

MASS-BALANCE TERMS

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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 concensus as is possible at this time.

It is necessary to specify the kind of mass (ice only, or ice+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. *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 usually observed at selected points, and areal 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 sub-surface accumulation and ablation must be included. The refreezing of melt water below the surface may be especially important in sub-polar glaciers, and temperature measurements ought to be made down to sufficient depth. If sub-surface deposition is suspected but only surface measurements are made, then this must be clearly stated.

Two time systems of measurement can be used, the *stratigraphic system* and 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 $^{18}\text{O}/^{16}\text{O}$ ratio (indicating a maximum in the temperature of snow condensation in the atmosphere) or other isotopic evidence, a prominent depth-hoar or low-density layer, or by other criteria. On high-polar plateaus, 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. Millimetres are normally used, except in very high precipitation areas where metres may be more logical. Alternatively, values can be given as weight per unit area (grammes per square centimetre or megagrammes per square metre). The metric system must be used; the *Système International* (SI) is recommended. These point values are measured in a vertical direction, so that they can be projected on a horizontal area.

1. *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, diagram I). 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, 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 $e_t = c_t - a_t$.

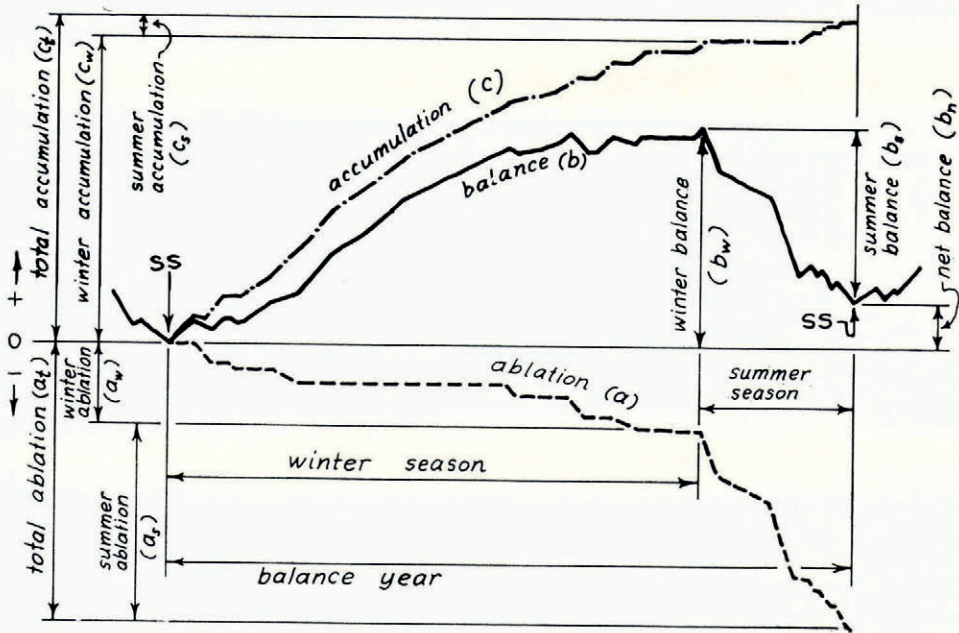
2. *The fixed-date system*

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, diagram II), 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.

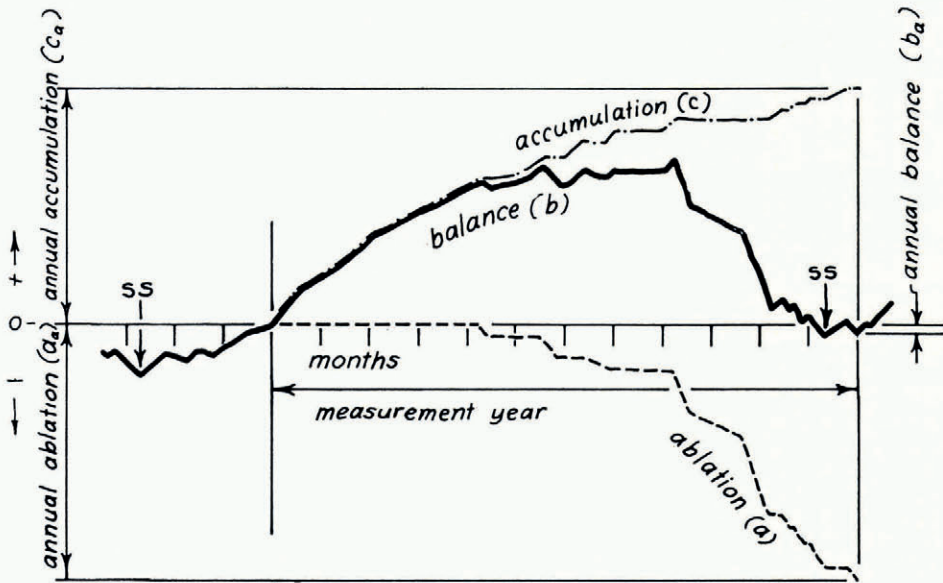
The total values of accumulation and ablation at the end of the measurement year are termed *annual accumulation* (c_a) and *annual ablation* (a_a). The algebraic sum is termed the *annual balance* (b_a) ($b_a = c_a + a_a$). The *annual exchange* (e_a) is given by $e_a = c_a - a_a$.

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.



I



SS : time of formation of a summer surface³

II

Fig. 1. Mass-balance terms as measured at a point on a glacier or ice cap.

1. *The 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 sum be assigned to definite points in time.

2. *The 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 THE STRATIGRAPHIC AND FIXED-DATE SYSTEMS

The accumulation, ablation, and balance *curves* for a point are identical regardless 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 values.

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 year is the *annual equilibrium line*. The ratio of area above the equilibrium line (the *accumulation area* (S_c)) to the total area (accumulation area (S_c) plus *ablation area* (S_a)) is called the *accumulation area ratio* (AAR).

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

A boundary between snow 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*.* The firn line will approximately coincide with the equilibrium line on temperate glaciers only.

* 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.

Mean values, taken over selected areas, 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 (1) material, (2) area of investigation, or (3) 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 (sub-surface) accumulation at a point as $c_t(e)$. So many combinations are possible that no standardization of specific symbols will be attempted here.