Glossary of glacier mass balance and related terms

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GLOSSARY OF GLACIER MASS BALANCE AND RELATED TERMS

Prepared by the Working Group on Mass-balance Terminology and Methods of the International Association of Cryospheric Sciences (IACS)

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Right: Grounded calving front of Store Gletscher, a western outlet of the Greenland Ice Sheet, August 2008 (Jason Box).

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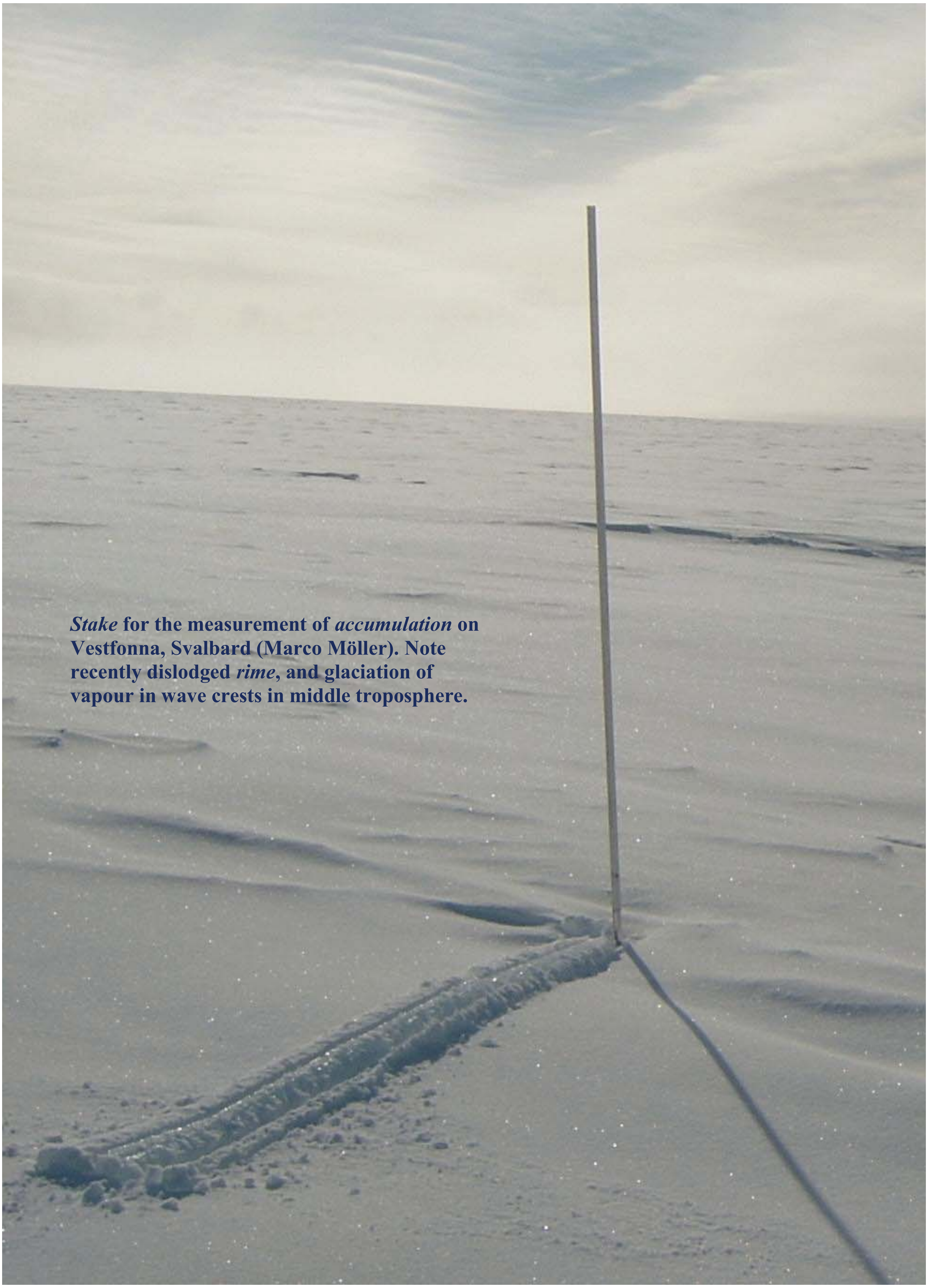

Stake **for the measurement of** ***accumulation*** **on Vestfonna, Svalbard (Marco Möller). Note recently dislodged** ***rime*****, and glaciation of vapour in wave crests in middle troposphere.**

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

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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 Ommanney, Tad Pfeffer, Bruce Raup, Gina Schmalzle, 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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IACS Working Group on Mass-balance Terminology and Methods

To enchain syllables, and to lash the wind, are equally the undertakings of pride, unwilling to measure its desires by its strength.

Samuel Johnson, 1755, *A Dictionary of the English Language*.

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 “firn”. 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:

a	ablation	c	accumulation	b	mass balance (c+a)
ρ	density	h	glacier thickness		
S	area	V	volume		
AAR	accumulation-area ratio	ELA	equilibrium-line altitude		

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 α 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:

a	annual	w	winter	s	summer		
sfc *or* s	surface	i	internal	bed *or* b	basal	f	frontal

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, $\dot{x} = \partial x / \partial t$. 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 $Dx / Dt = \partial x / \partial t + \vec{u} \cdot \nabla x$, where $\vec{u}$ is the velocity vector and ∇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 $\dot{a}_{\mathrm{b(fl)}}$ and $\dot{a}_{\mathrm{b(gr)}}$ 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 $c_{\mathrm{sfc(sn)}}$ and $c_{\mathrm{sfc(si)}}$ 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*.

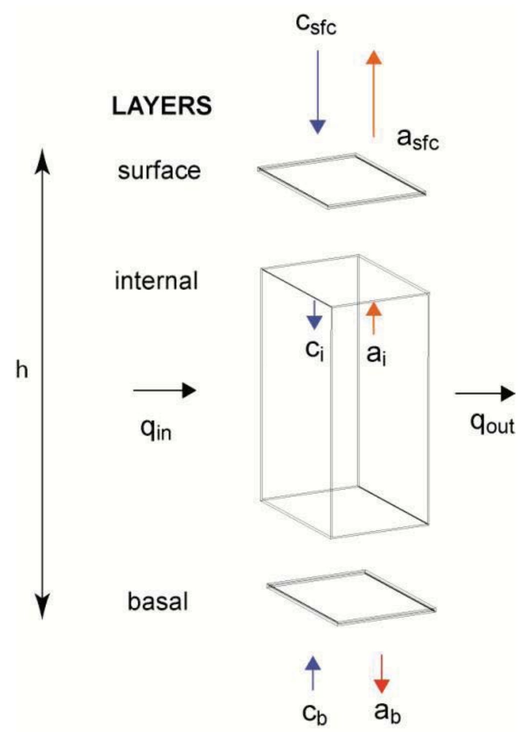


Figure 1. The mass balance of a column of glacier ice, firn and snow. In general, density ρ varies through the thickness $h = m / \bar{\rho}$; h may vary due to changes in either mass m or average density $\bar{\rho}$.

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

$$\dot{m} = \dot{c}_{\mathrm{sfc}} + \dot{a}_{\mathrm{sfc}} + \dot{c}_{\mathrm{i}} + \dot{a}_{\mathrm{i}} + \dot{c}_{\mathrm{b}} + \dot{a}_{\mathrm{b}} + (q_{\mathrm{in}} + q_{\mathrm{out}}) / ds \quad (1)$$

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

$$\dot{h} = \dot{b} - \nabla \cdot \vec{q} \ , \tag{2}$$

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 $(\dot{c}_{\text{sfc}} + \dot{a}_{\text{sfc}} + \dot{c}_{\text{i}} + \dot{a}_{\text{i}} + \dot{c}_{\text{b}} + \dot{a}_{\text{b}})$ 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 $\dot{b}$ 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 Δm for the span of time from t_0 to t_1 is linked to the mass-balance rate by

$$\int_{t_0}^{t_1} \dot{m}(t)\,dt = m(t_1) - m(t_0) = \Delta m \tag{3}$$

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 ΔM 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

Component	*Symbols*	*Constituents*
Surface accumulation	C_{sfc}	
Surface ablation	A_{sfc}	
Surface balance	B_{sfc}	$C_{\mathrm{sfc}} + A_{\mathrm{sfc}}$
Internal accumulation	C_{i}	
Internal ablation	A_{i}	
Internal balance	B_{i}	$C_{\mathrm{i}} + A_{\mathrm{i}}$
Basal accumulation	C_{b}	
Basal ablation	A_{b}	
Basal balance	B_{b}	$C_{\mathrm{b}} + A_{\mathrm{b}}$
Climatic balance	B_{clim}	$B_{\mathrm{sfc}} + B_{\mathrm{i}}$
Climatic-basal balance	B	$B_{\mathrm{clim}} + B_{\mathrm{b}}$
Calving	D	
Subaerial frontal melting and sublimation	$A_{\mathrm{f(air)}}$	
Subaqueous frontal melting	$A_{\mathrm{f(wtr)}}$	
Frontal ablation	A_{f}	$D + A_{\mathrm{f(air)}} + A_{\mathrm{f(wtr)}}$
Accumulation	C	$C_{\mathrm{sfc}} + C_{\mathrm{i}} + C_{\mathrm{b}}$
Ablation	A	$A_{\mathrm{sfc}} + A_{\mathrm{i}} + A_{\mathrm{b}} + A_{\mathrm{f}}$
(Total) mass balance	ΔM	$C + A = B + A_{\mathrm{f}}$

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:

$$\dot{B} = \frac{1}{S}\int_S \dot{b}\, ds \quad , \tag{4}$$

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

$$\dot{M} = \dot{B} + \dot{D} / S \quad , \tag{5}$$

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

$$\dot{D} = \int_P \dot{d}\, dp \quad , \tag{6}$$

and the calving flux per unit of distance along the margin (dimension [M L^{-1} T^{-1}]) is

$$\dot{d} = -\bar{\rho} h \vec{u}_D \tag{7}$$

Here the *calving velocity* $\vec{u}_D$ averaged over the glacier thickness at any point *p* on the margin is defined as

$$\vec{u}_D = \vec{u} - \dot{L} \ , \tag{8}$$

where $\vec{u}$ is the vertically-averaged horizontal velocity and $\dot{L}$ 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*.

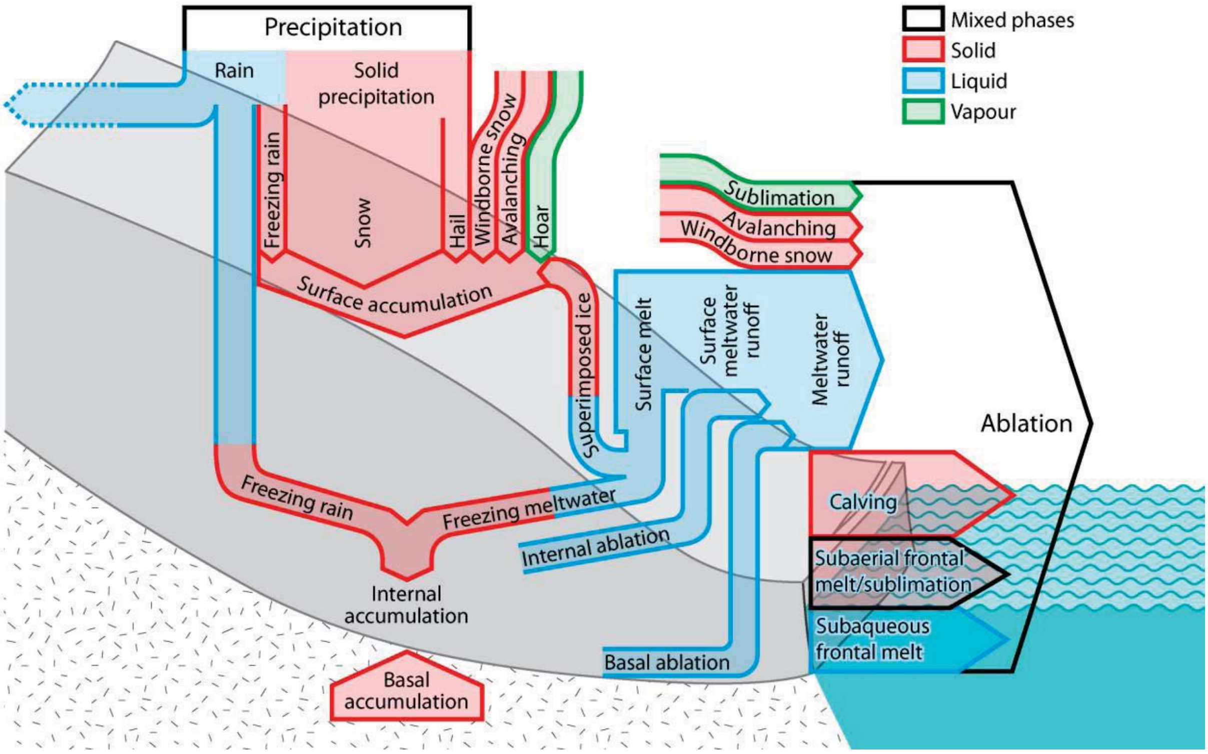


Figure 2. Components of the mass balance of a glacier. The arrows have arbitrary widths and do not indicate physical pathways of mass transfer.

Through (8), equation (7) has two components: the *ice discharge* and the mass "flux" $\bar{\rho} h \dot{L}$ 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 $\vec{q} = -\bar{\rho} h \vec{u}$, 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 $\vec{u}_D$ 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 $\vec{q}_{\mathrm{g}}$. The calving flux $\dot{d}_{\mathrm{f}}$ 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 $\dot{a}_{\mathrm{f}}$, the sum of the calving flux, subaerial frontal melting and sublimation $\dot{a}_{\mathrm{f(air)}}$, and subaqueous frontal melting $\dot{a}_{\mathrm{f(wtr)}}$. For an ice shelf or marine-terminating tongue, the sum of subaqueous frontal ablation and basal ablation is called submarine ablation.

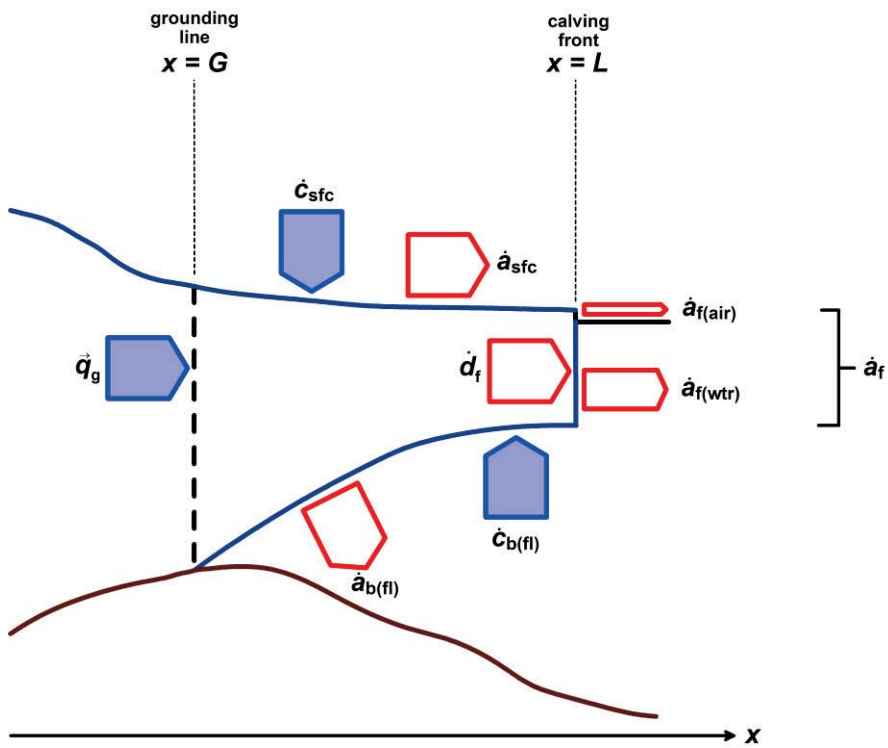


Figure 3. Mass-balance components of a floating tongue or ice shelf. Components of the internal mass balance are neglected. Shaded arrows represent gains by accumulation and flow. Unshaded arrows represent ablation. See text for notation.

4.4.1 Alternative formulations

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

$$\dot{M} \quad = \quad \int_S \dot{b}\, ds + \int_P \dot{d}\, dp \quad = \quad \dot{B} + \dot{D} \tag{9}$$

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 [M]) is

$$\Delta M \quad = \quad \int_{t_0}^{t_1} \left[\int_S \dot{b}\, ds + \int_P \dot{d}\, dp \right] dt \quad = \quad \int_S b\, ds + \int_P d\, dp\,, \tag{10}$$

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

$$\Delta M = \frac{1}{S}\int_S b\, ds + \frac{1}{S}\int_P d\, dp \tag{11}$$

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

$$b_\mathrm{a} = c_\mathrm{a} + a_\mathrm{a} = b_\mathrm{w} + b_\mathrm{s} \tag{12}$$

In the literature, b_n often appears in place of b_a; 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), $c_\mathrm{a} > b_\mathrm{w}$ and $a_\mathrm{a} < b_\mathrm{s}$.

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)

No information provided	1519
Fixed-date system	917
Stratigraphic system	931
Combined system	265
Other	188
Total of reported annual measurements	3820

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.

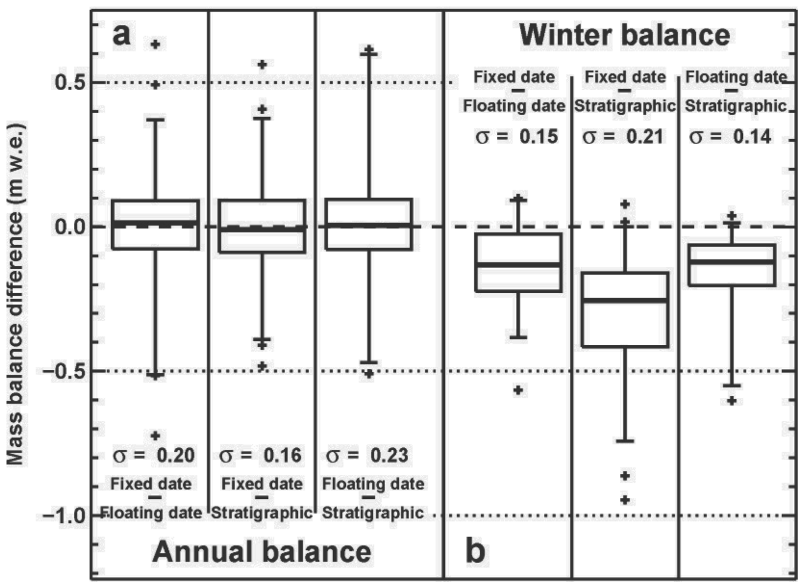


Figure 4. Distributions of differences between (a) annual and (b) winter balance measured in different time systems on two Swiss glaciers during 1960–2007 (after Huss et al. 2009). Bars range from the 2.5 to the 97.5 percentile, with outlying measurements beyond those percentiles represented by plus signs, and boxes cover the 25th to the 75th percentile of each distribution. The central thick line is the median and σ 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 [L^3] (volume)? Equivalently, when the balance is presented as a rate, is it [M T^{-1}] or [L^3 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

Quantity	*Symbol for dimension*	*Base unit*	*Abbreviation for unit*
length	L	metre	m
mass	M	kilogram	kg
time, duration	T	second	s
thermodynamic temperature	Θ	kelvin	K

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

Quantity	*Units*	*Special name*	*Symbol*
area	m^2		
volume	m^3		
speed	$m\ s^{-1}$		
acceleration	$m\ s^{-2}$		
density	$kg\ m^{-3}$		
surface density	$kg\ m^{-2}$		
force	$kg\ m\ s^{-2}$	newton	N
energy	$kg\ m^2\ s^{-2}$; N m	joule	J
power	$kg\ m^2\ s^{-3}$; $J\ s^{-1}$	watt	W
pressure, stress	$kg\ m^{-1}\ s^{-2}$; $N\ m^{-2}$	pascal	Pa
Celsius temperature	K	degree Celsius	°C
frequency	s^{-1}	hertz	Hz
plane angle	$m\ m^{-1}$	radian	rad
solid angle	$m^2\ m^{-2}$	steradian	sr

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 Some SI prefixes

Factor	*Prefix*	*Symbol*	*Factor*	*Prefix*	*Symbol*
10^{-9}	nano-	n	10^{6}	mega-	M
10^{-6}	micro-	μ	10^{9}	giga-	G
10^{-3}	milli-	m	10^{12}	tera-	T
10^{3}	kilo-	k	10^{15}	peta-	P

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 Accepted non-SI units

Quantity	*Unit*	*Symbol*	*Value in SI Units*
time, duration	minute	min	1 min = 60 s
time, duration	day	d	1 d = 86 400 s
plane angle	degree	°	1° = (π/180) rad
plane angle	minute	′	1′ = (π/10 800) rad
plane angle	second	″	1″ = (π/648 000) rad
mass	tonne	t	1 t = 1000 kg

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.

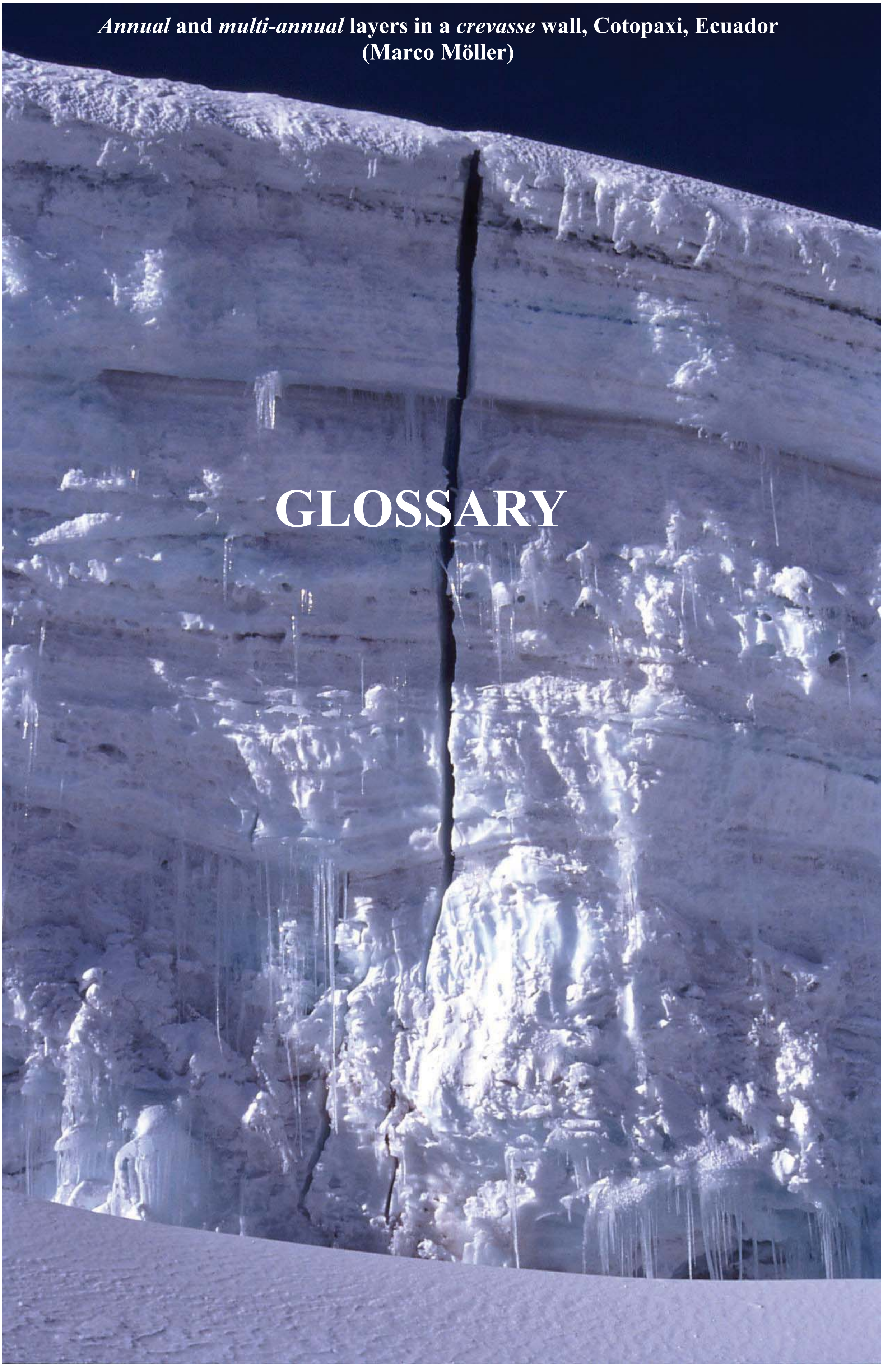
8 Format of the Glossary

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.

A

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 AAR_0, 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 AAR_0 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. AAR_0 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 AAR_0'.

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_{a} (point), A_{a} (glacier-wide)
See article *Annual ablation* under *Mass balance.*

Annual accumulation c_{a} (point), C_{a} (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_{a} (point), B_{a} (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 θ 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*.

B

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 [M 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 [L^3 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 $u_b\tau_b/L_f$ 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 τ_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 $T_B = \varepsilon T - T_{sky}$, where ε is the emissivity of the medium (on *glaciers*, a mixture of *ice*, air, and possibly water), T is its physical (thermodynamic) temperature and $T_{sky} \approx 3$ 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*.

C

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 [M T^{-1}], of *ice* by *calving* from a *glacier margin*.

Volumetric calving flux
The calving flux divided by average glacier *density* (dimension [L^3 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_{calv} can be determined by application of the principle of *conservation of mass* at the *glacier margin*:

$$u_{\mathrm{calv}} = u_{\mathrm{bal}} + u_{\mathrm{thin}} - \dot{L} \, ,$$

where u_{bal} is the *balance velocity*, u_{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 $b = c_{\mathrm{sfc}} + a_{\mathrm{sfc}} + c_{\mathrm{i}} + a_{\mathrm{i}} + c_{\mathrm{b}} + a_{\mathrm{b}}$ states that the climatic-basal mass balance b is the sum of *surface accumulation* c_{sfc}, *surface ablation* a_{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 γ 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 ρ 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 $\gamma/(\rho_w L_f)$, 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:

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

where $\dot{h}$ is the rate of change of glacier thickness, $\dot{b}$ is the *climatic-basal mass-balance rate* and $\nabla \cdot \vec{q}$ 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

$$\dot{b} = \dot{h} + \nabla \cdot \vec{q}$$

When the flux divergence $\nabla \cdot \vec{q}$ is positive, it is called the *submergence velocity*. When it is negative, it is called the *emergence velocity*.

Each of the terms in the continuity equation entails approximations in practical use. The term $\dot{h}$ assumes that the mean *density* is constant, the *point mass balance* is usually approximated by the *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.

Conventional balance
The *mass balance* of a *glacier*, the term having been introduced by Elsberg et al. (2001) to distinguish the mass balance from the *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 *area* and *area-altitude distribution* measured during the same time interval. Calculations of conventional balance require repeated mapping of glacier *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 *reference-surface balance* is a more relevant quantity.

Crater glacier
A *glacier* contained in or overflowing from a volcanic crater.

Crevasse
A crack formed in *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 *meltwater*, to the glacier interior and sometimes the glacier bed; see *moulin*. When crevasses in floating ice fill with surface meltwater, they may propagate to the base, causing the *ice shelf* or *floating tongue* to disintegrate. The fragments may contribute to an ice *melange*.

Crevasse stratigraphy
The observation of annual and other layer thicknesses in the walls of *crevasses* and similar nearly vertical exposures.

See *ice-core stratigraphy*.

Cryoconite
Dark, fine-grained debris on the *glacier* surface, often forming small, roughly circular patches. See *cryoconite hole*.

The word was introduced by Nordenskiöld in 1872.

Cryoconite hole
A small cylindrical hole on the surface of a *glacier*, formed by patches of *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 *ablation*. See also *weathering crust*.

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*.

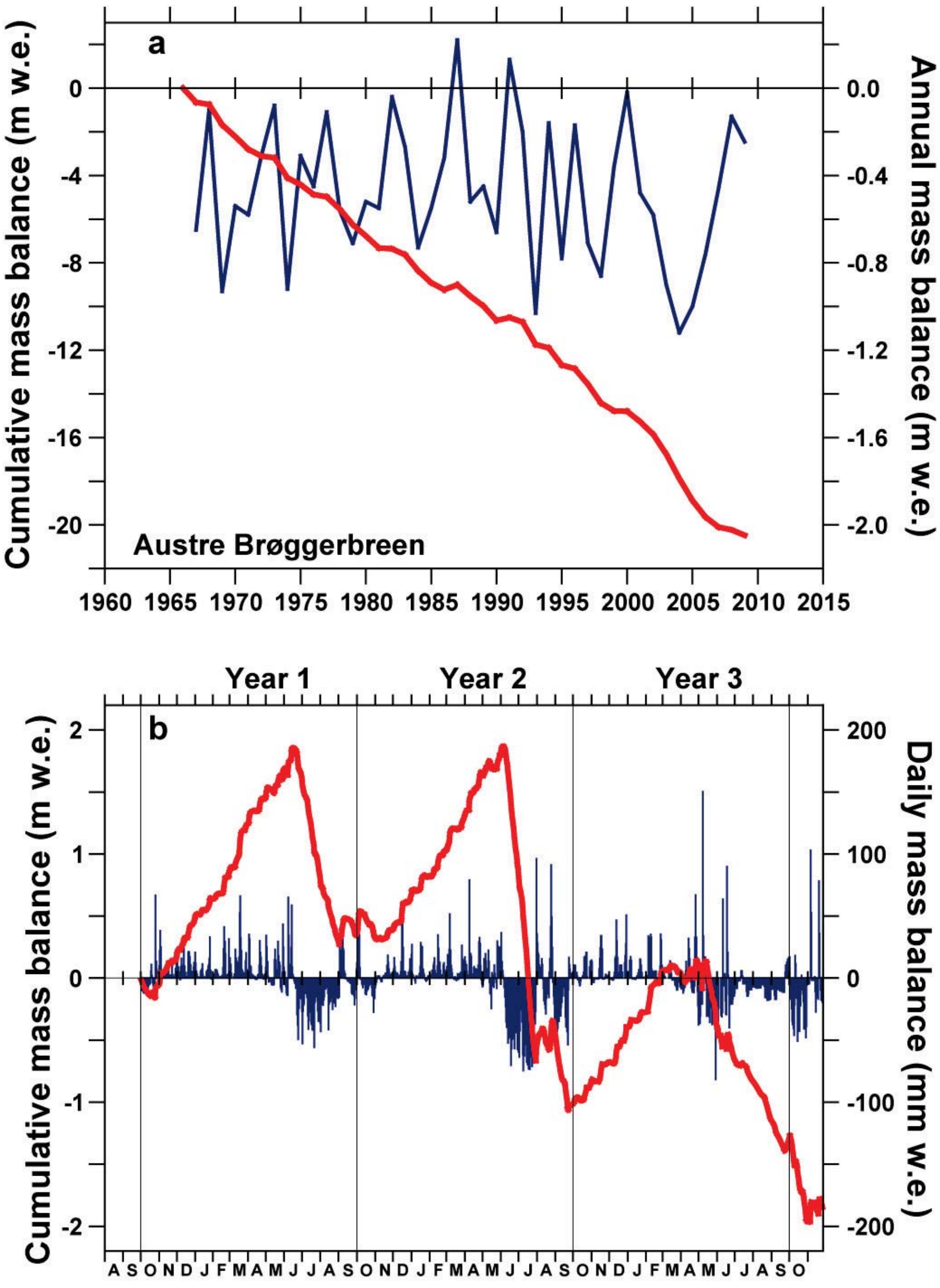


Figure 5. a: Cumulative mass balance relative to 1966 (red, left axis) and annual mass balance for 1966 to 2009 (blue, right axis) of Austre Brøggerbreen, Svalbard. b: Cumulative mass balance relative to 1 October of Year 1 (red, left axis) and daily mass balance (blue, right axis) over three mass-balance years of a representative northern-hemisphere glacier; after Huss et al. 2009.

D

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 $f = -a / \varphi$ between *surface ablation* a (which is negative) and the *positive degree-day sum* φ 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 ρ

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 facetted, 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 °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 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 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*.

F

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 $\rho_w gd$ exerted by water of depth d on adjacent *ice* of thickness $h = d + h_{flot}$ becomes just equal to the weight $\rho_i gh$ of the ice; ρ_w is the density of the water, ρ_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 $\partial\vec{q} / \partial x$ of the vertically integrated mass flux or volumetric flux with respect to horizontal distance x.

The integrated horizontal mass flux vector (dimension [M L^{-1} T^{-1}]), where ρ is the *density*, is

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

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^2 T^{-1}]) is

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

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, $\vec{q} \approx h\gamma\vec{u}_{\mathrm{sfc}}$. Here γ 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 ºC) when the pressure is equal to a standard pressure of 101 325 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_f, A_f
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*.

G

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 km^2 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* (kg m^{-2} a^{-1}), length change (m) and area (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 ºC. 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*.

H

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 ΔW 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 ΔW 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.

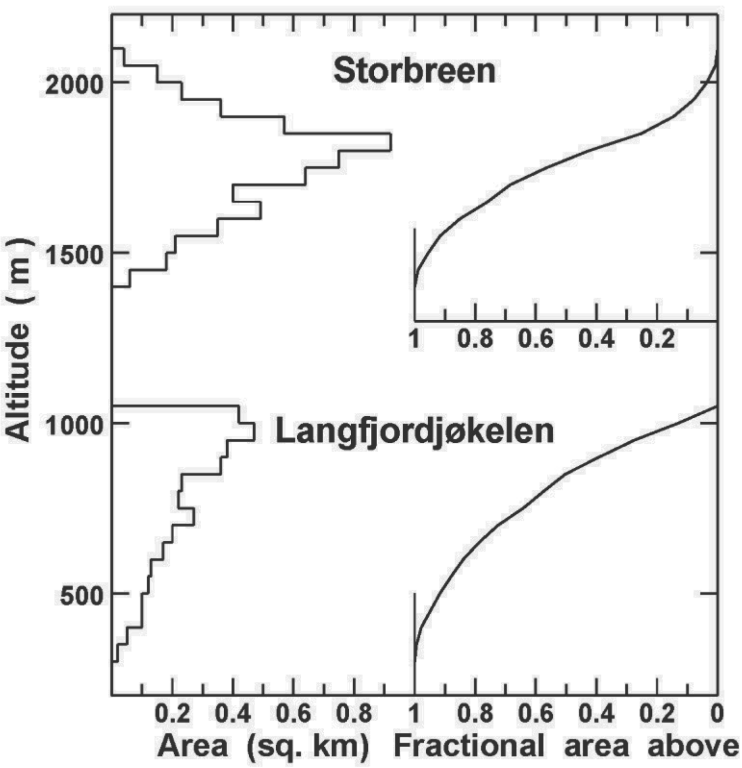


Figure 7. Hypsometric curves (left) and *cumulative* hypsometric curves (right) for two glaciers in Norway.

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 km^2 (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 km^2, 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 km^2 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*.

J

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*.

K

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* $\dot{b}$ as a function of the rate of change $\dot{h}$ of the ice-equivalent thickness, the spatial gradient of the thickness ∇h (usually approximated by the inclination of the surface), and the velocity at the surface $\vec{u}$:

$$\dot{b} = \dot{h} + \vec{u}_H \cdot \nabla h - \vec{u}_V \ ,$$

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.

L

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° 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° 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° 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*.

M

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 *accreted 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 Δm (point), ΔM (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_a (point), A_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_a (point), C_a (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_a (point), B_a (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,

$$b_a = c_a + a_a = b_w + b_s$$

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).

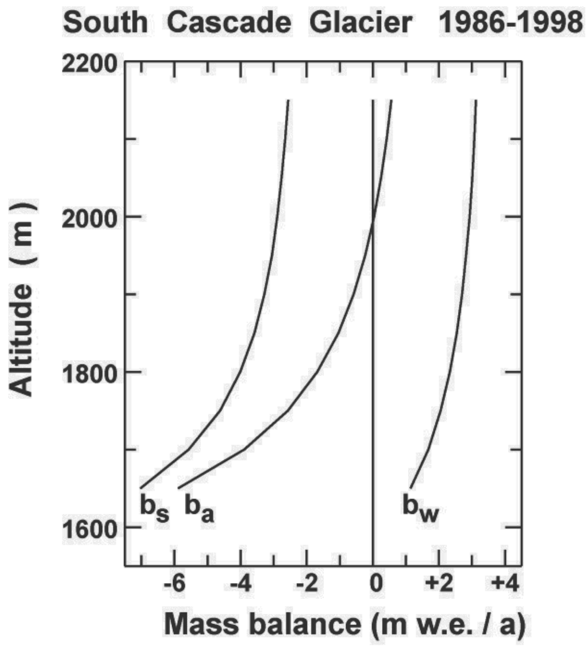


Figure 8. *Multi-annual* average mass-balance profiles, South Cascade Glacier, U.S.A.

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 $\bar{\dot{M}}$ over the interval Δt is related to the *mass balance* ΔM by $\bar{\dot{M}} = \Delta M / \Delta t$.

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, ρ_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 ρ_w and the area of the ocean (362.5 × 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 *im*balance). 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 km^2 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 K = 0 ºC, 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*.

N

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.

O

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*.

P

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*.

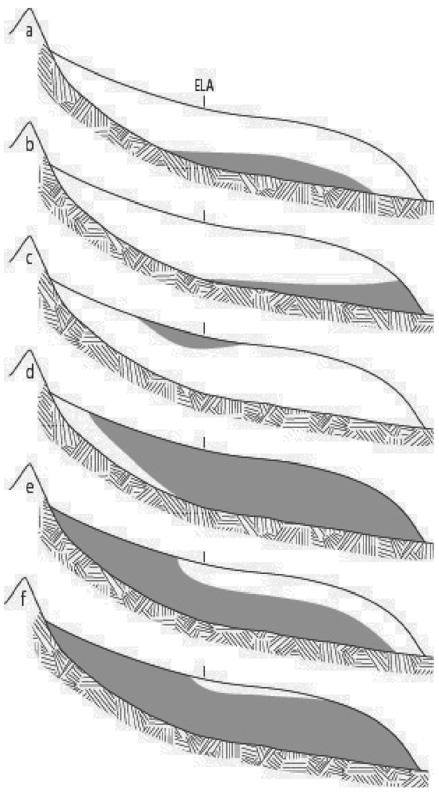


Figure 9. Schematic view of different polythermal structures encountered in glaciers. The temperate ice is shaded grey and the cold ice white (Pettersson, 2004).

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 ρ is the *density* of the dry snow or firn and ρ_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:

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

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 Δt, or as instantaneous values at intervals Δt, of near-surface air temperature T_i (i = 1, n), and the expression becomes:

$$\varphi = \Delta t \sum_{i=1}^{n} \max(0, T_i) \ ,$$

Δt 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 Δt 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 -9.8×10^{-8} K Pa^{-1} or, in ice of *density* 900 kg m^{-3}, about -0.86×10^{-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 -7.4×10^{-8} K Pa^{-1} and about -0.65×10^{-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*.

R

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 recalculation 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-firn 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 ε_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, ε_r'', 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 $\varepsilon_r'' = 0$. The real part of ε_r, denoted ε_r', 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 τ is often estimated with an expression due to Jóhannesson et al. (1989):

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

in which H' is a representative thickness of the glacier and $\dot{b}_T$ (< 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.

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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*.

S

Sastrugi
A variant spelling of *zastrugi*.

Scatterometer
A *radar* designed to measure microwave backscattering, quantified as the scattering coefficient or normalized radar cross section σ^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, ρ_w = 1000 kg m^{-3}, and the area of the ocean, 362.5×10^{12} 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, ρ_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 *glacieret*.

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).

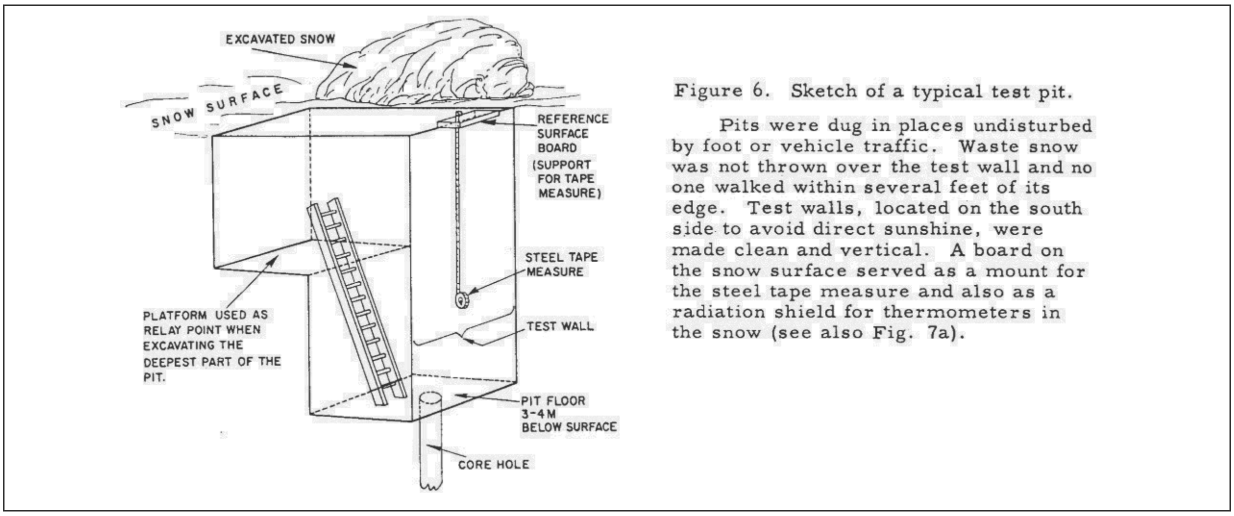

Figure 11. A diagram of a snow pit from a classical early study of snow stratigraphy in Greenland (Benson 1959, 1962).

Figure 12. A snow pit for observations of mass balance (Holmlund and Jansson 2002).

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 ρ_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 ρ_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 $b_a - b_w$; and when h_1 is negative an appropriate value (usually, outside the firn area, the density of ice) must be assumed for ρ_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.

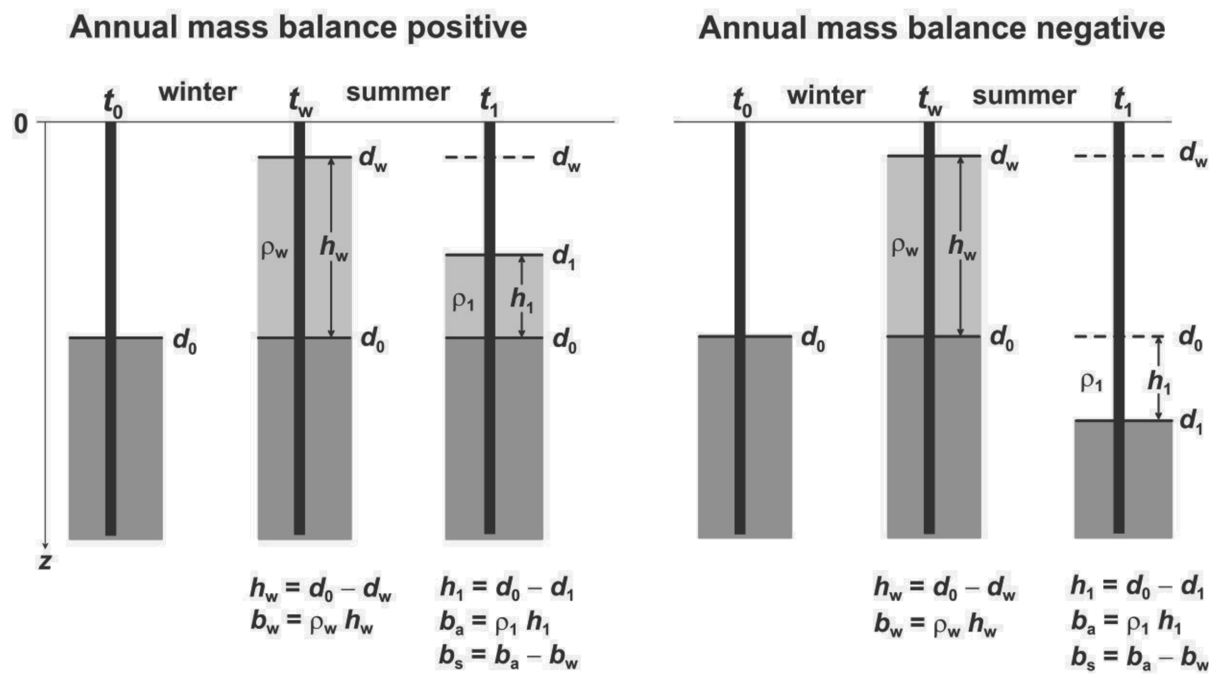

Figure 13. Stake measurements of seasonal mass balances in a year of positive (left) and a year of negative (right) *surface mass balance*, with no *superimposed ice*. The vertical coordinate is positive downwards, and all distances are measured from the origin z = 0 at the top of the stake. Light shading 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.

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, $dh/dt = 0$ 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*.

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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 Δh is the volume change of the entire glacier divided by the mean glacier *area* during the time span of the measurements:

$$\Delta h = 2(V_2 - V_1) / (S_2 + S_1) \ ,$$

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 ΔV is obtained from measurements of Δh 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 $V_2/S_2 - V_1/S_1$.

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*.

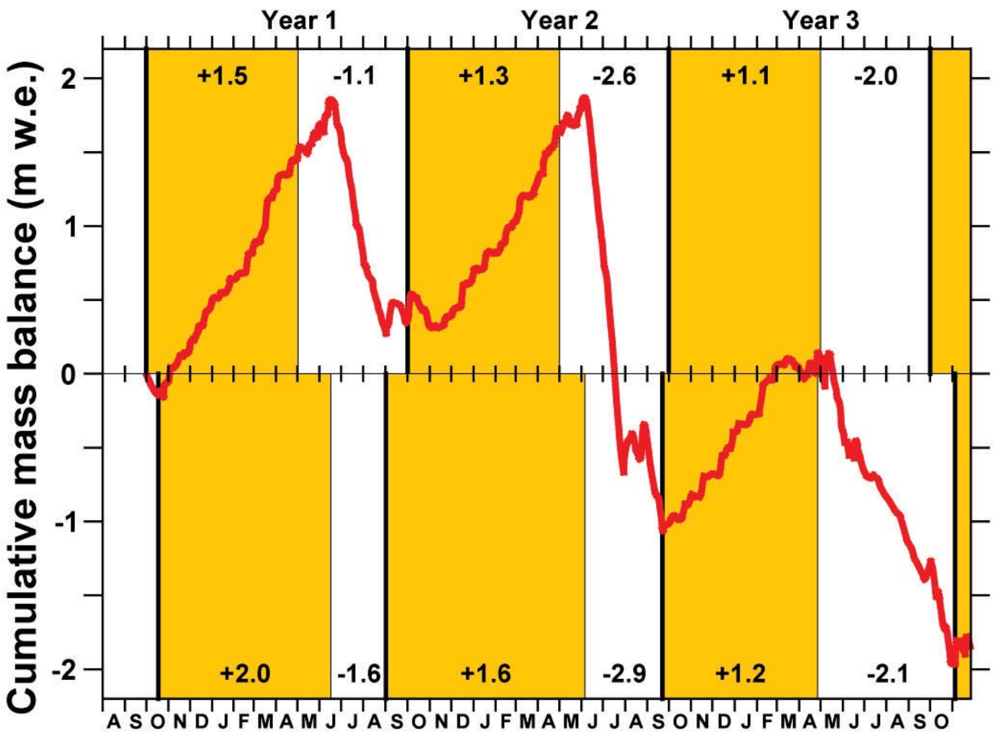

Figure 14. The *cumulative mass balance* over three mass-balance years, relative to 1 October of Year 1, of a representative northern-hemisphere glacier. In the upper half of the graph the *winter seasons* of the fixed-date system (1 October to 1 May) are shaded. In the lower half the winter seasons of the stratigraphic system (annual minimum of mass to annual maximum of mass) are shaded. For each time system the *winter balance* and *summer balance* are given for each season. After Huss et al. 2009.

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*, c_a minus 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.

V

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 $H = c S^{\gamma-1}$, which is the basis for the volume-area relation $V = c S^{\gamma}$. Here c and γ are parameters estimated from samples of glaciers with measured thicknesses. There is good evidence, as shown by Bahr et al. (1997), that estimates of γ 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 $\Delta V \simeq c(S_2^{\gamma} - S_1^{\gamma})$. 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*.

W

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 ΔW 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 *firn* 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 ΔI as ΔN. 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 ρ_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 m w.e. = 1000 kg m^{-2} / ρ_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 redeposited.

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 *stratigraphic system* the winter season ends when the glacier has attained maximum mass. In the *floating-date system* and the *fixed-date system*, the mass is not necessarily at its annual minimum or maximum when the winter season starts or ends.

World Data Centres (WDC)
A set of centres for the storage and dissemination of scientific data under the sponsorship of the *International Council for Science (ICSU)*.

The three World Data Centres for Glaciology are at the *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.

World Data System (WDS)
A body, founded in 2009, that provides an operational framework for the *World Data Centres* and *Data Analysis Services* of the *International Council for Science (ICSU)*.

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 *glaciers*.

The *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 *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 *Global Land Ice Monitoring from Space* initiative.

World Glacier Monitoring Service (WGMS)
The leading organization for the collection, storage and dissemination of information about *glacier fluctuations*.

The WGMS, formed in 1986 by merging the *Permanent Service on the Fluctuations of Glaciers* and the *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 *Global Terrestrial Network for Glaciers* (GTN–G) in close collaboration with the *National Snow and Ice Data Center* and the *Global Land Ice Measurements from Space* initiative.

Y

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.

Z

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*.

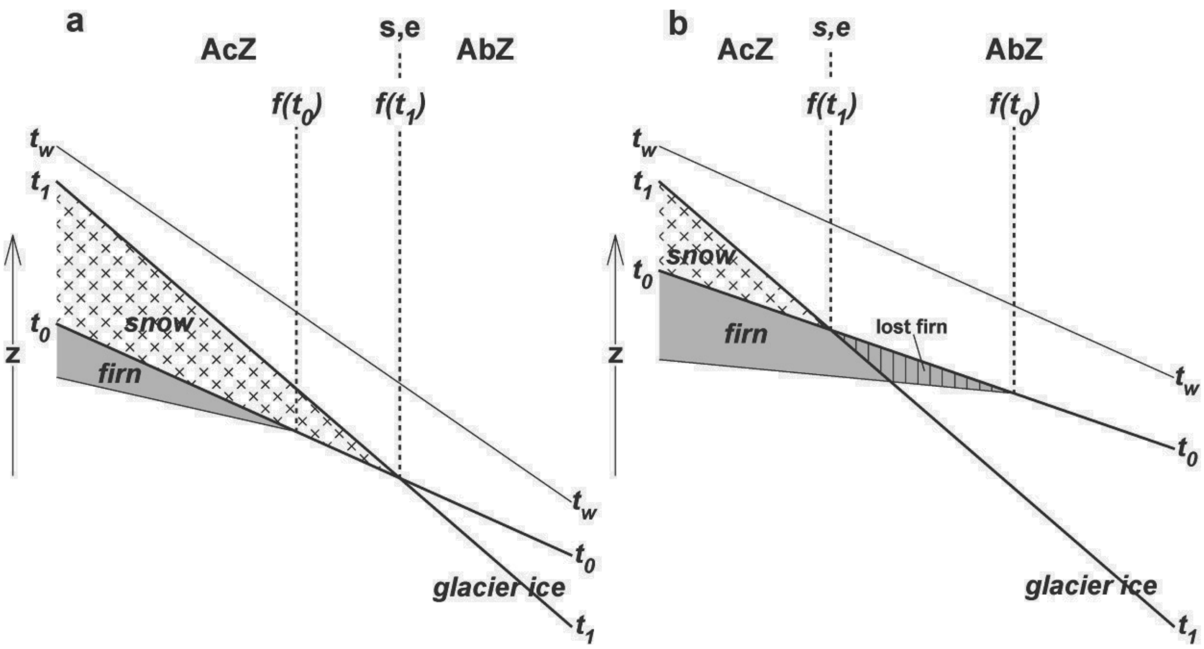

Figure 15. Glacier zonation on a representative *temperate glacier* during a) a year of more positive and b) a year of more negative *mass balance* than the previous year. At the start of each *mass-balance year* the glacier surface is at the line $t_0 - t_0$, the *summer surface*. It evolves (schematically, 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).

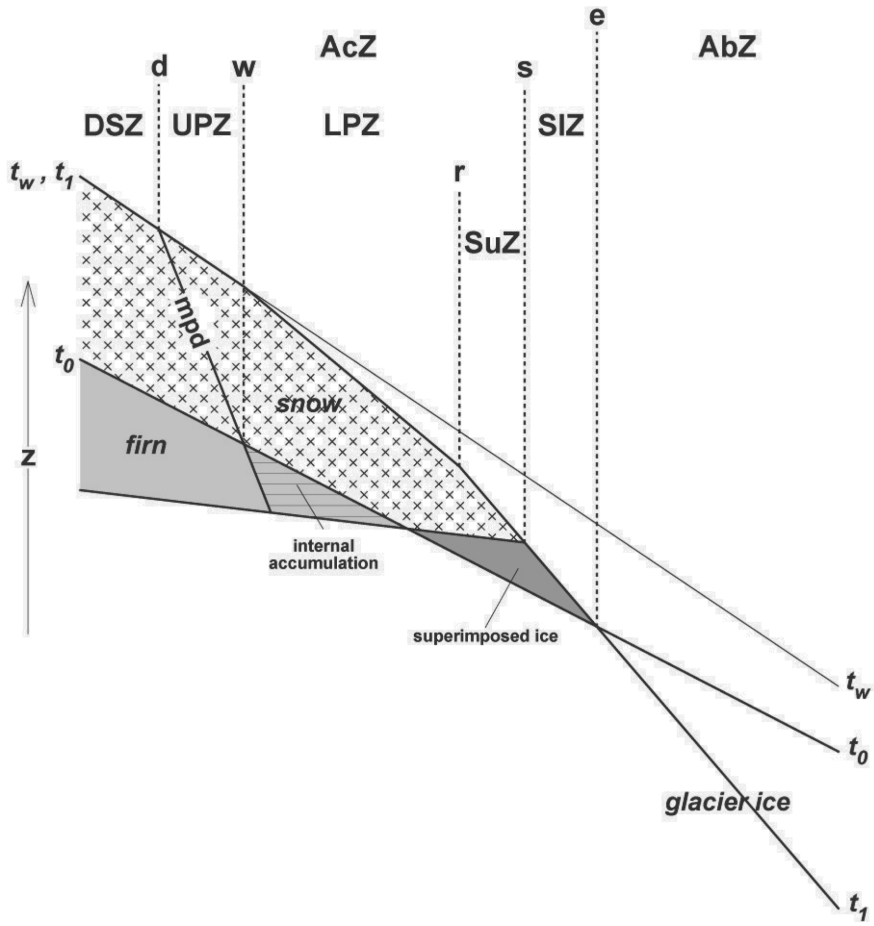

Figure 16. Glacier zonation and its balance-related aspects on a representative *cold glacier* or *polythermal glacier*. At the start of each *mass-balance year* the glacier surface is at the line $t_0 - t_0$, the *summer surface*. It evolves (schematically, the effects of ice flow being neglected) to $t_w - t_w$ 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)

Term	*Symbol*[1]	*Definition*
STRATIGRAPHIC SYSTEM		MEASUREMENT SYSTEM BASED ON EXISTENCE OF AN OBSERVABLE SUMMER SURFACE
Summer surface		Surface formed at time of minimum annual mass at each point, marking end of one balance year and start of next (NB: may be diachronous over the extent of the glacier)
Balance year		Time span between formation of two successive summer surfaces
Winter season		Time span from start of balance year to time of maximum glacier mass
Summer season		Time span from time of maximum glacier mass to end of balance year
Winter accumulation	c_w	Integral of accumulation $c(t)$ over winter season
Summer accumulation	c_s	Integral of accumulation $c(t)$ over summer season
Total accumulation	c_t	Integral of accumulation $c(t)$ over balance year
Winter ablation	a_w	Integral of ablation $a(t)$ over winter season
Summer ablation	a_s	Integral of ablation $a(t)$ over summer season
Total ablation	a_t	Integral of ablation $a(t)$ over balance year
Winter balance	b_w	Change in mass during winter season
Summer balance	b_s	Change in mass during summer season
Net balance	b_n	$c_t + a_t$; also $b_w + b_s$
Total exchange	e_t	$c_t - a_t$; also $b_w - b_s$
FIXED-DATE SYSTEM		MEASUREMENT SYSTEM BASED ON SPECIFIC CALENDAR DATES
Measurement year		Time between start and end of measurement
Annual accumulation	c_a	Integral of accumulation $c(t)$ over measurement year
Annual ablation	a_a	Integral of ablation $a(t)$ over measurement year
Annual balance	b_a	$c_a + a_a$
Annual exchange	e_a	$c_a - a_a$
OTHER		
Transient equilibrium line		Locus of points where balance $b(t)$ is zero
Equilibrium line		Locus of points where b_n is zero
Annual equilibrium line		Locus of points where b_a is zero
Accumulation area	S_c	Area above equilibrium line
Ablation area	S_a	Area below equilibrium line
Accumulation-area ratio	AAR	$S_c / (S_c + S_a)$
Transient snow line		Line separating snow from ice or firn at any time t
Firn line		Transient snow line at time of minimum snow cover
Firn		Snow which has passed through (at least) one summer

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

Property	*Expression*	*Remarks*
Ice point[1]	(T_m = 273.15 K = 0 ºC, p = 101 325 Pa)	Commonly called the melting point or freezing point
Triple point[1,2]	(T = 273.16 K, p = 611.7 Pa)	Temperature and pressure at which ice, water and water vapour are in thermodynamic equilibrium
Mean molecular weight[1]	0.018015 kg mol^{-1} ≅ 18 g mol^{-1}	Vienna Standard Mean Ocean Water (VSMOW)
Thermal conductivity[3]	$K = 2.238 - 0.0107\,T$ W m^{-1} K^{-1}	Pure ice, T in ºC
Effective thermal conductivity of dry snow[4]	$K_{eff} = 0.06 + 2.69 \times 10^{-6}\,\rho^2$	At –5 ºC; includes heat transfer by diffusion of vapour
Latent heat of vaporization[2]	L_v = 2500.8 kJ kg^{-1}	At 0 ºC
Latent heat of fusion[2]	L_f = 333.5 kJ kg^{-1}	Decreases nearly linearly to 289 kJ kg^{-1} at –20 ºC
Latent heat of sublimation[2]	L_s = 2834.2 kJ kg^{-1}	At 0 ºC; equal to $L_v + L_f$
Relative dielectric constant[5]	$\varepsilon_r' = 1$	Air
Relative dielectric constant[6]	$\varepsilon_r' = 88$	Water (0 ºC, below 500 MHz; decreases to 68 at 5 GHz and 42 at 10 GHz)
Relative dielectric constant[5]	$\varepsilon_r' \approx 3.15$	Ice of density 917 kg m^{-3}
Relative dielectric constant[5]	$\varepsilon_r' = (1 + 0.000845\,\rho)^2$	Firn of density ρ

1: BIPM 2006a; 2: Murphy and Koop 2005; 3: Pounder 1965; 4: Pitman and Zuckerman 1967; 5: real part only, Kovacs et al. 1995; 6: real part only, Ulaby et al. 1986.

Table B2 Temperature-dependent properties of pure ice (and supercooled water)

T (ºC)	ρ_i (kg m^{-3})	α_V (×10^{-6} K^{-1})	κ (×10^{-12} Pa^{-1})	e_{i*} (Pa)	e_{w*} (Pa)	K (W m^{-1} K^{-1})	C_p (J kg^{-1} K^{-1})
0	916.7	159	130	611.15	611.21	2.24	2114
−10	918.7	155	128	259.89	286.45	2.34	2036
−20	920.3	149	127	103.25	125.50	2.45	1958
−40	922.8	137	124	12.84	18.91	2.65	1806
−80	927.4	105	119	0.05	0.11	3.10	1517

T Temperature
ρ_i Density (Chemical Rubber Company 2008−09)
α_V Volumetric coefficient of thermal expansion (Chemical Rubber Company 2008−09)
κ Adiabatic compressibility (Chemical Rubber Company 2008−09)
e_{i*} 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)

Thickness of ice *h (m)*	*Pressure* *p (MPa)*	*Equilibrium temperature* T_m *(ºC)*
200	1.80	–0.1
500	4.50	–0.3
1000	9.00	–0.7
2000	17.99	–1.3
5000	44.98	–3.3

The pressure is $\rho_i g h$, with density $\rho_i = 917$ 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 -7.4×10^{-8} K Pa^{-1}.

Table B4 Properties of water at 0 °C and 1000 hPa

Property		*Magnitude*
Density[1]	$\rho_w =$	999.84 kg m^{-3}
Heat capacity at constant pressure[2]	$C_p =$	4211 J kg^{-1} K^{-1}
Equilibrium vapour pressure[2]	$e_{w*} =$	611.2 Pa
Latent heat of vaporization[2]	$L_v =$	2500.8 kJ kg^{-1}
Thermal conductivity[1]	$K_w =$	0.561 W m^{-1} K^{-1}
Viscosity[1]	$\nu =$	1793 µPa s

1: Chemical Rubber Company 2008–09; 2: Murphy and Koop 2005.

Table B5 Selected physical constants and reference values

Constant	*Magnitude*	*Remarks*
Speed of electromagnetic waves in a vacuum[1]	$c = 299\,792\,458$ m s^{-1}	$\approx 3 \times 10^8$ m s^{-1}
Gravitational constant[1]	$G = 6.67428 \times 10^{-11}$ m^3 kg^{-1} s^{-2}	
Gas constant[1]	$R = 8.3145$ J mol^{-1} K^{-1}	
Stefan-Boltzmann constant[1]	$\sigma = 5.6704 \times 10^{-8}$ W m^{-2} K^{-4}	
Reference value		
Mean radius of the Earth[2]	$R_E = 6371007$ m	Radius of a sphere of area equal to that of WGS84 reference ellipsoid
Acceleration due to gravity[3]	$g = 9.81$ m s^{-2}	"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%
Sea-level pressure[4]	$p_0 = 101\,325$ Pa	Pressure at sea level in the ICAO standard atmosphere
Area of the ocean[5]	$S_O = 362.5 \times 10^6$ km^2	Includes 1.555×10^6 km^2 beneath ice shelves

1: Mohr et al. 2006; 2: NIMA 2000; 3: BIPM 2006a; 4: International Civil Aviation Organization 1993. 5: from data of Wessel and Smith 1996, Fox and Cooper 1994.

Table B6 Density of frozen water in various forms

Material		*Density (kg m^{-3})*
SURFACE SNOW[1,2]		
	Newly fallen snow in cold, calm conditions	10 – 65
	Newly fallen snow near the *freezing point*	100 – 300
	Settled snow	200 – 300
	Wind-packed snow	350 – 400
DEPTH HOAR[2]		100 – 300
FIRN[1]		
	Firn	400 – 650
	Thawed and refrozen firn, and "firn-ice"	600 – 830
GLACIER ICE[2]		830 – 917
PURE MONOCRYSTALLINE ICE[3]		
	0 ºC	916.7
	–10 ºC	918.7
	–20 ºC	920.3
	–40 ºC	922.8
	–80 ºC	927.4

1: Seligman 1936 and others; 2: Paterson 1994; 3: Chemical Rubber Company, 2008–09.

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