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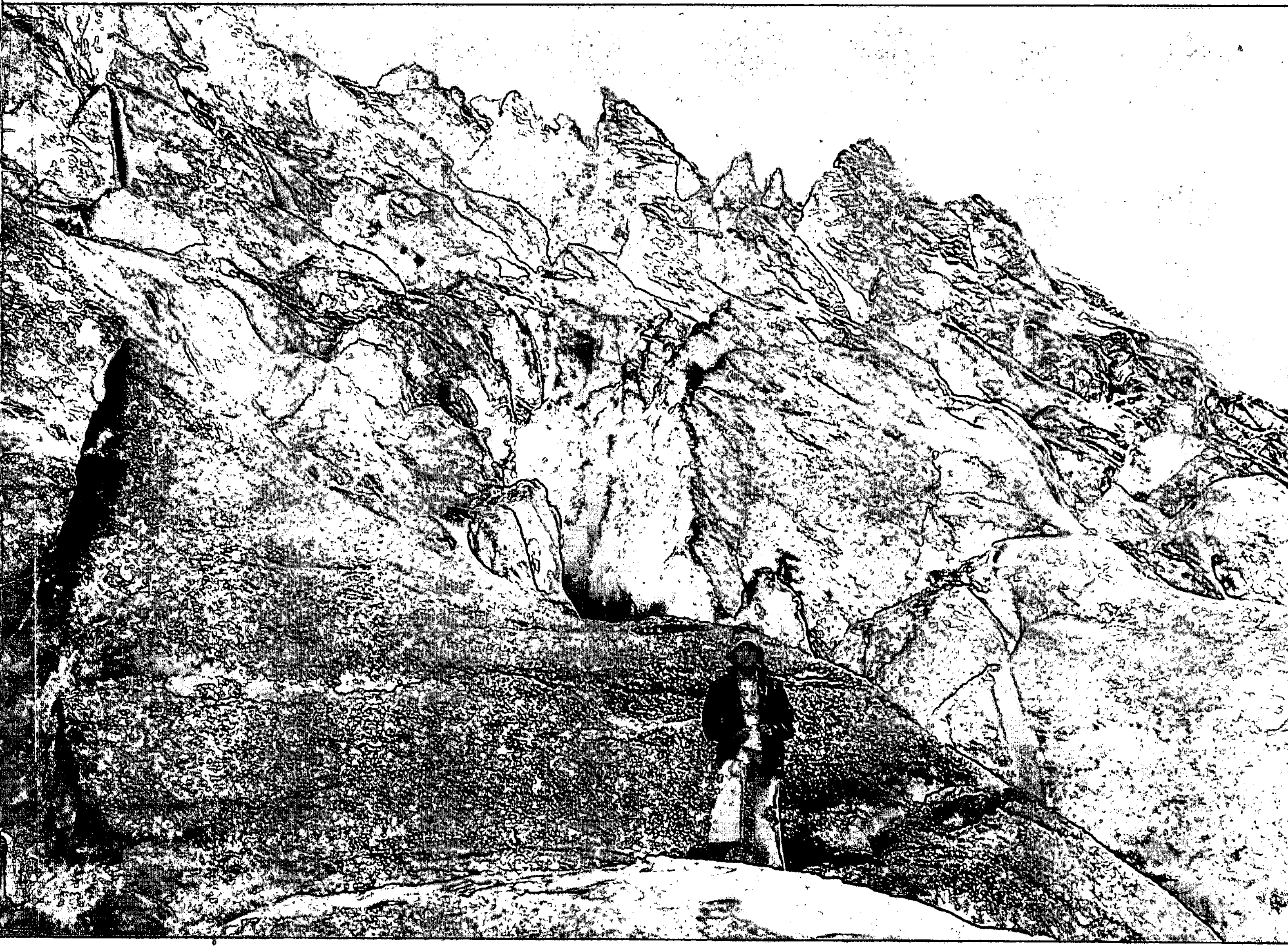
Analysis of Mass Balance Values and their Accuracy for Sentinel Glacier, British Columbia, Canada

O. Mokievsky-Zubok



SCIENTIFIC SERIES NO. 31
(Résumé en français)

INLAND WATERS DIRECTORATE,
WATER RESOURCES BRANCH,
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Cat. No.: En 36-502/31

CONTRACT #02KXKL327-3-8060
Thom Press Limited

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Abstract

The accuracy of mass balance measurements for Sentinel Glacier was determined by comparison of (1) a method, based on determination of difference between measured winter and summer balances with (2) an alternate method, the difference between the volume of remaining snow cover and ice and firn ablation. The difference ranged from 0.2% to 8.8% as related to the thickness of the snow cover. The greatest difference was obtained for deeper snowpacks. Both methods provide acceptable results but *Method 1* is considered less accurate.

Résumé

La précision des mesures de bilan de masse effectuées sur le Glacier Sentinel, a été déterminée en comparant les résultats obtenus par (1) une méthode basée sur le calcul de la différence entre le bilan d'hiver et celui de l'été, à ceux obtenus, (2) en faisant la différence entre le volume de la couverture neigeuse restante et celui de la glace et du névé soustraits par ablation. Cette différence se situait entre 0.2 et 8.8% de l'épaisseur de la couverture neigeuse; la plus grande valeur ayant été obtenue dans le cas d'un névé très épais. Les deux méthodes donnent des résultats acceptables mais la première méthode est considérée comme étant moins précise.

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INTRODUCTION

Attempts to attain absolute accuracy in mass balance values have failed so far (Hoinkes and Rudolf, 1962; Meier, and Tangborn, 1965; LaChapelle, 1965) because the accuracy of mass balance determination is difficult to assess (Paterson, 1970). Therefore detailed studies of error problem, as recommended by Kasser (1967) have great value.

Several different approaches and methods have been used (Tangborn, 1966; Menshutin, 1970). UNESCO/IASH guide (1970) advises that "simple measurements of known accuracy, frequently repeated, are preferred to highly complex or sophisticated measurements which cannot be maintained for a long time".

This mass balance study of the Sentinel Glacier is based on simple, frequent measurements. The methods employed are:

(a) *Method 1* based on determination of difference between measured winter and summer balances; and

(b) *Method 2* an alternate method in which mass balance is determined as the difference in the volume of remaining snow cover from the volume of ice and firn ablation (Mokievsky-Zubok, 1973 a).

Mass balance measurements have been taken since 1966. Detailed description of the methods and procedures is given elsewhere (Mokievsky-Zubok, 1973 b).

To evaluate the accuracy of those mass balance methods, the results were compared. The consistency of the results then determined the degree of difference. The percentage of difference and the difference in quantity of snow expressed in water equivalents, which were used to adjust the original results to the corrected values of mass balance, were calculated also.

Ablation at each stake is measured once every seven to ten days and three density calculations are performed on the glacier every two weeks. To check stake readings which are taken from the top of the stake to the snow or ice, and to verify snow depth measurements made at the start of the field season, three snow soundings are made at every stake reading where snow remains. The measurement of soundings, however, is not always accurate because of the glacier's topography and location in maritime climate (Mokievsky-Zubok, 1973 a, b).

RESULTS

Mass balance values obtained by the two methods are presented in Table 1, columns 8 and 9, and the corrected values (equations 3 and 4) in columns 13 and 14, respectively. In column 11, the calculated values for the difference in per cent are given. The difference in per cent is the relation of the difference between the results obtained from the two methods, to the thickness of the snowpack expressed in water equivalent. It may be represented by the formula:

$$E_{sp} = \frac{(b_{\bar{n}_1} - b_{\bar{n}_2})}{b_{\bar{w}}} \times 100 \qquad (1)$$

Where E_{sp} is the difference expressed as a percentage, $b_{\bar{n}_1}$ is the mass balance by Method 1, $b_{\bar{n}_2}$ is the mass balance by Method 2, and $b_{\bar{w}}$ is the winter balance. A bar over the symbol denotes values given in specific water equivalents, which are obtained by dividing total mass change by area. The value applies to the entire area of the glacier.

The variation of E_{sp} from year to year reflects the changeable conditions on the glacier which have influenced significantly the accuracy of the measurements.

The average difference in results, using the two methods, is 3.8% indicating an internal consistency. In 1970, the smallest difference of 0.2% was obtained due to the favourable measuring conditions; measurements of ablation and of the remaining snow cover were accurate because the firn was easily identifiable. In 1969, the greatest disparity of 8.8% occurred, as it was difficult to identify the firn surface because of the great snow depths and the presence of ice lenses. (In all calculations of b_w and b_n, snow depth variations in the snow/firn interface tend to be smoothed out). Although there is no general agreement on

Table 1. Determination of Corrected Values For Mass Balance 1967-1971.

1	2	3	4	5	6	7	8	9	10	11	12	13	14
Year	A	b_w	$b_{\bar{w}}$	b_s	$b_{\bar{s}}$	b_{n_1}	$b_{\bar{n}_1}$	$b_{\bar{n}_2}$	$(b_{\bar{n}_1} - b_{\bar{n}_2})$	E_{sp}	E_w	Corr. b_n	Corr. $b_{\bar{n}}$
	km^2	$10^6 m^3$	m	$10^6 m^3$	m	$10^6 m^3$	m	m	m	%	$10^6 m^3$	$10^6 m^3$	m
1966	1.985	6.509	3.28	6.217	3.13	+0.292	+0.15	–	–	–	–	–	–
1967	1.985	8.346	4.205	8.714	4.89	-0.368	-0.184	-0.368	0.184	4.4	0.365	-0.550	-0.277
1968	1.985	6.738	3.417	6.043	3.044	+0.740	+0.373	+0.228	0.145	4.2	0.287	+0.552	+0.278
1969	1.985	6.981	3.516	6.747	3.399	+0.234	+0.117	-0.196	0.313	8.8	0.621	-0.076	-0.038
1970	1.927	5.043	2.617	7.549	3.917	-2.506	-1.300	-1.294	0.006	0.2	0.012	-2.500	-1.297
1971	1.901	7.342	3.862	6.264	3.295	+1.078	+0.567	+0.504	0.063	1.6	0.120	+1.018	+0.535

error determination in mass balance studies, the percentage of difference E_{sp}, from year to year (Table 1) never exceeded 10% and can be considered satisfactory.

Column 12 in Table 1 gives the calculated difference in volume of snow expressed in $10^6 m^3$ of water. These values were calculated according to equation (2):

$$E_w = A \times (b_{\bar{n}_1} - b_{\bar{n}_2}) \qquad (2)$$

where E_w is a difference in quantity of water in $10^6 m^3$, A is total glacier area in km^2; $b_{\bar{n}_1}$ and $b_{\bar{n}_2}$ have been defined previously.

If E_w is known, then corrected mass balance values, corr b_n, can be determined from:

$$\text{corr } b_n = \left[b_w - (E_w/2) \right] - b_s \qquad (3)$$

where corr b_n is in $10^6 m^3$ of water, and b_s is the summer balance; and from:

$$\text{corr } b_{\bar{n}} = \frac{\left[b_w - (E_w/2) \right] - b_s}{A} = \frac{\text{corr } b_n}{A} \qquad (4)$$

where corr $b_{\bar{n}}$ is in meters of specific water equivalent. The mass balance has been recomputed for all of the years studied and results are presented in Table 1, columns 13 and 14.

CONCLUSIONS AND DISCUSSION

Prior to this report either of the two methods could have been considered equally accurate. Graphical analysis of obtained results, however, indicates that Method 2 is better. This is shown in Figure 1, where the results of Method 1 were plotted on the y-axis and those of Method 2 on the x-axis. Since the scale is the same for both axes, the points for both methods should fall on the line. Any deviation from this line reflects a difference in measurements.

In Figure 1, the values for Method 2 were consistently lower than those for Method 1. Method 2 is considered to be more accurate since the values were obtained from volume measurements of icemelt and snowmelt and of snow remaining at the end of the season.

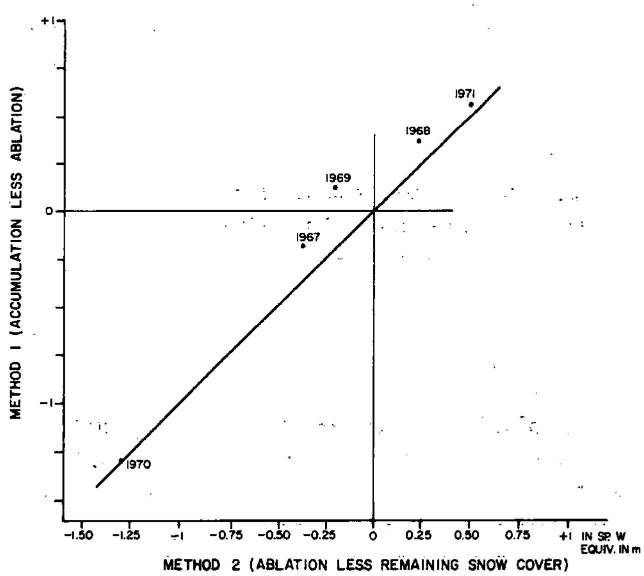

Figure 1. Graphical analysis of surface measurement methods.

The accuracy of Method 2 is supported primarily by the following:

1. Icemelt is easier to measure at the stakes throughout the summer. Errors of measurement are not likely to exceed ± 0.5 cm at a stake at any one time (Anonymous, 1967).

2. The remaining snow cover is relatively simple to measure because:

   (a) the depth of the remaining snow is shallow,
   (b) ice lenses, hard to penetrate with a sounding rod in spring, disappear or weaken by the end of the summer, making true firn easily detectable, and
   (c) knowledge of the depth of the snow cover is available from snow pits dug throughout the summer.

Method 2 is not absolutely accurate since all of the glacier cannot be sampled – steep and crevassed areas are not readily accessible. The latter comprise less than 10% of Sentinel Glacier and for most areas, topography and accumulation pattern are known. A minor error, however, is inevitable due to subjective construction of the isoplethes of accumulation and melt. Errors in these constructions are not eliminated or diminished even if the non-mechanical method of contouring maps is used for mass balance measurements.

As a final check, mass balance values and the percentage of difference from Table 1 were analysed graphically. Figure 2 shows two curves representing results obtained by Method 1 and corrected mass balance values, respectively. The curve for Method 1 is displaced from the centre line indicating more positive values for mass balance (Fig. 1). The curve for corrected mass balance values is nearly central.

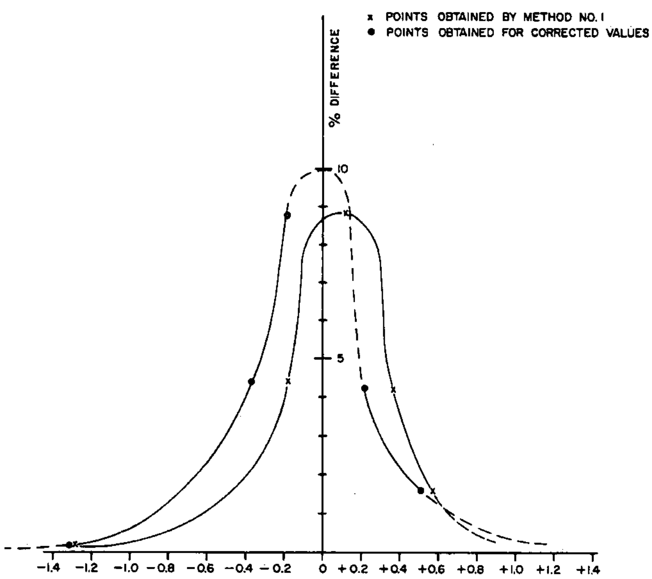

Figure 2 indicates that the smaller the values of mass balance, the higher the percentage difference; the larger the mass balance values, either positive or negative, the smaller the percentage difference. This shows that when large volumes of accumulation and melt are involved in the same balance year and the net balance is small, the difference in methods and in results (as expressed in percentage) becomes larger. It means also that when there is either distinct accumulation or ablation in the same balance year, the percentage difference is reduced.

In future investigation it can be expected that:

(a) If the same field procedures are followed in obtaining the mass balance, all values should fall on the curve as given in Figure 2, and
(b) In comparing Methods 1 and 2, assuming Method 2 is reasonably correct, the amount of probable error, both in percentage and volume, may be established and the corrected values of mass balance obtained.

To achieve better results it is necessary to determine the accumulation as accurately as possible. Densities can be measured accurately, but the variation in results is due mainly to the changeable snow depths.

With some adjustments for local conditions, the approach for corrected mass balance values developed at Sentinel Glacier could be useful at other glaciers. This approach could be applied particularly in areas with less snowfall which are not exposed to such peculiarities as ice layers or variable accumulation patterns characteristic of a maritime climate.

ACKNOWLEDGEMENTS

I am grateful to Dr. A. D. Stanley, Glaciology Division, Inland Waters Directorate and to Dr. J. P. Johnson, Jr., Carleton University, Ottawa, Ontario, for their valuable comments and suggestions throughout this study.

REFERENCES

Anonymous. 1967. "Hydrology of the Lewis Glacier, North Central Baffin Island, N.W.T. and Discussion of Reliability of the Measurements," *Geographical Bulletin*, Vol. 9, No. 3. pp. 232-61.

Hoinkes, H. and R. Rudolf. 1962. "Variations in the Mass Balance of Hintereisferner (Ötztaler Alps) 1952-1961, and Their Relation to Variations of Climatic Elements," *Commission of Snow and Ice*, Symposium of Obergurgl, September 9-18, IASH Publication No. 58, pp. 16-29.

Hoinkes, H. and R. Rudolf. 1962. "Mass Balance Studies on the Hintereisferner, Ötztaler Alps, 1952-1961," *Journal of Glaciology*, Vol. 4, No. 33, pp. 266-280.

Kasser, P. 1967. "Fluctuations of glaciers, 1959-1965," *International Commission on Snow and Ice*, UNESCO/IASH, p. 38.

LaChapelle, E.R. 1965. "The Mass Budget of Blue Glacier, Washington," *Journal of Glaciology*, Vol. 5, No. 41, pp. 609-23.

Meier, M. F. and W. V. Tangborn. 1965. "Net Budget and Flow of South Cascade Glacier, Washington," *Journal of Glaciology*, Vol. 5, No. 41, pp. 547-66.

Menshutin, V. M. 1970. "The Mass Balance of the Murukh Glacier (Western Caucasus) in 1966-1968," *Data of Glaciological Studies*, Issue 17, Institute of Geography of the Academy of Sciences of U.S.S.R. (text in Russian), pp. 292-96.

Mokievsky-Zubok, O. 1973a. "Determination of the Mass Balance on Sentinel Glacier, British Columbia, Canada", Department of the Environment, Inland Waters Directorate, Ottawa, Ontario, *Scientific Series*, No. 30.

Mokievsky-Zubok, O. 1973b. "Study of Sentinel Glacier, British Columbia, Canada, Within the International Hydrological Decade (IHD) Program: Procedures, and Techniques," Department of the Environment, Inland Waters Directorate, Ottawa, Ontario, *Technical Bulletin*, No. 77.

Paterson, W. S. B. 1970. *The Physics of Glaciers*. Oxford: Pergamon Press, p. 35.

Tangborn, W. V. 1966. "Glacier Mass Budget Measurements by Hydrologic Means," *Water Resources Research*, Vol. 2, No. 1, pp. 104-110.

UNESCO/IASH. 1970. "Combined Heat, Ice and Water Balances at Selected Glaciers Basins," *Technical Paper in Hydrology*, No. 5, p. 12.

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