Environment Canada   Environnement Canada

Determination of the Mass Balance on Sentinel Glacier, British Columbia, Canada

O. Mokievsky-Zubok

SCIENTIFIC SERIES NO. 30
(Résumé en français)

*INLAND WATERS DIRECTORATE,
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Abstract

Mass balance for Sentinel Glacier was determined for the period 1966-1971. Two surface measurement methods were used for the entire glacier; terrestrial photogrammetry was used for the tongue area.

Surface balance methods were compared to establish the degree of internal consistency and the magnitude of possible error. The terrestrial photogrammetry method gave the surface lowering of the exposed ice; changes in its elevation compared with surface ablation measurements gave the vertical component of ice flow for the lower part of the glacier.

Sentinel Glacier showed four years with a positive mass balance and two years with a negative mass balance. The total loss, however, exceeded gain by 28 cm of water for the entire surface of the glacier.

Résumé

On a établi le bilan de masse du glacier Sentinel pour la période de 1966 à 1971. On a employé deux méthodes de mesure en surface pour l'ensemble du glacier et la photogrammétrie terrestre pour la langue du glacier.

On a comparé les méthodes de mesure du bilan en surface afin d'en établir le degré d'uniformité et la valeur de l'erreur possible. Par photogrammétrie terrestre, on a obtenu la baisse de la surface de la glace exposée; les différences de hauteur comparées aux mesures d'ablation superficielle ont donné la composante verticale de l'écoulement de glace pour la partie inférieure du glacier.

Le glacier Sentinel compte quatre ans de bilan de masse positif et deux de bilan de masse négatif. Cependant, considérant la surface entière du glacier, la perte totale était 28 cm, en équivalent eau, plus grande que le gain.

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O. Mokievsky-Zubok

INTRODUCTION

Sentinel Glacier is small enough to make it suitable for detailed study in general and for the study of mass balance changes in particular. However, "one drawback of a small glacier is that it may be more susceptible to local peculiarities of the environment than a large glacier would be" (Paterson, 1966, p. 385). This is very much so for Sentinel Glacier. Local peculiarities and a maritime climate causing a changeable accumulation pattern and a very uneven melt accentuate difficulties in assessing mass balance correctly (Mokievsky-Zubok, 1973a).

Sentinel Glacier (49°54′N latitude, 122°59′W longitude) is located in Garibaldi Provincial Park, 70 km north of Vancouver, in the Coast Mountain Range in western Canada. The area of the glacier is currently about 2 km^2 but it is constantly diminishing. The total area of the basin draining into the Sentinel Glacier melt-water stream is 5 km^2.

Sentinel Glacier ranges in elevation from 1500 to 2100 m asl and its overall gradient is 17°. The glacier is surrounded by several prominent peaks and high ridges.

The earliest known photograph of Sentinel Glacier, taken in 1923, shows its terminus at the southern shore of Garibaldi Lake. Since then the glacier has retreated to its present position approximately 1.6 km away. The rate of retreat for the last 6 years is 24 m/yr.

In 1970 retreating ice exposed a wood fragment embedded in a moraine. The Radiocarbon Laboratory of the Geological Survey of Canada (GSC) reported its age to be 6170 ± 150 or 4220 B.C. (GSC 1477, Radiocarbon dates). Combined with the location of wood which was not far from the summit of the basin this indicates that at that time the present area of the glacier was covered with forest and that Sentinel Glacier has developed in the last 6000 years.

SURFACE BALANCE METHODS

In surface balance measurements two methods were employed each year to determine independent values for mass balance: the *standard method* (Method 1) and the *alternate method* (Method 2). This was considered necessary in order to establish the degree of internal consistency and to determine the magnitude of possible error.

The standard method is based on determining the difference between measured winter and summer balances according to

$$b_n = b_w + b_s$$

where b_n is the net mass balance,
b_w is the winter balance, and
b_s is the summer balance[1] (UNESCO/IASH, 1970).

[1]Winter balance is generally considered positive and the summer balance negative.

Table 1. Sentinel Glacier – Mass Balance, 1970-1971, by Method 1.

Elevation interval m	Area km^2	Winter balance Water Equivalent: Total $10^6 m^3$	Winter balance Water Equivalent: Spec. m	Summer balance Water Equivalent: Total $10^6 m^3$	Summer balance Water Equivalent: Spec. m	Net balance Water Equivalent: Total $10^6 m^3$	Net balance Water Equivalent: Spec. m
Under 1600	0.054	0.164	3.037	0.265	4.907	-0.101	-1.870
1600-1700	0.175	0.568	3.246	0.742	4.240	-0.174	-0.994
1700-1800	0.298	1.070	3.591	1.284	4.309	-0.214	-0.718
1800-1900	0.515	1.949	3.784	1.466	2.847	+0.483	+0.937
1900-2000	0.490	2.041	4.165	1.504	3.069	+0.537	+1.096
2000-2100	0.346	1.441	4.165	0.951	2.748	+0.490	+1.417
2100-2200	0.023	0.109	4.739	0.052	2.261	+0.057	+2.478
Totals	1.901	7.342	3.862	6.264	3.295	+1.078	+0.567

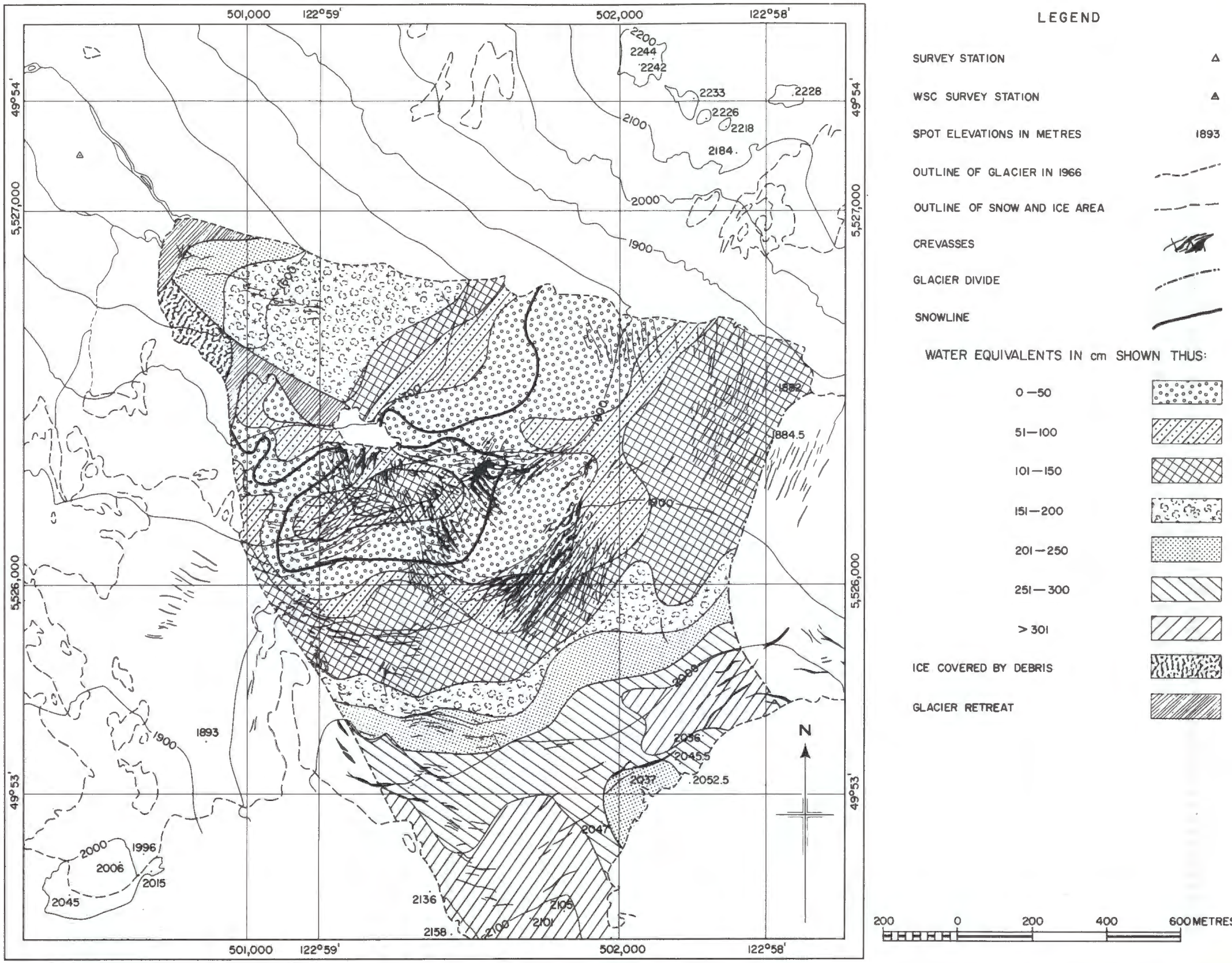

Figure 1. Map of mass balance (Method 2), May 20 to October 4, 1971.

Table 1 shows the mass balance values derived by this method. These values are given in metres of water (Østrem and Stanley, 1966). The specific values are obtained by dividing total mass of water equivalents by area. The specific value in metres represents a value across the entire area of the altitude zone indicated. In this report these values are termed "specific water equivalents". Positive and negative values indicate an increase or decrease, respectively, in the glacier's volume.

The *alternate method* determined the mass balance by subtracting the volume of remaining snow cover from ice and firn ablation. To obtain results by Method 2, two quantities must be known:

1. Volume of remaining snow cover.
2. Volume of ice melt.

To obtain the volume of the remaining snow cover, its thickness was sounded at the end of the ablation season by using the procedure described in the winter balance determination. The volume of ice melt was obtained throughout the summer from periodic readings of melt at the stakes below the snow line.

For the *alternate method*, values of soundings and ice melt in water equivalents were plotted on a map. Isopleths were drawn (Fig. 1) and calculations made similarly to work for Method 1.

Figure 1 shows: a) the location of the snow line at the end of the season; b) the increase in the ablation value from the snow line towards the terminus indicated by isopleths of melt with intervals of 50 cm of water equivalent; and c) the increase in accumulation towards the upper reaches of the glacier commencing at the snow line. The difference between the positive values above and negative values below the snow line represents the mass balance value obtained by Method 2. Tables of calculations are given in Appendix I.

To acquire a better understanding of the factors which influence the variation in the balance of Sentinel Glacier, the components of mass balance—winter balance, summer balance, and the surface lowering of the tongue—have been calculated.

For each year, graphs are drawn of snow density profiles, variations in net balance with elevation, daily values of sunshine, cloudiness, wind, temperature, precipitation and meltwater discharge. Maps are drawn of sounding profiles, winter balance, summer balance, net balance, and retreating snow line.

Graphs for daily values of meteorological conditions and meltwater discharge during the six years of study are presented in Appendix II. The maps have been replaced by a tabular summary of net mass balance expressed in water equivalents and tabulated for each contour interval, each year, with the exact dates of the field work. These tables are presented in Appendix III; they are copies of originals which will be used for a UNESCO report on the survey of glacier variations.

The study also provided information on mass balance fluctuations (Fig. 2), variations of net balance with elevation to show "activity index" (Fig. 3), and specific net balance as a function of the "accumulation area ratio" (AAR) (Fig. 4 and Appendix IV).

The activity index (Meier and Post, 1962), previously termed "energy of glacierization" (Schumskii, 1947; 1964), is the gradient of net budget with altitude measured at the equilibrium line. The Sentinel Glacier graph (Fig. 3) shows a variation in the activity index value, contrary to the assumption that for a particular glacier the activity index does not change significantly from year to year (Meier and Post, 1962). The graph shows also a steady ablation decrease with elevation.

A value described as the accumulation area ratio (AAR) is the amount of area above the equilibrium line divided by the total area (Meier and Post, 1962). At Sentinel Glacier, when the specific budget is zero (a balanced regime), the AAR is 0.61.

Winter Balance

Winter balance, generally measured late in spring, is the value of total winter accumulation less winter ablation to

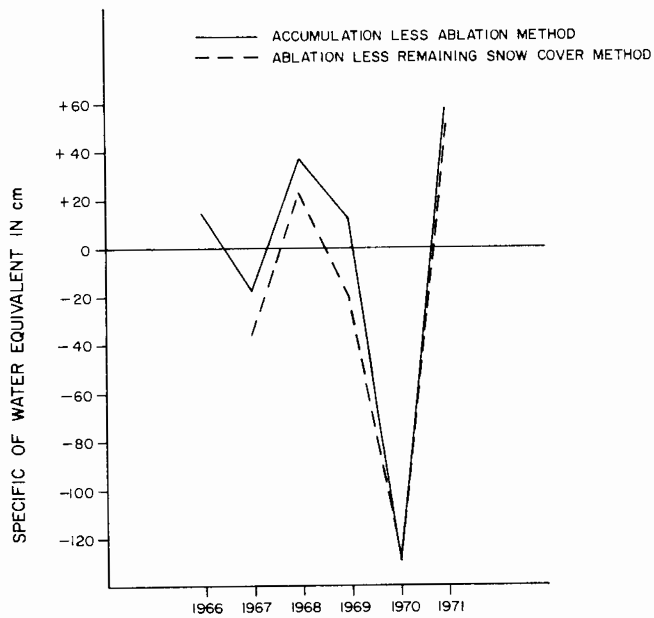

Figure 2. Net mass balance fluctuation at Sentinel Glacier, 1966-71.

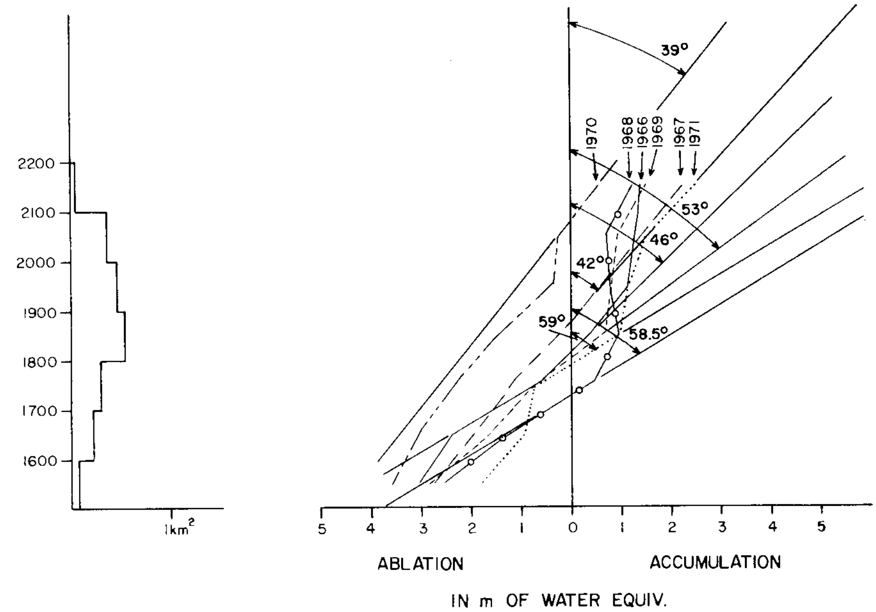

Figure 3. Combined graph variation of net balance with elevation to show activity index in degrees, 1966-1971.

the end of the accumulation period. The term 'accumulation' is taken to embrace all processes by which mass is added to a glacier, snowfield, or portion thereof, and the term 'ablation' includes processes by which mass is lost from the glacier or snowfield (UNESCO/IASH, 1970).

Winter balance at Sentinel Glacier was measured each year at the end of the accumulation season, normally in mid-May. To obtain the thickness of snow cover, snow depth was probed at 50-m intervals along longitudinal and transverse profiles (Fig. 5). This required an average of 180 soundings (i.e., approximately 90 per km^2) which varied in depth from 4 to more than 9 m.

For each sounding point on the sounding profiles, snow depth values in water equivalents were entered on a 1:10,000 scale map with a contour interval of 10 metres[1] (Fig. 6) and lines of equal snow depth were drawn at increments of 50 cm of water equivalent.

The area between successive isopleths and each elevation interval was planimetered and multiplied by the average water equivalent value to provide the water equivalent volume. Results for all elevation intervals were added; the sum represented the total winter balance expressed in cubic meters of water (Table 2).

Summer Balance

Summer balance is the value of total summer ablation less summer accumulation to the end of the ablation period. Summer balance was measured throughout each summer field season (Fig. 7) to the day when the glacier ice became covered with new snow that would remain until the next summer. On that day the new balance year was considered to have begun.

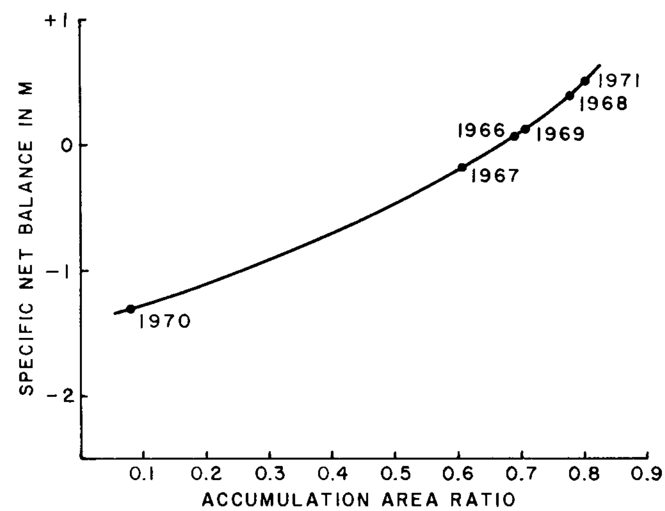

Figure 4. Specific net budget as a function of accumulation area ratio (AAR).

[1] One map of the glacier basin was prepared from photography taken in 1965 at the beginning of the program. A map of Sentinel Glacier has been compiled on a scale of 1:10,000 (as recommended by the International Commission of Snow and Ice (Kasser, 1967), from aerial photography, and published with contour intervals of 10 m by the Department of Energy, Mines and Resources (DEMR) in 1966.

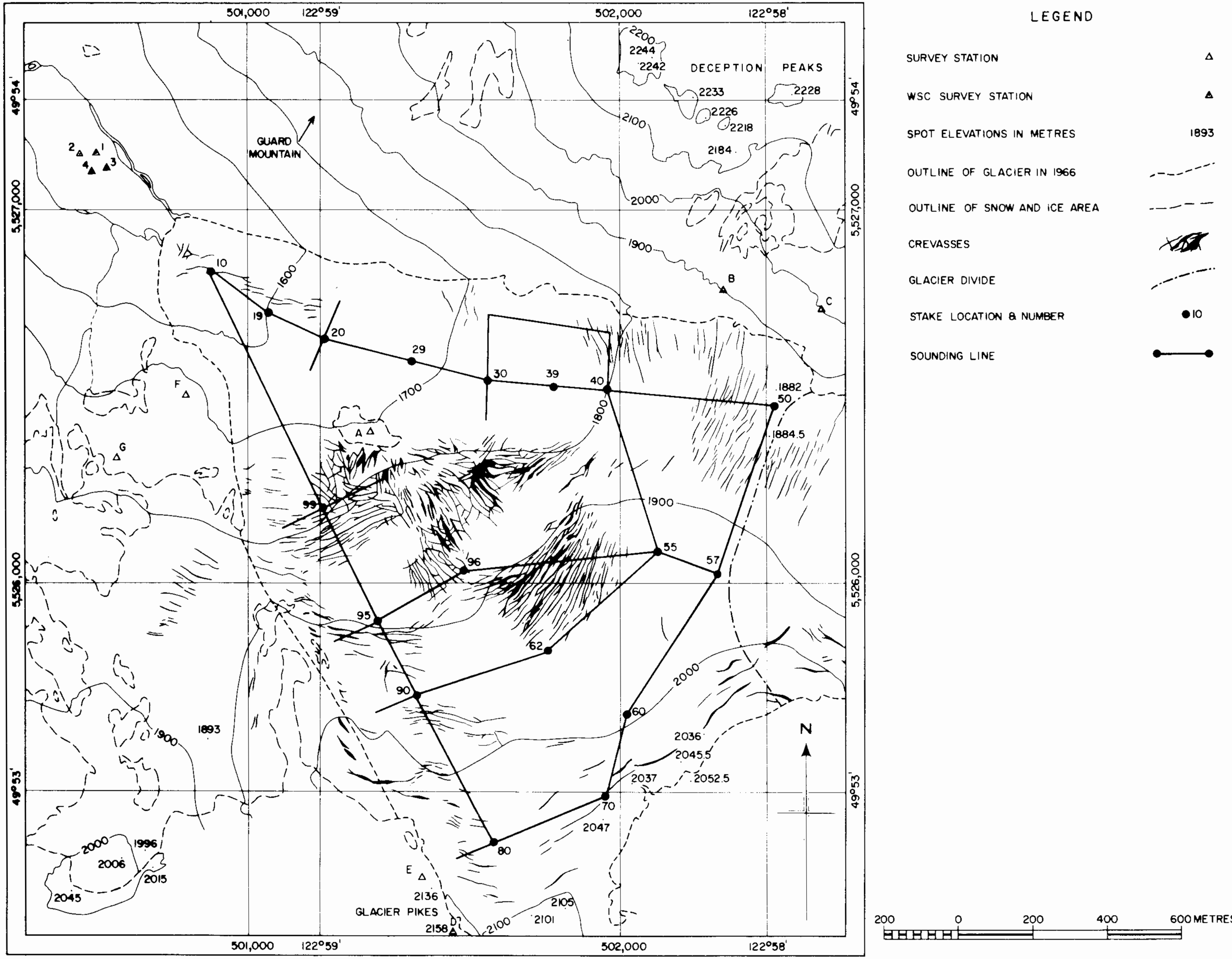

Figure 5. Map of provisional stake net, sounding profiles, and survey points.

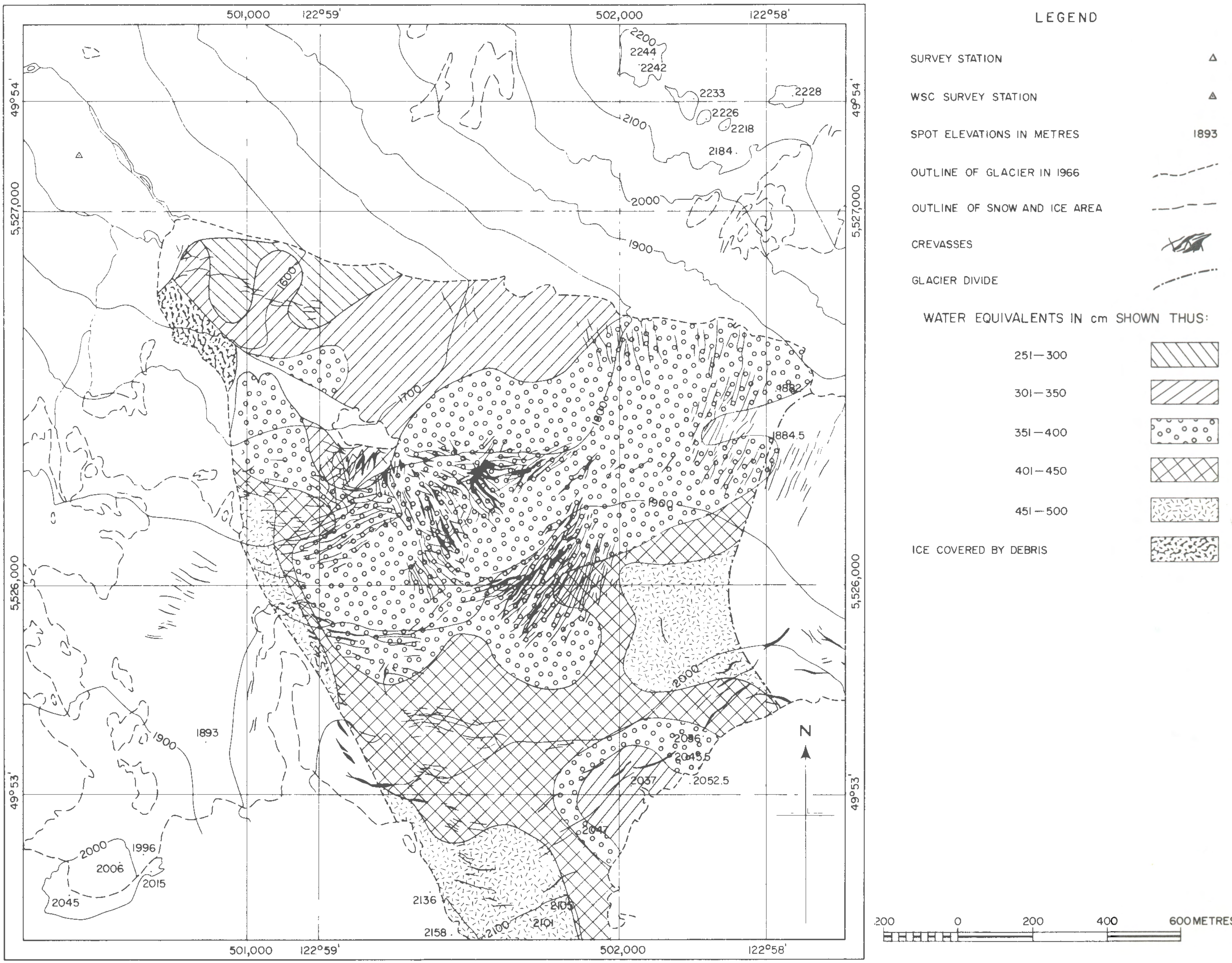

Figure 6. Map of winter balance (Method 1), to May 1971.

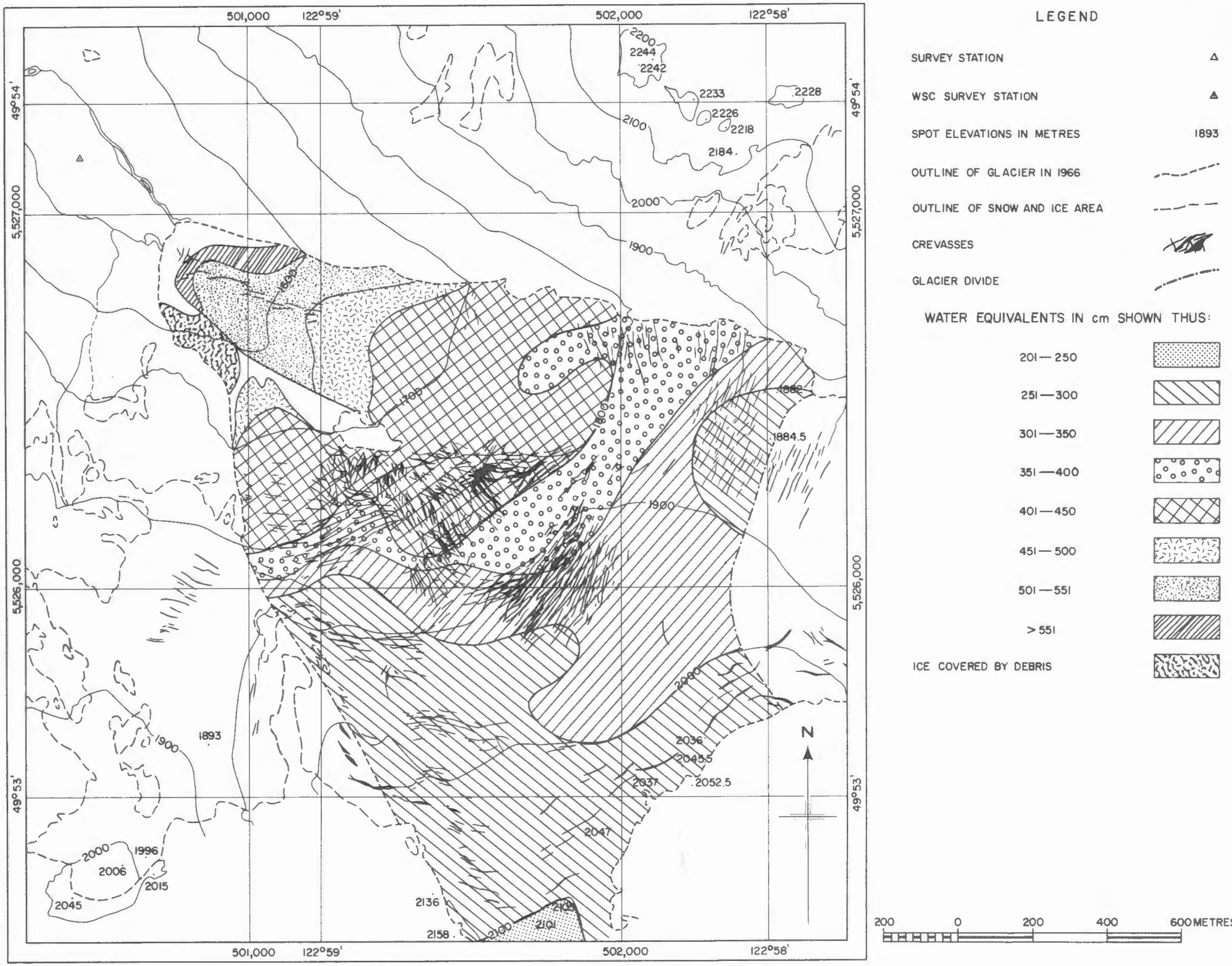

Figure 7. Map of summer balance (Method 1), to October 1971.

Table 2. Sentinel Glacier, Winter Balance 1970-1971.

Elevation intervals in metres	Isolines for height of water equivalents (cm): 250-300		300-350		351-400		401-450		451-500		Total area km²	Total water equiv. $10^6 m^3$	Specific water equiv. m
	Area km²	Water equiv. $10^6 m^3$	Area km²	Water equiv. $10^6 m^3$	Area km²	Water equiv. $10^6 m^3$	Area km²	Water equiv. $10^6 m^3$	Area km²	Water equiv. $10^6 m^3$			
Under 1600	0.023	0.063	0.031	0.101							0.054	0.164	3.037
1600-1700	0.030	0.082	0.114	0.370	0.031	0.116					0.175	0.568	3.246
1700-1800			0.122	0.396	0.153	0.574	0.017	0.072	0.006	0.028	0.298	1.070	3.591
1800-1900					0.488	1.830	0.017	0.072	0.010	0.047	0.515	1.949	3.784
1900-2000					0.167	0.626	0.238	1.011	0.085	0.404	0.490	2.041	4.165
2000-2100			0.051	0.166	0.046	0.172	0.160	0.680	0.089	0.423	0.346	1.441	4.165
2100-2200									0.023	0.109	0.023	0.109	4.739
Totals	0.053	0.145	0.318	1.033	0.885	3.318	0.432	1.835	0.213	1.011	1.901	7.342	3.862

Below the snow line, where ice is exposed, ablation measurements were relatively easy to conduct, assuming standard volume for the density of ice. In the area above the snow line, pits were dug throughout the season to monitor changes in snow density.

At the end of the ablation season, the depth of the remaining snow cover was measured at 50-m intervals in the same manner as the measurements of winter balance. The ablation data at each stake and the thickness of the remaining snow cover in water equivalents were plotted on separate maps on which isopleths of melt were drawn. The procedure and calculation of the results (Table 3) are identical to those described for winter balance.

Standard Method *vs.* Alternate Method

The mass balance values obtained by both methods and the difference between them are tabulated in Table 4. The tabulated values do not differ substantially. Especially interesting are the results for 1970 where a difference of 6 mm shows internal consistency. The degree of internal consistency and the magnitude of error are discussed separately (Mokievsky-Zubok, 1973b).

TERRESTRIAL PHOTOGRAMMETRY METHOD

The change in volume of a part of Sentinel Glacier was calculated from changes in the elevation of the glacier's surface determined by terrestrial photogrammetry (Method 3). These measurements were limited to the tongue area below the snow line because of technical problems in obtaining photographs at high elevations which would cover all the glacier, and because of the difficulty in using the plotter for charting elevation contours from white shadowless areas of firn. Nevertheless, the results obtained on the lowering of the exposed ice surface by terrestrial photogrammetry in 1966, 1968 and 1970 were useful; it was possible to make a comparison with surface ablation measurements and to obtain the vertical component of ice flow.

Surface Lowering Determined by Terrestrial Photogrammetry

Stereoscopic terrestrial photographs of the glacier tongue were taken from fixed survey points in 1966, 1968, and 1970. Each stereo pair shows points on the rock around the periphery of the glacier as well as on the ice surface. The control points were plotted and contours drawn with the use of a Wild A-7 Universal Autograph to make a topographic map at a scale of 1:2,500. This procedure required surrounding the desired portion of the glacier with fixed co-ordinates (Reid and Shastal, 1968).

To simplify the procedure, volumetric changes were computed on the basis of height zones—a height zone being defined as the surface area between two contours. The formula used for computing volumetric changes in the various height zones is that of Finsterwalder and Hauman (in: Reid and Shastal, 1968) but the procedure followed here, i.e., by Reid and Shastal, is slightly different. The volumetric change of a height zone is computed as the mean value of two areas, one produced by the horizontal movement of the lower contour during the time period under consideration, and the other produced by the horizontal movement of the upper contour during the same time period, multiplied by the difference in elevation of the two contours. The sum of the volumetric changes in the series of height zones, which comprise the ice area under study, represents the total surface change for the period between surveys.

Terrestrial Photogrammetric Method *vs.* Surface Method 1

Measurements of ice-surface lowering determined by terrestrial photogrammetry are dependent on the internal

Table 3. Sentinel Glacier, Summer Balance 1970-1971.

Elevation intervals in metres	Isolines for height of water equivalents, cm: 201-250		251-300		301-350		351-400		401-450		451-500		551		Total area km^2	Total water equiv. $10^6 m^3$	Specific water equiv. m
	Area km^2	Water equiv. $10^6 m^3$	Area km^2	Water equiv. $10^6 m^3$	Area km^2	Water equiv. $10^6 m^3$	Area km^2	Water equiv. $10^6 m^3$	Area km^2	Water equiv. $10^6 m^3$	Area km^2	Water equiv. $10^6 m^3$	Area km^2	Water equiv. $10^6 m^3$			
Under 1600											0.037	0.176	0.017	0.089	0.054	0.265	4.907
1600-1700							0.056	0.210	0.066	0.280	0.053	0.252			0.175	0.742	4.240
1700-1800									0.264	1.122	0.034	0.162			0.298	1.284	4.309
1800-1900			0.088	0.242	0.132	0.429	0.212	0.795	0.083						0.515	1.466	2.847
1900-2000			0.190	0.522	0.285	0.926	0.015	0.056							0.490	1.504	3.069
2000-2100			0.346	0.951											0.346	0.951	2.748
2100-2200	0.023	0.052													0.023	0.052	2.261
Totals	0.023	0.052	0.624	1.715	0.417	1.355	0.283	1.061	0.413	1.402	0.124	0.590	0.017	0.089	1.901	6.264	3.295

Table 4. Comparison of Mass Balance (Specific Water Equivalents in m) Obtained by Surface Measurement.

Year	Spec. Water Equiv. Method 1 m	Spec. Water Equiv. Method 2 m	Difference m
1966	+0.15		
1967	-1.184	-0.368	0.184
1968	+0.373	+0.228	0.145
1969	+0.117	- 0.196	0.313
1970	-1.300	-1.294	0.006
1971	+0.567	+0.504	0.063

movement of ice. They show effective surface change incorporating any internal (upward or downward) movement of ice. Therefore, the comparison of the results obtained by the two methods reveals what is happening within the ice itself.

The surface of Sentinel Glacier terminus rises gradually and the lower part of the ice is practically free of crevasses. In this section there are no obvious indications of movement, and the ice appears stagnant.

Five locations were chosen on the tongue area for comparative work. All five points were the permanent ablation stakes (numbers 10, 11, 12, 19, and 20 in Figure 8) which were used as reference points for recording surface melt during the ablation period in Method 1. They were identified on stereoscopic photographs as control points on the ice surface for drawing contours and calculating surface lowering by terrestrial photogrammetry.

Table 5 gives the results obtained by two different field approaches—that of the Water Survey of Canada, i.e., terrestrial photogrammetry (Method 3), and that of direct measurement of surface melt (Method 1) for the period 21 August 1966 to 24 August 1968.

The data obtained by Method 1 (Table 5), based on direct measurements of ice melt at stakes, are part of a continuous measurement program. The measurements are independent of any internal or upward movements of ice.

Although the findings of six years on variations in net balance with elevation show that ablation steadily decreases with rise in elevation (Fig. 9), the results obtained from terrestrial photogrammetry reveal that the greatest effective change in surface elevation occurred in the central portion of the tongue. The largest amount of ice melt (i.e., surface lowering) was at stake no. 19 (Fig. 8). From stake no. 19,

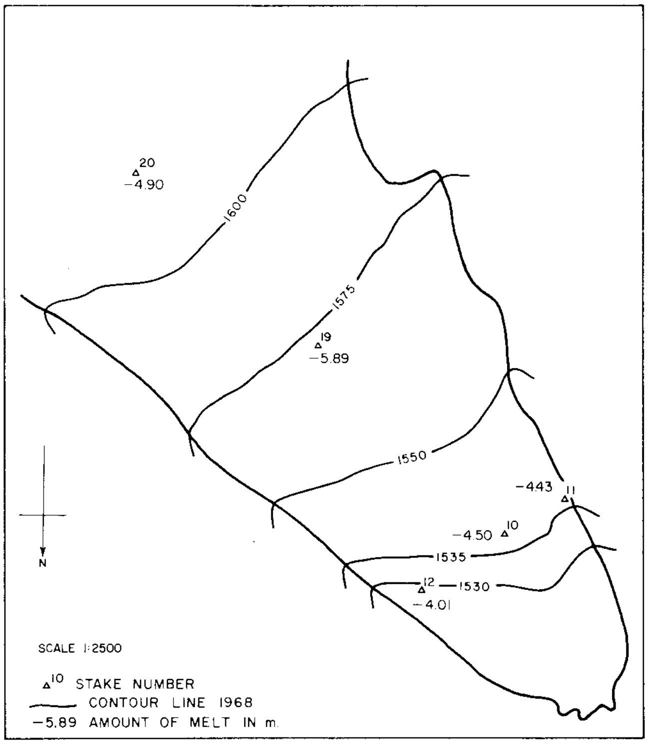

Figure 8. Sentinel Glacier – glacier's tongue and surface lowering distribution by terrestrial photogrammetry.

Table 5. Volumetric Changes at Ablation Stakes Obtained from Terrestrial Photogrammetry (Method No. 3) *vs.* Direct Measurement of Surface Melt (Method No. 1), 21 August 1966 to 24 August 1968.

Height zone m	Effective surface change of the zone m	Stake number	Stake elevation m	Elevation change Method No. 3 m	Surface melt Method No. 1 m	Difference No. 1 – No. 3 m
1524-30	3.91	12	1529	4.01	6.35	2.34
1530-36	4.21	11*	1536	4.43	4.80	0.37
1536-42	4.63	10	1537	4.50	6.34	1.84
1573-79	5.80	19	1577	5.89	4.93	-0.96
1615-22	4.82	20	1617	4.90	3.93	-0.97

*Located on debris-covered ice surface where ice melt has been retarded.

Table 6. Volumetric Changes at Ablation Stakes Obtained from Terrestrial Photogrammetry (Method No. 3) *vs.* Direct Measurement of Surface Melt (Method No. 1), 24 August 1968 to 11 September 1970.

Height zone m	Effective surface change of the zone m	Stake number	Stake elevation m	Elevation change Method No. 3 m	Surface melt Method No. 1 m	Difference No. 1 – No. 3 m
1520-25	4.87	12	1524	5.24	9.52	4.28
1525-30	6.14	11*	1527	6.02	7.94	1.92
1525-30	6.14	10	1528	6.26	9.06	2.80
1560-65	10.78	19	1564	10.75	7.27	-3.48
1605-10	7.78	20	1609	7.72	6.06	-1.66

*Located on debris-covered ice surface where ice melt has been retarded.

where the elevation was 1564 m asl, surface-lowering values decreased towards stake no. 20 (elevation 1609 m asl) as might be expected. However, less melting occurred in the vicinity of stakes no. 10, 11 and 12 which are at lower elevations where loss should be higher, thus showing inconsistency in height changes of the ice surface with rise in elevation.

There is no ready explanation, in terms of ablation, for the greatest effective change in surface lowering at stake no. 19. Since points at stakes no. 19 and no. 20 have more surface lowering than the lower three stakes no. 10, 11, and 12, an internal upward movement of the ice is indicated.

Table 6 shows volumetric changes for the period 1968-1970. Although there was much more melt than in the previous two years, the surface lowering trend remained the same.

The results obtained by both methods show different final values for ice loss at the same points for exactly the same period. The difference may be due to the glacier's internal flow. If this is so, then the difference between the two methods in ablation measurements of the tongue area should be equal to the magnitude of the upward component of internal ice movement.

At each point the vertical component Vc was calculated according to

$$Vc = A - T$$

where A is ablation by Method 1 and

T is surface change by the terrestrial photogrammetry method.

Vc can be positive or negative; positive if A>T, negative if A<T. If A>T, the flow of ice is directed downslope only.

On the basis of the stagnant appearance of the tongue of Sentinel Glacier, it is difficult to accept vertical movement of the ice. However, considering that the wave velocity on a glacier is about four times greater than the ice

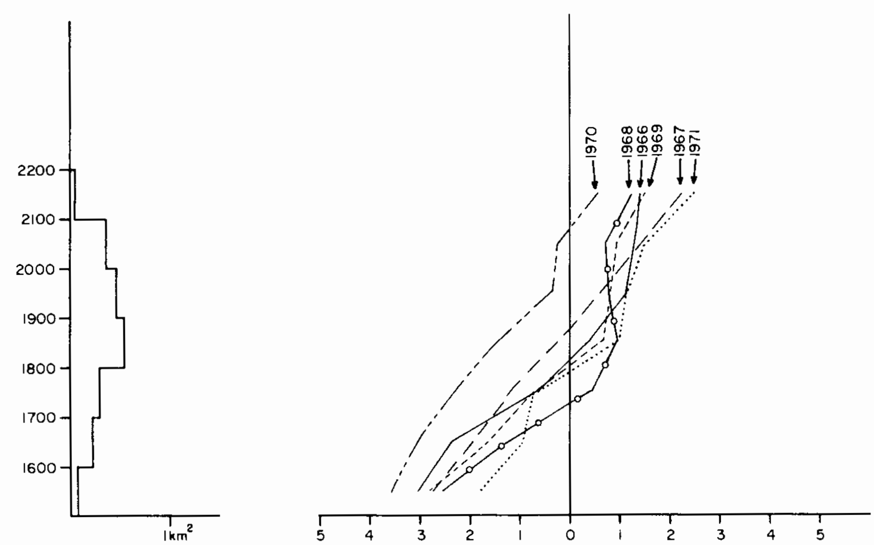

Figure 9. Variation of net balance with elevation, 1966-1971.

velocity (Paterson, 1970), and that in 1966, 1968, and 1969 mass balance showed a slight increase, it is possible that in response to this increase in mass the terminus thickened, thus affecting the magnitude of the vertical component of the internal ice flow.

The assumption that the vertical component exists should have more confirmation, but it offers at present a reasonable explanation for the difference in results by the two methods and for the peculiar pattern of the surface change distribution obtained by the terrestrial photogrammetry method.

SUMMARY

Mass balance values obtained by two methods, No. 1 and No. 2, were in fairly close agreement. This indicates that the results are internally consistent.

Ice melt determined by Method 1 and that determined by terrestrial photogrammetry at the same five points over the tongue area for exactly the same period produced a difference attributable to the internal flow of ice, i.e., the vertical component of the ice movement.

Between 1966-1971, Sentinel Glacier had four years with a positive mass balance and two years with a negative mass balance. However, the total loss was greater than the gain and exceeded the latter by 28 cm of water for the entire surface of the glacier.

ACKNOWLEDGEMENTS

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Appendix I

Sentinel Glacier, Tables of Calculations of Mass Balance

Appendix Ia. Sentinel Glacier, Net Mass Balance (1970-1971) by Method 2.

Elevation interval m	Area km^2	Remaining Snow Cover Water Equivalent Total $10^6 m^3$	Remaining Snow Cover Water Equivalent Spec. m	Ice and Firn Melt Water Equivalent Total $10^6 m^3$	Ice and Firn Melt Water Equivalent Spec. m	Net Balance Water Equivalent Total $10^6 m^3$	Net Balance Water Equivalent Spec. m	Remarks
<1600	0.054			0.106	1.741	-0.106	-1.963	
1600-1700	0.175			0.451	2.577	-0.451	-2.577	
1700-1800	0.298	0.051	0.323	0.588	4.200	-0.537	-1.802	
1800-1900	0.515	0.348	0.861	0.206	1.855	0.142	0.275	
1900-2000	0.490	0.803	1.638			0.803	1.638	
2000-2100	0.346	1.034	2.988			1.034	2.988	
2100-2200	0.023	0.074	3.217			0.074	3.217	
Totals	1.901	2.310		1.351		0.959	0.504	

Appendix Ib. Sentinel Glacier, Ice and Firn Melt (1970-1971) by Method 2.

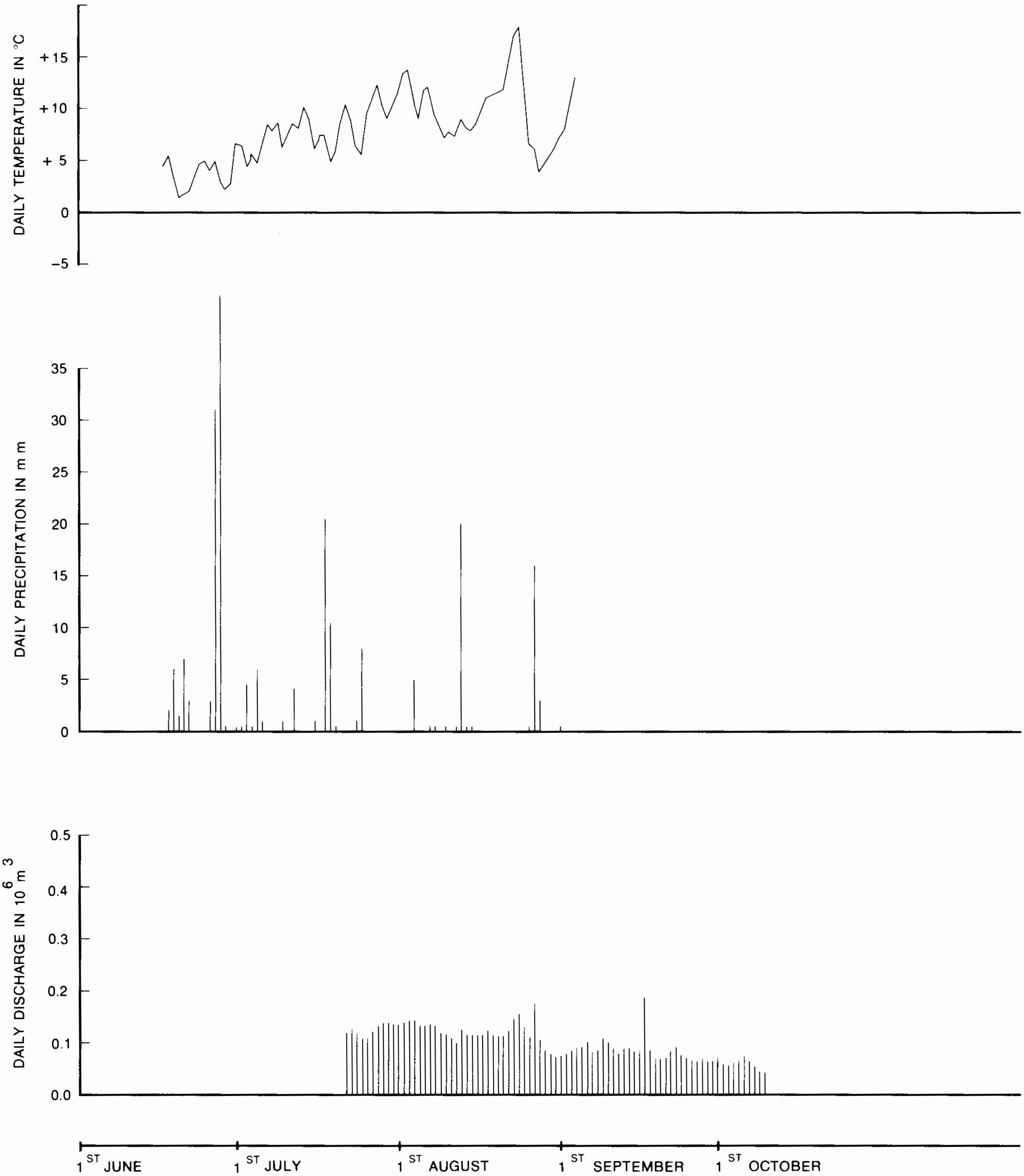
Elevation intervals m	Isolines for height of water equivalents, cm: 0-50 Area km^2	0-50 Water equiv. $10^6 m^3$	51-100 Area km^2	51-100 Water equiv. $10^6 m^3$	101-150 Area km^2	101-150 Water equiv. $10^6 m^3$	151-200 Area km^2	151-200 Water equiv. $10^6 m^3$	201-250 Area km^2	201-250 Water equiv. $10^6 m^3$	Total negative area km^2	Total water equiv. $10^6 m^3$	Spec. water equiv. m
<1600							0.030	0.052	0.024	0.054	0.054	0.106	1.963
1600-1700	0.005	0.013	0.027	0.203	0.030	0.037	0.113	0.198			0.175	0.451	2.577
1700-1800	0.085	0.213	0.049	0.368	0.006	0.007					0.140	0.588	4.200
1800-1900	0.065	0.163	0.028	0.021	0.018	0.022					0.111	0.206	1.855
1900-2000													
Totals	0.155	0.389	0.104	0.592	0.054	0.066	0.143	0.250	0.024	0.054	0.480	1.351	

Appendix Ic. Sentinel Glacier, Remaining Snow Cover (1970-1971) by Method 2.

Elevation intervals m	Isolines for height of water equivalents														Total positive area km^2	Total water equiv. $10^6 m^3$	Spec. water equiv. m
	0-50		51-100		101-150		151-200		201-250		251-300		300-350				
	Area km^2	Water equiv. $10^6 m^3$	Area km^2	Water equiv. $10^6 m^3$	Area km^2	Water equiv. $10^6 m^3$	Area km^2	Water equiv. $10^6 m^3$	Area km^2	Water equiv. $10^6 m^3$	Area km^2	Water equiv. $10^6 m^3$	Area km^2	Water equiv. $10^6 m^3$			
<1600																	–
1600-1700																	–
1700-1800	0.134	0.033	0.024	0.018											0.158	0.051	0.323
1800-1900	0.115	0.028	0.082	0.062	0.207	0.258									0.404	0.348	0.861
1900-2000	0.015	0.004	0.058	0.043	0.172	0.215	0.089	0.156	0.096	0.216	0.052	0.143	0.008	0.026	0.490	0.803	1.639
2000-2100									0.024	0.054	0.132	0.363	0.190	0.617	0.346	1.034	2.988
2100-2200													0.023	0.074	0.023	0.074	3.217
Totals	0.264	0.065	0.164	0.123	0.379	0.473	0.089	0.156	0.120	0.270	0.184	0.506	0.221	0.717	1.421	2.310	

Appendix II

Graphs of Summarized Meteorological Parameters and of River Discharge, 1966-1971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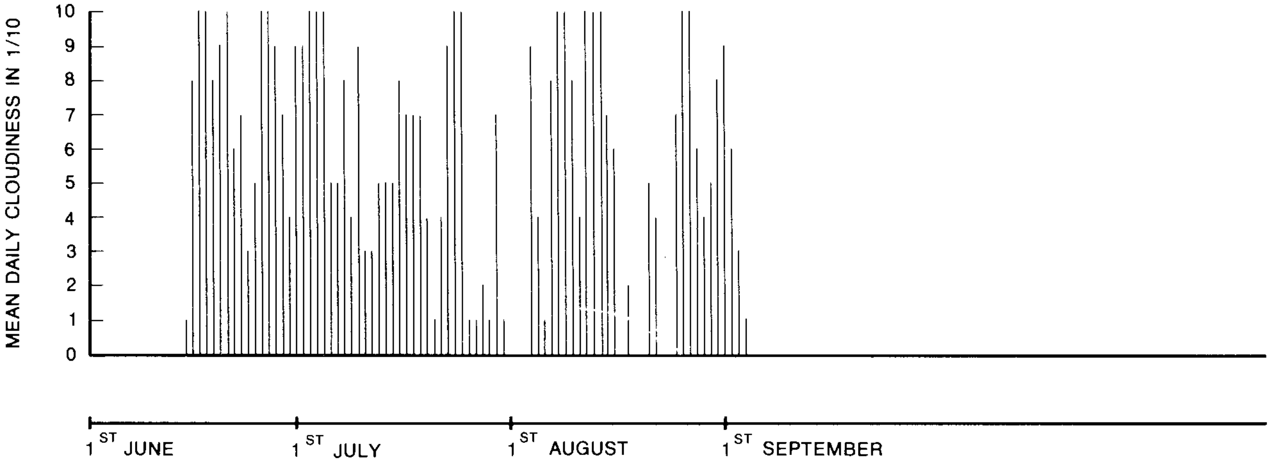
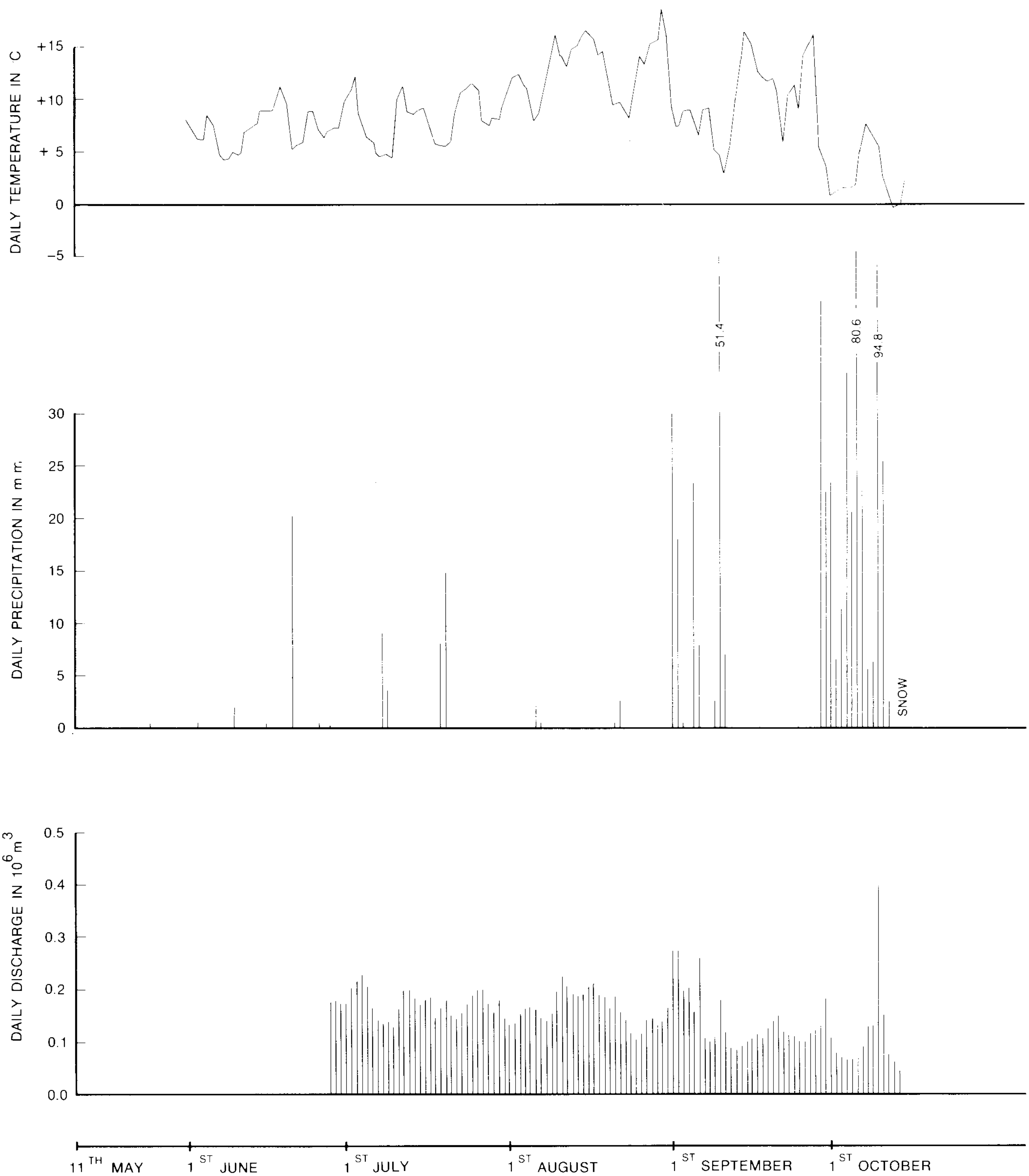
+15
+10
+5
0
−5
DAILY PRECIPITATION IN m m
35
30
25
20
15
10
5
0
DAILY DISCHARGE IN 10^6 m^3
0.5
0.4
0.3
0.2
0.1
0.0
1 ST JUNE
1 ST JULY
1 ST AUGUST
1 ST SEPTEMBER
1 ST OCTOBER


10
9
8
7
6
5
4
3
2
1
0
MEAN DAILY CLOUDINESS IN 1/10
1 ST JUNE
1 ST JULY
1 ST AUGUST
1 ST SEPTEMBER

SENTINEL GLACIER 1967



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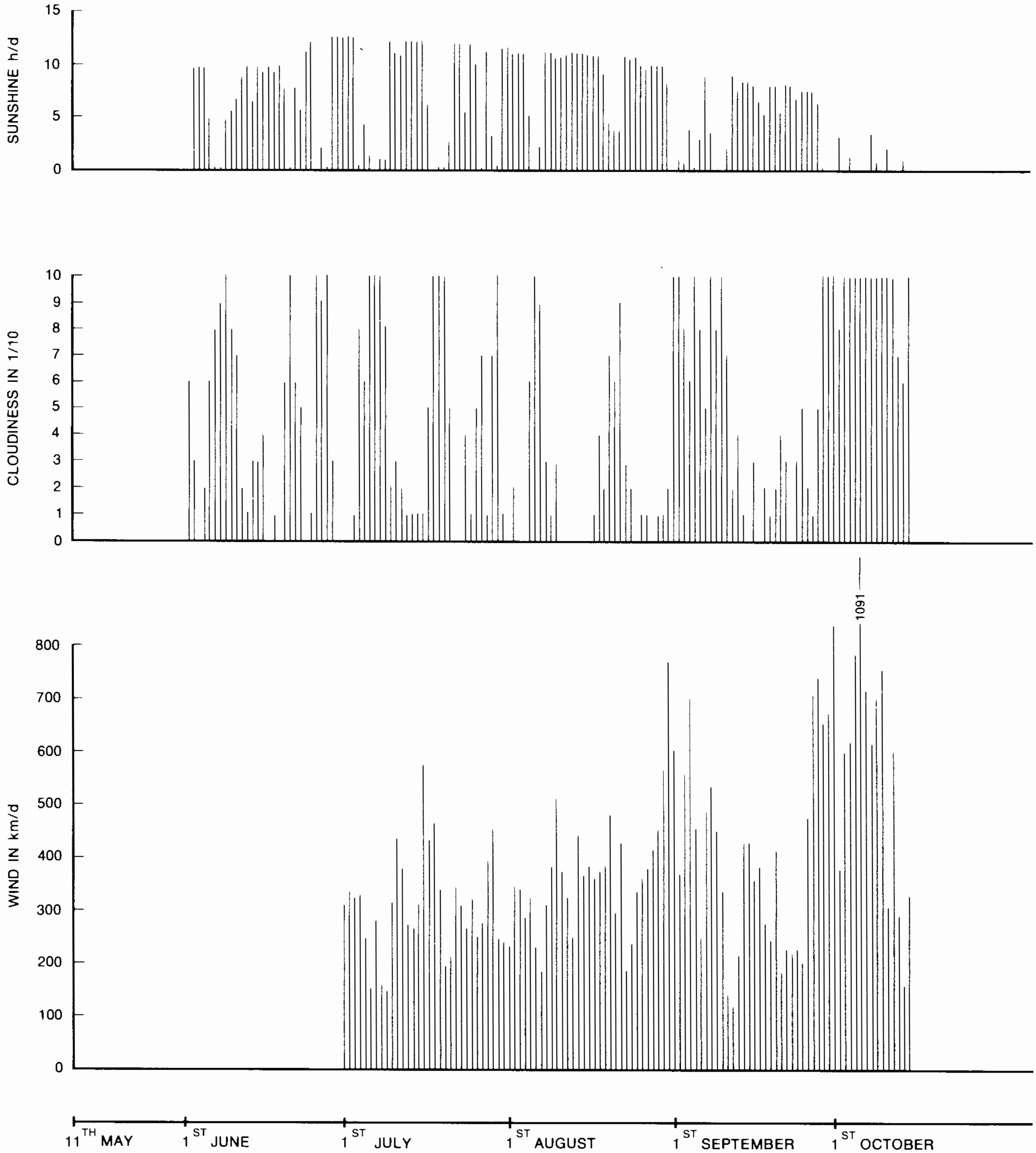

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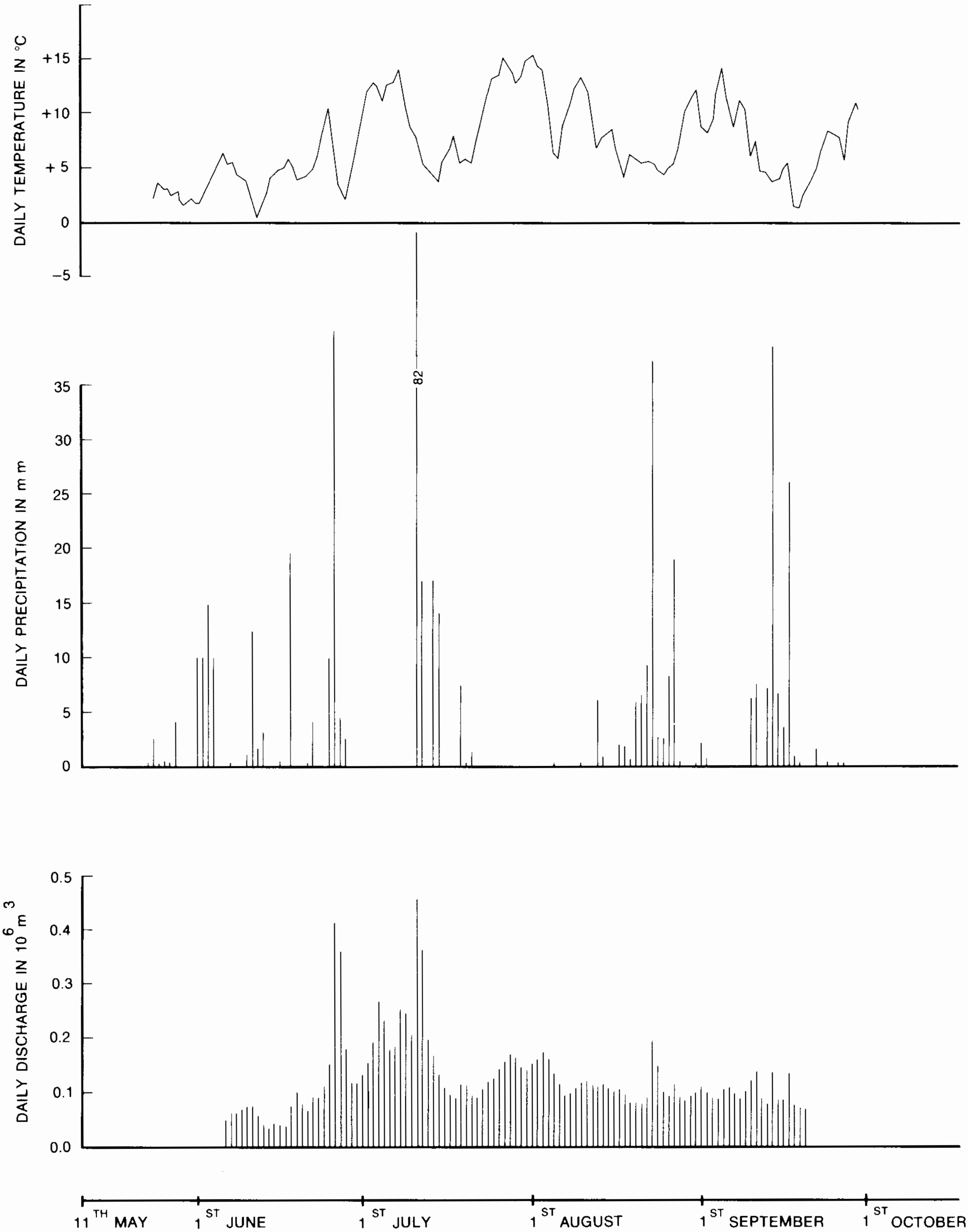

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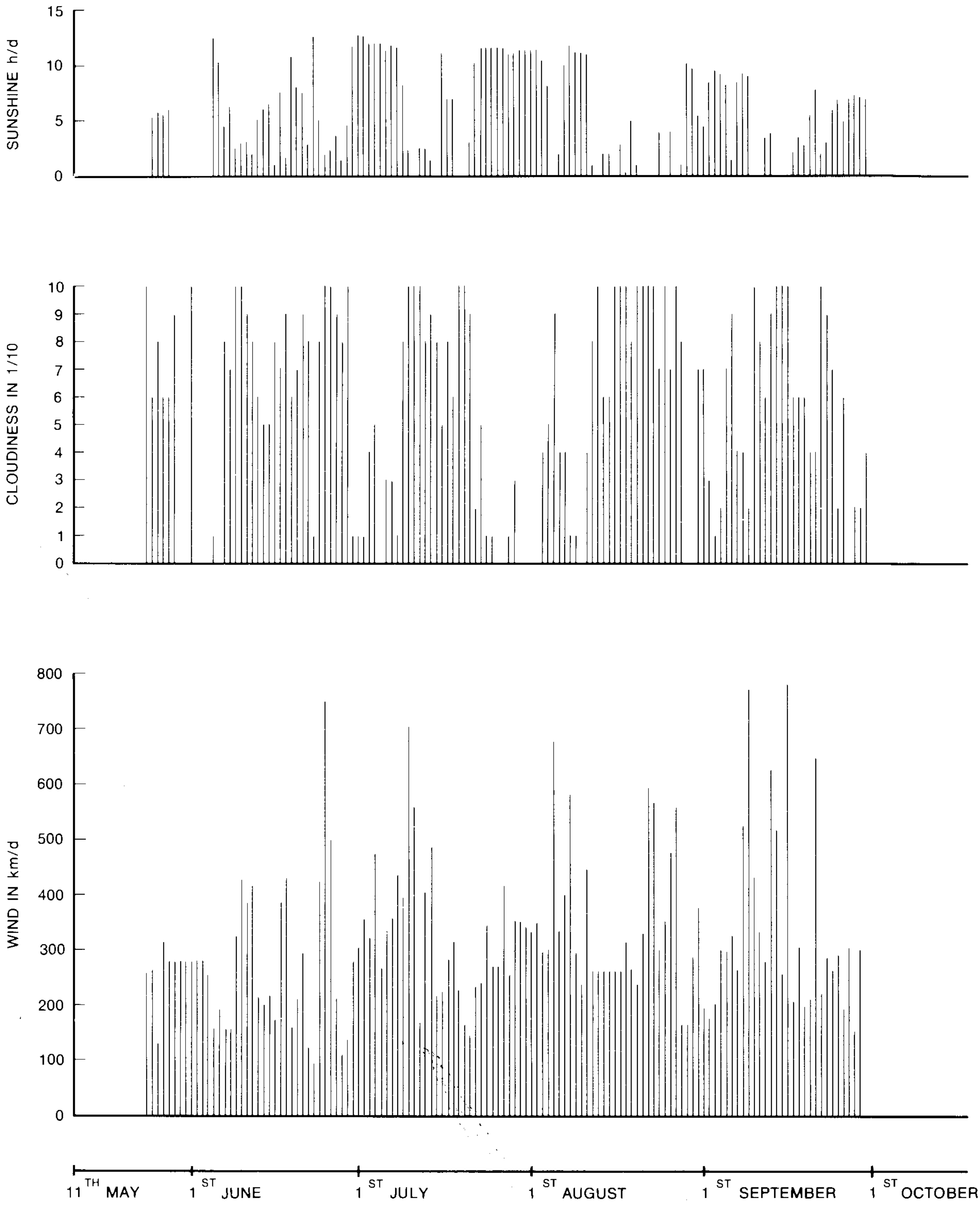

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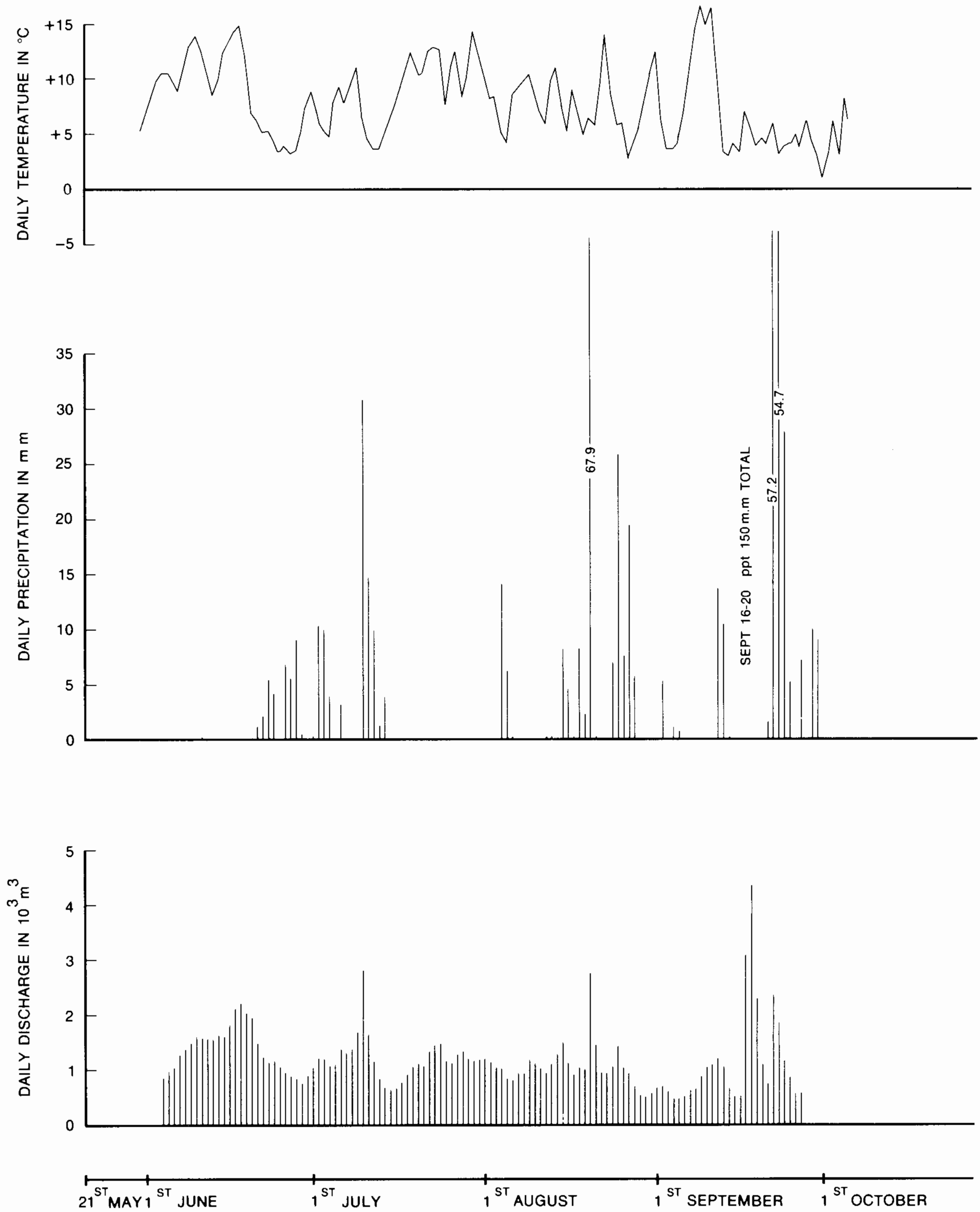

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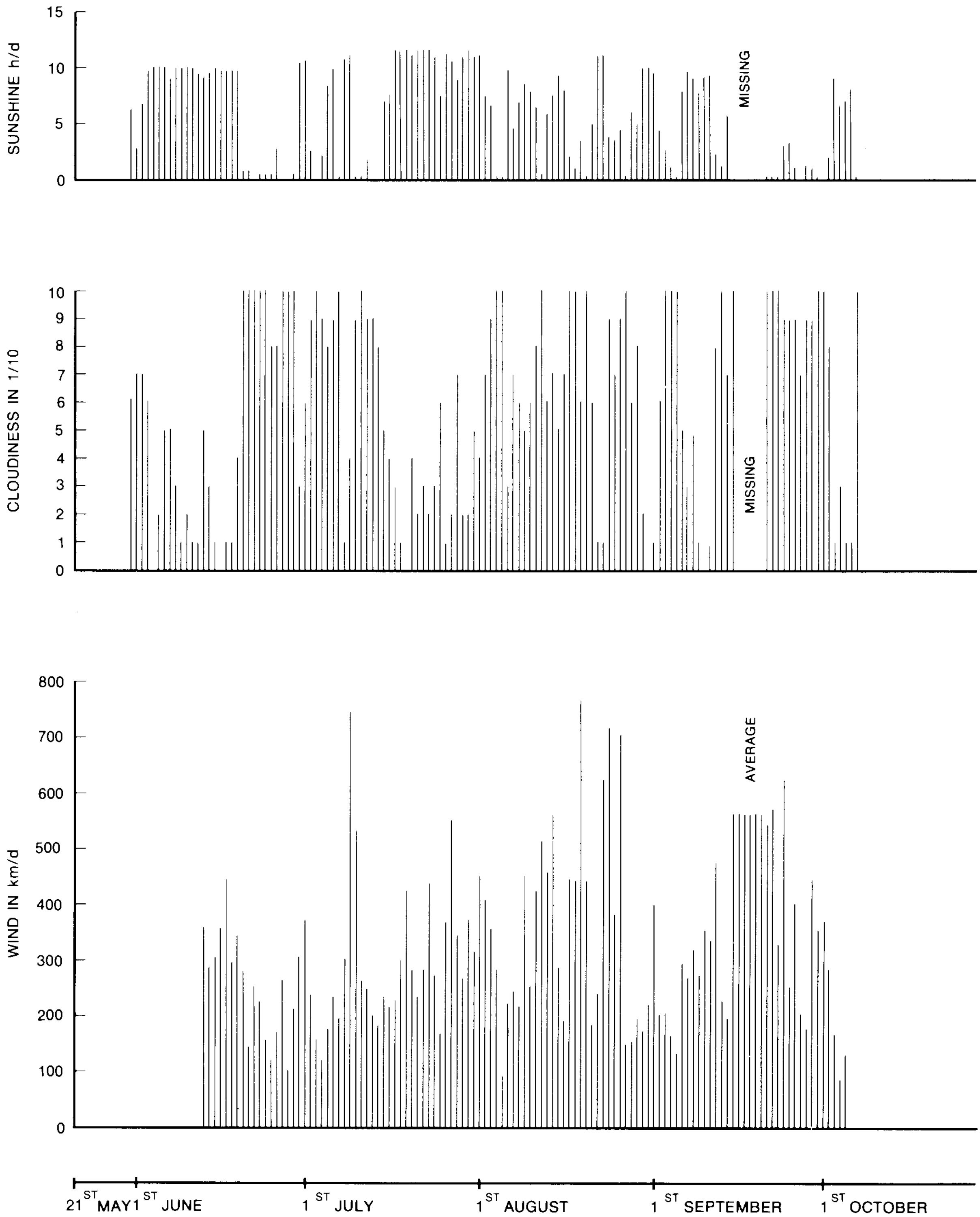

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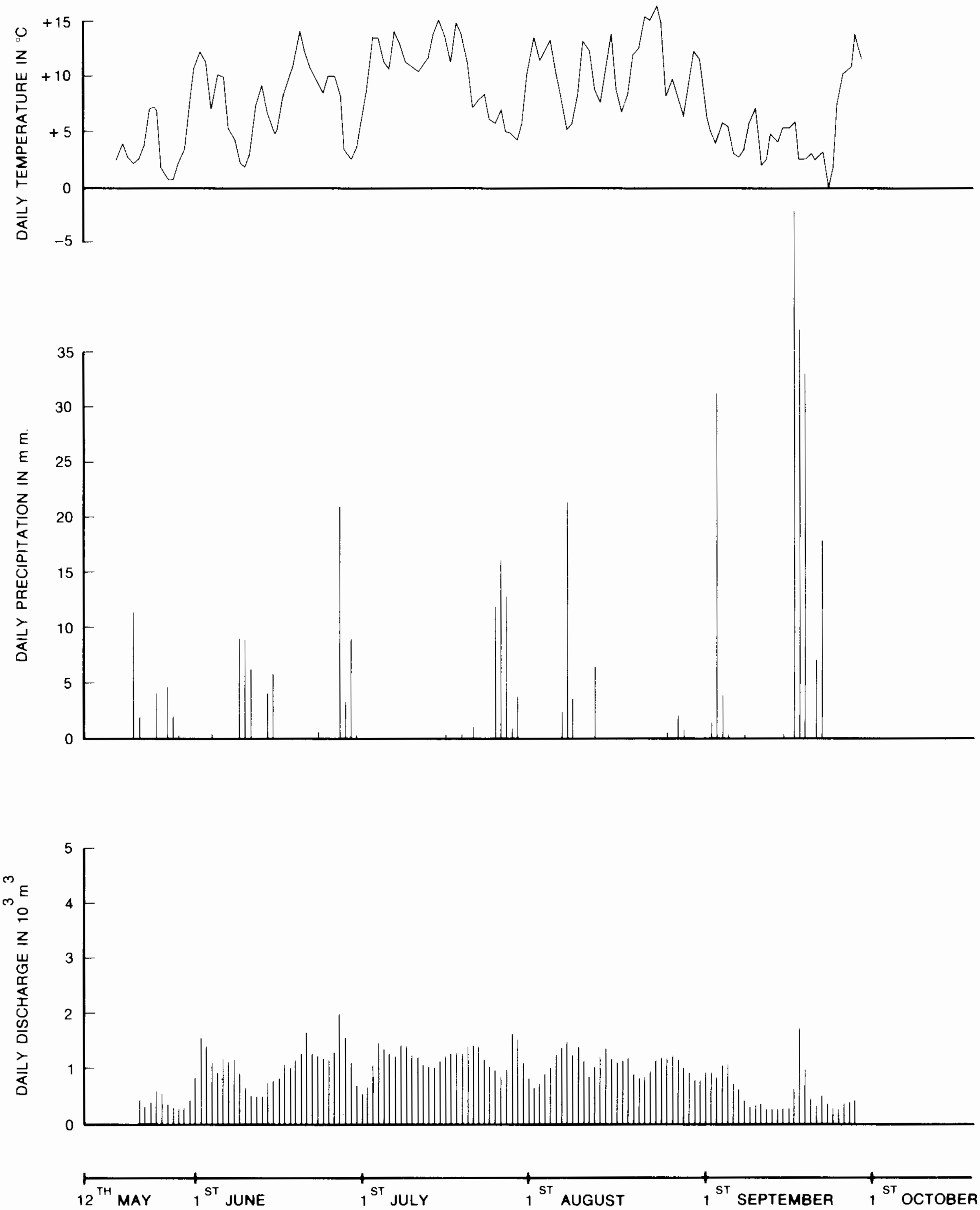

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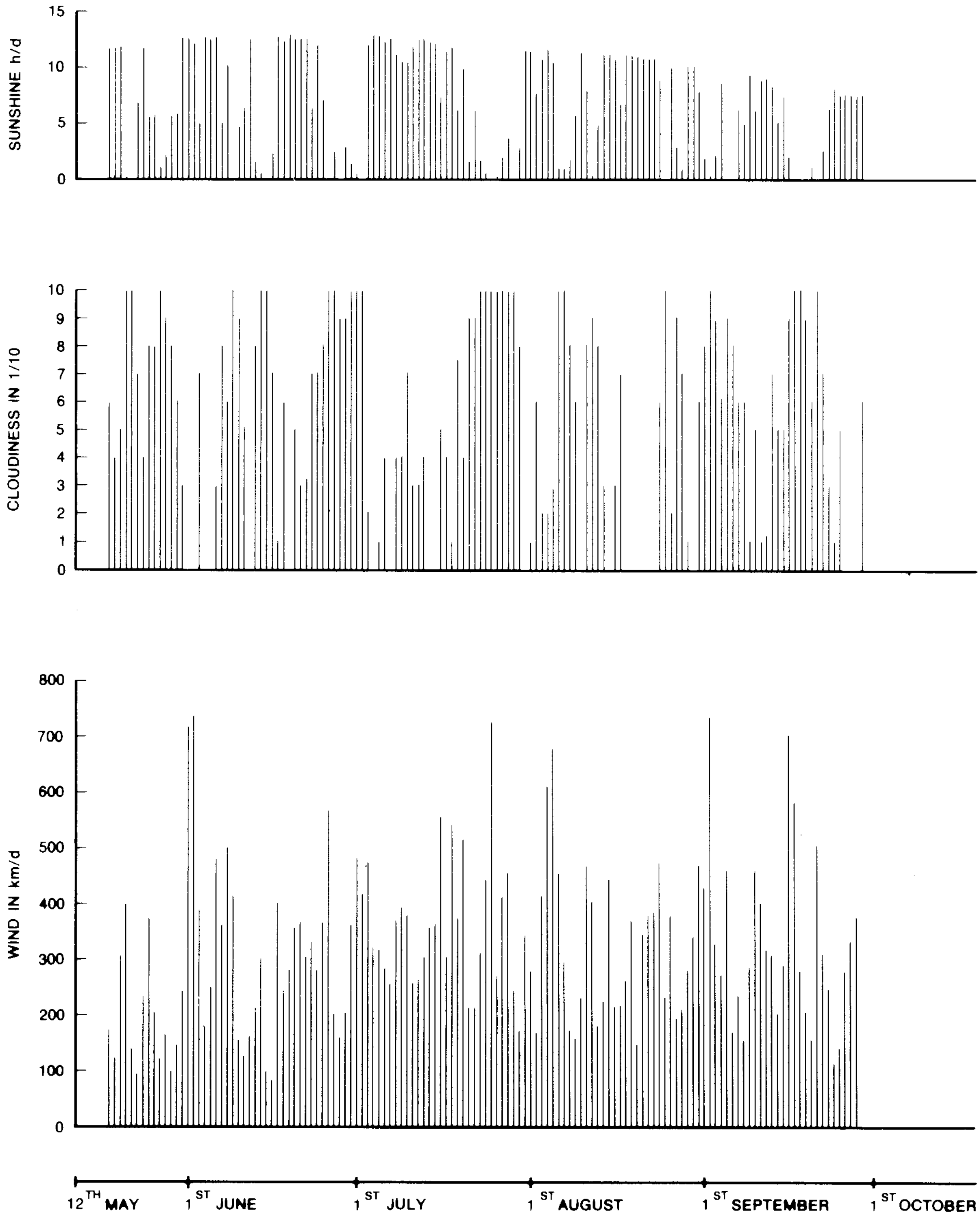

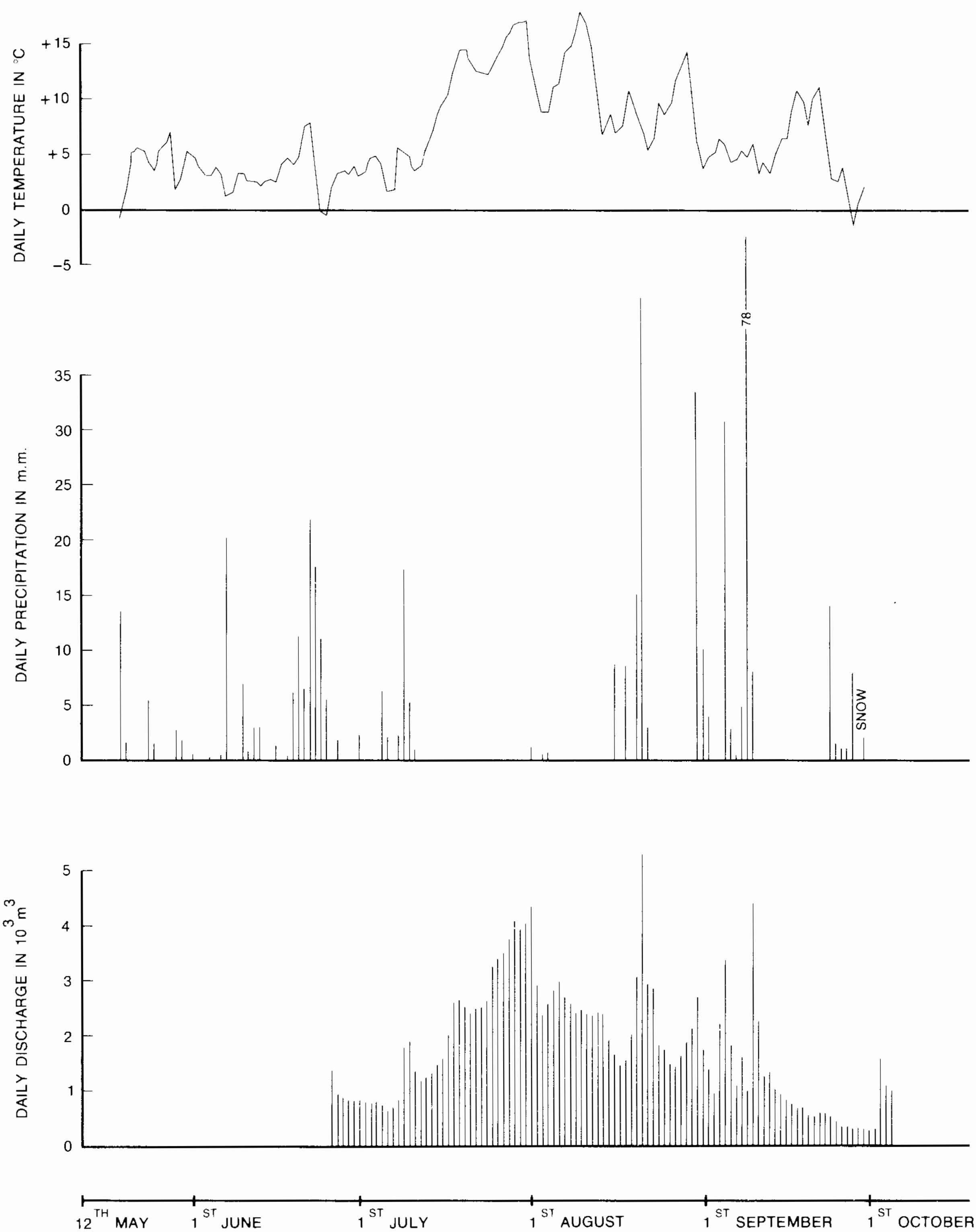
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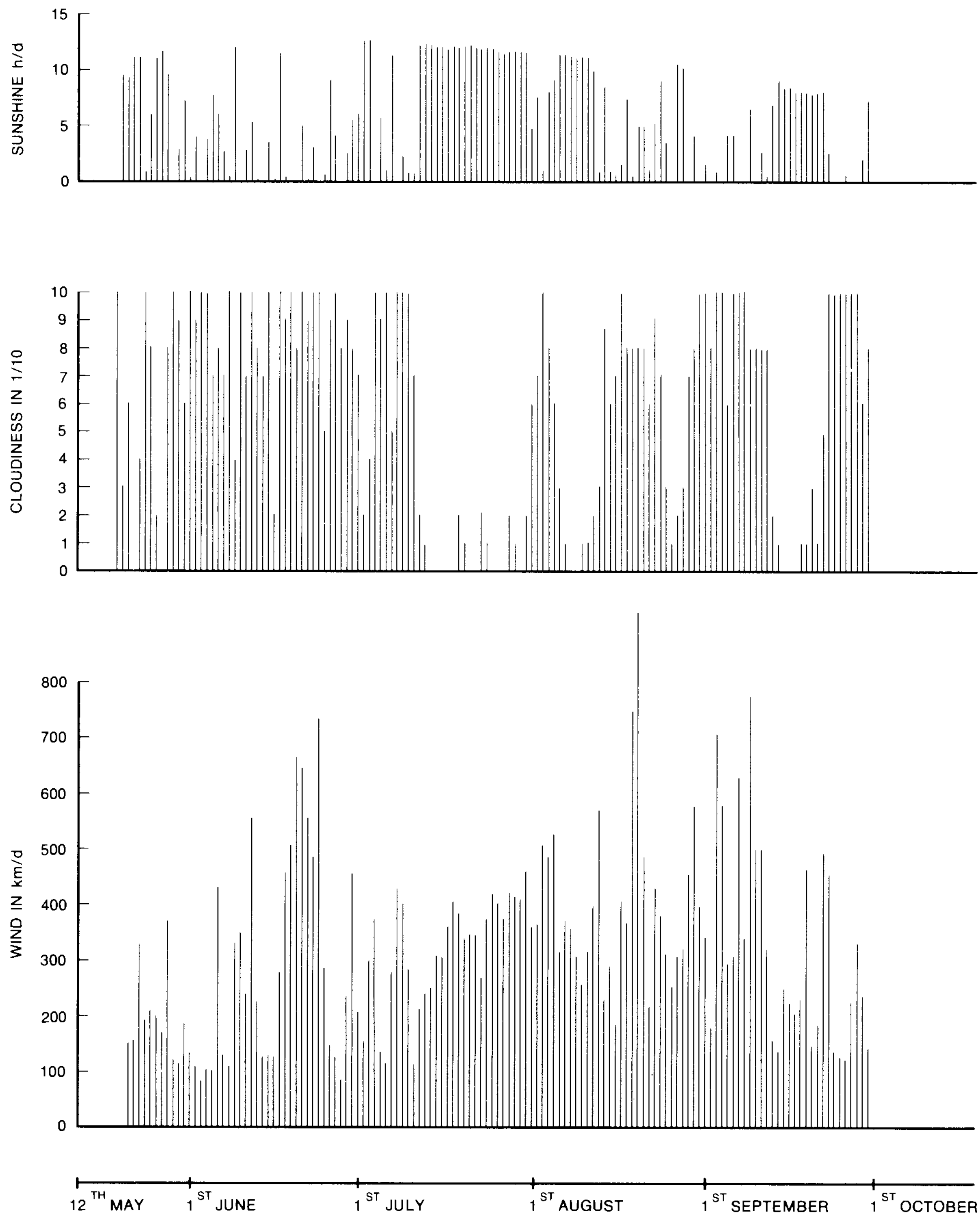
+15
+10
+5
0
−5
DAILY PRECIPITATION IN m.m.
35
30
25
20
15
10
5
0
78
SNOW
DAILY DISCHARGE IN 10³ m³
5
4
3
2
1
0
12TH MAY
1ST JUNE
1ST JULY
1ST AUGUST
1ST SEPTEMBER
1ST OCTOBER

SENTINEL GLACIER 1971



Appendix III

Summaries of Net Mass Balance, 1966-1971

CANADA

Glacier: Sentinel   Province: British Columbia

Lat.: 49°54′N   Long: 122°59′W

Year: 1965-66 Balance in m water equivalent: Area in km^2

Start 1 Oct. 1965		Winter to 16 June 1966	Summer to 6 Sept. 1966	
Contour Interval	Area	Winter balance	Summer balance	Net balance
>2100	0.023	3.40	2.25	+1.15
2000-2100	0.346	3.62	2.32	+1.30
1900-2000	0.490	3.68	2.53	+1.15
1800-1900	0.515	3.32	2.98	+0.34
1700-1800	0.300	3.01	3.66	-0.65
1600-1700	0.219	2.45	4.86	-2.41
<1600	0.092	2.44	4.64	-2.20
TOTALS	1.985	3.28	3.13	+0.15

Equilibrium Line: 1820 m

Submitted by:

Date:

CANADA

Glacier: Sentinel   Province: British Columbia

Lat.: 49°54′N   Long: 122°59′W

Year: 1966-67 Balance in m water equivalent: Area in km^2

Start 6 Sept. 1966		Winter to 6 June 1967	Summer to 8 Oct. 1967	
Contour Interval (in metres)	Area Km^2	Winter balance	Summer balance	Net balance
>2100	.023	4.48	2.26	+2.22
2000-2100	.346	4.40	3.00	+1.40
1900-2000	.490	4.54	3.94	+0.60
1800-1900	.515	4.42	4.65	-0.23
1700-1800	.300	3.80	5.14	-1.34
1600-1700	.219	3.53	5.50	-1.97
<1600	.092	3.21	6.00	-2.79
TOTALS	1.985	4.21	4.39	-0.18

Equilibrium Line: 1875 m

Submitted by:

Date:

CANADA

Glacier: Sentinel   Province: British Columbia

Lat.: 49°54′N   Long: 122°59′W

Year: 1967-68   Balance in m water equivalent: Area in km^2

Start 8 Oct. 1967		Winter to 23 May 1968	Summer to 1 Oct. 1968	
Contour Interval	**Area**	**Winter balance**	**Summer balance**	**Net balance**
>2100	0.023	3.55	2.26	+1.29
2000-2100	0.346	3.54	2.89	+0.65
1900-2000	0.490	3.43	2.71	+0.72
1800-1900	0.515	3.71	2.77	+0.94
1700-1800	0.300	3.47	3.01	+0.46
1600-1700	0.219	2.97	4.12	-1.15
<1600	0.092	2.14	4.66	-2.52
TOTALS	1.985	3.42	3.04	+0.38

Equilibrium Line: 1720 m

Submitted by:

Date:

CANADA

Glacier: Sentinel   Province: British Columbia

Lat.: 49°54′N   Long: 122°59′W

Year: 1968-69   Balance in m water equivalent: Area in km^2

Start 1 Oct. 1968		Winter to 30 May 1969	Summer to 6 Oct. 1969	
Contour Interval	**Area**	**Winter balance**	**Summer balance**	**Net balance**
>2100	0.023	4.22	2.74	+1.48
2000-2100	0.346	3.70	2.84	+0.86
1900-2000	0.490	3.85	3.08	+0.77
1800-1900	0.515	3.74	3.04	+0.70
1700-1800	0.300	3.24	3.96	-0.72
1600-1700	0.219	2.80	4.44	-1.64
<1600	0.092	2.23	5.06	-2.83
TOTALS	1.985	3.52	3.40	+0.12

Equilibrium Line: 1800 m

Submitted by:

Date:

CANADA

Glacier: Sentinel — Province: British Columbia

Lat.: 49°54′N — Long: 122°59′W

Year: 1969-70 Balance in m water equivalent: Area in km^2

Start 6 Oct. 1969		Winter to 18 May 1970	Summer to 30 Sept. 1970	
Contour Interval	Area	Winter balance	Summer balance	Net balance
>2100	0.023	3.26	3.26	0.00
2000-2100	0.346	2.94	3.23	-0.29
1900-2000	0.490	2.78	3.10	-0.32
1800-1900	0.515	2.56	4.02	-1.46
1700-1800	0.298	2.47	4.81	-2.34
1600-1700	0.186	2.14	5.14	-3.00
<1600	0.069	1.89	5.42	-3.53
TOTALS	1.927	2.62	3.92	-1.30

Equilibrium Line: 2080 m

Submitted by:

Date:

CANADA

Glacier: Sentinel — Province: British Columbia

Lat.: 45°54′N — Long.: 122°59′W

Year: 1970-71 Balance in m water equivalent: Area in km^2

Start Sept. 30, 1970		Winter to May 20th, 1971	Summer to Oct. 4th, 1971	
Contour Interval	Area	Winter balance	Summer balance	Net balance
>2100	0.023	4.74	2.26	+2.48
2000-2100	0.346	4.16	2.74	+1.42
1900-2000	0.490	4.16	3.07	+1.09
1800-1900	0.515	3.78	2.85	+0.93
1700-1800	0.298	3.59	4.31	-0.72
1600-1700	0.175	3.25	4.24	-0.99
<1600	0.054	3.04	4.91	-1.87
TOTALS	1.901	3.86	3.29	+0.57

Equilibrium Line: 1795 m

Submitted by:

Date:

Appendix IV

Calculations of Accumulation Area Ratio (AAR) for Sentinel Glacier, 1966-1971

Calculations of Accumulation Area Ratio (AAR) for Sentinel Glacier (using terminology of Meier and Post, 1962).

$$AAR = \frac{Sc}{Sc + Sa} = 1 - \frac{Sa}{Sc + Sa}$$

where

Sc is Accumulation area

Sa is Ablation area

1966 $AAR = \frac{1.374}{1.374 + 0.611} = 0.692$

1967 $AAR = \frac{1.211}{1.211 + 0.774} = 0.610$

1968 $AAR = \frac{1.556}{1.556 + 0.429} = 0.783$

1969 $AAR = \frac{1.399}{1.399 + 0.586} = 0.704$

1970 $AAR = \frac{0.170}{0.170 + 1.757} = 0.088$

1971 $AAR = \frac{1.514}{1.514 + 0.387} = 0.796$

Mokievsky-Zubok, O.

Determination of the mass balance on Sentinel Glacier, British Columbia, Canada.

DATE	ISSUED TO

GB
707
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No.30

Mokievsky-Zubok, O.

Determination of the mass balance on Sentinel Glacier, British Columbia, Canada.