Glossary of glacier mass balance and related terms

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GLOSSARY
OF GLACIER MASS
BALANCE
AND RELATED TERMS
Stake for the measurement of accumulation on Vestfonna, Svalbard (Marco Möller). Note recently dislodged rime, and glaciation of vapour in wave crests in middle troposphere.
Foreword

This glossary, produced by a Working Group of the International Association of Cryospheric Sciences (IACS), is the first comprehensive update of glacier mass-balance terms for more than 40 years. The mass balance of a glacier is a measure of the change in mass of the glacier, or part of it, over a period of time. Mass-balance data help to explain why a particular glacier system may be advancing or retreating and what climate drivers (e.g. decreased snow accumulation; increased surface melt) are responsible for the changes. Fluctuations of the size (most typically length, but also area and/or surface elevation) are observed for several thousand of the well over 100,000 glaciers distributed globally from equatorial mountains to polar ice sheets. However regular annual mass-balance measurements are made on fewer than 200 glaciers. Mass-balance information is essential for defining the links between past, present and future climate changes and changes to glaciers in assessments such as those made by the Intergovernmental Panel on Climate Change (IPCC). Having a systematic, concise and unambiguous mass-balance terminology is a critical part of this.

The first systematic attempts to define mass-balance terminology (UNESCO/IASH, 1970; Anonymous, 1969) were made during the United Nations Educational, Scientific and Cultural Organization (UNESCO) International Hydrological Decade (IHD, 1965-1974). The IHD programme provided an important impetus to international collaboration in hydrology and, in 1975, was succeeded by the UNESCO International Hydrological Programme (IHP). IHP has an emphasis on methodologies for hydrological studies, training and education in the water sciences and on the adaptation of the hydrological sciences to cope with the expected changing climate and environmental conditions. It is hence fitting that this glossary is published as part of the IHP series of Technical Documents in Hydrology.

This publication is also a crucial early milestone in the work of the International Association of Cryospheric Sciences. IACS is the eighth and newest Association of the International Union of Geodesy and Geophysics (IUGG). Although it has precedents reaching back to the 1894 International Commission on Glaciers, IACS only became a full IUGG Association in 2007. This volume is the first work conceived and completed during the period that IACS has been a full Association. IACS is grateful to the International Hydrological Programme of UNESCO for providing the opportunity to publish the glossary as the second volume in a joint series.

The mass-balance definitions and terminologies documented during the IHD have served well for more than 40 years. There are however some ambiguities in current usage, and new technologies (e.g. space-borne altimeters and gravimeters, ground penetrating radars, etc.) are now used for mass-balance measurements, particularly of ice sheets. This new glossary addresses these, promotes clarity, and provides a range of useful ancillary material.

IACS, and the glaciological community as a whole, is very grateful to the Chair of the Working Group, Graham Cogley, and his dedicated team of volunteers for producing this volume. It is intended that the Working Group will continue to serve and to produce further reference publications on topics such as mass-balance measurement techniques and guidelines for reporting measurement uncertainty.

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January 2011
Acknowledgements

The Working Group is very grateful to Garry Clarke, Charles Fierz, Andrew Fountain, Will Harrison, Jo Jacka and Tomas Jóhannesson for careful reviews of the entire Glossary which led to substantial improvements. We also owe a great debt to those colleagues who have commented on the Glossary in whole or in part: Liss Andreassen and colleagues at Norges Vassdrags og Elektrisitetsvesen, Dave Bahr, Andrey Glazovskiy, Barry Goodison, Jon Ove Hagen, Matthias Huss, Wilfried Haeberli and Vladimir Konovalov.

Many thanks also go to colleagues who have assisted in the compilation of the Glossary by discussing mass balance in general and advising on points of detail: Jason Amundsen, Richard Armstrong, Ed Bueler, Howard Conway, Hajo Eicken, Charles Fierz, Ralf Greve, Hilmar Gudmundsson, Jeff Kargel, Ian Joughin, Doug MacAyeal, Roman Motyka, Simon Ommmanney, Tad Pfeffer, Bruce Raup, Gina Schmalzl, Ben Smith, Sergey Sokratov, Martin Truffer, Ed Waddington, Mauro Werder and Dale Winebrenner.

Ken Moxham of the International Glaciological Society gave valuable advice about style. Eric Leinberger helped greatly by producing a professional-looking Figure 2 from our hand-drawn drafts. Sam Herreid generated the index.

The advice of the colleagues named above, and possibly of others whose names we have inadvertently omitted, has improved the Glossary in ways that are many and substantial, and has brought it closer to the ideal of a community-wide consensus than would otherwise have been possible. Nevertheless we owe it to our advisors to note that the Working Group has not been able to agree with them on all points, and that any remaining mistakes are our own fault.

We appreciate very much the willingness of UNESCO, through its International Hydrological Programme (IHP), to publish the Glossary of Glacier Mass Balance and Related Terms in its series Technical Documents in Hydrology and as IACS Contribution No. 2. Siegfried Demuth, chief of the IHP section on Hydrological Processes and Climate, and Vincent Leogardo of the IHP Secretariat, have been extremely helpful in seeing the Glossary through the process of publication.

Last but not least, we are grateful to the Bureau of the International Association of Cryospheric Sciences (IACS) for its steady and enthusiastic support of the Working Group and the Glossary.
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1 Introduction

The aim of this *Glossary of Glacier Mass Balance and Related Terms* is to update and revise what has long been the effective standard of mass-balance terminology (Anonymous 1969). Although Anonymous (1969) has served glaciology well for 40 years, there is widespread agreement on the need for a new look at terminology. The new Glossary reflects changes in practice with conventional measurement tools, and also in what is possible with the wide range of new tools which were not available in the 1960s, in particular those now available for the measurement of ice-sheet mass balance. The Glossary includes commentary on usage, particularly problematic usage, with recommendations where appropriate.

Similar publications have appeared in the past. Armstrong et al. (1973) focus strongly on sea ice. Kotlyakov and Smolyarova (1990) is a valuable multi-lingual source but does not cover mass balance as intensively as mass-balance specialists might wish. Nor does the Russian-language dictionary of Kotlyakov (1984). Glaciers Online (undated) is a valuable source for glaciological terms in general, with excellent illustrations. In neighbouring fields, American Meteorological Society (2000), European Avalanche Services (2009) and Canadian Avalanche Association (undated), Fierz et al. (2009), National Snow and Ice Data Center (undated), PhysicalGeography.net (undated), UNESCO (undated) and van Everdingen (2005) are all valuable tools. None of these, however, offers the scope or the kind of detail envisaged for this Glossary.

The scope of the Glossary extends beyond the measurement of mass balance. There are articles covering such subjects as glacier zonation; the definition of glacier features and morphological types of glaciers; the administrative structures within which mass-balance data are archived once collected; and the modelling of mass balance. We have also included some terms that are mainly of historical interest, and some technical terms from other disciplines that appear in reports of mass-balance measurements by newer methods.

The purpose of the Glossary is not to impose awkward constraints on the evolution of glaciological usage, but rather to promote clarity and reduce ambiguity in the communication of information about glacier mass balance, as well as to provide a range of useful ancillary material. The Glossary represents a consensus among a group of practising glaciologists.

We have tried to steer a middle course between being prescriptive, that is, laying down the law about how terms are to be used, and being descriptive, that is, simply recording the facts of current usage. For example we take a firm position on the meanings of “area” and “Julian day number”. The first is sometimes and the second often used in a way which is mistaken. Neither mistake is helpful, the first being harmful, and we think that both ought to be corrected. On the other hand, we accept that a number of technical terms have more than one meaning or sense, and simply record the variants. Examples include “snow” and “firm”. An example of a pair of terms requiring clear understanding, rather than prescriptive or descriptive definitions, is “internal accumulation” and “refreezing”, where we explain the difference of meaning and recommend that it be observed carefully.
2 History

The first measurements of mass balance were made as early as 1874 on Rhonegletscher, Switzerland. Chen and Funk (1990) were able to recover the measurements of annual mass balance for 1884–85 to 1908–09 from the earlier literature (e.g. Mercanton 1916). Unbroken series of measurements at two sites on Claridenfirn, Switzerland, began in 1914 and continue today. Ahlmann (1935, 1939) was a pioneer in the use of what are now regarded as “traditional” mass-balance methods. The longest continuous, modern series of annual measurements of glacier-wide mass balance was begun on the Swedish glacier Storglaciären in 1945–1946, followed by measurements on Taku Glacier in southeastern Alaska, Storbreen in Norway, and a growing number of glaciers in the Alps, western North America and other glacierized regions. As more measurement programs were initiated, it became clear that a uniform approach, as to both methods and terminology, was needed if comparisons were to be accurate and meaningful.

Widely used methods of “traditional” measurement are presented by Østrem and Brugman (1991), which evolved from Østrem and Stanley (1966, 1969), and also by Kaser et al. (2003). Hubbard and Glasser (2005) describe glaciological field methods more generally.

An early proposal for uniform usage in the study of mass balance came from Meier (1962). The terms and the organizing framework of that paper provoked considerable interest and discussion, and evolved into a consensus which was published as UNESCO/IASH (1970), although the source most often cited is Anonymous (1969), a digest of the UNESCO/IASH recommendations which appeared in the Journal of Glaciology. Some supplementary material, discussed below, appeared as UNESCO/IASH (1973). Anonymous (1969), while having no formal status, soon became the de-facto standard for the presentation of mass-balance data.

Anonymous (1969) has been a living, evolving standard over the past four decades. A notable early development appeared in the appendix of UNESCO/IASH (1973), and also as the paper by Mayo et al. (1972). This was a method for combining the stratigraphic and fixed-date “time systems” of Anonymous (1969). The fixed-date system was referred to as the annual system by Mayo et al., who introduced an extensive set of new definitions. Most of these were not adopted, and the main practical result of Mayo et al.’s work was that there are now not two but four recognized time systems, the combined system and the floating-date system being added to the original two.

Today, annual mass balance is measured each year on more than 100 glaciers, and seasonal balances on up to about 40 of those. These measurements are part of an integrated monitoring strategy, described in the Glossary (see Global Terrestrial Network for Glaciers). The data are submitted, according to specific guidelines (WGMS 2007b), to the World Glacier Monitoring Service in Zürich, which publishes regular summaries (e.g. WGMS 2007a, 2008a) of the results of mass-balance and other glaciological measurements. A recent survey of available datasets is in WGMS (2008b). The organizational history of mass-balance data management is covered by Radok (1997) and Jones (2008).

Among the important methodological developments of the past 20 years, the emergence of accurate techniques for measurement of the mass balance of ice sheets is particularly notable. The Working Group has made a special effort to cover the terminology of this subject. However, some of the techniques are still emerging (ISMASS Committee 2004), and the time may not be ripe for the specification of guidelines, still less of standards. On the other hand, it is preferable that usage be agreed upon before the terminology becomes fixed in inconsistent and ambiguous ways. Another development is that remotely sensed measurements of mass balance, particularly by geodetic methods, are now a reality. They can be expected to grow in importance, and we have compiled the Glossary with this likelihood in mind, as well as with an eye to the desirability of a common language for the study of glaciers of all sizes (including the ice sheets).

The Bureau of the International Association of Cryospheric Sciences (IACS) approved in principle the creation of a Working Group on Mass-balance Terminology and Methods at its meeting in Perugia in July 2007. The membership of the Working Group was recruited by announcing an invitation to volunteer at the Workshop on Mass-balance Measurements and Modelling held in March 2008 in
Skeikampen, Norway. The Working Group was constituted formally at the April 2008 IACS Bureau meeting in Vienna.

The Working Group’s activities are organized in terms of a number of themes. Future publications are intended to address subjects such as methods of measurement, guidelines for the reporting of measurement uncertainty, and access to mass-balance data. The present publication, however, is devoted to definitions and terminology.

3 Mass-balance Terminology

3.1 Sign convention
Studies of mass balance are usually not strongly tied to a two- or three-dimensional coordinate frame, especially when the glacier is one in a collection of “boxes” or “control volumes”. In such cases the most common sign convention is “positive inward”, meaning that flows across the boundary of the box are positive when the box gains, and negative when it loses, some of the flowing quantity. This is the main sign convention adopted in this Glossary. Accumulation is positive, ablation is negative, and balance calculations for the glacier require only additions, but exchanges with other boxes must be managed carefully. After leaving one box, such as a glacier, the sign of the flux must be changed before it enters any other box, such as the ocean.

The main alternative sign convention is that fluxes are positive in the positive coordinate direction. In many systems, a framework of orthogonal coordinates is an obvious way to describe space. This requires careful attention to plus signs and minus signs in algebraic descriptions of the balance of any part of the system. This sign convention is commonly used for glacier flow. For example, one horizontal coordinate may be oriented so that it increases in the downslope (often the downvalley) direction. Then the downslope horizontal component of the velocity vector is positive, and the flux divergence is positive where the flow accelerates and negative where it decelerates.

Whatever sign convention is adopted, reports of mass-balance investigations should state it clearly and use it consistently.

3.2 Notation
It is not possible to standardize all the uses of symbols in mass-balance work, but certain conventions are universally or at least very widely observed. The conventions described here differ from those of Anonymous (1969) in a number of respects.

3.2.1 Variables
The variables that appear most often in mass-balance studies are denoted as follows:

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>ablation</td>
</tr>
<tr>
<td>c</td>
<td>accumulation</td>
</tr>
<tr>
<td>b</td>
<td>mass balance (c+a)</td>
</tr>
<tr>
<td>ρ</td>
<td>density</td>
</tr>
<tr>
<td>h</td>
<td>glacier thickness</td>
</tr>
<tr>
<td>S</td>
<td>area</td>
</tr>
<tr>
<td>V</td>
<td>volume</td>
</tr>
<tr>
<td>AAR</td>
<td>accumulation-area ratio</td>
</tr>
<tr>
<td>ELA</td>
<td>equilibrium-line altitude</td>
</tr>
</tbody>
</table>

The use of $h$ for thickness (a vertical extent) promotes clarity by allowing the symbol $z$ to be reserved for elevations (that is, vertical coordinates). In algebraic expressions, AAR and ELA can be replaced by suitable mnemonic symbols, for example $a$ or $z_{eq}$.

Calving, a form of ablation, often requires a separate symbol. The Working Group suggests that calving be represented as a horizontal flux $\dot{d}$ or $\dot{D}$ (see section 3.2.4 for the significance of the overdot). The letter chosen suggests “detachment” rather than discharge. It should be understood that ice discharge at the calving front and calving itself are only equal at a calving front that neither advances nor retreats (see Formulations of Mass Balance, and also Capitalization, below).
3.2.2 Subscripts
Subscripts are used, among other purposes, for representing parts of the mass-balance year or of the column through the glacier:

<table>
<thead>
<tr>
<th>a</th>
<th>w</th>
<th>s</th>
<th>sfc or s</th>
<th>i</th>
<th>b</th>
<th>f</th>
</tr>
</thead>
<tbody>
<tr>
<td>annual</td>
<td>winter</td>
<td>summer</td>
<td>surface</td>
<td>internal</td>
<td>bed or basal</td>
<td>frontal</td>
</tr>
</tbody>
</table>

The absence of a subscript normally implies “annual”. The subscript n for “net” appears frequently in the literature; see the article *Net mass balance*. If the glacier has a floating portion, subscript g can be used when it is necessary to distinguish the grounding line from the front. Subscripts w and i are also used with density to distinguish water from ice.

3.2.3 Capitalization
In the absence of an overriding reason for contrary usage, which should be explained, lower-case symbols refer to quantities at a point on the glacier surface or to the column beneath such a point, and upper-case symbols refer to glacier-wide quantities. By analogy, quantities at points on the glacier outline and along the entire outline may also be distinguished by lower-case and upper-case symbols respectively.

3.2.4 Overdots
In studies of mass balance, the function of the overdot is to denote a derivative, usually a partial derivative, with respect to time. That is, if \( x \) is any variable, \( \dot{x} = \frac{\partial x}{\partial t} \). The overdot signifies that the variable is being expressed as a rate rather than as the equivalent *cumulative* sum, a distinction which is often needed for mass balance because measurements tend to be irregular in duration. There is no implication, as for example in some dynamical studies (Hutter 1983), that the derivative in question is a material derivative within a small volume following the flow (sometimes represented as \( D x / D t = \nabla x / \partial t + \vec{u} \cdot \nabla x \), where \( \vec{u} \) is the velocity vector and \( \nabla x \) is the spatial gradient of \( x \)).

3.2.5 Extensions
The Working Group recommends that extensions of the notation presented here should follow Anonymous (1969), in which further qualifications are added in parentheses after basic symbols. For example \( \dot{\omega}_{b(t)} \) and \( \dot{\omega}_{b(g)} \) could be defined to be basal ablation rates beneath floating and grounded portions respectively of the glacier, while surface accumulation as snow and as superimposed ice might be represented as \( \omega_{sfc(sn)} \) and \( \omega_{sfc(si)} \) respectively.

## 4 Formulations of Mass Balance

For convenience, although at the cost of some repetition, we present here a description of the term *mass balance*, which we define as the change of the mass of the glacier, or part of the glacier, over a stated span of time. The meaning of “mass balance” depends on the volume within which the mass is changing and on the span of time.

A fundamental question about mass balance is A) whether its dimension is [M] (mass) or [L^3] (volume). There are two possible answers, both internally consistent. The matter is complicated, however, by the need to answer two further questions: B) whether to treat the balance as a sum (dimension [M], for example) or a rate (dimension [M T^{-1}]), or in other words whether to divide the change of mass by the span of time; and C) whether to express the balance as a *glacier-wide* total (dimension [M]) or a *specific* quantity (that is, per unit of glacier *area*; dimension [M L^{-2}]). In this chapter we choose to take mass as the fundamental dimension, and we explain the different ways in
which questions B and C can be answered. The recommendations of the Working Group on question A are set out in section 6.2.

Figure 1. The mass balance of a column of glacier ice, firn and snow. In general, density \( \rho \) varies through the thickness \( h = m / \bar{\rho} \); \( h \) may vary due to changes in either mass \( m \) or average density \( \bar{\rho} \).

4.1 Mass balance of a column

We begin with an expression for the conservation of mass within a column of square cross section extending in the vertical direction through the glacier and having mass \( m \) (expressed here per unit of cross-sectional area; Figure 1). The horizontal dimensions of the column, \( ds = dx \, dy \), are fixed. The mass may change due to the addition or removal of mass either at the surface (that is, to or from a layer the base of which is the summer surface), or within the column (referred to as internal accumulation or internal ablation), or at the bed, or to the flow of ice into or out of the column. The mass-balance rate of the column, in specific units (dimension \([M \, L^{-2} \, T^{-1}]\); see section 7.1.1), is

\[
m = \dot{c}_{\text{sfc}} + \dot{a}_{\text{sfc}} + \dot{c}_i + \dot{a}_i + \dot{c}_b + \dot{a}_b + (q_{\text{in}} + q_{\text{out}}) / ds
\]

Equation (1) obeys the positive-inwards sign convention (section 3.1). In particular, if \( \bar{u} \) is the vertically-averaged horizontal velocity vector, \( q_{\text{in}} \) and \( q_{\text{out}} \) are of the form \( \bar{\rho} \bar{u} \, h \, dy \), but \( q_{\text{out}} \) is negative.

Equation (1) is more useful as a checklist than as a guide to how to measure the mass balance. It is not practicable to measure all of its components. Those that are not measured are usually, in practice, either corrected for or assumed (or sometimes shown) to be negligible. For example it may be assumed that internal accumulation \( c_i \) is zero because the glacier is a temperate glacier; or basal ablation \( a_b \) may be identified as critical for estimation by modelling because the column is afloat or is in the crater of an active volcano.
For brevity, in what follows the column-average density \( \bar{\rho} \) is held constant with respect to \( t \). Errors can be substantial if this assumption is wrong; see Sorge's law in the Glossary.

A special case of (1) is the well-known continuity equation

\[
\dot{h} = \dot{b} - \nabla \cdot \vec{q},
\]

in which, because the average density is constant, changes in \( h \) are due only to changes in mass. Each of the terms in (2) is expressed in ice-equivalent units (dimension [L T\(^{-1}\)]). Thus \( \dot{b} \) is equal to \((\dot{\epsilon}_{\text{flc}} + \dot{\alpha}_{\text{flc}} + \dot{\epsilon}_i + \dot{\alpha}_i + \dot{\epsilon}_b + \dot{\alpha}_b)\) divided by \( \bar{\rho} \). The two flow terms on the right in (1) are replaced by the representation of the flux divergence that is usual in dynamics. The flow vector \( \vec{q} \) is equal to \( h \vec{u} \), where \( \vec{u} \) is the vertically-averaged ice velocity, and obeys the same sign convention (positive in positive coordinate directions) as \( \vec{u} \).

4.2 Climatic mass balance and climatic-basal mass balance

In studies of glacier dynamics, the term \( b \) in (2) is often called the “mass balance”, or more appropriately the “mass-balance rate”. In this interpretation, “mass balance” excludes mass changes due to ice flow, which is not consistent with the more general definition of (1). To resolve this ambiguity, we introduce climatic-basal mass balance as an appropriate new name for the \( \dot{b} \) that appears in the continuity equation (equation 2). This terminology makes it clear that \( \dot{b} \) represents mass changes at and near the surface, which are driven primarily by climate, and those at the bed, but not those due to flow dynamics.

Sometimes, with the aim of emphasizing this distinction, \( \dot{b} \) is called the “surface mass balance”. The surface mass balance is the sum of surface accumulation and surface ablation, so this usage is accurate if the internal and basal terms in (1) are negligible. However an ambiguity arises because, in some recent studies, the meaning of “surface mass balance” has been extended so that it also includes internal accumulation. To avoid confusion the latter usage is better avoided, and instead we recommend the term climatic mass balance for the sum of the surface mass balance and the internal mass balance.

4.3 Mass-balance components

By the convention of section 3.2.3, the lower-case symbols in (1) denote components of the point mass balance. Table 1 introduces the equivalent upper-case symbols for the glacier-wide mass balance, which is derived in the next section. It is also convenient to introduce here the simple distinction between the mass-balance rate, in terms of which the formulations above have been cast, and the mass balance, which is a mass change rather than a rate. For example the point mass balance \( \Delta m \) for the span of time from \( t_0 \) to \( t_1 \) is linked to the mass-balance rate by

\[
\int_{t_0}^{t_1} \dot{m}(t) \, dt = m(t_1) - m(t_0) = \Delta m
\]

Whether to present the balance as a rate or not will depend on the context of the investigation.

The mass change relative to time \( t_0 \), considered as a function of time \( m(t) - m(t_0) \), is referred to as the cumulative mass balance (see also Figure 5).

The mass-balance components in Table 1 are defined in the Glossary. The symbols in the table are for the glacier-wide mass balance; the corresponding lower-case letters denote the mass balance of a column (the point mass balance). Except for the mass balance itself, for which \( \dot{M} \) and \( \Delta M \) are recommended, symbols for the mass-balance rate are the same as for the corresponding mass-balance component but with an overdot. In measurements of the mass balance, and often in models of its short-term evolution, the mass of the glacier is neither known nor needed. However the symbol \( M \) for total glacier mass is likely to be in increasing demand in studies of the long-term future of glaciers.
4.4 Glacier-wide mass balance

In what follows, the glacier-wide mass balance is expressed in specific units and as a rate, and the area $S$ of the glacier is taken implicitly to be a function of time. Alternative but equivalent formulations are illustrated in section 4.4.1, and Figure 2 illustrates the processes that may contribute to the glacier-wide mass balance.

Table 1  Recommended notation for components of the mass balance

<table>
<thead>
<tr>
<th>Component</th>
<th>Symbols</th>
<th>Constituents</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface accumulation</td>
<td>$C_{sfc}$</td>
<td>$C_{sfc}$</td>
</tr>
<tr>
<td>Surface ablation</td>
<td>$A_{sfc}$</td>
<td>$A_{sfc}$</td>
</tr>
<tr>
<td>Surface balance</td>
<td>$B_{sfc}$</td>
<td>$C_{sfc} + A_{sfc}$</td>
</tr>
<tr>
<td>Internal accumulation</td>
<td>$C_i$</td>
<td>$C_i$</td>
</tr>
<tr>
<td>Internal ablation</td>
<td>$A_i$</td>
<td>$A_i$</td>
</tr>
<tr>
<td>Internal balance</td>
<td>$B_i$</td>
<td>$C_i + A_i$</td>
</tr>
<tr>
<td>Basal accumulation</td>
<td>$C_b$</td>
<td>$C_b$</td>
</tr>
<tr>
<td>Basal ablation</td>
<td>$A_b$</td>
<td>$A_b$</td>
</tr>
<tr>
<td>Basal balance</td>
<td>$B_b$</td>
<td>$C_b + A_b$</td>
</tr>
<tr>
<td>Climatic balance</td>
<td>$B_{clim}$</td>
<td>$B_{sfc} + B_i$</td>
</tr>
<tr>
<td>Climatic-basal balance</td>
<td>$B$</td>
<td>$B_{clim} + B_b$</td>
</tr>
<tr>
<td>Calving</td>
<td>$D$</td>
<td></td>
</tr>
<tr>
<td>Subaerial frontal melting and sublimation</td>
<td>$A_{(air)}$</td>
<td>$D + A_{(air)} + A_{(wtr)}$</td>
</tr>
<tr>
<td>Subaqueous frontal melting</td>
<td>$A_{(wtr)}$</td>
<td></td>
</tr>
<tr>
<td>Frontal ablation</td>
<td>$A_f$</td>
<td>$D + A_{(air)} + A_{(wtr)}$</td>
</tr>
<tr>
<td>Accumulation</td>
<td>$C$</td>
<td>$C_{sfc} + C_i + C_b$</td>
</tr>
<tr>
<td>Ablation</td>
<td>$A$</td>
<td>$A_{sfc} + A_i + A_b + A_f$</td>
</tr>
<tr>
<td>(Total) mass balance</td>
<td>$\Delta M$</td>
<td>$C + A = B + A_f$</td>
</tr>
</tbody>
</table>

To obtain the glacier-wide climatic-basal mass-balance rate, we add together the climatic-basal rates of a set of columns (as in Figure 1) over the area $S$:

$$\dot{\Delta} = \frac{1}{S} \int_S \dot{\Delta} \, ds ,$$  \hspace{1cm} (4)

but this is not a complete statement of the mass-balance rate because it omits frontal ablation, that is, mass loss by calving, subaerial frontal melting and sublimation (above the waterline) and subaqueous frontal melting (below the waterline). (See also Table 1.) Mass loss at the glacier front due to processes other than calving can be significant, and even dominant. For simplicity, however, in what follows we assume processes other than calving to be negligible and write the complete glacier-wide mass-balance rate as

$$\dot{M} = B + \dot{D} / S ,$$  \hspace{1cm} (5)

where the calving flux (dimension $[MT^{-1}]$) along the perimeter $P$ of the calving margin is

$$\dot{D} = \int_P \dot{\Delta} \, dp ,$$  \hspace{1cm} (6)
and the calving flux per unit of distance along the margin (dimension [M L^{-1} T^{-1}]) is

\[ \dot{d} = -\bar{\bar{\rho}} h u_D, \]

(7)

Here the **calving velocity** \( u_D \) averaged over the glacier thickness at any point \( p \) on the margin is defined as

\[ \bar{u}_D = \bar{u} - \bar{L}, \]

(8)

where \( \bar{u} \) is the vertically-averaged horizontal velocity and \( \bar{L} \) is the rate of advance of the margin, both reckoned normal to the margin; if the flow direction is at right angles to the margin then \( L \) is the length of the **flowline** that reaches the margin at \( p \).

Figure 2. Components of the mass balance of a glacier. The arrows have arbitrary widths and do not indicate physical pathways of mass transfer.

Through (8), equation (7) has two components: the **ice discharge** and the mass “flux” \( \bar{\bar{\rho}}h\bar{L} \) implied by changes in the position of the **calving front**. The ice discharge is defined everywhere on the glacier, not just at the calving front. It can be represented (Figure 3) as \( \bar{q} = -\bar{\bar{\rho}} h \bar{u} \), here in mass units rather than the ice-equivalent units of (2).

The glacier may be delineated such that other mass changes due to flow must be considered, as when separate mass balances are calculated for the grounded and floating portions. The balance is also sometimes calculated for only part of the glacier. In both these cases a term analogous to \( \dot{D} \) must be retained in (5) to represent ice flow, inward or outward, across the boundary of the study region. If the boundary itself is mobile, as when a **grounding line** or drainage **divide** migrates, its motion must also be represented. For example migration of the divide results in both inflow and outflow becoming zero on both sides of the new divide and ceasing, in general, to be zero at the old. On each side of the
divide, a relation analogous to (7) can be invoked with $\bar{u}_D$ playing the role of “divide velocity”, positive in the direction of the growing glacier.

Figure 3 is a two-dimensional representation of a flowline with horizontal coordinate $x$, with $x = G$ at the grounding line and $x = L$ at the calving front. At the grounding line $x = G$ the inflow to the floating portion is equal to the ice discharge $\dot{q}_g$. The calving flux $\dot{a}_c$ at $x = L$ is obtained from equations (8) and (7). When frontal ablation other than by calving is significant, the total loss at the front can be represented (Table 1) as $\dot{a}_c$, the sum of the calving flux, subaerial frontal melting and sublimation $\dot{a}_{f(air)}$, and subaqueous frontal melting $\dot{a}_{f(wtr)}$. For an ice shelf or marine-terminating tongue, the sum of subaqueous frontal ablation and basal ablation is called submarine ablation.

![Figure 3. Mass-balance components of a floating tongue or ice shelf. Components of the internal mass balance are neglected. Shaded arrows represent gains by accumulation and flow. Unshaded arrows represent ablation. See text for notation.](image)

**4.4.1 Alternative formulations**

In (5), $\dot{M}$ is a glacier-wide specific mass-balance rate with dimension $[\text{M L}^{-2} \text{T}^{-1}]$. To illustrate our recommended notation, the glacier-wide mass-balance rate with dimension $[\text{M T}^{-1}]$ is

$$\dot{M} = \int_S \dot{b} \, ds + \int_p \dot{d} \, dp = \dot{B} + \dot{D}$$

(9)

with no separate symbol to distinguish, for example, the $\dot{B}$ of (5) from the $\dot{B}$ of (9). This distinction should be made by stating the units of the quantity. The glacier-wide mass balance (dimension $[\text{M}]$) is

$$\Delta M = \int_0^t \left[ \int_S \dot{b} \, ds + \int_p \dot{d} \, dp \right] \, dt = \int_S \dot{b} \, ds + \int_p \dot{d} \, dp ,$$

(10)
where in the second equality \( b = \int_{t_0}^{t_1} \dot{b} \, dt \) is the specific point mass balance (with dimension \([M \, L^{-2}]\)), implicitly over the columns within \( S \), and similarly \( d = \int_{t_0}^{t_1} \dot{d} \, dt \) is the calving loss (dimension \([M \, L^{-1}]\)) along the calving margin \( P \), both over the time span from \( t_0 \) to \( t_1 \). The corresponding glacier-wide specific mass balance (dimension \([M \, L^{-2}]\)), again with no separate symbol, is

\[
\Delta M = \frac{1}{S} \int_S \dot{b} \, ds + \frac{1}{S} \int_P \dot{d} \, dp
\]  

(11)

We expect that normally the various qualifying adjectives and nouns will be used only when necessary to eliminate ambiguity.

4.5 Seasonal mass balance

Mass-balance measurements have traditionally spanned either a year or a winter season or summer season, although shorter-term measurements have always played a role in detailed studies, and multi-annual measurements by geodetic methods have long been used as checks on the accuracy of annual measurements by the glaciological method. Recent developments have increased the importance of geodetic methods greatly. Moreover, gravimetric methods and mass-balance modelling both promise to make high temporal resolution (days) available routinely.

Nevertheless the traditional focus on the seasonal cycle is as important as ever. The annual and seasonal balances at a point on the glacier are related by

\[
b_a = c_a + a_a = b_w + b_s
\]  

(12)

In the literature, \( b_a \) often appears in place of \( b_w \); see the article Net mass balance in the body of the Glossary. Seasonal mass balances are usually not expressed as rates. Each of the simple equalities in (12) is a complete description of the climatic-basal mass balance over a period of a year, and for many purposes, especially when only surface quantities need to be considered, no further detail is needed. However it is difficult to measure the annual accumulation and annual ablation, and indeed impossible with only one or two visits to the glacier each year. This makes the second, seasonal equality in (12) very important, because measurements of winter balance and summer balance are in practice the only way to isolate the two main climatic forcings. It should be stressed, however, that in general both \( b_w \) and \( b_s \) have components of accumulation and ablation, so that, notwithstanding the second equality in (12), \( c_a > b_w \) and \( a_a < b_s \).

5 Reporting of Mass-balance Data

In a typical mass-balance programme based on the glaciological method, only the two seasonal terms of (12) are measured, and often only the annual term. The minimal requirements for reporting a mass-balance measurement are therefore quite simple: the annual balance, or the winter balance and summer balance if they are known separately, for the whole and possibly for parts of the glacier; the area of the glacier, and when applicable the area-altitude distribution, are also among the minimal data requirements because they are needed for conversion between glacier-wide and specific units. Certain other data are also essential, primarily glacier location, survey dates and the dates to which the measurement refers.

Minimum and maximum glacier elevations, reported separately from the area-altitude distribution, are highly desirable. It is usual to report the accumulation-area ratio and equilibrium-line altitude when they are relevant and the method of measurement allows their determination. Precise dates and spatial details are in general even more important for understanding of the newer methods than of the
traditional methods. Other information which is needed for comparison and analysis of mass-balance data, and is often not reported, relates to the treatment of the non-surface terms in (1), and to the time system in which the measurement was made. Problems related to time systems are discussed in section 6.1.

All glacier mass-balance data should be reported routinely to the World Glacier Monitoring Service, Zürich, which provides guidelines for submission (WGMS 2007b) and publishes a short annual tabulation on the internet, a more detailed biennial summary (e.g. WGMS 2007a) and a comprehensive summary every five years (e.g. WGMS 2008a).

6 Departures from Anonymous (1969)

This new set of recommendations departs from the practices recommended in Anonymous (1969), but apart from minor points of detail there are in fact only two departures, described in section 6.1 and section 6.2.

The leading feature of Anonymous (1969) was a coordinated set of terms, with accompanying definitions and recommended notation, which is summarized in Appendix A. Two “time systems” were identified, the stratigraphic system and the fixed-date system, for measurements based respectively on the quasi-annual span between successive summer surfaces (that is, between successive annual minima of the mass of the glacier) and on fixed field-survey dates. There was a separate set of terms for each system. Several ancillary observed quantities were defined, all having a connection with the equilibrium line, which has long had a status almost as fundamental as the mass balance itself. Anonymous (1969) also discussed the nature of firn at length, and its suggested definition (in essence, “snow which has survived a summer but is not yet ice”) has been adopted widely.

6.1 Time systems

Like other standards, Anonymous (1969) has been extended liberally ad hoc. For example “winter and summer seasons are not defined” in the fixed-date system. These two terms refer exclusively to the stratigraphic system, yet fixed-date winter and summer mass balances have been published. More seriously, although the time systems have taken firm root, the separate terminologies for stratigraphic and fixed-date mass balances have become entangled with each other in contemporary usage. For example “net balance” and “total accumulation” are stratigraphic-system terms, and “annual balance” and “annual accumulation” are the corresponding terms in the fixed-date system, but usage in the literature often deviates from these definitions. Phrases such as “net annual balance” appear regularly; “net” and “annual” are often used one for the other; and “total” is used occasionally with the technical meanings given in Anonymous (1969) but more commonly with its plain-English meaning. Evidently glaciologists have found the plain-language meanings of these adjectives more valuable than their technical meanings. In short, in this Glossary “net” and “total” are no longer understood as having the meanings assigned to them by Anonymous (1969), and the loss of the connection to the stratigraphic system means that they are often redundant. The situation is made more complicated by the later addition of the combined time system, the name of which is at least self-explanatory, and the floating-date system, which differs from the fixed-date system in that the survey dates are allowed to vary from year to year.

We therefore adopt a different approach to time systems. We retire the terminological distinction drawn by Anonymous (1969) between the stratigraphic and fixed-date systems by the use of the adjectives “net”, “annual” and “total”. We emphasize strongly that we are not retiring the time systems themselves, and indeed that, by requiring authors to be explicit about which time system is in use and about the dates of observations, the intention is to make the distinctions clearer. (The various time systems are explained in more detail in the body of the Glossary.)
Table 2 seems to suggest that the importance of time-system information is not widely appreciated. It is also possible that many of the reported measurements do not fit readily into any of the time systems.

**Table 2**  Time systems of annual measurements of mass balance reported to WGMS (up to 2008)

<table>
<thead>
<tr>
<th>Time System</th>
<th>Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>No information provided</td>
<td>1519</td>
</tr>
<tr>
<td>Fixed-date system</td>
<td>917</td>
</tr>
<tr>
<td>Stratigraphic system</td>
<td>931</td>
</tr>
<tr>
<td>Combined system</td>
<td>265</td>
</tr>
<tr>
<td>Other</td>
<td>188</td>
</tr>
<tr>
<td><strong>Total of reported annual measurements</strong></td>
<td><strong>3820</strong></td>
</tr>
</tbody>
</table>

Insufficient information about the dates of field or remote-sensing surveys is an impediment to analysis. For example, very few of the fixed-date measurements listed in Table 2 are accompanied by information on how or whether the field observations, generally made on floating dates, are corrected to the fixed dates. Often, the dates themselves are not reported, making comparison with meteorological and other data difficult or impossible. A more general problem is that measurements in the various systems can differ substantially.

Figure 4 shows that differences between determinations of $\dot{b}_a$ in the floating-date, fixed-date and stratigraphic systems can reach 0.5 m w.e. a$^{-1}$. Summed over the years, the deviations cancel and the median difference is negligible, but single-year differences of 0.2 m w.e. a$^{-1}$ are typical. Such differences, due solely to differences in time system, are large enough to affect the precision of comparative analyses, and it is essential that the analyst be aware of them.

Figure 4. Distributions of differences between (a) annual and (b) winter balance measured in different time systems on two Swiss glaciers during 1960–2007 (after Huss et al. 2009). Bars range from the 2.5 to the 97.5 percentile, with outlying measurements beyond those percentiles represented by plus signs, and boxes cover the 25th to the 75th percentile of each distribution. The central thick line is the median and $\sigma$ is the standard deviation.
Geodetic measurements of mass balance do not fit into any established time system. Their starting and ending dates do not coincide in general with dates of annual minimum and maximum glacier mass. While this does not affect their status as measurements of “change in the mass of a glacier … over a stated span of time”, the amplitude of the annual cycle of mass change may be large by comparison with the measured change and, if the aim is to calculate an annual or seasonal balance, seasonal corrections may be essential if the dates are far enough from the ends of winter or summer. The problem is reduced when the survey dates are an integer number of years apart, but even then the comparability of such measurements with conventional measurements might be in doubt.

It is beyond the present scope to offer solutions in detail for these difficulties with time systems, but some points are clear. The Working Group recommends that:

1. Survey dates, and if different the dates over which the mass balance is reported, be regarded as integral parts of any report of a measurement of mass balance. Each date should be given to the nearest day. Where applicable, ranges of dates should be given. Where, as in the stratigraphic system, a mass-balance survey refers to an epoch that may be unknown or even to a diachronous surface, the survey date should be given nevertheless.

2. The method of measurement be described as part of routine metadata. As a minimum this means assigning the measurement to a time system when such an assignment makes sense, and describing seasonal corrections whenever they are made.

3. Reports of measurements include dated glacier area and hypsometric data as well as information on how to obtain maps, including digital elevation models and glacier outlines when available.

These recommendations imply an increase in the burden of reporting. Measurements of mass balance are sometimes made by volunteers, and are often incidental to research campaigns that have other primary purposes.

6.2 Dimensions

A fundamental question about mass balance is related to its dimension: is it [M] (mass) or [L³] (volume)? Equivalently, when the balance is presented as a rate, is it [M T⁻¹] or [L³ T⁻¹]? There are two schools of thought, both internally consistent, on this point.

One school holds that the mass in question should be divided immediately by the density of water to yield an equivalent volume of water: if the mass is stated per unit area, for example in kg m⁻², dividing by the density in kg m⁻³ yields a length, which is expressed in metres of water equivalent. All subsequent calculations are done in volumetric or “water-equivalent” units.

The other school holds that the division by density is a convenience rather than a fundamental operation. Mass or specific mass units (kg or kg m⁻² respectively) are the fundamental units, and water equivalents are used for ease of visualization.

Diverging from Anonymous (1969), we have accorded primacy to mass units rather than volumetric units. This means that, although we do not discourage use of the metre and millimetre water equivalent, we consider that usage and understanding would be the better for a stronger emphasis on the difference between mass and volume. Geodetic measurements of mass balance most commonly consist of a volume-balance measurement coupled with an assumption about density, and gravimetric measurements with accelerometers are direct measurements of mass change. Thus the difference between mass and volume will grow in importance as geodetic and gravimetric methods become more widely used.

However we do not suggest that the metre or millimetre water equivalent should be discarded, nor do we expect that they will be. On the contrary, we suggest that the units metre water equivalent and metre ice equivalent should be accorded the status of extensions of the SI. See section 7.2, and see also the articles in the body of the Glossary on ice equivalent, mass-balance units and water equivalent.
7 Units of Measurement

With three exceptions (see section 7.2), the units in which mass-balance quantities are reported are those of the Système International d’Unités or SI (BIPM 2006a, with a summary in BIPM 2006b).

7.1 Essentials of the Système International d’Unités (SI)

7.1.1 Base quantities
The fundamental concept in the SI is that of a quantity. Each quantity has its own dimension, and a unit is associated with it. There are seven base quantities. The four base quantities which are used in studies of glacier mass balance are listed in Table 3 with their units.

Table 3 Some base quantities of the SI

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Symbol for dimension</th>
<th>Base unit</th>
<th>Abbreviation for unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>length</td>
<td>L</td>
<td>metre</td>
<td>m</td>
</tr>
<tr>
<td>mass</td>
<td>M</td>
<td>kilogram</td>
<td>kg</td>
</tr>
<tr>
<td>time, duration</td>
<td>T</td>
<td>second</td>
<td>s</td>
</tr>
<tr>
<td>thermodynamic temperature</td>
<td>Θ</td>
<td>kelvin</td>
<td>K</td>
</tr>
</tbody>
</table>

7.1.2 Derived quantities
The SI defines a large number of derived quantities with corresponding derived units which are products of powers of the base units. Some derived units have special names and symbols (abbreviations). Table 4 gives some examples of derived quantities used in mass-balance work and in closely related subjects.

Table 4 Some derived quantities of the SI

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Units</th>
<th>Special name</th>
<th>Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>area</td>
<td>m²</td>
<td></td>
<td></td>
</tr>
<tr>
<td>volume</td>
<td>m³</td>
<td></td>
<td></td>
</tr>
<tr>
<td>speed</td>
<td>m s⁻¹</td>
<td></td>
<td></td>
</tr>
<tr>
<td>acceleration</td>
<td>m s⁻²</td>
<td></td>
<td></td>
</tr>
<tr>
<td>density</td>
<td>kg m⁻³</td>
<td></td>
<td></td>
</tr>
<tr>
<td>surface density</td>
<td>kg m⁻²</td>
<td></td>
<td></td>
</tr>
<tr>
<td>force</td>
<td>kg m s⁻²</td>
<td>newton</td>
<td>N</td>
</tr>
<tr>
<td>energy</td>
<td>kg m² s⁻²; N m</td>
<td>joule</td>
<td>J</td>
</tr>
<tr>
<td>power</td>
<td>kg m² s⁻³; J s⁻¹</td>
<td>watt</td>
<td>W</td>
</tr>
<tr>
<td>pressure, stress</td>
<td>kg m⁻¹ s⁻²; N m⁻²</td>
<td>pascal</td>
<td>Pa</td>
</tr>
<tr>
<td>Celsius temperature</td>
<td>K</td>
<td>degree Celsius</td>
<td>℃</td>
</tr>
<tr>
<td>frequency</td>
<td>s⁻¹</td>
<td>hertz</td>
<td>Hz</td>
</tr>
<tr>
<td>plane angle</td>
<td>m m⁻¹</td>
<td>radian</td>
<td>rad</td>
</tr>
<tr>
<td>solid angle</td>
<td>m² m⁻²</td>
<td>steradian</td>
<td>sr</td>
</tr>
</tbody>
</table>

Plane angle and solid angle, being ratios of base quantities and derived quantities respectively, are examples of dimensionless quantities. They have the dimension “1”.
7.1.3 Multiples and submultiples
Decimal multiples and submultiples of SI units may be distinguished when convenient by selecting from a set of SI prefixes. Some that arise in mass-balance studies are given in Table 5. Stylistic rules for combining prefixes with units, and prefix symbols with unit abbreviations, are explained in BIPM (2006b). When base units and derived units are used with no prefixes, the resulting set of units is said to be coherent. The adjective “coherent” appears to have been chosen to stress that, when only coherent units are used, conversion factors between units are never needed. Otherwise, however, there is no implication that coherent units are superior to “non-coherent” units.

The Working Group recommends that the prefixes centi-, deci-, deca- and hecto- be used sparingly in reports of mass balance, preferably only in units such as the decibel and hectopascal which have an unshakeable place in usage for historical reasons. The centimetre and the gram are not recommended. They introduce an avoidable risk of numerical error.

Table 5

<table>
<thead>
<tr>
<th>Factor</th>
<th>Prefix</th>
<th>Symbol</th>
<th>Factor</th>
<th>Prefix</th>
<th>Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{-9}$</td>
<td>nano-</td>
<td>n</td>
<td>$10^9$</td>
<td>mega-</td>
<td>M</td>
</tr>
<tr>
<td>$10^{-6}$</td>
<td>micro-</td>
<td>μ</td>
<td>$10^9$</td>
<td>giga-</td>
<td>G</td>
</tr>
<tr>
<td>$10^{-3}$</td>
<td>milli-</td>
<td>m</td>
<td>$10^{12}$</td>
<td>tera-</td>
<td>T</td>
</tr>
<tr>
<td>$10^3$</td>
<td>kilo-</td>
<td>k</td>
<td>$10^{15}$</td>
<td>peta-</td>
<td>P</td>
</tr>
</tbody>
</table>

7.1.4 Non-SI units
The SI also recognizes a number of non-SI units. Those in Table 6 are some that are “accepted for use with the International System of Units”. Of those that are “used by special interest groups for a variety of purposes”, only the bar (a unit of pressure; 1 bar = $10^5$ N m$^{-2}$) and the atmosphere (1 atm = 101 325 N m$^{-2}$) need to be mentioned here.

Table 6

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Unit</th>
<th>Symbol</th>
<th>Value in SI Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>time, duration</td>
<td>minute</td>
<td>min</td>
<td>1 min = 60 s</td>
</tr>
<tr>
<td>time, duration</td>
<td>day</td>
<td>d</td>
<td>1 d = 86 400 s</td>
</tr>
<tr>
<td>plane angle</td>
<td>degree</td>
<td>°</td>
<td>1° = ($\pi/180$) rad</td>
</tr>
<tr>
<td>plane angle</td>
<td>minute</td>
<td>’</td>
<td>1’ = ($\pi/10 800$) rad</td>
</tr>
<tr>
<td>plane angle</td>
<td>second</td>
<td>”</td>
<td>1” = ($\pi/648 000$) rad</td>
</tr>
<tr>
<td>mass</td>
<td>tonne</td>
<td>t</td>
<td>1 t = 1000 kg</td>
</tr>
</tbody>
</table>

7.2 Extensions of the SI in glaciological usage

7.2.1 The year
The year is not an SI unit. In the form of the “tropical year 1900”, it was once the basis for the definition of the second, but fell into disfavour because of the ability of modern physics to supply more precise measures of time based on atomic phenomena. The duration of a single orbit of the Earth around the Sun is intrinsically a variable and not a constant, and it can be defined in more than one astronomically plausible way. A definition of the year, therefore, cannot be both precise and general.

Yet the annual cycle is a fundamental attribute of the terrestrial environment. In the study of mass balance, the year is synchronized not directly with the Earth’s orbit but rather with the local hydrological cycle as it affects each glacier, or alternatively with the civil calendar. We define the
mass balance as a “change in mass ... over a stated span of time”. It can be treated as a sum, with
dimension [M]. Often, however, the most fitting interpretation is that the mass balance is a rate, with
dimension [M T⁻¹], and in this interpretation the appropriate unit of time is the year.
The year is also firmly established in other branches of glaciology, particularly dynamic
glaciology, in which it is natural to express rates of motion, such as speed and velocity (m a⁻¹), and of
deformation or strain rate (a⁻¹), as rates per year.
Of the three kinds of glaciological year – the mass-balance year in the stratigraphic system, the
fixed-date system and the floating-date system – none is specifiable exactly in terms of the SI base
unit of time, the second, although two are specifiable exactly (with due allowance for leap years) in
terms of the day, which is an accepted non-SI unit.
The Working Group recommends that the year be considered to be a practical extension of the SI,
with the symbol “a”. Normally the duration of the year need not be specified more precisely than as
under Year in the Glossary. In accurate work the time coordinate is best represented in terms of the
Julian date or the day of the year.

7.2.2 The metre water equivalent
The Working Group recommends that the metre water equivalent, abbreviated as “m w.e.” and
defined in the Glossary, be considered an extension of the SI. The metre water equivalent is oriented
parallel to the local vertical axis at the Earth’s surface and is connected tightly by definition to the unit
kg m⁻² (surface density).

7.2.3 The metre ice equivalent
The metre ice equivalent, abbreviated “m ice eq.” and defined in the Glossary, is also considered to be
an extension of the SI.

8 Format of the Glossary

Each article in the body of the Glossary begins with a bold-font head term – the word or phrase that is
about to be defined. The head term may be qualified to explain what part of speech (adjective, noun,
verb, ...) it is. In a few cases a recommended algebraic symbol, selected with the aim of increasing
clarity, is given after the head term.
The head term is followed by a definition paragraph, consisting usually of a single noun phrase or
sentence giving the essence of the meaning of the head term. The definition paragraph may be
followed by one or more paragraphs of commentary or background information.
When the head term has more than one distinct meaning, the distinct definitions are numbered.
Some head terms, for example “Mass balance” and “Microwave remote sensing”, have nested
subheadings for closely related terms, and these are italicized.
Italicized words or phrases elsewhere are cross-references to other articles in the Glossary.
Annual and multi-annual layers in a crevasse wall, Cotopaxi, Ecuador
(Marco Möller)

GLOSSARY
Acronyms

AAR
Accumulation-area ratio.

CIG
International Glacier Commission.

DAS
Data Analysis Services.

DEM
Digital elevation model.

DTM
Digital terrain model. See digital elevation model.

DGPS
Differential Global Positioning System.

ELA
Equilibrium-line altitude.

FoG
Fluctuations of Glaciers.

GCOS
Global Climate Observing System.

GIA
Glacial-isostatic adjustment.

GLIMS
Global Land Ice Measurements from Space.

GLONASS
See global navigation satellite system.

GNSS
Global navigation satellite system.

GPR
Ground-penetrating radar.

GPS
Global Positioning System.

GRACE
Gravity Recovery and Climate Experiment. See gravimetric method.

GTN-G
Global Terrestrial Network for Glaciers.
GTOS
Global Terrestrial Observing System.

IACS
International Association of Cryospheric Sciences.

ICESat
Ice, Cloud and land Elevation Satellite. See laser altimeter.

ICSI
International Commission on Snow and Ice.

ICSIH
International Commission on Snow and Ice Hydrology.

ICSU
International Council for Science.

IGS
International Glaciological Society.

InSAR
Interferometric synthetic aperture radar.

IUGG
International Union of Geodesy and Geophysics.

LIA
Little Ice Age.

NSIDC
National Snow and Ice Data Center.

PDD
Positive degree-day.

PGR
Post-glacial rebound. See glacial isostatic adjustment.

PSFG
Permanent Service on the Fluctuations of Glaciers.

RES
Radio-echo sounding. See ground-penetrating radar.

SAR
Synthetic aperture radar. See InSAR.

SI
Système International d’Unités. See chapter 7.

SLE
Sea-level equivalent.
SRTM
*Shuttle Radar Topography Mission.*

SSC
*Seasonal sensitivity characteristic.*

SWE
Snow water equivalent. See *passive-microwave sensor.*

TTS/WGI
*Temporary Technical Secretariat for the World Glacier Inventory.*

WDC
*World Data Centres.*

WDS
*World Data System.*

WGI
*World Glacier Inventory.*

WGMS
*World Glacier Monitoring Service.*
Ablation

a (point), A (glacier-wide)

1. All processes that reduce the mass of the glacier.

2. The mass lost by the operation of any of the processes of sense 1, expressed as a negative number (see mass-balance units).

The main processes of ablation are melting and calving (or, when the glacier nourishes an ice shelf, ice discharge across the grounding line). On some glaciers sublimation, loss of windborne snow and avalanching are significant processes of ablation.

“Ablation”, unqualified, is sometimes used as if it were a synonym of surface ablation, although internal ablation, basal ablation, and frontal ablation, especially calving, can all be significant in some contexts.

Ablation area

A synonym of ablation zone.

Ablation season

A time span extending from a seasonal maximum of glacier mass to a seasonal minimum.

The ablation season is the same as the summer season on most glaciers, which are of winter-accumulation type. Special cases include glaciers of summer-accumulation type and year-round ablation type, and glaciers that have more than one ablation season during the year.

Ablation zone

The part of the glacier where ablation exceeds accumulation in magnitude, that is, where the cumulative mass balance relative to the start of the mass-balance year is negative.

Unless qualified, for example by giving a date within the year, references to the ablation zone refer to its extent at the end of the mass-balance year. The extent of the ablation zone can vary strongly from year to year. See zone.

Ablatometer

A device installed at the glacier surface for the measurement, during the ablation season, of changes in elevation of the glacier surface relative to a fixed elevation, such as that of the top of a mass-balance stake embedded in the ice beneath the surface.

A star ablatometer is an array of rigid metal arms that can be attached to a stake and levelled. A graduated rod is lowered through holes in the arms to measure changes in the surface elevation, yielding a considerably larger sample than that obtained from readings of the stake alone.

Sometimes an ablatometer is actually a sonic ranger.

Accreted ice

Ice formed by the freezing of water at the base of an ice body.

See basal accumulation, marine ice.

Accumulation

c (point), C (glacier-wide)

1. All processes that add to the mass of the glacier.

2. The mass gained by the operation of any of the processes of sense 1, expressed as a positive number (see mass-balance units).

The main process of accumulation is snowfall. Accumulation also includes deposition of hoar, freezing rain, solid precipitation in forms other than snow, gain of windborne snow, avalanching and basal accumulation (often beneath floating ice). See also internal accumulation.
Unless the rain freezes, rainfall does not constitute accumulation, nor does the addition of debris by avalanching, ashfall or similar processes.

**Accumulation area**  
A synonym of *accumulation zone*.

**Accumulation-area ratio**  
AAR  
The ratio, often expressed as a percentage, of the area of the *accumulation zone* to the area of the *glacier*.

The AAR is bounded between 0 and 1. On many glaciers it correlates well with the *climatic mass balance*. The likelihood that the climatic mass balance will be positive increases as the AAR approaches 1.

Unless qualified by a different adjective, references to the AAR refer to the *annual AAR*.

**Annual AAR**  
The AAR at the end of the *mass-balance year*.

Annual AARs can vary greatly from year to year, but an average over a number of years, when compared with the *balanced-budget AAR*, gives a measure of the *health* of the glacier. If the difference is large and in the same direction over a considerable time, a prolonged period of non-zero *mass balance* can be expected as the glacier seeks *equilibrium*.

**Balanced-budget AAR**  
The AAR, sometimes denoted AAR₀, of a glacier with a mass balance equal to zero.

Glaciers do not in general have mass balances equal to zero. The balanced-budget AAR is usually estimated as the AAR at which a curve (often linear) fitted to a relation between AAR and the annual surface mass balance $B_{sfc}$ observed over a number of years, crosses the axis $B_{sfc} = 0$.

The AAR₀ of non-calving glaciers has been found to vary roughly between 0.5 and 0.6 on average, although the range of variation is substantial. On calving glaciers it is typically larger, approaching 1.0 on the Antarctic Ice Sheet. AAR₀ can exceed 0.8 on tropical glaciers of *year-round ablation type*. The balanced-budget AAR may differ from the *steady-state AAR* because it summarizes observations made in conditions that may not approximate to steady state.

**Equilibrium AAR**  
A synonym of *balanced-budget AAR*.

**Steady-state AAR**  
The AAR of a glacier in *steady state*.

The steady-state AAR is difficult to estimate because glaciers are seldom if ever in steady state. In practice, it must be estimated by modelling. To emphasize that the balanced-budget AAR and steady-state AAR are distinct concepts, the steady-state AAR should be given a distinctive symbol, perhaps AARᵢ.".

**Transient AAR**  
The AAR at any instant, particularly during the *ablation season*.

**Accumulation season**  
A time span extending from a seasonal minimum of *glacier* mass to a seasonal maximum.

The accumulation season is the same as the *winter season* on most glaciers, which are of *winter-accumulation type*. Special cases include glaciers of *summer-accumulation type* and *year-round ablation type*, and glaciers that have more than one accumulation season during the year.

**Accumulation zone**  
The part of the glacier where *accumulation* exceeds *ablation* in magnitude, that is, where the *cumulative mass balance* relative to the start of the *mass-balance year* is positive.
Unless qualified, for example by giving a date within the year, references to the accumulation zone refer to its extent at the end of the mass-balance year. The extent of the accumulation zone can vary strongly from year to year. The accumulation zone is not the same as the firn area. See zone.

**Active-microwave sensor**
See article Active-microwave sensor under Microwave remote sensing.

**Activity index**
The mass-balance gradient at the balanced-budget ELA.

**Advance**
Increase of the length of a flowline, measured from a fixed point.

In practice, when the advance is of a land-terminating glacier terminus, the fixed point is usually downglacier from the glacier margin, that is, on the glacier forefield. The quantity reported is most often the amount of advance rather than the length itself.

*Retreat* is the opposite of advance, that is, retreat of the terminus.

**Albedo**
The ratio of the reflected flux density to the incident flux density, usually referring either to the entire spectrum of solar radiation (broadband albedo) or just to the visible part of the spectrum.

The broadband albedos of glacier surfaces exceed 0.8 for freshly fallen snow, are less for aged snow and firn, and are significantly less for exposed glacier ice. Snow and ice that are sediment-laden or covered by debris can have albedos still lower. The difference between the albedos of snow and glacier ice is significant in the seasonal evolution of the energy balance and therefore of the rate of surface ablation; see degree-day factor.

Spectral albedo is the albedo at a single wavelength or, more loosely, over a narrow range of wavelengths.

**Alpine glacier**
See mountain glacier.

**Altimetry**
A remote-sensing technique in which surface altitudes (elevations) are estimated as a function of the travel time of a pulse of electromagnetic radiation transmitted from and received by a precisely located altimeter.

Altimeters are mounted on either satellite or aircraft. Satellite altimeters use on-board Global Positioning System (GPS) instruments and star trackers to determine orbital position and altimeter pointing angles. Aircraft systems measure the altimeter trajectory using GPS and inertial navigation systems. Accurate altimetry measurements, especially those acquired from space, require corrections for variations in atmospheric and ionospheric conditions, and for variations in orbital position of the sensor.

Altimeters are either laser altimeters or radar altimeters. Each of the two radiation bands has strengths and weaknesses with respect to footprint size and ability to sample through atmospheric obstructions such as clouds.

Altimetry measurements are compared with surface elevations obtained at identical points in horizontal space at an earlier time to calculate elevation changes which can then be used to compute volume changes. The earlier elevation measurement is commonly obtained from a previous altimetry pass, but can also be derived from other sources such as topographic maps. A mass balance is obtained from knowledge of the ice-column density usually supplied by Sorge’s law.

**Altitude**
The vertical distance of a point above a datum.

The vertical datum is usually an estimate of mean sea level. Older measurements were often determined in a local coordinate system and were not tied to a global reference frame. Some were
made not with surveying instruments but with barometers, in reliance on the decrease of atmospheric pressure with altitude. It is now usual to measure altitude or elevation using the Global Positioning System or an equivalent global navigation satellite system.

Altitude and elevation are synonyms in common usage, although altitude is less ambiguous. The unqualified word “elevation” can also refer, for example, to the act of elevating or to angular distance above a horizontal plane.

**Annual (adj.)**
Descriptive of a period equal or approximately equal in duration to a calendar year, such as a hydrological year or mass-balance year.

“Annual” often has a meaning equivalent to “end-of-summer”, which is more explicit but longer and also depends on summer being a well-defined season.

Formerly (Anonymous 1969; Appendix A) “annual mass balance” was a technical term in the fixed-date system, to be distinguished from “net mass balance” in the stratigraphic system, but this distinction is no longer recommended.

**Annual AAR**
See article Annual AAR under Accumulation-area ratio.

**Annual ablation** $a_s$ (point), $A_s$ (glacier-wide)
See article Annual ablation under Mass balance.

**Annual accumulation** $c_s$ (point), $C_s$ (glacier-wide)
See article Annual accumulation under Mass balance.

**Annual ELA**
See article Annual ELA under Equilibrium-line altitude.

**Annual equilibrium line**
See article Annual equilibrium line under Equilibrium line.

**Annual exchange**
See article Annual exchange under Mass balance.

**Annual mass balance** $b_s$ (point), $B_s$ (glacier-wide)
See article Annual mass balance under Mass balance.

**Annual snowline**
See article Annual snowline under Snowline.

**Area** $S$
Extent in two spatial dimensions, always understood in mass-balance work (when the two dimensions are horizontal) to be map area, that is, the extent of the glacier or part thereof when the glacier outline is projected onto the surface of an ellipsoid approximating the surface of the Earth or onto a planar (horizontal) approximation to that ellipsoid.

In mass-balance studies, except for ice discharge and for the special case of frontal ablation, lengths such as layer thicknesses are always measured parallel to the vertical axis and not normal to the glacier surface. When calculating volumes within a specified outline, the area to be used is therefore the integral of $dS$ (an element of projected area) and not the integral of $\sec \theta \, dS$, the so-called “true” area (where $\theta$ is the slope of the glacier surface).

The glacier area excludes nunataks but includes debris-covered parts of the glacier. However, delineating the glacier where it is debris-covered can be very difficult, because the debris may cover stagnant ice and there may be no objective way to distinguish between the debris-covered glacier and contiguous ice-cored moraine.
Area-altitude distribution
The frequency distribution of glacier area with surface altitude (elevation), generally presented as a hypsometric curve or table giving the area of the glacier within successive altitude intervals. See hypsometry.

Area-averaged (adj.)
Descriptive of a quantity that has been averaged over part or all of the area of the glacier.

The area-averaged mass balance is simply the specific mass balance of the region under consideration. The adjective has sometimes been used to emphasize that the specific mass balance is that of the whole glacier and not of a “specific” location (see point mass balance). “Mean specific mass balance” has been used in the same sense.

Avalanche
A slide or flow of a mass of snow, firn or ice that becomes detached abruptly, often entraining additional material such as snow, debris and vegetation as it descends.

The duration of an avalanche is typically seconds to minutes.

Avalanching
Mass transfer by avalanches which redistribute snow, firn and ice.

Avalanching from a valley wall to the glacier surface constitutes accumulation. Avalanching from the glacier margin constitutes ablation.

Azimuth
1 The horizontal angle, in radians or degrees, measured at any point between a line heading in a reference direction and a line heading in a particular direction.

In geography and navigation, azimuths are measured clockwise from geographical north.

2 The along-track coordinate in the coordinate frame of an airborne or orbiting radar, a usage deriving from the azimuth (in sense 1) of the direction of travel of the radar. See range.
Balance (adj.)
For most terms in which “balance” is used as an adjective, see the equivalent entry under “mass-balance”. In ordinary usage the prefix “mass-” is omitted when there is no risk of confusion.

Balanced-budget (adj.)
Descriptive of a glacier with a mass balance equal to zero on average over a number of years. See steady state.

Balanced-budget AAR
See article Balanced-budget AAR under Accumulation-area ratio.

Balanced-budget ELA
See article Balanced-budget ELA under Equilibrium-line altitude.

Balance flux
The hypothetical horizontal mass flux (dimension \([\text{M} \text{T}^{-1}]\)) through a vertical cross section that would be equal to the mass balance (usually the climatic mass balance) over the region upglacier from the cross section.

Comparison of balance flux and actual mass flux at the same cross section gives an indication of the health of the glacier. If the mass balance of the glacier is zero it follows that at the terminus the balance flux and mass flux are equal, and if there is also no calving that they are equal to zero. If the two are equal at all cross sections the glacier is in steady state.

Volumetric balance flux
The balance flux divided by average density (dimension \([\text{L}^3 \text{T}^{-1}]\)).

Balance velocity
The volumetric balance flux divided by the area of the vertical cross section through which it passes.

Comparison of balance velocity to actual velocity, that is, to the actual volumetric flux (mass flux divided by average density) divided by the area of the vertical cross section, gives an indication of the health of the glacier. See balance flux.

Balance year
The mass-balance year.

Basal ablation \(a_b\) (point), \(A_b\) (glacier-wide)
The removal of ice by melting at the base of a glacier. See mass-balance units.

At the base of grounded temperate ice, melting is either fuelled by the geothermal heat flux and the conversion of the kinetic energy of basal sliding to heat, or results from variations of the pressure-melting point. Pressure melting, however, tends to be balanced by regelation.

Typical continental geothermal heat fluxes \(G\) of 0.05–0.15 W m\(^{-2}\) imply potential basal ablation \(G/L_f\) of 5–14 mm w.e. a\(^{-1}\), where \(L_f\) is the latent heat of fusion. Much greater geothermal heat fluxes are found in areas of active volcanism. If all of the energy of basal sliding is converted to heat, basal ablation \(u_b\sqrt{\tau_b}/L_f\) at rates of 3–30 mm w.e. a\(^{-1}\) is implied by sliding velocities \(u_b\) of 10–100 m a\(^{-1}\) and basal shear stress \(\tau_b\) of \(10^5\) Pa. Basal ablation rates tens or hundreds of times greater are implied beneath ice streams.

At the base of an ice shelf or floating tongue, melting occurs because of convection of warmer sea water to the ice-water interface, supplying the required latent heat of fusion. The rate of melting depends on the temperature of the sea water and the efficiency of the heat transfer between the sea water and the base of the ice shelf. Basal ablation rates beneath ice shelves or floating tongues can reach tens of m w.e. a\(^{-1}\), equivalent to heat transfer at hundreds of W m\(^{-2}\).
Basal accumulation \( c_b \) (point), \( C_b \) (glacier-wide)

The freezing of water to the base of the glacier, increasing the mass of the glacier and raising its basal temperature if that temperature is below the freezing point. See mass-balance units.

The result of basal accumulation is typically observable in ice cores or at glacier margins as accreted ice that is relatively clear, often with some concentration of dispersed sediments incorporated from the glacier bed during freezing. Accreted ice may also be distinguishable from glacier ice (the latter sometimes referred to as meteoric ice in this context) by differences in isotopic content, geochemical composition and optical properties, and may have distinctive dielectric properties by which it can be recognized in ground-penetrating radar records.

Accreted ice at the base of an ice shelf is referred to as marine ice.

For purposes of the glaciological method, basal accumulation is indistinguishable from internal accumulation in that both represent addition of mass to the glacier that goes unaccounted for by surface observations.

Basal mass balance \( b_b \) (point), \( B_b \) (glacier-wide)

The change in the mass of the glacier due to basal accumulation and basal ablation over a stated period. See mass-balance units, climatic-basal mass balance.

Benchmark glacier

In the monitoring strategy of the United States Geological Survey, a glacier on which detailed measurements of seasonal glacier mass changes, meteorological environment, and streamflow variations are collected on a continuing basis.

See reference glacier, tier.

Bergschrund

A crevasse at the head of a glacier that separates flowing ice from stagnant ice, or from a rock headwall.

From an ice-dynamical point of view the bergschrund is the headward boundary of the glacier, while for hydrological and other purposes, including glacier inventory, the stagnant ice above the bergschrund is part of the glacier.

Bergschrund is an anglicized word of German origin.

Blowing snow

Snow entrained, suspended and transported by the wind at heights greater than 2 m above the surface.

The height of 2 m is a convenient separator between blowing snow, which reduces horizontal visibility significantly, and drifting snow. See windborne snow.

Blue ice

Dense glacier ice with a blue appearance accounted for by lack of air bubbles.

The crystal structure absorbs all colours except the blue part of the visible spectrum. Strictly, blue ice is ice that has originated by recrystallization upglacier and, having followed a trajectory through the interior of the glacier, becomes exposed at the surface downglacier, a locally zero or negative surface mass balance being implied. The term is used loosely, however, to refer to all exposed ice on the Antarctic Ice Sheet; again, the absence of snow and firn implies a locally negative surface mass balance.

Bomb horizon

A horizon of enhanced radioactivity in snow, firn or ice, originating from fallout from atmospheric nuclear tests.

The bomb horizon originating from nuclear tests during the 1950s and 1960s has been detected on glaciers. The maximum rate of production of radioactive isotopes is datable to 1963, which makes the bomb horizon a useful marker horizon. A similar horizon is that due to the accident at the Chernobyl nuclear power station in 1986.
**Bomb layer**
A synonym of *bomb horizon*.

**Boundary**
The surface separating the *glacier* from its surroundings.

The term is often simply a synonym of *glacier margin* or *glacier outline*, but it can be useful to have a separate word that is understood to encompass the glacier surface and the glacier bed as well.

**Brightness temperature**
The conventional measure of the intensity of microwave emission from a natural medium, defined as $T_B = \varepsilon T - T_{\text{sky}}$, where $\varepsilon$ is the emissivity of the medium (on glaciers, a mixture of ice, air, and possibly water), $T$ is its physical (thermodynamic) temperature and $T_{\text{sky}} \approx 3 \text{ K}$ (and therefore often neglected) is an equivalent measure of downwelling emission from the sky; the temperatures are expressed in kelvins, the emissivity being dimensionless.

In dry snow, the emissivity is determined by volume scattering at interfaces such as grain boundaries and larger structures such as layers of *depth hoar*. Grain growth rate depends on both temperature and *accumulation* rate, and this behaviour is exploited to estimate the accumulation rate as a function of $T_B$ and $T$.

Scattering at air-water interfaces is much more effective than at air-ice interfaces. When *meltwater* appears at the surface, subsurface scattering ceases to be significant and the emissivity approaches unity. $T_B$ changes abruptly as meltwater comes and goes, and continued monitoring of these changes yields reliable estimates of the *melt extent* and duration of *melting*. Analogous phenomena – abrupt changes in the intensity of backscattered radiation – are also seen by *scatterometers* and imaging *radars*. 
Calving \( d, D \)
The component of ablation consisting of the breaking off of discrete pieces of ice from a glacier margin into lake or sea water, producing icebergs, or onto land in the case of dry calving.

Calving excludes frontal melting and sublimation, although in practice it may be difficult to measure the phenomena separately. For example subaqueous frontal melting may lead to the detachment of icebergs by undercutting or by encouraging the propagation of crevasses.

Calving flux
The mass flux, with dimension \([\text{M T}^{-1}]\), of ice by calving from a glacier margin.

Volumetric calving flux
The calving flux divided by average glacier density (dimension \([\text{L}^3 \text{T}^{-1}]\)).

Calving front
A glacier margin from which discrete pieces of ice calve or break off, to become icebergs if the margin stands or floats in sea or lake water.

Calving rate
Either the calving flux or the calving velocity, depending on the context.

Calving velocity
The volumetric calving flux divided by the area of projection of the calving glacier margin onto a vertical plane normal to the mean direction of the ice flow. See calving.

Denoting horizontal velocity components in the direction of the ice flow as \( u \), the calving velocity \( u_{\text{calv}} \) can be determined by application of the principle of conservation of mass at the glacier margin:

\[
u_{\text{calv}} = u_{\text{bal}} + u_{\text{thin}} - \dot{L},
\]

where \( u_{\text{bal}} \) is the balance velocity, \( u_{\text{thin}} \) is the thinning velocity and \( \dot{L} \) is the rate of change of the glacier’s length reckoned from a fixed point upglacier from the margin.

Cartographic method
Like topographic method, a synonym of geodetic method in the context of measurement of mass balance.

Chionosphere
The part of the Earth’s surface lying above the regional snowline.

Though useful, the term, due originally to Kalesnik, is in fact confined to the Russian literature. “Chion” is a Greek word for snow.

Cirque glacier
A glacier occupying a cirque.

A cirque is a rounded recess with steep sides and back wall, formed on a mountainside by glacial erosion. Cirque is an anglicized French word that has displaced the synonyms “corrie” (from Scots Gaelic) and “cwm” (from Welsh) of early glaciological usage.

Climatic-basal mass balance \( b \) (point), \( B \) (glacier-wide)
The sum of the climatic mass balance and the basal mass balance.

The expression \( b = c_{\text{sfc}} + a_{\text{sfc}} + c_i + a_i + c_b + a_b \) states that the climatic-basal mass balance \( b \) is the sum of surface accumulation \( c_{\text{sfc}} \), surface ablation \( a_{\text{sfc}} \), internal accumulation \( c_i \), internal ablation \( a_i \), basal accumulation \( c_b \) and basal ablation \( a_b \).
The sum of $c_b$ and $a_b$ is the basal mass balance. The sum of $c_i$ and $a_i$ is the internal mass balance. The sum of $c_{sfc}$ and $a_{sfc}$ is the surface mass balance. The sum of the surface mass balance and internal mass balance (the first four quantities on the right of the expression) is the climatic mass balance. The sum of the six quantities on the right (that is, of the climatic mass balance and the basal mass balance) is the climatic-basal mass balance.

The climatic-basal mass balance includes all those components of mass change that do not arise from glacier flow or frontal ablation. The qualifier “basal” does not exclude a role for the climate, for example through interactions between the atmosphere and the ocean.

**Climatic mass balance** $b_{clim}$ (point), $B_{clim}$ (glacier-wide)

The sum of the surface mass balance and the internal mass balance; see also climatic-basal mass balance.

The term is introduced to preserve the distinction between its two components, which is compromised if surface mass balance is redefined to include internal accumulation.

The qualifier “climatic” reflects the fact that the surface and internal balances both depend strongly on interaction between the glacier, the hydrosphere and the atmosphere.

**Climatic snowline**

See snowline.

**Coffee-can method**

A means of measuring the submergence velocity or emergence velocity of the glacier surface by anchoring a stand for a global navigation satellite system (GNSS; usually a Global Positioning System) receiver to the body of the glacier, using a suitable object (such as a coffee can) as an anchor connected to the surface by a cable under tension.

The essence of the method is that measured changes in the exposed length of the cable (or equivalent measurements of the local surface mass balance), and in the surface elevation (measured by the GNSS receiver), yield two of the three terms in the continuity equation and allow the third term, the submergence or emergence velocity (that is, the flux divergence) to be determined.

Corrections may be needed for the densification (that is, settling) of firn beneath the anchor and for downslope advection of the anchor. The coffee-can method has been used mainly in the accumulation zones of ice sheets, where the surface mass balance can be obtained by ice-core stratigraphy. However in the ablation zone the emergence of cables emplaced for other reasons, such as the measurement of temperature profiles, can serve a similar purpose.

**Cold-based glacier**

A glacier whose bed is below its pressure-melting point, implying that there is no liquid water at the bed; dry-based glacier is a synonym.

**Cold content**

The amount of energy required to raise the temperature of a body of frozen water to the freezing point.

The cold content $\gamma$ of a layer between the surface and depth $Z$ is usually expressed per unit area, in J m$^{-2}$:

$$\gamma = C_p \int_0^Z \rho(z)(T_f - T(z)) \, dz,$$

where $C_p$ is the heat capacity of ice (Table B2), and $\rho$ and $T$ are density and temperature respectively at depth $z$; $T_f$ is the freezing point. Sometimes the cold content is expressed as the equivalent depth $\gamma'(\rho \cdot L_f)$, where $L_f$ is the latent heat of fusion, of refreezing water (with temperature equal to the freezing point) that would yield the required energy.

**Cold firn zone**

See infiltration-recrystallization zone.
Cold glacier
A glacier consisting of cold ice, except possibly in a surface layer up to 10–15 m thick that might warm to the melting point seasonally, and possibly right at the bed.

See polythermal glacier, temperate glacier, dry-based glacier, warm-based glacier.

Cold ice
Ice at a temperature below its pressure-melting point; see temperate ice.

Cold infiltration-recrystallization zone
See infiltration-recrystallization zone.

Combined system
A combination of two time systems of mass-balance measurement, usually of the stratigraphic system with either the fixed-date system or the floating-date system.

As originally defined (Mayo et al. 1972), the combined system accounted rigorously for differences between the stratigraphic and fixed-date systems, but this rigorous accounting has been found impractical in most measurement programmes and various simplifications have been adopted.

Condensation
The process by which a vapour changes phase into a liquid; see latent heat of vaporization.

Congelation
1 The freezing of liquid water in the absence of pre-existing ice; see infiltration ice, recrystallization.

2 Addition of ice to the base of sea ice by freezing.

If new and young ice are not deformed into rafts or ridges, they will continue to grow by congelation. Congelation ice has distinctive columnar crystal texture due to the downward growth of the crystals into the water. It is very common in Arctic pack ice and fast ice. In limnology it is called “black ice”. Congelation derives from “congeal”, meaning freeze or thicken, increase in viscosity.

Conservation of mass
The principle that mass in a system is neither created nor destroyed, expressed by the relation: the rate of change of mass in an element of the system equals the rate at which mass enters the element minus the rate at which mass leaves the element.

The definition rests on the convention that all flows are positive in the positive coordinate direction. With the commonest alternative convention, that inward flows are positive and outward flows are negative, the definition would be read with “plus” replacing “minus”.

Continuity equation
The mathematical expression of the conservation of mass or (ice-equivalent) volume, the principle being that the rate of change of storage of material in an element is the rate of flow of material into the element minus the rate of flow of material out of the element; in ice-equivalent units:

\[ \dot{h} = \dot{b} - \nabla \cdot \dot{q} \]

where \( \dot{h} \) is the rate of change of glacier thickness, \( \dot{b} \) is the climatic-basal mass-balance rate and \( \nabla \cdot \dot{q} \) is the volumetric flux divergence. (The rates are positive in the positive coordinate direction.) To determine \( \dot{b} \), the element is taken to be a vertical column through the glacier, and the equation is rearranged as

\[ \dot{b} = \dot{h} + \nabla \cdot \dot{q} \]
When the flux divergence $\nabla \cdot \vec{q}$ is positive, it is called the \textit{submergence velocity}. When it is negative, it is called the \textit{emergence velocity}.

Each of the terms in the continuity equation entails approximations in practical use. The term $\hat{h}$ assumes that the mean \textit{density} is constant, the \textit{point mass balance} is usually approximated by the \textit{surface mass balance}, while the calculation of the flux divergence nearly always requires an assumption about the unknown vertical profile of the horizontal component of ice velocity.

\textbf{Conventional balance}

The \textit{mass balance} of a glacier, the term having been introduced by Elsberg et al. (2001) to distinguish the mass balance from the \textit{reference-surface balance}, which is the balance the glacier would have if the glacier surface geometry were fixed in time.

Conventional balances are obtained when point measurements over a particular time interval are extrapolated to the glacier \textit{area and area-altitude distribution} measured during the same time interval. Calculations of conventional balance require repeated mapping of glacier \textit{hypsometry} at intervals appropriate to the rate of change of the surface geometry. However, maps are often re-calculated at longer time intervals, the reported balances being a combination of conventional and reference-surface balances.

Conventional balances are relevant for hydrological applications because they represent the actual mass change of a glacier. Conventional balances are not simply correlated to variations in climate because they incorporate both climate forcing and changes in glacier hypsometry. For glacier/climate investigations the \textit{reference-surface balance} is a more relevant quantity.

\textbf{Crater glacier}

A glacier contained in or overflowing from a volcanic crater.

\textbf{Crevasse}

A crack formed in \textit{glacier ice} when tensile stresses exceed the tensile strength of the ice.

The tensile stresses, and the tensile strength of the ice, are variable, and compressive stress at depth is believed to play a role in limiting the depth to which surface crevasses propagate. This depth can be up to a few tens of metres, or more if the crevasse is filled with water.

Crevasses are conduits for the transfer of water, including surface \textit{meltwater}, to the glacier interior and sometimes the glacier bed; see \textit{moulin}. When crevasses in floating ice fill with surface meltwater, they may propagate to the base, causing the \textit{ice shelf} or \textit{floating tongue} to disintegrate. The fragments may contribute to an ice \textit{melange}.

\textbf{Crevasse stratigraphy}

The observation of annual and other layer thicknesses in the walls of \textit{crevasses} and similar nearly vertical exposures.

See \textit{ice-core stratigraphy}.

\textbf{Cryoconite}

Dark, fine-grained debris on the \textit{glacier} surface, often forming small, roughly circular patches. See \textit{cryoconite hole}.

The word was introduced by Nordenskiöld in 1872.

\textbf{Cryoconite hole}

A small cylindrical hole on the surface of a \textit{glacier}, formed by patches of \textit{cryoconite} that absorb more short-wave radiation than the surrounding ice, melting downwards at a faster rate and adding to sub-metre-scale spatial variability in \textit{ablation}. See also \textit{weathering crust}.

\textbf{Cumulative (adj.)}

Descriptive of a quantity that has been summed over a span of time.
Cumulative mass balance

The mass of the glacier, or part of the glacier, at a stated time relative to its mass at some earlier time $t_0$, considered as a function of time, $M(t) - M(t_0)$. See Figure 5, and section 4.3.

Figure 5. a: Cumulative mass balance relative to 1966 (red, left axis) and annual mass balance for 1966 to 2009 (blue, right axis) of Austre Brøggerbreen, Svalbard. b: Cumulative mass balance relative to 1 October of Year 1 (red, left axis) and daily mass balance (blue, right axis) over three mass-balance years of a representative northern-hemisphere glacier; after Huss et al. 2009.
Data Analysis Services (DAS)
A series of services for the storage, analysis and dissemination of scientific data under the sponsorship of the International Council for Science (ICSU).

In 2009, the Data Analysis Services and the World Data Centres (WDC) were reorganized within ICSU’s new World Data System (WDS).

Day of the year
One plus the number of days elapsed since 0.0 hours on 1 January of a given calendar year.

The day of the year is not the same as the Julian day number or the Julian date.

Dead ice
Any part of a glacier that does not flow at a detectable rate. Stagnant ice is a synonym.

Debris-covered glacier
A glacier that supports a layer of rock, dust or ash detritus on most or all of the surface of its ablation zone.

In the accumulation zone any deposited debris is buried by later snowfalls, but in the ablation zone debris remains at the surface and englacial debris is added to the surface layer from beneath as ice ablates away.

The debris cover affects the rate of ablation, with very thin debris resulting in accelerated melt and debris thicker than a few tens of millimetres reducing the melting rate.

Degree-day
The name of a derived unit, the K d, equal in magnitude to a departure of temperature, above or below a reference temperature, averaging 1 K over a period of 1 day.

Different choices of the reference temperature lead to different kinds of degree-day, such as the heating degree-day and freezing degree-day. The kind that is relevant in studies of mass balance is the positive degree-day (above the reference temperature 0 ºC).

Degree-day factor
In a positive degree-day model, the coefficient of proportionality \( f = -\alpha / \varphi \) between surface ablation a (which is negative) and the positive degree-day sum \( \varphi \) over any period.

The degree-day factor parameterizes all of the details of the energy balance that results in ablation by melting and possibly sublimation, and it is therefore a simplification. It is usually treated as one or more constants; in particular, it is different for snow and for glacier ice, because the ice is generally less reflective than snow. It is usually expressed in mm w.e. K\(^{-1}\) d\(^{-1}\) or kg m\(^{-2}\) K\(^{-1}\) d\(^{-1}\).

Densification
The conversion of snow to firn and then to glacier ice.

Newly fallen snow (Table B6) has a variable density depending on the meteorological conditions of its formation and deposition. The density of dry snow increases rapidly at first, by the conversion of snowflakes to grains. Then, usually under the pressure of an increasing overburden of newer snow, density increases more slowly by settling of the grains to about 550 kg m\(^{-3}\), representing the maximum practically attainable packing. Snow becomes firn (in the structural sense) over a range of density beginning at about 400 kg m\(^{-3}\).

Beyond the maximum packing density, even slower mechanisms of densification – sintering and plastic deformation of the grains, and recrystallization – become dominant. When the firn reaches a density of about 830 kg m\(^{-3}\), the pore spaces between crystals are closed off, air can no longer flow (as opposed to diffusing through the crystal lattices), and the substance is deemed to be glacier ice.

When there has been no melting, densification rarely proceeds beyond 400 kg m\(^{-3}\) over the course of a typical mid-latitude winter. Depending on the accumulation (that is, loading) rate, glacier ice may
be produced in times from a few years to a few centuries. Melting followed by refreezing can yield bulk densities near that of pure ice in times shorter than a day.

**Density**
The ratio of the mass of any substance to the volume that it occupies.

Density is expressed in kg m\(^{-3}\). The density of the matter constituting the glacier can range from as low as 10 kg m\(^{-3}\), at the surface in unusual weather, to the density of pure ice at depths at which all air has been squeezed out of bubbles. See Table B6, and densification.

It is very common to assume that the bulk density of the glacier is 900 kg m\(^{-3}\). This reduced density is a rough-and-ready allowance for the presence of snow and firn, large voids (crevasses, moulins and subglacial cavities) and sediment. Where a large proportion of the glacier thickness consists of snow and firn, a bulk density even lower than 900 kg m\(^{-3}\) is appropriate. Where there is relatively little snow or firn, and the temperature is very low, a higher density, approaching or even exceeding the conventional 917 kg m\(^{-3}\), may be appropriate.

In studies of mass balance, however, densities are never known with the accuracy of laboratory measurements of pure ice, which are made by measuring the lattice parameters of single crystals. Typical field instruments are hand-held corers and spring balances, and inaccuracies of the order of 4–8% are usual. Better accuracy is possible in principle with advanced devices such as neutron-scattering probes, but these are not in routine use.

In some circumstances, such as when a load of low-density snow produces compensating densification at depth, the density of the mass gained or lost by the glacier may be assumed equal to the bulk density. See Sorge’s law.

**Deposition**
The process by which a vapour changes phase directly into a solid; resublimation is a synonym. See latent heat of sublimation.

**Depth hoar**
A layer of ice crystals, usually cup-shaped and faceted, formed by vapour transfer (sublimation followed by deposition) within dry snow beneath the snow surface.

Depth hoar is associated with very fast crystal growth under large temperature gradients. Sometimes a layer of depth hoar forms just above, and may assist in identifying, the summer surface. The low density and low strength of depth hoar can make it difficult to retrieve unbroken core sections during coring, and can complicate estimates of accumulation by microwave remote sensing. Layers of depth hoar also increase the likelihood of avalanching.

**Diachronous** (adj.)
Of a surface or layer, spanning time.

The word diachronous is needed most commonly when the surface or layer did not form instantaneously. The summer surface may be diachronous, forming at different times over a span of days or weeks, but it is assumed to be instantaneous. In a record of a ground-penetrating radar traverse, a marker horizon may be valuable in the determination of mass balance if it is an isochrone, but not if it is diachronous.

**Diamond dust**
An optically and physically thin layer of ground-level cloud composed of small ice crystals that settle slowly.

Typically diamond dust forms by the mixing of relatively moist air from aloft into a low-level inversion layer in which the temperature is \(-40 \, ^\circ C\) or lower, so that, upon saturation, vapour is deposited as ice crystals and not water droplets. It can be the most significant form of precipitation, and therefore of accumulation, in the interior of Antarctica, but is difficult to measure with accuracy.

**Dielectric constant**
See relative dielectric constant.
Digital elevation model (DEM)
An array of numbers representing the *elevation* of part or all of the Earth’s surface as samples or averages at fixed spacing in two horizontal coordinate directions.

Digital elevation models are now the preferred means of representing the *elevation changes* on which *mass-balance* measurements by *geodetic methods* are based. The elevation change is calculated by subtracting an earlier DEM from a later DEM. See *Finsterwalder’s method*.

A “triangulated irregular network” or TIN is a particular, more sophisticated data structure for the representation of surfaces. A “digital terrain model” is a set of arrays of numbers, including arrays not just of elevations but also of variables derived from elevation such as slope and orientation; this term, however, is often used as a synonym of “digital elevation model”.

Direct method
See *glaciological method*.

Discharge
The rate of *flow of ice* or water through a vertical section perpendicular to the direction of the flow.

Care is needed because discharge can refer to either *ice discharge* or *meltwater discharge*, as well as being used in hydrology to refer to water flow from basins in which there are no *glaciers*.

Ice discharge
*Mass flux* or volumetric flux of ice through a glacier cross section or “gate”.

The gate can be anywhere on the glacier, but is often at or close to the *terminus*. If the terminus is a *calving front*, ice discharge is usually in discrete pieces that, when discharged into a body of water, become icebergs, and the ice discharge is equivalent to the *calving flux* plus the flux due to *advance* (positive) or *retreat* (negative) of the calving front.

*Avalanching* from the *glacier margin*, for example from the margin of a hanging glacier, may constitute ice discharge; see also *dry calving*.

Meltwater discharge
The rate of flow through a cross section, usually a stream cross section, of water produced by melting of *glacier ice, firn* or *snow* that is removed from the glacier in surface, englacial or subglacial flows. See *runoff*.

The measured discharge may include a contribution from *rainfall* on the glacier, and typically includes contributions from unglacierized parts of the drainage basin.

Meltwater discharge is always reported as volume per unit time.

Divide
A line separating two contiguous *glaciers*, the horizontal *flow of ice* diverging on each side of the line. See *glacier margin, glacier outline*.

Downwasting
Thinning of the *glacier* due to *ablation*. See *dynamic thinning*.

Drifting snow
*Snow* entrained and transported within 2 m of the surface by the wind.

The height of 2 m is a convenient separator between drifting snow, which does not reduce sensibly the horizontal visibility at eye level, and *blowing snow*. See *windborne snow*.

Dry-based glacier
A *glacier* whose bed is below its *pressure-melting point*, implying that there is no liquid water at the bed. *Cold-based glacier* is a synonym.

Dry calving
*Ice discharge* from a *glacier margin* onto land, usually in discrete pieces.
**Dry-snow line**
The set of points on a glacier separating the dry-snow zone from the percolation zone. See zone.

**Dry-snow zone**
Region of the glacier where there is neither surface melting nor rainfall. See zone.

**Dust**
An accumulation of aerosol that, when deposited on the surface of a glacier, modifies the mass balance through its effect on surface albedo.

  Saharan dust, for instance, sometimes has a substantial impact on the mass balance of European glaciers. Volcanic eruptions can deliver dust and ash to nearby, and sometimes to distant, glaciers. In extreme cases the added material can turn the glacier into a debris-covered glacier.

  Dust can help to define the summer surface, and a dateable dust layer in firn or glacier ice can be useful as a marker horizon.

**Dynamic thinning**
The reduction of glacier thickness, in excess of that due to ablation, that results when the flux divergence is positive, that is, when more mass flows out of the thinning region than flows in. See downwasting.

  Dynamic thinning, when not compensated by thickening in a downstream part of the glacier, implies an enhanced calving flux at the glacier terminus, or an advance of the terminus, or both. See also calving velocity.
E

Elevation
See altitude.

Elevation change
Vertical change in glacier surface elevation (altitude), typically derived from two elevation measurements, adjusted if necessary for the difference of their respective datum surfaces, at the same (or nearly the same) horizontal coordinates.

The elevation of the surface can change due to: (i) ablation and accumulation at the surface and bottom of the glacier; (ii) compaction (densification) of snow and firn; (iii) emergence and submergence resulting from ice flow; (iv) changes in subglacial water pressure; (v) tectonic and isostatic movements of the glacier bed; and (vi) geomorphic processes (abrasion, plucking; lodgement of sediment) at the bed. Changes due to (iv) and (vi) can usually be neglected in mass-balance studies, although a correction is sometimes applied for glacial isostatic adjustment (GIA).

Surface elevation change is usually similar to thickness change, but (iv–vi) above produce elevation changes without changes of the thickness or glacier mass, while (ii) above produces a decrease of thickness with no accompanying change of mass. See continuity equation, geodetic method.

In turn, large changes of glacier thickness lead to isostatic changes of the bed elevation.

Emergence velocity
The vertical component, when it is directed upward, of the glacier-flow velocity vector at the glacier surface, at a point fixed in space.

When the component is directed downward, it is called the submergence velocity. The emergence velocity is related through the continuity equation to the climatic-basal mass balance and the rate of thickness change.

The component is typically upward in the ablation zone and downward in the accumulation zone.

End-of-summer (adj.)
See annual.

End-of-summer snowline
See article Annual snowline under Snowline.

Energy balance
A relation describing the change in the amount of energy stored within a defined volume owing to flows of energy across the boundary of the volume.

A change in the amount of stored energy, due for example to the advection or conduction of heat or the absorption or emission of radiation, will result in a change in the temperature or the phase, or both, of the material in the volume. Phase changes, in particular melting and freezing but also sublimation and deposition, couple the energy balance strongly to the mass balance. For example they determine the amount of ablation by melting and sublimation, and so the energy balance must be determined using either an energy-balance model or a temperature-index model in any attempt to model ablation.

The surface energy balance is that of an interface or degenerate volume, the thickness of which approaches zero, at the surface of the glacier. Glaciers also have internal and basal energy balances. In cold glaciers and some polythermal glaciers, the largest component of the internal energy balance is usually the heat source due to refreezing. In both the internal and basal energy balances, friction is a mechanical source of heat and heat is conducted (or advected) between adjacent volumes that are not isothermal. The geothermal heat flux is usually a significant term in the basal energy balance and basal mass balance of grounded ice, but the resulting contribution to the climatic-basal mass balance
is generally small. Exchanges of heat with sea or lake water must be considered where the ice is afloat.

**Energy-balance model**
A model of mass balance in which ablation by melting and sublimation is estimated by solving the surface energy balance.

Energy balance models require more input information than temperature-index models, but are preferred for being based on a more complete description of processes, and for superior accuracy when the input information can be supplied accurately.

**Energy of glacierization**
A less-used synonym of activity index, appearing mainly in the Russian-language literature.

**Englacial**
Pertaining to the interior of the glacier, between the summer surface and the bed.

**Equilibrium**
A state in which the mass balance is equal to zero over one or more years.

Equilibrium may hold for a single column, for an entire flowline, or for an entire glacier. See steady state.

**Equilibrium AAR**
See article Equilibrium AAR under Accumulation-area ratio.

**Equilibrium line**
The set of points on the surface of the glacier where the climatic mass balance is zero at a given moment (Figure 6).

The equilibrium line separates the accumulation zone from the ablation zone. It coincides with the snowline only if all mass exchange occurs at the surface of the glacier and there is no superimposed ice.

Unless qualified by a different adjective, references to the equilibrium line refer to the annual equilibrium line. See also equilibrium-line altitude, firn line, snowline, transient equilibrium line, zone.

**Annual equilibrium line**
The equilibrium line at the end of the mass-balance year.

At the annual equilibrium line, annual ablation balances annual accumulation and the annual mass balance is zero.

**Transient equilibrium line**
The equilibrium line at any instant, where cumulative ablation balances cumulative accumulation relative to the start of the mass-balance year.

See snowline, firn line.

Figure 6. The transient snowline, which happens to coincide with the transient equilibrium line, on Baby Glacier, Axel Heiberg Island, August 1977. The terminus is at 715 m and the transient equilibrium line at about 900 m above sea level. The annual ELA for 1976–77 was at about 980 m. Photo courtesy of J. Alean.
**Equilibrium-line altitude**  
ELA  
The spatially averaged altitude of the *equilibrium line*.  
The ELA may be determined by direct visual observation, but is generally determined, in the context of *mass-balance* measurements, by fitting a curve to data representing *surface mass balance* as a function of altitude (see *mass-balance profile*). This is often an idealization, because the equilibrium line tends to span a range of altitudes. Many approximations of the ELA have been suggested; the *glaciation level* and the *mid-range altitude* are examples.  
The ELA is understood to be the *annual ELA* unless it is qualified as the *transient ELA*.  

**Annual ELA**  
The ELA at the end of the *mass-balance year*.  
The annual ELA is not in general the same as the average altitude of the *annual snowline*. The *superimposed ice zone* lies below the annual snowline and above the annual ELA. However, if there is no *superimposed ice*, the annual snowline can be used as a proxy for the annual ELA.  

**Balanced-budget ELA**  
The ELA, sometimes denoted $\text{ELA}_0$, of a glacier with a *climatic mass balance* equal to zero on average over a number of years.  
The balanced-budget ELA is usually estimated as the altitude at which a curve fitted to an observed relation between annual ELA and annual mass balance $B_a$ crosses the axis $B_a = 0$. The uncertainty in such estimates can be substantial, especially when mass-balance sampling is sparse or the *equilibrium zone* occupies a large fraction of the glacier surface.  
The balanced-budget ELA may differ from the *steady-state ELA* because it is estimated from observations made in conditions that may not approximate to *steady state*. In particular, most measurements of mass balance published over the past several decades have been negative.  

**Steady-state ELA**  
The ELA of a glacier in *steady state*.  
The steady-state ELA is difficult to estimate because glaciers are seldom if ever in steady state. It must usually be estimated by modelling. To emphasize that the balanced-budget ELA and steady-state ELA are distinct concepts, the steady-state ELA should be given a distinctive symbol, perhaps $\text{ELA}_0'$.  

**Transient ELA**  
The ELA at any instant, particularly during the *ablation season*.  
The transient ELA is not in general the same as the average altitude of the *transient snowline*. The *superimposed ice zone* lies below the transient snowline and above the transient ELA.  

**Equilibrium zone**  
Part of a *glacier* bounded by two contours of surface *elevation*, within which the *equilibrium line* lies.  

**Evaporation**  
The process by which a liquid changes phase into a vapour. See *latent heat of vaporization, Table B1*.  

**Evapotranspiration**  
The process by which a liquid changes phase into a vapour, explicitly including the transpiration that happens at the stomata of the leaves of plants. See *evaporation*.  

**Expanded foot**  
The fan of *glacier ice* formed when a *valley glacier* or *outlet glacier* flows beyond its constricting valley walls onto lowland terrain and expands laterally.  

**Expanded-foot glacier**  
A glacier with an *expanded foot*, the lateral expansion of which is too limited to justify calling the glacier a *piedmont glacier*.
Facies
A collection of attributes serving to distinguish one part of the glacier from others; by extension, the part of the glacier so distinguished.

The term, originally Latin for “face, outward appearance”, was borrowed from geology. Examples of diagnostic attributes include ice lenses in the firn, indicating refreezing and therefore the percolation facies; the absence of such lenses, possibly suggesting the dry snow facies; or the seasonal exposure of glacier ice, indicating the ablation facies.

In glaciology the term zone is equivalent and is now more common.

Feature tracking
A method for estimating glacier surface velocities by measurement of the positions of easily distinguishable features on repeated images of known date. See speckle tracking.

Surface debris and crevasses are the most commonly measured features.

Finsterwalder’s method
A method for the measurement of elevation change by comparison of contours on maps of two dates.

The area between the later and the earlier instance of each contour is measured. The average elevation change of the region between any two contours is the sum of the area changes (later minus earlier) of the two contours, divided by the sum of the earlier and later areas of the region and multiplied by the difference of the contour elevations.

The method, described by Finsterwalder (1953), is now less used, having been superseded by the preparation and subtraction of digital elevation models.

Firn
1 Snow that has survived at least one ablation season but has not been transformed to glacier ice.

This sense prevails in the study of mass balance. Snow becomes firn, by definition, at the instant when the mass-balance year ends. See zone.

2 Structurally, the metamorphic stage intermediate between snow and ice, in which the pore space is at least partially interconnected, allowing air and water to circulate; typical densities are 400–830 kg m$^{-3}$ (Table B6).

In this sense, the firn is generally up to a few tens of metres thick on a temperate glacier that is close to a steady state, and up to or more than 100 m thick in the dry snow zone on the ice sheets.

Firn area
The zone of the glacier where the summer surface is underlain by firn instead of glacier ice.

Changes in extent of the firn area, and thickness of the firn, complicate mass-balance calculations by the geodetic method since Sorge’s law no longer applies.

The firn area is not the same as the accumulation zone.

Firn-ice zone
See infiltration zone.

Firn limit
A synonym of firn line.

Firn line
The set of points on the surface of a glacier delineating the firn area and, at the end of the mass-balance year, separating firn (usually above) from glacier ice (usually below).

In steady state and equilibrium, and in the absence of superimposed ice, the firn line coincides with the equilibrium line. However, the equilibrium line will generally be above the firn line in a year.
of negative mass balance; in a year of positive mass balance it will in general be below the firn line of the previous year (see Figure 15).

**Fixed-date system**
The time system in which mass balance is determined by conducting field surveys on fixed calendar dates.

The fixed date representing the start of the mass-balance year is usually at the start of the local hydrological year. To determine seasonal balances, a fixed date is chosen to represent the mean date of the end of the accumulation season. Due to logistical constraints it is often impossible to conduct field surveys on these exact dates. Therefore the data need to be corrected, which is often done by estimating ablation and accumulation between the survey date and the fixed date using meteorological data from a nearby weather station or a database of upper-air measurements.

See also measurement year, stratigraphic system, floating-date system, combined system.

**Floating-date system**
The time system in which mass balance is determined by conducting field surveys on floating calendar dates.

Annual field surveys are usually carried out close to the beginning of the hydrological year. For the determination of seasonal mass balances, a survey is carried out close to the end of the accumulation season, without interpolation or extrapolation to a fixed date.

The duration of the mass-balance year varies in the floating-date system. See also measurement year, stratigraphic system, fixed-date system, combined system.

**Floating tongue**
The terminal part of a glacier, the weight of which is partially or entirely supported by lake or sea water.

Lateral stress from valley walls, and possibly from ice rises and other grounded parts of the glacier, supports a significant part of the weight of the floating ice, in which respect floating tongues generally differ from ice shelves.

**Flotation**
The transition from being grounded to being afloat, made when the pressure $p_wgd$ exerted by water of depth $d$ on adjacent ice of thickness $h = d + h_{flot}$ becomes just equal to the weight $p_i gh$ of the ice; $p_w$ is the density of the water, $p_i$ is the depth-averaged density of the ice (allowing for example for crevasses and possibly snow or firn) and $h_{flot}$ is the freeboard, that is, the elevation of the ice surface above the water level.

The definition neglects tidal flexure and some other lesser phenomena. It represents mutual hydrostatic equilibrium of the column of water and the adjacent column of ice: the water below $d$ supports the weight of both columns, which are at rest with respect to each other. If the two densities are known, a measurement of the freeboard of floating ice is a measurement of ice thickness, which is required for the calculation of ice discharge.

The condition for flotation is $d = h \rho_i / \rho_w$. A condition for being afloat is $d \geq h \rho_i / \rho_w$.

The spellings “flotation” and “floatation” are equally acceptable, although the former is more common.

**Flow**
Motion of an ice body by a combination of internal deformation, rigid displacement over the bed and deformation of bed material.

Rigid displacement over the bed is called basal sliding, and implies that the ice at the bed is at its pressure-melting point.

The speed and direction of the flow are determined by a balance of forces. In the momentum balance, acceleration terms are negligible. Typically, gravity is balanced by pressure and frictional forces.
Flowline

1. A sequence of columns of infinitesimal cross section, each extending vertically from base to surface of the glacier, arranged so that each column but the first gains mass by flow from an upglacier neighbour and each column except possibly the last loses mass by flow to a downglacier neighbour.

2. The trace of such a sequence on the glacier surface.

Ideally, the upglacier and downglacier walls of all the columns would be at right angles to the local horizontal velocity vector. It is assumed that flow through the other two walls of the columns may be neglected, by allowing an implicit relative width of the flowline to vary and thus to account for transverse straining. In practice, velocity measurements are usually sparse or lacking and it is necessary to construct the flowline from the surface topography. The topography is averaged within a radius of the order of the glacier thickness, to suppress the effect on calculations that might be exerted by short-wavelength topographic features that are not due to the glacier flow.

The definitions may be extended to accommodate interrupted glaciers, in which part of the “flow” is by avalanching from an upper part to a lower part.

Fluctuations of Glaciers (FoG)

A database containing information on glacier changes, such as in length, area, mass, mass balance and volume, archived and published by the World Glacier Monitoring Service and its predecessor organisations since 1895.

Flux divergence

The divergence $\nabla \cdot \vec{q}$ of the horizontal flux vector $\vec{q}$, which is the integral through the glacier thickness $h$ of the vertical profile of the horizontal mass flux vector $\rho \vec{u}$ or velocity vector $\vec{u}$.

For one-dimensional flow, for example along a flowline, the divergence reduces to the derivative $\frac{\partial \vec{q}}{\partial x}$ of the vertically integrated mass flux or volumetric flux with respect to horizontal distance $x$.

The integrated horizontal mass flux vector (dimension $[ML^{-1}T^{-1}]$), where $\rho$ is the density, is

$$\vec{q} = \int_0^h \rho(x) \vec{u}(x) \, dz$$

When it is reasonable to assume incompressibility of the medium, that is, when snow and firn occupy only a small fraction of the total thickness, a simpler definition of the volumetric flux vector (dimension $[L^2T^{-1}]$) is

$$\vec{q} = \int_0^h \vec{u}(x) \, dz$$

Because the vertical profile of the velocity is generally not known, an approximation is usually made: in volumetric units, with $h$ the ice-equivalent thickness, $\vec{q} \approx h \gamma \vec{u}_{se}$. Here $\gamma$ is the ratio of the mean velocity through the glacier thickness to the surface velocity and ranges from $\gamma = 1$ for pure sliding motion down to $\gamma \approx 0.8$ or lower for motion due solely to deformation.

See emergence velocity, submergence velocity.

Flux-divergence method

Application of the continuity equation to determine mass balance at a point using measurements on the glacier surface or remotely of thickness, thickness change and surface velocity.

The required data may be obtained:

1. for thickness, from boreholes or radar;
2 for thickness change, from repeated optical surveying, laser altimetry, radar altimetry, photogrammetry, or Global Positioning System determinations of altitude;
3 for surface velocity, from repeated optical surveying or Global Positioning System determinations of stake locations or feature tracking.

In the case of several repeated thickness change and velocity determinations, thickness can also be obtained as the solution of a problem in geophysical inverse theory.

**Forbes band**
See ogive.

**Forefield**
See glacier forefield.

**Freeboard**
The elevation of the surface of a floating ice body above the surface of the water in which it is afloat. See flotation.

**Freezing**
The process by which a liquid changes phase into a solid; a synonym of solidification.

**Freezing point** \( T_m \) or \( T_f \)
The temperature, equal to 273.15 K (0 °C) when the pressure is equal to a standard pressure of 101325 Pa, at which pure water freezes, releasing an amount of energy known as the latent heat of fusion (Table B1). Melting point is a synonym.

Strictly the freezing point is the (temperature, pressure) pair of numbers, but the variation of pressure at the surface of the glacier has negligible effect and the term is applied to the temperature alone.

See pressure-melting point, ice point.

**Freezing rain**
Rain that freezes upon impact, forming a surface coating of glaze, or after percolating below the glacier surface.

**Front**
See glacier front.

**Frontal ablation** \( a_t, A_t \)
Loss of mass from a near-vertical glacier margin, such as a calving front.

The processes of mass loss can include calving, subaerial melting and subaerial sublimation, and subaqueous frontal melting.

**Fusion**
The process by which a solid changes phase into a liquid; a synonym of melting. See latent heat of fusion, Table B1.
Geodetic method
Any method for determining mass balance by repeated mapping of glacier surface elevations to estimate the volume balance; cartographic method and topographic method are synonyms.

The conversion of elevation change to mass balance requires information on the density of the mass lost or gained, or an assumption about the time variations in density (see Sorge’s law). Elevation changes are commonly measured using repeated altimetry, photogrammetry or ground surveys. In the past, glacier mapping relied on ground surveying with theodolites and similar instruments, but global navigation satellite system receivers are now usual, offering more rapid and more accurate coverage. The entire glacier surface may be mapped, but more sparse elevation measurements, for example along a central flowline, are often extrapolated to the full glacier surface.

Glacial isostatic adjustment (GIA)
A change of glacier surface elevation due to vertical motion of the glacier bed under the influence of mass redistribution in the underlying solid Earth.

Present-day mass redistribution in the Earth’s interior is dominated by continuing adjustment to the redistribution of surface water at the end of the most recent ice age. Corrections are also required for vertical motions of tectonic origin in some regions, such as the Karakoram.

Glaciated
Covered by glacier ice in the past, but not at present. See glacierized, which refers to present-day coverage.

Glaciation level
In any small glacierized region, the average of the elevations of the highest unglacierized peak and the lowest glacierized peak.

The glaciation level has been used as a regional-scale proxy for the steady-state ELA, although a correction is required for this purpose because the glaciation level is known to be systematically higher by about 200 m. See mid-range altitude.

Glaciation limit
A less-used synonym of glaciation level.

Glacier
A perennial mass of ice, and possibly firn and snow, originating on the land surface by the recrystallization of snow or other forms of solid precipitation and showing evidence of past or present flow.

For mass-balance purposes glaciers are delineated, when possible, by outlines across which there is no flow, so that transfer of mass as ice across those outlines is zero. Any change of the outline during the study period must be allowed for appropriately. If part of the outline fails the no-flow test, such as at a grounding line, the ice discharge must be included as a component of the mass balance.

In contrast to what is natural in dynamic glaciology and glacial geomorphology, for mass-balance purposes the glacier consists only of frozen water. Sediment carried by the glacier is deemed to be outside the glacier. Meltwater in transit or in storage, for example in supraglacial lakes or subglacial cavities, is also regarded as being outside the glacier.

Glaciers may contain or consist of other glaciers. The more generic term glacier complex is available for objects that may be divisible into more than one glacier, and the term ice body is available for any object that is made mainly of ice and may or may not be a glacier.

Glacier complex
A number of contiguous glaciers; a generic term for all collections of glaciers that meet at divides.
Glacieret
A very small glacier, typically less than 0.25 km² in extent, with no marked flow pattern visible at the surface.

To qualify as a glacieret, an ice body must persist for at least two consecutive years.

Glacierets can be of any shape, and usually occupy sheltered parts of the landscape. Windborne snow and avalanches can be dominant contributors to the accumulation of glacierets.

Glacier fluctuations
Glacier changes with time, such as changes of length, area, thickness, volume and mass.

Glacier forebay
The water in front of a calving glacier into which icebergs are discharged.

Glacier forefield
An unglacierized area abutting on a glacier margin.

Glacier front
The terminus of the glacier.

Glacier ice
1 Ice that is part of a glacier, as opposed to other forms of frozen water such as ground ice and sea ice.

2 Ice that is part of a glacier, having formed by the compaction and recrystallization of snow to a point at which few of the remaining voids are connected, and having survived at least one ablation season.

In this more restricted sense, the term refers to the body of the glacier, excluding not only snow and firn but also superimposed ice, accreted ice and marine ice. See zone.

The density at which voids cease to form a connected network, that is, the density at which firn becomes glacier ice, is conventionally taken to be near to 830 kg m⁻³ (Table B6).

Glacier inventory
A detailed record of the attributes of the glaciers in a region. See World Glacier Inventory.

Glacierized
Of a region or terrain, containing glaciers or covered by glacier ice today. See glaciated, which refers to past coverage.

Glacier margin
The line separating the glacier from ice-free terrain. See divide, glacier outline, boundary, terminus.

Glacier outline
The line in horizontal space separating the glacier from unglacierized terrain or, at divides, from contiguous glaciers. See glacier margin, boundary.

Glacier table
A rock that rests on a pedestal of ice formed when ablation of the ice beneath the rock is less than ablation of the surrounding bare ice.

Glacier terminus
See terminus.

Glacier tongue
See tongue.
Glacier-wide (adj.)
Descriptive of a quantity that, whether or not it is expressed in specific units, has been measured or estimated over the entire glacier.

The adjective is used to emphasize that the mass balance is that of the entire glacier and not that at a “specific” location (for which the recommended term is point mass balance).

Glaciological method
A method of determining mass balance in situ on the glacier surface by measurements of accumulation and ablation, generally including measurements at stakes and in snow pits; direct method has long been a synonym.

The measurements may also rely on depth probing and density sampling of the snow and firn, and coring. They are made at single points, the results from a number of points being extrapolated and integrated to yield the surface mass balance over a larger area such as an elevation band or the entire glacier. The internal mass balance and basal mass balance, and ice discharge if any, are treated separately.

Glaciological noise
In an ice core, fluctuations in layer thicknesses that are due not to variations in the rate of spatially averaged annual accumulation but to redistribution of snow by the wind, including the migration of snow dunes and zastrugi across the core site.

Glaze
1 A solid surface deposit formed by the freezing of supercooled raindrops or possibly of condensed water vapour, distinguished from rime by having a density near that of ice. See also hoar.

In this sense, glaze represents accumulation.

2 A surface deposit of ice formed by a short episode of melting that results only in recrystallization and not in percolation and is followed by a return to sub-freezing temperatures.

In this sense, glaze is largely responsible for the creation of the summer surface.

Global Land Ice Measurements from Space (GLIMS)
An initiative launched during the 1990s to monitor the world’s glaciers, relying primarily on optical satellite imagery.

GLIMS (Rau et al. 2005; Raup et al. 2007a, 2007b) is a leading source of information about glacier extent, as described by digitized glacier outlines, and glacier fluctuations. It involves a large number of investigators distributed around the world. It is coordinated at the University of Arizona, Tucson, and its database is developed and maintained at the National Snow and Ice Data Center, Boulder, Colorado, U.S.A.

Global navigation satellite system (GNSS)
Any satellite navigation system that provides positioning information to suitable receivers located anywhere on the Earth or in its vicinity.

The United States’ Global Positioning System was the only fully operational GNSS until September 2010, when the Russian GLONASS achieved full global coverage. The Galileo system under development by the European Union is scheduled to become operational in 2013.

Global Positioning System (GPS)
A constellation of satellites, currently 24 to 32 in number, orbiting at an altitude of 20,200 km, the pattern of the orbits being designed so that, in principle, at least six satellites transmitting timing and orbital-position information are above the horizon at any point on the Earth’s surface at any time; the satellites constitute the “space segment”, and the system is completed by a “control segment”, monitoring and synchronizing the satellites from ground stations, and a “user segment” or GPS receiver.
A GPS receiver converts the transit time of each transmitted message to the distance of the transmitting satellite, and uses the resulting distances and the transmitted information about satellite positions to determine its own position by trilateration. A minimum of four satellites must be observed to solve for the three-dimensional position \((x, y, z)\) of the receiver’s antenna.

The Global Positioning System, developed by the United States Department of Defense, has transformed the practice of positioning, both for ground and airborne surveys and for positioning of Earth-monitoring satellites in orbits lower than those of the GPS constellation. Accuracies better than a few metres are readily attainable in ground surveys. Accuracy improves with observing time.

In differential GPS or DGPS operations, a receiver is installed at a base station the location of which is known precisely. The location deduced from signals received by the base receiver is compared with the known location, and the difference is used to correct the locations of a mobile receiver, sometimes called a rover. Absolute positions in an appropriate coordinate frame can be determined with accuracies better than 0.1 m.

**Global Terrestrial Network for Glaciers (GTN–G)**

Part of two related systems, the Global Terrestrial Observing System (GTOS) and the Global Climate Observing System (GCOS), for the detection and management of global and regional environmental change in support of the United Nations Framework Convention on Climate Change and the work of the Intergovernmental Panel on Climate Change.

Since its creation in 1998 the GTN–G has been managed by the World Glacier Monitoring Service (WGMS) in close collaboration with the US National Snow and Ice Data Center (NSIDC) and the Global Land Ice Measurements from Space initiative (GLIMS). GTN–G implements an integrated, multi-tier monitoring strategy, and is responsible for providing data on mass balance \((\text{kg m}^{-2} \text{a}^{-1})\), length change (m) and area \((\text{km}^2)\) of glaciers other than the ice sheets, defined as Essential Climate Variables, to GCOS and GTOS.

**GRACE**

The Gravity Recovery and Climate Experiment. See gravimetric method.

**Gravimetric method**

A technique in which glacier mass variations are calculated from direct measurements of Earth’s gravity field.

Satellite gravimetry is at present the most feasible method for determining glacier mass balance from changes in gravity. The Gravity Recovery and Climate Experiment (GRACE) consists of two polar-orbiting satellites separated by about 200 km along-track, and is the primary mission for this work to date. Precise measurements of range and range rate are used to construct local gravity fields after correcting for non-gravitational accelerations. Suitable models are used to remove gravity variations resulting from atmospheric, hydrospheric and lithospheric mass variations, leaving a time series that represents the glacier mass balance (usually summed and shown as the cumulative mass balance). GRACE spatial and temporal resolutions as good as 2 arc degrees and 10 days have been achieved. Satellite gravimetry is limited by the quality of observations used to constrain the models of non-glacial mass variations, and at present it can resolve only large and rapidly changing glacier complexes or glacierized regions. A distinctive advantage of the method is that it yields a direct measure of mass and does not require density corrections such as those required for geodetic methods.

Glacier mass balance has also been estimated using ground-based gravimeters. Measurements at two or more times yield the change in absolute gravity that results from the change in vertical position of a sensor on the glacier surface or at a fixed position above it, and from changes in glacier mass. This technique may become more widely developed as gravimeter resolution, precision and portability improve.

**Gravity Recovery and Climate Experiment (GRACE)**

See gravimetric method.
Grounding line
The set of points separating the floating part of a glacier from the grounded part. See flotation.

Usually the floating part is downstream and the grounded part is upstream. However, the “shorelines” of subglacial lakes are grounding lines.

Ground-penetrating radar (GPR)
A radar, usually a pulsed system with one transmitting and one receiving antenna, operating at a frequency suitable for imaging the subsurface.

In glaciology, low frequencies (2–220 MHz) are suitable for ice thickness measurements whereas higher frequencies of several hundred MHz are suitable for snow thickness measurements, including detection of the current summer surface and older annual layering (see radar method). Higher frequencies yield better resolution but may not allow very deep penetration; lower frequencies exhibit the reverse properties. Choice of frequency is therefore paramount.

Radar imaging of the subsurface relies on accurate determination of the two-way travel time of the radar wave, which depends on the density. Reflections are caused by contrasts in the (complex) relative dielectric constant at interfaces between layers. Illustrative values of the real part of the relative dielectric constant, at frequencies used by ground-penetrating radars, are 1 for air, ~3.15 for pure ice, ~10 for bedrock and 88 for water at 0 °C. Interfaces between these media tend to be identifiable readily. More subtle contrasts between layers, due to variations in density, water content, salinity or the concentration of solid impurities, can also be identified. See marker horizon, and also bomb horizon.

The term ground-penetrating radar is now used more often than the synonymous and more descriptive radio-echo sounding. Sometimes the term “tomography” is used with the same meaning.

Growth time
The time scale for a glacier to attain steady state from an initial state of zero mass. See response time.
Hanging glacier
A glacier, usually small, that clings to a steep slope, or a glacier that terminates abruptly at the top of a cliff.

Health
The extent to which the mass balance, usually averaged over a period of some years, differs from zero, growth or equilibrium representing "good health" and a negative mass balance representing "poor health".

The term is generally used only informally.

Hoar
A surface deposit of interlocking ice crystals formed by the deposition of water vapour. See also glaze, rime; depth hoar.

Homogenization
A procedure to correct mass-balance measurement time series for artefacts and biases that are not natural variations of the signal itself but originate from changes in instrumentation or changes in observational or analytical practice.

Systematic artefacts can distort or even hide the true signal. Homogenization may lead to the detection and removal of measurement errors. Gaps in the time series may be filled by interpolation or modelling at the same time as the homogenization procedure.

The uncorrected measurements should remain available after the homogenized measurements have been published.

See reanalysis.

Hydrological method
A method of determining the mass balance indirectly by solving the water balance for the change in storage $\Delta W$ in a drainage basin:

$$\Delta W = P - E - Q,$$

with $P$ the precipitation, $E$ the evapotranspiration and $Q$ the discharge, each of these quantities being a total over a stated span of time.

In practical work the hydrological method can be applied only to an entire drainage basin. It does not provide any information on the spatial distribution or gradients. The quantity $\Delta W$ will include changes in storage in lakes, seasonal snowpatches, soil and aquifers as well as in the glacier. Each of these changes must be accounted for to isolate the mass balance of the glacierized part of the catchment, but the changes in storage other than in the glacier and the snow cover are often assumed to be negligible over annual periods.

Hydrological year
A period of one year, synchronized with the natural progression of the hydrological seasons by specifying the calendar date of its first day.

Generally in glaciology the hydrological year is found to be convenient because it begins near the start of the accumulation season and ends near the end of the ablation season. For example the appropriate dates are 1 October to 30 September in the mid-latitudes of the Northern Hemisphere. The concept of the hydrological year is most useful where the accumulation and ablation seasons are well differentiated, as on mid-latitude glaciers and most high-latitude glaciers, but it is less well suited to those regions in which there are more than two hydrological seasons, as in the tropics, or in which most of the accumulation occurs in the same season as most of the ablation, as in monsoon climates (see summer-accumulation type.).
**Hypsometric curve**
A graph of the *area-altitude distribution*, as in Figure 7; hypsographic curve is a synonym.

The hypsometric curve shows the area-altitude distribution by plotting *area* on the horizontal axis versus *altitude* on the vertical axis. Intervals on the altitude axis are commonly 25, 50 or 100 metres.

![Hypsometric curves](image)

**Figure 7.** Hypsometric curves (left) and *cumulative* hypsometric curves (right) for two glaciers in Norway.

**Hypsometry**
The measurement of the distribution of glacier area with surface *altitude (elevation)*, or more loosely the result of such measurement.

Hypsometric and topographic data are essential for converting measurements of the *mass-balance profile* to glacier-wide estimates of the *mass balance*.

Hypsography is a synonym. See *area-altitude distribution, hypsometric curve*. 
I

Ice
Water substance in the solid phase.

Ice can occur in many forms. At and near the Earth’s surface, ice always crystallizes in the hexagonal system. This phase is designated ice Ih, the Roman numeral I distinguishing it from more than a dozen other phases and the letter h distinguishing it from the metastable cubic phase ice Ic.

See, among other articles, glacier ice and diamond dust.

Ice apron
1 A synonym of mountain apron glacier.
2 A conglomerate of snow, refrozen meltwater and blocks of ice resulting from dry calving, found fringing the base of a steep terminus, typically that of a cold glacier.

Ice body
Any continuous mass of ice, possibly including snow and firn, at or beneath the Earth’s surface.

Glaciers, ice shelves, ice floes, icebergs, a continuous cover of sea ice, ice wedges in permafrost, and accumulations of ice in caves are all examples of ice bodies.

Ice cap
A dome-shaped ice body with radial flow, largely obscuring the subsurface topography and generally defined as covering less than 50 000 km² (see ice sheet).

The flow pattern is less influenced by the subsurface topography than is true of icefields and valley glaciers. The definition embraces small as well as large ice bodies.

The usage “(polar) ice cap” for the sea-ice cover of the Arctic Ocean or Southern Ocean is confusing and best avoided.

Ice-core stratigraphy
The determination of layering, usually identifiable as annual or seasonal, in an ice core by visual, chemical, or isotopic methods; more loosely, the result of such determination.

After correction for thinning due to ice flow, the resulting layer thicknesses are measures of climatic mass balance. If there is no ablation, they are measures of accumulation.

While some information can be obtained from cores even when the ice is not cold, ice-core stratigraphy is usually done on cores through cold ice, such as in Greenland or Antarctica.

Ice discharge
See article Ice discharge under Discharge.

Ice equivalent
A unit, in full the “metre [of] ice equivalent”, that is an extension of the SI for describing glacier mass in specific units as the thickness (in “m ice eq.”) of an equal mass having the density of ice.

Ice equivalents can be converted to kg m⁻² by multiplying by the density of ice, and to water equivalents (m w.e.) by multiplying by the density of ice and dividing by the density of water (with sufficient accuracy, 1000 kg m⁻³).

Icefall
A steep reach of a glacier where the ice becomes heavily crevassed, commonly when flowing over a bedrock step.

Icefield
A large ice body that covers mountainous terrain but is not thick enough to obscure all of the subsurface topography, its flow therefore not being predominantly radial as is that of an ice cap.
**Ice flux**
See mass flux, flux divergence.

**Ice mass**
A synonym of ice body.

**Ice melange**
See melange.

**Ice-penetrating radar**
*Ground-penetrating radar* when it is used to penetrate ice.

**Ice piedmont**
An expanse of glacier ice covering a lowland, nourished by two or more upland tributary glaciers.

**Ice plain**
Part of an ice stream extending upglacier from the *grounding line* and having a surface slope so small as to suggest that it is not far from the transition to being afloat. See *flotation*.

The upglacier limit of the ice plain may be marked by a measurable break of surface slope, or may be indistinct. Ice plains are documented from several of the ice streams of Antarctica.

**Ice point**  \( T_m \) or \( T_f \)
The narrowly correct name of what in everyday usage is called the melting point or freezing point of water. See pressure-melting point.

**Ice raft**
Part of an ice stream raised slightly higher, and flowing slightly more slowly, than surrounding ice.

The attributes that define the ice raft suggest that basal sliding is relatively slow at its bed, and therefore that it might represent a persistent “sticky spot”.

**Ice rise**
An area of grounded ice surrounded or almost surrounded by shelf ice or the ice of a floating tongue.

Currently the largest ice rise, with an area of 44,000 km², is Berkner Island in the Ronne-Filchner Ice Shelf.

**Ice rumple**
A small ice rise, generally of irregular outline, or a group of small ice rises.

**Ice sheet**
An ice body that covers an area of continental size, generally defined as covering 50,000 km² or more.

Currently there are only two ice sheets, the Greenland Ice Sheet and the Antarctic Ice Sheet. The latter is sometimes subdivided into the East Antarctic Ice Sheet and the West Antarctic Ice Sheet.

See ice cap.

**Ice shelf**
A thick and extensive ice body attached to a coast and floating on the sea, gaining mass by flow from grounded glacier ice. See floating tongue, shelf ice.

Ice shelves are much thicker than sea ice. Currently, nearly all are located in Antarctica. The mass balance of an ice shelf may have significant components of both gain and loss at the base.

**Ice stream**
A part of an ice sheet or ice cap with strongly enhanced flow, often separated from surrounding ice by strongly sheared, crevassed margins.
“Pure” ice streams are bounded by ice on either side and lack significant non-glacial topographic control, while “topographic” ice streams are constrained by the topography. An ice stream of the latter type is similar to an outlet glacier, but outlet glaciers do not necessarily have strongly enhanced flow velocity.

**Infiltration**
The entry of a liquid such as water into a permeable solid such as snow or firn, and, more loosely, the percolation of the liquid through the void spaces of the solid.

In general, two forces govern infiltration: gravity and capillary tension. The latter allows the solid to draw in the liquid and is determined by adhesive molecular forces, which can be substantial in materials with very small pores. The rate of infiltration of a liquid into a permeable solid is determined by the porosity and liquid content of the solid and by its hydraulic conductivity.

**Infiltration ice**
In Russian-language usage, ice derived from the refreezing of meltwater that has saturated the void spaces in snow or firn. See congelation, recrystallization, superimposed ice.

**Infiltration zone**
In the Russian-language literature, part of the lower percolation zone where meltwater is abundant in the snow and firn, but the firn is either a survival from previous years of more positive mass balance or is advected by the glacier flow from higher elevations. See zone.

The infiltration zone is sometimes also referred to as the “firn-ice zone”.

**Infiltration-congelation zone**
In the Russian-language literature, a synonym of superimposed ice zone. See zone.

**Infiltration-recrystallization zone**
A term in Russian-language usage referring to the lower percolation zone, where enough meltwater is produced at the surface to percolate out of the snow and into the firn. See zone.

In the “cold infiltration-recrystallization zone”, generally at higher elevation and sometimes called the “cold firn zone”, the meltwater refreezes in the firn because the temperature is below the freezing point. This refreezing is the dominant mechanism for the formation of glacier ice. In the “warm infiltration-recrystallization zone”, generally at lower elevation and sometimes called the “warm firn zone”, the temperature is at or near the freezing point and refreezing makes a lesser contribution to the formation of ice.

The runoff limit may lie within the warm firn zone, or within the cold firn zone where slopes are steep.

**Inland ice**
A translation, seen infrequently in earlier English-language literature, of “inlandsis”, an originally Danish word which is the word for ice sheet in several European languages.

**InSAR**
An acronym for interferometric synthetic aperture radar, an instrument (and by extension a method) for microwave remote sensing of the topography, velocity field and other characteristics of a surface.

A synthetic aperture radar (SAR) consists of a side-looking radar system that takes advantage of the forward motion of the radar platform to synthesize a very long antenna, enabling a much higher ground resolution than in ordinary radar altimetry. Each SAR acquisition contains information on the amplitude and phase of the radiation reflected from the target and received at the antenna.

Interferometric SAR requires the calculation of differences in phase between two co-registered SAR images obtained with slightly different viewing geometries, either at the same time from two antennae, or at two different times from one antenna. These phase differences yield fringe patterns (interferograms) that are an expression of both surface topography and surface motion.
If the surface is not in motion, or the time between images is sufficiently short, phase differences can be converted to surface elevations with knowledge of the attitude and orbital position of the interferometer; more specifically, the baseline length, or distance between the two orbital positions, must be known. Using InSAR to detect motion of the surface requires imagery from two different epochs (repeat-pass interferometry). In this case topographic effects are removed using an independently derived digital elevation model.

**Interferometer**

An instrument that relies on the interference of waves, particularly electromagnetic waves, from a common source such as a radar to measure the length or displacement of a target with an ambiguity that is an integer multiple of the wavelength. See InSAR.

**Interferometry**

Measurement of the interference of waves, particularly electromagnetic waves, from a common source such as a radar, with the aim of obtaining information about the topography, velocity field and other characteristics of the glacier surface. See InSAR.

**Internal ablation** $a_i$ (point), $A_i$ (glacier-wide)

Loss of mass from a glacier by melting of ice or firn between the summer surface and the bed. See mass-balance units.

Internal ablation can occur due to strain heating of temperate ice as the ice deforms. However, the largest heat sources for internal ablation are likely to be the potential energy released by downward motion of the ice and of meltwater. The magnitude of the former is equivalent to a few mm w.e. a$^{-1}$, and of the latter, which occurs mainly in conduits transferring water from the glacier surface to the bed, to up to a few tens of mm w.e. a$^{-1}$. (These rates are expressed over the extent of a typical valley glacier.)

**Internal accumulation** $c_i$ (point), $C_i$ (glacier-wide)

Refreezing of water within a glacier, between the summer surface and the bed, which goes undetected by measurements of surface mass balance.

See mass-balance units, zone.

Accumulation beneath the summer surface is the refreezing of surface meltwater (or freezing of rain) that is in transit and otherwise would have left the glacier as runoff. In the case of meltwater, it may be regarded as redistributing mass within the glacier. This may require careful accounting in the calculation of mass balance.

Internal accumulation proceeds by the freezing of water that percolates early in the ablation season into firn that is still cold, heating the firn in the process, or by the freezing of retained pore water during the accumulation season, also releasing latent heat and thus slowing the downward advance of the winter cold wave.

The term is reserved for refreezing beneath the summer surface, that is, within the firn or the ice. Meltwater that refreezes within the snow does not constitute internal accumulation since it is accounted for by end-of-season density measurements as part of conventional mass-balance measurements. Internal accumulation may be small in magnitude, and negligible on temperate glaciers, but if not accounted for it constitutes a bias towards overestimation of mass loss.

In remote-sensing studies, it is not always possible to detect the summer surface. In addition models of the surface mass balance do not always distinguish between internal accumulation and refreezing within the snow. To avoid confusion, it is advisable to use “internal accumulation” only in the sense given above and to use the more inclusive “refreezing” only for “internal accumulation plus refreezing within the snow”. Refreezing within the snow should be described as such explicitly.

**Internal mass balance** $b_i$ (point), $B_i$ (glacier-wide)

The change in the mass of the glacier due to internal accumulation and internal ablation over a stated period.

See mass-balance units, climatic mass balance.
International Association of Cryospheric Sciences (IACS)
A body of the International Union of Geodesy and Geophysics (IUGG) founded in 2007 to encourage and promote research in cryospheric sciences and to facilitate the standardisation of measurement or collection as well as analysis, archiving and publication of data on cryospheric systems.

The IACS is the successor of the International Commission on Snow and Ice (ICSI).

International Commission on Snow and Ice (ICSI)
A former body of the International Association of Hydrological Sciences of the International Union of Geodesy and Geophysics (IUGG).

The ICSI can be traced back to the merger in 1939 of the International Commission on Snow with the International Glacier Commission. It became the International Association of Cryospheric Sciences, which is a full member of the International Union of Geodesy and Geophysics, in 2007. Concurrently, a new commission of the International Association of Hydrological Sciences, the International Commission for Snow and Ice Hydrology, was formed to maintain and promote contacts between the cryospheric and the hydrological sciences.

International Commission on Snow and Ice Hydrology (ICSIH)
A commission of the International Association of Hydrological Sciences launched in 2005.

The goal of ICSIH is to promote the scientific study of the processes of snow, permafrost and ice dynamics, the interactions between snow, permafrost and ice and ecosystems, and the impact of snow, permafrost and ice on runoff generation, rivers and lakes.

International Council for Science (ICSU)
A non-governmental organisation, founded in 1931, representing a global membership that includes both national scientific bodies and international scientific unions, and coordinating interdisciplinary research to address major issues of relevance to science and society.

The name International Council for Science was adopted by the International Council of Scientific Unions in 1998, but the acronym ICSU was deliberately retained.

International Glacier Commission (CIG)
A body founded in 1894 to coordinate the monitoring of glacier fluctuations.

Data collected under the auspices of the International Glacier Commission were mostly about fluctuations of glacier length. The work begun by the International Glacier Commission is traceable continuously to that coordinated by the present-day World Glacier Monitoring Service.

Interrupted glacier
A glacier consisting of two or more parts between which mass transfer or “flow” to the lower part is by avalanching.

Whether to regard the parts as separate entities is a matter of convenience. See regenerated glacier.

Inversion
A layer of the atmosphere in which temperature increases with height.

An inversion develops above a glacier surface when the air transfers heat to the surface, for example because the air is warmer than the snow or ice (which cannot have a temperature above the freezing point) or because of strong radiative cooling from the surface. The inversion in the temperature profile makes the atmosphere strongly stable, such that vertical motions of air parcels, whether convective or orographic, are retarded or suppressed.

Isochrone
A surface that formed at the same time over its entire extent. See marker horizon.
Julian date
The number of days elapsed since noon (12.0 h UTC) on 1 January 4713 BC in the proleptic Julian calendar, or 24 November 4714 BC in the proleptic Gregorian calendar.

The Julian date is a real number, not an integer. At 0.0 h UTC on 1 January 2000 AD it was 2451544.5. The Julian date is not the same as the day of the year.

Properly implemented, as for example by Press et al. (1992), an algorithm to convert between calendar dates and Julian dates is the best way to ensure that the time coordinate is represented correctly when studying the long-term evolution of mass balance in calendar time.

A proleptic calendar is one that is extended to dates before its first historical use.

Julian day number
The integer part of the Julian date.
Kinematic method
Any method of determining the mass balance that involves measurement or calculation of glacier flow, including the flux-divergence method, the kinematic-equation method and methods in which the mass balance is determined as the sum of the discharge through a cross section and the surface mass balance of the region upglacier from the cross section.

Information about density is needed to convert the volumetric fluxes obtained by kinematic methods to mass fluxes.

Kinematic-equation method
A method of determining the spatial distribution of the mass balance by solving the equation of the kinematic boundary condition at the surface for the ice-equivalent mass-balance rate \( b \) as a function of the rate of change \( \hat{h} \) of the ice-equivalent thickness, the spatial gradient of the thickness \( \nabla h \) (usually approximated by the inclination of the surface), and the velocity at the surface \( \vec{u} \):

\[
b = \hat{h} + \vec{u}_H \cdot \nabla h - \vec{u}_V,
\]

where subscripts H and V denote horizontal and vertical vector components respectively of \( \vec{u} \). It is assumed that the basal ice velocity is zero, for example because the ice is frozen to the bed.
Lake-terminating glacier
A glacier the terminus of which stands or floats in a lake.
  See calving, tidewater glacier.

Laser altimeter
An instrument for altimetry, and in mass-balance studies for the measurement of elevation change by repeated altimetry, that uses pulses of laser radiation, for example at 532 nm (green) or 1024 nm (near infrared) wavelengths.

There are both profiling and scanning laser altimeters. A profiling system is nadir-pointing, while a scanning system uses a rotating mirror, or a series of sensors arrayed in a parallel (pushbroom) configuration, to obtain a swath rather than a linear profile of measurements.

The Ice, Cloud and land Elevation Satellite (ICESat, 2003–2010) measured surface elevations with approximately 70 m footprint and 170 m along-track spacing. Adjacent tracks are separated by a few to a few tens of kilometres, the lesser separations being found at the polar extremities of the orbit. Sources of error include sensor saturation, atmospheric scattering effects, and inaccurate knowledge of the laser pointing angles. Aircraft altimeters have footprints of 1 m or smaller and along-track spacing on the order of 1 to 3 m, and are less affected by atmospheric and pointing errors. Laser altimeters are unable to obtain measurements through clouds.

Laser is an acronym standing for light amplification by stimulated emission of radiation. A related term, lidar (light detection and ranging), applies more generally to the measurement of scattered light from distant targets.

Laser altimetry
The measurement of surface elevation (altitude) with a laser altimeter.

Particularly when used to measure elevation change, laser altimetry has become a leading source of data for the measurement of mass balance by the geodetic method. If, for logistical or financial reasons, it is not possible to survey the whole glacier by airborne laser altimetry, it is necessary to extrapolate to obtain a glacier-wide geodetic mass balance.

Latent heat
The energy taken up or released per unit mass by a system in a reversible change of phase at constant temperature and pressure.

In glaciology and meteorology, the latent heats of evaporation (condensation), fusion (solidification or freezing), and sublimation (deposition or resublimation) of water phases are of importance. See Table B1, Table B4.

Latent heat of evaporation $L_v$
See latent heat of vaporization.

Latent heat of fusion $L_f$
The energy taken up by a substance as it changes phase from solid to liquid, or released as it changes phase from liquid to solid.

The amount of energy taken up in the fusion or released in the freezing of water is 333.5 kJ kg$^{-1}$ at 0$^\circ$ C. See Table B1.

Latent heat of sublimation $L_s$
The energy taken up by a substance as it changes phase from solid to vapour, or released as it changes phase from vapour to solid.

The amount of energy taken up in the sublimation or released in the deposition (resublimation) of water is 2834.2 kJ kg$^{-1}$ at 0$^\circ$ C. See Table B1.
**Latent heat of vaporization**  \( L_v \)
The energy taken up by a substance as it changes phase from liquid to vapour, or released as it changes phase from vapour to liquid. A synonym of *latent heat of evaporation*.

The amount of energy taken up in the *evaporation* or released in the *condensation* of water is 2500.8 kJ kg\(^{-1}\) at 0\(^\circ\) C. See Table B1.

**Lidar**
Light detection and ranging. See *laser altimeter*.

**Little Ice Age (LIA)**
A period of greater *glacier* mass and extent, relative to the preceding and following periods, with increased glacier thickness and extension to lower *altitudes*.

In different regions of the Earth, in both hemispheres, the Little Ice Age began and ended at different times, beginning as early as about AD 1300 and ending as late as about AD 1900, with one or more glacier advances distinguishable during that period. In many regions the LIA maximum glacier extent was also the maximum extent of the entire Holocene (the past 10 000 years). Gain of mass usually resulted from both enhanced *accumulation* and reduced *ablation*. See *trimline*. 
Margin
See glacier margin.

Marine ice
*Ice* formed by the freezing of sea water at the base of an *ice shelf*.

The formation of marine ice can contribute substantially to ice-shelf mass balance (see basal accumulation), and marine ice can be a substantial component of the ice shelf itself. See also acereted ice.

Marker horizon
A distinctive, datable layer in *ice, firn* or *snow*; see isochrone.

*Ice-core stratigraphy* relies on an uninterrupted series of annual marker horizons. Volcanic eruptions and nuclear tests (see bomb horizon) yield marker horizons which allow the measurement of average accumulation rates. Marker horizons with relative dielectric constants that contrast strongly enough allow the mapping of accumulation with ground-penetrating radar.

Mascon
The mass of a thin layer of uniform thickness added to or subtracted from a reference model of the solid and liquid Earth over a specified region, particularly a glacierized region, during a specified period. See GRACE, gravimetric method.

Mascon is an abbreviation by geodesists of “mass concentration”, coined originally to stand for a large positive gravitational anomaly. In modern usage the mascon itself is a number representing the mass of the layer as a surface density (kg m⁻²), although the word is often used loosely to refer to the “mascon region”, that is, the region over which the mass is added or subtracted. The “mascon parameters” are sets of coefficients describing the difference of gravitational potential that arises due to the mascon.

Mass balance \( \Delta m \) (point), \( \Delta M \) (glacier-wide)
The change in the mass of a glacier, or part of the glacier, over a stated span of time; the term *mass budget* is a synonym. See mass-balance units for recommended units.

The span of time is often a year or a season. A seasonal mass balance is nearly always either a winter balance or a summer balance, although other kinds of season are appropriate in some climates, such as those of the tropics. The definition of year depends on the method adopted for measurement of the balance. See time system.

The reference in the definition to a glacier means that a particular volume of space is being studied. A properly delineated glacier has no mass transfer of *ice* across its boundary other than as *ice discharge*. However, the mass balance is often quoted for volumes other than that of the whole glacier, for example a column through the glacier, the part of the glacier upglacier or downglacier from the grounding line, or a band defined by two contours of surface elevation. It is necessary in such cases to make clear that the study volume is something other than the whole glacier, and also to make clear which components of the mass balance are being reported. The quantity reported may be the climatic mass balance or the climatic-basal mass balance, but will often be the surface mass balance. In all cases the need for a defined study volume is fundamental because without it the principle of conservation of mass cannot be invoked.

The study volume may change over the study period. The surface and bed elevations may change, and the areal extent is unlikely to be the same at the end of the period as it was at the beginning. Whether these changes are significant will depend not just on their magnitude and the accuracy with which they can be determined but on the purpose of the investigation. See conventional balance, reference-surface balance.
Annual ablation $a$ (point), $A$ (glacier-wide)  
Ablation integrated over the mass-balance year.  
Annual ablation is the sum of winter ablation and summer ablation where winter and summer are well-differentiated. Formerly it was referred to as “total ablation” when working in the stratigraphic system (Anonymous 1969; Appendix A).

Annual accumulation $c$ (point), $C$ (glacier-wide)  
Accumulation integrated over the mass-balance year.  
Annual accumulation is the sum of winter accumulation and summer accumulation where winter and summer are well-differentiated. Formerly it was referred to as “total accumulation” when working in the stratigraphic system (Anonymous 1969; Appendix A).

Annual exchange  
Annual accumulation minus annual ablation.  
Ablation is defined to be negative, so the annual exchange may also be regarded as the sum of the absolute values of accumulation and ablation. It is a possible measure of the amplitude of mass exchange between the glacier and its environment, but the mass-balance amplitude is more often used for that purpose.  
Formerly annual exchange was defined only in the fixed-date system and total exchange was defined as its equivalent in the stratigraphic system (Anonymous 1969; Appendix A).

Annual mass balance $b$ (point), $B$ (glacier-wide)  
The sum of accumulation and ablation over the mass-balance year, equivalent to the sum of annual accumulation and annual ablation, and also to the sum of winter mass balance and summer mass balance where winter and summer are well-differentiated; that is,  
$$b = c + a = b_w + b_s$$

For reasons explained more fully under Net mass balance, the term annual mass balance replaces the formerly distinct terms “annual balance” and “net balance”, which were used in the fixed-date system and the stratigraphic system respectively (Anonymous 1969; Appendix A). The adjective “annual” describes the time span of the mass-balance measurement more adequately than the adjective “net”, which does not refer to a time period but rather to the mass that is remaining after all deductions (here ablation) have been made.

Net ablation  
The sum, if negative, of accumulation and ablation over any time period; if the sum is positive then net ablation is zero.  
In the ablation zone the net ablation is equal to the mass balance.

Net accumulation  
The sum, if positive, of accumulation and ablation over any time period; if the sum is negative then net accumulation is zero.  
In the accumulation zone the net accumulation is equal to the mass balance. The term appears often in ice-core studies, where the layer thickness is related to the mass balance.

Net mass balance $b_n$ (point), $B_n$ (glacier-wide)  
According to Anonymous (1969), the sum of accumulation and ablation over the mass-balance year in the stratigraphic system.  
In common usage, “net balance” has a number of meanings inconsistent with that of Anonymous (1969; Appendix A). It is used for the balance over approximately one year, regardless of the time system (see fixed-date system, floating-date system), and for balances over other periods than the mass-balance year. In these usages “net” has its plain-language meaning, referring to the change of mass after all deductions (here ablation) have been made.
To resolve this ambiguity, it is recommended that the original definition of “net mass balance” be retired, and that i) *annual mass balance* be used instead for the mass balance over a mass-balance year in any time system; and ii) explicit information about the time system be given as metadata whenever it is relevant (as it is for all measurements by the *glaciological method*). The adjective “net” thus becomes a plain-language word, and in many cases becomes redundant because the meaning of “balance” includes the meaning of “net”.

**Point mass balance**

*Mass balance* at a particular location on the *glacier*, for example at an ablation *stake* or a *snow pit*.

The point referred to is at the top of a vertical column through the glacier. Most measurements of point mass balance are actually measurements of *surface mass balance*. That is, they exclude the *internal mass balance* and *basal mass balance*, which are either assumed to be negligible or corrected for later, and the *flux divergence* of the column.

In the absence of an overriding reason for a different notation, point balances are indicated by lower-case letters, for example $b_w$ for the winter balance, while glacier-wide balances are denoted by upper-case letters, for example $B_w$.

**Specific mass balance**

*Mass balance* expressed per unit area, that is, with dimension [M L$^{-2}$] or [M L$^{-2}$ T$^{-1}$]; see *specific*.

The prefix “specific” is not necessary in general. The units in which a quantity is reported make clear whether or not it is specific. Specific mass balance may be reported for a point on the surface, a column of unit cross section, or a larger volume such as an entire *glacier* or a collection of glaciers. In the latter two cases the term “mean specific mass balance” has been used, although the adjective “mean” is also not necessary.

The definition of “specific” apparently offered by Meier (1962) has led to some confusion. He wrote:

... quantities measured at a point will first be discussed. [They] should all be prefaced by the word *specific* ... . Specific budget terms have dimensions of [length] or [length]/[time].

The confusion arises because of the primacy given by Meier to *water-equivalent* dimensions (“[length]”). The adjective “specific” indicates that the quantity has dimension [M L$^{-2}$] or [M L$^{-2}$ T$^{-1}$], not that it is being measured at a point.

The adjective “point”, as in *point mass balance*, should be used when clarity is needed.

The unit of *area* lies in the horizontal plane, not a plane parallel to the glacier surface. For mass-balance purposes this rule applies even when the surface is vertical. For example, at a *calving front* the *frontal ablation* is equal to the mass of the entire volume lost by *calving*, *melting* and *sublimation*. If quoted as a specific quantity it is divided by the horizontal area over which the balance is to be stated, such as that of the entire glacier for a *glacier-wide mass balance*.

The glaciological usage is not that which prevails in some other sciences, where often a specific quantity is either a dimensionless ratio of the value of a property of a given substance to the value of the same property of some reference substance, or is a quantity expressed per unit mass.

**Summer ablation**

$a_s$ (point), $A_s$ (glacier-wide)

*Ablation* integrated over the *summer season*.

Summer ablation is not the same as *summer mass balance*. It is generally more negative because some of the lost mass may be offset by *accumulation*. *Mass-balance* measurements by the *glaciological method* generally measure *summer mass balance* and not summer ablation.

**Summer accumulation**

$c_s$ (point), $C_s$ (glacier-wide)

*Accumulation* integrated over the *summer season*.

Part or all of summer accumulation may be lost by *ablation* before the end of the summer season.
**Summer mass balance**  \( b_s \) (point), \( B_s \) (glacier-wide)
The sum of accumulation and ablation over the summer season.

**Surface ablation**  \( a_{sfc} \) (point), \( A_{sfc} \) (glacier-wide)
Ablation at the surface of the glacier, generally measured as the lowering of the surface with respect to the summer surface, corrected for the increase in density of any residual snow and firn and multiplied by the density of the lost mass.

**Surface accumulation**  \( c_{sfc} \) (point), \( C_{sfc} \) (glacier-wide)
Accumulation at the surface of the glacier, generally measured as the rise of the surface with respect to the summer surface multiplied by the density of the added mass.

**Surface mass balance**  \( b_{sfc} \) (point), \( B_{sfc} \) (glacier-wide)
The sum of surface accumulation and surface ablation.

This is the sense in which the term is understood in descriptions of measurements by the glaciological method, in which the internal mass balance is treated separately. Recently, in estimates of ice-sheet mass balance by modelling, the term has been extended to include internal accumulation. This extended meaning is discouraged. The unambiguous term climatic mass balance is recommended for the sum of the surface mass balance and the internal mass balance.

**Winter ablation**  \( a_w \) (point), \( A_w \) (glacier-wide)
Ablation integrated over the winter season.

**Winter accumulation**  \( c_w \) (point), \( C_w \) (glacier-wide)
Accumulation integrated over the winter season.

Winter accumulation is not the same as winter mass balance. It is generally larger because some of the accumulated mass may be lost by ablation. Mass-balance measurements by the glaciological method generally measure winter mass balance and not winter accumulation.

**Winter mass balance**  \( b_w \) (point), \( B_w \) (glacier-wide)
The sum of accumulation and ablation over the winter season.

**Mass-balance amplitude**
One half of the difference between winter mass balance and summer mass balance, \((B_w - B_s)/2\).

Summer mass balance is generally negative because ablation dominates in the summer season.

A more general definition, \((C_a - A_a)/2\) or one half of the annual exchange, could be offered in terms of annual accumulation and annual ablation, but these quantities are so seldom measured that a calculation from seasonal balances is more practicable.

The balance amplitude tends to be large in maritime climates, in which accumulation is large, and small in continental climates, in which accumulation is small. In consequence the mean balance amplitude is well correlated with the interannual variability of annual mass balance, and, when it can be estimated from climatological information, has been used as an estimator of the magnitude of the annual mass balance itself.

**Mass-balance gradient**
The rate of change of mass balance with altitude, that is, the derivative \(db/dz\) of the mass-balance profile \(b(z)\).

If mass balance varies linearly with altitude, the mass-balance gradient will be constant with \(z\); if not, the gradient will vary with \(z\).

The mass-balance gradient at the equilibrium-line altitude is called the activity index.

**Mass-balance index**
The rate of change \(db/dx\) of mass balance with horizontal distance from the upper end of a flowline.

The term has also been used informally for a variety of measures of the mass balance.
Mass-balance profile
The variation $b(z)$ of mass balance with altitude (Figure 8).

Mass-balance rate
The change of mass per unit of time as the interval of mass change approaches zero, obtained in practice by dividing the mass balance by the duration over which it is measured or modelled. See mass-balance units.

The qualifiers “instantaneous” and “average” can be used to distinguish between the rate in the mathematical sense and the rate as obtained in practice. For example, the average mass-balance rate $\bar{M}$ over the interval $\Delta t$ is related to the mass balance $\Delta M$ by $\bar{M} = \Delta M / \Delta t$.

Mass-balance ratio
The ratio of the mass-balance gradient in the ablation zone to the mass-balance gradient in the accumulation zone, each of these gradients being assumed constant and that in the accumulation zone also being assumed non-zero.

Mass-balance sensitivity
The change in mass balance due to a change in a climatic variable such as air temperature or precipitation.

Sensitivities to temperature and precipitation are often expressed as changes in response to a 1 K warming or a 10% precipitation increase, resulting in a negative sensitivity to temperature and a positive sensitivity to precipitation.

Sensitivities are generally derived from mass-balance modelling, that is, from the difference in mass balance between model runs with and without climate perturbation, but they have also been estimated from mass-balance and climate observations.

Mass balance does not vary linearly with the climate in general. That is, $dB/dT$ and $dB/dP$ are not constant, but they may be assumed constant as a good approximation for small changes of the climatic variable.

The “dynamic” mass-balance sensitivity changes as the extent and area-altitude distribution of the glacier or glacierized region evolve. In contrast, the “static” sensitivity neglects these geometric changes, although it may still vary with, for example, components of the surface energy balance.
Mass-balance units
The dimension of mass balance is [M] (mass). The dimension of the mass-balance rate is [M T^{-1}] (mass per unit time). When the mass balance is presented per unit area, it is called specific mass balance and its dimension becomes [M L^{-2}], while the dimension of the mass-balance rate becomes [M L^{-2} T^{-1}]. When water-equivalent units are adopted (see below), the dimension becomes [L^3] or [L^3 T^{-1}], the corresponding specific units being [L] or [L T^{-1}].

The unit for expressing mass or change of mass numerically is the kilogram (kg). When more convenient the petagram (Pg) or gigatonne (Gt; 1 Gt = 1 Pg = 10^{12} kg) can be substituted. When mass balance is expressed per unit area, its unit is kg m^{-2}.

The unit kg m^{-2} is usually replaced by the millimetre water equivalent, mm w.e. This substitution is convenient because 1 kg of liquid water, of density 1000 kg m^{-3}, has a vertical extent of exactly 1 mm when distributed uniformly over a horizontal area of 1 m^2. The units kg m^{-2} and mm w.e. are therefore numerically identical. More formally, the metre water equivalent (m w.e.) is an extension of the SI that is obtained by dividing a particular mass per unit area by the density of water, $\rho_w$:

$$1 \text{ m w.e.} = 1000 \text{ kg m}^{-2} / \rho_w$$

Because of the risk of confusion with the metre ice equivalent, or with ordinary lengths, it is important that the qualifier “w.e.” not be omitted.

Mass balances can also be stated in m^3 w.e. (1 m^3 w.e. = 1 m w.e. distributed uniformly over 1 m^2) or km^3 w.e. Note that 1 km^3 w.e. is numerically identical with 1 Gt.

For the mass-balance rate, appropriate units are kg a^{-1} or kg m^{-2} a^{-1} (or m^3 w.e. a^{-1} or mm w.e. a^{-1}) when the time span is an integer multiple of 1 year. Over shorter intervals the unit of time should be the second or the day.

Mass units (kg or m^3 w.e.) are useful for hydrological and oceanographic purposes, while specific mass units (kg m^{-2}, mm w.e., m w.e.) are needed when comparing the mass balances of different glaciers and for studying glacier-climate relations.

To convert, with sufficient accuracy for many purposes, to the frequently needed sea-level equivalent (SLE), mass balance in kg m^{-2} is first converted to kg by multiplying by the area of the glacier, and then divided by the product of $\rho_w$ and the area of the ocean ($362.5 \times 10^{12}$ m^2; Table B5). The sign of SLE is opposite to that of glacier mass balance, a loss from the ice being deemed to be an equivalent gain for the ocean.

Mass-balance year
The time span, equal or approximately equal in duration to one calendar year, to which the annual mass balance in any time system refers.

In the stratigraphic system the annual mass balance is the change of mass during the period between formation of two successive minima in the sequence of annual cycles of mass growth and decline. These minima are usually reached at different times in successive years, and the duration of the mass-balance year may therefore vary irregularly and substantially in duration from year to year. Point mass balances can be determined unambiguously in the stratigraphic system, but glacier-wide determinations require the assumption that the diachronous character of the summer surface can be neglected.

In the fixed-date system the first day of the mass-balance year is always on the same calendar date, which is typically chosen to coincide with the start of the local hydrological year, for example 1 October in the mid-latitudes of the Northern Hemisphere or 1 April in the mid-latitudes of the Northern Hemisphere, or sometimes with the average date of minimum annual mass. The mass-balance year is 365 (or 366) days long.

In the floating-date system the mass-balance year is defined by the calendar dates of the two successive surveys, which may vary from year to year and may or may not be 365 (or 366) days apart.

Formerly (Anonymous 1969; Appendix A) the mass-balance year was defined only in the stratigraphic system.
Mass budget
A synonym of mass balance.

Mass budget is a more correct term than mass balance, but is used less often. While water balance and energy balance refer to equations in which the change in storage is only one of the terms, common glaciological usage equates mass balance with the change in storage (in other words, with the mass imbalance). It is unlikely that this usage will change.

Mass conservation
See conservation of mass.

Mass flux

1 The horizontal rate of flow of mass through a plane normal to the direction of the horizontal velocity vector.

Depending on the context, the flux may be through an element of area at a given position in the vertical plane, through a unit of width extending from the glacier bed to the surface, or through an entire glacier cross section.

2 The vertical rate of flow of mass at the glacier surface or bed.

In sense 2, the flux at the surface is equal to the sum of surface accumulation and surface ablation, or in other words to the surface mass balance. Equivalently the flux at the bed is equal to the basal mass balance.

Mass turnover
The renewal of the mass of a glacier by mass-balance processes.

Mass turnover is measured most usefully by the mass-turnover time, which is the mass of the glacier divided by the mass-balance amplitude, with the latter expressed as an annual rate. Mass-turnover times range from several decades for glacierets to tens of thousands of years for ice sheets.

See response time.

Measurement year
The time span, equal or approximately equal in duration to one calendar year, between two surveys constituting a measurement of annual mass balance in any time system.

Formerly (Anonymous 1969; Appendix A) the measurement year was defined only in the fixed-date system.

Melange
A floating agglomerate of icebergs and larger fragments of sea ice that forms when a glacier calves icebergs more quickly than they melt or are evacuated by wind or ocean currents.

The melange may be strong enough to retard the accelerated discharge of grounded ice that would otherwise be expected (from the elimination of back-stress) after a calving event.

The word, originally French, means “mixture”. In tectonics and petrology it refers to a body of deformed rocks characterized by the inclusion of native and exotic blocks in a pervasively sheared, commonly fine-grained, matrix.

Melt
1 (v.) To undergo fusion, or (when used transitively) to cause to undergo fusion. See latent heat of fusion.

2 (n.) The liquid produced by the process of fusion (see meltwater).

Melt extent
The spatial extent (dimension [L^2]) of melting on the surface of the glacier.

The melt extent can be measured by microwave remote sensing of the brightness temperature with a passive-microwave sensor, or equivalent analysis of radar or scatterometer imagery. The
spatial resolution of passive-microwave radiometers and scatterometers being low at present (several km or coarser), the method is mainly exploited on ice sheets and large ice caps.

Melting
The process by which a solid changes phase into a liquid; a synonym of fusion. See ablation.

Melting index
A measure, with dimension \([L^2 T]\) and units such as \(\text{km}^2 \text{d}\), of the spatiotemporal extent of surface melting.

The melting index, usually obtained by remote sensing, is the integral over a defined region and time span of the time-varying melt extent, and is approximated in practice as a regional sum of products at local scale (such as that of the pixels of a passive-microwave sensor) of the melt extent and the duration of melting. The accuracy of the duration is principally determined by the frequency of imaging, which tends to be high at high latitudes because most orbital sensors are in polar orbits. The melting index is a valuable proxy indicator in the absence of more direct measures of melting.

The melting index is sometimes called the melt index or the surface-melt index, and is formulated in slightly different ways by different authors.

Melting point
The temperature, \(T_m = 273.15 \text{ K} = 0 ^\circ \text{C}\), at which ice undergoes fusion when the pressure is equal to a standard pressure of 101 325 Pa and the latent heat of fusion is made available to fuel the change of phase. Freezing point is a synonym.

Strictly the melting point is the (temperature, pressure) pair of numbers, but the variation of pressure at the surface of the glacier has negligible effect and the term is applied to the temperature alone.

See pressure-melting point, ice point.

Meltwater
The liquid resulting from melting of ice, firn or snow.

Meltwater discharge
See article Meltwater discharge under Discharge.

Meltwater runoff
See article Meltwater runoff under Runoff.

Microwave remote sensing
Remote sensing with an active-microwave sensor or a passive-microwave sensor.

At frequencies between about 1 GHz and 40 GHz, microwaves are capable of penetrating clouds, and orbiting sensors can measure surface properties in all atmospheric conditions. Corrections must be made for scattering resulting from atmospheric and ionospheric variations. At frequencies below a few GHz, the depth of penetration beneath the glacier surface becomes great enough to permit active-microwave imaging or profiling of the subsurface from the surface or from aircraft.

The terms microwave and radar are often used interchangeably. This is mainly because the boundary between the lower-frequency radio and higher-frequency microwave regions of the electromagnetic spectrum is fixed differently, between 0.3 and 300 GHz (wavelengths of 1 m to 1 mm), by different authorities.

Active-microwave sensor
A sensor transmitting radiation and receiving reflections in the radio or microwave regions of the electromagnetic spectrum; in glaciological applications, either an imaging radar or a radar configured as a scatterometer or radar altimeter.
Frequencies from about 1–2 MHz up to about 15 GHz have various applications in the study of mass balance with active-microwave sensors. See ground-penetrating radar, InSAR, Shuttle Radar Topography Mission.

**Passive-microwave sensor**
A radiometer sensing the emission of radiation at microwave frequencies from a medium.

Frequencies from about 5 GHz up to 37 GHz are used in the study of quantities related to mass balance with passive-microwave sensors. The intensity of emission depends on the temperature of the medium and its emissivity. See brightness temperature.

Microwave radiometers in orbit have resolutions of a few to a few tens of kilometres, so that they are best suited to monitoring of extensive ice and snow covers. All are in polar, sun-synchronous orbits, and offer daily near-global coverage. At high latitudes, coverage is available at least twice daily, that is, from an ascending (south to north) pass, typically in the afternoon or evening, and a descending (north to south) pass, typically in the morning.

SMMR, the Scanning Multi-channel Microwave Radiometer, operated from 1978 to 1987. SSM/I, the Special Sensor Microwave Imager, was first launched in 1987 and has operated on several different satellites since. AMSR-E, the Advanced Microwave Scanning Radiometer for the Earth Observing System, has operated since 2002.

In snow hydrology, passive-microwave radiometers are operational tools for the estimation of snow water equivalent (“SWE”).

**Mid-range altitude**
The average of the minimum altitude and maximum altitude of the glacier.

The mid-range altitude is of interest in itself as a measure of the vertical location of the glacier, but has also been shown to be (to within the accuracy of measurements) an unbiased estimator of the balanced-budget ELA. See glaciation level.

**Moulin**
A deep shaft, nearly vertical and of roughly circular cross section, formed when surface meltwater enlarges a crack in the ice by transferring kinetic and thermal energy to its walls.

Moulins connect to the englacial drainage network, facilitating transfer of surface meltwater to the bed. The meltwater resulting from enlargement of the moulin is an instance of internal ablation. Moulins may play a significant role in supplying lubricant to the bed.

The word is French for mill, referring to the swirling motion of the water as it descends the shaft.

**Mountain apron glacier**
A small glacier of irregular outline, elongate along slope, in mountainous terrain.

**Mountain glacier**
1 A glacier that is confined by surrounding mountain terrain, also called an alpine glacier.

2 A glacier in mountainous terrain that is a cirque glacier, a niche glacier, a crater glacier, or a mountain apron glacier. See also valley glacier.

Sense 2 is that in which the term is used in the World Glacier Inventory, but the more general sense 1 is also widely used.

**Multi-annual** (adj.)
Spanning more than one year, but referring to duration, for example of a measurement, rather than to persistence; see perennial.
National Snow and Ice Data Center (NSIDC)
An organization that manages and distributes data and supports research about all aspects of the cryosphere and, notably for studies of glacier fluctuations, houses the databases of the Global Land Ice Measurements from Space initiative and the World Glacier Inventory.

NSIDC is part of the Cooperative Institute for Research in Environmental Sciences at the University of Colorado, Boulder, U.S.A., and is the site of one of the World Data Centers for Glaciology.

Net (adj.)
Descriptive of a quantity that is the final result of a series of additions and subtractions, especially, in the context of mass balance, of mass-balance components.

Formerly (Anonymous 1969; Appendix A) net mass balance was a technical term in the stratigraphic system, to be distinguished from “annual mass balance” in the fixed-date system, but this usage is no longer recommended (see article Annual mass balance under Mass balance).

Net ablation
See article Net ablation under Mass balance.

Net accumulation
See article Net accumulation under Mass balance.

Net mass balance
See article Net mass balance under Mass balance.

Névé
1 A synonym of firn, of French origin, now little used.

2 A little-used synonym of snowfield, or sometimes of accumulation zone.

Niche glacier
A small glacier in a gully or depression, elongate downslope.

Nunatak
A mountain, or any exposed ground, projecting from and surrounded by glacier ice.

The word is a 19th-century borrowing from the Greenlandic language.
Ogive
Arcuate bands or waves, convex downglacier, that develop in an icefall. Alternating light and dark bands are called banded ogives or Forbes bands. Each pair of bands, that is, one crest (light) and one trough (dark), represents a year’s movement through the icefall. It can be shown that, to yield visible banding, ice must flow through the icefall in a time shorter than the duration of the ablation season or accumulation season. James Forbes was the first to describe ogives, in 1843.

Orographic snowline
See snowline.

Outlet glacier
A glacier, usually of valley-glacier form, that drains an ice sheet, icefield or ice cap. In the accumulation zone the glacier outline may not be well-defined because of the subdued relief.

Outline
See glacier outline.
Passive-microwave sensor
See article Passive-microwave sensor under Microwave remote sensing.

Penitente
A spike-like irregularity of the glacier surface, significantly taller than wide and on occasion reaching heights as great as a few metres.

Penitentes are an extreme form of the metre-scale roughness which must be accounted for in all ablation measurements using stakes. They are usually found together in large numbers when low temperature and intense solar radiation favour ablation by sublimation and the consequent amplification of small surface irregularities.

The word is Spanish and is generally not anglicized; the final e is retained (and pronounced).

Percolation
The movement of a liquid such as water through the void spaces of a permeable solid such as snow or firn, the rate of movement being governed by the porosity and liquid content of the solid, the geometric attributes of the pores, including their diameter and tortuosity, and the response of the pore walls to wetting. See infiltration.

Percolation zone
The part of the glacier where water from surface melting or rainfall percolates into the subsurface; see percolation, zone.

In the upper percolation zone, above the wet-snow line, water percolates only into the snow. In the lower percolation zone, also called the wet-snow zone, water percolates into the firn below the summer surface. The lower percolation zone contains the slush zone.

If, having percolated, the water refreezes, it warms its surroundings by releasing latent heat. If it refreezes in the firn, the result is internal accumulation. If it refreezes as a layer immediately above the summer surface, it forms superimposed ice. If this superimposed ice becomes exposed by continued surface ablation, the resulting superimposed ice zone is conventionally regarded as distinct from the percolation zone.

Perennial (adj.)
Persisting for an indefinite time longer than one year.

Perennial refers to the persistence of an object rather than, for example, to the duration of a measurement. See multi-annual.

Permanent Service on the Fluctuations of Glaciers (PSFG)
The immediate precursor, established in 1962, of the present-day World Glacier Monitoring Service.

The name of the Permanent Service on the Fluctuations of Glaciers survives in the form of the “PSFG number” which is assigned to glaciers in the Fluctuations of Glaciers database of the World Glacier Monitoring Service.

Permittivity
See relative dielectric constant.

Photogrammetry
Quantitative analysis of photographs, usually vertical aerial photographs but also aerial oblique or terrestrial oblique photographs, to determine the coordinates in a specified coordinate system of features visible in the photographs.

Photogrammetry, or “measurement of photographs”, is now understood to embrace measurements of images in general, including negative images on film, diapositives (positive images on film) and digital images, and images obtained by sensors on orbiting satellites as well as by airborne sensors.
**Piedmont glacier**
A glacier the lower tongue of which is fan-shaped and significantly wider than the upper tongue.

The lateral expansion of a piedmont glacier is markedly greater than that of an expanded-foot glacier. In some classifications piedmont glaciers are distinguished from expanded-foot glaciers by requiring that a piedmont glacier have two or more coalescing tributaries. See the related but not synonymous ice piedmont.

**Point mass balance**
See article *Point mass balance* under *Mass balance*.

**Polar glacier**
An obsolete term, due to Ahlmann (1935), originally in the form “high-polar glacier”, describing a glacier with an accumulation zone in which there is little or no melting and the temperature is below the freezing point to depths of at least 200 m. See *cold glacier*, *polythermal glacier* for rough equivalents in modern terminology.

**Polythermal glacier**
A glacier containing some *cold ice* and some *temperate ice*.

Classically, as first described, a polythermal glacier has a basal layer of temperate ice overlain by a layer of cold ice (panel a in Figure 9), above which there may be a surface layer up to about 10–15 m thick that warms to the melting point seasonally. See *cold glacier*, *temperate glacier*.

![Figure 9. Schematic view of different polythermal structures encountered in glaciers. The temperate ice is shaded grey and the cold ice white (Pettersson, 2004).](image)

Different types of polythermal glacier are found in different regions depending on the climate and the glacier geometry (Figure 9).

**Porosity**
The fraction of any given volume not occupied by solid matter, and therefore available for occupation by fluids such as air and water.
In snow and firn the porosity is nearly equal to \(1 - \rho/\rho_i\), where \(\rho\) is the density of the dry snow or firn and \(\rho_i\) the density of ice.

**Positive degree-day**

The name of a derived unit, the \(K_d\), equal in magnitude to a 1 K excess of temperature above the melting point (273.15 K, 0 ºC) averaged over a period of 1 day.

See positive degree-day sum.

**Positive degree-day sum**

The integral, in \(K_d\) (kelvin days), of the excess of temperature \(T\) above the melting point \(T_m\) (273.15 K, 0 ºC) over a span of time:

\[
\phi = \int_{t_1}^{t_2} \max[0, T(t) - T_m] \, dt,
\]

where the span extends from \(t_1\) to \(t_2\) and \(t\) is measured in days. In practical work, the temperature is available over the span in degrees Celsius as a series of averages over some time step \(\Delta t\), or as instantaneous values at intervals \(\Delta t\), of near-surface air temperature \(T_i\) \((i = 1, n)\), and the expression becomes:

\[
\phi = \Delta t \sum_{i=1}^{n} \max[0, T_i],
\]

\(\Delta t\) being expressed in days.

The \(T_i\) are often mean daily temperatures, in which case \(\Delta t = 1\), but positive degree-day sums can also be accumulated over intervals such as an hour or a month. The latter have also been referred to as positive degree-month sums. The quantity “positive degree-day sum” is often abbreviated PDD and shortened to “positive degree-days”, which can lead to confusion because the latter is the name of the unit in which the former is measured.

At temperatures near \(T_m\), the positive degree-day sum becomes inaccurate as the time step \(\Delta t\) becomes large, each mean temperature \(T_i\) representing a distribution of instantaneous temperatures of which some are opposite in sign to \(T_i\). Mean temperatures slightly below \(T_m\) are wrongly estimated to contribute nothing to the positive degree-day sum while mean temperatures slightly above \(T_m\) contribute too little.

Positive degree-day models, in which a degree-day factor represents the proportionality between surface ablation and the positive degree-day sum, are a leading form of temperature-index model.

**Precipitation**

Liquid or solid products of the condensation of water vapour that fall from clouds or are deposited from the air onto the surface.

**Pressure-melting point**

The temperature at which ice and water are in thermodynamic equilibrium at a given pressure.

The pressure-melting temperature is 273.15 K when the pressure is 101 325 Pa, changing, when the water is saturated with air, at \(-9.8 \times 10^{-8}\) K Pa\(^{-1}\) or, in ice of density 900 kg m\(^{-3}\), about \(-0.86 \times 10^{-3}\) K m\(^{-1}\). This means, for example, that beneath 4000 m of such ice the pressure-melting temperature is 269.75 K. For pure water and ice the corresponding rates are \(-7.4 \times 10^{-8}\) K Pa\(^{-1}\) and about \(-0.65 \times 10^{-3}\) K m\(^{-1}\) (see Table B3).

Factors other than pressure can alter the melting point; see temperate ice.

The pair (273.15 K, 101 325 Pa) is known in thermodynamics as the ice point. The specified pressure is the sea-level pressure of the standard atmosphere defined by the International Civil Aeronautical Organization (1993). See also triple point.

**Proglacial**

Pertaining to an object in physical contact with, or close to, the glacier margin.
Radar
A method of, and by extension an instrument for, detecting and locating objects by sensing radiation transmitted by the instrument and reflected from the objects. See active-microwave sensor.

The depth to which a radio or microwave signal is likely to penetrate ice or snow before being absorbed or scattered depends on the frequency (or equivalently the wavelength). In the case of scattering, the penetration depth also depends on the size of any inhomogeneities in the ice; those smaller than the wavelength of the signal cause less scattering. In glaciology, the lower frequencies (about 2 to several hundred MHz) are the basis for ground-penetrating radar (see also radar method), while frequencies of 1 to 15 GHz, at which effective penetration depths can still reach some metres, are used in radar altimeters mounted on aircraft or satellites (see also InSAR, Shuttle Radar Topography Mission).

Radar is an acronym standing for radio detection and ranging.

Radar altimeter
An instrument for altimetry that transmits and receives pulses of microwave radiation.

Satellite radar altimeters (including ERS-1 and 2, Envisat and others) typically operate in the Ku band (13.5 GHz; 22 mm wavelength) and were designed primarily for oceanographic monitoring. Because of their relatively large footprint (several km), they are best suited for measuring elevations of gently-sloping regions of the ice sheets. Steep or undulating terrain produces complex waveforms and difficulties in achieving accurate estimates of range (i.e. distance). Surface and volume scattering also affect the radar pulse and create uncertainty in the effective depth of the reflecting horizon. Surface dielectric properties and roughness that cause scattering are time-varying and introduce errors in calculations of elevation change.

Recent radar altimeters use synthetic aperture processing (see InSAR) that increases resolution and decreases slope errors relative to earlier radar altimeters. The Shuttle Radar Topography Mission (SRTM) used a C-band radar (5.6 GHz; 54 mm wavelength) and synthetic aperture processing to obtain an accurate map of surface elevations with near-global coverage. CryoSat-2, launched in April 2010, will also use InSAR to map glaciers and ice sheets.

Radar altimetry
See radar altimeter.

Radar method
A method of determining net accumulation by interpreting a subsurface horizon detected by ground-penetrating radar, either from the surface or remotely, as an isochrone.

The thickness of the layer between the isochrone and the surface, multiplied by its density, is the net accumulation since the date of the isochrone. With a suitable choice of radar frequency, the isochrone may be as recent as the summer surface, allowing the measurement of snow depth. The dates of older isochrones are obtained by ice-core stratigraphy in one or more nearby boreholes, from which the density profile can also be obtained. In creating the depth-age scale from which the date is derived, changes of layer thickness caused by ice flow are considered. The density profile enables conversion to water-equivalent or ice-equivalent units.

Radio-echo sounding
See radar, ground-penetrating radar.

Rain
Precipitation other than dew that falls from the air as liquid.

Rainfall
The amount of rain that falls during a stated period.
**Rammsonde**
A device for measuring the penetration hardness (also called the ram resistance) of snow or firn, a quantity formerly believed to be a reliable guide to the density, and still commonly used in assessments of the risk of snow avalanches.

**Range**
1 (n.) The distance to a target such as a glacier surface from an active sensor such as a sonic ranger or a radar.

2 (n.) The cross-track coordinate in the coordinate frame of an airborne or orbiting radar. See azimuth.

3 (v.) Of an active sensor, to measure the distance to, that is, to “range to”, a target.

Senses 2 and 3 have evolved from sense 1, which originated in gunnery but has become common in several branches of remote sensing.

**Reaction time**
The time required for a change in forcing of mass balance to result in an observable response of the geometry, particularly the length, of the glacier.

The reaction time is not a physical property of the glacier. Estimates of the reaction time depend on, among other things, the precision of observation and the extent to which the glacier is out of equilibrium. See response time.

**Reanalysis**
Re-examination and possible modification of a series of measurements of mass balance in the light of methods or data not available when the measurements were made.

The modifications, in addition to the correction of processing and other errors, often include correction of biases identified by comparison of annual measurements by the glaciological method with one or more multi-annual measurements by geodetic methods covering the same time span. These corrections are made only when one or other of the two types of measurement can be shown clearly to be more accurate than the other. The uncorrected measurements should remain available after the corrections have been made and published.

The glaciological meaning of reanalysis is only roughly comparable to its meaning in meteorology, where a reanalysis is a recalculatin of variations of the state of the atmosphere over periods of decades using a uniform system of data assimilation and analysis.

See homogenization.

**Reconstructed glacier**
A synonym of regenerated glacier.

**Recrystallization**
1 The metamorphosis, without melting but not necessarily without advection in the vapour phase, of an assemblage of grains of snow and old crystals of ice to a new assemblage of crystals of ice, generally resulting in changes of mean crystal size and orientation (fabric) and, of most significance for mass-balance purposes, an increase of density.

See congelation, infiltration ice, glacier.

2 The formation of a new assemblage of crystals from an old assemblage.

Sense 1 is the meaning of the term in studies of the densification of snow, while sense 2 is its everyday meaning.
Recrystallization zone
In the Russian-language literature, where it is sometimes also referred to as the “snow zone”, a synonym of dry-snow zone. See zone.

Recrystallization-regelation zone
In the Russian-language literature, where it is sometimes also referred to as the “snow-firm zone”, a term for the upper percolation zone. See zone.

In this context the Russian word “regelatsiya” refers to refreezing, not to regelation.

Reference glacier
In the monitoring strategy of the Global Terrestrial Network for Glaciers, a glacier with a long-term, continuous, continuing programme of mass-balance observations.

See tier, benchmark glacier.

Reference-surface balance
The glacier-wide mass balance that would have been observed if the glacier surface topography had not changed since a reference date.

The time-invariant surface is called the “reference surface”, and is defined at some convenient time within a mass-balance programme, often at the start (Elsberg et al. 2001). The reference-surface balance is obtained when point measurements are extrapolated from their actual altitude to the altitude of the reference surface at the same horizontal position, and then extrapolated over the reference area. The reference surface is likely to differ from the actual surface in both area and area-altitude distribution.

Differences in area and area-altitude distribution feed back on the magnitude of glacier response to climate. The reference-surface balance does not incorporate any of these feedback effects and is therefore more closely correlated to variations in climate than is the conventional balance.

Refreezing
The freezing of meltwater generated at the glacier surface, or of rain, that percolates to some depth at which the temperature is below the freezing point.

Refreezing below the summer surface represents internal accumulation. Percolating water may also refreeze at the base of snow overlying impermeable glacier ice, in which case it is called superimposed ice. See zone.

The release of latent heat heats the layer within which the water freezes.

Regelation
The freezing of meltwater due to a change in pressure alone.

The term is often used for “pressure melting and regelation”. Regelation happens because the pressure-melting point of ice varies inversely with pressure. Water in equilibrium with ice will freeze, releasing the latent heat of fusion, 333.5 kJ kg⁻¹, if there is a decrease of pressure, as on the downglacier face of a bump in the bed of a temperate glacier. Ice in equilibrium with water will melt if there is an increase of pressure, as on the upglacier face of the bump. However, the latent heat of fusion must be supplied for this change of phase. A natural source is the latent heat released by regelation on the downglacier face. If pressure melting and regelation are unequal, there will be a contribution to basal ablation or basal accumulation.

Smaller bumps are more favourable to pressure melting and regelation than larger ones.

The Russian word “regelatsiya” refers to refreezing rather than to regelation.

Regenerated glacier
The lower part of an interrupted glacier.

Regional snowline
See article Regional snowline under Snowline.
Relative dielectric constant
The ratio $\varepsilon_r$ of the electric displacement (electric flux per unit area) at any point in a dielectric (that is, non-conducting) medium to the displacement that an identical electric field would produce in a vacuum, measured at the same point.

The relative dielectric constant, which is not in fact a constant and is more properly called the relative permittivity, is a complex number. Its imaginary part, $\varepsilon''$, is sensitive to attenuation of microwaves by absorption and other phenomena; it is sometimes called the dielectric loss. Ice, however, is generally assumed to be a low-loss medium, and its dielectric loss is approximated as $\varepsilon'' = 0$. The real part of $\varepsilon_r$, denoted $\varepsilon'$, depends on frequency and temperature, and more subtly on variations in crystalline fabric and the presence of impurities. It determines the geometry of wave propagation, including refraction at and reflection from interfaces between layers within the medium.

See ground-penetrating radar, Table B1.

Remote sensing
Measurement of surface properties with a sensor distant from the surface, such as on an airplane or satellite, or of subsurface properties with a sensor on or distant from the surface, either with a signal emitted by the sensor (active remote sensing) or a signal emitted or reflected by the surface (passive remote sensing).

See active-microwave sensor, feature tracking, ground-penetrating radar, InSAR, laser altimeter, microwave remote sensing, passive-microwave sensor, photogrammetry, radar altimeter, scatterometer, Shuttle Radar Topography Mission.

Response time
The $e$-folding time scale for the transition of a glacier, following a step change in mass balance, from one steady state to another.

Response times have been formulated for various attributes of the glacier such as volume and length. They can be confused easily with the mass-turnover time; the reaction time; and the growth time.

The volumetric response time is the most commonly seen formulation. Here the glacier changes from an initial volume $V_1$ to a later volume $V_2$, and the response time is the time needed for the volume to change by $(V_2 - V_1) (1 - e^{-1})$, where $e = 2.71828...$ is the base of natural logarithms. The response time is much shorter than the time required to attain volume $V_2$. Indeed, in this formulation the time to attain volume $V_2$ is infinite. The change between state 1 and state 2 is assumed to be “small”.

The response time for volume is somewhat shorter than that for length, that is, for the length to change by $(L_2 - L_1) (1 - e^{-1})$.

The response time is an idealization. The essence of the idea is that the glacier “remembers” its earlier steady state because it adjusts its size and shape by flow. The volume response time $\tau$ is often estimated with an expression due to Jóhannesson et al. (1989):

$\tau = H'/(-\dot{b}_r)$

in which $H'$ is a representative thickness of the glacier and $\dot{b}_r$ ($< 0$) a representative mass-balance rate, in ice-equivalent units, in the vicinity of the terminus. $H'$ is somewhat larger than the mean ice thickness, and approaches the maximum thickness where the bed geometry is simple (no troughs). These two variables are rather easy to estimate but should be considered as scales rather than exact quantities. The expression has been used widely, but not always with the caution due to its generalized nature.

Resublimation
The process by which a vapour changes phase directly into a solid; deposition and desublimation are synonyms. See latent heat of sublimation.
Retreat
Decrease of the length of a flowline, measured from a fixed point.

In practice, when the retreat is of a land-terminating glacier terminus, the fixed point is usually downglacier from the terminus, that is, on the glacier forefield. The quantity reported is most often the amount of retreat rather than the length itself.

Advance is the opposite of retreat, that is, advance of the terminus.

Rime
A solid surface deposit formed by the rapid freezing of supercooled water, distinguished from glaze by being less dense (Figure 10). See also hoar.

Figure 10. Rime, or possibly hoar, recently dislodged from an accumulation stake by solar heating (foreground) and still coating meteorological instruments (background), on Vestfonna, Svalbard.

Rock glacier
A mass of rock fragments and finer material in a matrix of ice, showing evidence of past or present flow.

Runoff
1 Discharge of water divided by the area of the drainage basin contributing water to the measurement cross section, expressed in specific units such as mm w.e. d\(^{-1}\) or kg m\(^{-2}\) s\(^{-1}\).

2 The flux of water leaving the glacier.

Sense 2 is common in mass-balance studies, especially in studies of ice-sheet mass balance.

See mass-balance units; it is useful to have one word for total flux and a different word for specific flux, so the distinction between discharge and runoff is to be encouraged. Runoff includes meltwater discharge but also water from other sources than melt, such as rainfall.

Meltwater runoff
The component of runoff (in sense 2) produced by melting of glacier ice, firn or snow that is removed in surface, englacial or subglacial flows.

Meltwater runoff is not the same as surface ablation by melting, because surface meltwater may refreeze in the glacier (see refreezing, internal accumulation), and part of the meltwater runoff may originate from basal ablation or internal ablation. Nor is it usually the same as the total runoff, which
is likely to include contributions from unglacierized parts of the drainage basin, and may include a contribution from rainfall on the glacier.

**Runoff limit**

The altitude above which all rainfall and surface melt, if any, refreezes in the snow or firn, and below which part or all of it runs off the glacier. See zone.
Sastrugi
A variant spelling of *zastrugi*.

**Scatterometer**
A *radar* designed to measure microwave backscattering, quantified as the scattering coefficient or normalized radar cross section $\sigma_0$, from natural media.

Exposed *glacier ice* in the *ablation zone* lacks a distinctive *mass-balance*-related signature at microwave wavelengths. In the *percolation zone*, subsurface ice lenses are strong scatterers, but there is a sharp reduction in backscattering when *meltwater* appears at the surface. When wet, the surface becomes a more nearly specular (forward) reflector and appears radar-dark instead of radar-bright. In the *dry-snow zone* radar returns are unaffected by liquid water, which is absent, and the scattering coefficient contains information on *snow* grain size and possibly on the *accumulation* rate.

Scatterometers have relatively poor spatial resolution (several to some tens of kilometres), which can be improved by temporal averaging, but they compensate by offering wide and frequent coverage. SeaWinds, on the polar-orbiting QuikSCAT satellite (1999-2009) has been a productive scatterometer. Intended for the measurement of ocean-surface wind speeds, it has also proved valuable for measuring the extent and duration of *melting* on *ice caps* and *ice sheets*. See also *brightness temperature*.

**Sea ice**
*Ice* formed at the sea surface by the *freezing* of sea water.

Except where it forms ridges, sea ice is up to a few metres thick, in which respect it differs from *shelf ice*. See also *marine ice*.

**Sea-level equivalent**
The change in mean global sea level that would result if a mass of water were added to or removed from the ocean; in glaciology, the mass is usually equal respectively to that lost or gained by a *glacier*.

Sea-level equivalent is usually abbreviated as SLE, and customary units are m SLE (for large masses), mm SLE or mm a $^{-1}$ SLE. The sign of glacier *mass balance* is opposite to that of SLE, a loss from the glacier being deemed to be an equivalent gain for the ocean.

SLE is often estimated by dividing the mass by the product of the *density* of (fresh) water, $\rho_w = 1000 \text{ kg m}^{-3}$, and the area of the ocean, $362.5 \times 10^{12} \text{ m}^2$, with a change of sign when necessary.

More accurate estimates of SLE must account for shoreline and *grounding-line* migration, altering ocean area; isostatic adjustment of the land surface and ocean floor to changing patterns of loading by water and ice; and flow of *meltwater* into aquifers and enclosed basins rather than to the ocean. It is also necessary to differentiate between floating and grounded *ice*. The SLE of grounded ice is proportional to $h (\rho_i / \rho_w) - d$, where $h$ is the total thickness of the ice, $\rho_i$ its density, and $d$ the depth of the sea water in which it stands. (If $d$ is not zero, some of the grounded ice is already displacing sea water.) Apart from a small effect on sea water density due to reduction of salinity upon melting, any ice body floating in the sea has $d \geq h (\rho_i / \rho_w)$, and therefore its SLE is zero.

**Seasonal sensitivity characteristic (SSC)**
A set of sensitivities, $C_{T,k}$ (in m w.e. K$^{-1}$) and $C_{P,k}$ (in m w.e.), of *annual mass balance* $B_a$ to changes in monthly mean temperature $T_k$ and normalized monthly precipitation $P_k / P_{ref,k}$, where $k = 1, ..., 12$ is the month index and $P_{ref,k}$ is the monthly precipitation averaged over a reference period.

The SSC, which is estimated either from observations or from model calculations, was introduced by Oerlemans and Reichert (2000). It consists of two sets of 12 numbers each:

$$C_{T,k} = \frac{\partial B_a}{\partial T_k} \quad ; \quad C_{P,k} = \frac{\partial B_a}{\partial (P_k / P_{ref,k})}$$

Describing seasonal sensitivity with a resolution of 1 month is a matter of convenience.
Serac
A tower or block of glacier ice bounded by intersecting crevasses.
The term is of French origin.

Shelf ice
Ice forming part of an ice shelf, whether glacier ice, marine ice or ice originating from accumulation on the surface of the ice shelf.

Shuttle Radar Topography Mission (SRTM)
A flight of the space shuttle Endeavour in February 2000 which yielded an interferometric digital elevation model, with ~90 m horizontal resolution (~30 m for the conterminous United States), of the Earth’s land surfaces roughly between latitudes 54° S and 60° N. See InSAR.

The effective penetration depth of the radar pulse into snow can be of the order of metres at the 5.6 GHz frequency of the shuttle radar. This, and the boreal mid-winter date of the mission, are leading contributors to uncertainty in SRTM data for mass-balance applications.

Slush
Snow or firn mixed with an amount of liquid water equalling or exceeding that required to fill the voids; soaked snow.

Slush avalanches (“slushflows”) can be a significant means of downslope transfer of mass, and hence of accelerating ablation by melting because of the increase of temperature with decreasing altitude.

Slush limit
A synonym of runoff limit. See zone.

Slush zone
The part of the glacier between the snowline and the runoff limit, that is, the lowest part of the percolation zone. See zone.

Snow
1 Solid precipitation in the form of ice crystals, chiefly in complex branched hexagonal form and often agglomerated into snowflakes; or an accumulation of the same on the Earth’s surface.

2 Solid precipitation that has accumulated on the summer surface on a glacier and that transforms to firn at the end of the mass-balance year. See zone.

In this sense, which prevails almost universally in the study of mass balance, snow may contain ice in the form of lenses or pipes which are the result of refreezing of meltwater.

3 An accumulation of solid precipitation on a glacier that has not yet attained a density through compaction sufficient to restrict the circulation of air and water significantly.

In this structural sense, the dividing line between snow and firn is diffuse but is conventionally taken to be near to a density of 400 kg m⁻³ (see Table B6).

Snow classification
The systematic description of a snow cover, usually seasonal rather than perennial, recording morphological, process-related and other attributes.

Guidelines for the classification of snow are given by Colbeck et al. (undated [1990?]) and by Fierz et al. (2009).

Snow depth
In the firn area, the vertical distance between the glacier surface and the summer surface; outside the firn area, the vertical distance between the glacier surface and the ice surface (which may be superimposed ice or glacier ice) at the time of observation.
**Snowfall**
The depth of snow that falls from the air and accumulates on the surface during a stated period. Snowfall excludes the deposition of windborne snow.

**Snowfield**
A more or less extensive and persistent mass of snow. Snowfields are more extensive than snowpatches, but the distinction is not made precisely in common usage. A snowfield that is perennial may be difficult to distinguish from a glacier.

**Snowline**
A set of points forming the lower limit of a snow-covered area; on a glacier, the line separating snow surfaces from ice or firn surfaces, and also separating the percolation zone from either the superimposed ice zone or the ablation zone (see also zone).

The set of points need not form a continuous curve. The snow-covered area of the glacier may include outliers (isolated patches of snow surrounded by firn or ice) and may exclude inliers (isolated patches of exposed firn or ice).

The snowline is usually easy to see, because the snow above it is brighter than the firn or ice below it. It may therefore be mapped by analysis of suitable imagery. When, and only when, there is no superimposed ice, the snowline coincides with the equilibrium line.

Unless qualified by a different adjective, references to the snowline are understood to refer to the annual snowline. It is common for "snowline" to be used as an abbreviation of "average altitude of the snowline".

**Annual snowline**
The snowline at the end of the ablation season, usually representing the highest position of the snowline during the mass-balance year; end-of-summer snowline is a synonym.

The snowline of any given balance year is established at the end of that balance year. If this newly established snowline is lower than the previous year's firn line, it also becomes the new firn line.

**Climatic snowline**
A synonym of regional snowline.

**End-of-summer snowline**
A synonym of annual snowline.

**Orographic snowline**
The imaginary line formed by the generalized lower limit of perennial snowpatches on the terrain surface between glaciers at the end of the ablation season.

The orographic snowline is so called (originally by Ratzel in 1886) because its altitude is predominantly defined by local topography and exposure.

**Regional snowline**
The mean orographic snowline on a regional scale; climatic snowline is a synonym.

**Transient snowline**
The snowline at any instant, particularly during the ablation season. See Figure 6.

**Snowpatch**
A mass of snow of restricted extent, especially one that persists through most or all of the ablation season.

Snowpatches are less extensive than snowfields, but the distinction is not made precisely in common usage. A snowpatch that is perennial may be difficult to distinguish from a glacier.
Snow pit
A hole dug into snow or firn to facilitate observation and sampling of density, snow and firn structure and associated grain sizes, layering and other attributes.

Snow-pit measurements are part of the basis of the glaciological method (see stake).

A snow pit (Figure 11) can be excavated by hand using shovels (common on most smaller glaciers) or by trenching using a larger machine such as a tracked vehicle or caterpillar (now common in work on ice sheets). Coring by means of a barrel corer is a much less labour-intensive alternative to, and can to some extent replace, snow pits in determining bulk density of the snow and firn. Cores, however, are not as well suited for detailed observations of stratigraphy because of their small size relative to what can be observed on a snow-pit wall (Figure 12).

Snow zone
See recrystallization zone.

Snow-firn zone
See recrystallization-regelation zone.
Solidification
The process by which a liquid changes phase into a solid; a synonym of freezing.

See latent heat of fusion.

Solid precipitation
Precipitation that falls in a solid state, such as sleet, snow or hail.

Sonic ranger
A device that measures the distance to a target, such as the glacier surface, by timing the return of echoes from acoustic (typically ultrasonic) pulses emitted by the device itself.

A suitably mounted sonic ranger can yield a continuous record of relative change of surface height and, given information on density changes, can contribute to monitoring of accumulation or ablation.

Knowledge is required of the speed of sound in the medium traversed by the pulse and its echo, which may in turn require knowledge of the temperature of the medium. The medium is usually air.

Sorge’s law
The proposition that a glacier with a constant accumulation rate and no melting has a constant profile of density as a function of depth beneath the surface; by extension, and more loosely, the proposition that an unchanging density profile is sustained by the climatic mass balance.

It follows from Sorge’s law that a thickness change can be converted to an equivalent change of mass by multiplying by the density of glacier ice. This approach has been used in most mass-balance calculations by geodetic methods.

Sorge’s law was originally introduced to describe densification of high polar snowpacks where melt is negligible. When Sorge’s law is invoked in its looser sense, the constancy of the density profile is usually assumed rather than measured.

The name, given by Bader (1954) in recognition of Ernst Sorge’s observations in Greenland in 1930–1931, is pronounced as two syllables, the first stressed, with s as English z and with hard g.

Specific (adj.)
Descriptive of a quantity expressed as mass per unit area (dimension \([M \, L^{-2}]\)), and therefore in units such as kg m\(^{-2}\) (which is numerically equivalent to mm water equivalent).

In mass-balance studies, the prefix “specific” is not necessary in general. The units in which a quantity is reported make clear whether or not it is specific. See specific mass balance.

The glaciological usage is not that prevailing in some other sciences, where often a specific quantity is either a dimensionless ratio of the value of a property of a given substance to the value of the same property of some reference substance, or is a quantity expressed per unit mass.

Specific mass balance
See article Specific mass balance under Mass balance.

Speckle tracking
The measurement of surface velocity as the rate of displacement of correlated patterns of speckle, or noise, in successive radar-interferometric images of the glacier. See InSAR, radar.

The speckle originates from large numbers of statistically independent scatterers in the scene. Small “chips” or windows from a later image are matched to a similar chip from an earlier image. Measured from the earlier chip, the distance to and bearing of the later chip that exhibits the greatest correlation with the earlier chip is taken to be the vector displacement that has accumulated between the dates of the images. Speckle tracking (e.g. Gray et al. 2001) is less precise than interferometric measurement of velocity but, relying only on image intensity rather than on both the intensity and the phase of the complex radar signal, is more robust.

See feature tracking.

Stagnant ice
Any part of a glacier that does not flow at a detectable rate; a synonym of dead ice.
Stake
A pole or rod that has been emplaced in a vertical hole drilled into the glacier surface; may also be referred to as a mass-balance stake, or as an accumulation stake or ablation stake as appropriate.

The change in height of the glacier surface relative to the top of the stake is the basis for a measure of the sum of accumulation and ablation (that is, of surface mass balance). The five quantities measured (Figure 13) over the course of the mass-balance year are: at $t_0$, when by definition there is no snow, the distance $d_0$ from the stake top to the summer surface; at $t_w$, the distance $d_w$ from the stake top to the surface and (in a nearby snow pit or with a coring device) the mean density $\rho_w$ of the snow (if any); the winter balance is not necessarily positive); and at $t_1$, the distance $d_1$ from the stake top to the surface and the mean density $\rho_1$ of the snow (if any). The layer thicknesses $h_w$ and $h_1$ are obtained by subtraction, as beneath the figure; note that in the right part of the figure the annual balance is negative because the thickness $h_1$ is negative. When the balance is positive the stake measurements are often supplemented by digging or probing to sample local variability. It is not possible to measure the density of mass that is lost between any two survey dates. For example the summer balance is commonly evaluated as $b_s = b_w$; and when $h_1$ is negative an appropriate value (usually, outside the firn area, the density of ice) must be assumed for $\rho_1$. At the instant following $t_1$, any residual snow is deemed to become firn and the glacier surface, at $d_1$, becomes the summer surface $d_0$ of the next balance year.

![Figure 13. Stake measurements of seasonal mass balances in a year of positive (left) and a year of negative (right) surface mass balance, with no superimposed ice. The vertical coordinate is positive downwards, and all distances are measured from the origin $z = 0$ at the top of the stake. Light shading represents snow; dark shading represents firn or glacier ice. Measurements are made at $t_0$, the start of the accumulation season; at $t_w$, the start of the ablation season; and at $t_1$, the end of the mass-balance year. The winter balance $b_w$ is the change of mass between $t_0$ and $t_w$. The summer balance $b_s$ is the change of mass between $t_w$ and $t_1$.](image)

Stake measurements are reliable only when the stake can be assumed neither to have sunk into the ice or firn nor to be floating in water contained within the drill hole. Additionally, settling of firn between the summer surface and the bottom of the stake (a change in the height of the summer surface
that is due only to a change in density must be corrected for. If the stake is not protruding vertically from the ice, but at an inclination to the vertical, or if it is bent, geometric corrections are required so as to yield the correct exposed length. If the surface is rough, as for example in a field of penitentes, measurements are made to a plane that approximates the average surface. If heat transfer from the stake has enhanced ablation in its immediate surroundings, the resulting surface depression is compensated for by measuring from the stake top to the maximum surface height of the surroundings.

Stake measurements are part of the basis of the glaciological method of measuring glacier mass balance (see snow pit). Stakes can be made of many materials, bamboo, aluminium and polyvinylchloride (PVC) being most common.

The surface mass balance is calculated as the change in height of the surface below the top of the stake, multiplied by the vertically-averaged density of the matter added or removed. The result is a point mass balance.

Stake farm
A group of stakes placed within a small area on the surface of a glacier, serving to improve estimates of the small-scale variability, and therefore of the sampling uncertainty, of surface mass balance.

Steady state
A state of the glacier in which over many years the thickness at the end of each mass-balance year remains unchanged, that is, $\frac{dh}{dt} = 0$ at every point; see equilibrium, balanced-budget.

It follows from the definition that the glacier-wide mass balance, including frontal ablation, is zero, because the glacier must flow at just the rate required to eliminate thickness changes due to the climatic-basal mass balance.

Steady state is a valuable idealization, and may be realized roughly when the climate is constant, or changes only slowly, over periods considerably longer than the response time of the glacier.

Steady-state AAR
See article Steady-state AAR under Accumulation-area ratio.

Steady-state ELA
See article Steady-state ELA under Equilibrium-line altitude.

Stratigraphic system
The time system in which the determination of mass balance is based on the identification of successive annual minima, and for seasonal balances annual maxima also, in the mass of the glacier or a part of the glacier.

In field work, annual mass balance is determined by the detection of two successive summer surfaces, usually at individual observation sites. In the ablation zone, the earlier summer surface has disappeared by the time the later one is observed, but its vertical position is known from earlier observations. For seasonal balances, it is not possible to determine the annual maximum of mass with a single field survey that can be scheduled to coincide only roughly with the expected date of the maximum. Thus, in the stratigraphic system, seasonal balances by the glaciological method are actually measured in a combined system.

Continuously recording sensors, such as snow pillows and sonic rangers, can yield accurate stratigraphic-system estimates of seasonal balances at single points, but they are not in wide use.

The annual extrema of mass may be reached at different times at different sites on the glacier. Glacier-wide balances in the stratigraphic system can be determined rigorously only by accurate spatially-distributed modelling or by gravimetric methods. Determinations based on field measurements must assume that the diachronous character of the summer surface can be neglected.

The duration of the mass-balance year varies in the stratigraphic system. See also measurement year, and fixed-date system, floating-date system, combined system.

Subglacial
Pertaining to the glacier bed or to the material below the bed.
Sublimation
The process by which a solid changes phase directly into a vapour without melting. See latent heat of sublimation, Table B1.

Submergence velocity
The vertical component, when it is directed downward, of the glacier-flow velocity vector at the glacier surface, at a point fixed in space.

When the component is directed upward, it is called the emergence velocity. The submergence velocity is related through the continuity equation to the climatic-basal mass balance and the rate of thickness change.

The component is typically upward in the ablation zone and downward in the accumulation zone.

Sub-polar glacier
An obsolete term, due to Ahlmann (1935), describing a glacier with an accumulation zone in which, except for possible seasonal warming and melting near the surface, the temperature is below the freezing point to depths of 100 m or more.

The term is sometimes used as if it were a synonym of polythermal glacier.

Summer ablation
\( a_s \) (point), \( A_s \) (glacier-wide)
See article Summer ablation under Mass balance.

Summer accumulation
\( c_s \) (point), \( C_s \) (glacier-wide)
See article Summer accumulation under Mass balance.

Summer-accumulation type
A type of glacier on which the regional seasonality results in extrema of ablation rate and accumulation rate at roughly the same time.

On a glacier of summer-accumulation type, mass balance remains relatively stable throughout the year. This is typical of high-altitude, low-latitude glaciers with a summer precipitation maximum.

Summer mass balance
\( b_s \) (point), \( B_s \) (glacier-wide)
See article Summer mass balance under Mass balance.

Summer season
The time span from the end of the winter season to the end of the mass-balance year.

The length of the summer season may vary greatly from year to year. The term is best suited to glaciers of winter-accumulation type. See accumulation season.

In the stratigraphic system the summer season starts when the glacier has attained maximum mass and ends when the glacier has attained minimum mass. In the floating-date system and the fixed-date system, the mass is not necessarily at its annual maximum or minimum when the summer season starts or ends.

Summer surface
The surface formed at the time of minimum annual mass at each point on the glacier, marking (in the stratigraphic system) the end of one mass-balance year and the start of the next. See zone.

In general the summer surface is diachronous. For example, when the higher reaches of a glacier start to gain mass, the lower parts may still be ablating.

The summer surface is the surface on which the first snow of the new balance year falls. It is easily detectable when it consists of glacier ice, which now includes superimposed ice added during the previous balance year. In the firn area it is recognizable as a well-marked crust, that is, a thin, relatively strong layer with a density near that of ice, and sometimes also (or instead) as a layer of depth hoar at the base of the current year’s accumulation.

The crust typically originates by recrystallization of the surface snow in late summer to form glaze. It may also be marked by an accumulation of sediment or wind-blown dust. It can be difficult to
detect when melting and snowfall alternate during the transition between the ablation season and the accumulation season. In some mass-balance programmes the summer surface is “labelled” in the vicinity of stakes with a distinctive material, such as sawdust, during a visit late in the ablation season.

**Superimposed ice**

Ice accumulated on the current summer surface, during the current mass-balance year, by the refreezing there of rain or meltwater. See zone.

Superimposed ice is not the same thing as internal accumulation, which represents refreezing below the summer surface. Superimposed ice becomes glacier ice at the end of the mass-balance year.

Superimposed ice requires special attention in conventional mass-balance programmes. In a pair of stake measurements, at the start and end of the ablation season, accumulation of superimposed ice causes a decrease of the distance from the top of the stake to the ice surface (regardless of any overlying snow). This decrease is real and not, for example, due to faulty book-keeping.

**Superimposed ice zone**
The part of the glacier where superimposed ice is exposed. See zone.

The superimposed ice zone occupies the range of elevations below the snowline and above the equilibrium line. Superimposed ice may also be found beneath snow of the current year at elevations above the snowline. Whether exposed or beneath the surface, it requires special attention in mass-balance measurements.

**Supraglacial**
Pertaining to the surface of the glacier or to features on the surface.

**Surface ablation** $a_{sfc}$ (point), $A_{sfc}$ (glacier-wide)

See article Surface ablation under Mass balance.

**Surface accumulation** $c_{sfc}$ (point), $C_{sfc}$ (glacier-wide)

See article Surface accumulation under Mass balance.

**Surface density**
The SI name of the derived unit kg m$^{-2}$, mass per unit area. See section 7.1.2.

It can be helpful to regard the product of a thickness and a density as a surface density. For example mass balance, when expressed in specific units, is a surface density.

**Surface mass balance** $b_{sfc}$ (point), $B_{sfc}$ (glacier-wide)

See article Surface mass balance under Mass balance.

**Surge** ($n.$; also v.)

Abnormally fast flow of a glacier over a period of a few months to years, during which the glacier margin may advance substantially.

A surge-type glacier exhibits quiescent phases, typically lasting some decades, during which velocities are lower than in a “normal”, non-surge-type glacier. The ice discharge is thus too small to maintain the longitudinal profile of the glacier, which thickens in its upper reaches and thins in its lower reaches. Surges recur at quasi-periodic, glacier-specific intervals, and transfer large quantities of ice from the thickened upper part to the thinned lower part. Velocities during the surge are often greater by an order of magnitude than those during the quiescent phase.

A surge-type glacier will almost always be out of balance. That is, a surge-type glacier cannot be in steady state. Surge-type glaciers may end on land or in water, and the proportion of glaciers that are of surge type varies from region to region. The mechanism of surging is poorly understood. Surges seem, however, to be related to changes in the subglacial hydrological regime and not primarily to climatic fluctuations. Although surging is best documented on smaller glaciers, many larger outlet glaciers of ice caps have been observed to surge, and there may be a connection with the unsteady behaviour exhibited by some ice streams.
Surge-type glacier
A glacier that has been observed to surge, or is inferred from evidence such as contorted medial moraines to have surged in the past.

Synthetic Aperture Radar Interferometry
See InSAR.
Temperate glacier
A glacier consisting of temperate ice over its entire thickness and extent, except for a surface layer of the order of 10–15 m thick which may experience seasonal cooling.

By definition a temperate glacier is a wet-based glacier. See cold glacier, polythermal glacier.

Temperate ice
1 Ice that contains a liquid phase of no more than moderate salinity with which it is in thermodynamic equilibrium at the solid–liquid phase boundaries.

2 Less precisely, ice that is at its pressure-melting point.

Other factors, notably the salinity of water inclusions, can be of comparable importance to the hydrostatic pressure for determination of the melting point. Sense 2 is adequate for simple purposes, but the details illuminated by Lliboutry (1971) and Harrison (1972) are likely to be of practical importance in detailed work.

Temperature-index model
A model of mass balance in which surface ablation is estimated as a function of temperature, usually near-surface air temperature measured either on the glacier or at the nearest weather station; temperatures may also be taken from upper-air soundings, meteorological reanalyses or climate models.

A leading form of temperature-index model is the positive degree-day model, in which a degree-day factor represents the dependence of ablation on temperature. Temperature-index models are valuable because they require only simple input variables and perform well when suitably calibrated, for example by allowing for the differences in reflectivity between surfaces of ice and snow by choosing a smaller degree-day factor for snow than for ice.

See energy-balance model.

Temporary Technical Secretariat for the World Glacier Inventory (TTS/WGI)
A body established in 1975 to prepare guidelines for the compilation of a world glacier inventory and to collect inventories from different countries.

In 1986, the Temporary Technical Secretariat for the World Glacier Inventory was merged with the Permanent Service on the Fluctuations of Glaciers to form the World Glacier Monitoring Service.

Terminus
The lowest end of a glacier, also called glacier snout, glacier front or glacier toe.

The term, the plural of which is either “terminuses” or “termini”, is applicable primarily to glaciers with well-defined tongues, and to ice streams. See glacier margin.

Thickness
The vertical distance between any two surfaces, and in particular between the glacier surface and the summer surface, or the glacier surface and the bed.

Glacier thickness is measured ideally by interpolating from a dense array of point measurements, constructed for example from ground-penetrating radar traverses. However the measurement density is often less than ideal, as when the array consists of a single traverse or even just a small number of boreholes. On most glaciers there are no thickness measurements at all and the thickness must be estimated, for example by volume-area scaling or as a function of surface slope and estimated basal shear stress.

The definition of thickness as a vertical distance is adopted almost invariably in studies of mass balance, but not in all branches of cryospheric science. For example Fierz et al. (2009) define thickness as the coordinate normal to the slope, measured from the base of a layer of snow.
Thickness change
The change in the thickness of the glacier at a defined horizontal location.

Thickness can change at a point due to ablation and accumulation at the surface and bottom of the glacier, compaction of snow and firn, or a non-zero emergence velocity or submergence velocity (see continuity equation). Thickness change is often used interchangeably with elevation change, but the two are not necessarily the same. For example, elevation can change due to glacial isostatic adjustment or vertical tectonic motions, without a change in glacier thickness. The thickness change at a point is not equivalent to the climatic-basal mass balance at that point because the thickness change may be due in part to emergence or submergence (see continuity equation). Thickness change at a point is therefore not a direct indicator of the local climate.

The glacier-wide mean thickness change \( \Delta h \) is the volume change of the entire glacier divided by the mean glacier area during the time span of the measurements:

\[
\Delta h = \frac{2(V_2 - V_1)}{(S_2 + S_1) },
\]

where \( V \) is volume, \( S \) is area, and subscripts 1 and 2 refer to measurements at an earlier and later time, respectively. The quantity \( (V_2 - V_1) = \Delta V \) is the volume change. Usually the two volumes are not known separately, and \( \Delta V \) is obtained from measurements of \( \Delta h \) by geodetic methods.

The mean thickness change, if multiplied by the density of the mass gained or lost, is equal to the glacier-wide mass balance over the period of the thickness change.

The mean thickness change differs from the change of mean thickness, which is \( \frac{V_2}{S_2} - \frac{V_1}{S_1} \).

Thinning flux
The mass flux through a vertical cross section corresponding to the decrease of mass upglacier from the section (that is, the integral of density over the thickness of the glacier and the upglacier area).

Volumetric thinning flux
The thinning flux divided by average density.

Thinning velocity
The volumetric thinning flux divided by the area of the vertical cross section through which it passes.

Tidewater glacier
A glacier that terminates in the sea, with terminus either floating or grounded below sea level. See floating tongue, tidewater instability.

The adjective indicates geographical setting, and not that tides play a role in the mass balance.

Tidewater instability
Unsteady, perhaps quasi-periodic, behaviour (Meier and Post 1987) of a tidewater glacier that undergoes alternating episodes of slow advance and rapid retreat.

The conditions permitting advance to the advanced position in the first place, and the triggers for subsequent unstable retreat, are both poorly understood, although they may involve variations in basal water pressure and probably involve variations of the climatic mass balance.

Once retreat has begun, however, observation and simulation (Schoof 2007) agree that, if the bed is grounded below sea level but has a slope opposed to that of the surface, the retreat will continue until the grounding line reaches a part of the bed that slopes in the same direction as the surface. During this unstable retreat, enhanced calving leads to a positive feedback in which accelerated flow and dynamic thinning extend far upglacier from the part that is grounded below sea level. Mass loss is far greater than, and essentially independent of, the climatic mass balance.

Tier
One of the levels in the multi-level monitoring strategy of the Global Terrestrial Network for Glaciers. See reference glacier, and also benchmark glacier.
Tier 1 is a conceptual level that integrates monitoring studies at lower levels into large-scale transects across environmental gradients.

Tier 2 consists of glaciers on which extensive mass-balance measurements are made and research is conducted to improve process understanding and model calibration.

A Tier-3 glacier is one on which mass balance is measured using cost-saving methodologies.

On Tier-4 glaciers measurements, for example of length changes and volume changes, are made to assess the representativeness of more detailed measurements on nearby Tier-2 and Tier-3 glaciers.

A Tier-5 glacier is a glacier included in a glacier inventory, the latter ideally repeated at intervals of a few decades.

**Time system**
A protocol for identifying stages in the evolution of the mass balance of the glacier over the mass-balance year, making it possible to quantify the mass change during each stage objectively.

Four time systems are recognized. Figure 14 illustrates the differences between the original two. See combined system, fixed-date system, floating-date system, stratigraphic system.

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**Tongue**
1. The lower, elongate part of a valley glacier or outlet glacier.

2. A floating extension of a glacier or ice stream, laterally unconfined but markedly longer than wide.
Topographic method
Like cartographic method, a synonym of geodetic method in the context of measurement of mass balance.

Total ablation
A term formerly used in the stratigraphic system (Anonymous 1969; Appendix A) for annual ablation.

Total accumulation
A term formerly used in the stratigraphic system (Anonymous 1969; Appendix A) for annual accumulation.

Total exchange
A term formerly used (Anonymous 1969; Appendix A) for the difference between annual accumulation and annual ablation, \( e_a - a_a \), in the stratigraphic system.

Note that ablation is defined to be negative. See annual exchange.

Total mass balance
The sum of the climatic-basal mass balance and frontal ablation, or equivalently the sum of accumulation and ablation; a synonym of mass balance.

The adjective “total” was formerly a technical term in the stratigraphic system (Anonymous 1969; Appendix A). It is now needed only when it is important to emphasize that all the components of the mass balance are being studied.

Transient (adj.)
Of a state or entity, changing with time or persisting for only a short time.

Transient AAR
See article Transient AAR under Accumulation-area ratio.

Transient ELA
See article Transient ELA under Equilibrium-line altitude.

Transient equilibrium line
See article Transient equilibrium line under Equilibrium line.

Transient snowline
See article Transient snowline under Snowline.

Trimline
A line separating tracts of unglacierized terrain of strikingly different appearance, the appearance of one of the tracts being interpretable as due to recent deglaciation.

The trimline usually separates terrain with more mature vegetation, deglaciated in the more distant past or never glaciated at all, from terrain exposed during the retreat of glaciers from their Little Ice Age maximum extents. The separation may also be marked in part by terminal moraines. The trimline can be used to reconstruct former glacier extent and volume. Reliably dated trimlines have been used in this way to estimate long-term average mass balance.

Triple point
The temperature, 273.16 K by definition, and pressure, 611.657 Pa, at which ice, water and water vapour are in thermodynamic equilibrium.

The term “point” derives from the practice in thermodynamics of choosing temperature and pressure as the coordinates of a two- or higher-dimensional phase diagram.
Valley glacier
A glacier flowing down a valley and in consequence having a distinct tongue. The glacier outline is well-defined.

Volume–area scaling
A method of relating glacier volume or volume changes to glacier area or area changes, based on a tendency for glacier thickness to be well correlated (to “scale”) with glacier area.

Glacier volume $V$ is the product of area $S$ and mean thickness $H$. Measured mean thicknesses are well described by a relation of the form $H = c S^{\gamma}$, which is the basis for the volume-area relation $V = c S^\gamma$. Here $c$ and $\gamma$ are parameters estimated from samples of glaciers with measured thicknesses. There is good evidence, as shown by Bahr et al. (1997), that estimates of $\gamma$ from observations are nearly consistent with theoretical expectation. Mean thickness is also sometimes estimated as a function of average surface slope and basal shear stress.

Volume–area scaling is both a way of estimating regional and global glacier volumes from abundant data on glacier area, and a possible way of estimating (with large random uncertainty) the volume balance of single glaciers from successive measurements of area $S_1$ and $S_2$, for example as $\Delta V = c(S_2^{\gamma} - S_1^{\gamma})$. It can also be used, as a practical alternative to ice-flow modelling, to estimate glacier area changes in attempts to model the response of glaciers to climatic change.

Glacier volume is also expected, and found, to scale with glacier length, particularly when the length is that of a flowline.

Volume balance
The change in the volume of a glacier, or part of a glacier, over a stated span of time.

A volume balance contains no information about the density of the matter within the volume gained or lost. It is meaningful in itself, but is often an intermediate product in the determination of mass balance by geodetic methods.

Balances expressed in ice-equivalent or water-equivalent units, such as $m^3$ w.e. a$^{-1}$, are not volume balances but mass balances.

Volumetric balance flux
See article Volumetric balance flux under Balance flux.

Volumetric calving flux
See article Volumetric calving flux under Calving flux.

Volumetric thinning flux
See article Volumetric thinning flux under Thinning flux.
Warm-based glacier
A glacier whose bed is at its pressure-melting point. Wet-based glacier is a synonym.

Warm firn zone
See infiltration-recrystallization zone.

Warm infiltration-recrystallization zone
See infiltration-recrystallization zone.

Water balance
A relation describing the change in the amount of water stored within a defined volume owing to transfers of water across the boundary of the volume.

The general water balance equation is

$$\Delta W = P - E - Q,$$

where $P$ is precipitation, $E$ is evapotranspiration, $Q$ is runoff and $\Delta W$ is the change in storage.

The water balance is the basis of the hydrological method of determination of glacier mass balance. Typically in glaciological research the defined volume is a drainage basin tributary to a discharge measurement station near to the glacier margin, and not all of the basin is glacierized. Transfers of water by precipitation and evapotranspiration will include transfers not passing through the boundary of the glacier, and stores of water will include lakes, seasonal snowpatches, soil and aquifers as well as the glacier. Changes in each of the non-glacial stores must be accounted for to isolate the glacier mass balance.

It can be convenient in glacier hydrology to distinguish between meltwater runoff from glacier ice and firm and runoff from the basin-wide snowpack, the latter including the snow on the glacier. Denoting these stores by $I$ and $N$ respectively, and assuming that changes in other stores are negligible,

$$\Delta I = \Delta N - E_i - Q_i,$$

$$\Delta N = P_n - E_n - Q_n.$$

Snowfall $P_n$ that does not evaporate or run off must accumulate, contributing to the ice balance $\Delta I$ as $\Delta N$. The total runoff is the sum of runoff from snow $Q_n$, runoff from ice and firn $Q_i$ and runoff of liquid-water inputs.

Water equivalent
A unit, in full the “metre of water equivalent”, that is an extension of the SI for describing glacier mass in specific units as the thickness of an equal mass having the density of water.

1 kg of liquid water, of density $\rho_w = 1000$ kg m$^{-3}$, has a vertical extent of exactly 1 mm when distributed uniformly over a horizontal area of 1 m$^2$. More formally, the metre water equivalent (m w.e.) is obtained by dividing a particular mass per unit area by the density of water:

$$1 \text{ m w.e.} = 1000 \text{ kg m}^{-2} / \rho_w.$$

Water equivalents (m w.e.) can be converted to kg m$^{-2}$ by multiplying by the density of water, and to ice equivalents (m ice eq.) by multiplying by the density of water and dividing by the density of ice.

Water year
The hydrological year.

Weathering crust
A friable surface layer, of reduced density, that develops due to small-scale variations of the melting rate of ice in the presence of cryoconite.
Short-term measurements of surface lowering are unreliable as estimates of surface ablation when there is a weathering crust. The crust may reach a thickness of the order of 100–200 mm over several days, only to be removed abruptly by rain or strong winds.

**Wet-based glacier**
A glacier the bed of which is at its pressure-melting point. Warm-based glacier is a synonym.

**Wet-snow line**
The set of points on a glacier separating the upper percolation zone, at higher elevation, from the lower percolation zone or wet-snow zone. See zone.

The wet-snow line has no surface expression, but is significant as the upper limit of the region where internal accumulation may happen.

**Wet-snow zone**
The part of the accumulation zone of a cold glacier or polythermal glacier where all of the snow reaches the melting point during the ablation season.

The wet-snow zone is sometimes referred to as the lower percolation zone. See zone.

**Wind ablation**
Mass loss, local or glacier-wide, by wind scour.

Snow lost to wind ablation on one part of the glacier surface is often re-deposited in more sheltered parts of the glacier surface, making no contribution to glacier-wide ablation.

**Windborne snow**
Blowing snow or drifting snow.

Windborne snow may be redistributed from one part of the glacier to another. It contributes to the glacier-wide mass balance only when it is carried across a lateral boundary of the glacier, either inward or outward, or when it suffers sublimation instead of being re-deposited.

**Wind scour**
The entrainment and removal of surface snow by the wind.

The resulting windborne snow may be re-deposited elsewhere in more sheltered parts of the glacier surface, or may be transported off the glacier.

**Winter ablation**  \( a_w \) (point), \( A_w \) (glacier-wide)
See article Winter ablation under Mass balance.

**Winter accumulation**  \( c_w \) (point), \( C_w \) (glacier-wide)
See article Winter accumulation under Mass balance.

**Winter-accumulation type**
A type of glacier, typically at mid-latitudes or high latitudes, on which the regional seasonality leads to accumulation predominating in the winter season and ablation predominating in the summer season.

**Winter mass balance**  \( b_w \) (point), \( B_w \) (glacier-wide)
See article Winter mass balance under Mass balance.

**Winter season**
The time span from the start of the mass-balance year to the time of maximum glacier mass (see zone).

The term is best suited to glaciers of winter-accumulation type. See accumulation season.
In the \textit{stratigraphic system} the winter season ends when the glacier has attained maximum mass. In the \textit{floating-date system} and the \textit{fixed-date system}, the mass is not necessarily at its annual minimum or maximum when the winter season starts or ends.

\textbf{World Data Centres (WDC)}
A set of centres for the storage and dissemination of scientific data under the sponsorship of the \textit{International Council for Science (ICSU)}.

The three World Data Centres for Glaciology are at the \textit{National Snow and Ice Data Center}, University of Colorado, Boulder, U.S.A.; the Scott Polar Research Institute, University of Cambridge, Cambridge, England; and the Cold and Arid Regions Environmental and Engineering Research Institute (CAREERI), Lanzhou, China.

\textbf{World Data System (WDS)}
A body, founded in 2009, that provides an operational framework for the \textit{World Data Centres} and \textit{Data Analysis Services} of the \textit{International Council for Science (ICSU)}.

\textbf{World Glacier Inventory (WGI)}
A cooperative project, organized during the International Hydrological Decade (1965–1974) on the basis of suggestions first made in the 1950s, for the collection of morphometric and other basic information about all of the world’s \textit{glaciers}.

The \textit{World Glacier Monitoring Service} (WGMS 1989) reported on the status of the WGI in the late 1980s. In 1998 the World Glacier Monitoring Service and the US \textit{National Snow and Ice Data Center}, having pooled their data sources, made an enlarged version of the WGI available online at the NSIDC website. This version is incomplete. Completion of the WGI is the aim of collaborative efforts by many investigators under the auspices of WGMS, NSIDC and the \textit{Global Land Ice Monitoring from Space} initiative.

\textbf{World Glacier Monitoring Service (WGMS)}
The leading organization for the collection, storage and dissemination of information about \textit{glacier fluctuations}.

The WGMS, formed in 1986 by merging the \textit{Permanent Service on the Fluctuations of Glaciers} and the \textit{Temporary Technical Secretariat for the World Glacier Inventory}, is based in Zürich, Switzerland. It coordinates the work of local investigators through a network of national correspondents in countries involved in glacier monitoring. WGMS runs the \textit{Global Terrestrial Network for Glaciers} (GTN–G) in close collaboration with the \textit{National Snow and Ice Data Center} and the \textit{Global Land Ice Measurements from Space} initiative.
Year
The duration of the Earth’s revolution round the Sun, forming a natural but slightly variable unit of time.

In glaciology, as in other disciplines concerned with the natural progression of the seasons, the year may vary in length for reasons of necessity or convenience, and depending on whether the particular investigation requires precise treatment of calendar time. For the latter, see Julian date.

In mass-balance practice the year is always either exactly or approximately 365 calendar days long (the duration of a calendar year which is not a leap year; see hydrological year, mass-balance year). However the sidereal year is very nearly equal to 365.2564 mean solar days. In turn, the mean solar day is very nearly equal to 86 400 seconds, and 1 day is defined in the Système International d’Unités as an accepted non-SI unit equal to 86 400 seconds exactly.

The practice when brevity is desirable, regardless of hemisphere, is to identify the hydrological year, mass-balance year or measurement year by the calendar year in which it ends. For example the mass-balance year 2000 began in calendar year 1999 and ended in calendar year 2000.

Year-round ablation type
A type of glacier on which ablation by melting or sublimation occurs throughout the year.

Year-round ablation is typical of glaciers in the inner tropics, where there are two seasonal temperature maxima each year, and seasonal temperature variations are smaller than diurnal temperature variations. The seasonal variation of mass balance is affected more by variation of accumulation rates between wet and dry seasons than by variation of ablation rates between winter and summer. Year-round ablation is also observed at low altitude on glaciers in some warm maritime climates, as in Norway, and on high-latitude glaciers where ablation is predominantly by sublimation, as in the Dry Valleys of Antarctica.
Zastrugi
Ridges of hard snow alternating with wind-eroded furrows parallel to the wind direction, with typical lengths of metres and heights less than a metre.

The word is the plural of Russian “zastruga”, and alludes to the result of planing a wooden surface with a jack plane.

Zone
A part of the glacier, and especially of the glacier surface, distinguished from other parts by the prominence or predominance of a particular mass-balance process.

The temperate glacier of Figure 15 and the cold glacier of Figure 16 are end members of a continuum. Many glaciers have attributes, including patterns of zonation, that are intermediate between these end members.

The conventional system of zones in the English-language literature diverges in part from that in Russian-language work (Shumskiy 1955). For the latter, which is based on the relative magnitudes of accumulation, melting and cold content, see infiltration zone, infiltration-congelation zone, infiltration-recrystallization zone, recrystallization zone, recrystallization-regelation zone.

Figure 15. Glacier zonation on a representative temperate glacier during a) a year of more positive and b) a year of more negative mass balance than the previous year. At the start of each mass-balance year the glacier surface is at the line $t_0 - t_0$, the summer surface. It evolves (schematically, the effects of ice flow being neglected) to $t_w - t_w$ at the end of the accumulation season, when the mass of the glacier reaches its annual maximum, and then to $t_1 - t_1$ at the end of the ablation season, when it becomes the summer surface of the next balance year. e: equilibrium line; s: snowline; f: firn line at the start and end of the balance year; AbZ: ablation zone (the zone below e); AcZ: accumulation zone (the zone above e).
Figure 16. Glacier zonation and its balance-related aspects on a representative cold glacier or polythermal glacier. At the start of each mass-balance year the glacier surface is at the line $t_0 - t_0$, the summer surface. It evolves (schematically, the effects of ice flow being neglected) to $t_w - t_w$ at the end of the accumulation season, when the mass of the glacier reaches its annual maximum, and then to $t_1 - t_1$ at the end of the ablation season, when it becomes the summer surface of the next balance year. “mpd” is the maximum depth to which meltwater percolates before refreezing.

The zones are: AbZ: ablation zone (the zone below e); AcZ: accumulation zone (all the zones above e); SIZ: superimposed ice zone; SuZ: slush zone, a part of LPZ; UPZ: upper percolation zone; LPZ: lower percolation zone or wet-snow zone; DSZ: dry-snow zone.

The zones are separated by the lines: e: equilibrium line; s: snowline; r: runoff limit or slush limit (position variable, depending especially on the surface slope); w: wet-snow line (intercept of mpd on summer surface, separating UPZ and LPZ); d: dry-snow line (surface outcrop of mpd).
# Appendix A – Terms Defined in Anonymous (1969)

<table>
<thead>
<tr>
<th>Term</th>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>STRATIGRAPHIC SYSTEM</td>
<td></td>
<td>Measurement system based on existence of an observable summer surface</td>
</tr>
<tr>
<td>Summer surface</td>
<td></td>
<td>Surface formed at time of minimum annual mass at each point, marking end of one balance year (NB: may be diachronous over the extent of the glacier)</td>
</tr>
<tr>
<td>Balance year</td>
<td></td>
<td>Time span between formation of two successive summer surfaces</td>
</tr>
<tr>
<td>Winter season</td>
<td></td>
<td>Time span from start of balance year to time of maximum glacier mass</td>
</tr>
<tr>
<td>Summer season</td>
<td></td>
<td>Time span from time of maximum glacier mass to end of balance year</td>
</tr>
<tr>
<td>Winter accumulation</td>
<td>$c_w$</td>
<td>Integral of accumulation $c(t)$ over winter season</td>
</tr>
<tr>
<td>Summer accumulation</td>
<td>$c_s$</td>
<td>Integral of accumulation $c(t)$ over summer season</td>
</tr>
<tr>
<td>Total accumulation</td>
<td>$c_t$</td>
<td>Integral of accumulation $c(t)$ over balance year</td>
</tr>
<tr>
<td>Winter ablation</td>
<td>$a_w$</td>
<td>Integral of ablation $a(t)$ over winter season</td>
</tr>
<tr>
<td>Summer ablation</td>
<td>$a_s$</td>
<td>Integral of ablation $a(t)$ over summer season</td>
</tr>
<tr>
<td>Total ablation</td>
<td>$a_t$</td>
<td>Integral of ablation $a(t)$ over balance year</td>
</tr>
<tr>
<td>Winter balance</td>
<td>$b_w$</td>
<td>Change in mass during winter season</td>
</tr>
<tr>
<td>Summer balance</td>
<td>$b_s$</td>
<td>Change in mass during summer season</td>
</tr>
<tr>
<td>Net balance</td>
<td>$b_n$</td>
<td>$c_i + a_i$; also $b_w + b_s$</td>
</tr>
<tr>
<td>Total exchange</td>
<td>$e_t$</td>
<td>$c_i - a_i$; also $b_w - b_s$</td>
</tr>
<tr>
<td>FIXED-DATE SYSTEM</td>
<td></td>
<td>Measurement system based on specific calendar dates</td>
</tr>
<tr>
<td>Measurement year</td>
<td></td>
<td>Time between start and end of measurement</td>
</tr>
<tr>
<td>Annual accumulation</td>
<td>$c_a$</td>
<td>Integral of accumulation $c(t)$ over measurement year</td>
</tr>
<tr>
<td>Annual ablation</td>
<td>$a_a$</td>
<td>Integral of ablation $a(t)$ over measurement year</td>
</tr>
<tr>
<td>Annual balance</td>
<td>$b_a$</td>
<td>$c_a + a_a$</td>
</tr>
<tr>
<td>Annual exchange</td>
<td>$e_a$</td>
<td>$c_a - a_a$</td>
</tr>
</tbody>
</table>

OTHER

<table>
<thead>
<tr>
<th>Term</th>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transient equilibrium line</td>
<td></td>
<td>Locus of points where balance $b(t)$ is zero</td>
</tr>
<tr>
<td>Equilibrium line</td>
<td></td>
<td>Locus of points where $b_n$ is zero</td>
</tr>
<tr>
<td>Annual equilibrium line</td>
<td></td>
<td>Locus of points where $b_s$ is zero</td>
</tr>
<tr>
<td>Accumulation area</td>
<td>$S_c$</td>
<td>Area above equilibrium line</td>
</tr>
<tr>
<td>Ablation area</td>
<td>$S_a$</td>
<td>Area below equilibrium line</td>
</tr>
<tr>
<td>Accumulation-area ratio</td>
<td>AAR</td>
<td>$S_c / (S_c + S_a)$</td>
</tr>
<tr>
<td>Transient snow line</td>
<td></td>
<td>Line separating snow from ice or firn at any time $t$</td>
</tr>
<tr>
<td>Firn line</td>
<td></td>
<td>Transient snow line at time of minimum snow cover</td>
</tr>
<tr>
<td>Firn</td>
<td></td>
<td>Snow which has passed through (at least) one summer</td>
</tr>
</tbody>
</table>

1: Lower-case symbols are for point mass-balance quantities, and the corresponding upper-case symbols are for areal, including glacier-wide, mass-balance quantities.

The terminology in this Glossary diverges at several points from that summarized above.
Appendix B – Constants and Properties

Table B1  Physical properties of water substance

<table>
<thead>
<tr>
<th>Property</th>
<th>Expression</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ice point(^1)</td>
<td>(T_m = 273.15 \text{ K} = 0 \text{ ºC}, p = 101 \text{ 325 Pa})</td>
<td>Commonly called the melting point or freezing point</td>
</tr>
<tr>
<td>Triple point(^1,2)</td>
<td>(T = 273.16 \text{ K}, p = 611.7 \text{ Pa})</td>
<td>Temperature and pressure at which ice, water and water vapour are in thermodynamic equilibrium</td>
</tr>
<tr>
<td>Mean molecular weight(^1)</td>
<td>0.018015 kg mol(^{-1}) (\equiv 18 \text{ g mol}^{-1})</td>
<td>Vienna Standard Mean Ocean Water (VSMOW)</td>
</tr>
<tr>
<td>Thermal conductivity(^3)</td>
<td>(K = 2.238 – 0.0107 \text{ } T \text{ W m}^{-1} \text{ K}^{-1})</td>
<td>Pure ice, (T) in ºC</td>
</tr>
<tr>
<td>Effective thermal</td>
<td>(K_{\text{eff}} = 0.06 + 2.69 \times 10^{-6} \rho^2)</td>
<td>At –5 ºC; includes heat transfer by diffusion of vapour</td>
</tr>
<tr>
<td>conductivity of dry snow(^4)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Latent heat of vaporization(^2)</td>
<td>(L_v = 2500.8 \text{ } \text{kJ kg}^{-1})</td>
<td>At 0 ºC</td>
</tr>
<tr>
<td>Latent heat of fusion(^2)</td>
<td>(L_f = 333.5 \text{ } \text{kJ kg}^{-1})</td>
<td>Decreases nearly linearly to 289 kJ kg(^{-1}) at –20 ºC</td>
</tr>
<tr>
<td>Latent heat of sublimation(^2)</td>
<td>(L_s = 2834.2 \text{ } \text{kJ kg}^{-1})</td>
<td>At 0 ºC; equal to (L_v + L_f)</td>
</tr>
<tr>
<td>Relative dielectric</td>
<td>(\varepsilon_r' = 1)</td>
<td></td>
</tr>
<tr>
<td>constant(^5)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Relative dielectric</td>
<td>(\varepsilon_r' = 88)</td>
<td></td>
</tr>
<tr>
<td>constant(^6)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Relative dielectric</td>
<td>(\varepsilon_r' \approx 3.15)</td>
<td></td>
</tr>
<tr>
<td>constant(^5)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Relative dielectric</td>
<td>(\varepsilon_r' = (1 + 0.000845 \rho)^2)</td>
<td></td>
</tr>
<tr>
<td>constant(^5)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>


Table B2  Temperature-dependent properties of pure ice (and supercooled water)

<table>
<thead>
<tr>
<th>(T) (ºC)</th>
<th>(\rho_i) (kg m(^{-3}))</th>
<th>(\alpha_V) (\times 10^{-6} \text{ } \text{K}^{-1})</th>
<th>(\kappa) (\times 10^{-12} \text{ } \text{Pa}^{-1})</th>
<th>(e_{v*}) (Pa)</th>
<th>(e_{w*}) (Pa)</th>
<th>(K) (W m(^{-1}) K(^{-1}))</th>
<th>(C_p) (J kg(^{-1}) K(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>916.7</td>
<td>159</td>
<td>130</td>
<td>611.15</td>
<td>611.21</td>
<td>2.24</td>
<td>2114</td>
</tr>
<tr>
<td>–10</td>
<td>918.7</td>
<td>155</td>
<td>128</td>
<td>259.89</td>
<td>286.45</td>
<td>2.34</td>
<td>2036</td>
</tr>
<tr>
<td>–20</td>
<td>920.3</td>
<td>149</td>
<td>127</td>
<td>103.25</td>
<td>125.50</td>
<td>2.45</td>
<td>1958</td>
</tr>
<tr>
<td>–40</td>
<td>922.8</td>
<td>137</td>
<td>124</td>
<td>12.84</td>
<td>18.91</td>
<td>2.65</td>
<td>1806</td>
</tr>
<tr>
<td>–80</td>
<td>927.4</td>
<td>105</td>
<td>119</td>
<td>0.05</td>
<td>0.11</td>
<td>3.10</td>
<td>1517</td>
</tr>
</tbody>
</table>

\(T\)  Temperature  
\(\rho_i\)  Density (Chemical Rubber Company 2008–09)  
\(\alpha_V\)  Volumetric coefficient of thermal expansion (Chemical Rubber Company 2008–09)  
\(\kappa\)  Adiabatic compressibility (Chemical Rubber Company 2008–09)  
\(e_{v*}\)  Equilibrium vapour pressure (Murphy and Koop 2005)  
\(e_{w*}\)  Equilibrium vapour pressure over supercooled water (Murphy and Koop 2005)  
\(K\)  Thermal conductivity (Pounder 1965)  
\(C_p\)  Heat capacity at constant pressure (Murphy and Koop 2005)
Table B3  Pressure dependence of the melting point of ice (after Wagner et al. 1994)

<table>
<thead>
<tr>
<th>Thickness of ice ( h ) (m)</th>
<th>Pressure ( p ) (MPa)</th>
<th>Equilibrium temperature ( T_m ) (ºC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>1.80</td>
<td>–0.1</td>
</tr>
<tr>
<td>500</td>
<td>4.50</td>
<td>–0.3</td>
</tr>
<tr>
<td>1000</td>
<td>9.00</td>
<td>–0.7</td>
</tr>
<tr>
<td>2000</td>
<td>17.99</td>
<td>–1.3</td>
</tr>
<tr>
<td>5000</td>
<td>44.98</td>
<td>–3.3</td>
</tr>
</tbody>
</table>

The pressure is \( \rho_i g h \), with density \( \rho_i = 917 \text{ kg m}^{-3} \) and \( g \) acceleration due to gravity (Table B5). The equilibrium temperature is that of pure ice and water, changing with pressure at \(-7.4 \times 10^{-8} \text{ K Pa}^{-1}\).

Table B4  Properties of water at 0 ºC and 1000 hPa

<table>
<thead>
<tr>
<th>Property</th>
<th>Magnitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density(^1)</td>
<td>( \rho_w = 999.84 \text{ kg m}^{-3} )</td>
</tr>
<tr>
<td>Heat capacity at constant pressure(^2)</td>
<td>( C_p = 4211 \text{ J kg}^{-1} \text{ K}^{-1} )</td>
</tr>
<tr>
<td>Equilibrium vapour pressure(^2)</td>
<td>( e_{w*} = 611.2 \text{ Pa} )</td>
</tr>
<tr>
<td>Latent heat of vaporization(^2)</td>
<td>( L_v = 2500.8 \text{ kJ kg}^{-1} )</td>
</tr>
<tr>
<td>Thermal conductivity(^1)</td>
<td>( K_w = 0.561 \text{ W m}^{-1} \text{ K}^{-1} )</td>
</tr>
<tr>
<td>Viscosity(^1)</td>
<td>( \nu = 1793 \mu\text{Pa s} )</td>
</tr>
</tbody>
</table>


Table B5  Selected physical constants and reference values

<table>
<thead>
<tr>
<th>Constant</th>
<th>Magnitude</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed of electromagnetic waves in a vacuum(^1)</td>
<td>( c = 299\ 792\ 458 \text{ m s}^{-1} )</td>
<td>( \approx 3 \times 10^8 \text{ m s}^{-1} )</td>
</tr>
<tr>
<td>Gravitational constant(^1)</td>
<td>( G = 6.67428 \times 10^{-11} \text{ m}^3 \text{ kg}^{-1} \text{ s}^{-2} )</td>
<td></td>
</tr>
<tr>
<td>Gas constant(^1)</td>
<td>( R = 8.3145 \text{ J mol}^{-1} \text{ K}^{-1} )</td>
<td></td>
</tr>
<tr>
<td>Stefan-Boltzmann constant(^1)</td>
<td>( \sigma = 5.6704 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4} )</td>
<td></td>
</tr>
<tr>
<td>Mean radius of the Earth(^2)</td>
<td>( R_E = 6371007 \text{ m} )</td>
<td>Radius of a sphere of area equal to that of WGS84 reference ellipsoid</td>
</tr>
<tr>
<td>Acceleration due to gravity(^3)</td>
<td>( g = 9.81 \text{ m s}^{-2} )</td>
<td>“Standard acceleration due to gravity” is exactly 9.80665 m s(^{-2}), but the acceleration at sea level varies with location within a range of about 0.5%</td>
</tr>
<tr>
<td>Sea-level pressure(^4)</td>
<td>( \rho_0 = 101\ 325 \text{ Pa} )</td>
<td>Pressure at sea level in the ICAO standard atmosphere</td>
</tr>
<tr>
<td>Area of the ocean(^5)</td>
<td>( S_O = 362.5 \times 10^6 \text{ km}^2 )</td>
<td>Includes ( 1.555 \times 10^6 \text{ km}^2 ) beneath ice shelves</td>
</tr>
</tbody>
</table>

### Table B6  Density of frozen water in various forms

<table>
<thead>
<tr>
<th>Material</th>
<th>Density (kg m$^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SURFACE SNOW$^{1,2}$</strong></td>
<td></td>
</tr>
<tr>
<td>Newly fallen snow in cold, calm conditions</td>
<td>10 – 65</td>
</tr>
<tr>
<td>Newly fallen snow near the <em>freezing point</em></td>
<td>100 – 300</td>
</tr>
<tr>
<td>Settled snow</td>
<td>200 – 300</td>
</tr>
<tr>
<td>Wind-packed snow</td>
<td>350 – 400</td>
</tr>
<tr>
<td><strong>DEPTH HOAR$^2$</strong></td>
<td>100 – 300</td>
</tr>
<tr>
<td><strong>FIRN$^1$</strong></td>
<td></td>
</tr>
<tr>
<td>Firn</td>
<td>400 – 650</td>
</tr>
<tr>
<td>Thawed and refrozen firn, and “firn-ice”</td>
<td>600 – 830</td>
</tr>
<tr>
<td><strong>GLACIER ICE$^2$</strong></td>
<td>830 – 917</td>
</tr>
<tr>
<td><strong>PURE MONOCRYSTALLINE ICE$^3$</strong></td>
<td></td>
</tr>
<tr>
<td>0 °C</td>
<td>916.7</td>
</tr>
<tr>
<td>–10 °C</td>
<td>918.7</td>
</tr>
<tr>
<td>–20 °C</td>
<td>920.3</td>
</tr>
<tr>
<td>–40 °C</td>
<td>922.8</td>
</tr>
<tr>
<td>–80 °C</td>
<td>927.4</td>
</tr>
</tbody>
</table>

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(Underlined titles are hyperlinks.)


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