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# Glacier Mass Balance

## 1. Introduction: Definitions and processes

*Definition*:
Mass balance is the change in the mass of a glacier or ice body, or part thereof, over a stated span of time:

$$\Delta M = \int_{t_1}^{t} \dot{M}\, dt$$

The term **mass budget** is a synonym. 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 Chap. 4).

The **(cumulative) mass balance**, *b,* is the sum of **accumulation**, *c,* and **ablation**, *a* (the ablation is defined here as negative). The symbol, *b* (for point balances) and *B* (for glacierwide balances) has traditionally been used in studies of surface mass balance of valley glaciers.

$$b = c + a = \int_{t_1}^{t} (\dot{c} + \dot{a})\, dt$$

Mass balance is often treated as a rate, b or B dot.

### Accumulation

*Definition:*

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.

*Components:*

- **Snow fall** (usually the most important).
- **Deposition of 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), **freezing rain, solid precipitation** in forms other than snow (re-sublimation composes 5-10% of the accumulation on Ross Ice Shelf, Antarctica).
- **Gain of windborne blowing snow and drifting snow** (can be important for the survival of, for example, small cirque glaciers).
- **Avalanching** (→ can generate glaciers below the "climatic" boundary for glacier formation).
- **Basal freeze-on** (usually beneath floating ice)
- **Internal accumulation** (see Chap. 7).

*Note*: Unless it freezes, rainfall does not constitute accumulation, and nor does the addition of debris by avalanching, ashfall or similar processes.

### Ablation

*Definition:*

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.

*Components:*

- **Melting** (usually the most important on land-based glaciers. Melt water that re-freezes onto another part of the glacier is not referred to as ablation).
- **Calving** (or, when the glacier nourishes an ice shelf, ice discharge across the grounding line): Calving is iceberg discharge into seas or lakes; important, for example, in Greenland and Antarctica, where approximately 50% and 90%, respectively, of all ablation occurs via calving; also important in Svalbard and Alaska, Arctic Canada and Russia.
- **Loss of windborne blowing snow and drifting snow**
- **Avalanching**
- **Sublimation** (important, for example, at high altitudes in low latitudes (tropical glaciers), in dry climates, and on blue-ice zones in Antarctica; is a function of vapour pressure)

***Note the difference between***

a) **precipitation** (includes solid precipitation and rain) and **surface accumulation** (does not include rain). Note, that 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.

b) **Meltwater** and **Meltwater runoff** (A portion of melt may refreez; the latter refers to the meltwater that does not refreeze)

c) **Meltwater runoff** and **Runoff** (the latter includes rain or any other source of water other than meltwater.

d) **Accumulation** and **Net accumulation** (the latter is a balance, i.e. accumulation plus ablation. It is identical to the mass balance in case the balance is positive. It equals zero in case the balance is negative).

## 2. Annual mass balance

**Annual mass balance** ($b_a$) is the mass balance at the end of a **balance year**. It can also be described as the sum of the **winter balance** ($b_w$) and **summer balance** ($b_s$), which is negative.

$$b_n = b_w + b_s = c_t + a_t = c_w + a_w + a_s + a_s$$

Mass balance can be calculated at a point (indicated by small letters, $b_a$) or volume for the whole glacier (indicated by capital letters, $B_a$). The annual balance $B_a$ of the entire glacier with area $A$ is given by

$$B_a = \int b_a dA$$

$B_n$ divided by the glacier area is called the **(mean) specific mass balance**, although terminology in the literature is not consistent. Mass balance terms are stated as **water equivalent** (w.e.), so that comparisons can be made between different glaciers and different years. Water equivalent represents the volume of water that would be obtained from melting the snow or ice. The value in meters water equivalent is obtained through dividing the volume by the area, i.e. the mass balance value states how much the glacier has become thicker or thinner (in water depth) if the mass addition or loss is distributed over the whole glacier surface. Annual mass balances are usually illustrated as shown in Figure 1.

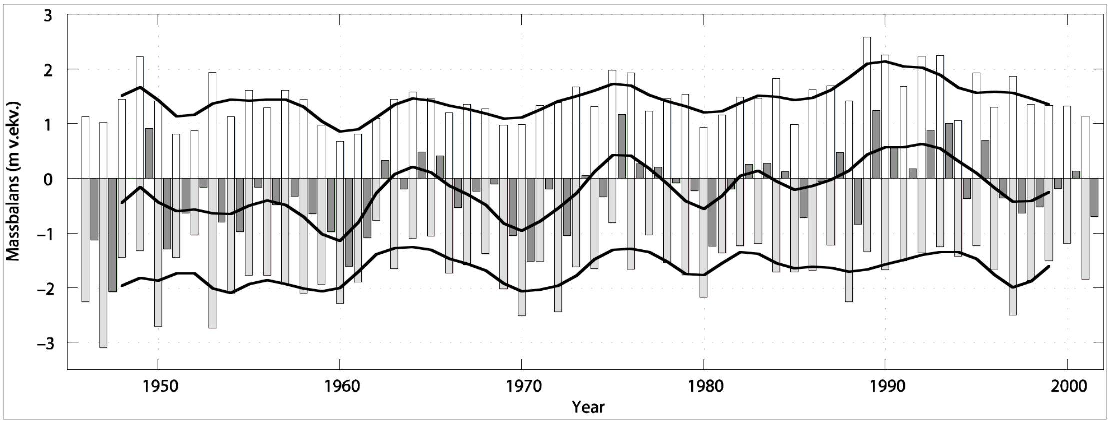

Figure 1. Winter- (white), summer- (grey), and net mass balance (black) for Storglaciären 1946 - 2002. The black lines show the running 5-year average.

## 3. Seasonal variations in mass balance

Accumulation and ablation are usually seasonally governed, and so the mass balance undergoes an annual cycle of growth (positive mass balance) and diminishment (negative mass balance). At mid-latitudes, there are distinctly different accumulation and ablation seasons, i.e. it snows mainly during the winter and melts during the summer (Figure 2). This is different from e.g. tropical regions, where ice melting and accumulation occur at the same time.

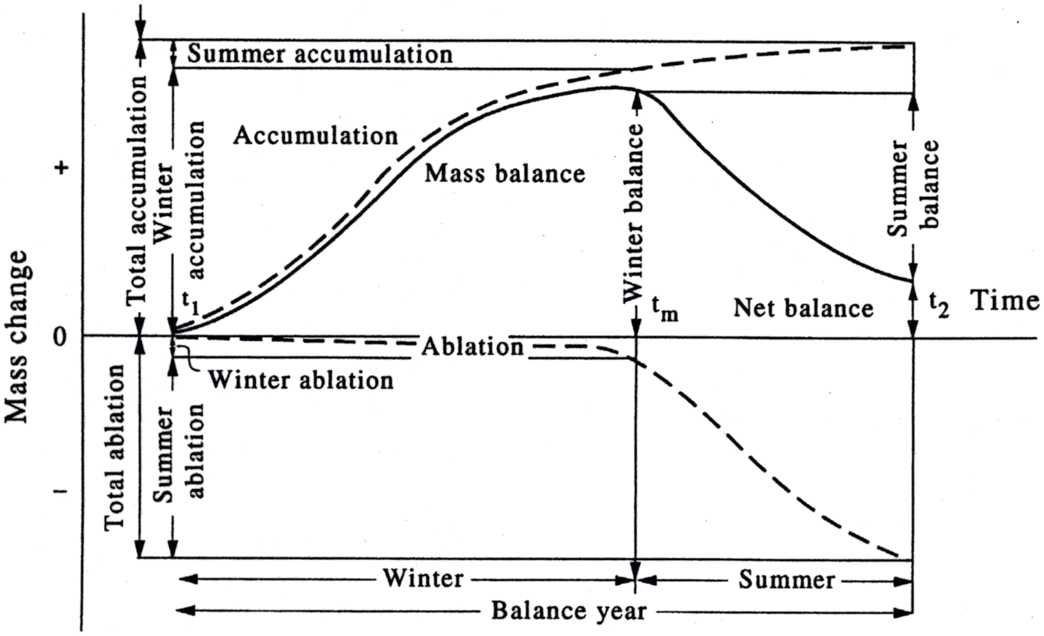

Figure 2. Variation of accumulation, ablation, and mass balance during a glaciological year for a glacier with distinct accumulation and ablation seasons.

## 4. Time systems

When reporting annual or seasonal mass balances it is essential to provide information about the time system the measurement refers to. This is also important to be able to compare observations with model results. Four time systems have been used:

### *a) Stratigraphic system*

Time system for the determination of mass balance 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 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 approximately with the expected date of the maximum. Thus, in the stratigraphic system, seasonal balances 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 observation sites. Glacier-wide balances in the stratigraphic system can only be determined rigorously by accurate spatially distributed modelling. Determinations based on field measurements require the assumption that the diachronous character of the summer surface can be neglected. The duration of the mass-balance year varies in the stratigraphic system varies from year to year.

### *b) 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 local hydrological year, or sometimes with the average date of minimum annual mass. The mass-balance year is 365 (or 366) days long. 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.

### *c) 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) the mass-balance year was defined only in the stratigraphic system.

### *d) 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.

Differences between determinations of $B_a$ in the floating-date, fixed-date and stratigraphic systems can be substantial exceeding 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.

## 5. Specific mass balance

*Mass balance* expressed per unit area, that is, with dimension [M $L^{-2}$ $T^{-1}$] or [M $L^{-2}$]. 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 (if it is a surface mass balance), a column of unit cross-section, or a larger volume such as the entire glacier. In the latter case the term "mean specific mass balance" has been used, although the adjective "mean" is also not necessary.

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 the terminus of a calving glacier ablation is equal to the mass of the entire calved volume, and if quoted as a specific quantity is divided by the horizontal area over which the calved volume extended.

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.

## 6. Mass balance units

The dimension of *mass balance*, if expressed as a rate, is [M $T^{-1}$], mass per unit time. When it is treated as a rate of change of mass per unit *area*, it is called *specific mass balance* and its dimension becomes [M $L^{-2}$ $T^{-1}$]. When it is treated as a change of mass, it is called *cumulative mass balance* and its dimension becomes [M] or [M $L^{-2}$]. When *water-equivalent* units are adopted (see below), the dimension becomes [$L^3$ $T^{-1}$], or [L $T^{-1}$] for specific mass balance; equivalently the dimension becomes [$L^3$], or [L], for cumulative mass balance.

The unit for expressing 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 thickness of exactly 1 mm when distributed uniformly over 1 $m^2$. The units kg $m^{-2}$ and mm w.e. are therefore numerically identical. More formally, the metre water equivalent (m w.e.) is an extension of the SI that is obtained by dividing a particular mass per unit area by the density of water, $\rho_w$:

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

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

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

When mass balance is treated as a rate, the 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 other intervals the unit of time should be the second or the day, or the mass balance should be presented as a cumulative mass balance.

Mass units (kg or $m^3$ w.e.) are useful for hydrological and oceanographic purposes, while specific mass units (kg $m^{-1}$, mm w.e., m w.e.) are needed when comparing the mass balances of different glaciers, for example when studying glacier-climate relationships.

To convert 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 minus the product of $\rho_w$ and the area of the ocean (362.5 × $10^{12}$ $m^2$). The minus sign accounts for the sign of SLE being opposite to that of glacier mass balance, a loss from the ice being deemed to be an equivalent gain for the ocean.

# 7. Conventional and reference-surface mass balance

**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 hypsometry 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.

**Reference-surface balance**

The 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 assigned the altitude of the reference surface at the same horizontal position and then extrapolated over the reference area. Note that the reference surface is likely to differ from the actual surface in both area and area-altitude distribution.

Differences in surface area and area-altitude distribution feedback 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 the conventional balance.

# 8. Superimposed ice and internal accumulation

## 8.1 Superimposed ice

Percolating water through the entire snow pack and refreezing at the ice surface creates **superimposed ice**. Superimposed ice forms primarily on subpolar glaciers and can become several decimetres thick. If part of the superimposed ice survives the summer and is left the melt season, the snow line and equilibrium line no longer correspond at the end of the balance year. In this case, the equilibrium line lies below the snow line.

## 8.2 Internal accumulation

Re-freezing of percolated water in the firn zone beneath the previous year’s level is known as **internal accumulation**. The process can be a problem for traditional mass balance measurements because changes in density beneath the previous year’s level are not usually recorded in measurements of summer ablation. The true ablation is less than calculated because a part of the ablation water re-freezes lower down, resulting in an under-estimation of the mass balance.

Internal accumulation consists of two components

*a)* Refreezing of melt water percolating in cold firn in spring, $b_p$

b) Refreezing of water held by capillary forces when the cold wave penetrates in the firn in winter (=irreducible water content), $b_c$

Internal accumulation may constitute a significant term in the glacier mass balance (e.g. estimates of 7-64% of net accumulation on northern Alaskan glaciers.

The amount is constrained by the cold content of the firn and the irreducible water content. For a given temperature profile maximum $b_p$ is given by

$$b_{p,\max} = \frac{c_{pi}}{L_f} \int_{H_{sf}}^{H_0} \rho \Delta T dz$$

$\Delta$T= temperature difference to melting point at depth z, $H_{sf}$=depth of snow-firn transition, $H_0$ is depth of the 0°C isotherm, $c_{pi}$=heat capacity of ice, $L_f$=latent heat of fusion ($0.334\text{x}10^{-6}$ $\text{Jkg}^{-1}$). For unlimited water availability the amount is limited by the cold content. For a given density profile, maximum $b_c$ is given by

$$b_{c,\max} = \int_{H_{sf}}^{H_0} \theta_{pi} (1 - \frac{\rho}{\rho_i}) dz$$

$\theta_{pi}$=irreducible water content.

# 9. Equilibrium, firn, snow line

## 9.1 Equilibrium line

The set of points on the surface of the glacier where the climatic mass balance is zero at a given moment. 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.

**Annual equilibrium line**

The set of points on the glacier surface where annual ablation balances annual accumulation, that is, where the annual mass balance is zero.

**Transient equilibrium line**

The set of points on the glacier surface where, at any instant, cumulative ablation balances cumulative accumulation since the start of the mass-balance year.

## 9.2 Equilibrium-line altitude, ELA

The spatially averaged *altitude* of the *equilibrium line*. The ELA is generally determined, in the context of *mass-balance* measurements, by fitting a curve to data representing *point 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. The ELA is understood to be the *annual ELA* unless it is qualified as the *transient ELA*.

***Balanced-budget ELA***

The ELA, sometimes denoted $\text{ELA}_0$, of a glacier with a climatic mass balance equal to zero on average over a number of years.

The balanced-budget ELA is usually estimated as the altitude at which a curve fitted to an observed relation between annual ELA and mass balance $B$ crosses the axis $B = 0$. 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 published measurements of mass balance are 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 is usually approximated by the *balanced-budget ELA*. To emphasize that the balanced-budget ELA and steady-state ELA are distinct concepts, the steady-state ELA should be given a distinctive symbol.

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

The transient ELA is not in general the same as the *transient snowline*. The *superimposed ice zone* lies below the transient snowline and above the transient ELA.

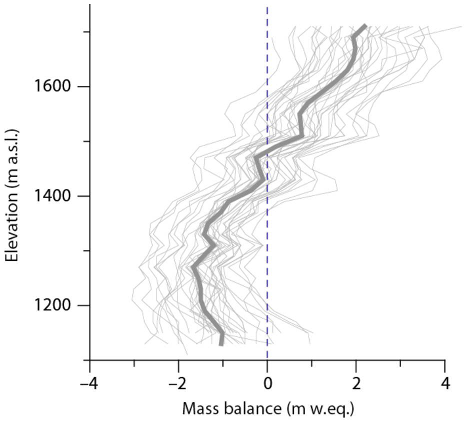

Figure 3. Net balance as a function of altitude on Storglaciären, 1961-2000. The thick line illustrates the average. Note, the profile is similar from year to year and more or less only evenly displaced depending upon the mass balance. The ELA is the elevation where the mass balance is zero.

## 9.3 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 and below it in a year of positive mass balance.

## 9.3 Snow line

The set of points on a glacier forming the lower boundary of the snow-covered area. The set of points need not form a continuous curve. The snow-covered area of the glacier may include outliers (isolated patches of snow) 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.

# 10. 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. Mass balance does not vary linearly with temperature in general; that is, $db/dT$ is not a constant.

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 have also been estimated from mass-balance and climate observations. In contrast to the "dynamic" sensitivity, the "static" mass-balance sensitivity neglects changes in glacier size and geometry. The sensitivity is a measure to compare how different glaciers react to a climate change. The concept has been used widely to assess the response of the mass balance to future climate change.

Sensitivity is affected by:

- Glacier surface slope (large slope → high sensitivity)
- Morphology: inclination and proportion near the equilibrium line (small inclination → large proportion → high sensitivity, (Fig. 4)
- Climate: continental glaciers have lower sensitivity, while maritime glaciers have a higher sensitivity. Values exceeding -2 m a-1 have been obtained from modelling.

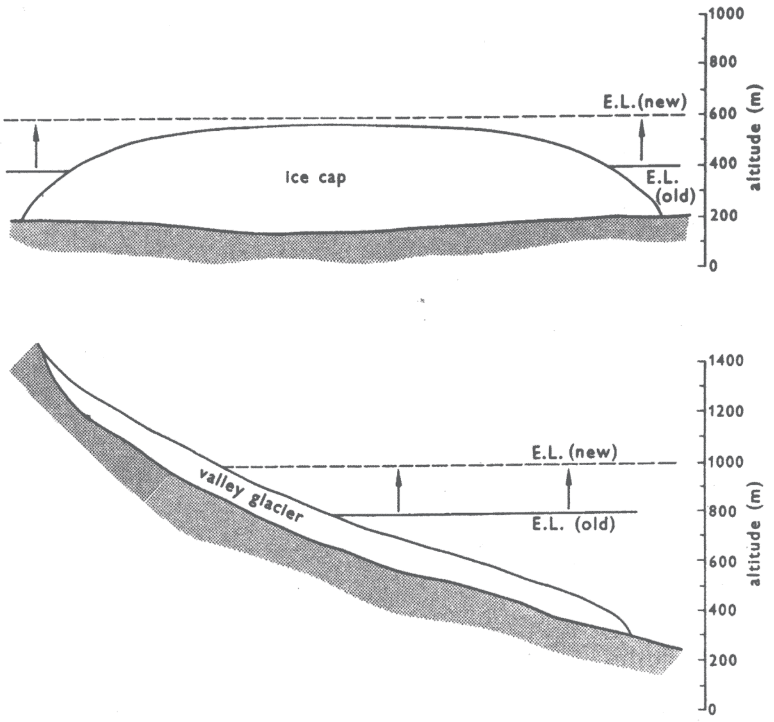

Figure 4. Effects of an increase in equilibrium line altitude on a small ice cap and a valley glacier. Observe the large sensitivity of the ice cap (Sugden & John 1984, p.105).

## 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 to changes in monthly mean temperature $T_k$ and monthly precipitation $P_k$, , where k = 1, ..., 12 is the month index and precipitation is normalized by $P_{ref,k}$, the monthly precipitation averaged over a reference period (Fig. 5). The SSC was introduced by Oerlemans and Reichert (2000). Algebraically it consists of two sets of 12 numbers each:

$$C_{T,k} = \frac{\partial B}{\partial T_k} \quad ; \quad C_{P,k} = \frac{\partial B}{\partial (P_k / P_{\mathrm{ref},k})}$$

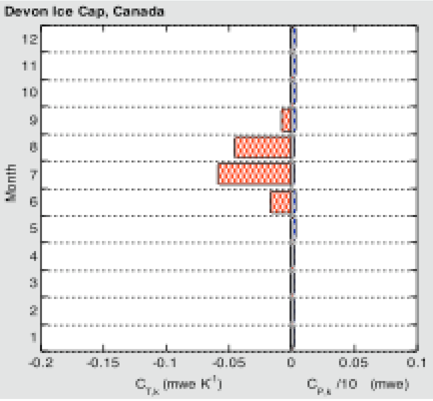

Figure 5. Seasonal sensitivity characteristic of Devon Ice Cap, Canada.

The change in mass balance due to a temperature change is computed by multiplying the sensitivities by the temperature change. This is done most accurately using seasonal sensitivities instead of annual sensitivities because temperature changes are often not homogeneous throughout the year.

## References

Elsberg, D.H., W.D. Harrison, K.A. Echelmeyer and R.M. Krimmel, 2001, Quantifying the effects of climate and surface change on glacier mass balance, *Journal of Glaciology*, **47**(159), 649–658.

Harrison, W., Elsberg, Cox and March, 2005. Different balances for climatic and hydrological applications. *J. Glaciol*., page 176.

Huss, M., A. Bauder and M. Funk, 2009, Homogenization of long-term mass-balance time series, *Annals of Glaciology*, **50**(50), 198–206.

Oerlemans, J. and B.K. Reichert. 2000. Relating glacier mass balance to meteorological data by using a seasonal sensitivity characteristic. *J. Glaciol*., 46(152), 1–6.

Sugden, D. and B. John, 1984. *Glaciers and Landscape*. Edward Arnold, London, 376 pp.

***Other useful references on Mass Balance***

Bamber, J. and A. Payne, 2004. *Mass Balance of the Cryosphere*. Cambridge University Press. 644 pp.

Cogley, J.G. 2005. Mass and energy balances of glaciers and ice sheets. In *Encyclopedia of Hydrologiacl Sciences*, vol. 4, edited by M.G. Anderson, 2555-2573, John Wiley, Hoboken, New Jersey.

Dyurgerov, 2002. *Glacier Mass Balance and Regime: Data of Measurements and Analysis*. Institute of Arctic and Alpine Research, University of Colorado. Occasional Paper No. 55.

Dyurgerov M. B., and M. F. Meier (2005), Glaciers and the changing Earth system: a 2004 snapshot (Occasional Paper 58, Institute of Arctic and Alpine Research, Univ. of Colorado, Boulder, Colorado).

Østrem, G. and Brugmann, M., 1991. *Glacier Mass-Balance Measurements. A Manual for Field and Office Work*. NHRI Science Report 4, NVE, Oslo, 224 pp.