# The Glaciers of the Dolomites: last 40 years of melting

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**Abstract.** Small alpine glaciers located below the regional equilibrium line altitude are experiencing considerable ice losses and are expected to fragment into smaller glacial bodies and eventually disappear. Monitoring such glaciers by satellite remote sensing is often challenging because their size and surrounding topography are incompatible with the current spatial resolution of non-commercial satellites. The Italian Dolomites (S-E Alps) are a region clearly illustrating such challenges and where no long-term glacier mass balance data are available. This renowned alpine sector hosted tens of glaciers up until a few decades ago, with now only twelve remaining. This study presents a multi-decadal (1980s-2023) estimation of surface elevation change and geodetic mass balance of the current mountain glaciers present in the area. Calculations are based on geodetic data: high resolution and accuracy is obtained with uncrewed aerial vehicle (UAV) Structure from Motion (SfM) and airborne Light Detection and Ranging (LiDAR), from 2010 to 2023. SfM on historical aerial imagery is used for previous decades. We found an average cumulative surface elevation change of -28.7 $\pm$ 2.6 m from 1980s to 2023, 33% of which occurred between 2010-2023. The average geodetic mass balance rate for the whole period is -0.64 $\pm$ 0.06 m w.e. yr$^{-1}$, varies widely among sites, and is less negative than the alpine reference glaciers mass balance. Regionally, 66% of the volume loss is related to the *Marmolada* Glacier alone. Losses of ice mass and area show that the Dolomites are rapidly losing their glaciers.

## 1 Introduction

Glaciers worldwide have been losing mass at alarming rates over the past decades (Zemp et al., 2019; Hugonnet et al., 2021). This is particularly evident in regions where warming is occurring at a faster rate than global average (Rantanen et al., 2022; ICCI, 2022). Among these regions are the European Alps (Hock et al., 2019), where severe impacts on the cryosphere have been observed because of rising temperature (Auer et al., 2007), changes in seasonal precipitation patterns, total radiation, humidity, and snow accumulation (Gobiet et al., 2014; Rumpf et al., 2022).

The European Alps can effectively be considered the birthplace of modern glaciology (Clarke, 1987). Despite the progressive improvement of *in-situ* (Huss et al., 2015; WGMS, 2021) and remotely sensed cryosphere monitoring efforts for the European Alps (Davaze et al., 2020; Paul et al., 2020; Sommer et al., 2020), areas remain where only scattered data and observations are available. One of those regions are the Italian Dolomites (S-E Alps).

The Dolomites are mostly known for their landscapes, resulting from an extremely rich geological diversity (Panizza, 2009). They represent a complex area from a socio-economic, geographical and cultural point of view, and for this reason have been studied intensively in terms of geology, geomorphology, and biodiversity (Bosellini et al., 2003; Panizza, 2009; Pignatti and Pignatti, 2014). However, glaciers of this region have always remained on the margins of scientific exploration.

Glaciers in the Dolomites region were numerous until a few decades ago (CGI-CNR, 1962). The complex topography of the area ensures that many sites are orographically protected from direct sunlight and favour the accumulation of snow through avalanches. Until recently, such a context allowed the existence of glaciers well-below the environmental equilibrium line altitude (envELA) (Castiglioni, 1925; Žebre et al., 2021), which in the Eastern Alps during the 20th century ranged from 2700 to 3100 m a.s.l. (Žebre et al., 2021). Only a few massifs had an accumulation basin located above the envELA, allowing larger ice bodies to develop, such as the *Marmolada* and *Fradusta* Glaciers.

Assessing the state of glaciers through their mass balance is considered an essential component in the global climate-related set of observations (Zemp et al., 2009). At the regional scale, this involves generating large composite datasets through *in-situ* measurements and remote sensing campaigns. Various techniques have been developed over the last few decades to improve remote measurements of glacier mass change (Berthier et al., 2023). Workflows involving sensors mounted on uncrewed aerial vehicles (UAVs) or helicopters are particularly effective for monitoring smaller topography-bounded glaciers. Among such settings, one technique that has been successfully used is Structure from Motion (SfM) (Carrivick et al., 2016). SfM allows both terrestrial (e.g., Piermattei et al., 2015; Marcer et al., 2017) and aerial (e.g., Smith et al., 2016) high-resolution surveys relying on photos taken from different positions. The same workflow can be applied to historical imagery initially acquired for mapping purposes, allowing for the retrieval of past glacier change (Mertes et al., 2017; Knuth et al., 2023). Despite the large improvements in the applications of SfM, the state-of-the-art for high-resolution topographic surveys remains Light Detection and Ranging (LiDAR) (Bhardwaj et al., 2016). LiDAR is an active remote sensing technique that uses a laser pulse and its two-way travel time to reconstruct the surrounding scene. It can be used to monitor surface elevation changes at different scales, depending on the sensor and platform used (e.g., Knoll and Kerschner, 2009; Fischer et al., 2016; Okyay et al., 2019; Securo et al., 2022).

To the best of our knowledge, no specific studies have been conducted regarding the current status of Dolomites glaciers, or about their decadal change. The aim of our work is to fill this gap, providing a description of the mountain glaciers in the region and quantifying their evolution during the last 40 years. To achieve these objectives, surface elevation changes and geodetic mass balance of the 12 current Dolomites mountain glaciers were calculated from the 1980s to 2023, with almost one measurement per decade. Available temperature, precipitation and snow accumulation data from the regional network of weather stations is used to contextualize the results.

## 2 Previous glaciological research in the Dolomites

The first study to mention the Dolomites glaciers dates to 1888 (Richter). In his volume, the Austrian glaciologist described the then-known glaciers in the eastern alpine region, including two of the largest ice bodies of the Dolomites: *Marmolada* and *Travignolo* Glaciers. However, the first work introducing topographical maps and quantitative information was compiled by *Olinto Marinelli* (1910). Thereafter, the available information about the glaciers of the Dolomites mostly comes from works that have dealt generally with glaciers in the Italian Alps (e.g., Porro, 1925; CGI-CNR, 1962; Smiraglia et al., 2015).

Data presented in wider Italian Alps or pan-alpine products is not always accurate for the Dolomites. In the past, only sporadic attention, from a glaciologic point of view, has been paid to specific massifs (Castiglioni, 1925, 1930; Nangeroni, 1938; Del Longo et al., 2001; Cibien et al., 2007). Some more information is available from institutional reports edited for administrative regions, but considering the incompleteness of these dispatches, they are not discussed here. According to the national Italian inventory (CGI-CNR, 1962), in the late 1950's, the Dolomites were hosting 33 glaciers, with a total surface of 8.19 $km^2$.

The last partial survey of the Dolomites glaciers area was carried out by the Regional Environmental Protection Agency of the Veneto region (ARPAV), which analysed the surface variations for 27 main glacial bodies of the Dolomites (Crepaz et al., 2013), representing the 72% of the total glacierised area in the region. Results show an area loss of approximately 50% from 1910 to 2009. The most recent inventory available for Italian glaciers (Smiraglia et al., 2015) reports that 51 glacial bodies were present in the Dolomites in 2009, spanning a total area of 5.04 $km^2$ and making up 1.4% of the total Italian glacierised area. Among the 51 glacial bodies, 13 are classified as mountain glaciers while 38 are considered snow or ice patches. When we use the term ice patch, we refer to the description of ice patch of glacial origin proposed in Serrano et al. (2011).

The only glacier of the Dolomites that has been extensively studied in the past years is the largest in the area, the *Marmolada Principale* Glacier. It was surveyed with ground-penetrating radar in 2004 and 2014, revealing a 30% reduction in thickness, hinting at an imminent fragmentation and a likely complete disappearance before 2050 (Santin et al., 2019). The transition between glacial and periglacial landforms in the area is discussed in Seppi et al. (2014), while studies focused on rock glaciers (Krainer et al., 2010, 2012) and debris covered glaciers (Securo et al., 2024a) have also been done recently. Despite their limited size, the glaciers and glacial bodies in the Dolomites are also investigated in relation to geohazards. This is first-handedly confirmed by the deadly Marmolada ice and rock avalanche occurred on 3 July 2022 (Olivieri and Bettanini, 2023; Bondesan and Francese, 2023), but also by debris flow events on *Monte Pelmo*, closely related to the *Val D'Arcia* glacial body (Del Longo et al., 2001; Chiarle et al., 2007) and by the instability of moraines from the little ice age (Zanoner et al., 2017).

As this work specifically focuses on the remaining mountain glaciers of the Dolomites area, attention is given to the following ranges (Fig. 1): *Popera, Cristallo, Sorapiss, Antelao, Marmolada* and *Pale di San Martino*. Other Dolomites massifs still host minor ice deposits, but being now devoided of any dynamics (Smiraglia et al., 2015), they are not considered in this work. *Fradusta* and *Marmolada* Glaciers, which recently experienced fragmentation, will still be treated as single glaciers (Table. S1).

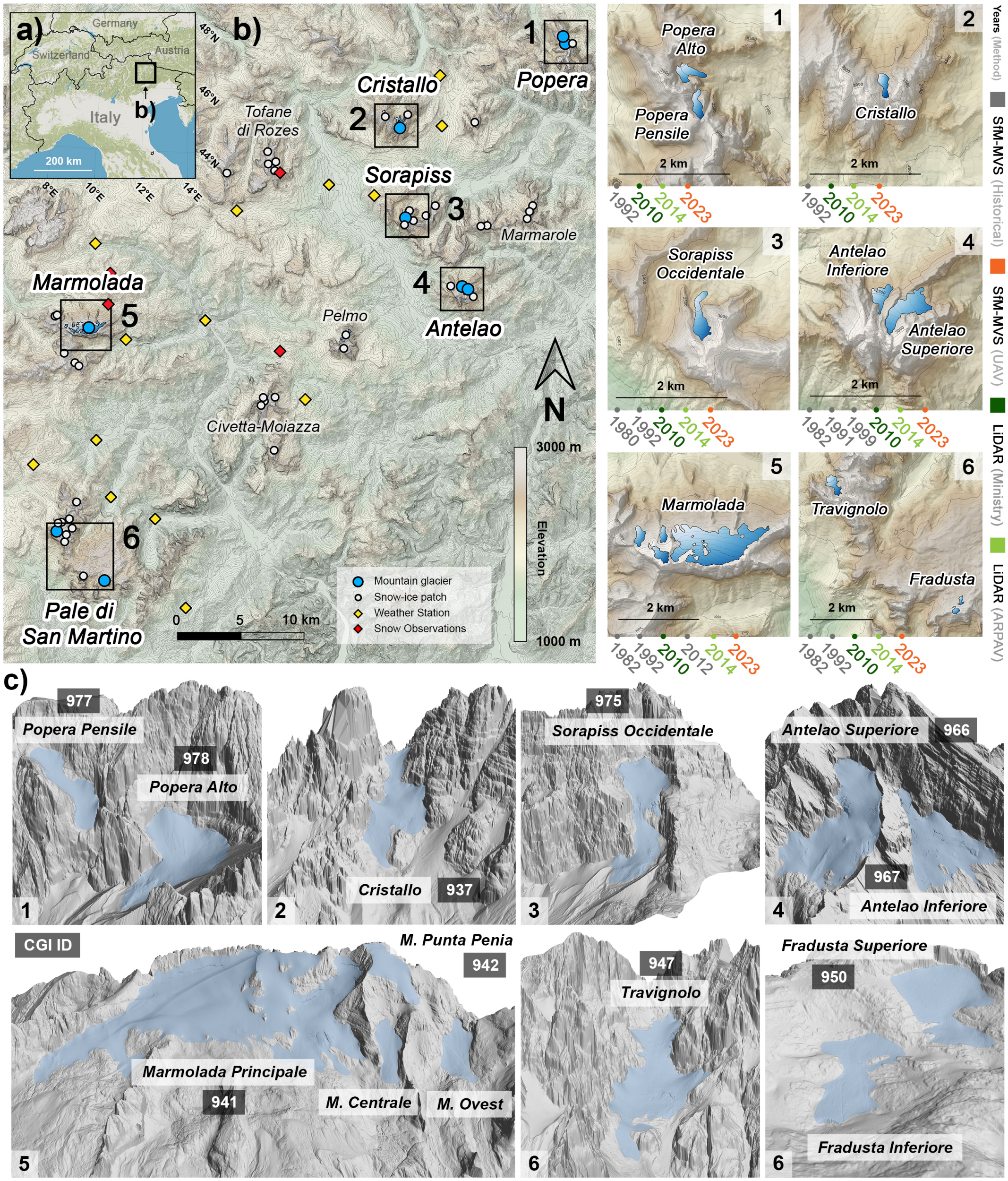


**Figure 1.** The Dolomites in the European Alps (*©Map Tiler - © OpenStreetMap contributors 2023. Distributed under the Open Data Commons Open Database License (ODbL) v1.0.*) (a). Location of the 6 mountain areas hosting active glaciers in the region, location of snow ice patches (white dots), mountain glaciers (light-blue dots) (Smiraglia et al., 2015), Automatic Weather Stations (AWS) (yellow) and snow depth observations stations (red) (b). 3D views of the Dolomites glaciers derived from 2014 LiDAR data and IDs of the glaciers from the Italian Glacier Inventory (Smiraglia et al., 2015) (c). A few AWS used in this study are located outside of map b.

## 3 Data and methods

In this study aerial photographs spanning three decades (1980-2012), airborne LiDAR (2010-2014), UAV and aerial surveys (2023) were used to produce dense point clouds of the Dolomites glaciers and assess their change through time. Data acquisition and pre-processing, point clouds generation, point clouds alignment and error assessment and weather stations data processing are described in four separate sections (Fig. S1). When decades such as 1980s, 1990s and 2000s are mentioned in the text, we are always referring to multiple years of available data (Fig. 1).

### 3.1 Acquisition and pre-processing

All imagery used was pre-processed using Adobe Photoshop (v. 2023) to improve the exposure of heavily shadowed areas. The archive photos span from the 1980s to 2012 (Table S2, Fig. S2). Digital photos from 2010 and 2012 have an optimal quality for SfM processing, but lack metadata. Older analogue aerial imagery was scanned with a non-photogrammetric scanner and therefore lacks distortion and internal orientation info that should be used for camera calibration.

Airborne LiDAR surveys were performed in 2010 and 2014 using an Optech ALTM 3100 instrument mounted on a helicopter. The produced dense point clouds included areas outside of the glaciers. The Ground Control Points (GCPs) used during georeferencing of all aerial photos were retrieved manually from 2010 LiDAR point clouds using the point list picking tool, in the open-source software CloudCompare (v.2.12). Prior to GPCs point retrieval, the PCV (*Portion de Ciel Visible*) plug-in, a generalization of Tarini et al. (2003) algorithms, was used to improve 3D visualization. Preference was given in picking points that were steady and well recognisable over time also in older photos, such as big boulders and bedrock features. The number of GCPs per area varied between 6 and 30 depending on glacier size and image quality. 2023 UAV and aerial surveys lacked of GCPs collected on site and therefore needed the same use of LiDAR-derived points to improve accuracy and precision.

### 3.2 Structure from Motion workflow and area mapping

This work used Structure from Motion (SfM) to retrieve the former glacier surface as dense point clouds, which were later compared with 2010 LiDAR data, taken as most reliable reference. The SfM workflow was entirely performed using the software Agisoft Metashape (v. 2.0.4) and is similar to part of Knuth et al. (2023) processing of photos that have no camera calibration info nor fiducial marks available. The archive images were adjusted and standardised by manually picking pseudo-fiducial markers (i.e., consistent point in the photo frames notches) from each photo frame and performing the calibration in Agisoft Metashape. The subsequent photo alignment was done using 200,000 tie points and 20,000 key points with the maximum quality, generating for each scene a sparse point cloud. GCPs were manually placed and adjusted in all the photos.

GCPs known coordinates input allowed the adjustment of sparse point cloud position, scale, camera positions and the subsequent dense point cloud generation. A few scenes required also the computation of a triangular mesh generated by linear interpolation of points to close data voids in the dense point clouds. The same mesh with additional texture can be used for visual interpretation of results (Fig. 2). Digital Elevation Models (DEMs) and orthophotos were also generated for each survey to enable the manual mapping of glacier areas during all reconstructed time-steps, done in QGIS (v. 3.28). We used the surface

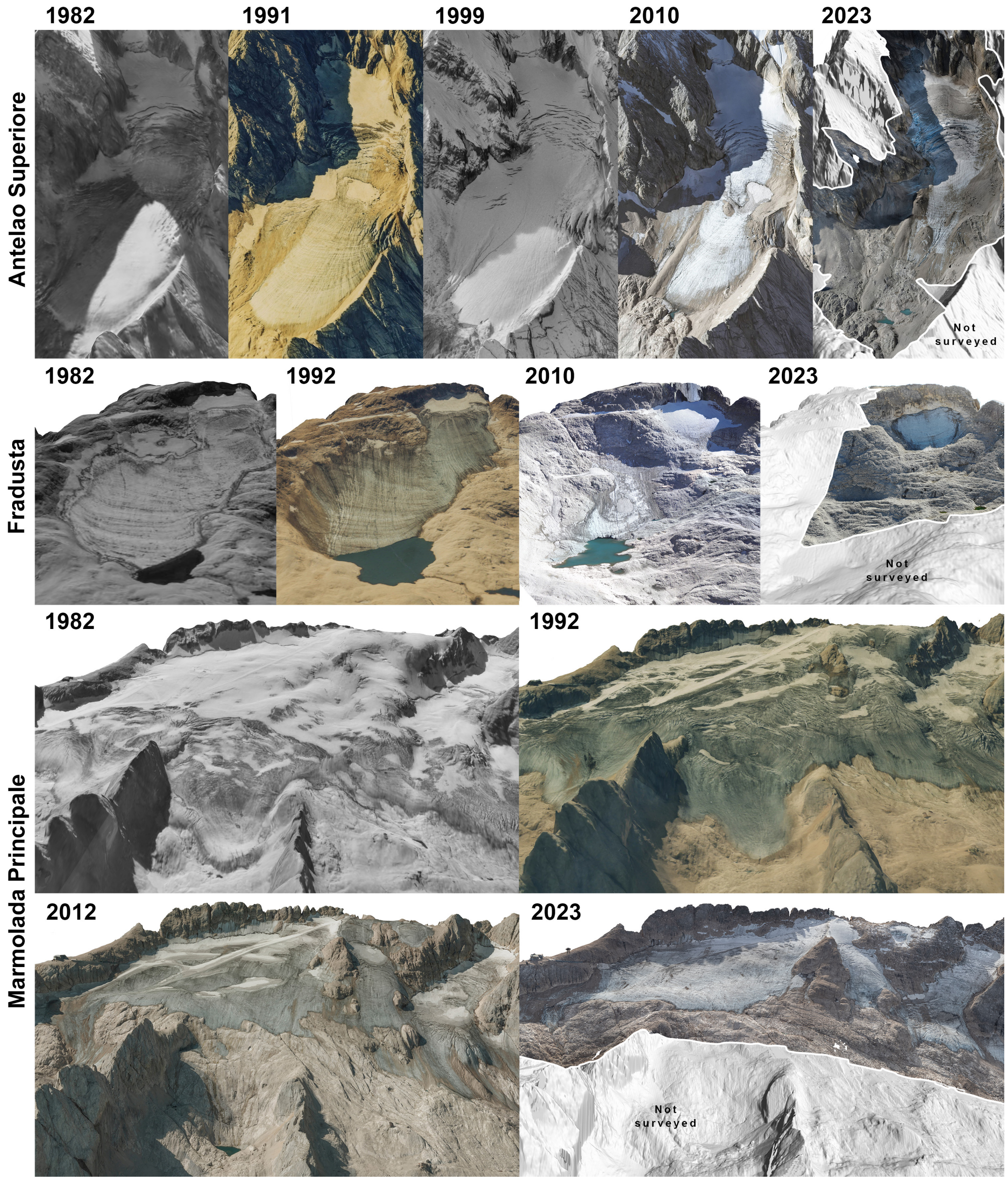


**Figure 2.** Examples of the reconstructed 3D textured meshes of *Antelao Superiore, Fradusta and Marmolada Principale g*laciers during different decades. Reconstructions of *Popera, Sorapiss Occidentale, Cristallo, Antelao Inferiore, and Travignolo* Glaciers are shown in supplementary materials (Fig. S3).

lowering observed during the multi-temporal comparisons combined with direct observations on site to assess the glaciers end when the presence of debris cover prevented the delineation of glaciers perimeter using mapping alone. The report of SfM output is available in the supplementary material (Table S3).

### 3.3 Point cloud comparison and error assessment

SfM and LiDAR dense point clouds were used to detect and quantify surface elevation change. The entire processing was conducted in CloudCompare (v.2.12). 2010 LiDAR point clouds are the most reliable product available in this study were used to refine alignment through manual point picking, adjusting the misaligned 1980s, 1990s and 2000s point clouds. Once aligned, point clouds from different years were compared to 2010 LiDAR using the Multi Scale Model to Model Cloud Comparison (M3C2, Lague et al., 2013) algorithm. M3C2 is a robust solution to assess the differences between point clouds without the need of surface meshing or DEM generation. M3C2 workflow efficiently manages complex terrain features like flat and vertical surfaces within a single scene and was already used in similar applications (e.g., Midgley and Tonkin, 2017; Mishra et al., 2022). In certain reconstructions of the older scenes (1980s), the point cloud output of solely SfM contained small void areas in correspondence with the underexposed sectors or because of snow. In those cases we used the Metashape-produced 3D triangular meshes, that were sampled and processed in CloudCompare as the other point clouds thereafter.

The M3C2 output that holds the computed differences was rasterised and imported in QGIS (v. 3.28). Here, we used the mapped polygons of the glaciers during all available time-steps, to compute zonal statistics. The statistics were computed on two different polygons for each site: common area (i.e., glacier area in common during the two time-steps of each comparison) and total area (i.e., largest glacier area between the two time-steps of each comparison). A density conversion factor of 850 kg m$^{-3}$ (Huss, 2013) was used to convert surface elevation change values of common area to geodetic mass balance. Every comparison included 2010 LiDAR data as reference and was never been done using two historical SfM point clouds at a time, to reduce sources of uncertainties.

The error in surface elevation change varies for each comparison and comes from different sources: (i) LiDAR vertical accuracy ($\delta_{\mathrm{L}}$), (ii) alignment error between the point clouds on stable terrain ($\delta_{\mathrm{AL}}$) and (iii) error of measurements (i.e., distance uncertainty, $\delta_{\mathrm{M3C2}}$). $\delta_{\mathrm{L}}$ was quantified by the LiDAR surveyors that compared the dataset vertical accuracy with known points measured with differential GPS, and was $\pm 0.12$ m. $\delta_{\mathrm{AL}}$ was measured for each individual comparison using M3C2 in the frontal and lateral areas outside of the glaciers that share an average slope value to the latter. Slope similarity between glaciers and stable terrain was calculated in CloudCompare using the geometric feature verticality (Harshit et al., 2022), computed on a cylinder with a search radius of 5 m for all point clouds. Areas of the point clouds above and below the mean glacier verticality $\pm 2\ \sigma$ (95% confidence interval) and inside the glaciers area have been filtered out before using M3C2 again, this time for $\delta_{\mathrm{AL}}$ calculation. $\delta_{\mathrm{M3C2}}$ was available as a direct output of the previous processing (i.e., distance uncertainty) and its mean value per glacier was retrieved using zonal statistics. $\delta_{\mathrm{L}}$, $\delta_{\mathrm{AL}}$ and $\delta_{\mathrm{M3C2}}$ were summed in quadrature to estimate the overall uncertainty of surface elevation change, $\delta_{\mathrm{S}}$. The contribution of uncertainties in area were not considered during this phase.

The error of geodetic mass balance ($\delta_{\mathrm{MB}}$) estimations included an additional uncertainty interval in density conversion ($\delta_{\rho}$) of $\pm 60$ kg m$^{-3}$ (Huss, 2013). This was added to the $\delta_{\mathrm{S}}$ using the product error propagation formula (1) (Taylor, 1997):

$$\delta_{MB} = |S\rho|\sqrt{\left(\frac{\delta_S}{S}\right)^2 + \left(\frac{\delta_\rho}{\rho}\right)^2} \quad (1)$$

Considering our dataset, the reconstruction of older glaciers surface using scanned imagery was limited in accuracy because of: (i) a lack of photogrammetric quality scans of the negatives; (ii) the presence of heavily shaded zones or clean snow; (iii) the reduced availability of suitable spots for GCPs picking in some scenes. These sources of errors are harder to quantify and reduced the number of historical photos suitable for such application. Further sources of uncertainty may be related to the temporal coverage of aerial photography that was not uniform over all glacial bodies and years (Table S2).

### 3.4 Weather station network

Precipitation and temperature time series from twenty automatic weather stations (AWSs) of the ARPAV network were integrated with the datasets from two AWSs managed by the autonomous province of *Bolzano*, which altogether guarantee an adequate spatial coverage of the study area (Fig. 1). The selection of the AWSs was based both on their spatial distribution and proximity to the six mountain areas hosting Dolomites glaciers, as well as on the availability of continuous time series of temperature and precipitation starting at least 20 years before 2022. A linear interpolation was employed to fill temperature gaps of 3 days or fewer, while no reconstruction was performed on precipitation data. Additionally, years with missing data exceeding 5% of the accumulation (November to April) or ablation (June to August) season were excluded from the analysis. This was implemented at the level of individual AWSs, ensuring the availability of data for each year after averaging across all stations. All the time series begin between 1985 and 2001 and end between 2020 and 2022, with 77% of them spanning over more than 30 years, and 9% spanning less than 26 years. Due to fewer AWSs deployed in the 1980s and as a consequence of data cleaning, only 36 to 64% of the stations present temperature (23-64% for precipitation) data from 1985 to 1991. However, from 1992 onwards, the data coverage increases drastically.

For each station the standardised anomaly index (SAI) (Katz and Glantz, 1986) was calculated, defined as (2):

$$SAI = \frac{x_a - x_m}{\sigma} \quad (2)$$

where $x_a$ is either the total precipitation during the accumulation season (for the precipitation SAI, Pr SAI), or the mean temperature during the ablation season (for the temperature SAI, T SAI). $x_m$ and $\sigma$ are the mean and standard deviation of temperature and precipitation over the reference period 1991-2020. The accumulation and ablation seasons were defined according to local climatology. Finally, SAI values were averaged across all weather stations, resulting in unique Pr and T SAI time series representing the entire region. The pre-processing applied to AWS data may result in an underestimation of total precipitation and therefore of the Pr SAI. Conversely, with regards to temperatures, we expect that the reconstructed data do not significantly alter the mean, as they are prone to distribute randomly both above and below the average.

Daily snow depth measurements from four stations managed by ARPAV provided snowfall information between the 1980s-1990s and 2023, occurring above 1900 m a.s.l (Fig. 1). These measurements were obtained from both automatic and manual snow monitoring stations. The automatic stations deploy an ultrasound sensor and record a value every 30 minutes, while the manual measurements are taken once per day at 8:00 A.M. The *Fedaia* station has the longest time series, starting in 1980, while *Ra Vales*, *Monti Alti di Ornella*, and *Col dei Baldi* began recording data in 1993, 1986, and 1987, respectively. Using this data, we show the October to June snow depth on the ground for the most relevant years of our study (1982, 1992, 2010, 2014, 2023). Additionally, we calculated the October to June snow depth on the ground averaged over the five reference years for each station, as well as the total annual snow accumulation from 1980s to 2023.

## 4 Results

The dataset used in this study allowed to obtain the topographic surface and area changes of Dolomites glaciers from the 1980s to 2023, enabling the estimation of their geodetic mass balance. Out of the 9 glaciers analysed, *Sorapiss Occidentale* surface was reconstruced since 1980, *Antelao Superiore, Antelao Inferiore, Marmolada, Travignolo* and *Fradusta* since 1982, *Popera Alto, Popera Pensile* and *Cristallo* since 1992 (Fig. 2 and Fig. S3).

### 4.1 Area loss

The manually mapped areas of the Dolomites glaciers (Table S4) showed a retreat from 4.11 to 1.81 km$^2$ between the 1980s and 2023 (-56%). The loss during the last 13 years (2010-2023) was 0.88 km$^2$ (Fig. 3), corresponding to a relative reduction of 33%. The area losses presented here are referred only to the glaciers selected in this study and as such are an underestimation of the total area loss involving all the ice bodies in the Dolomites. In 1980s and 1990s the Dolomites glaciers were larger in number, with several of them that are now completely melted, turned into permanent ice patches without apparent ice dynamics or buried by debris.

Relative area loss (1980s-2023) showed a wide range of values, between 9% and 89%. Where surface debris cover was abundant like in *Popera Alto*, *Travignolo* and *Sorapiss*, we observed only minor area losses, especially during the last decade. The glaciers less surrounded by steep topography were the two affected by the largest area change from the 1980s: *Fradusta* (-89%) and *Marmolada* (-60%). The latter were also the only glaciers that underwent fragmentation, with the lower part of the *Fradusta* (*F. Inferiore*) being the only ice body completely extinct among our dataset. All area variations were almost completely related to glacier fronts except for *Marmolada*, where even the upper portions were affected by retreat.

*Marmolada* Glacier still remains the largest glacier of the Dolomites, contributing to 66% of total area losses from 1980s and currently representing 55% of the total glacier area of the Dolomites.

### 4.2 Surface elevation change and mass balance

The average surface elevation change per site was calculated for three periods: 1980s with -5.2 m, 1990s-2010s with -14.1 m and 2010s with -9.3 m. Due to the lack of data in 1999 and 2001 it was not possible to resolve the 1990s-2000s period at decadal frequency (Table S5).

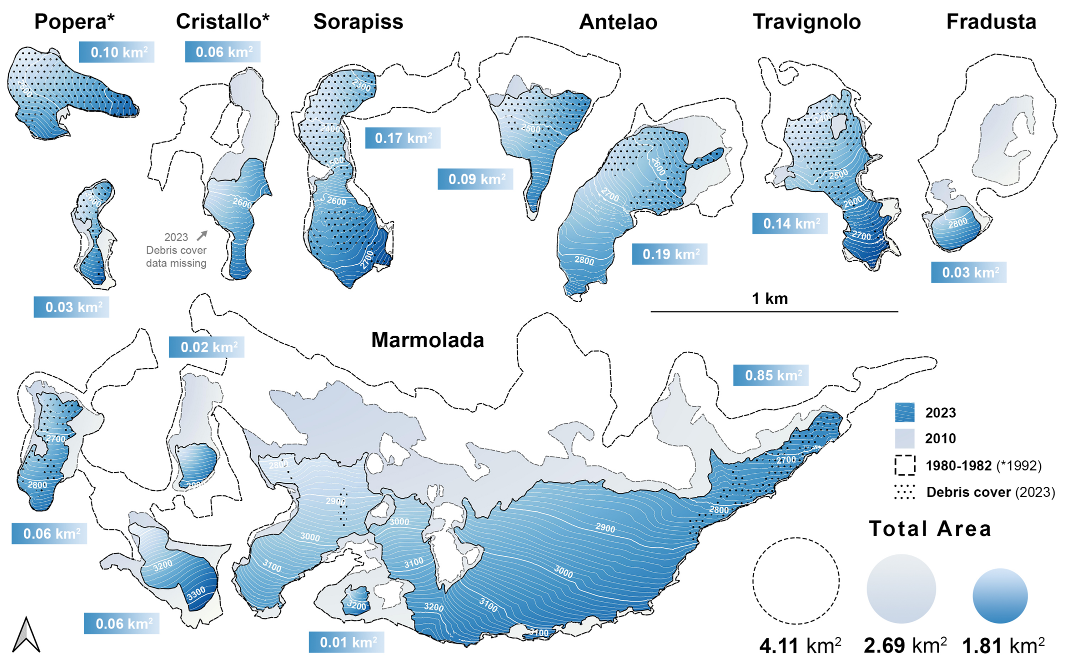


**Figure 3.** Areas of the Dolomites glaciers in 1980-1982 (dashed line), 2010 (grey) 2023 (blue) and debris cover in 2023 (dots). The oldest year available for *Popera* and *Cristallo* is 1992 (*). Cristallo 2023 debris cover data are not available due to the presence of snow of negligible thickness at the time of acquisition.

Between 1980s and 2010 the Dolomites glaciers experienced the greatest reduction in thickness in their frontal parts, except for *Popera Pensile* and *Sorapiss Occidentale*, which instead showed greater losses in their upper portions (Fig. 4). *Marmolada*, *Fradusta*, and *Antelao Superiore* Glaciers showed the highest cumulative thickness losses, exceeding 50 m at their former fronts.

The largest values of glacier surface elevation loss between 1980s and 2023 can be observed in *Fradusta* Glacier, with an average loss of 49.70 m. The smallest changes occurred in *Popera Pensile* and *Popera Alto glaciers*, with -17.0 and -19.9 m respectively (Table S5).

Surface elevation change calculations during the 2010-2023 interval were more accurate than for the 1980s-2010 interval, with an uncertainty $\delta_S$ ranging between 0.3-0.4 m, and allowed a uniform comparison of the glacier behaviour during the last decade. In this time interval the acquisition were consistent with dates close to the end of the ablation season, and all glaciers were surveyed (Fig. 5a). The average surface elevation changes between 2010 and 2014 are shown in Fig. S4, with 5 glaciers (*Popera Alto and Pensile, Sorapiss, Antelao Inferiore, Marmolada*) that recorded a surface elevation increase since 2010. During 2010-2023 *Marmolada Principale, Marmolada Ovest* and *Antelao Superiore* experienced the greater losses, exceeding 30 m. The highest absolute values, corresponding to almost -35 m, were reached in the area involved in the ice avalanche that happened in a detached part of *Marmolada Principale*, on 3rd July 2022 (Olivieri and Bettanini, 2023; Bondesan and Francese,

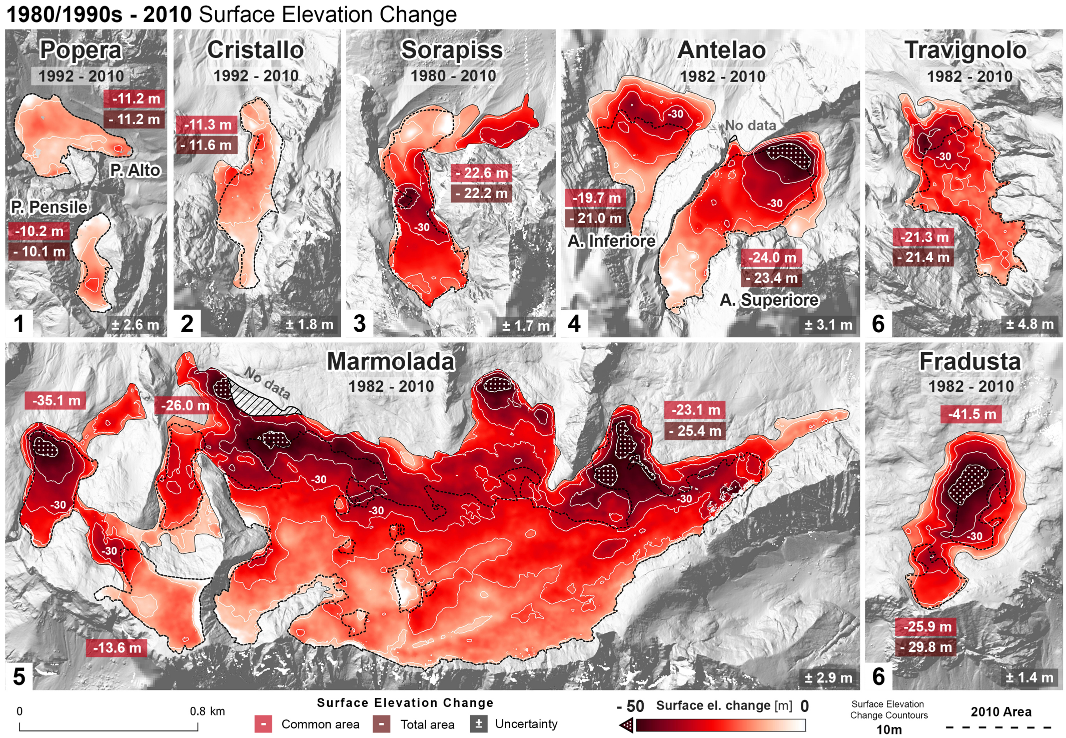


**Figure 4.** Surface elevation change (m) of the Dolomites glaciers from 1982 (1980 for *Sorapiss*; 1992 for *Popera* and *Cristallo*) to 2010. Average surface elevation change is reported for every glacier using common area (red) and total area (brown). Surface elevation change uncertainty ($\delta_S$) is reported for each comparison in grey.

2023). These are shown by the Kernel density plots of surface elevation loss (Fig. 5b, *Marmolada Collapse*). The *Fradusta Inferiore* Glacier was not included in the common area measurements as it had already disappeared before 2023 surveys took place.

During the last 13 years we observed the only thickness increases in the central part of the *Sorapiss Occidentale* Glacier, which is currently debris covered (Fig. 3). On that glacier a rise of more than 10 m was observed close to a wide serac whose presence is possibly related to a small surge induced by a recent rockfall (Fig. 5a) in the accumulation area as well as by internal glacier dynamics. Rockfall debris and boulders may also have contributed to the increase of surface elevation. A very small area of the *Marmolada Principale* Glacier retained a similar surface elevation to that of 2010. This is well visible in Fig. 5a, where it appears as an oblique line crossing the glacier from SW to NE. This feature is not natural, being related to the artificial redistribution of snow operated to maintain ski routes on the glacier.

The average annual geodetic mass balance rate for the Dolomites glaciers varied from -0.45 $\pm$ 0.08 m w.e. $yr^{-1}$ in the 1980s, to -0.65 $\pm$ 0.08 m w.e. $yr^{-1}$ between 1990s and 2010, and -0.63 $\pm$ 0.05 m w.e. $yr^{-1}$ in the last 13 years (Fig. 6, Table S6).

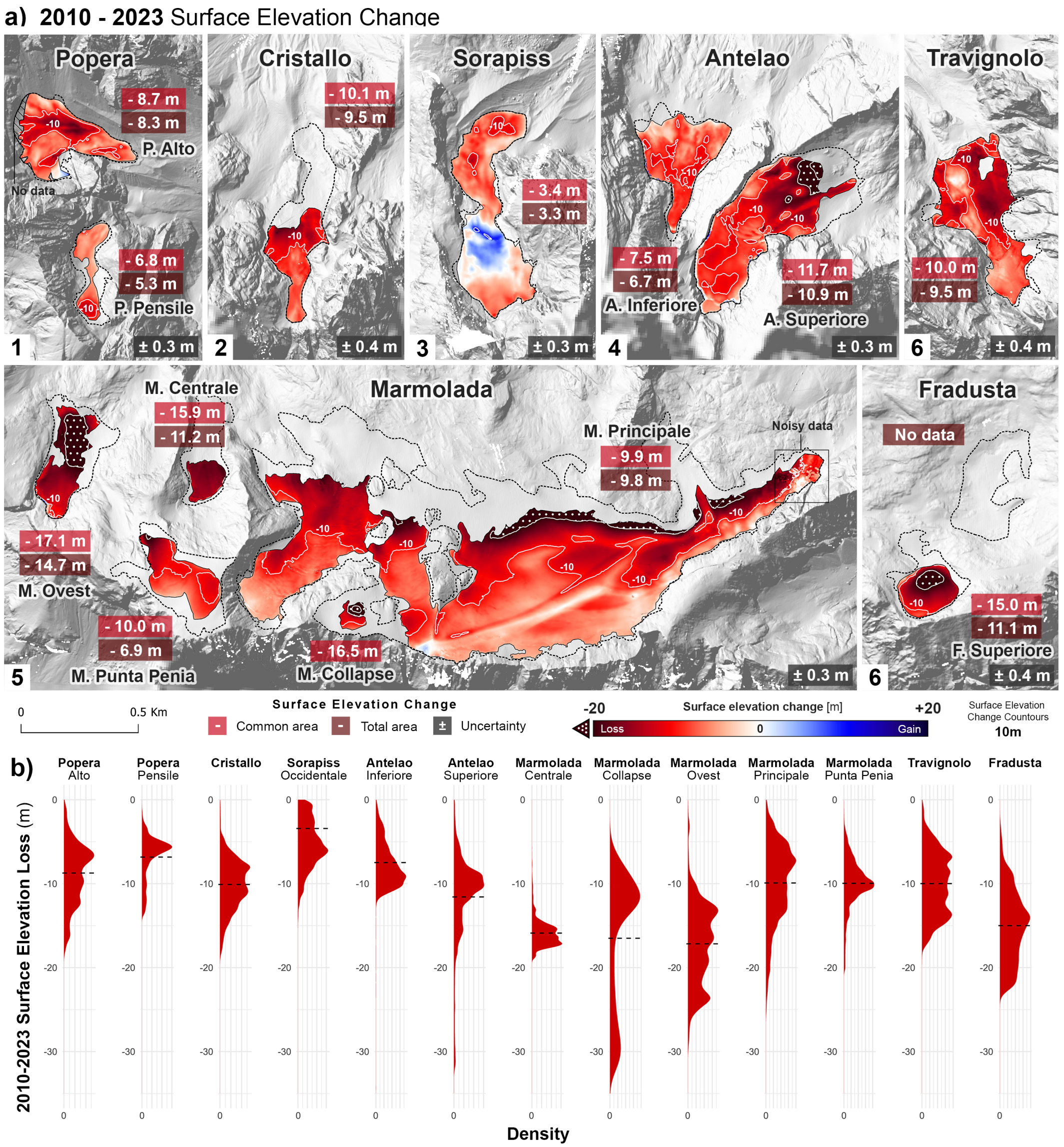


**Figure 5.** Surface elevation change (m) measured across the Dolomites glaciers from 2010 to 2023. Average surface elevation change is reported for every glacier using common area and total area (a). Surface Elevation Change uncertainty ($\delta_S$) is reported for each comparison in grey. Kernel density distribution plot for surface elevation loss with mean loss (black dotted line), with all former *Marmolada* Glacier section presented as divided plots (b).

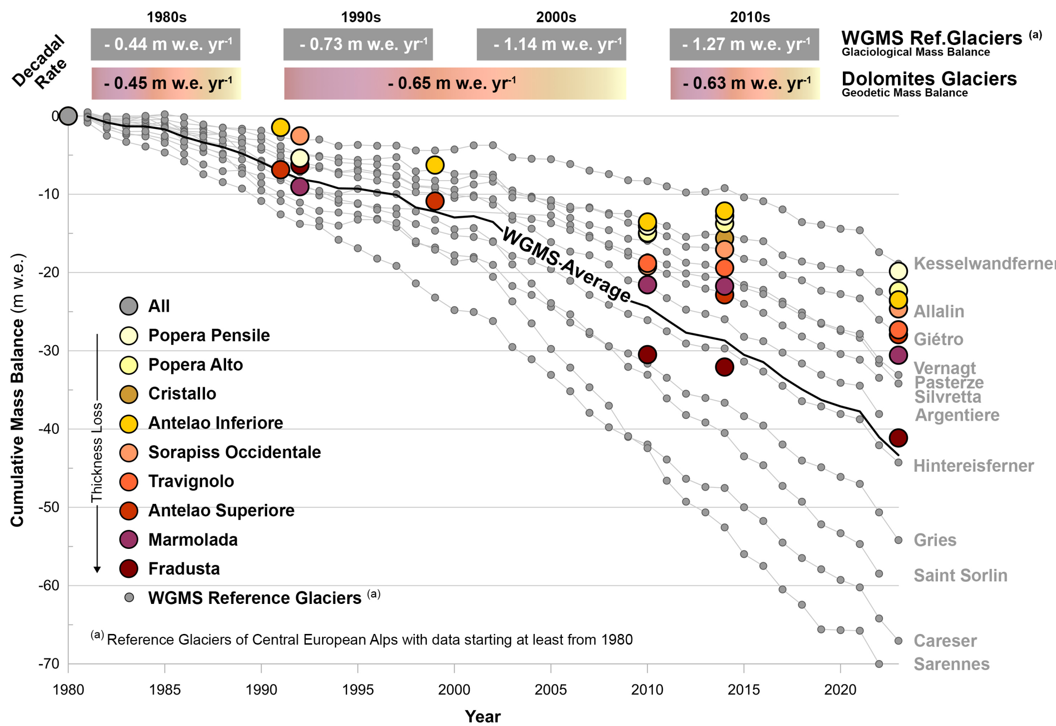


**Figure 6.** Mass balance (mb) rates of World Glacier Monitoring Service's (WGMS, 2021) Reference Glaciers (RGs) with *in-situ* data starting earliest in 1980 and the Dolomites glaciers. Among our mb, measurements starting from 1982 were corrected to 1980 using the average mb loss. Mb of Dolomites glaciers with measurements starting from the 1990s were calculated back to the 1980s using the average mb rate of all Dolomites glaciers during the 1980s (i.e., 0.45 m w.e. $yr^{-1}$). Three RGs lack 2023 data (i.e., *Argentiere, Saint Sorlin, Serennes*).

Total volume loss in the entire observation period was approximately 0.105 Gt, with 0.083 Gt lost between the 1980s and 2010, and 0.022 Gt lost during the 2010-2023 interval (Table S7). The *Marmolada* Glacier by itself counted for 65.7% of total volume losses. Other major contributors included *Antelao Superiore* and *Fradusta* Glaciers with 7.9% and 7.3%, respectively.

Our results show that the use of total area among each comparison in the geodetic mass balance leads to an underestimation of the m w.e. loss when compared to calculations based on common area. In our case the bias introduced by total area led to an underestimation between 1% and 31% of the common area geodetic mass balance, depending on the site and considered time step. There were some cases of decadal comparison (1980s-2010 in *Cristallo, Antelao Inferiore* and *Marmolada*) where total glacier area produced larger geodetic mass balance losses than calculations using common area.

### 4.3 Climate data

The general trend for temperature and precipitation SAI showed more frequent positive values towards the end of the 1985-2022 time frame (Fig. 7a), meaning above long-term average temperatures and precipitation. On the contrary, negative SAI means below the long-term average temperature or precipitation. The nine lowest T SAI values fell within the first 15 years

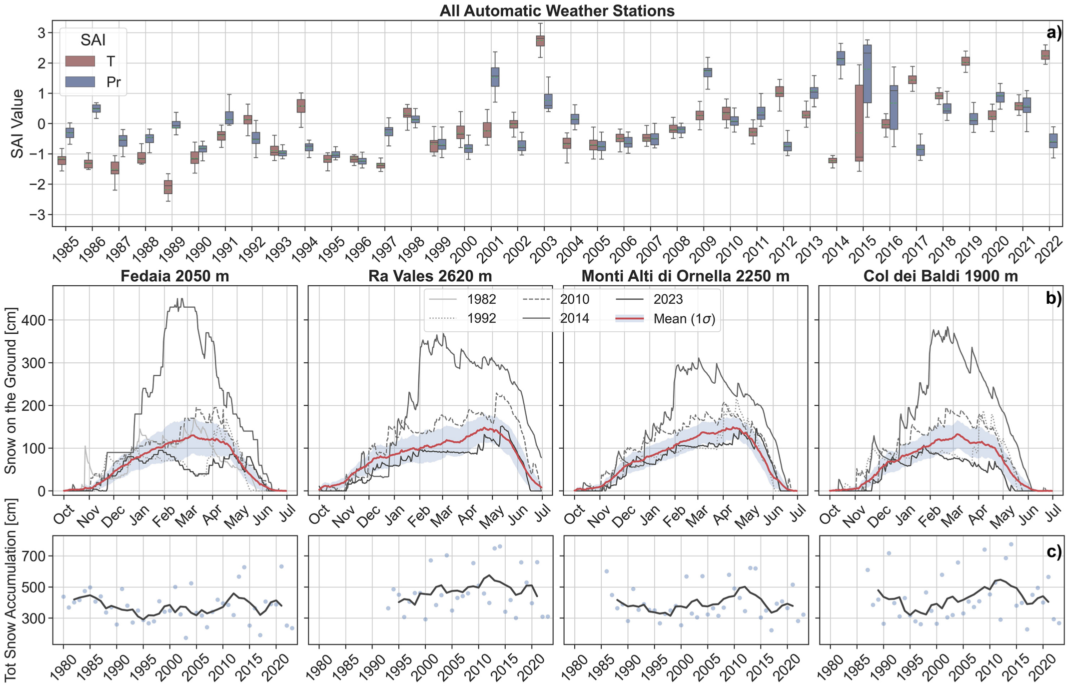


**Figure 7.** T SAI (red boxes) and Pr SAI (blue boxed) calculated between 1985 and 2022 and averaged over 22 AWS. The boxes show the quartiles (Q) of the dataset, with the central black line representing the median and green line the mean. The whiskers extend to Q1 – 1.5*(Q3-Q1) and Q3+ 1.5*(Q3-Q1), where Q1 and Q3 are the first and third quartiles (a). Snow depth on the ground between October and June for the most relevant years of the study and the 1980s/1990s – 2023 mean ± 1 $\sigma$ (red line and grey shade) for *Fedaia*, *Ra Vales*, *Monti Alti di Ornella*, and *Col dei Baldi* stations (b). Total annual snow accumulation and 5-year centered running mean (black line) for the same snow monitoring stations (c). The years shown in the plot refer to hydrological years, e.g. 2023 refers to 2022-23.

(1985-2000), with the only exception of 2014 (T SAI = -1.23). Among the ten highest events, seven were in the last 15 years (2007-2022). Exceptions were years 1994, 1998 and 2003, with the latter showing the highest T SAI with a value of 2.74. The minimum T SAI was recorded in 1989 with -2.18. Concerning the Pr SAI, the rising trend was less pronounced than for temperature, but still showed a clear increase. Indeed p-values were $1.1 \cdot 10^{-2}$ for Pr SAI and $1.9 \cdot 10^{-5}$ for T SAI. In this case, six of the ten lowest Pr SAI fell before 2000, and eight of the highest were recorded after 2008. Pr SAI was greatest in 2014 with a value > 2 and lowest in 1996 with -1.22. In the first half of the time series the T SAI tended to be lower than the Pr SAI, while in the second half, this trend progressively reversed. Furthermore, SAI values, particularly regarding temperature, were more positive towards the end of the time frame. Temperatures rose by 0.4-0.6 °C per decade since 1985, while precipitation showed an increase that lasted about 15 years from 1995, culminating in the extremely snowy year of 2014 (Fig. 7b). *Fedaia* station, the only one providing data since 1980, did not show any trend for the total snow accumulation (p-value = 0.61; Fig. 7c), however, increased extreme events could be observed in the last decade of its time frame. The snow monitoring stations did not show any trend for the total snow accumulation (p-values = 0.54-0.95; Fig. 7c), however, extreme events (above 95$^{th}$ percentile) were observed in 2013 and 2014 for all the stations.

Snow height on the ground showed a peak in March or April depending on the station altitude (Fig. 7b). Among the investigated years, 2023 and 1992 values lied below the mean for most of the accumulation season, getting close to or even overtaking the mean only in April (April and May for the highest stations of *Ra Vales* and *Monti Alti di Ornella*).

## 5 Discussion

### 5.1 Climate trends impacting the Dolomites cryosphere

There are numerous studies describing the characteristics of the recent climate regime change occurring in the Alps (Huss et al., 2017; Hock et al., 2019). The main parameters influencing the response of the alpine cryosphere are linked to the increase in summer temperatures and modifications in precipitation and snowfall patterns (Žebre et al., 2021). In the Eastern Alps mean summer temperature increased by about 2.0°C since 1979, leading to an increased ablation which results more effective also due to the extension of the ablation season (Colucci and Guglielmin, 2015; Colucci et al., 2021). Mean annual air temperature increased by 0.3 $\pm$ 0.2°C per decade. On the other hand, while the fraction of precipitation falling as rain has increased compared to that of snow in low and mid-altitude areas, this effect has not yet been observed in winter at high-altitude glacial basins. Additionally, there is generally an average increase in snowfall amounts during the winter season at high altitudes in the Alps from 1971 (Matiu et al., 2021). However, the increase in snow, particularly linked to extreme events (e.g., the winter of 2014), has not been able to counterbalance the increase in summer temperatures, resulting in consistently negative mass balances after 2001 (Hugonnet et al., 2021). Only in very limited areas where the highest mean annual precipitation is recorded, some small residual glacial bodies have slowed their reduction (Scotti et al., 2014; Colucci et al., 2021).

Using the SAI index, it is possible to observe how in the last two decades unfavourable conditions for glaciation prevailed. Only a few exceptions exist, notably 2014 which shows a winter precipitation anomaly with Pr SAI > 2. That year was very favourable for glaciation in all of the eastern Alps (Colucci et al., 2021), although the overall alpine mass balance remained negative (WGMS, 2021). On the contrary, the mass loss of the glaciers was particularly noteworthy in the hydrological year 2021/2022 (Voordendag et al., 2023). 2022 was by far the most extreme melting year among those analysed, with an extremely effective ablation season (T SAI = 2.24) and a dry accumulation season (Pr SAI = -1.58). Within alpine mass balance records, the ablation season of 2022 results were unprecedented.

Overall, in the Dolomites we can observe an extremization of the ablation period with higher mean and extreme temperatures associated with a slight increase in snowfall on glacial basins, which is however insufficient to counterbalance the temperature increase. According to such climatic evolution, the Dolomites are rapidly turning from being mountains hosting sites favourable to local glaciation, to areas where peri-glacial processes will progressively gain importance.

## 5.2 The Dolomites glaciers within the European Alps

The European Alps are home to 12 Reference Glaciers (RGs) with available glaciological mass balance data from before 1980 (WGMS, 2021). These can be used as benchmarks for our results, considering that the study area lacks any long-term mass balance monitoring program. All the Dolomites glaciers exhibit a geodetic mass balance within the range of the RGs, with values at the upper end, similar to the RGs that have lost less m w.e. during the last four decades (Fig. 6). The *Fradusta* Glacier is the only site that presents a cumulative mass balance close to the 1980-2023 RG average. Glaciers with debris cover (*Popera Alto* and *Pensile, Sorapiss Occidentale*) or topographically shadowed (*Cristallo, Antelao Inferiore*) display mass balances that are comparable to those of other RGs (e.g. *Kesselwandferner, Allalingletscher, Giétro Glacier*), although these are larger and lie at higher altitudes. In terms of decadal mass balance rates, the Dolomites match the behaviour of RGs during the 1980s (-0.45 m w.e. $yr^{-1}$ ), while are always lower than the average rates during the following decades. Dolomites glaciers mass balance rates are half of the average RGs rate during the last 13 years, with -0.63 m w.e. $yr^{-1}$ against -1.27 m w.e. $yr^{-1}$. If we consider all 17 RGs available in Central Europe from 2010 to 2023 the average mass balance rate equals to -1.44 m w.e. $yr^{-1}$ (WGMS, 2021).

The apparent resistance of the Dolomites glaciers to climate change is due to several factors: (i) the orographic protection offered by the complex topography of these mountains; (ii) the importance of avalanches in the dynamics of these glaciers; (iii) the abundant debris cover that affects the remaining glacial volumes. All these factors contribute to dampening the effects of climate change, as observed in similar contexts in the Alps. Glaciers behaving similarly are for example found in the easternmost sector of the Alps (Julian Alps), or in the Orobic Alps (Southern-Central Alps), where topography feedback and conditions similar to the ones characterizing the Dolomites glaciers are found. *Montasio Occidentale* glacier and *Canin East* ice patches, in the Julian Alps, share less negative mass balance rates, with -0.09 m w.e. $yr^{-1}$ (2006-2019; De Marco et al., 2020) and -0.10 m w.e. $yr^{-1}$ (2010-2023; Colucci et al., 2021). *Lupo* Glacier, the only glacier in the Orobic Alps which is routinely monitored by *Servizio Glaciologico Lombardo* (SGL), instead exhibits a mass balance rate of -1.08 m w.e. $yr^{-1}$ (2010-2023), although heavily negatively influenced by 2022 and 2023 seasons (Hagg et al., 2017).

Cumulative geodetic mass balance measurements derived from single years during different decades, as used in this study, can be impacted by seasonal variability influencing the surveys. The presence of residual snow on glacier surface and firn, can alter the measurements introducing a bias. This bias is already partially included in the ±60 kg $m^{-3}$ used as density conversion factor uncertainty ($\delta_\rho$). From our observations, this might have influenced data in 1980s, ensuing geodetic results with a negative bias in the mass balance, albeit within the methodology error. 1991-1992 glacier conditions at the time of the survey instead appear optimal. The same issues that affected the 1980s surveys may have influenced the 2010 surveys too, although with less intensity. Data from 2014 cannot be considered useful for assessing the state of glaciers, as thick residual snow was present on almost all the considered sites. Surveys from 2023 were carried out during the best possible time window and present no bias.

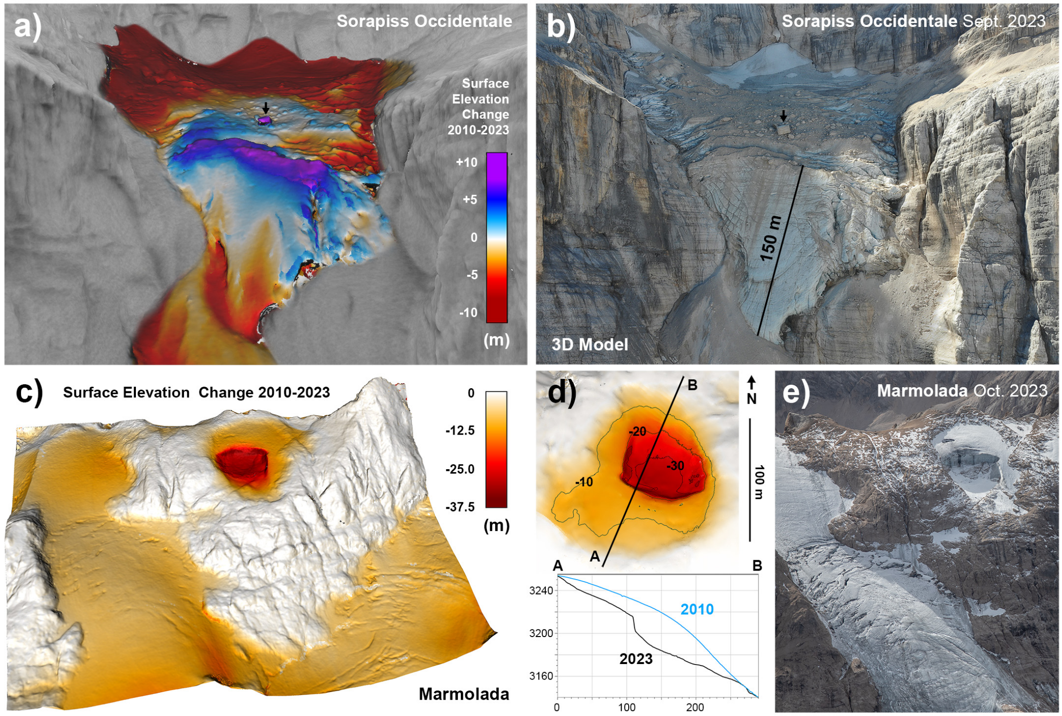


**Figure 8.** *Sorapiss Occidentale* surface elevation change (a) and 3D model (b). The black arrow is used as a reference between subplot a and b. Surface elevation change of *Marmolada* Glacier (c); zoom on the area interested by the ice avalanche happened on July 3rd, 2022 with vertical profile in 2010 and 2023 (d), and an aerial photo of the release zone (e).

## 5.3 Local glaciological variability within the Dolomites

The glaciers of the Dolomites are all classified as very small glaciers (< 0.5 km$^2$), except for *Marmolada Principale*. Their short-term mass balance is influenced by local topography and avalanche accumulation, rather than by climate conditions alone.

An example of the influence of local topography on glacier evolution is *Sorapiss Occidentale*, where a steep rock wall separates the upper cirque from the lower portion of the glacier. The upper portion, where the highest thickness losses are observed, was completely debris free until a recent rockfall, which occurred after 2010 (Fig. 8a). The lower part of the glacier, where a thick layer of debris is present, extends almost up to the frontal moraine. The overload caused by the recent rockfall appears to have produced a small surge in its central crevassed portion, as proven by the advanced position of the crevasses between 2010 and 2023 surveys. The increases in the surface elevation are related to the volume of the rock and debris fallen but cannot explain the relative elevation gain values larger than 10 m by itself (Fig. 8a). Similar processes, involving actual surges and not only partial advances, have been observed for other alpine glaciers before on rare occasions (e.g., Deline, 2001).

The *Marmolada* Glacier, in its main sector, *Marmolada Principale*, is by far the largest of the area. Thickness losses here appear to be inversely proportional to its elevation during all four decades of our study, although the maximum losses measured in the recent period (2010-2023) are linked to the ice avalanche detached from one of its highest portions (Fig. 8b). The former *Marmolada* glacier is now divided into 6 different parts, each with varying degrees of thickness loss (Fig. 5b). The presence of cold ice has been detected in some of them (Forte et al., 2020). It should be noted that the thickness losses of *Marmolada Principale* may have been reduced by anthropic activities related to the ski slope maintenance and the use of geotextile sheets, as reported during some ablation seasons (e.g., Baroni et al., 2015).

Mapping the exact extent of fully debris cover glacier portions like *Popera Alto* and *Sorapiss Occidentale* is not straightforward, especially concerning the precise location of the glacier's end. Dead ice patches in front of the actual glacier are not always easy to distinguish from the main glacial body if additional data (e.g., ground penetrating radar) are not available (Santin et al., 2023) (e.g., Fig. 9a, c). Another challenging issue regards evaluating the dynamic behaviour of these debris-covered fronts.

Some of the Dolomites glaciers, such as *Fradusta Superiore*, *Popera Pensile*, and *Antelao Inferiore*, are now at the border between the classification of mountain glaciers and ice patches. Despite this, they can still be classified as glaciers due to the evidence of recent dynamics and internal deformation through the presence of open crevasses. For example, *Antelao Inferiore* still presents visible crevasses and *Popera Pensile* and *Fradusta Superiore* show the presence of a *bergschrund* and annual layering (Fig. 9a, b). The outcropping ice/firn surface is often characterised by irregularly spaced convex bands of ice rich in fine sediment. These features are consistent with variations in ice/firn velocity across the glacier, with the fastest flow being observed away from the ice margins (Hughes, 2007; Colucci and Guglielmin, 2015), suggesting the presence of ice movement.

Projecting our mass balance trends into the future is not straightforward due to the high range of morphological differences of each ice body considered here. Processes like debris cover increase or glacier segmentation may contribute to different responses to ongoing warming, making these glaciers more resilient. The shrinkage and rapid disappearance of glaciers in the Dolomites may find a counterpart behaviour exhibited since the Little Ice Age in glaciers of the Julian Alps (e.g.,*Canin* Glacier and *Triglav* Glacier, Colucci, 2016; Colucci and Žebre, 2016) or in other minor glacial bodies in *Prokletije* (Albania), *Durmitor* (Montenegro) and *Pirin* (Bulgaria) mountain ranges (Hughes, 2010; Gachev et al., 2016; Hughes and Woodward, 2016; Hughes, 2018). A similar evolution awaits all glaciers sharing low elevation and small size in the European Alps (Cook et al., 2023).

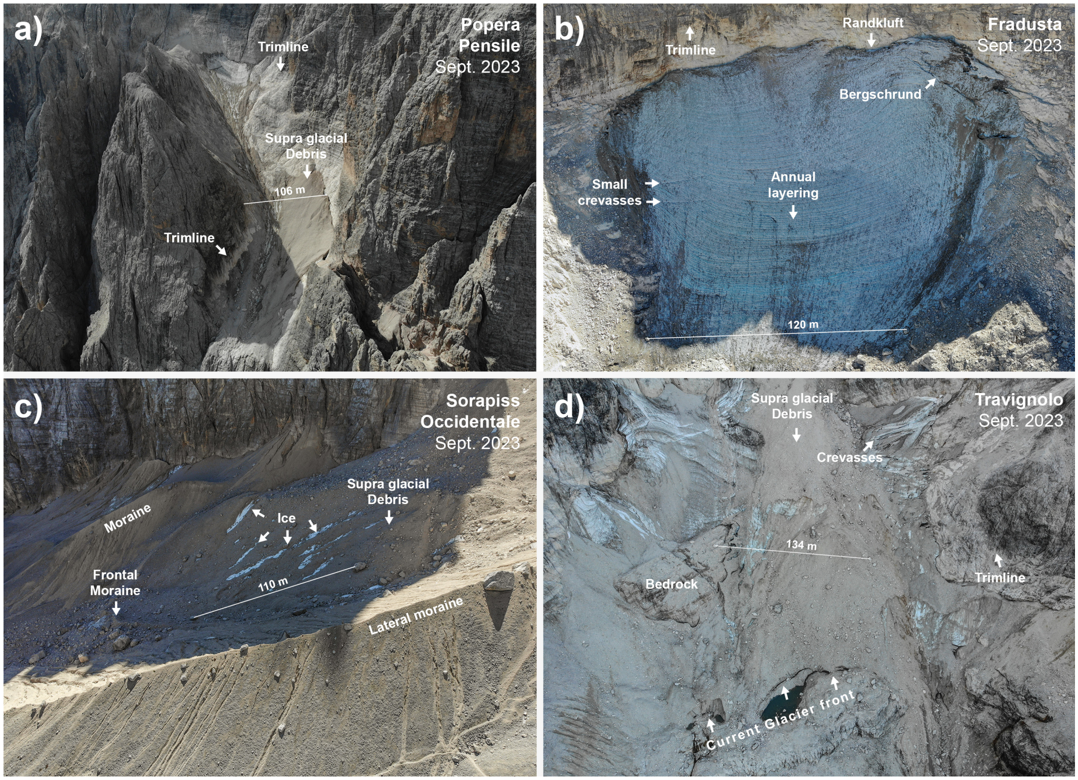


**Figure 9.** Photos of different settings of the Dolomites glaciers and their relationship with local topography: (a) *Popera Pensile*, (b) *Fradusta Superiore* (merge of multiple photos), (c) frontal part of *Sorapiss Occidentale*, (d) *Travignolo* Glacier front.

## 6 Conclusions

We quantified the last 40 years of ice melting in the remaining Dolomites glaciers, highlighting how local topography can act as positive feedback in slowing mass loss compared to the larger reference glaciers of the European Alps. The existing glaciers in the region lost 56% of their area and $0.64 \pm 0.06$ m w.e. yr$^{-1}$ from the early 1980s to 2023. The cumulative estimated volume loss is 0.105 Gt, of which 0.022 Gt in the last 13 years (2010-2023). In the late 1950's the Dolomites were hosting 33 glaciers, of which only 9 are still considered mountain glaciers today (Smiraglia et al., 2015).

All the glaciers in the Dolomites currently have their accumulation areas below the envELA and are projected to disappear or segment into minor glacial bodies in a few decades. Their fate appears inevitable even if a 1991-2020 steady-state climate is assumed. Only locally, favorable feedback may be brought by the debris coverage. A few glacial bodies may eventually shift from glacial to periglacial, thus becoming more resilient in a warming climate.

Although this work adds new quantitative information that fills part of the existing gap, we strongly encourage more specific monitoring for some if not all these sites at least on an annual basis. This is of even greater importance in the context of the present climate trend, which is leading to a rapid degradation of the Dolomites glacial bodies. As evidenced by e.g. the ice avalanche of *Marmolada* Glacier in July 2022, the final stages of the disappearance of these glaciers may result in parossistic events, which in turn pose risks in an extremely popular tourist area.

*Data availability.* Archivial imagery are accessible online (https://idt2.regione.veneto.it/portfolio/aereofototeca/). LiDAR and AWSs data can be requested to ARPAV (https://www.arpa.veneto.it). 2023 surveys will be made available on request. Processed data will be made accessible in Zenodo (Securo et al., 2024b).

*Author contributions.* Conceptualization: AS, RRC. Investigation: AS. Methodology: AS, CDG, RRC. Supervision: RRC. Visualization: AS, CDG. Writing – original draft preparation: AS, CDG, RRC, GB. Writing – review and editing: all authors.

*Competing interests.* The contact author has declared that none of the authors has any competing interests.

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