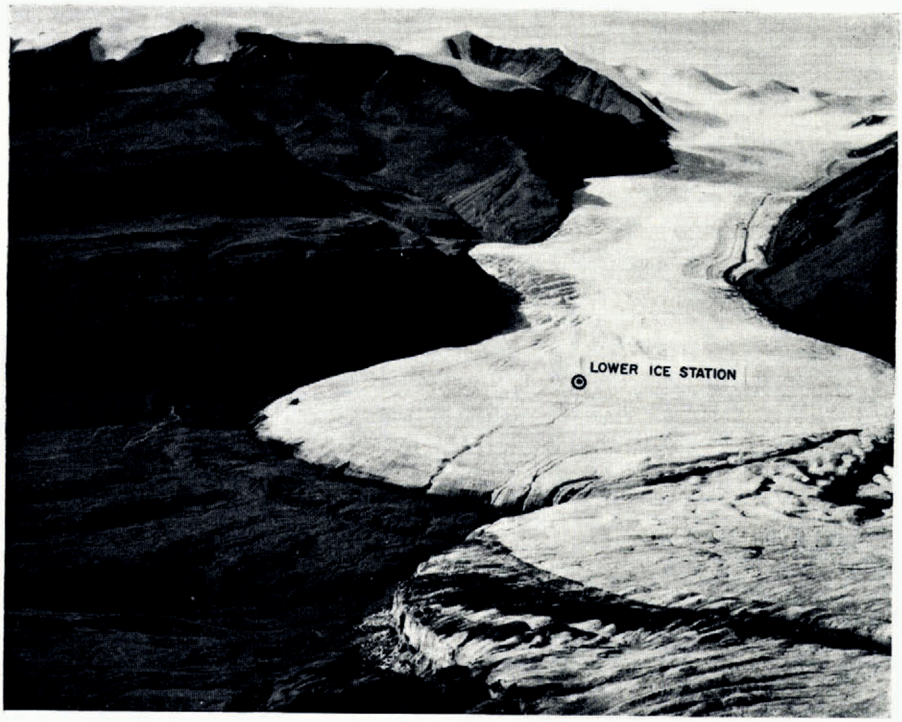

Fig. 4. The site of the ablation measurements on the White Glacier, Axel Heiberg Island: the surrounding of the Lower Ice Station.

Measurement of Ablation

Ablation quantities can be obtained from various measurements such as: surface lowering, run-off from supraglacial basins, mass change, and ice discharge past the equilibrium line of a glacier in a balanced state. All except the latter were tried and a discussion of the precision and accuracy of each follows.

Surface lowering

Measuring the lowering of the surface level relative to a fixed point is the common method of assessing mass wastage. The height difference is converted to a mass figure by multiplying by the density which is assumed to remain constant with respect to time and space.

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On the *White Glacier, Axel Heiberg Island*, surface lowering was measured in the centre of the tongue about half a kilometre from the edge by various methods (Fig. 4 and 5). Five bamboo poles were drilled into the ice ("Lower Ice Diamond") 20 m from the meteorological station. In a shallow drainage basin, located 60 m up-glacier from the station, 11 aluminum poles were inserted and two star ablatometers were installed. In addition, four stakes of the longitudinal profile (L), spaced at 100 m intervals, were included in this ablation survey.

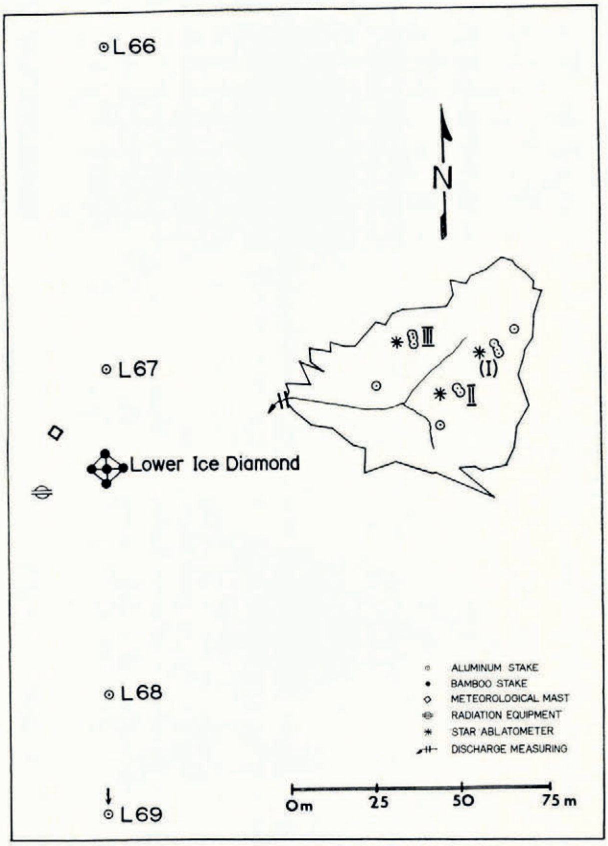

Fig. 5. The locations of various ablation and micro-meteorological measurements in the test area at the Lower Ice Station.

Stake measurement

Melt hollows caused by the heat absorption of the stake and the complex micro-relief of the ice surface made the usual technique of measuring surface lowering on stakes difficult and often inaccurate. Some consistency and objectivity was achieved by measuring to the underside of a 50-cm straight edge laid first parallel then perpendicular to the direction of glacier flow. This technique is referred to as the straight-edge method. The mean of the two readings, however, does not necessarily represent the true lowering of the surface surrounding the stake as the rate of lowering of the peaks of the micro-relief, the points in contact with the straight edge, may differ from that of the total surface. The measuring error for this method at any one stake was found to average ± 0.5 cm for the many different surface conditions in the test area during one summer. In addition, the often large standard deviations associated with the mean of several stake readings indicated uncertainties in the daily values which were frequently of the same order of magnitude as the values themselves.

The star ablatometer

In an attempt to obtain a more accurate surface lowering value for an area of 1 m radius around a stake, a portable ablatometer was designed (Fig. 6). A six-arm metal star is mounted on the stake. Thirty-six points are measured by the lowering of a thin rod through the six sleeved holes in each arm. The rod contacts a variety of surface points including both peaks and depressions of the micro-relief and penetrates the larger cryoconite holes and some of the spaces between loose crystals. Thus the star ablatometer incorporates some information on the changes within the weathering crust in the surface lowering value and therefore yields a more accurate measure of ablation than the straight-edge method. The equipment is removed between measurements, thus obviating the interference that additional stakes would cause. From repeated measurements during a time of no ablation the instrumental error was found to be approximately ± 0.3 cm. With the large number of observations available from the star ablatometer the probability that the sample mean is representative of the true mean is

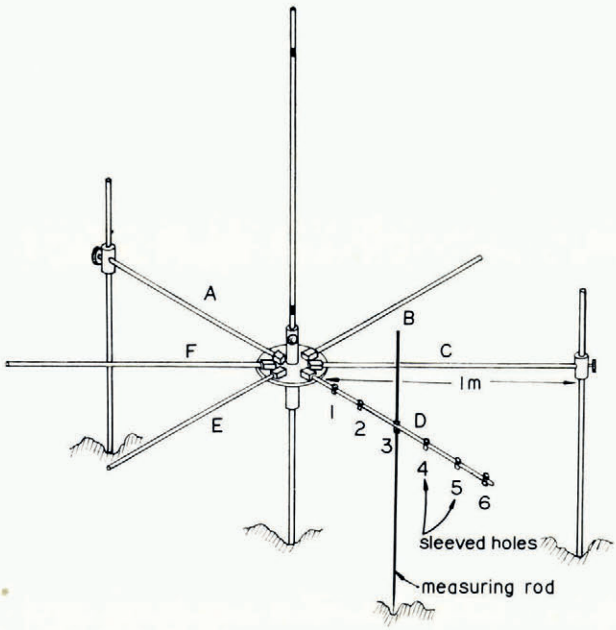

Fig. 6. The star ablatometer.

99 per cent, accepting the above stated accuracy. The probability of obtaining true daily mean values with an accuracy of ± 0.5 cm from the 5 stakes of the "Lower Ice Diamond" using the straight-edge method was at the most 90 per cent. A Buchow, Höhne and Raeuber error-graph, as reproduced by Untersteiner (1961), was used to establish these probabilities. It must be stressed that even these mean values are, because of the changes in the weathering crust from one reading to the next, not necessarily accurate measures of true ablation.

The ablatograph

Attempts to obtain continuous records of the surface lowering with ablatographs equipped with different types of floats produced very doubtful values. It became obvious that, particularly on days of high insolation, due to the considerable changes in the weathering crust, ablatographs, however well designed, are unable to measure the very thing for which they are made, i.e. the short-term variations in the ablation rate.

Comparison of the surface lowering data

Table II gives the short-period surface lowering values and their 68 per cent confidence limits $\sigma/n^{\frac{1}{2}}$, as obtained by the various measuring techniques used at the different locations of the test area on Axel Heiberg Island. All data are converted to centimetres of water to permit direct comparison with the run-off data and the melt calculated from the meteorological elements. The differences between the daily values for the various sites are often considerable —in some cases more than 200 per cent. The totals for the entire observation period differ much less, only up to 20 per cent. The standard errors of the sample means of daily surface lowering for the "Lower Ice Diamond" average 47 per cent, while the corresponding error of the sample mean for the season amounts to 3 per cent. Likewise the errors for the short-period values obtained from the two star ablatometers average 17 per cent (II) and 13 per cent (III), while the standard errors for the sample means for the total surface lowering at the two sites are less than 2 per cent.

The fact that the differences between the values at the various sites are greater for short periods than for long ones substantiates the idea that the errors in short-period measurements are largely compensatory in time due to the fluctuating nature of the weathering crust. Discrepancies in both daily and longer-term values between the different sites clearly indicate an

Table II. Comparison of Ablation Values obtained by Different Methods and at Different Locations near Lower Ice Station, A.H.I., Summer 1961. Values are given in cm of water

Date	*Straight-edge 5 stakes in diamond near met. mast*	*Ablatograph near met. mast*	*Star ablatometers 36 readings in basin*		*Straight-edge 11 random stakes in basin*		*Straight-edge 4 individual stakes in L-profile*			
1961	*mean* ($\bar{x}$) ± *error* $\sigma/n^{\frac{1}{2}}$		*No. II* $\bar{x}$ ± *error*	*No. III* $\bar{x}$ ± *error*	$\bar{x}$ ± *error*	*Run-off from basin*	L66	L67	L68	L69
July										
21	2.0±0.3		1.5±0.2	—	1.4±0.5*					
22	1.4±0.2		2.3±0.5	—	1.4±0.5*					
23	2.2±0.2	2.5	3.8±0.4	2.6±0.1	2.3±0.2	3.3	9.0	7.2	7.2	8.8
24	1.5±0.3									
25	2.2±0.3									
26	3.2±0.2		8.7±0.8	10.0±0.5	8.9±0.9					
27	1.2±0.1									
28	1.1±0.6						10.4	8.8	11.0	9.7
29	0.2±0.1									
30	1.4±0.2	2.0	1.9±0.5	2.1±0.4	1.1±0.1	2.7				
31	2.6±0.5	—	8.1±0.7	4.5±0.7	2.5±0.2	4.1				
Aug.										
1	9.1±0.6									
2	2.2±0.4									
3	5.3±0.3						27.0	23.6	26.8	24.1
4	6.2±0.3		29.9±1.1	30.2±0.9	29.3±4.4					
5	1.0±0.2									
6	1.5±0.3									
7	7.2±0.4									
8	2.1±0.5						15.8	16.3	20.9	18.6
9	4.0±0.2	2.8	3.0±0.5	4.2±0.3	4.0±0.3	1.2				
10	2.5±0.3	1.7	3.1±0.6	2.3±0.3	2.5±0.4	1.4				
11	1.8±0.3	—		1.9±0.2	1.8±0.4	2.8				
12	0.9±0.2		0.9±0.6	1.0±0.2	0.7±0.1					
13	1.0±0.2	—	1.1±0.1	1.3±0.2	1.4±0.2	0.8	7.2	6.1	7.4	9.5
14	1.2±0.3	—	1.1±0.1	1.7±0.2	1.2±0.2	0.7				
15	1.1±0.2	1.5	1.6±0.1	1.5±0.2	1.2±0.3	0.8				
16	1.2±0.3		1.2±0.5	1.3±0.3	0.7±0.2					
17	1.6±0.3	—	1.6±0.2	1.6±0.3	2.1±0.1	1.4	3.6	3.4	4.5	4.1
18	2.0±0.6	—	1.1±0.1	1.8±0.3	1.4±0.4	0.8				
Total	70.9±2.1		65.9±1.1	68.0±1.2	63.9±1.4		73.0	65.4	77.8	74.8

* Incomplete data.

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additional problem—that unexpectedly large spatial variations in the amounts of surface lowering, and therefore also in ablation, occur over short distances on seemingly uniform surfaces. These must be attributed to changes, which would be hard to observe, in albedo, in micro-relief (causing differences in sensible and latent heat exchanges), in the physical properties of that surface layer which undergoes weathering, and in the melt-water drainage.

Based on this latter observation, the 1962 surface lowering on the White Glacier was measured in close proximity to the site of the energy-balance study. A simple frame ablatometer, similar to the star ablatometer, constructed from "Dexion" slotted angle aluminum, permitted 36 individual readings evenly distributed over an area of 1 m^2. Thirteen short-period mean surface lowering values (24 to 48 h) obtained with this equipment between 16 and 31 July had standard errors between 4 per cent and 18 per cent.

In 1963 further surface lowering measurements were carried out approximately in the centre of the ablation area of the *Sverdrup Glacier, Devon Island*. Eleven bamboo stakes were drilled into the ice in the vicinity of the meteorological mast and along the perimeter of a supraglacial drainage basin. Despite the precaution of using the straight-edge method the standard deviation of the daily means gained from the stakes was frequently extremely high, again suggesting that ablation varies considerably over short distances.

In order to increase the accuracy of the measurements, near the meteorological mast a device was constructed similar to the frame ablatometer used on Axel Heiberg Island. It consisted of three stakes arranged in a triangle, with legs of 1 m, between which was stretched a marked wire. Measurements were made along the wire at 10 cm intervals with a probe. This allowed 30 individual readings to be made in an area of 0.5 m^2. This number of readings allows 95 per cent confidence that the sample mean does not differ from the population mean by more than ± 0.25 cm of water. A second such ablatometer was set up in the upper part of the catchment basin to provide a check on the representativeness of the mast-site observations. The seasonal values for the two ablatometers are 58.1 cm and 66.1 cm respectively and 78.7 cm for the stakes. The measuring error for these ablatometers was determined to be ± 0.3 cm. The difference between the two ablatometers is significant at the 1 per cent level. This was expected as the difference in surface albedo between the two areas was 10 per cent, the upper site having the lower albedo. The high value given by the stakes may partly be due to accelerated melt in their immediate vicinity.

Direct Measurement of Mass Loss

If one accepts that one of the major sources of error in short-term ablation measurements on ice is the variation in surface density then an assessment of mass, rather than surface-level, change would be more valid.

Ambach (1963[a], [b]) suggested calculating the change in density (or porosity) from measurements of the radiation extinction within the upper ice layers. He and his co-workers developed several small size thermo- and photo-electrical receivers to measure the radiation intensity, balance and direction. This approach produced some interesting results, as for example those reported from Greenland (Ambach, 1963[a]). But still very large numbers of measurements within the area and time period are necessary because of the great variations in the weathering crust over short distances.

Hubley (1954) discussed the problems for the case of snow from a theoretical point of view and presented an equation for ablation which includes both changes in surface level and density as functions of time.

$$\frac{\mathrm{d}M}{\mathrm{d}t} = \rho_h \frac{\mathrm{d}h}{\mathrm{d}t} + \int_0^h \frac{\mathrm{d}\rho}{\mathrm{d}t}\,\mathrm{d}z \qquad (1)$$

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where M is the total mass of snow in a column of unit area and height h, having a density ρ, which is a function of depth z. LaChapelle (1959) developed a practical field method for snow. He showed that, when density is a function of time, mass loss can be found by integration between two successive depth–density curves. The idealized situation is depicted in Figure 7. The change in mass ΔM between times t_0 and t_1, is given by

$$\Delta M = \int_0^{h_0} \rho(h, t_0)\, \mathrm{d}h - \int_0^{h_0} \rho(h, t_1)\, \mathrm{d}h. \tag{2}$$

The difficulty with this technique is in making a sufficient number of density measurements to draw depth–density curves. This is possible although tedious for snow surfaces but next to impossible for ice.

An alternate method is to core into the glacier from an established reference horizon. The ablation is equal to the difference between the mass of ice in the core at two successive readings. This method is extremely simple requiring only a coring device. While having a rather small sampling area, the standard SIPRE 3-inch (7.6 cm) diameter coring auger is readily available. In 1963, this sampling technique was extensively used on Devon Island after some exploratory

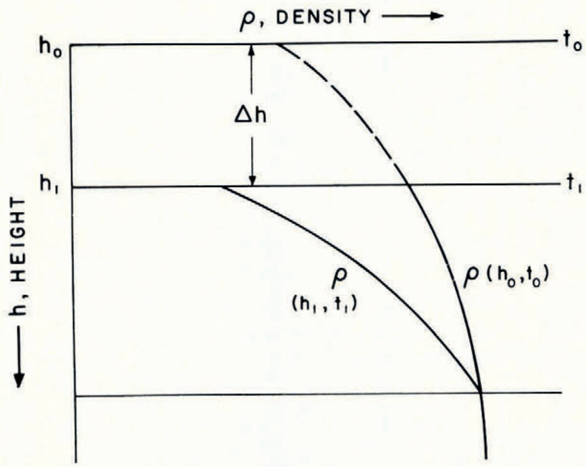

Fig. 7. Two successive ideal depth–density curves on a melting glacier (after LaChapelle, 1959).

studies with more sophisticated equipment, as for example a specially designed hot-point corer of 26 cm diameter which failed in application. Although there were usually only two density values measured per profile, the data permitted plotting simple depth–density curves as shown in Figure 8. Figure 8a illustrates a case in which there was sub-surface melt amounting to more than one half of the actual mass loss, and Figure 8b presents a situation in which there was a low density surface layer which vanished without additional sub-surface melt. Daily mass-loss measurements accrued for the period 15 July to 6 August 1963. The primary source of error in direct mass-change measurements with the coring technique was the fact that each area could only be sampled once. The lateral variation in the depth of the weathering crust is such that an erroneous impression of mass loss or gain may result. The weathering crust tends to be deeper over ridges than in depressions where radiation has less access and where running water erodes much of it. Thus it becomes necessary to adopt the subjective procedure of sampling in selected topographically similar locations. It is estimated that, despite this difficulty, the errors of direct mass-loss measurements are less than those of any of the other techniques discussed in this paper. Large numbers of samples and the development of a larger diameter corer would allow a more representative assessment of the mass losses.

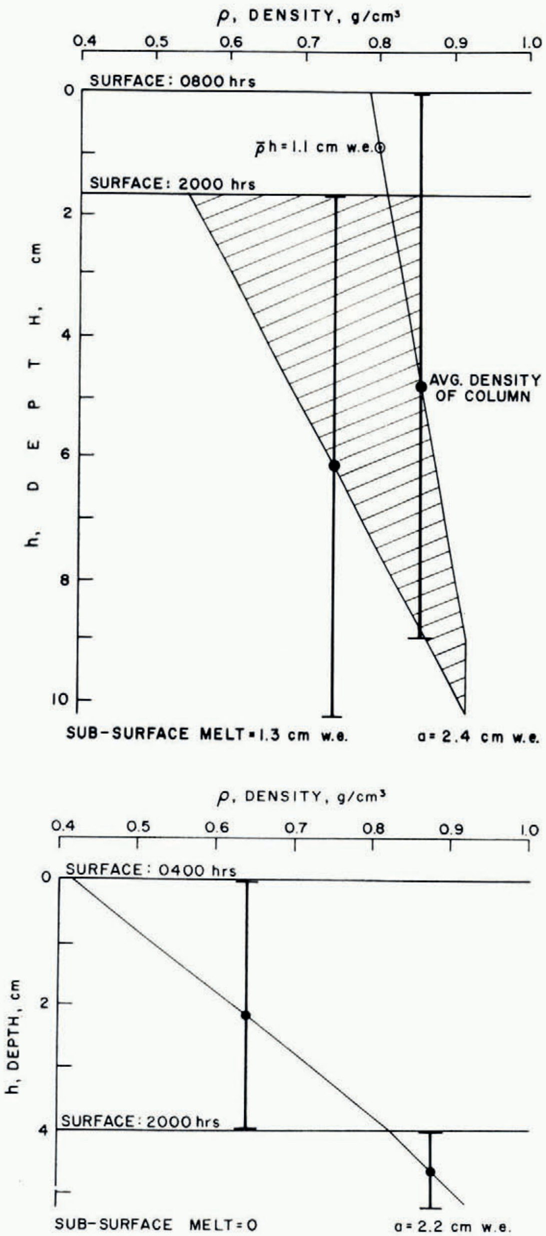

Fig. 8. Examples of field determinations of mass loss. Figure 8a (above) shows the case for clear sky conditions with sub-surface melt (16 July 1963) and Figure 8b (below), the case for rain and wind with surface scour (29 July 1963).

Surface Run-off Measurements

Assuming that the ice is impermeable and that evaporation is negligible then surface run-off should be equal to the amount of ice melted and within a small drainage basin there should be little time lag between the melt and the run-off. On both the White and the Sverdrup Glaciers small drainage basins (3 360 m² and 4 860 m²) were delineated for selected periods of

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measurements of discharge using the sodium dichromate method (Dumas, 1952–53). This technique is described fully by Adams (1961, 1966) and Keeler (1964). As the colorimetric analysis of the collected samples was quite time-consuming, it was only possible to sample every six hours on Axel Heiberg Island and every four hours on Devon Island. It was found that spot discharge quantities with the dilution method are accurate to ±5 per cent even under field conditions, however the necessity for interpolation to derive the daily hydrograph decreases the accuracy for the daily quantities. Time lags between the melt and discharge peaks of from three to six hours, depending on the permeability of the weathering crust must be taken in consideration when calculating daily melt. Consequently the ablation values gained by this method do not constitute a reliable standard against which to judge values obtained by other methods.

Comparison of Various Measures of Ablation

Values of ablation calculated from the energy balance (A_c) were compared with those measured from surface lowering (A_m) and were found to be in closer agreement over long than short periods. To assess the hypothesis that the difference between observed and calculated short-term ablation stands in a causal relationship to changes in the micro-climatic conditions prevailing at the surface, the ratio of measured ablation to ablation calculated from the energy balance has been plotted against the per-cent contribution of radiation to the total energy sources (Fig. 9). While the scatter is great there appears to be a trend indicative of under-estimates of ablation during periods of high insolation and the converse during periods of low insolation. An alternative plotting of A_m/A_c versus the sunshine duration (expressed in per cent of possible) was tried; however, a similarly low correlation was obtained. It is clear that no single climatic parameter can be used to establish the relationship between ablation and climate.

Ablation quantities obtained by various methods of measurement are compared with the melt calculated from the energy balance in Table III. As mentioned before it can be seen that over long periods the differences are negligible while for short periods they are considerable. In all cases direct measurements of mass change seem to correlate better with expected melt than do measurements of surface lowering. It is not known why the discharge figure for 2 August is so low in comparison with the other values of ablation.

Table III. Comparison of Values of Ablation (in cm of Water) Obtained by Various Methods, Devon Island, Summer 1963

	Method			
Date	*Energy balance*	*Surface lowering*	*Mass change*	*Discharge*
15 July	1.7	1.0	2.0	
16	2.9	1.4	3.1	
20	1.6	0.5	1.5	1.8
21	1.8	0.5	2.2	1.2
23	2.0	1.0	2.4	
25	3.0	2.4	2.7	
26	3.1	2.5	3.0	
27	3.6	4.4	3.7	
28	3.0	5.5	2.6	
29	1.0	4.3	2.3	1.9
30	2.1	3.0	1.7	1.6
1 August	5.4	6.1	6.0	
2	4.1	5.4	4.8	1.9
3	2.4	1.5	1.0	1.3
4	2.3	2.0	2.0	
5	1.4	1.3	1.5	
6	0.3	1.1	0.9	
Total	41.7	43.9	43.4	

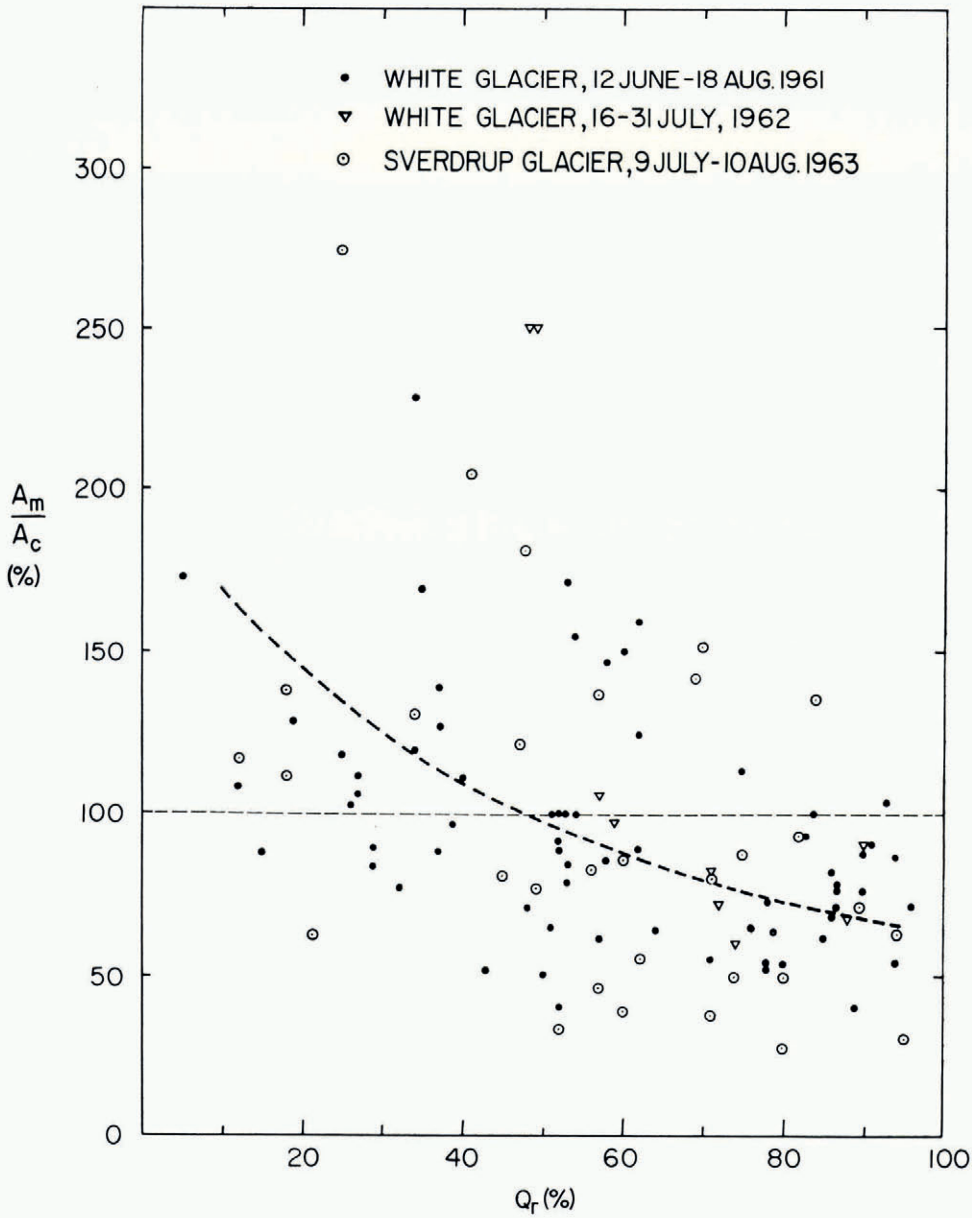

Fig. 9. Plot of the ratio of ablation measured from stakes to ablation calculated from the energy balance versus the per cent contribution of radiation to the energy sources.

Summary and Conclusions

The large differences in the short-period ablation values obtained from various methods of measurement and from energy balance calculation (Tables I and II) reveal a systematic error which is related to mass losses in the weathering crust.

An investigation of the various errors involved (instrumental, sampling and the above mentioned systematic error) led to the following conclusions: (1) The usual techniques of measuring ablation with stakes, ablatometers and ablatographs are, in many cases, inadequate for assessing short-term values. (2) The discharge method, in spite of highly accurate individual readings, does not provide a satisfactory measure for short-term ablation because of the varying time-lag between melt and run-off, and the laborious field-work entailed. (3) The direct measurement of mass loss (surface lowering plus melt in the weathering crust) is feasible with relatively simple equipment and yields data which are in fairly close agreement with the calculated short-term ablation values (Table III). It appears that this method is more satisfactory than any other both in terms of accuracy and expediency in the field. The development of more sophisticated equipment could improve the results obtained.

Spatial variations in the weathering crust occurring even over short distances were found to be of considerable significance in the short-term ablation measurements. Consequently any short-period micro-climatic observations must be carried out in the closest proximity possible to the ablation measurements with which they are to be correlated.

Fortunately, over longer time spans the main errors inherent in short-term ablation measurements are not accumulative but clearly cancel out, and are therefore of little consequence in mass-balance computations.

ACKNOWLEDGEMENTS

The main support for this investigation was provided by the National Research Council of Canada. The Arctic Institute of North America, through its Devon Island Project, supported the field work of C. M. Keeler on the Sverdrup Glacier. The assistance in the field and in the office by many is gratefully acknowledged. Particular thanks go to W. Peter Adams, who collected most of the 1961 ablation data.

MS. received 20 May 1968

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