The mass balance of glaciers

The **mass balance** is the **difference** between the snow that has **accumulated** (accumulation) and the snow and ice that has **melted or disappeared** in the course of a year (ablation). A glacier in equilibrium with the climate has a mass balance of zero on average, and a glacier in disequilibrium with the climate has a mass balance that is farther from zero the farther it is from its equilibrium state.

1. How is the mass balance of glaciers measured?

Figure 1: Installation of a bamboo ablation stake with a steam drill in the ablation zone of the West Changri Nup Glacier, with Mount Everest visible in the background. [Source: © Patrick Wagnon]

The mass balance of a glacier between two periods can be measured in two ways: either by summing the ablation and accumulation (**glaciological method**), or by measuring its volume change (**geodetic method**). These two types of measurement are very **complementary**.

The glacier mass balance is the integral of all mass fluxes across the glacier contour. The mass balance ΔM, expressed in kg or m^3 water equivalent (w.e.), is defined as follows [36]:

$$\Delta M = \int_A (b_s + b_e + b_b)\, dA$$

Where A (m^2) is the map view area of the glacier, b_s, b_e and b_b are the surface mass balances, englacial and basal, expressed in kg m^{-2}. For most glaciers, the dominant term in the integral is the surface mass balance, and thus the glacier-scale mass balance can be written:

$$\Delta M = \int_A b_s\, dA$$

Figure 2: Measurement of point mass balance using a corer coupled with density measurements in the accumulation zone of the Mera glacier at 6350 m altitude, a.s.l., with Mount Everest visible in the background. [Source: © Bruno Jourdain]

The glaciological method consists of a direct measurement of b_s, at an annual or sub-annual frequency, if possible. In the ablation zone, mass balance is measured by monitoring the emergence of stakes inserted in the ice (Figure 1). In the accumulation zone, mass balance is measured by manual coring (Figure 2). ΔM is therefore the area-weighted average of point measurements extrapolated over the entire glacier. This extrapolation adds some uncertainty.

The geodetic method aims to measure the total volume change of the glacier by repeated surveys of its surface topography. The most common method is to **differentiate between two digital terrain models** (DTMs) obtained either by airborne photogrammetry or by satellite topographic missions. In this case, the total volume change of the glacier (ΔV in m^3) is expressed as follows:

$$\Delta V = r^2 \sum_{k=1}^{K} \Delta h_k$$

Where r^2 is the area of a pixel (in m^2), K is the number of pixels over the glacier area, and Δh_k (in m) is the change in thickness of each pixel. The change in volume is then converted to a change in mass by making an assumption about the density, which introduces an uncertainty of about 10%.

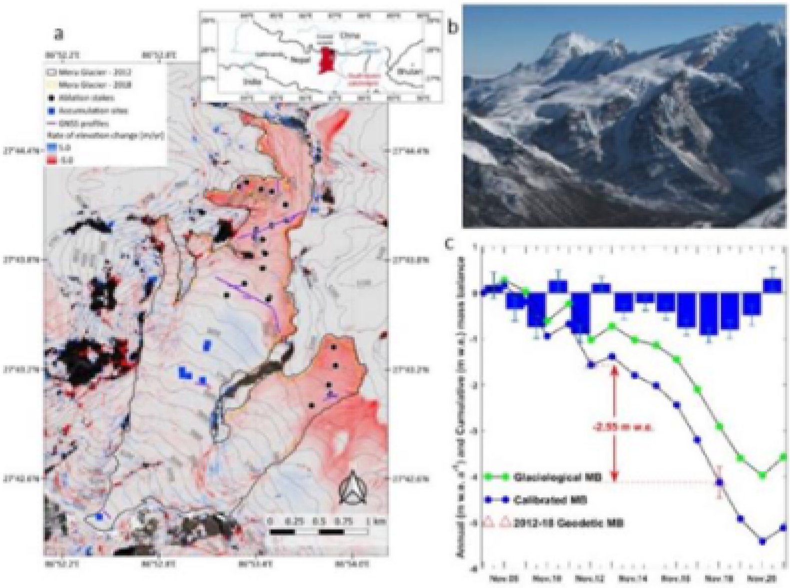

Figure 3: An example of monitoring the Mera glacier (Everest region, Nepal). Panel b is a photo of the glacier taken in October 2010 (© P. Wagnon). The map (panel a) shows the thickness changes over the period 2012-2018 (blue to red gradients) obtained by DTM difference, as well as the network of ablation stakes (black dots) and accumulation measurement sites (blue squares). The graph (panel c) shows the annual mass balance for the period 2007-2021 (blue histograms), as well as the cumulative mass balance before (black line and green dots) and after (black line and blue dots) adjustment on the 2012-2018 geodetic balance. [Source: adapted from Wagnon et al [37], article distributed under Creative Commons license (CC BY 4.0)]

These two methods **measure different quantities**, as the geodetic method also incorporates b_e and b_b. Sometimes these two terms are nontrivial contributors to the glacier-scale mass balance, and can lead to discrepancies between geodetic and glaciological mass balances. Glacier-scale mass balances measured with the glaciological method may be biased and must be calibrated with geodetic measurements [37].

2. The example of the Mera glacier

To illustrate, let us take the example of the Mera Glacier, located about 30 km south of Mount Everest in Nepal and which **has been monitored for mass balance since 2007**. Figure 3 shows the observation network deployed on the Mera glacier in Nepal, which flows from the summit of the same name at 6500 m a.s.l. to its front at 4900 m a.s.l..

The mass balance is determined **twice a year** from measurements of emergences from regularly distributed ablation stakes in the lower part of the glacier below 5600 m, as well as from measurements of accumulation by coring at various altitudes, up to the top of the glacier. The area-weighted average of the mass balance obtained at each ablation or coring site at each elevation is the total mass balance. Between 2007 and 2021, the Mera glacier lost mass, -0.37 ± 0.22 m e./year on average, but with high interannual variability. The year 2017-18 showed the most negative mass balance of the series with -0.92 ± 0.16 m e./year, related to a marked deficit of precipitation, while 4 years saw the glacier slightly gain mass, sometimes thanks to record precipitation as it was the case during the passage of typhoon Phailin between 13 and 15 October 2013 [37].

Notes and references

Cover image. [Source: © Bruno Jourdain]

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