Theoretical background of glacier mass balance measurements

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1. **Mass balance terminology and theoretical considerations**

2. **Methods for mass balance monitoring**

3. **Specificities related to different climate conditions**

1. **Mass balance terminology and theoretical considerations**

2. Methods for mass balance monitoring

3. Specificities related to different climate conditions

Some interesting literatures!

Cogley, J.G., R. Hock, L.A. Rasmussen, A.A. Arendt, A. Bauder, R.J. Braithwaite, P. Jansson, G. Kaser, M. Möller, L. Nicholson and M. Zemp. 2011. *Glossary of Glacier Mass Balance and Related Terms.* IHP-VII Technical Documents in Hydrology No. 86, IACS Contribution No. 2, UNESCO-IHP, Paris.

Kaser, G., A. Fountain and P. Jansson. 2003. *A manual for monitoring the mass balance of mountain glaciers.* IHP-VI Technical Documents in Hydrology No. 59, ICSI, UNESCO, Paris.

Francou, B. and B. Pouyaud. 2004. *Metodos de observacion de glaciares en los Andes tropicales, mediciones de campo y procesamiento de datos.* IRD, IHH, INAMHI, INRENA, SENAMHI, EMAAP-Q, INGEOMINAS, LGGE.

Short insight on the mass balance terminology

Mass balance

Change in the mass of a glacier, or part of the glacier, over a stated span of time*;* mass budget is a synonym.

The span of time is often a year or a season. A seasonal mass balance is classically a *winter balance* or *a summer balance. BUT other kinds of season are appropriate in some climates,* such as those of the tropics (dry/rainy).

In studies of mass balance, where the glacier is considered as a "box", the most common sign convention is "positive inward".

=> Flows across the boundary of the box are **positive when the box gains, and negative when it loses**.

- Accumulation is positive,
- Ablation is negative,

and consequently balance calculations for the glacier require only additions.

The mass balance variables ...

a	ablation	c	accumulation	b	mass balance (c+a)

... and commonly associated subscripts

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

Lower-case symbols refer to quantities at a point on the glacier surface.

Upper-case symbols refer to glacier-wide quantities.

Summer ablation	a_s (point), A_s (glacier-wide)

Overdots

The function of the overdot is to denote a derivative, usually a partial derivative, with respect to time.

$$\dot{x} = \partial x / \partial t$$

The overdot signifies that the variable is expressed as a rate.

Other used variables in mass balance studies

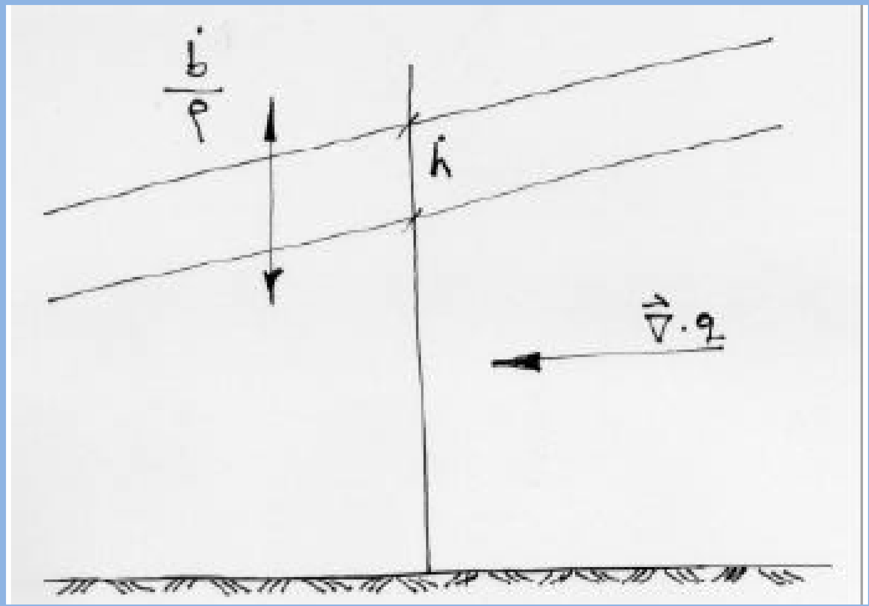
ρ	density	h	glacier thickness
S	area	V	volume
AAR	accumulation-area ratio	ELA	equilibrium-line altitude

Point thickness changes

The change with time of the thickness of a column of ice at any point on a glacier, $\dot{h}$, can be expressed by the continuity equation in ice equivalent units:

$$\dot{h} = \frac{\dot{b}}{\rho} - \vec{\nabla} q \quad (1)$$

Where, $\dot{b}$, is the mass balance rate, ρ is the glacier density and $\vec{\nabla} q$ the horizontal gradient of ice flux



Point thickness changes

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$$\dot{h} = \frac{\dot{b}}{\rho} - \vec{\nabla} q \quad (1)$$

When equation (1) is integrated over the entire glacier surface, $\vec{\nabla} q$ becomes zero and the mass balance equals the thickness change multiplied by the denisty of the glacier (geodetic method).

Accumulation and ablation

Mass gain, *c*, or loss, *a*, can take place:
- on the glacier surface: c_{sfc}, a_{sfc},
- within the body of the glacier (internal): c_i, a_i,
- at the glacier base (basal): c_b, a_b.

Internally, mass may accumulate when melt water from the surface refreezes in cold interior, and mass may be lost when the water thermally erodes internal passages in temperate glaciers.

Basal ablation occurs by melting due to the geothermal heat. However, on mountain glaciers, basal ablation is usually insignificant in comparison to surface loses (except on active volcanos).

For temperate mountain glaciers, the mass changes on the glacier surface largely dominate the mass balance, and internal and basal processes are in most cases ignored.

Accumulation and ablation

Surface accumulation processes include:
- Snowfall
- Wind drift
- Avalanches
- Resublimation
- Condensation

Surface ablation processes include:
- Melting
- Snow drift
- Ice avalanches
- Calving
- Sublimation

The integration over time of the mass balance rate at any specific point *P(x,y,z)* on the glacier surface gives the **net mass balance at that point**.

$$b(P) = \int_t \dot{b}(P)dt \qquad (2)$$

The spatial integration of *b(P)* over the surface area *dS* leads to the **total glacier mass balance** in (m3 w.e.) or (kg), :

$$B = \int_t \int_S \dot{b}(P)dtdS = \int_S b(P)dS = \rho dV \qquad (3)$$

This equals the volume change *dV* multiplied by the glacier density.

The surface-area corresponds to the horizontal projection of the entire glacier surface.

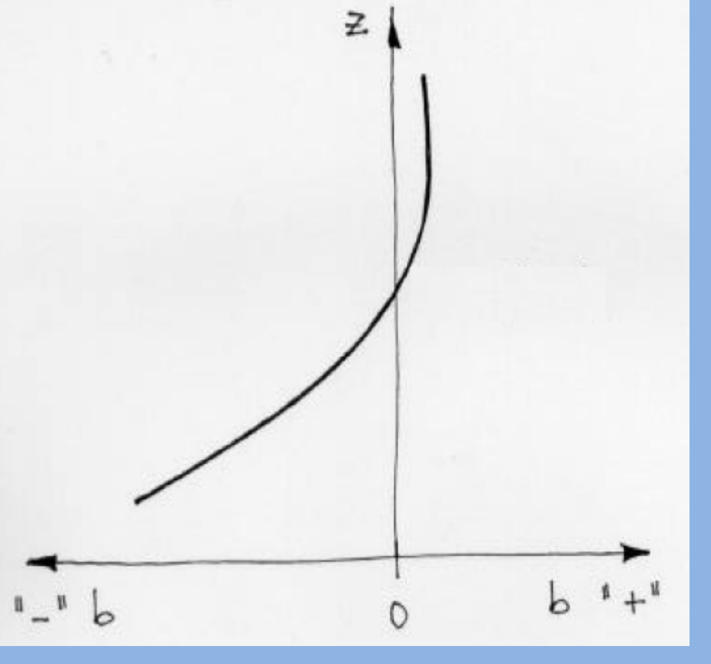
To compare the mass balance between glaciers of different surface-area the **mean specific mass balance** is calculated as:

$$\overline{b} = \frac{B}{S_G} = \frac{\rho \Delta V}{S_G} = \rho \overline{\Delta h} \qquad (4)$$

Which corresponds to the $\overline{\Delta h}$ multiplied by the density. Unit is in (m w.e.) or (kg m-2)

The Vertical Mass-balance Profile (VBP)

If the mass balance is calculated for individual altitude intervals, the mean specific mass balance can be depicted as a function of altitude, *b(z)*, showing the vertical mass balance profile: VBP.

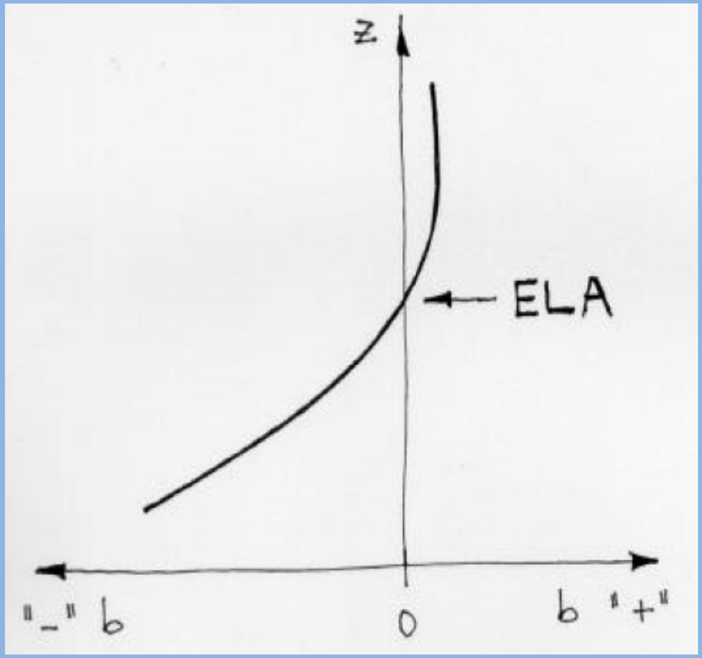


The glacier mass balance differs from year to year, BUT ***the VBP typically exhibits the same shape and only its intercept changes***.

The Equilibrium-Line Altitude (ELA)

The ELA is defined as the altitude where the VBP is zero.

This is the location where the net mass change is zero.



The Accumulation-Area Ration (AAR)

The AAR is the ratio of the surface of the accumulation area (S_C) to the total surface area of the glacier (S_G).

$$AAR = \frac{S_C}{S_G} \qquad (5)$$

The AAR is applied to the glacier at the end of the balance year.
Empirically, the AAR is about 0.6 - 0.7 for alpine glaciers in the mid latitudes but higher in the tropics.

Because the AAR is based on the location of the ELA, the two variables are directly related.

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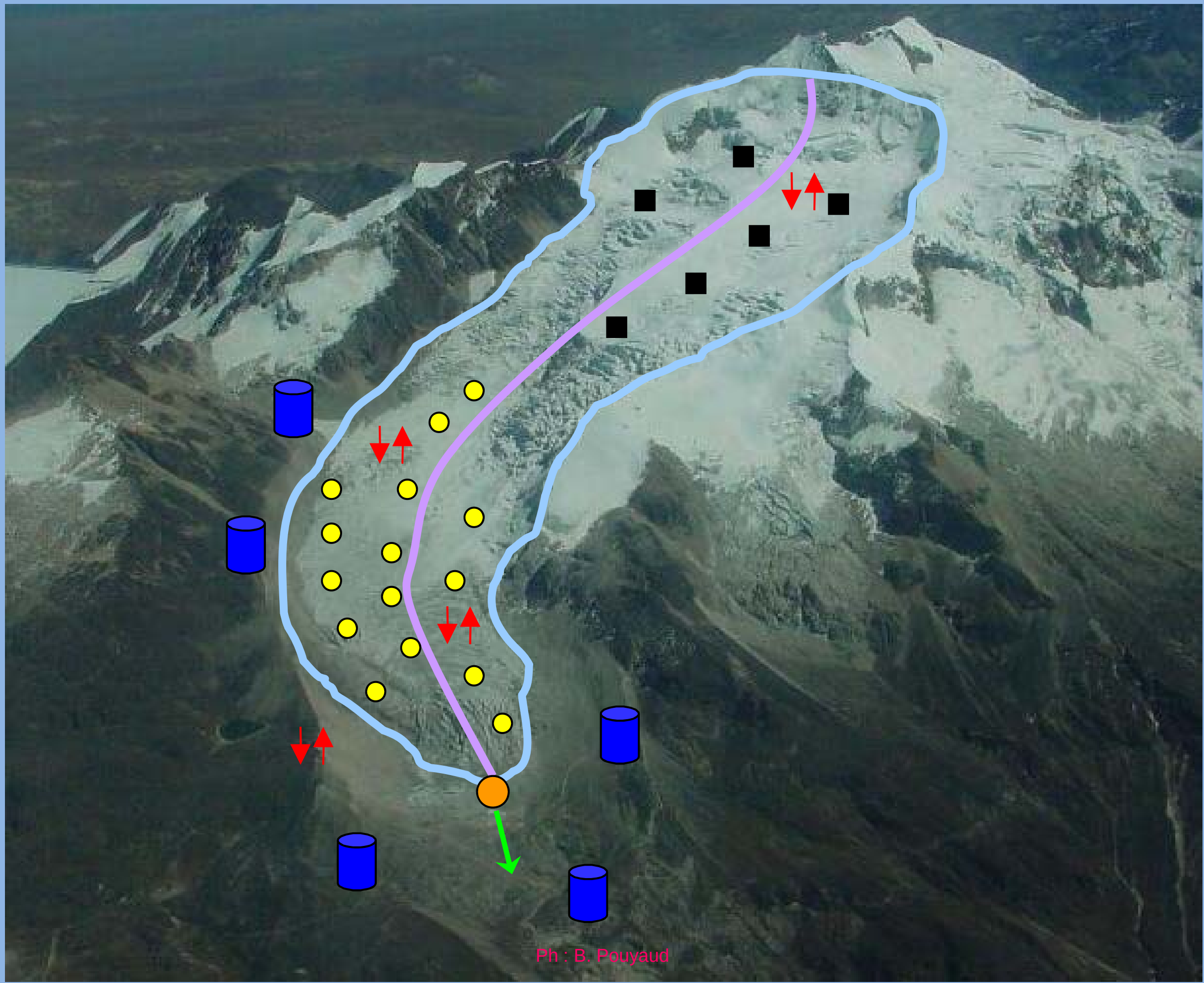
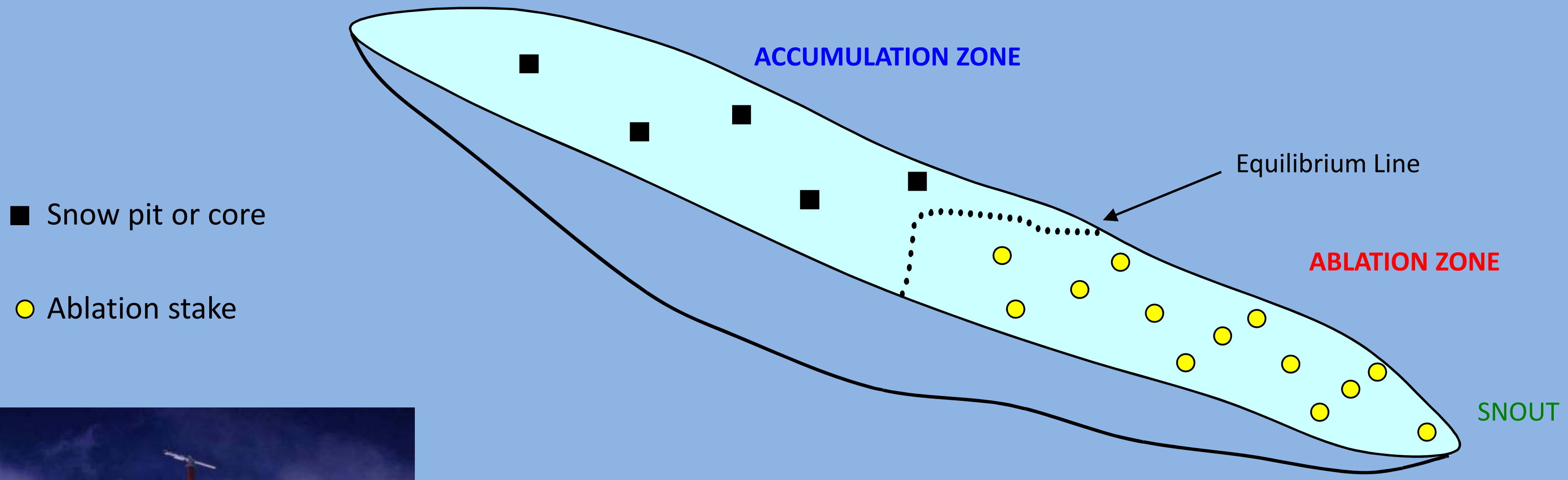
Measured parameters



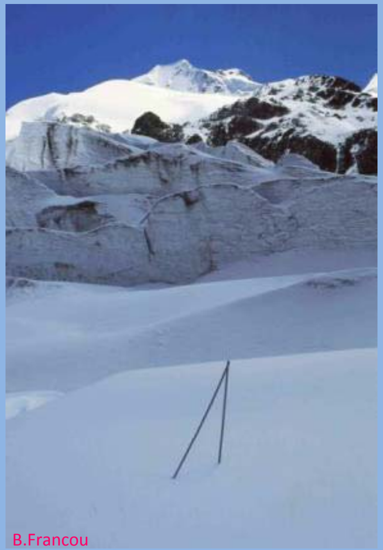
- Surface-area (km²)
- Length (m or km)
- Snout position (X, Y, Z)
- Accumulation (m w.e.)
- Ablation (m w.e.)
- SEB (W/m²)
- Precipitation (mm)
- Runoff (L/s or m3/s)

The glaciological method

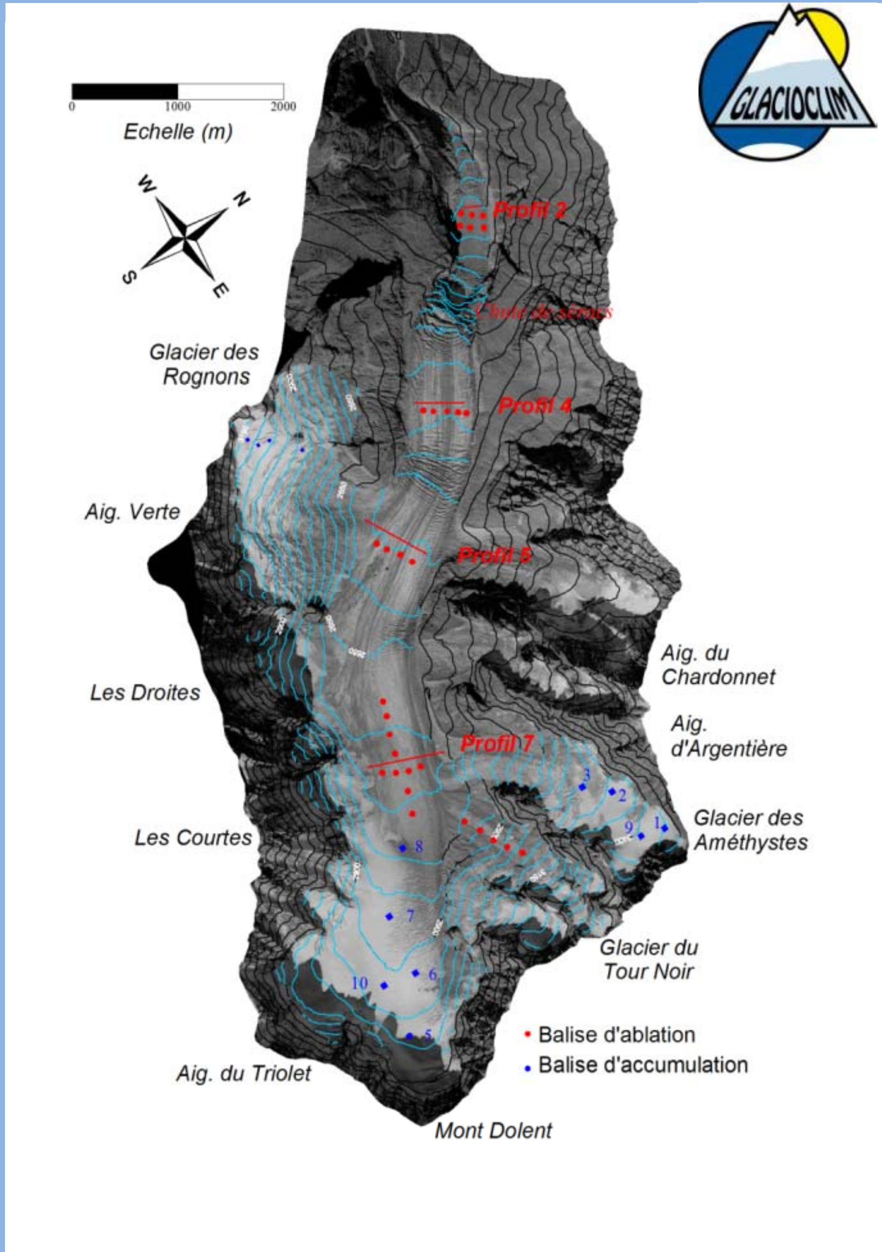


Snow core

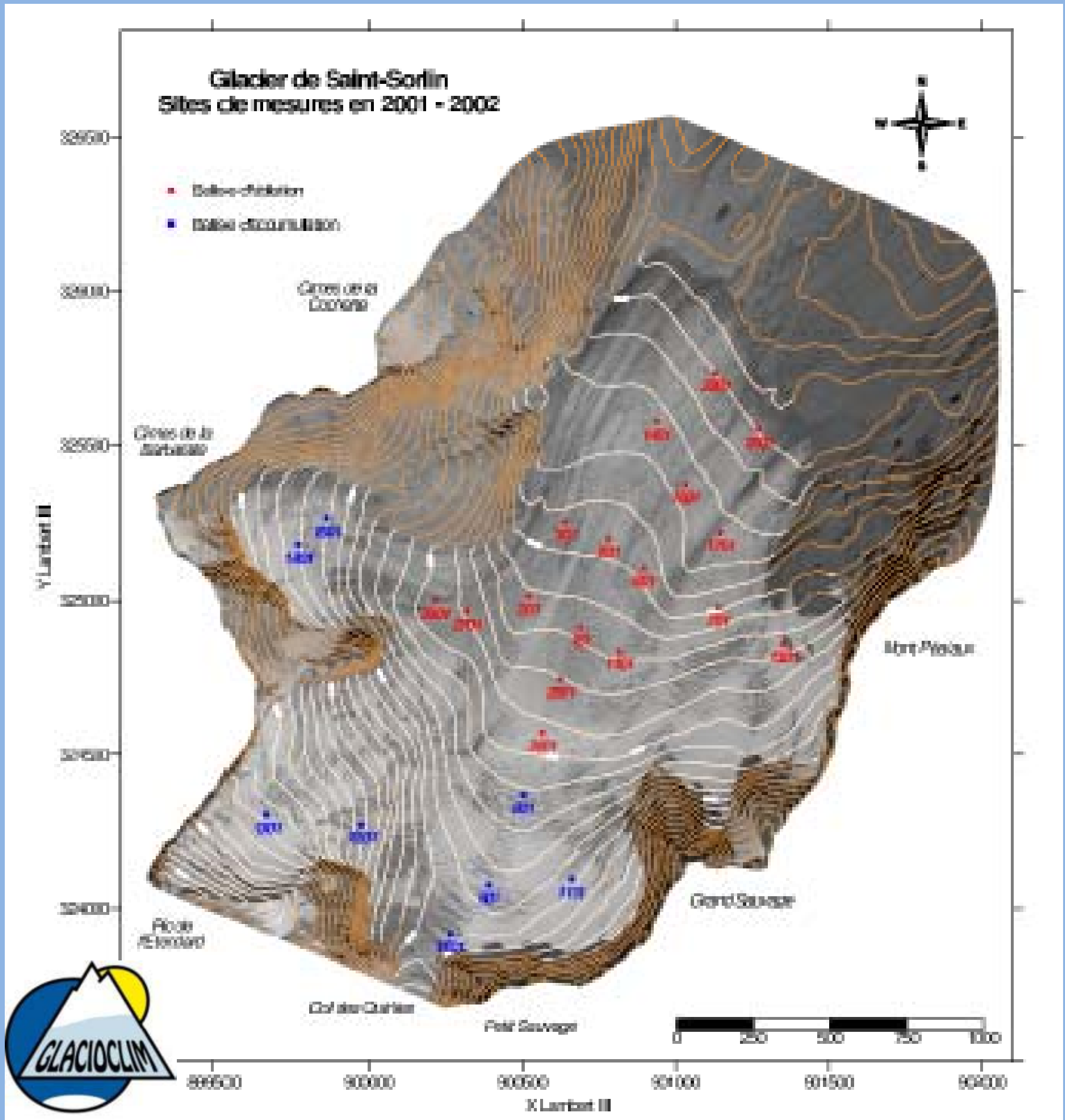
Snow pit



Ablation stake

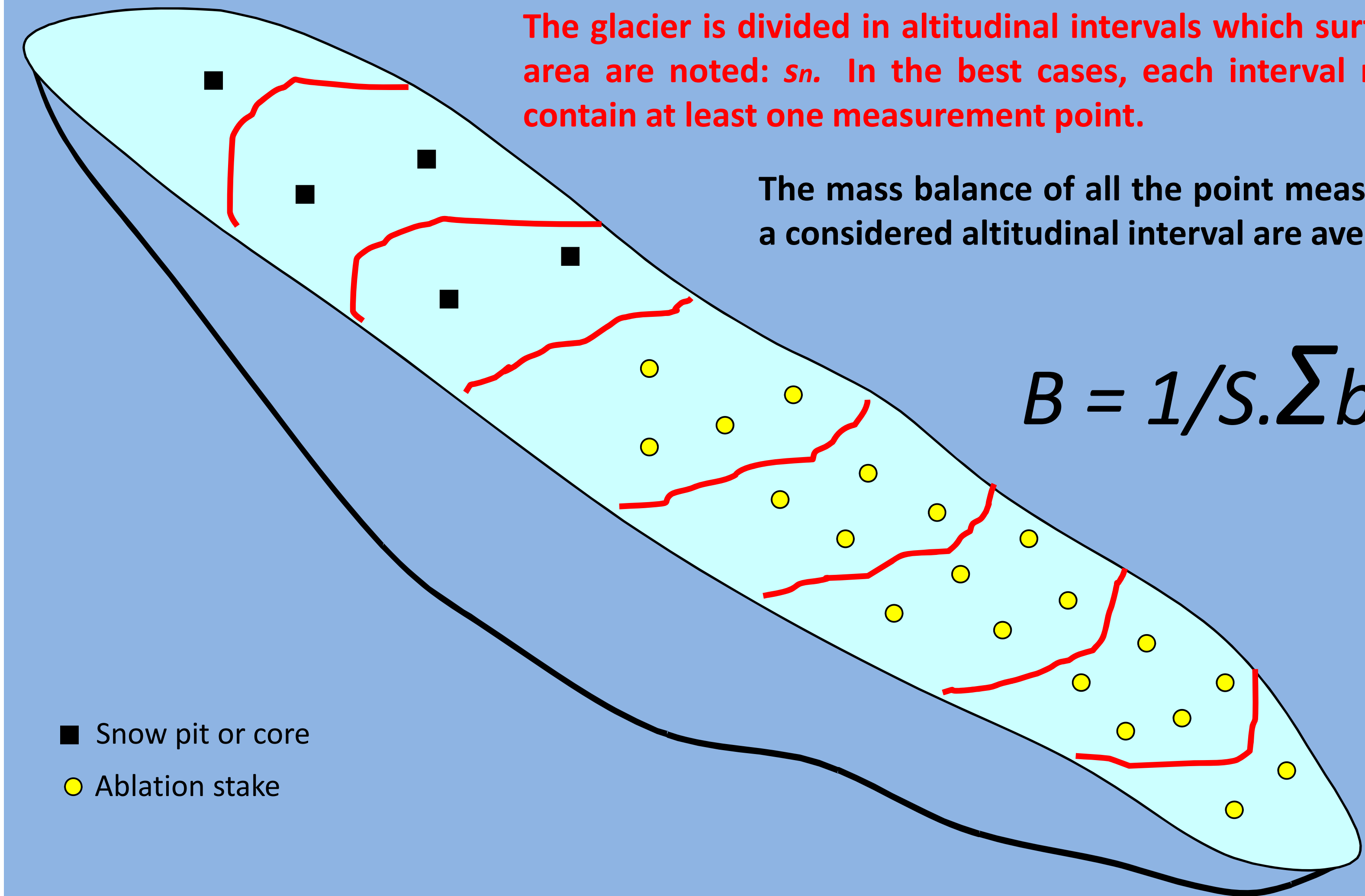


Mass balance measurements profiles (red = stakes; blue snow pits), Argentière Glacier (French Alps)



Mass balance measurements locations (red = stakes; blue snow pits), regularly distributed on Saint Sorlin Glacier (French Alps)

From points mass balance to glacier-wide mass balance



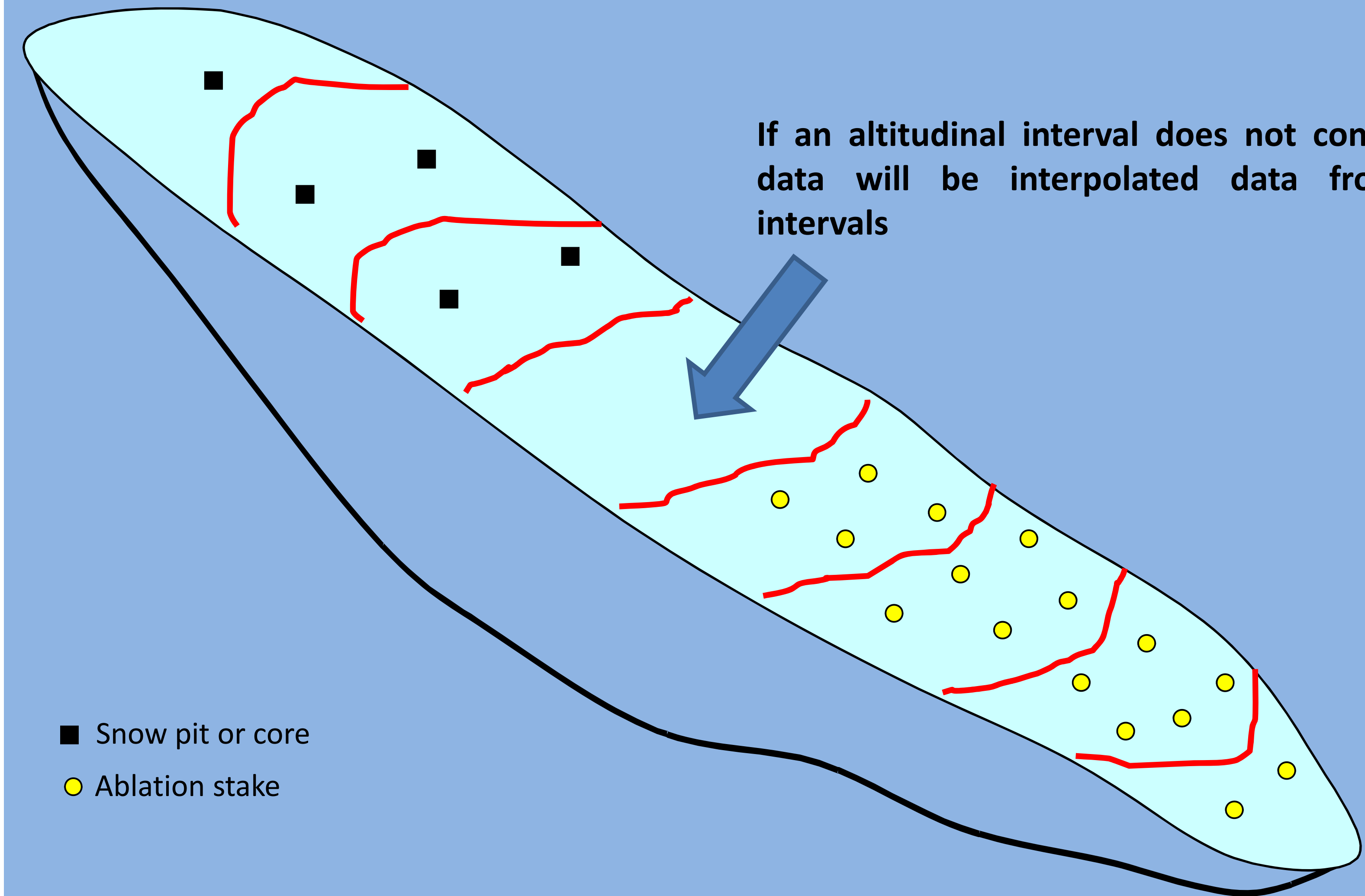
The glacier is divided in altitudinal intervals which surface-area are noted: s_n. In the best cases, each interval must contain at least one measurement point.

The mass balance of all the point measurements within a considered altitudinal interval are averaged: b_n

$$B = 1/S.\sum b_n.s_n$$

From points mass balance to glacier-wide mass balance

If an altitudinal interval does not contain any stakes, data will be interpolated data from neighboring intervals



Carrying out mass balance measurements

Accumulation measurements

Accumulation measurements

The net accumulation is measured by digging pits in the area of a glacier where snow has accumulated during the period of investigation (t1 to t2).

The amount of accumulated snow is measured in water equivalent length units (m w.e.) or water mass per area units (kg m-2).

It is calculated from **measured snow depths and the respective snow density**.

The snow cover has to be penetrated to the last observation dates horizon (t1) either by digging snow pits or by taking cores with a drill.

Accumulation measurements

The identification of previous year layers

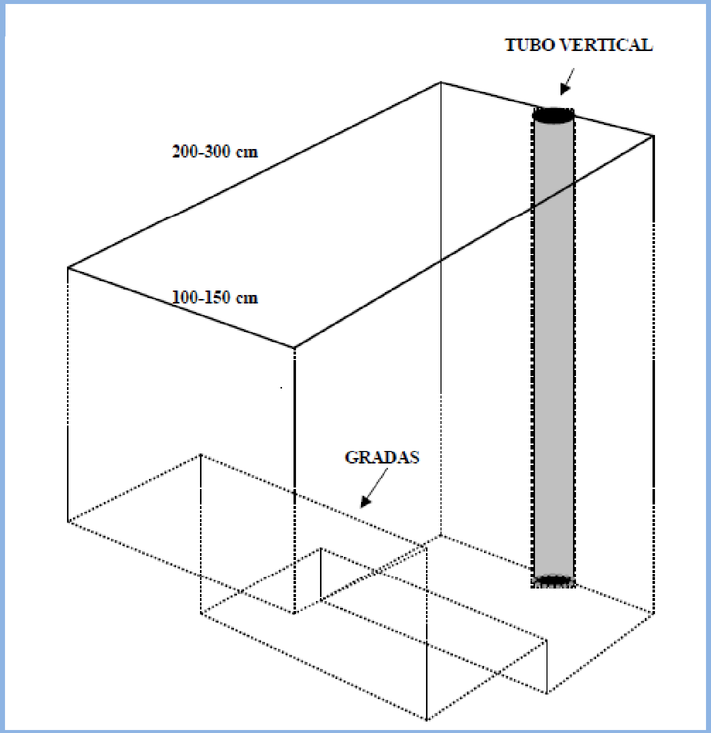
Easy to determine in the ablation zone because of the ice surface.

In the accumulation zone any natural or artificial marking made at t1 will be buried by snow by t2.

- Under mid-latitude conditions, a well definable layer develops at the end of the ablation season.
  The surface had experienced melting, collected dust during the ablation season, and re-froze before the arrival of winter snow.
  The reference layer is dusty and hard.
  All snow superimposed on this hard dusty layer is considered to be new accumulation.

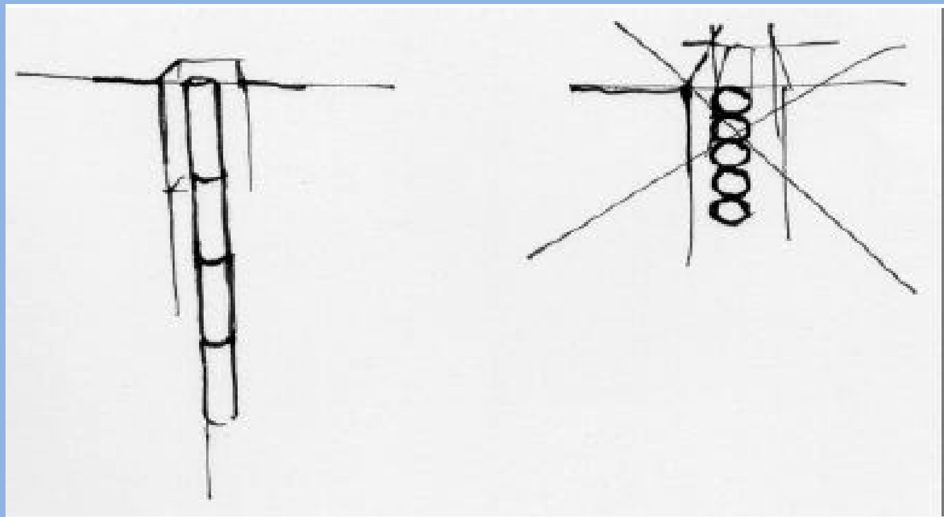
- Under low latitude conditions measurements of net accumulation are more complicated.
  Neither in the monsoon type regime nor in tropical regimes does a hard dusty layer develop.
  Articifial markers are needed.

Accumulation measurements: snow pit



The measuring-wall is oriented to avoid direct sunlight.

Accumulation measurements: snow pit



Sampling is better made vertically

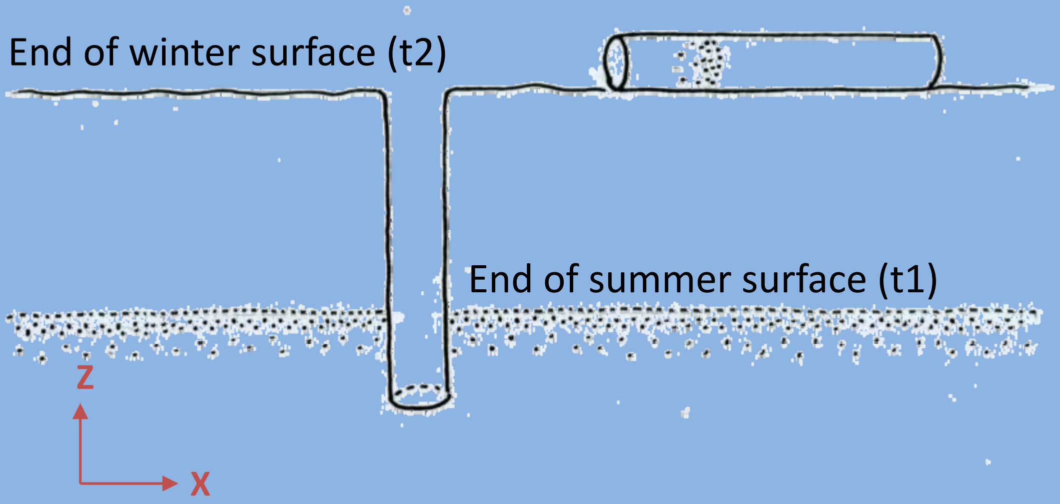
The sharp edge of the density tube must not affect the sample

Accumulation measurements: snow pit

A stratigraphic description of the snow layers can be very helpful when analysing the data and when comparing the results from different snow pits.

This should consider major changes in the snow pack: **change from crystals to grains, dust layers, descriptive free water content, ice layers, etc.**), which can be related to certain weather conditions throughout the accumulation season.

Accumulation measurements: snow core



Accumulation measurements: snow core

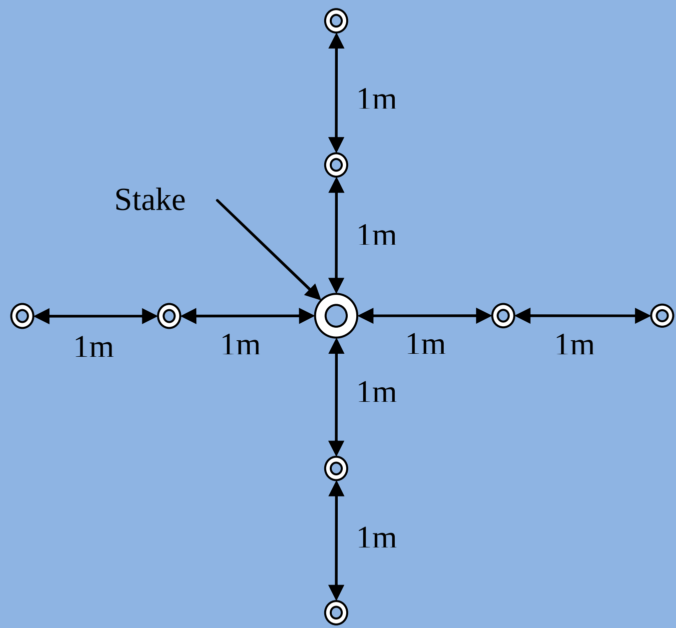
Snow core in the accumulation zone
with the dust layer of previous summer

Snow core in the ablation zone
with the snow/ice transition

Accumulation measurements: snow core

Weight

Accumulation measurements: snow probing



Accumulation measurements: other alternatives

Accumulation stake with sawdust sprinkled around

Accumulation stake

Accumulation measurements: other alternatives

Measurements along a crevasse wall

Carrying out mass balance measurements

Ablation measurements

Ablation measurement at stakes

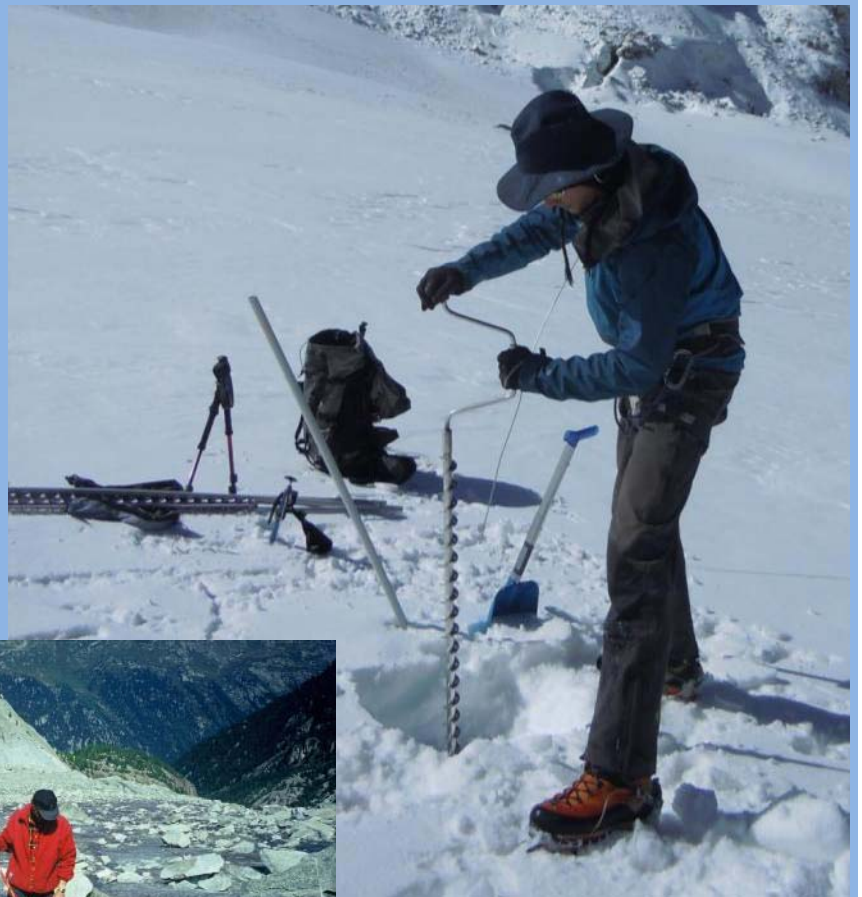
Typically, stakes are drilled into the glacier in the ablation zone and changes in surface level are measured against stake height.

The density of glacier ice is considered constant at 900 kg m-3, and the specific mass balance in (m w.e.) or (kg m-2) is calculated from the product of the level change between readings and the ice density.

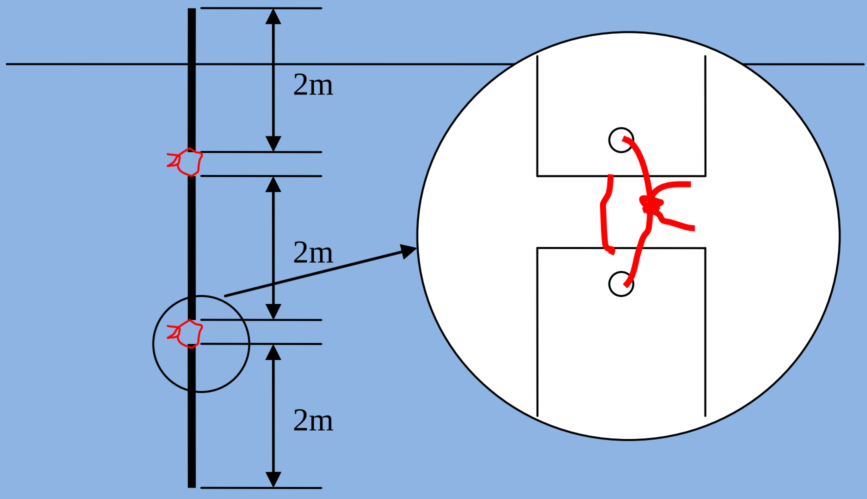
In the accumulation zone, if firn ablation can be expected, stakes must also be set in those areas, generally placed in the coring hole.

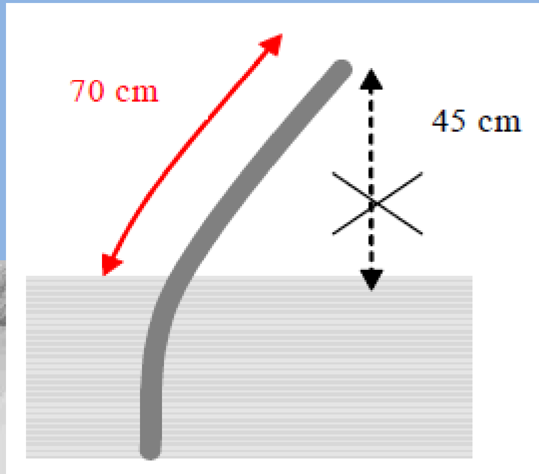
Density of the ablated material must be made prior to the ablation, i.e. during the accumulation measurements.

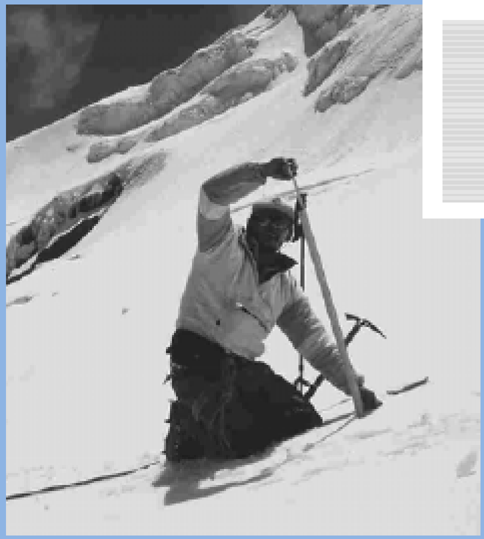
Steam drill // Hand brace drill to insert stakes into the glacier

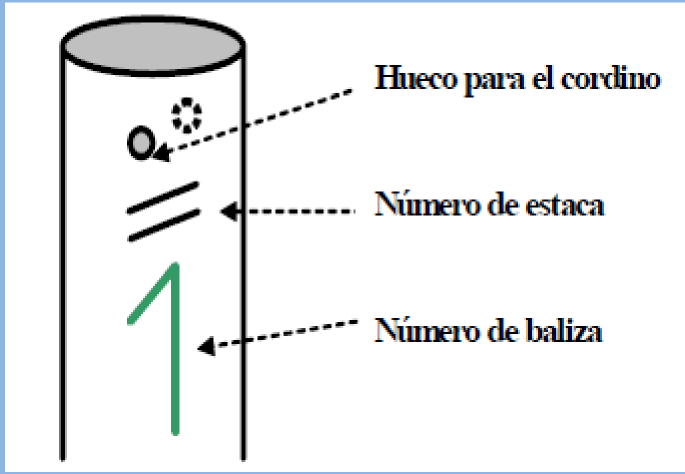


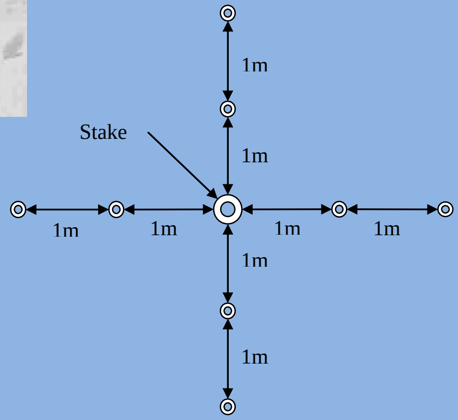
Ablation measurements at stakes



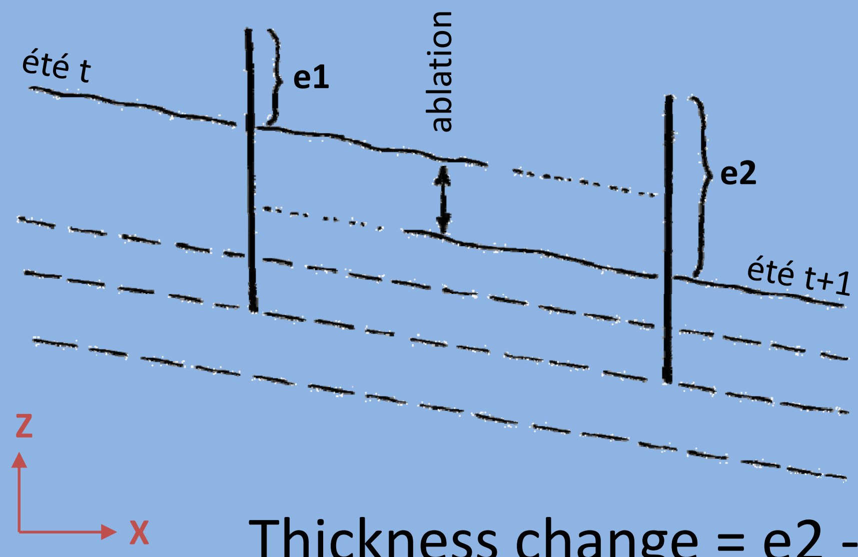








Ablation measurement at stakes

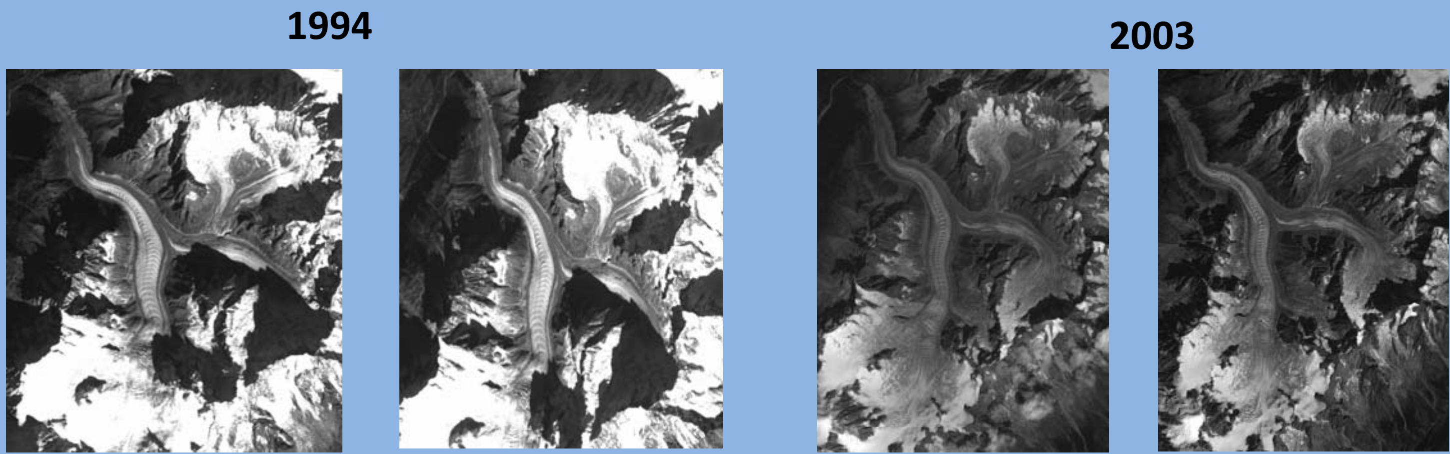


Thickness change = e2 - e1

Ablation = thickness change * density

Other methods for mass balance measurements

The geodetic method



Aereal photographs pairs

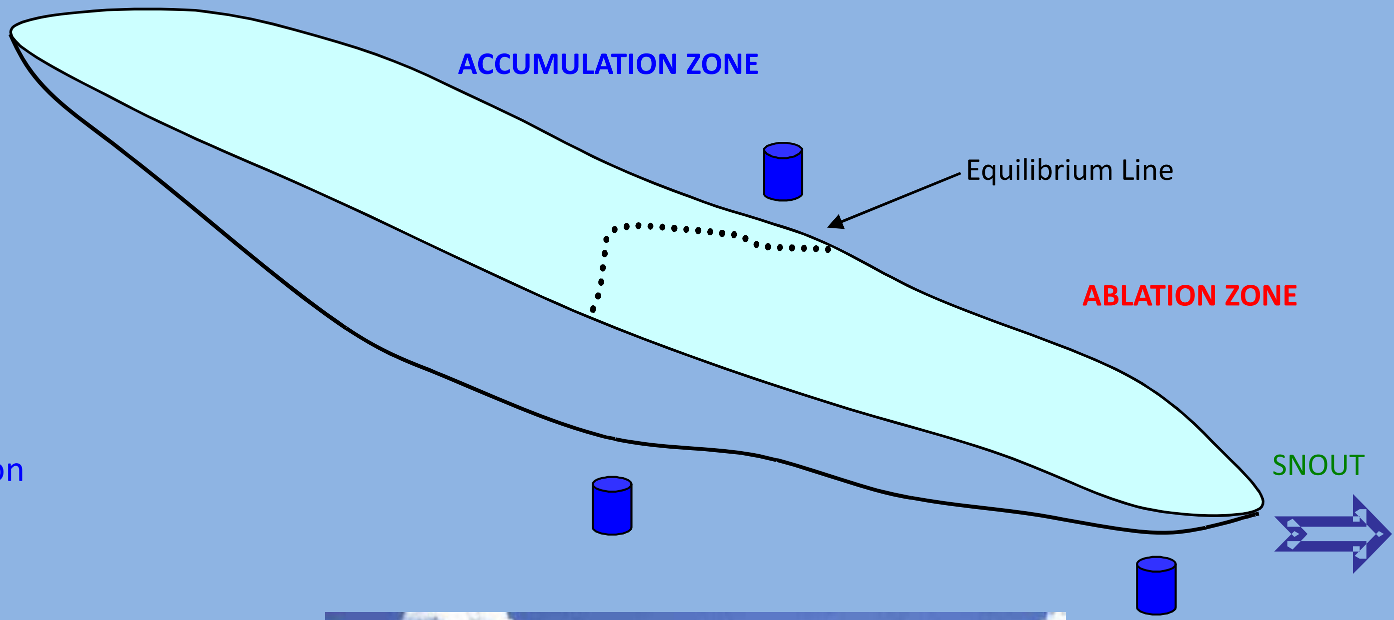
DEM #1

DEM #2

DEM #2 - DEM #1 = thickness changes

⇨ Thickness changes * ice density = mass balance

The hydrological method



Runoff station

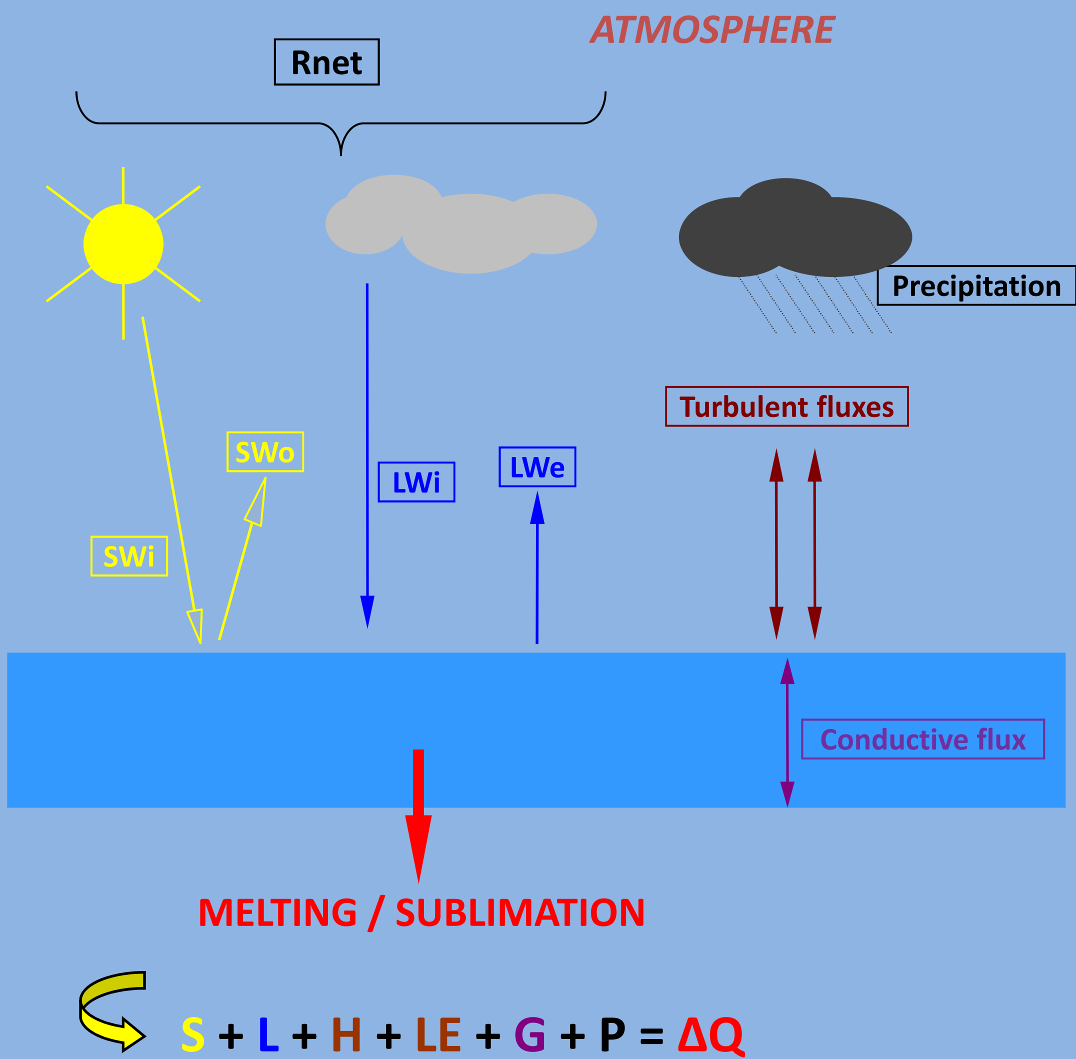
Rain gauge

Rain gauge

Runoff station

Surface energy balance

AWS (5430 m a.s.l.)
Guanaco Glacier, Chile



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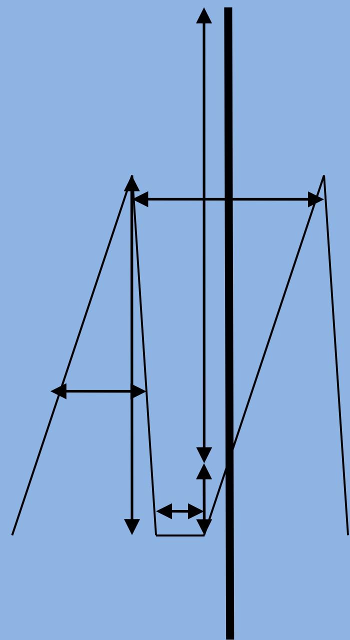
Below specific climate conditions, different accumulation and ablation processes can be found:

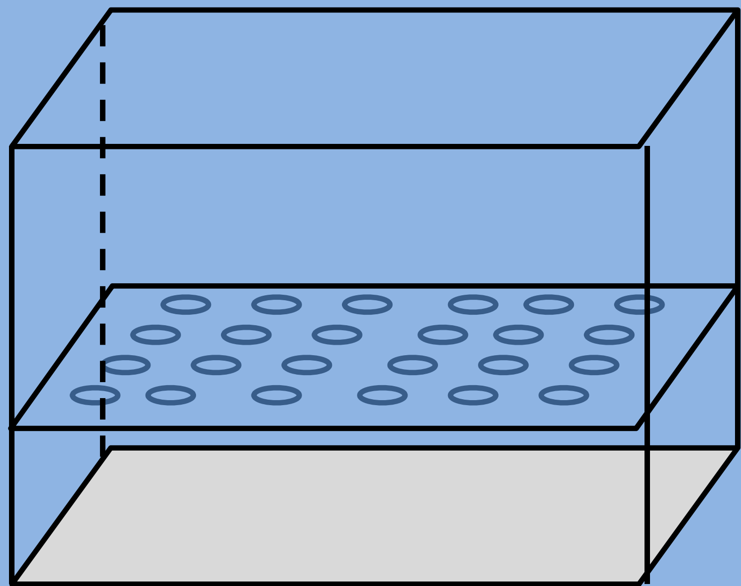
- Sublimation
- Superimposed ice
- Internal accumulation

Snow and ice penitents

Example of the dry Andes of Chile and Agentina
Penitents result from differential ablation with sublimation on the penitents and melting in the hollows (i.e. between the penitents walls)



The use of lysimeters to computed sublimation.



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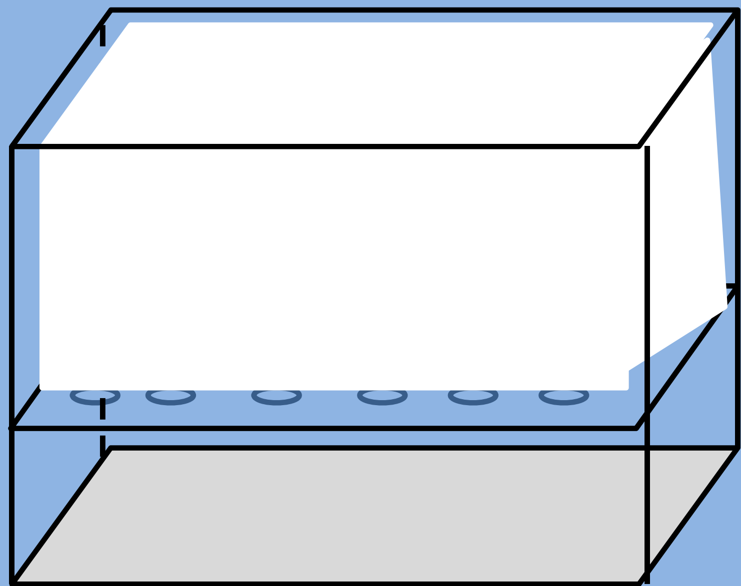

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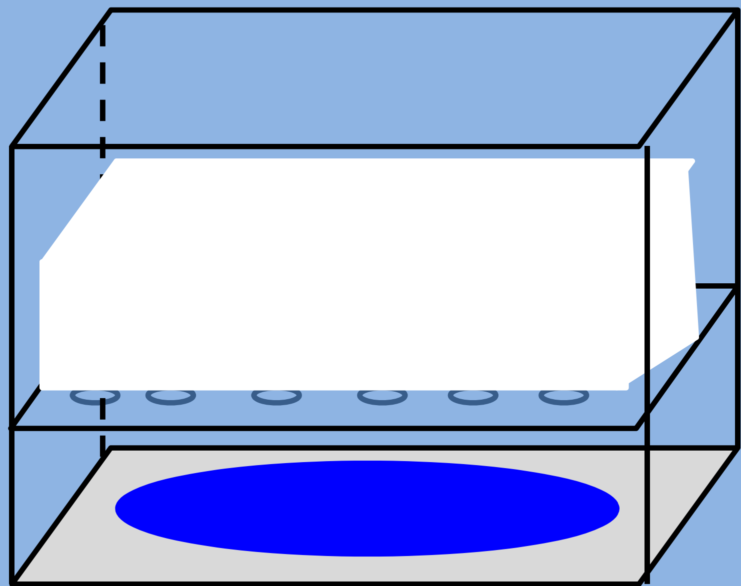

The best way to computed mass changes at the scale of the entire glacier surface when sublimation/pentinents/superimposed ice are found is probably to use terrestrial lidar measurements.

Thank you for your attention