United Nations Educational, Scientific and Cultural Organization

A contribution to the
International Hydrological Decade

Combined heat, ice and water balances at selected glacier basins

A guide for
compilation and assemblage of data
for glacier mass balance
measurements

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Preface

The International Hydrological Decade (IHD) 1965-1974 was launched by the General Conference of Unesco at its thirteenth session to promote international co-operation in research and studies and the training of specialists and technicians in scientific hydrology. Its purpose is to enable all countries to make a fuller assessment of their water resources and a more rational use of them as man's demands for water constantly increase in face of developments in population, industry and agriculture. In 1968 National Committees for the Decade had been formed in 100 of Unesco's 122 Member States to carry out national activities and to contribute to regional and international activities within the programme of the Decade. The implementation of the programme is supervised by a Coordinating Council, composed of twenty-one Member States selected by the General Conference of Unesco, which studies proposals for developments of the programme, recommends projects of interest to all or a large number of countries, assists in the development of national and regional projects and co-ordinates international co-operation.

Promotion of collaboration in developing hydrological research techniques, diffusing hydrological data and planning hydrological installations is a major feature of the programme of the IHD which encompasses all aspects of hydrological studies and research. Hydrological investigations are encouraged at the national, regional and international level to strengthen and to improve the use of natural resources from a local and a global perspective. The programme provides a means for countries well advanced in hydrological research to exchange scientific views and for developing countries to benefit from this exchange of information in elaborating research projects and in implementing recent developments in the planning of hydrological installations.

As part of Unesco's contribution to the achievement of the objectives of the IHD the General Conference authorized the Director-General to collect, exchange and disseminate information concerning research on scientific hydrology and to facilitate contacts between research workers in this field. To this end Unesco has initiated two collections of publications: 'Studies and Reports in Hydrology' and 'Technical Papers in Hydrology'.

The collection 'Technical Papers in Hydrology' is intended to provide a means for the exchange of information on hydrological techniques and for the co-ordination of research and data collection.

The acquisition, transmission and processing of data in a manner permitting the intercomparison of results is a prerequisite to efforts to co-ordinate scientific projects within the framework of the IHD. The exchange of information on data collected throughout the world requires standard instruments, techniques, units of measure and terminology in order that data from all areas will be comparable. Much work has been done already towards international standardization, but much remains to be done even for simple measurements of basic factors such as precipitation, snow cover, soil moisture, streamflow, sediment transport and ground-water phenomena.

It is hoped that the guides on data collection and compilation in specific areas of hydrology to be published in this collection will provide means whereby hydrologists may standardize their records of observations and thus facilitate the study of hydrology on a world-wide basis.

Contents

Foreword

The IHD project concerned with the combined heat, ice and water balances at selected glacier basins marks an important step in broadening the understanding of snow hydrology, high mountain and glacier hydrology, and the relation of glacier variations to changes in climate. The specific objective of the project is to obtain sufficient information to define and understand heat, ice and water balances and how they change with time at a number of glacier basins situated in widely differing environments in many parts of the world.

This guide, which deals with ice and water balances, will be followed by a companion volume on heat balances. It is published with the intention of providing a basis for international co-operation in attaining standardized measurements of glacier mass balances. This project is intimately linked to many other Decade projects such as the world inventory of perennial ice and snow masses, variations of existing glaciers and the world water balance. Guidance materials to these may also be found in other publications in the 'Technical Papers in Hydrology' collection. The project is also an extension of the representative and experimental basins programme, a cornerstone of the IHD programme since a glacier basin is a hydrologic basin in which the effects of snow and ice reach their ultimate development. Thus, the project demonstrates the interdependence of all hydrological research and the importance of international co-ordination of studies in scientific hydrology.

This technical guide was prepared by a Working Group of the International Commission of Snow and Ice of the International Association of Scientific Hydrology, under the chairmanship of Dr. M. F. Meier. Unesco gratefully acknowledges this work.

1 Introduction

Much of hydrological science involves interactions between rain, evapotranspiration, infiltration, ground water and streamflow. Snow is difficult to treat with the usual rational equations of hydrology because snow accumulation and wastage is complex and not sufficiently understood. Relatively little study has gone into understanding snow distribution, the meteorological causes of changes in the snowpack and its physical, thermal, and hydraulic properties, and the hydrology of basins where substantial amounts of water are stored seasonally or from year to year in the form of snow. Drainage basins dominated by glaciers are ideal sites for the study of these problems, because here the collection, storage, movement and release of melt water is dominated by the unique properties of snow and ice. This is an example of thermodynamic hydrology, where the heat balance largely determines the water balance, and the techniques as well as the approach are not conventional.

A deeper understanding of glacier and snowfield hydrology will have an immediate impact on the proper development and management of water resources. The bulk of the streamflow used by man in some areas is derived from relatively high precipitation rates and snowmelt on glaciers or near-glacier environments in mountains.

Civilization encroaches more and more on these environments both in high altitudes and in high latitudes. At present, glacier ice covers about 11 per cent of the land surface and temporarily stores perhaps three-quarters of all the earth's fresh water. Glaciers occur on all continents, at almost all latitudes, under a vast spectrum of meteorological activity, and in almost all major climatic zones from polar to tropical. The occurrence of glaciers in countries outside the polar regions generally identifies areas of high precipitation, cold temperatures, low evaporation and seasonal water storage; thus these areas are of hydrological interest.

Although heat balances have been measured for short periods at numerous points on glacier or snow surfaces, few attempts have been made to determine the heat balance of a whole glacier or snowy drainage basin. Mass balance measurements have been made on many glaciers, and liquid water run-off measurements have been made below some, but each of these measuring techniques is susceptible to a certain fixed (and usually unknown) error. Only in a very few instances have mass (or ice) and water balances been measured independently so the results could be compared, and in no cases have heat, ice and water balances been measured independently for appreciable lengths of time so that the interactions between the various terms of the balance equations, as well as their absolute accuracy, could be determined. Most studies of snow hydrology have suffered from the same problem: heat, ice or water balances have been measured singly, only rarely have all three balances been measured and combined.

A series of measurements of the relations of the mass and water balances of glaciers to the mass and heat fluxes from their external environment are urgently needed. These measurements should be taken for comparable periods during a number of years at selected, representative glacier basins distributed through many different climatic régimes. The measurements should be made at many different scales in space and in time so that the broadest understanding of these phenomena will emerge. This is the rationale of the Combined Heat, Ice and Water Balances at Selected Glacier Basins project of the International Hydrological Decade.

2 Relation to other projects of the Decade

The World Inventory of Perennial and Annual Snow and Ice Masses (resolution I-12 and resolution II-13)[1] will provide information on the location of snow and ice masses; the Combined Balances project will permit cause and effect interpretation of this distribution in terms of macroscale and mesoscale meteorologic processes.

Measurement of Glacier Variations on a Worldwide Basis (resolution I-13) will provide information on changes in glacier mass; the Combined Balances project will permit interpretation of these fluctuations in terms of changes in specific climatic elements and will also relate mass changes of the glaciers to the amount of melt water and streamflow produced.

The World Water Balance (resolution I-7) is an important theme of the Decade. This is an attempt to determine the amounts of water in its different forms which participate in the hydrological cycle, and the residence times on land of each of these forms of water. A huge amount of water is temporarily stored on land in the form of snow and ice at any instant in time. The amount of this mass which participates in the hydrological cycle depends upon precipitation rates, form of the precipitation, and the heat flux at the surface. Therefore, the Combined Balances project will provide essential information for an understanding of world water balances.

The Representative and Experimental Basins programme (resolution I-11) provides another cornerstone to the IHD. Co-ordinated, standardized studies of these individual hydrological units will yield improved understanding of hydrological processes. The Combined Balances project is an extension of the Representative and Experimental Basins concept to the field of snow and ice. A glacier basin is a hydrological basin in which the effects of snow and ice reach their ultimate development, and this type of basin should be considered in the broad Representative and Experimental Basin programme.

The project on Chronological Hydrology (resolution I-21) specifically utilizes glacier variations as geochronological indicators. Effects of Physiographic Features on Precipitation (resolution I-28) recognizes the difficulty of predicting precipitation distribution in mountainous areas, where snow normally makes up a large portion of the precipitation. Measurement of Snowfall and Snowpack (resolution I-52) is a project motivated by the need for improved instrumentation and techniques for measuring snow. These three projects are obviously related to the Combined Balances project.

1. Numbers in this section refer to resolutions of the IHD Co-ordinating Council, as listed in two reports: No. I is the report of the First Session, Paris, 24 May to 3 June 1965 (Unesco/NS/198); No. II is the report of the Second Session, Paris, 19-25 April 1966 (Unesco/NS/204).

3 The Combined Balances project

In order to obtain sufficient information to define and understand heat, ice and water balances and how they change with time at a number of glacier basins situated in widely differing environments in many parts of the world, the following points must be stressed: (a) measurements will be standardized and synchronized internationally, and the results will be widely disseminated; (b) simple measurements of known accuracy, frequently repeated, are preferred to highly complex or sophisticated measurements which cannot be maintained for a long period of time; (c) internal consistency of results will be determined by evaluation of many elements in the balance equation so that the absolute accuracy of the data can be verified; (d) measurements will be extended to cover whole drainage basins, or, where this is not possible, typical areas within drainage basins.

Heat, ice and water balances will be measured in each area together with the pertinent meteorological variables. From these results, the relation of growth and wastage of the snow and ice masses to the mass and heat flux from the external environment will be defined, and the measurement of all balances will verify the absolute accuracy of the results. The programme will continue to the end of the Decade, so that the changing atmospheric circulation patterns should produce a wide variety of local conditions and provide more reliable longer-term averages. It will not be possible to operate micrometeorological stations the year around, so complete measurements will be made only during certain important periods during the spring, summer and autumn, and approximate techniques will be used to fill in during the rest of the year.

In order to extend point measurements to glacier drainage basins, additional instrument set-ups, snow-line maps, and approximate techniques for extending data coverage will be required. In order to extend the coverage further—from the scale of individual drainage basins to atmospheric circulation patterns on a global basis—chains of glacier basin stations over the world will be operated. One chain will extend along the western mountains of the Americas from Arctic Alaska to the Antarctic Peninsula. Another chain of stations will extend from the Tien Shan and Pamir Mountains westward through Europe to the West Coast of North America at latitudes between 35° and 55°. A third chain will extend from the Polar Urals westward through Scandinavia, Iceland, Canada, to Arctic Alaska at approximately the latitude of the Arctic Circle. Stations located along these three profiles are of highest priority. Other glacier basin stations may be constituted in other parts of the world in order to derive a more complete geographical coverage. These chains of stations will extend the detailed results through several scales, permitting interpretation of small-scale phenomena in terms of large-scale changes in atmospheric circulation and global water balances, without omitting the processes which operate at intermediate or mesoscales.

Lists of stations known to be operating, proposed stations and areas where stations are needed along the north-south and west-east chains are given in Appendix I.

Selection of basin

A drainage basin selected for study as part of the Combined Balances project should, if at all possible, meet the following requirements:

1. The drainage basin should be well defined hydrologically and include a glacier which covers at least 30 per cent of the drainage area above the proposed streamflow measuring site.
2. The glacier should not be unusual or abnormal

in regard to size, mode of snow and ice accumulation, activity and other characteristics when compared with other glaciers in the vicinity.

3. The site should lie on or close to one of the three international profiles.
4. There should be a reasonable prospect of measuring simultaneously heat, ice and water balances for at least three years during the Decade.

Balance equations and terms

The more important terms in the heat, ice and water-balance equations can be written as follows:

Heat balance: $F_r + F_c + F_l + F_p + F_f = F_t$

where:

F_r = radiative heat flux;
F_c = sensible heat flux;
F_l = latent heat flux from condensation/evaporation;
F_p = heat content of precipitation;
F_f = receipt of heat due to freezing of water;
F_t = change in heat content due to temperature change in the snow/ice mass.

Ice balance: $I_p + I_l - I_r + I_f = I_m$

where:

I_p = precipitation in the solid phase;
I_l = condensation/evaporation of ice;
I_r = discharge of ice or snow from calving, snowdrift, avalanches, etc.;
I_f = ice formed by freezing of water;
I_m = change in total ice mass.

Water balance: $W_p + W_l - W_r - W_f = W_m$

where:

W_p = precipitation in the liquid phase;
W_l = condensation/evaporation of water;
W_r = run-off of water.
W_f = freezing of water to ice;
W_m = change in total water mass.

These various terms and equations are interrelated in many ways, so that measurement of some terms permits calculation of other terms. In most situations these equations can be vastly simplified. For instance, on polar glaciers during the entire year and on most subpolar glaciers in the winter, the only important terms are F_r, F_c, F_l, F_p, F_t, I_p, I_r and I_m, and often the terms F_l, F_p and I_r are small enough to be neglected. On a temperate, maritime glacier in the summer, the important terms are usually F_r, F_c, F_l, F_f, I_f, I_m, W_p and W_r.

The three balances mentioned above can be applied to a whole basin or to any vertical prism through the snow and ice mass at a point, and usually these processes need only be measured in an exchange layer near the surface. The balance equations apply for a whole year or for any shorter time interval. Thus by measuring all or most of the more important terms in the above equations, as well as their change with time, strong checks are provided on the absolute accuracy of the results.

Normally it is not possible to distinguish ice balances from mass (ice plus water) balances. Thus common glaciological techniques of mass balance measurements will be used for ice balances, except for sophisticated micrometeorological studies where the small amount of liquid water near the snow or ice surface must be known to determine F_f. In some other situations it may also be necessary to distinguish W_m from the total mass $(I_m + W_m)$.

Instruments and measurements

The evaluation and development of improved instruments for measuring a wide variety of physical parameters is a necessary part of this project. There is a great need for low-power recorders and sensors which will operate unattended for long periods in alpine and subpolar areas. New instruments will be tested throughout the Decade.

The types of instruments needed and measurement periods necessary for the more important terms in a basic, simple programme of heat, ice and water balance measurements are shown in Table 1.

It should be possible for one small party, visiting the glacier three to six times during the year (but not in winter), to operate and service these instruments.

In addition to the measurements listed above, the extent of the snow and ice cover on the drainage basin should be recorded at frequent intervals by photography or mapping. A detailed topographic map is required, showing surface elevations at the time of the IHD studies. On glaciers where there are important changes, repeated measurements of elevation or re-mapping may be necessary. More

TABLE. 1. Type of instrument and period necessary for measurement of heat, ice and water balance

Instrument	Measurement period
Heat balance	
Glass-covered radiometers (pair); Thermometer for night snow surface temperature	All summer, or at least during selected periods in summer representing major weather types
Sunshine recorder	Summer
Thermograph[1] (2 m above snow)	Summer
Anemometer[1] (2 m above snow)	Summer
Hygrograph[1] (2 m above snow) or wet/dry bulb thermometers	Summer
Plastic lysimeter, weighing balance[2]	Selected periods in summer
Snow thermometers or thermistor string with ohmmeter	Spring, and at times of heat balance measurements if snow not isothermal
Hand centrifuge or calorimeter or pycnometer[2]	At times of heat balance measurements
Ice and mass balances	
Storage precipitation gauges (at least four)	Read after major storms in spring, summer, autumn, if possible
Thermograph (mounted at approximate mean altitude of basin)	All year (summer only if rain not possible at other times of year)
Drift meter (if blowing snow is important)	Whenever necessary
Ablation stakes (at least fifty) and an appropriate drill	Summer
Probe	Summer
Pits or cores	Summer
Density tubes, weighing balance	Summer
Appropriate geodetic instruments	Whenever necessary
Water balance	
Limnograph (water-stage recorder) or staff gauge	All year if possible, or at least during spring, summer and autumn
Current meter or salt dilution apparatus	As often as necessary to define a precise water-stage/discharge relation (rating curve)
Storage precipitation gauges (see above)	

1. Preferably at three or more levels above the snow to determine gradients; measurements at a single level will suffice for crude approximations.
2. Not necessary for all glacier stations.

sophisticated measurements (especially of radiative and sensible heat fluxes) may be undertaken if this can be done without neglecting other elements in the basic programme. Gauges for the continuous recording of precipitation, ice mass and snow temperature will also add to the value of the results. Detailed maps of snow-fall and avalanche distribution are particularly desirable, as are data on vertical gradients of precipitation and air temperature. At least one standard climatological station, at which air temperature, humidity, wind speed and direction, and barometric pressure are measured on a routine basis would be a desirable addition to the programme in each drainage basin. If this is not possible, a long-term climatological station should be located near the basin.

At some basins it may not be possible to start all aspects of this project at once. Mass balance measurements should be instituted first, with water and heat balances following as soon as circumstances permit.

Recommended terms for mass (ice) balance measurements are presented in Appendix 2. Specific standards for heat, mass (ice) and water-balance measurements will be presented in the companion volume.

Dissemination of results

In order to permit free study and comparison of the results from stations all over the world by scientists in all nations, tabular summaries of the more important numerical results should be sent, as soon as possible after the conclusion of a balance year, to the IGY World Data Centres (Glaciology) A, B and C. A specific format for reporting results will be presented in the companion volume with a list of recommended standard observations.

Scientific conclusions should be published in official IHD publications or in any standard scientific journals which have wide international distribution. Copies of these reports should also be sent to the IGY World Data Centres (Glaciology), A, B and C.

Appendix 1

List of stations known (on 25 September 1967), proposed or needed

Latitude	Longitude	Glacier	Mountain range	Country	Responsible agency	Starting date
North-south chain						
69° N.	144° W.	McCall	Brooks	United States	University of Alaska	1968
63° N.	145° W.	Gulkana	Alaska	United States	U.S. Geological Survey	1966
60° N.	149° W.	Wolverine	Kenai	United States	U.S. Geological Survey	1966
56° N.	130° W.	Berendon	Coast	Canada	Dept. Energy, Mines, Resources	1967
50° N.	123° W.	Place	Coast	Canada	Dept. Energy, Mines, Resources	1965
50° N.	123° W.	Sentinel	Coast	Canada	Dept. Energy, Mines, Resources	1966
48° N.	121° W.	South Cascade	Cascade	United States	U.S. Geological Survey	1957
38° N.	120° W.	McClure	Sierra Nevada	United States	U.S. Geological Survey	1966
19° N.	99° W.	(?)		Mexico	(Station urgently needed)	—
11° N.	74° W.	(?)	S.N. da Santa Marta	Colombia	(Station urgently needed)	—
10° S.	77° W.	Uruashraju	Blanca	Peru	Corp. Peruana del Santa	
33° S.	70(?)° W.	Olivares Gamma	Central Andes	Chile	University of Chile	
37° S.	71° W.	Sierra Velluda	Central Andes	Chile	University of Chile (proposed)	—
47-51° S.	73-74(?)° W.	(?)	Patagonia	Chile or Argentina	(Station urgently needed)	—
55° S.	72-63(?)° W.	(?)	Darwin	Chile	(Station urgently needed)	—
55° S.	37° W.	(?)	South Georgia	United Kingdom	(Station urgently needed)	—
64-70° S.	60-65° W.	(?)	Antarctic Peninsula	(?)	(Station urgently needed)	—
West-east chain (~ 45° N. lat.)						
43° N.	77° E.	Tuyuksu	Northern Tien Shan	U.S.S.R.	Acad. Sci. Kazak. S.S.R., Alma Ata	1968
39(?)° N.	73(?)° E.	Abramov	Alaji	U.S.S.R.	Hydromet. Institute, Tashkent	1967
39(?)° N.	72(?)° E.	(?)	Pamir	U.S.S.R.	Hydromet. Institute, Tashkent	1970(71?)
43° N.	43° E.	Gergeti	East Caucasus	U.S.S.R.	Transcaucasus Hydromet. Inst., Inst. Geog., Tbilisi	1968
43° N.	42° E.	Marukh	West Caucasus	U.S.S.R.	Hydromet. Obs., Inst. Geography, Rostov	1967
47° N.	13° E.	Übergossene Alm	Hochkönig	Austria		
47° N.	13° E.	Sonnblick	Hohe Tauren	Austria	Univ. Salzburg	1963
47° N.	11° E.	Schnee	Zugspitze	Germany (Federal Republic)	Com. f. Glaziologie, Munich	
47° N.	11° E.	Hintereis	Ötztaler Alpen	Austria	Univ. Innsbruck	1952
47° N.	11° E.	Kesselwand	Ötztaler Alpen	Austria	Univ. Innsbruck	1957
47° N.	11° E.	Vernagt	Ötztaler Alpen	Austria	Com. f. Glaziologie, Munich	1965
47° N.	11° E.	Langtaler	Ötztaler Alpen	Austria	Com. f. Glaziologie, Munich	1963
46° N.	8° E.	Aletsch	Berner Oberland	Switzerland	VAWE-ETH, Zürich	1927

Latitude	Longitude	Glacier	Mountain range	Country	Responsible agency	Starting date
46° N.	6° E.	Sarennes	Grandes-Rousses	France	Dir. Forêts	1948
46° N.	6° E.	Saint-Sorlin	Grandes-Rousses	France	Univ. Grenoble, Lab. Glaciologie CNRS	1957
46° N.	6° E.	Blanc	Écrins	France	Univ. Grenoble, Lab. Glaciologie CNRS	1967
47° N.	7° E.	Mer de Glace	Mont Blanc	France	Univ. Grenoble, Lab. Glaciologie CNRS	1960
42° N.	0° E.	(?)	Pyrénées	France or Spain	(Station urgently needed)	—
45° N.	110° W.	Grasshopper	Rocky	United States	Montana State University	1967
52° N.	116° W.	Ram River	Rocky	Canada	Dept. Energy, Mines, Resources	1966
52° N.	116° W.	Peyto	Rocky	Canada	Dept. Energy, Mines, Resources	1965
51° N.	118° W.	Woolsey	Selkirk	Canada	Dept. Energy, Mines, Resources	1965
48° N.	121° W.	South Cascade	Cascade	United States	U.S. Geological Survey	1957
50° N.	123° W.	Place	Coast	Canada	Dept. Energy, Mines, Resources	1965
50° N.	123° W.	Sentinel	Coast	Canada	Dept. Energy, Mines, Resources	1966
West-east chain (~ 66° N. lat.)						
65° N.	60(?)° E.	Bolshaja Khodata	Polar Ural	U.S.S.R.	Inst. Geog. Acad. Sciences	1958
68° N.	8° E.	Störglaciären	Kebnekaise	Sweden	Univ. Stockholm	1945
68° N.	7° E.	Storsteinfjell-breen				1963
68° N.	7° E.	Blåisen				1962
62° N.	5° E.	Ålfotbreen				1962
62° N	4° E.	Vetledalsbreen	Jostedalsbreen			1967
62° N.	4° E.	Nigardsbreen	Jostedalsbreen			1961
60° N.	4° E.	Folgefonni		Norway	Water Res. Elect. Board	1962
60° N.	3° E.	Hardangerjö-kulen				1962 1962
62° N.	3° E.	Storbreen	Jotunheimen			1948
62° N.	2° E.	Hellstugu-breen	Jotunheimen			1962
62° N.	2° E.	Memurubreen	Jotunheimen			1967
62° N.	2° E.	Gråsubreen	Jotunheimen			1962
65° N.	20° W.	(?)	(?)	Iceland	(Station urgently needed)	—
70° N.	70° W.	Decade	Baffin Island	Canada	Dept. Mines, Energy, Resources	1965
79° N.	90° W.	White	Axel Heiberg	Canada	McGill Univ.	1959
69° N.	144° W.	McCall	Brooks	United States	Univ. Alaska	—
63° N.	145° W.	Gulkana	Alaska	United States	U.S. Geological Survey	1966

Appendix 2 *Mass balance terms*

The terms presented here can be used for most mass and ice balance measurements. The purpose of this section is to reduce the ambiguity and confusion caused by the use of a large number of alternate schemes and definitions. Discussions with several dozen distinguished glaciologists from many countries, extending over two years, have produced this scheme. Although not perfect and not agreeable to all, it is believed to be as close to a consensus as is possible at this time.

It is necessary to specify the kind of mass (ice only, or ice plus water) included in the balance terms for various applications. When dealing with hydrological balances one normally includes all water in any phase in the mass balance terms. When dealing with heat balances, liquid water and ice must be considered separately. Under special conditions (as in some flow studies) one might also consider debris as a part of the mass. Although the definition of mass may vary, the mass balance terms are similar for all applications. The term 'accumulation' is taken to embrace all processes by which mass is added to a glacier, snow-field, or portion thereof. The term 'ablation' includes processes by which mass is lost from the glacier or snow-field. Calving may be treated separately.

When mass-balance calculations are based on measurements on a glacier surface the values are compiled from point observations. The measurement points normally move with the ice flow, but values at points fixed in space are needed for mass balance calculations. Corrections may therefore be needed to relate observations to fixed points.

The main part of the change in mass is usually assumed to take place in a relatively thin surface layer of the glacier. This is the only part normally involved in heat balance measurements. In mass balance measurements, however, one considers the mass exchange extending from the base to the surface of the glacier, so that the subsurface accumulation and ablation must be included. The refreezing of melt water below the surface may be especially important in subpolar glaciers, and temperature measurements ought to be made down to sufficient depth. If subsurface deposition is suspected but only surface measurements are made, then this must be clearly stated.

Two time systems of measurement can be used: (a) the stratigraphic system; and (b) the fixed-date system. The stratigraphic system is based on the existence of an observable summer surface, which is assumed to be formed at the time of minimum mass at the site. The summer surface may be an identifiable horizon of concentrated debris particles, a discontinuity between old ice or firn below and much younger snow above, a peak in the $O^{18}:O^{16}$ ratio (indicating a maximum in the temperature of snow condensation in the atmosphere) or other isotropic evidence, a prominent depth hoar or low density layer, or by other criteria. On high polar plateaux, there may be little ablation and no melting, so that the time of minimum mass cannot be defined visually. In this case the prominent depth hoar layer formed in snow deposited in autumn can be used as a 'summer surface'.

The fixed-date system involves measurements made at certain specific days or whenever possible, and the measurements are not necessarily related to any observable features in the snow, firn or ice.

It is very important that one system be used for all measurements. One cannot combine the two systems without introducing errors.

Mass balance measurements at a point

All mass balance measurements at points should be symbolized by small letters and reported as equivalent volumes of water per unit area; in this way the mass balance values have the dimension of length. The metric system must be used; the Système Internationale (SI) is recommended. Millimetres are normally used, except in very high precipitation areas where metres may be more logical. Alternatively, values can be given as mass per unit area (kilogrammes per square metre). These point values are measured in a vertical direction, so that they can be projected on a horizontal area.

The stratigraphic system. The formation of a summer surface determines the change from one balance year to the next, the 'balance year' being the time interval between the formation of two consecutive summer surfaces (not necessarily 365 days). All mass balance terms vary with time. The 'balance' (b) at any time is the change in mass, expressed as water equivalent, relative to the previous year's summer surface (see Fig. 1(a)). The change in mass from the summer surface up to the maximum value of the balance curve is called the 'winter balance' (b_w). The time when this maximum value occurs divides the balance year into one 'winter season', with generally increasing balance at the site; and one 'summer season', when the balance generally decreases. The change in mass during the summer season is called 'summer balance' (b_s).

The 'accumulation' (c) curve shows the result of an integration, with respect to time, of the accumulation rate. 'Total accumulation' (c_t) is the result of an integration taken from the beginning to the end of the balance year. Total accumulation is divided into the 'winter accumulation' (c_w) and the 'summer accumulation' (c_s). In a similar way,

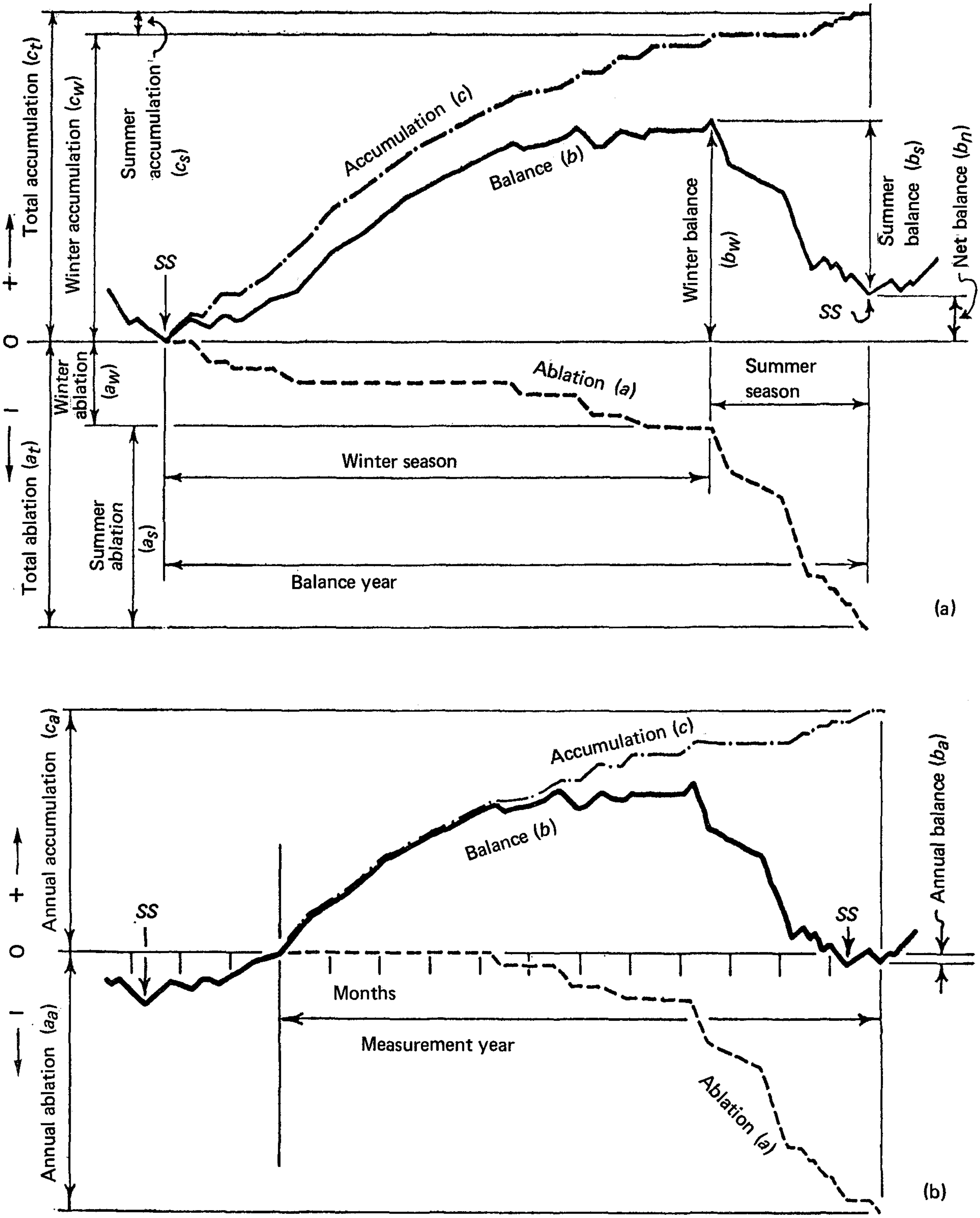

FIG. 1(a) and (b). Mass balance terms as measured at a point on a glacier or ice cap. ss = time of formation of a summer surface.

the 'ablation' (a) curve shows the integrated ablation through the balance year. The value at the end of the balance year is termed total ablation (a_t), which is divided into 'winter ablation' (a_w) and 'summer ablation' (a_s).

At all times the balance is the algebraic sum of the accumulation and the ablation at the actual time, $b = c + a$ (accumulation is considered positive and ablation negative). At the end of the balance year this difference expresses the 'net balance' (b_n) of the year. The 'winter balance' is the change in balance from the beginning to the end of the winter season; the 'summer balance' is the change in balance from the beginning to the end of the summer season. The net balance is therefore also expressed by the difference in winter and summer balance. Thus $b_n = c_t + a_t = b_w + b_s$. All balance quantities should be given with the appropriate sign (+ or —). One useful parameter is the 'total exchange', which is given by $e_t = c_t - a_t$.

Fixed-date system. In this alternative scheme the 'measurement year' is defined by fixed calendar dates. In many cases, it will be preferable to use a measurement year which coincides with the local hydrologic year. The 'balance' (b), 'accumulation' (c), and 'ablation' (a) curves are the same as in the stratigraphic system. The time-integrations, however, are taken over the period defined by the measurement year (see Fig. 1(b)), so the values of b, c and a at the end of year will not be same as in the stratigraphic system. Winter and summer seasons are not defined.

The total values of accumulation and ablation at the end of the measurement year are termed 'annual accumulation' (c_a) and annual ablation (a_a). The algebraic sum is termed the 'annual balance' (b_a) ($b_a = c_a + a_a$). The 'annual exchange' (e_a) is given by $e_a = c_a - a_a$.

Mass balance terms for an area

The terms for an area are analogous to those defined for a point, but are symbolized by capital letters. The quantitative results depend upon which time system is used.

Stratigraphic system. The areal mass balance quantities (C, A, B) are found by integrating the stratigraphic system point values over the area. So the areal total accumulation, ablation and balance are symbolized by C_t, A_t and B_t, winter accumulation and ablation by C_w and A_w, etc. The balance year is normally of different length on various parts of the glacier, and the integration therefore cannot be clearly defined with regard to time. Only if the summer surfaces are formed almost simultaneously over the whole glacier, can the area be assigned to definite points in time.

Fixed-date system. Similarly, point values found according to the fixed-date system are integrated over the area to give areal values. In this case the point values refer to the same time interval, and the areal values are here assigned to definite instants in time.

Comparison of stratigraphic and fixed-date systems

The accumulation, ablation and balance curves for a point are identical regardless of which system is used. As the length of the balance year, which is used in the stratigraphic system, is different from the measurement year in the fixed-date system, the total values c_t, a_t, b_t and annual values c_a, a_a and b_a may be very different for a single year. This automatically means that the areal values are also different. However, over a long period of time, the two systems will give results which tend to approach the same average value.

In many areas it will be more efficient to work with summer surfaces in the field; a single trip just after the close of the balance year will suffice to define most of the important parameters, and when working with deep pits or cores one only has summer surfaces (or other indication of variations in b) to mark the different years. On the other hand, when comparing mass balance data with heat or water balances, a fixed-date system is preferred.

A fixed-date system may be necessary because of logistical considerations. It is very important not to mix the two systems in any set of observations from a single glacier or snow-field.

Other useful terms

A line connecting points, at any instant, where the balance (b) is zero is called the 'transient equilibrium line'. This can be defined under either the stratigraphic or fixed-date systems. The line connecting points where the net balance (b_n) is zero at the end of a balance year is called the 'equilibrium line', as defined under the stratigraphic system. The equivalent line at the end of a fixed-date year is the 'annual equilibrium' line. The ratio of area above the equilibrium line (the 'accumulation area' (S_c)) to the total glacier area is called the 'accumulation area ratio' *(AAR)*. The area below the equilibrium line is called the 'ablation area' (S_a).

$$AAR = \frac{S_c}{S_c + S_a} = 1 - \frac{S_a}{S_c + S_a}.$$

A boundary between snow (last winter's accumulation) and ice or firn at any instant in time is called the 'transient snow line'. The highest position reached by this line in the summer (more properly, the transient snow line at the time of minimal areal extent of snow cover on a glacier or in a certain defined region) is called the 'firn line'.[1] The firn line will approximately coincide with the equilibrium line on temperate glaciers only.

'Mean values', taken over selected areas of the whole glacier, of net balance, total accumulation, annual balance and other measurements are designated by the appropriate lower-case point symbol with a bar over it, e.g. $\bar{b}_n$, $\bar{c}_t$, $\bar{b}_a$.

Another kind of 'mean value', taken over periods of many years, may be designated by $\langle B_n \rangle$, $\langle \bar{b}_n \rangle$, $\langle c_t \rangle$, etc.

In many reports it will be necessary to assign symbols to designate other things, such as (a) material, (b) area of investigation, or (c) surface/englacial/subglacial phenomenon. It is recommended that those symbols be individually defined in each report and placed in parentheses following the symbol for the mass balance term. Thus, one might wish to designate the mean ablation of ice only in the ablation area as $\bar{a}_t(i, a)$; or the annual balance of snow only for a whole region $B_a(s, r)$; or the englacial (subsurface) accumulation at a point as $c_t(e)$. So many combinations are possible that no standardization of specific symbols will be attempted here.

1. Firn is defined as snow which has passed through one summer; thus snow becomes firn, by definition, at the instant the summer comes to an end. The firn line may extend over ground that is bare of snow during other years.

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United Nations Educational, Scientific and Cultural Organization

A contribution to the
International Hydrological Decade

Combined heat, ice and water balances at selected glacier basins

Part II : specifications, standards and data exchange

unesco iash

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Preface

The International Hydrological Decade (IHD) 1965–74 was launched by the General Conference of Unesco at its thirteenth session to promote international co-operation in research and studies and the training of specialists and technicians in scientific hydrology. Its purpose is to enable all countries to make a fuller assessment of their water resources and a more rational use of them as man's demands for water constantly increase in face of developments in population, industry and agriculture. In 1972 National Committees for the Decade had been formed in 107 of Unesco's 129 Member States to carry out national activities and to contribute to regional and international activities within the programme of the Decade. The implementation of the programme is supervised by a Co-ordinating Council, composed of twenty-one Member States selected by the General Conference of Unesco, which studies proposals for developments of the programme, recommends projects of interest to all or a large number of countries, assists in the development of national and regional projects and co-ordinates international co-operation.

Promotion of collaboration in developing hydrological research techniques, diffusing hydrological data and planning hydrological installations is a major feature of the programme of the IHD which encompasses all aspects of hydrological studies and research. Hydrological investigations are encouraged at the national, regional and international level to strengthen and to improve the use of natural resources from a local and a global perspective. The programme provides a means for countries well advanced in hydrological research to exchange scientific views and for developing countries to benefit from this exchange of information in elaborating research projects and in implementing recent developments in the planning of hydrological installations.

As part of Unesco's contribution to the achievement of the objectives of the IHD the General Conference authorized the Director-General to collect, exchange and disseminate information concerning research on scientific hydrology and to facilitate contacts between research workers in this field. To this end Unesco has initiated two collections of publications: 'Studies and Reports in Hydrology' and 'Technical Papers in Hydrology'.

The collection 'Technical Papers in Hydrology' is intended to provide a means for the exchange of information on hydrological techniques and for the co-ordination of research and data collection.

The acquisition, transmission and processing of data in a manner permitting the intercomparison of results is a prerequisite to efforts to co-ordinate scientific projects within the framework of the IHD. The exchange of information on data collected throughout the world requires standard instruments, techniques, units of measure and terminology in order that data from all areas will be comparable. Much work has been done already towards international standardization, but much remains to be done even for simple measurements of basic factors such as precipitation, snow cover, soil moisture, streamflow, sediment transport and ground-water phenomena.

It is hoped that the guides on data collection and compilation in specific areas of hydrology to be published in this collection will provide means whereby hydrologists may standardize their records of observations and thus facilitate the study of hydrology on a world-wide basis.

CONTENTS

FOREWORD

The IHD project concerned with the combined heat, ice and water balances at selected glacier basins marks an important step in broadening the understanding of snow hydrology, high mountain and glacier hydrology, and the relation of glacier variations to changes in climate. The specific objective of the project is to obtain sufficient information to define and understand heat, ice and water balances and how they change with time at a number of glacier basins situated in widely differing environments in many parts of the world.

In this second part of "Combined heat, ice and water balances at selected glacier basins", the emphasis is on specifications and standards for types, locations and timing of measurements, with particular attention given to heat balances. It is published with the intention of providing a basis for international co-operation in attaining standardized measurements of all three glacier balances. This project is intimately linked to many other Decade projects such as the world inventory of perennial ice and snow masses, variations of existing glaciers and the world water balance. Guidance materials to these may also be found in other publications in the 'Technical Papers in Hydrology' collection. The project is also an extension of the representative and experimental basins programme, a cornerstone of the IHD programme since a glacier basin is a hydrologic basin in which the effects of snow and ice reach their ultimate development. Thus, the project demonstrates the interdependence of all hydrological research and the importance of international co-ordination of studies in scientific hydrology.

This technical guide was prepared by a Working Group of the International Commission of Snow and Ice of the International Association of Scientific Hydrology, under the chairmanship of Dr. M.F. Meier. A subcommittee of this Working Group dealt specifically with heat balances. Unesco gratefully acknowledges this work.

1 INTRODUCTION

During the International Geophysical Year, many useful glacier mass balance results were obtained. However, very few stations produced heat balance data which could be directly compared with those from any other station (Hoinkes, 1964). In the years since the IGY, no major solutions to the problem of making accurate and standardized heat balance measurements have appeared. It is now apparent that proper measurement of all components in a heat balance involves considerable expense, as well as sophisticated instrumentation and highly competent scientists, and it is not likely that more than a very few nations can afford to do this work.

Therefore, this Combined Balances project of the International Hydrological Decade is built around two kinds of stations:

a. A large number of Standard Stations will produce data on ice and water balances, as well as basic data for the correlation of meteorological and glaciological conditions. A certain minimum number of prescribed instruments will be operated to obtain daily measurements over a major portion of the ablation season at one location on a glacier. Other measurements will be made to extend the data coverage over a larger area or the complete drainage basin at monthly intervals. The minimum level of precision of the daily and monthly values will be specified, and tabulations of data will be exchanged between projects through the World Data Centres and the Permanent Service on the Fluctuations of Glaciers.

b. A limited number of Special Stations will be established to study heat and mass exchange processes, and to develop procedures for relating the simple measurements obtained at Standard Stations to actual heat exchange conditions. At these Special Stations, all of the daily measurements prescribed for Standard Stations will be made, and in addition complete, modern heat balance instruments will be operated. These will be of sufficient precision and sophistication so that all components of the heat balance are measured with confidence. These results will then be used to verify existing techniques and to derive new procedures for analyzing the data obtained at Standard Stations in terms of more meaningful heat balance and glacier-meteorological relationships.

The philosophy is to compute, at frequent intervals, approximate heat balances from simple data, using a modified aerodynamic approach, at one site at each standard station; to extend these results to cover larger areas by simpler measurements at less frequent intervals; and to calibrate and refine the standard station heat balance computations by means of a few special stations where heat balances will be determined by rigorous, modern methods such as the eddy correlation technique. All levels of activity, therefore, are of equal importance to the total programme.

Standard Stations should include, where possible, observations over a whole glacier drainage basin. Only in this way can heat, ice and water balances be directly compared. However, in some areas this may not be possible: the glaciers are too large, or the financial and economic resources are too small. In order to permit investigations in these areas, compromise programmes will be allowed. These could take the form of intensive heat and ice balances measured at just one point or in one small area, coupled with or without water balances measured over a larger or different area. Such work will not be discouraged, but it should be kept in mind that such an investigation is susceptible to large absolute errors; the self-checking feature of complete balances is missing. On the other hand, rigid adherence to whole-glacier measurements might limit the programmes in some areas to tiny glaciers existing just at the equilibrium line altitude, and this is not a desirable sampling of glacier-atmosphere interactions.

Much of the effort for Standard Stations will involve daily measurements at a single observational site. Other measurements, made less often, will extend over the larger area of interest.

HEAT BALANCE

Daily observations at one site

These observations are preferably to be taken at a centrally located site in the accumulation zone of the glacier but near its lower limit, where the surface is nearly horizontal or has a relatively even slope, a representative surface condition, and, if possible, an exposure and horizon reasonably representative of the glacier as a whole. If this location is impractical, another location representative of a larger homogeneous area may be chosen. The site is to be described as a Station Description. If a second site can be operated, it should be in the middle of the ablation area.

The measurements listed below are to be taken continuously during the major portion of the main ablation season. Longer periods of measurement are desirable, and in some areas may be essential. A shorter period of observation is not recommended, but is permissible if appreciable ablation does not go unmeasured. The following daily observations are prescribed; the frequencies of observation are given in Table 1.

1. Global solar radiation.-- This should be measured with a pair of glass-covered pyranometers (e.g., Kipp or Eppley type) and recorder. The instruments must be maintained in an absolutely level orientation, one pointing up and one pointing down, and the glass domes carefully cleaned of hoarfrost, rime, or snow accumulations. The instruments should be located so that no shadows of other installations fall on them for more than a few minutes per day. The instruments, recorder, and computation procedure should be capable of defining daily sums of incoming and reflected solar radiation with a standard error not greater than 1 MJ/m^2 (25 ly). Report daily incoming and reflected sums in MJ/m^2, to nearest 0.1, 0.5, or 1 MJ/m^2 depending on

precision of instrument, or report incoming radiation and albedo. If radiometers cannot be operated, sunshine duration must be recorded, and it is very important to specify the type of instrument used to measure sunshine duration. A sunshine duration meter might also be operated to provide data in case of radiometer/recorder failure.

Table I. -- Types and frequencies of observations to be performed at the main site.

Note: -- Frequency of observations defined as: c, continuously through season; 5c, continuously for selected 5-day periods; ½d, twice daily; ¼d, four times a day; d, daily; 5d, every 5 to 10 days.

Type of observation	Standard station: Minimal programme	Standard station: Recommended programme	Optional programme	Special station: Suggested programme
Radiation				
Sunshine recorder	c			c
Glass-covered pyranometers (2)		c	c	c
All-wave net radiometer			c	
Long-wave radiometers (2)				c
Temperature				
Air at 2 m, thermograph in shelter	c	c		c
Air, profile 0.5-2 m, thermistor or thermocouple, recording			5c	c
Snow surface (glass thermometer)		d		c
Snow at 0, 2, 5, 10, 20 cm below surface, recording			5c	c
Nocturnal crust thickness	d	d	d	d
Humidity				
Hygrograph at 2 m in shelter	d	c	c	c
Profile 0.5-2 m wetted thermistors, thermocouples, or more sophisticated sensors, recording			5c	c
Cloud cover	½d	¼d	¼d	¼d
Wind				
Daily totals at 2 m	d	½d		
Recording at 2 m			c	c
Profile 0.5-2 m, recording			5c	c
Wind direction, 2 m		d	5c	c
Precipitation				
Standard gauge	d	d	d	c
Measurements on ground after each snowfall	d	d	d	d
Evaporation/condensation				
Lysimeter			5c	d
Blowing snow				
Snow drift meter			d	d
Air pressure				
Aneroid barometer		d		
Barograph			c	c
Ablation				
Bulk ablation	5d	d-5d	d	d
Liquid water content				d
Snow surface characteristics	5d	5d	d	d

2. Air temperature.-- Air temperature sensors are to be properly shielded against errors due to incident and reflected solar radiation. Furthermore, they should be well ventilated. Outputs should be recorded continuously or at intervals of not more than 30 minutes. The air temperature sensor should be maintained at 2 m & 20 cm above the mean show surface, and it should not be located down the prevailing wind direction from another large installation. Daily means should be recorded to $0.5^{o}C$, and these means should have an absolute precision indicated by a standard error of $1^{o}C$ or less.

3. Minimum snow surface temperature.-- A simple minimum-registering glass (not plastic) thermometer, laid directly on the snow surface and not shielded against radiation, will suffice. Daily minimum values should not exceed $0.5^{o}C$.

4. Nocturnal crust. -- The thickness of the nocturnal crust should be measured each morning to an accuracy of 1 cm and reported to the nearest cm.

5. Humidity.-- This should be measured at a height of 2 m & 5 cm above the snow. A high quality, recording instrument is recommended, and the type of instrument used should be described. A ventilated psychrometer is required in order to calibrate the sensor used for the continuous record. Values should have a standard error at any instant of 10 per cent relative humidity or less, and daily means should be recorded to 1 per cent.

6. Cloud cover.-- Observations of cloud cover type and amount should be made at least twice a day, and preferably four times a day. Average values of cloud cover amount for the daylight portion of each day should be reported. In case of fog, times of beginning and ending at the main site should be recorded.

7. Wind speed.-- A well calibrated anemometer should be mounted on a stand so that its axis is kept vertical (& 10^{o}) and the cups are maintained at an elevation of 2 m & 20 cm above the mean surface. It should be located up wind and some distance away from other installations. The instrument should have a precision (standard error) of 5 per cent or less for winds in the range 1-15 m/s. If a recording anemometer is not used, the daily wind run totals should be read at standard times twice a day. Tabulate mean wind speeds for the day to the nearest 0.1 m/s. The wind direction should also be measured at the two standard times.

8. Precipitation.-- A standard precipitation gauge with wind shield should be mounted vertically (& 5^{o}) with an orifice of at least 200 cm^2 at 1.5 m above the snow surface. When precipitation occurs as snow, the gauge reading will be very inaccurate and supplemental readings of new snow depth and density on the glacier surface are essential. These supplemental measurements should be taken over a broad area in the vicinity of the precipitation gauge to get a valid average. Snow and other forms of frozen precipitation should be separated on the basis of direct observation. For a more complete discussion on the proper measurement of precipitation see Unesco/IASH (1970a). Every effort should be made to derive daily totals of precipitation accurate (standard error) to 2 mm of water. Tabulate to nearest millimetre. The dimensions of the precipitation gauge and the type of wind shield should be reported.

9. Air pressure.-- An aneroid barometer, read daily, or a recording barograph is recommended. These data are useful for computing specific humidity and calibrating a hygrograph with a psychrometer.

10. Ablation.-- Measurement of this parameter is most difficult and will require the greatest care and attention of the observer. A measuring procedure sufficiently precise to give daily values of water-equivalent accurate to at least 4 mm (standard error), which are representative of the measurement site is desired. This requires measurements at many closely spaced points to properly define the surface lowering, density-depth profiles taken at appropriate intervals (daily to every few days) depending on the rate of change of density with time, and proper attention to such problems as the refreezing of water in the snow and the settlement of snow around ablation stakes or the supports of ablation-measuring devices (LaChapelle, 1959). The required number of points (which may be as few as 10 or as many as 100) should be determined by measuring ablation at 10 to 20 points, determining the mean daily ablation and the standard deviation of individual values from the mean, and applying a simple statistical analysis (e.g., Untersteiner, 1961, p. 159-160) to determine the required number of sample points for a 90 per cent probability of determining the mean within the required 4 mm of water-equivalent. This experiment should be repeated as the snow surface roughness changes during the season. By arranging the points along a line parallel to the wind direction, valuable information on the surface roughness parameter (z_0) can be obtained. Depending on the amount of ablation, the characteristics of the snow, and the availability of skilled observers, it may or may not be possible to make daily observations accurate to 4 mm of water-equivalent. If this accuracy cannot be obtained, then careful ablation measurements at less frequent intervals (every 5 to 10 days) are recommended. Less accurate daily measurements are not recommended. Report daily or 5-10 day totals in millimetres of water-equivalent.

11. Snow surface characteristics.-- A description of the character of the snow surface should be made every 5-10 days, or daily if the surface conditions are changing. This should include roughness, type of relief (such as sastrugi or sun cups), wetness, dirt, surface water run-off, and so forth.

12. Additional measurements at the main site.-- If at all possible, long-wave or all-wave radiometers, lysimeters to measure evaporation/condensation or ablation, snow drift meters, and liquid-water content measuring devices should be employed. These cannot be considered essential to all programmes, because of the expense involved.

Other observations

In order to extend heat balance results from the main site to cover a larger area, the following measurements need to be performed. It is best if these are done on the first day of each month during the main ablation season. If the drainage basin is not too large or inaccessible, these observations should cover the entire area.

1. Maps should be drawn of the distribution of snow, firn, and ice over the basin. Percentages of snow, firn, and ice in relation to the measured area should be reported on the first day of the month, and should be

correct to a standard error of 5 per cent of the total basin area.

2. The mean albedo of snow, firn, and ice should be measured at a sufficient number of points to derive a mean value for each type of surface accurate to 0.05 (standard error). This can be done with a portable pyranometer of the same type used at the main site.

3. By use of a Tagbogenmesser,* computation from a topographic map, or other technique, the percentage of total possible solar radiation incident on the snow or ice surface should be measured at at least 20 points scattered over the drainage basin, and values computed for the first day of each ablation season month.

4. Snow temperature/depth profiles to depths of 5 m or more should be taken at about 5 locations over the drainage basin, on about the first day of the month, as long as subfreezing temperatures exist. These temperatures should be accurate to 0.5°C. In some areas, these temperatures should also be measured in ice.

5. Air temperature should be recorded at 2 m above a ridge crest or mountain top, well away from the influence of the glacier wind or localized inversions. The sensor, height above ground, and accuracy should be similar to the temperature sensor at the main site. If possible, humidity measurements could also be made at this location.

6. If possible, 2 m air temperature should also be measured at a low altitude in or near the drainage basin, with a similar instrument.

7. Precipitation should be recorded at at least two locations in the drainage basin, away from the main site, and with similar instruments including wind shields. A larger number of storage precipitation gauges is preferred. The catch in those gauges should be checked against actual measurements of snow on the ground, and the necessary corrections applied to the results.

ICE BALANCE

Ice balance data cannot be obtained on a daily basis (except for ablation at one site), but will be collected at intervals of about once a month during the ablation season. Measurements should be scheduled so that a minimum of interpolation will be necessary to report ice balance quantities as of the first day of each month. Totals for the beginning and end of each balance year are essential; monthly values during the main ablation season are strongly recommended.

In general, the measurement technique should be such that a precision of 5 per cent (standard error) can be obtained for directly measured quantities at individual points.** Enough measuring points are required so

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* A device that measures the arc of the sun as seen from any location, at any time of year.

** If ablation rates are low, arrays of stakes will be necessary at each measurement point. The numbers of stakes necessary at each point can be computed from the same statistical test mentioned earlier (Untersteiner, 1961, p.159-160).

that area integrations are also accurate to about 5 per cent, making a total precision of area-averaged quantities of about 9 per cent. This may require from 20 to 50 points (or even more) per basin depending on the roughness of the surface and the spatial dispersion of ice balance quantities. The required number of measurement points will have to be determined by each investigator, and this may have to be done by intuitive judgement. Non-glacierized portions of the drainage basin should have a sample point density equal to the density on the glacier. Sufficient density-depth profiles should be made to ensure that the areal variation in density is accounted for within the required 5 per cent accuracy.

On many glaciers the length of the ablation season will vary markedly with altitude. In this case, the usual stratigraphic system of ice balance measurements (Unesco/IASH, 1970b) yields results which cannot be clearly defined with regard to time. Thus these results cannot be related to heat and water balance results. However, by use of a combined system, the advantages of using natural horizons can be retained and the ice balance results can be directly related in time to other balance quantities. This combined system is described in the Appendix.

The following quantities should be measured and reported:

1. Monthly values of the ice balance, given separately as averages over glacier and whole drainage basin (millimetres of water-equivalent), are recommended.

2. Other ice balance quantities should be reported at end of season only, and given separately as averages over at least 8 intervals of altitude on the glacier only (millimetres of water-equivalent). These include:

a. Net or annual balance

b. Total or annual accumulation (alternatively, maximum or winter balance)

c. Total or annual ablation

3. These values are to be reported at end of season only:

a. Accumulation-area ratio or glacier ratio

b. Area of glacier and perennial snow and ice at end of balance year, and change from year before (km^2)

c. Length of glacier at end of balance year, and change from year before (km or m)

d. Altitude of the equilibrium line

4. Additional ice balance data can be obtained by measuring the ice-flow discharge through a cross-section of a glacier and comparing this with surface ice balance measurements made above or below the cross-section. This experiment is optional.

WATER BALANCE

Water run-off data are the only measurable parameters which are a true integration over the whole area of the drainage basin. Thus these data have a special significance: they can serve as a standard for the evaluation of the other area-sampled ice, water and heat balance results. Every effort should be made to obtain accurate run-off data, continuous in time over periods at least equal to the whole ablation season and preferably for the whole year.

Run-off data should be obtained at a gauging station (limnigraph) that has a relatively stable water level/discharge rating curve. Frequent calibrations (by current meter, salt dilution, or other technique) are necessary even after the rating curve has been established, to verify that no shifting of the rating has occurred.

The measuring procedure should be sufficiently accurate so that daily totals of run-off are measured with a standard error of less than 8 per cent under normal (ice-free) conditions, and monthly or twice monthly totals accurate to 5 per cent. At the beginning of the ablation season when ice and snow may cover the stream every effort should be made, by frequent flow velocity measurement, to reduce the error in daily totals to 10 per cent or less.

Daily values should be reported for as long a period during the year as measurements can be made, and should be given as millimetres averaged over the drainage basin area. In addition, twice monthly and monthly values (also in millimetres) should be tabulated.

In addition to run-off, a water balance computation requires knowledge of evaporation/condensation of water, rainfall, and the change of mass from ice to water (or vice versa). A large number of precipitation gauges, properly located and carefully utilized, together with accurate measurements of ice balance, may permit the estimation of evaporation/condensation. Alternatively, evaporation/condensation might be estimated from heat balance data obtained at the main site. Only by comparing all three balances, with careful attention to error magnitudes, can one obtain a valid and demonstrable description of how the ice mass in a glacier drainage basin changes in response to its external environment.

TOPOGRAPHIC MAP

An accurate, up-to-date topographic map is required in order to properly compile ice balance results and other areally distributed data. Thus it should preferably be compiled by air or terrestrial photogrammetry from pictures taken during the International Hydrological Decade. If the glacier is shrinking or growing markedly during this period, two maps may be required. Maps compiled from plane-table or other ground surveys will suffice if they meet the specific accuracy standards. The whole drainage basin should be mapped. The master copy of the map should be on scale-stable material (not paper).

Map scale and contour interval should be adjusted to the size and slope of the basin. For a basin 3 km in longest dimension, map scales 1:2,500 to 1:5,000 are appropriate, but if the basin is 6 km long, the scale should be

1:5,000 to 1:10,000. Larger scales are, of course, desirable but not necessary. The contour interval should be an even value which is about 1/100 or less of the total relief in the basin.

The accuracy of the map should be such that 90 per cent of the point locations have a horizontal position error less than 5 mm or 1 per cent of the scale, and the scale factor for the map as a whole should be correct to 1 per cent. The accuracy of vertical locations should be such that 90 per cent of the point elevations are correct to within half a contour interval.

3 SPECIAL STATIONS

The purpose of the Special Stations is to derive means of relating simple observations of air temperature, wind speed, etc., to the actual heat flux between atmosphere and snow surface. Accurate measurement of heat flux components is a very difficult and expensive task. These measurements cannot be expected as part of a routine programme at many stations. We hope that standardized observations at many stations can be related to the pertinent atmospheric processes through analysis techniques developed at the few Special Stations. Thus the Special Stations will be entirely research-oriented, and will have to be operated by extremely competent and knowledgeable meteorologists and glaciologists.

Special Stations can exist for heat balance work alone. That is, the area-wide ice balance and water balance measurements stipulated for Standard Stations are not required for Special Stations. However, it is absolutely essential that all Special Stations perform all the measurements listed under 'daily observations at one site' for Standard Stations, for the same period of time, and at the same (or better) levels of precision. Perhaps a Special Station will have to be operated on a site covered only by seasonal snow; that is permissible if the snow lasts sufficiently long into the summer so that useful data are obtained at the height of ablation conditions.

All major components of the heat balance are to be measured, directly or indirectly; incoming and reflected solar radiation, incoming and outgoing long-wave radiation, sensible heat flux from the air and precipitation, latent heat flux, heat flux from below the surface, and the mass (ice and water) flux. The techniques for doing this will be developed by the individual investigators, who also may experiment with empirical or theoretical relations between these measured quantities and the 'index' observations of the Standard Stations. It is hoped that the most modern sensors, such as sonic anemometers for eddy correlation measurements, and modern digitized data reduction systems can be used at some of these Special Stations.

These Special Stations are highly important: they are in fact the cornerstones for the whole programme. Although they will be expensive, the critical role they will play in the success of this major international effort should prove to be ample justification for sufficient funding, and in addition each station should make fundamental new contributions to our knowledge of micro-meteorology and air-snow interactions.

INSTRUMENT CALIBRATION

In order to analyse the data obtained at Standard Stations and to compare results on a hemispheric or global basis, it is necessary to have standard calibrations of instruments and methodology. Appreciable absolute errors cannot be tolerated. This standardization requires an international exchange of calibration data, and preferably on-site visits for national and perhaps international co-ordination and co-operation in devising proper techniques for producing really comparable results. Calibration results should be distributed along with data tabulations and station descriptions.

DATA EXCHANGE

Certain data from all stations will be of interest to all Combined Balance programme investigators on a current basis. These data should be transmitted to World Data Centres A, B, and C (Glaciology); certain summaries of results should also be transmitted to the Permanent Service on Glacier Fluctuations. Modern metric (SI) units are to be used throughout. Three different data reports should be transmitted to the Centres:

a. Station Description. This should be submitted only once unless major revisions are required, at the time of filing the first tabulation of daily values or annual summary. The following information should be given:

1. Name and location of station, principal investigator, sponsoring institute or agency

2. Dimensions (length, area, altitude range) of glacier

3. Dimensions (length, area, altitude range) of drainage basin

4. Major items of instrumentation and location

5. Calibration data on instruments

6. Supplemental or related stations (locations, instruments, frequency of observations).

7. Availability of data

8. Existing publications

b. Tabulation of Daily Values. This should be a table for each month giving daily totals or means of certain heat, ice, and water balance parameters. Most of these readings will be taken at the main site on the glacier. It is suggested that the data be submitted to the Centres as soon after the year of collection as possible. Copies of these standard tables can then be sent to interested investigators on request. It is recognized that these data are tentative, subject to possible revision by the individual investigator, and are not to be published without the express permission of the investigator(s) who collected them. The following daily totals or means are to be reported; results should be separated into daytime and night-time half-days if possible:

1. Global solar radiation and net solar radiation (MJ/m^2), or duration of sunshine (hours)

2. Cloudiness during daylight hours (tenths)

3. Air temperature at main site on glacier (^{o}C)

4. Air temperature at other sites (^{o}C)

5. Snow surface temperature (^{o}C)

6. Nocturnal crust thickness (cm)

7. Wind speed (m/s)

8. Humidity (relative, specific, or dew point)

9. Precipitation as rain (mm)

10. Precipitation as snow (mm of water-equivalent)

11. Ablation (mm of water-equivalent)

12. Run-off

13. Other parameters, such as mean precipitation averaged over drainage basin

c. Annual Summary. This should be a tabulation of monthly or annual values of certain heat, ice and water balance quantities as mentioned in the text above, together with a list of new publications resulting from the project and any revisions in the Station Description.

5 REFERENCES

Hoinkes, H.C. 1964. Glacial meteorology. In: Research in geophysics, vol. 2, Chap. 15, p. 391-424, Hugh Odishaw (Ed), Cambridge, Mass., MIT Press, 595 p.

LaChapelle, E.R. 1959. Errors in ablation measurements from settlement and subsurface melting. Journal of Glaciology, vol. 3, no. 26, p. 458-467.

Untersteiner, N. 1961. On the mass and heat budget of Arctic sea ice. Archiv für Meteorologie, Geophysik, und Bioklimatologie, Ser. A, Bd.12, 2. Ht., p. 151-182.

Unesco/IASH. 1970a. Seasonal snow cover. Paris, Unesco, 38 p. (Technical papers in hydrology, no. 2)

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APPENDIX

A system to combine stratigraphic and annual mass balance systems

Most glacier mass balance data are collected through the use of stakes, pits, cores, or probing to or from a reference horizon. This is normally a summer horizon - either a winter snow/ice interface in the ablation area as measured in spring, or a snow/firn interface in the accumulation area as measured in spring or summer. This interface, termed summer surface, may form at different times of the year in different parts of the world or even on the same glacier.

In a pit or core in the accumulation area, the mass of ice material between two consecutive summer surfaces can be measured. This mass, in Mg/m^2 or metres of water equivalent, may be the balance (the difference between accumulation and ablation) at that point for the time interval between the formation of the two summer surfaces. However, in the percolation or soaked facies an appreciable part of the material deposited in this time interval may have been melted and subsequently redeposited (refrozen) in lower layers, below the lower of the two summer surfaces of interest. Detection of this problem is not easy, and analysis of the resulting balance may be even more difficult. It is assumed that any appreciable mass redeposited below a summer surface of interest can be calculated from repeated depth-density profiles and added to the balance above the summer surface.

A difficult problem in relating mass balance quantities to meteorologic and hydrologic quantities in this Combined Heat, Ice, and Water Balances programme stems from the fact that summer surfaces may form at different times in different places. This means that a simple integration over the glacier of mass balance data related to summer surfaces produces a result that has no clear meaning with respect to time. Thus these data cannot be directly related to heat or mass flux data obtained by other techniques.

Mass balance terms based on observable summer surfaces were proposed by Meier (1962). The stratigraphic system is a modification in terminology of the basic mass balance concepts. This stratigraphic system works well for individual points. However, in order to compare ice balance data with hydrologic (water balance) data, these point values must be integrated over a whole glacier or drainage basin. If, as is usually the case, the summer horizons are not formed synchronously over the whole area this integration is an invalid measure of snow and ice storage. Therefore, a different system, the annual system (fixed-date system), has been conceived to relate glaciological data to hydrological data. Unfortunately, glaciological programmes using only the annual system cannot take advantage of convenient reference horizons in the field, so the field work may be extremely difficult or exorbitantly expensive. These two systems are described in Unesco/IASH (1970b) but no attempt was made to show how they might be combined.

Presented here is a way to combine these two systems into a unified whole. The vital key to a combination of these systems is identification of the material under consideration. This identification is, of course, useful additional information for any description of the meteorological-hydrological environment. Four types of material which may be found on a glacier in one specific year are defined -- snow, old firn and ice, late snow, and new firn -- as follows: The highest (most recent) summer surface found in a pit dug in winter (or early spring) before the beginning of appreciable, continuous melting is termed ss_o. The material above ss_o is termed snow (s) and the material below it is old firn and ice (i). The highest (most recent) summer surface found in a pit in the upper regions of the glacier calendar after the beginning of new snow accumulation following a period of melting in summer is termed ss_1. The material above ss_1 is now termed late snow (ls) and the material below ss_o yet above ss_1 is now termed new firn (f). Superimposed ice formed during the year under consideration is included in snow (s).

The variation in these units of the mass balance may be illustrated by graphs showing the changing balance with time, b(t), at specific points on a glacier, expressed as mass per unit area (Mg/m^2) or simply in water equivalent (m) (Fig. 1). The balance quantities are designated by the letter b with qualifying symbols, as follows: the subscript $_o$ refers to the initial measurements made at or near the beginning of the year to relate fixed-date system measurements to stratigraphic units; the subscript $_1$ refers to the final measurements made at or near the end of the year to relate the two systems; the subscript a refers to certain measurements made (or calculated) exactly at the end of the hydrologic year, and the subscript n refers to measurements related to the minimum firn and ice or the minimum total mass near (but not necessarily at) the end of a hydrologic year; the letter x identifies balance quantities at the time of the maximum total balance in the hydrologic year. Letters in parentheses following the b indicate the material being measured. A lack of parentheses following the b indicates that the total mass (undifferentiated) is considered. The hydrologic year, often defined as 1 October to 30 September, runs from t_o to t_1. Arrows pointing up indicate an addition of mass as time proceeds; the corresponding balance quantities are taken as positive.

Measurements made at specific points can be plotted as curves of balance changes with time (Fig. 1), and the following quantities can be defined:

1. $b_o(s)$, the initial snow balance, is the snow at the beginning of the hydrologic year.

2. $b_o(i)$, the initial ice balance, is the old firn and ice loss after the start of the hydrologic year and before ablation ceases in winter.

3. $b_m(s)$, the measured winter snow balance, is the snow above the summer surface ss_o as measured directly by field work in late spring.

4. $b_1(ls)$, the final late snow balance, is the new snow at the end of the hydrologic year, the same as $b_o(s)$ for the year following.

5. $b_1(i)$, the final ice balance, is the old firn and ice loss after the end of the hydrologic year before ablation ceases for the next winter, the

same as $b_o(i)$ for the year following.

6. $b_n(f)$, the net firnification, is the amount of new firn formed at about the end of the hydrologic year (either just before or just after). It is therefore the mass between the successive surfaces ss_o and ss_1, and is usually measured in pits well after its time of formation.

7. $b_n(i)$, the net ice balance, is the corresponding change in mass between ss_o and ss_1 in the ablation area where this change is negative; thus it records the loss of ice and old firn from the end of one melt season to the end of the next.

8. $b_w(s)$, the maximum snow balance, is the hypothetical maximum mass of the snow during the hydrologic year. This value will occur at a different time at each place and thus will probably not be measured directly.

Mass balance data may next be considered in terms of diagrams showing the area-average balance curve b(t). Alternatively, one could plot the total balance curve B(t) using a different vertical scale of cubic metres instead of metres of water equivalent. In the material to follow, a bar over a symbol indicates an area average, as in Unesco/IASH (1970b).

A plot might be made of b(t) on which are shown the area-averaged values similar to the point values b_w and bn as given in Unesco/IASH 1970b). However, this scheme usually is not workable in practice. This is because the terms b_o, b_w, bn, and b_1 have no relation to the corresponding values measured relative to summer surfaces at the individual points. What is needed is a scheme in which the point data, taken only a limited number of times during a year and usually referenced to summer surfaces, can be combined directly. In order to do this, the summer surfaces must be included in the area-average diagrams. This is done by dividing the balance curve b(t) into its four components: old firn and ice, snow, new firn, and late snow (Fig. 2). The largest mass, old firn and ice, is plotted at the bottom -- it can only decrease or remain constant during any one year. Above it is plotted snow, which increases during the first part of the year; during the last part of the year it decreases due to ablation and is converted to new firn. Towards the end of the year, late snow is deposited on top of a melt surface, causing the snow below that surface to be converted to firn. The amount of new firn after all the snow is eliminated and/or converted remains relatively constant. The interface between (snow plus new firn) and (old firn and ice) is summer surface ss_o. The interface between new firn and late snow is summer surface ss_1. The interface between snow and new firn is shown as a jagged line; it has little physical significance.

The point data taken at specific times during the field season (or determined after-the-fact) can now be averaged over the glacier and shown on the area-average balance diagram (Fig. 2). Now a large number of balance terms can be precisely defined. One important quantity is the annual balance b_a. Another important balance quantity is the difference between old firn and ice melt, $b_n(i)$, the net ice balance, and snow which lasts through the melt season and is preserved as new firn, $b_n(f)$, the net firnification. This difference is here called the firn and ice net balance $b_n(fi)$. This is in fact the quantity most often reported by glaciologists as 'net balance' but is not the area-average net balance b_n indicated in Unesco/IASH (1970b).

The terms b_w (winter balance) and b_n (here termed the total mass net balance are analogous to the stratigraphic system point terms b_w and b_n in Unesco/IASH (1970b). The time interval t_o' to t_1' is a balance year which is unique to each glacier and each year, and is not necessarily 365 days long. Also included in this figure are the new terms b_x, the maximum balance, and $b_w(s)$, the maximum winter snow balance (of the hydrologic year). In order to relate b_n to b_a or vice versa, two additional terms are proposed: b_o, the initial balance increment, and b_1, the final balance increment.

On some glaciers, all the snow is normally converted to firn before the end of the hydrologic year, and it is convenient to measure firn and ice balances at this time. Therefore three additional terms are defined: the annual firnification $b_a(f)$, the annual ice balance $b_a(i)$, and the firn and ice annual balance $b_a(fi)$ (Fig. 2). These units are analogous to $b_n(f)$, $b_n(i)$, and $b_n(fi)$, respectively.

Other area-averaged terms shown on Fig 2, exactly equivalent to the corresponding values shown on Figure 1, are $b_o(s)$, the initial snow balance; $b_o(i)$, the initial ice balance; $b_1(ls)$, the final late snow balance; $b_1(i)$, the final ice balance; and $b_m(s)$, the measured winter snow balance.

The annual balance, b_a, is an important quantity because it represents the total change in storage (of snow, firn, and ice) during a hydrologic year. Thus this value can be compared directly with the difference between precipitation as snow and meltwater run-off, if net evaporation/condensation and net changes in liquid water storage are negligible. b_a can be measured directly, or computed as b_a = $b_a(f)$ & $b_a(i)$ - $b_o(s)$ & $b_1(ls)$ if $b_a(f)$ is definable. The annual balance can also be calculated, more indirectly, from balance year (stratigraphic system) quantities as b_a = - $b_o(s)$ & $b_o(i)$ & $b_n(i)$ & $b_n(f)$ - $b_1(i)$ & $b_1(ls)$.

It is important to define the maximum winter snow balance $b_w(s)$ on the glacier during the year, because it is often impossible to measure the actual winter snow accumulation. The term $b_m(s)$, a measured but lower value at about the right time of year, can often be used as a basis for computing $b_w(s)$ if sufficient supplementary meteorological data are available. The same statement can be made about b_w and b_x. Although b_w and b_x occur at the same instant in time, $b_w(s)$ can occur at a later date. Note that b_x & b_o = b_w. Normally, only one or two of these four balance quantities ($b_w(s)$, b_w, b_x, or $b_m(s)$) would be reported. It must be stressed that none of these can be calculated by averaging point values of b_w (winter balance) because the balance reaches a maximum at different times at the different points.

These terms are listed and defined in Table I.

The apparent complexity of this scheme is somewhat misleading; only about half of these terms would be reported in any given study. All terms are shown on one diagram in order to make precise distinctions between quantities measured or reported. At many glaciers, some of the correction terms, such as b_o, $b_o(s)$, $b_1(s)$, $b_1(ls)$ and $b_o(i)$, will be zero or small, and if so can be neglected to simplify the calculations.

This scheme, although appearing somewhat cumbersome, gives the author a code for expressing whichever units he prefers in exact, definable and comparable terms.

Table I. -- Combined mass balance terms

Symbol	Name of term	Explanation
Stratigraphic system		
$b_m(s)$	Measured winter snow balance	Balance measured to the summer surface (ss_o) in late winter or spring, measured in pits, cores, and by probing.
$b_w(s)$	Maximum winter snow balance	Maximum of snow mass during the balance year, computed from graph of $b_s(t)$ or graphs of $b(t)$ and $b_i(t)$ before and after time of $b_m(s)$.
b_w	Winter balance	Maximum value of the balance in relation to balance at t_o'; amplitude of mass change during the balance year. Computed from changes in $b(t)$ before and after time of $b_m(s)$.
$b_n(f)$	Net firnification	The increment of new firn in the accumulation area, as measured after ablation ceases in autumn in pits or cores. Date ablation ceased indicated under value.
$b_n(i)$	Net ice balance	Old firn and ice melt in the ablation area of a single melt season, measured with stakes once during period when ice is covered by snow and again after ablation ceases.
$b_n(fi)$	Firn and ice net balance	Change in mass of firn and ice during a single melt season; the mass between two consecutive summer surfaces. $b_n(fi) = b_n(f) \& b_n(i)$.
b_n	Total mass net balance	Change in snow, firn, and ice storage between times of minimum mass; net change in mass during one balance year. $b_n = b_o - b_1 \& b_a$.
Terms relating annual and stratigraphic systems		
b_o	Initial balance increment	Change in balance between first time of minimum balance (t_o') and t_o; computed from graph of $b(t)$.
$b_o(s)$	Initial snow balance	Snow accumulated on summer surface (ss_o), measured at t_o with pits or cores.
$b_o(i)$	Initial ice balance	Old firn and ice melt in the ablation area after t_o and before melt begins the following spring, measured by ablation stakes at t_o and during period when ice is covered by snow.
b_1	Final balance increment	Change in balance between time of minimum mass (t_1') and the end of the hydrologic year (t_1), computed from graph of $b(t)$.
$b_1(ls)$	Final late snow balance	Snow accumulated on summer surface (ss_1), measured at t_1 with pits or cores.
$b_1(i)$	Final ice balance	Old firn and ice melt in the ablation area after t_1 and before melt begins the next spring, measured by ablation stakes at t_1 and during period when ice is covered by snow.

Symbol	Name of term	Explanation
Annual	(fixed-date system)	
b_x	Maximum balance	Maximum value of the balance in relation to balance at t_o; amplitude of mass change during hydrologic year. Occurs at same time as b_w. $b_x = b_w - b_o$.
$b_a(f)$	Annual firnif-ication	The new firn formed on the glacier during the hydrologic year, measured at t_1 in pits or cores. Not definable if snow melt continues after t_1.
$b_a(i)$	Annual ice balance	Old firn and ice melt in the ablation area during the hydrologic year, measured by stakes at t_o and t_1.
$b_a(fi)$	Firn and ice annual balance	The change in mass of firn and ice during the hydrologic year from t_o to t_1, also the mass between two consecutive summer surfaces at t_1. $b_a(fi) = b_a(f)$ & $b_a(i)$.
b_a	Annual balance	Change in snow, firn, and ice storage between t_o and t_1; approximately the difference between precipitation as snow and meltwater run-off for one hydrologic year. Can be measured directly at t_o and t_1. $b_a = b_a(fi) - b_o(s)$ & $b_1(ls)$ if $b_a(fi)$ is defined.

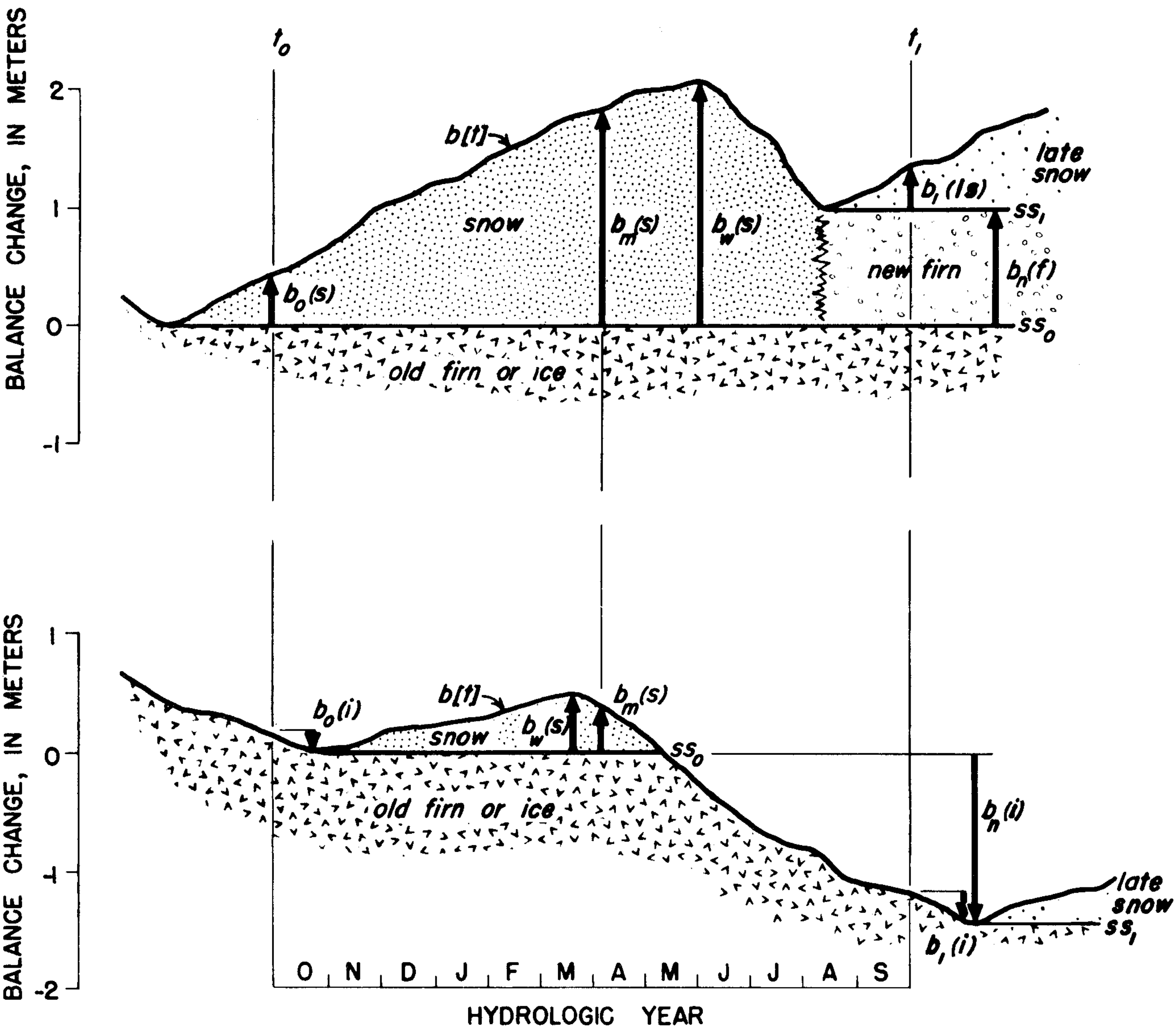

Figure 1.-- Balance quantities measured at a typical point in an accumulation area (above) and at a typical point in an ablation area (below). Vertical scale is metres of water-equivalent with an arbitrary zero.

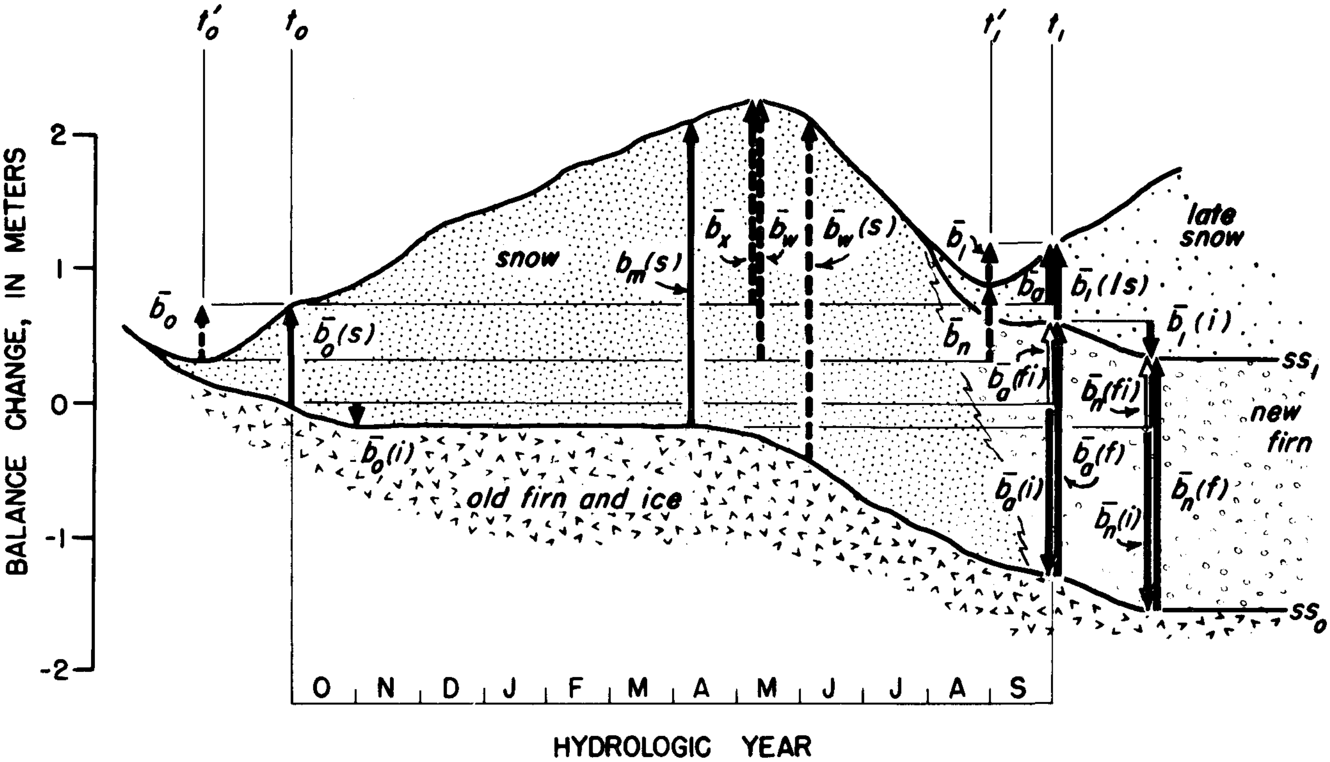

Figure 2. -- Area-averaged balances. All balance terms are shown on one diagram for reference purposes. No one programme should expect to report all these possible terms, but only those selected as most relevant to the particular environment and observational scheme. Conveniently measurable quantities shown with solid arrows, quantities derived from knowledge of the area-averaged balance curve b(t) shown with dashed arrows, calculated quantities shown with open arrows. Vertical scale is metres of water-equivalent with an arbitrary zero.