

Glacier surface area delineation based on optical remote sensing

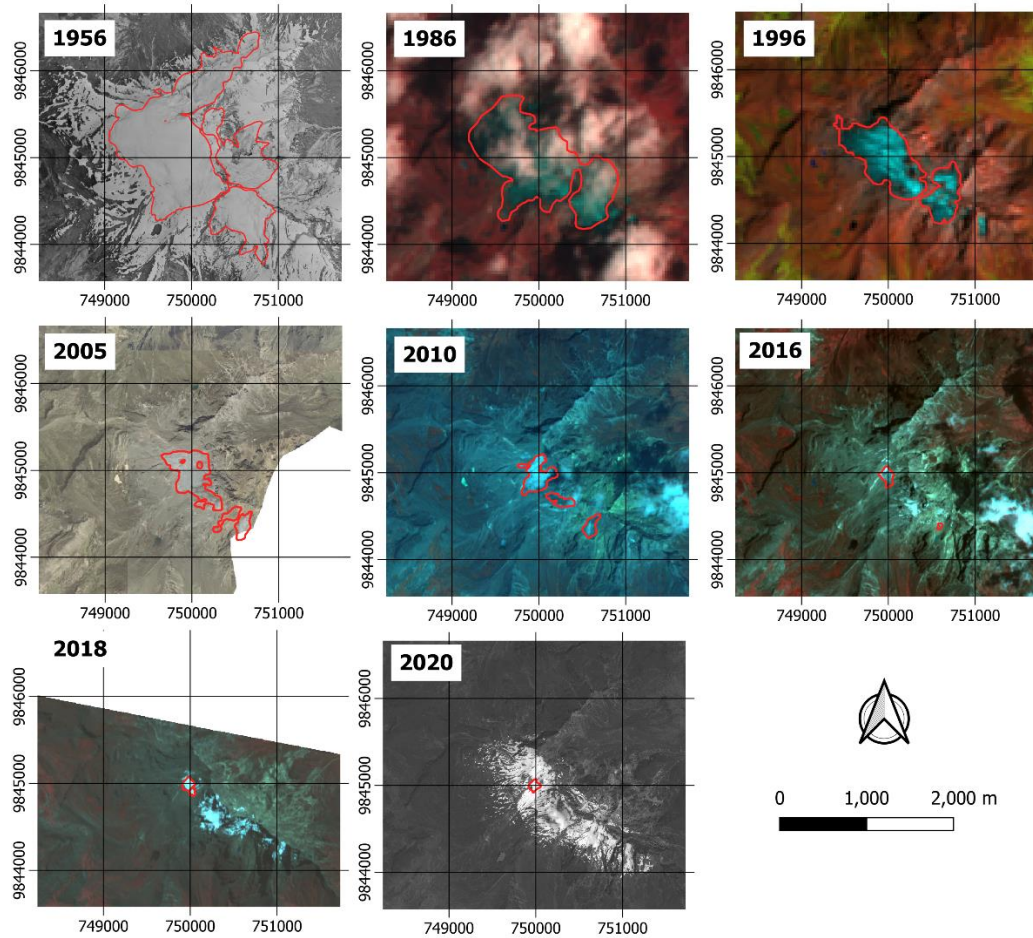


Figure S1. Glacier outlines (red lines) of the Carhuairazo ice-cap derived from multisensor satellite imagery for different dates for the 1956–2020 period. The background corresponds to true-color composites. The sensors used are listed in Table 1 in the main manuscript.

Glacier boundaries were delineated through a GIS-based approaches that combined automated techniques with manual refinement (Figure S1). All images were orthorectified using DEMs to correct distortions caused by terrain relief and sensor viewing geometry, ensuring geometric consistency. For historical aerial photos, glacier outlines were mapped manually. In the case of satellite imagery, initial outlines were generated using semi-automated methods based on the Normalized Difference Snow Index (NDSI) or band ratios, following established approaches (Paul and others., 2017). The resulting polygons were then refined through manual editing to correct misclassifications, supported by auxiliary datasets such as false-color composites and hillshade maps derived from DEMs. The glacier surface area reported in 1979 was derived from aerial photogrammetry using STEREOCORD (Jordan and Hastenrath, 1998), whereas the glacier surface areas reported for 2023 and 2024 were measured *in-situ* with DGPS by Vaca-Cárdenas and others., (2025).

Comparison with previous estimates of elevation change.

The purpose of comparing the dh/dt estimates from this study is to assess their consistency with regional-scale mass change estimates, such as those reported by Hugonnet and others., (2021) for a similar period (2010/11–2020). To ensure direct comparability, our data (original spatial resolution of 10 m) were resampled to the coarser 100-m grid used by Hugonnet and others., (2021). Also, the glacier outlines digitized from the satellite imagery as described in the previous section were considered. These steps prevent a misinterpretation of the true discrepancy between the data.

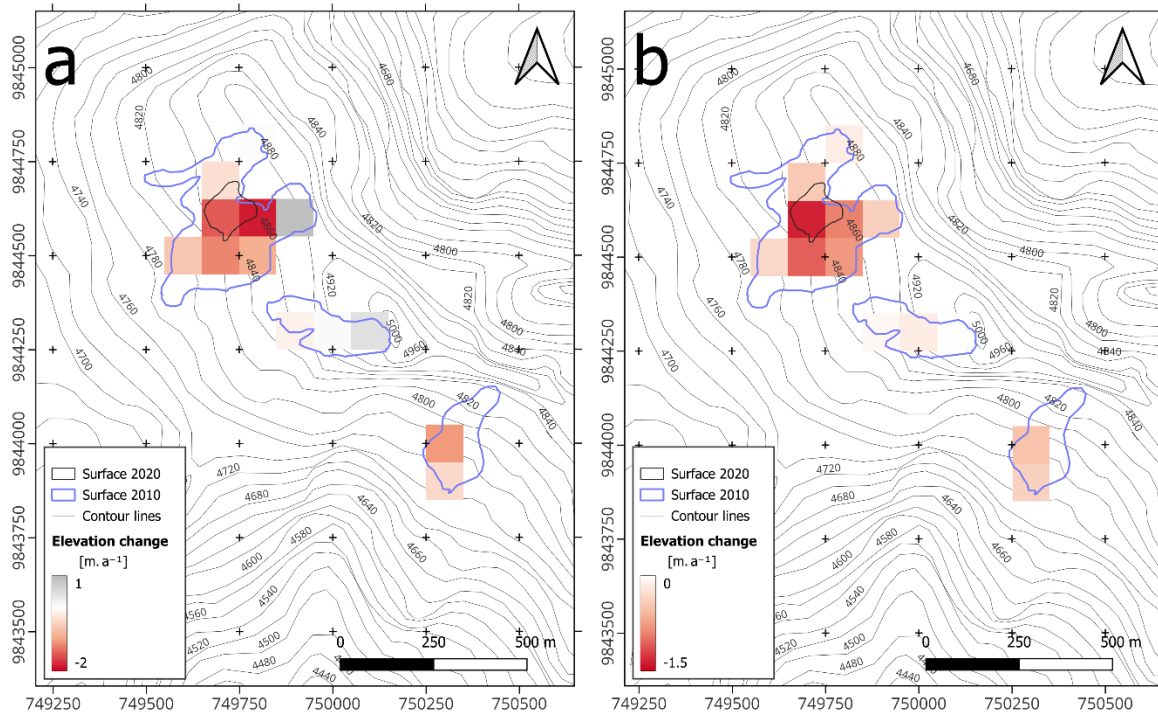


Figure S2. Annual elevation change distribution during the 2010/2011–2020 period: a. from Hugonnet et al. (2021) and b. from this study.

Overall, there is an agreement in both datasets, given average mass balance rates of -0.71 in Hugonnet and others (2021) and -0.72 m w.e. a^{-1} in this study. Although both datasets exhibit a comparable magnitude of thinning, with elevation changes ranging from 1 to -2 m a^{-1} in Hugonnet and others., (2021) and from 0 to -1.5 m a^{-1} in this study, Figure S2 shows that the regional dataset does not fully capture the spatial variability of dh/dt across the glacier.

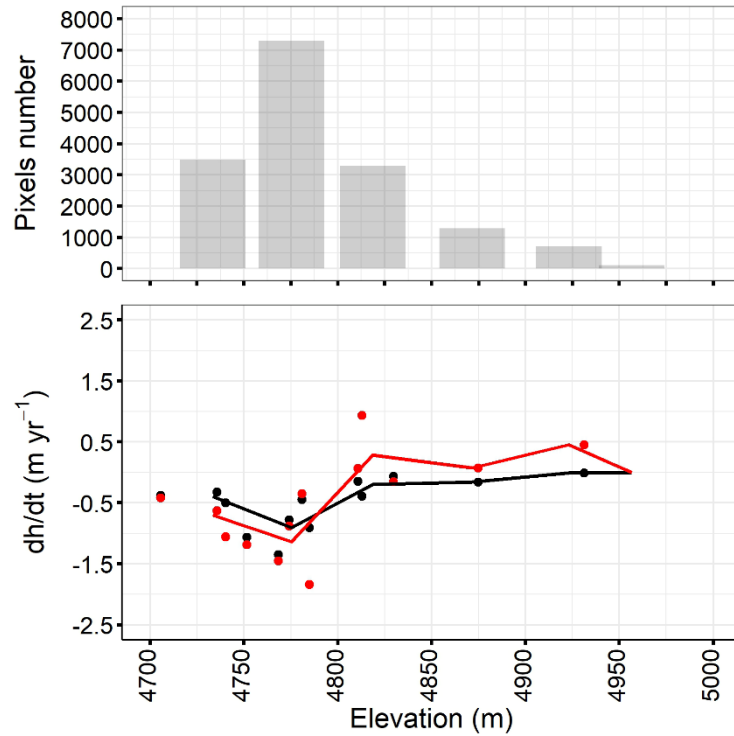


Figure S3. Hypsometry in 2011 (grey bars) and the elevation change rates as a function of the elevation for the study period 1956–2020.

When comparing the elevation change profiles differences emerge in the vertical gradient, thus the regional product tends to underestimate thinning below approximately 4,780 m a.s.l and overestimate thinning above this elevation (Figure S3). This contrasting behavior results in a compensation effect, whereby the overestimation at higher elevations offsets underestimation of mass loss at lower elevations. This indicates that, despite localized deviations in the magnitude of surface lowering, the regional product reproduces the general thinning trend observed at local scale.

Effect of volcanic ash changing the surface of the Carihuairazo ice cap.

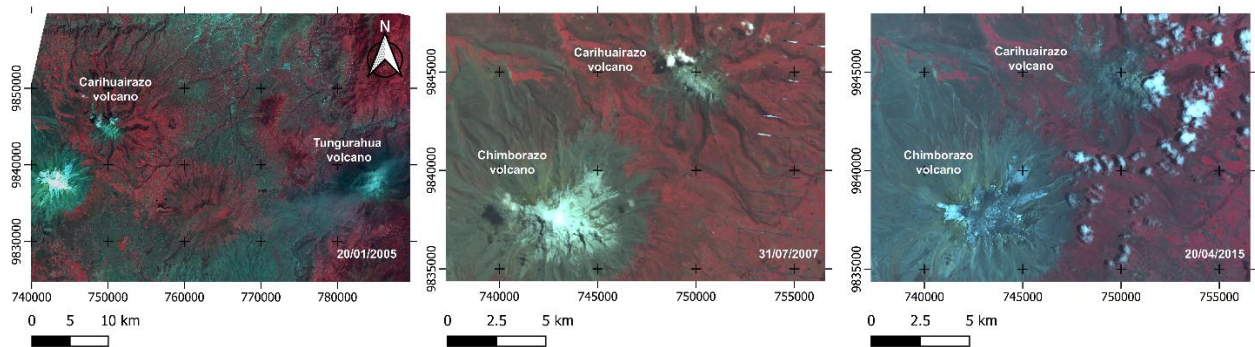


Figure S4. The deposition of volcanic ash at the glacier surface diminished the albedo and enhanced the absorption of solar radiation. This impact of the surface energy balance likely increased the amount of energy available at the surface, thereby accelerating melt rates. a) SPOT5 (20/01/2005), b) Landsat 7 (31/07/2007), c) ASTER (20/04/2015).