



Seven decades of glacier loss on the Nevados de Chillán volcanic complex, Chile

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Abstract. Glaciers on the Nevados de Chillán volcanic complex are rapidly retreating, with anticipated consequences for agroforestry, tourism, and regional human and ecological security. Quantifying their mass balance is critical for understanding current meltwater contributions and for anticipating future water availability as these glaciers continue to shrink. Here we estimate the geodetic mass balance of all 28 documented glaciers on the Nevados de Chillán complex. An uncrewed aerial vehicle (UAV) campaign conducted in March 2024 provided updated elevation data for 11 glaciers on the complex, allowing calculation of volume change from 1954–2024 (70 years). For all 28 glaciers, we analyzed airplane and satellite digital elevation models (DEMs) to estimate volume change from 1954–2025 (71 years). The total glacier area of the complex declined from 16.02 km² in 1975 to 2.91 km² in 2000 and 1.90 km² in 2019, totaling an 88 % reduction over 44 years. Our results show a clear acceleration in glacier mass loss after 2000 for the glaciers surveyed with UAV and satellite data. Mean annual specific mass balance of the whole complex was -0.42 ± 0.20 m w.e. yr⁻¹ from 1954–2000, accelerating to -0.60 ± 0.38 m w.e. yr⁻¹ from 2000–2025, representing an approximately 40 % increase in the rate of mass loss. Over 2000–2025, the Cerro Blanco subcomplex lost mass at -0.70 ± 0.38 m w.e. yr⁻¹ and Glaciar Nevado, the largest glacier on the complex, at -0.72 ± 0.38 m w.e. yr⁻¹. Significant post-2000 declines in

February and March streamflow at the Río Diguillín are consistent with the complex having passed peak water. Regional water resource planning should consider how increasing glacier melt rates on the Nevados de Chillán complex will impact the timing and volume of future water availability.

1 Introduction

Mountain glaciers have immense value due to their support of municipal and agricultural water demands, alpine ecosystems, and mountain tourism (Immerzeel et al., 2020). Mountain glaciers are retreating, on average, as global temperatures rise (Hugonnet et al., 2021; Zemp et al., 2015). Quantifying this retreat is essential to forecasting downstream water availability (Aguayo et al., 2024; Mark et al., 2015; Ultee et al., 2022).

Glacier retreat is well studied in Chile, particularly in the Maipo basin surrounding the capital city of Santiago, and on the Patagonian Ice Fields (e.g. Ayala et al., 2020; Carrasco-Escaff et al., 2023; Farías-Barahona et al., 2020; Schaefer et al., 2015). Compared to the extensive literature on glaciers in central Chile and Patagonia, south-central Chile remains relatively understudied, leaving the current state of its glaciers not yet fully characterized. Located between the arid Mediterranean climate to the north and the temperate

climate to the south, south-central Chile ($\sim 35\text{--}40^\circ\text{S}$) encompasses a transitional zone where mean annual precipitation increases from $\sim 447\text{ mm yr}^{-1}$ in the semi-arid central region to over 3751 mm yr^{-1} in the humid temperate south (Caro et al., 2024; Valdés-Pineda et al., 2014). Unraveling glacier retreat and hydroclimatic trends across this steep climatic gradient is therefore valuable for understanding how glaciers respond to markedly different precipitation and temperature regimes within a relatively narrow latitudinal band. Although several important studies have documented glacier retreat in this region (e.g. Barria et al., 2019; Brock et al., 2007; Rivera et al., 2006), further research is needed to quantify glacier loss rates and improve water availability forecasting as glaciers continue to shrink.

The relative contribution of glacier melt is becoming increasingly important as south-central Chile's traditionally humid environment shifts from year-round precipitation to increasingly rain-free summer seasons, steadily decreasing annual mean precipitation, and increased drought frequency and severity (Garreaud et al., 2020; Rubio-Álvarez and McPhee, 2010; Sarricolea et al., 2017). Even small glaciers have been shown to have significant impacts on basin runoff (Nolin et al., 2010), suggesting that small alpine glaciers in south-central Chile, such as those on the Nevados de Chillán, may have outsized impacts on downstream water availability.

Nevados de Chillán is a glacierized volcanic complex in the Ñuble region of south-central Chile. Existing geodetic studies of Nevados de Chillán's glaciers solely assess change in glacier area and do not document change in glacier volume (e.g. Zenteno, 2008). While glacier area change provides some insight into climate impacts on glacier retreat, precise glacier elevation change measurements are required to accurately reconstruct the melt rate and hydrological contributions of mountain glaciers in south central-Chile (e.g. Mejías et al., 2025). Our study provides such data for Nevados de Chillán.

Despite frequent eruption events, the Nevados de Chillán volcanic complex was last estimated to have 28 mountain glaciers (Fig. 1B) (DGA, 2022). However, it is not clear how many of these glaciers still exist or are now debris covered. Published observations of the glaciers of Nevados de Chillán indicate a $> 45\%$ reduction in area from 1863–1975, and $> 90\%$ loss in glacier area by 2019 (DGA, 2022). While previous studies documented change in glacier area, there are no long-term estimates of glacier mass balance that account for all glaciers in the complex. Robust mass-balance (MB) measurements are necessary to accurately determine volume change, sensitivity to climate changes, relative contribution of glacier melt to regional water availability, mountain hazards, and other dynamics that control high-elevation landscapes (Owen et al., 2009). Many of these issues remain unexplored in Ñuble. Previous studies have provided estimates of Chilean glacier mass balance at a variety of scales, ranging from regional to specific glacier analyses. Dussailant et al. (2019) reported a mass bal-

ance of $-0.31 \pm 0.19\text{ m w.e. yr}^{-1}$ in the Central Andes and $-0.57 \pm 0.22\text{ m w.e. yr}^{-1}$ in Northern Patagonia. Caro et al. (2024) estimated a 2000–2019 mean annual mass balance of $-0.29 \pm 0.14\text{ m w.e. yr}^{-1}$ for the Maipo River basin (33°S), versus $-0.47 \pm 0.19\text{ m w.e. yr}^{-1}$ for the Baker River basin (47°S). On the Echaurren Norte Glacier (33°S), Farías-Barahona et al. (2019) estimated a mean glacier mass balance of $-0.68 \pm 0.09\text{ m w.e. yr}^{-1}$ from 1955–2015, showing a sharp increase in glacier loss from 2010 onwards with a mass balance of $-1.20 \pm 0.09\text{ m w.e. yr}^{-1}$.

While regional-scale glacier analyses provide useful benchmarks, variability in specific glacier mass balance underscores the importance of finer-scale studies rather than relying solely on regional averages or nearby glacier measurements. Therefore, this paper provides geodetic mass balance estimates for all 28 glaciers on Nevados de Chillán across seven decades. For the full complex, we estimate mass balance for 1954–2000 (46 years) by differencing the Instituto Geográfico Militar (IGM) topographic map DEM and the Shuttle Radar Topography Mission (SRTM) DEM, for 2000–2018 (18 years) by differencing the SRTM and an Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) DEM, and for 2000–2025 (25 years) by differencing the SRTM and a Pléiades stereo DEM. For the 11 glaciers surveyed in our 2024 UAV campaign, we additionally estimate mass balance for 2000–2024 (24 years) at higher spatial resolution. Glacier area change is quantified using inventories from 1975 (DGA, 2011), 2000 (DGA, 2014), or 2019 (DGA, 2022). Further, we analyze topographic and temporal patterns in glacier melt rates, crucial to inform landscape changes and impacts on regional water management.

2 Study Area

The Nevados de Chillán (36.86°S , 71.39°W) volcanic complex is in the Ñuble Region of south-central Chile (Fig. 1A). Nevados de Chillán falls within the Itata River basin, which covers an area of $11\,294\text{ km}^2$ (Bobadilla et al., 2024). The volcanic complex spans approximately 14 kilometers from northwest to southeast and comprises 13 stratovolcanoes, which are grouped into the Cerro Blanco, Puerto los Baños, and Las Termas subcomplexes (Fig. 1B) (Dixon et al., 1999; Naranjo et al., 2008). The maximum altitude of the study area is on the summit of the Cerro Blanco subcomplex, 3151 m above sea-level (m.a.s.l.). The glaciers vary in size and are found on all aspects of the peaks. The largest glacier on the complex, Glaciar Nevado, is housed on the Cerro Blanco subcomplex, has a south-westerly aspect, and covered approximately 0.68 km^2 in 2019 (Fig. 1B) (DGA, 2022). The Chilean Water Directorate (Dirección General de Aguas, DGA) estimates that there were 28 glaciers on the complex as of 2019. Both glaciers disappeared from the Puerto los Baños subcomplex and three glaciers disappeared from the north face of the Las Termas subcomplex between 2000 and

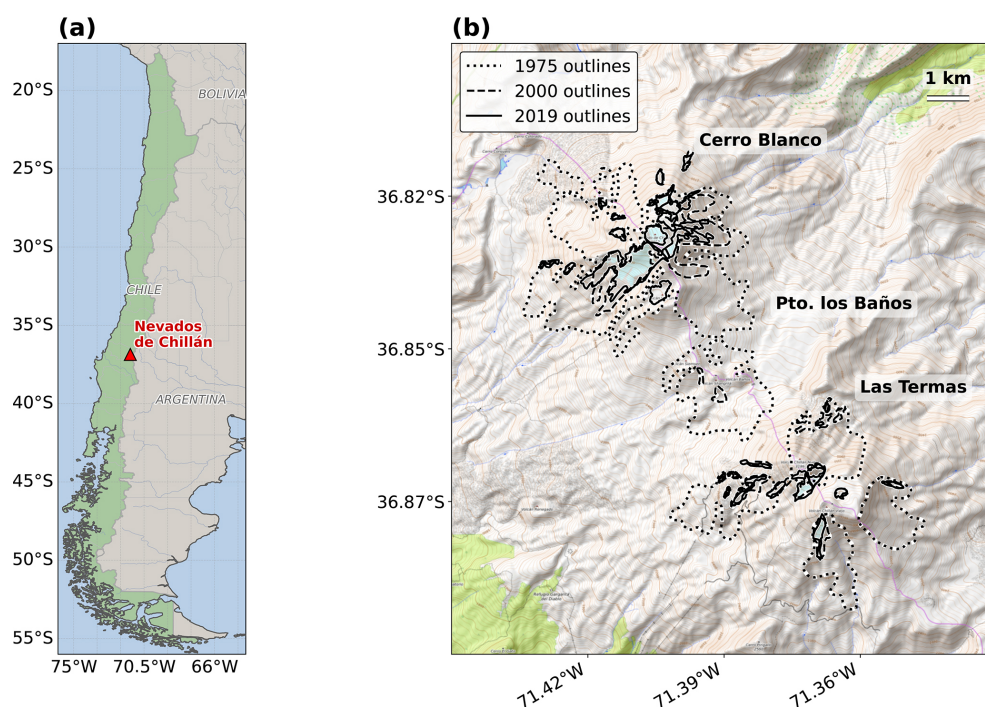


Figure 1. (a) Location of the Nevados de Chillán volcanic complex (red triangle) in the Ñuble region of Chile, South America, and (b) topographic map view (© OpenTopoMap contributors) of the Nevados de Chillán complex showing the Cerro Blanco, Puerto los Baños, and Las Termas subcomplexes, with glacier outlines from the 1975 (dotted), 2000 (dashed), and 2019 (solid) inventories (DGA, 2011, 2014, 2022).

2019, while several glaciers on the Cerro Blanco subcomplex fractured into smaller ice bodies during the same period (DGA, 2014, 2022). Glacier area decreased from 16.02 km² in 1975, to 2.91 km² in 2000, and 1.90 km² in 2019, totaling an 88 % decrease in glacier area over 44 years (DGA, 2014, 2022).

The region has a Mediterranean climate, characterized by warm summers and winters with heavy precipitation (Bobadilla et al., 2024). Given the near total absence of precipitation in summer months, glaciers and seasonal snowmelt are essential components of summer streamflow in the Ñuble region (Ayala et al., 2016; Ragettli and Pellicciotti, 2012). Notably, agriculture accounts for 96.3 % of water consumption in the Itata River basin, with irrigation demand peaking in late summer when glacier runoff is highest (Bobadilla et al., 2024; Webb et al., 2020; Bellisario et al., 2013; McCarthy et al., 2022). As droughts become more frequent, summer glacier discharge plays an increasingly critical role in meeting Ñuble's water needs (Bobadilla et al., 2024; Ayala et al., 2016; Ragettli and Pellicciotti, 2012; Garreaud et al., 2020; Rubio-Álvarez and McPhee, 2010).

3 Methods

Figure 2 presents the methodological workflow for implementing the geodetic mass balance approach, a highly reliable method to estimate glacier mass loss (Huss and Hock,

2015; Hugonnet et al., 2021; Cogley, 2009; Schuster et al., 2023). A DEM derived from a 1954 topographic map (IGM), and satellite-derived DEMs from 2000 (SRTM), 2018 (ASTER), and 2025 (Pléiades), were used to reconstruct historic glacier surface elevations (Table 1). We also conducted a UAV survey in March 2024 to generate a detailed DEM of the western and southern faces of the complex (Table 1, Sect. 3.1 and 3.2). We differenced the historic aerial (IGM), recent satellite (SRTM, ASTER, and Pléiades), and UAV DEMs and clipped the differenced rasters to glacier areas reported by the DGA for the years 1975, 2000, and 2019 (DGA, 2011, 2014, 2022) to estimate glacier volume loss and calculate mean annual geodetic mass balance (Sect. 3.4 and 3.5). Next, we analyze temperature, precipitation, and streamflow data from nearby meteorological stations and co-located gauges, assessing for hydroclimatic trend magnitude and significance (Sect. 3.6). Finally, we assess the relationship between glacier surface elevation change and topographic variables through statistical tests of rank correlation and spatial autocorrelation (Sect. 3.7).

3.1 UAV Image Acquisition

A DJI Mavic 3 Enterprise (M3E) UAV integrated with a GPS Real-Time Kinematic (RTK) solution module was used for RGB imaging of Nevados de Chillán and the generation of a DEM. The DJI M3E UAV houses an L2D-20c Hasselblad brand camera designed for photogrammetry. This camera has

Table 1. Sources for DEMs differenced for glacier volume loss estimates.

Source	Vehicle Type	DEM	Survey Date	Resolution (px ^{−1})
IGM	Airplane	Topographic Map	1954	30 m
SRTM	Satellite	C-band radar	11–22 February 2000	30 m
ASTER	Satellite	Stereo optical imagery (VNIR bands 3N/3B)	1 March 2018	30 m
This study	UAV	4/3'' (~ 0.94 cm) CMOS RGB Camera	12 and 14 March 2024	7.82 cm (Cerro Blanco) and 16.70 cm (Las Termas)
Pléiades	Satellite	Stereo optical photogrammetric DEM	14 April 2025	1 m native resolution, resampled to 30 m

4/3'' (~ 0.94 cm) Complementary Metal Oxide Semiconductor (CMOS) digital image sensor, 20 MP effective resolution, and mechanical shutter. We utilized GPS-RTK for cm accuracy positioning during flight and for precise georeferencing of captured pictures. GPS-RTK provides a solution to improved UAV positioning in lieu of ground control points (Wigmore and Mark, 2017). RTK position accuracy is 1 cm + 1 ppm (horizontal) and 1.5 cm + 1 ppm (vertical). No ground control points were used; all image georeferencing relied on the onboard GPS-RTK positioning system.

The UAV flight campaign was carried out during the best light conditions, around midday on the 12 and 14 March 2024 and in peak-ablation season (i.e. snow-free conditions). Automated flight plans were designed using the DJI Pilot application, with a fixed flight altitude of 145 m above ground level for the Cerro Blanco subcomplex, and 315 m above ground level for the Las Termas subcomplex. Higher flight altitude was required for the Las Termas subcomplex to map the larger area (11.5 km² compared to 1.75 km² for the Cerro Blanco subcomplex) with limited battery capacity, which yielded higher resolution images of Cerro Blanco compared to Las Termas (Sect. 3.2). The flight path was programmed with 70 % and 80 % horizontal and vertical overlap respectively, to ensure successful 3-D model construction through SfM in image post-processing. Due to heavy winds and technical difficulties, manual flight and image capture was required over many sections on the Cerro Blanco subcomplex, resulting in a greater root mean square error (RMSE) when compared to the Las Termas subcomplex.

3.2 UAV Image Processing

We used Metashape (Version 2.1.2), a proprietary software by AgiSoft (Westoby et al., 2012; Over et al., 2021) widely used in similar glacier UAV studies (e.g. Wigmore and Mark, 2017; Kaufmann et al., 2018; Wigmore and Molotch, 2023; Rossini et al., 2023), to process the UAV images. As in previous studies, images were processed using the SfM photogrammetry workflow in Metashape, which reconstructed the 3-D geometry of the study scene by identifying common

points that occur in multiple images from different angles and distances (Westoby et al., 2012). These common points were tracked from image to image, enabling estimation of camera position and object coordinates which were continuously refined using non-linear least-squares minimization as additional images are processed (Westoby et al., 2012). A dense point cloud was generated by aligning these tie-points with a multiple-view stereo algorithm (Frazier and Singh, 2021; Kaufmann et al., 2018). All 1046 images were successfully aligned for Las Termas (RMS reprojection error: 0.22 px; coordinate precision: 4.31 cm), and for Cerro Blanco, 1095 of 1110 images were aligned (RMS reprojection error: 0.26 px; coordinate precision: 2.50 cm). Next, a triangular irregular network mesh was used to estimate 3-D point positions within the selected coordinate system to create a continuous mesh (Westoby et al., 2012). This mesh was then smoothed and an orthomosaic was produced. Finally, a digital elevation model (DEM) was generated from the dense point cloud (Frazier and Singh, 2021; Rossini et al., 2023). The relatively lower flight altitudes over Cerro Blanco yielded a higher DEM resolution in this area (7.82 cm px^{−1}) compared to Las Termas (16.70 cm px^{−1}). However, the RMSE was larger for the Cerro Blanco subcomplex than the Las Termas subcomplex (20.03 versus 9.24 cm, respectively), which was likely a result of manual UAV flying and image capture on the Cerro Blanco subcomplex.

3.3 Satellite and Airborne Elevation Products

We differenced DEMs across seven decades using a combination of historical, satellite, and UAV-derived elevation data, to compute glacier volume loss over time. UAV-derived DEMs, acquired in March 2024, provide high-accuracy subcomplex-level elevation data for 11 glaciers and serve as an independent validation of the full-complex Pléiades 2025 estimates for the same area the following year. Although all DEMs were resampled to a common 30 m grid for differencing, UAV-derived 30 m pixels benefit from averaging many centimeter-scale measurements, yielding more reliable elevation values than equivalent-resolution satellite stereo prod-

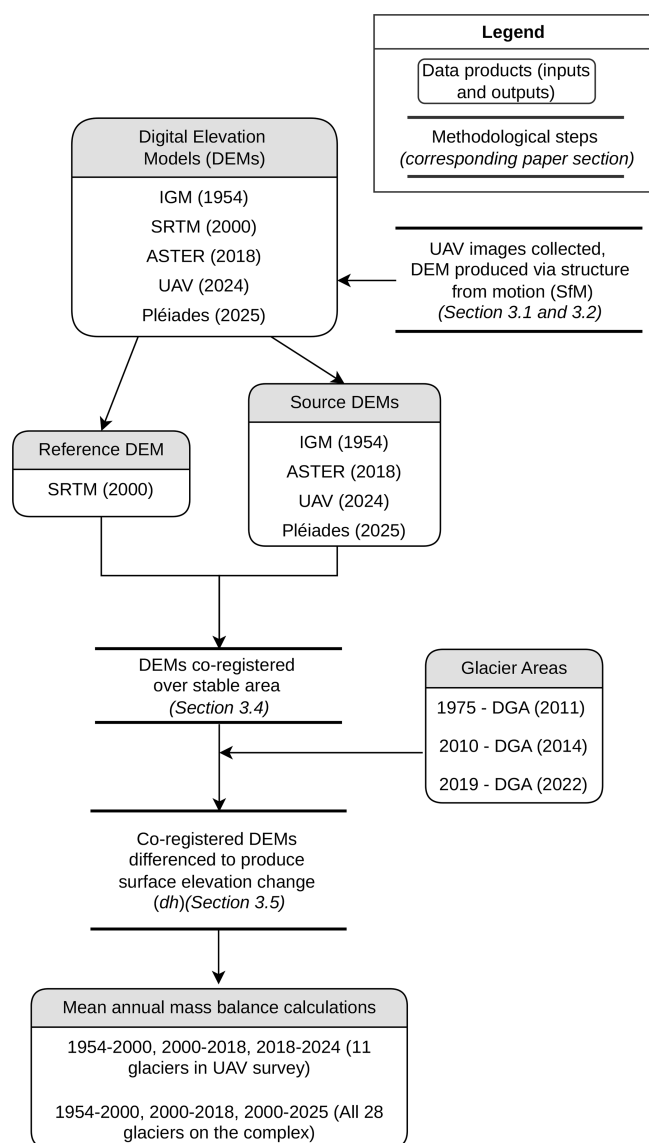


Figure 2. Methodological workflow detailing the DEMs accessed (IGM, SRTM, ASTER, and Pléiades) and created (UAV) to represent glacier elevation (Sect. 3.1 and 3.2), DEM co-registration (Sect. 3.3) and differencing to estimate glacier mass balance (Sect. 3.4).

ucts. All DEMs selected were from the southern hemisphere ablation season ($\sim$ February–April) to minimize the presence of snow cover influencing ground elevation measurements.

3.3.1 Instituto Geográfico Militar DEM

The IGM DEM product was generated by interpolating elevations from the 1 : 50 000 scale topographic map “Nevados de Chillán” produced by the IGM. Published in 1968 using aerial photos from 1954, this map was built using UTM Zone 19 South and provides contour lines every 25 m and spot heights of several summits across the study area, referred

to the PSAD56 datum. As the map exists only in paper format, the copy available in the Geography Department at the Universidad de Concepción was scanned, georeferenced, and digitized using the methods described in DGA (2022). The map was then displayed on ArcGIS Pro for georeferencing, employing coordinates of more than a dozen locations corresponding to the intersections between lines defining the UTM coordinate grid closest to the glacier. Subsequently, contour lines and spot heights were digitized on screen, producing two shapefiles: one of polylines (contours) and one of points (spot heights), with their corresponding elevation assigned as an attribute. The contour polylines were then disaggregated into their respective vertex points, with a mean inter-vertex distance of 36.4 ± 21.5 m, and merged with the point shapefile, a merged file that was then reprojected into WGS84 datum. These points were used to create a 30 m resolution DEM via interpolation employing the Inverse Distance Weighting (IDW) method. IDW was preferred over other common interpolation methods, such as ANUDEM-based methods, because the hydrological stream network correction, central to these approaches, assumes a stable river network, which is not the case in a rapidly deglaciating catchment (Hutchinson, 1989).

3.3.2 Shuttle Radar Topography Mission DEM

The second DEM used in this study was the SRTM 1 Arc-Second Global DEM for February 2000 (USGS EROS Archive, 2018). SRTM provides a global 30 m resolution DEM produced from a C-band (5.6 cm) radar antenna with observations from 11–22 February 2000, during peak summer ablation for Chilean glaciers, making it an excellent reference for glacier ice elevation (USGS EROS Archive, 2018).

Both Hugonnet et al. (2021) and Dussaillant et al. (2019) utilized the DEM co-registration and differencing approach used herein to estimate mean glacier elevation change. Both Hugonnet et al. (2021) and Dussaillant et al. (2019) used ASTER stereo DEMs as a source of elevation data across multiple epochs, an approach we also adopt here for 2018. When compared to SRTM, ASTER is known to suffer from signal attenuation and reduced vertical accuracy over steep north-facing slopes due to shadowing effects, and over low-contrast snow and ice surfaces (Berthier et al., 2024; Girod et al., 2017). For these reasons, SRTM is used as the 2000 baseline elevation reference in this study, taking advantage of its radar-based acquisition geometry and ablation-season timing to minimize snow contamination and stereo-matching errors. ASTER is retained as a complementary source for an intermediate 2018 epoch, where its known limitations over snow and ice are mitigated by strict quality filtering described in Sect. 3.3.3.

3.3.3 Advanced Spaceborne Thermal Emission and Reflection Radiometer DEM

The ASTER DEM used in this study is a bias-corrected 30 m resolution stereo DEM acquired on 1 March 2018, obtained from the archive produced for Hugonnet et al. (2021). A scene from March 2008 was also evaluated but excluded after quality filtering due to near-zero median elevation differences over glacier terrain, which was indicative of residual snow bias. The 2018 ASTER DEM provided by Hugonnet et al. (2021) was processed using the MMASTER workflow (Girod et al., 2017), which applies cross-track polynomial, along-track sum-of-sines, and jitter bias corrections using TanDEM-X as a co-registration reference. The ASTER acquisition dates fell within the southern hemisphere ablation season, minimizing the influence of seasonal snow cover on glacier surface elevations. Prior to co-registration and differencing, the DEM was geoid-corrected from ellipsoidal to orthometric heights using the EGM96 undulation grid via the *pyproj* library. Quality filtering was applied following Hugonnet et al. (2021), including a stereo correlation threshold of ≥ 60 to mask low-confidence pixels, a spatial outlier filter removing pixels differing from SRTM by more than ± 200 m, and a snow bias check based on the median elevation difference over the glacier area. Of ten candidate scenes evaluated for the study area, one scene, acquired on 1 March 2018, passed all quality criteria with $\geq 30\%$ glacier coverage and a near-zero median elevation difference over glacier terrain ($+0.11$ m), indicating minimal snow bias, and was retained for analysis.

3.3.4 Pléiades DEM

The Pléiades DEM used in this study was obtained from DGA under the Chilean Transparency Act. The DEM was built by DGA from Pléiades-1A stereoscopic imagery (PHR1A sensor, panchromatic band) acquired on 17 April 2025 over the Nevados de Chillán complex. The source imagery had virtually no cloud cover and a ground sampling distance of 0.73 m. The April acquisition date falls at the end of the southern hemisphere ablation season, minimizing the influence of seasonal snow cover. The photogrammetric processing was performed using the Ames Stereo Pipeline (ASP, version 3.5.0; Beyer et al., 2018) with RPC camera models provided with the imagery. Prior to image registration, bundle adjustment was applied to refine the camera models and reduce systematic errors. Stereo correlation was performed using the ASP command *parallel_stereo* and the resulting point cloud was rasterized with *point2dem*. The resulting DEM provided full coverage of the Nevados de Chillán glacier complex. We geoid-corrected the DEM to orthometric heights using the EGM96 undulation grid, consistent with all other ellipsoidal DEMs in this study.

3.4 DEM reprojection, alignment, and co-registration

All DEMs were first reprojected to the same coordinate system and 30 m resolution, and aligned on the same grid as the SRTM DEM using the *rasterio* Python library with bilinear interpolation. Border artifact regions in the IGM 1954 and Pléiades 2025 DEMs were masked by manually digitizing validity polygons around the high-quality central areas of each DEM in ArcGIS Pro. Next, we co-registered the reprojected and aligned DEMs over stable terrain surrounding the glaciers. DEM co-registration improves accuracy when comparing elevation between DEMs by reducing horizontal and vertical shifts between images (Berthier et al., 2024). Glaciated terrain was masked during co-registration using the union of the 1975, 2000, and 2019 DGA glacier inventories, ensuring that formerly glaciated terrain deglaciated between inventories was not misclassified as stable ground. As in Berthier et al. (2024), we implemented the Nuth and Kääb (2011) algorithm via the xDEM Python package (Version 0.2.2; xDEM Contributors, 2026), using the glacier union mask described above to define stable terrain for co-registration. For the Cerro Blanco UAV DEM, which had insufficient stable terrain pixels to constrain horizontal shifts, a vertical shift only was applied. Maps of stable areas used for glacier co-registration are provided in Appendix A.

3.5 Computing Glacier Mass Balance

Glacier mass balance was computed by clipping the co-registered DEMs to the 1975, 2000, and 2019 glacier areas and differencing the co-registered DEMs to calculate the change in height per pixel (Δh). Vertical ice loss was then converted to specific mean annual glacier mass balance, via the relative average densities of glacier ice (ρ_{ice}) and water (ρ_{water}), measured in meters water equivalent per unit area per year (m w.e. yr^{-1}):

$$\text{MB} = \frac{\left(\frac{\Delta \bar{h}}{A_{\text{start}}} \right)}{\left(\bar{A} \times \Delta t \right) \times \left(\frac{\rho_{\text{ice}}}{\rho_{\text{water}}} \right)} \quad (1)$$

where $\Delta \bar{h}$ is the mean elevation change over the starting glacier area, A_{start} , $\bar{A} = \frac{(A_{\text{start}} + A_{\text{end}})}{2}$ is the mean glacier area following Zemp et al. (2019), Δt is the epoch duration in years, $\rho_{\text{ice}} = 850 \pm 60 \text{ kg m}^{-3}$ (Huss, 2013), and $\rho_{\text{water}} = 1000 \text{ kg m}^{-3}$. The start area corresponds to the 1975 (DGA, 2011), 2000 (DGA, 2014), or 2019 (DGA, 2022) inventory. The uncertainty on ρ_{ice} is propagated into the mass balance uncertainty and combined with the elevation-derived uncertainty following Zemp et al. (2019) as:

$$\sigma_{\text{MB}} = \sqrt{\sigma_{\text{elev}}^2 + \sigma_{\rho}^2} \quad (2)$$

where

$$\sigma_{\rho} = \left| \frac{\Delta \bar{h}}{\Delta t} \right| \times \left(\frac{\sigma_{\text{ice}}}{\rho_{\text{water}}} \right) \quad (3)$$

and $\sigma_{\text{ice}} = 60 \text{ kg m}^{-3}$ (Huss, 2013).

This workflow was repeated for each glacier on the complex. Mass balance for all 28 glaciers was estimated for 1954–2000 using the IGM and SRTM DEMs, and for 2000–2018 using the SRTM and ASTER DEMs, and for 2000–2025 using the SRTM and Pléiades DEMs. For the 11 glaciers covered by the UAV survey, mass balance was additionally estimated for 2000–2024, providing a higher-accuracy subcomplex-level record independent of satellite stereo imagery. Mass balance was calculated using the mean area approach following Zemp et al. (2019) as described above. For 1954-based epochs, the 1975 glacier inventory (DGA, 2011) was used as the start area – glacier outlines are not clearly delineated on the 1954 IGM topographic map, precluding direct digitization of 1954 glacier extents – thus the 1975 inventory represents the closest available approximation to the 1954 ice extent. For 2000-based epochs, the 2000 inventory (DGA, 2014) was used as the start area and the 2019 inventory (DGA, 2022) as the end area.

Normalized mean absolute deviation (NMAD) was computed over stable off-glacier terrain following co-registration as:

$$\text{NMAD} = 1.4826 \cdot \text{median}(|\Delta z_i - m_{\Delta z}|), \quad (4)$$

where Δz_i are elevation differences over stable off-glacier terrain and $m_{\Delta z}$ is their median. NMAD values computed over stable terrain after co-registration were 11.13 m (IGM DEM), 5.84 m (ASTER DEM), 4.64 m (Las Termas UAV), 11.18 m (Cerro Blanco UAV), and 3.63 m (Pléiades DEM). The higher NMAD for the Cerro Blanco UAV DEM reflects the limited stable terrain extent surrounding that subcomplex. The higher NMAD for the IGM 1954 DEM reflects the inherent geometric uncertainty of a topographic map-derived DEM relative to modern satellite and UAV products.

The stable-terrain NMAD does not account for the spatial autocorrelation of DEM errors when integrating elevation change over a glacier area and therefore cannot be used directly as a mass balance uncertainty estimate. Thus, we implement a two-step uncertainty propagation pipeline following Hugonnet et al. (2022) using the xDEM Python package (xDEM Contributors, 2026). In the first step, a spatially variable per-pixel elevation error map $\sigma(x, y)$ is inferred from stable off-glacier terrain using the xDEM function `infer_heteroscedasticity_from_stable`, which models error as a function of terrain slope and maximum curvature via two-dimensional binning (Hugonnet et al., 2022). Where insufficient stable terrain pixels were available for heteroscedastic modelling (Cerro Blanco UAV DEM), a spatially uniform error equal to the stable-terrain NMAD was used.

In the second step, the spatial correlation structure of elevation errors is characterized by fitting a spherical variogram model to the empirical variogram of off-glacier elevation differences. The uncertainty in mean glacier elevation change

$\sigma_{\Delta h}$ is then propagated following Rolstad et al. (2009):

$$\sigma_{\Delta h} = \sigma_{\text{pixel}} \times \sqrt{\frac{A_{\text{corr}}}{A_{\text{glacier}}}}, \text{ if } A_{\text{corr}} < A_{\text{glacier}} \quad (5)$$

$$\sigma_{\Delta h} = \sigma_{\text{pixel}} \times \sqrt{\frac{A_{\text{pixel}}}{A_{\text{glacier}}}}, \text{ if } A_{\text{corr}} \geq A_{\text{glacier}} \quad (6)$$

where $A_{\text{corr}} = \pi L^2/2$ is the area of spatial correlation, L is the variogram range, A_{glacier} is the glacier area, and A_{pixel} is the pixel area (900 m^2 at 30 m resolution). The first form applies where the glacier area exceeds the correlation area; the second applies for small glaciers where the correlation area exceeds the glacier extent. Estimated variogram ranges were 882 m (IGM 1954), 505 m (Cerro Blanco UAV 2024), 637 m (Las Termas UAV 2024), 187 m (Pléiades 2025), and 13 m (ASTER 2018). Mass balance uncertainty is then derived as:

$$\sigma_{\text{MB}} = \sigma_{\Delta h} \times \frac{\rho_{\text{ice}}}{\rho_{\text{water}} \times \Delta t} \quad (7)$$

where Δt is the epoch duration in years. Resulting mass balance uncertainties were $\pm 0.31 \text{ m w.e. yr}^{-1}$ (SRTM-IGM, 1954–2000), $\pm 0.30 \text{ m w.e. yr}^{-1}$ (Cerro Blanco UAV-SRTM, 2000–2024), $\pm 0.16 \text{ m w.e. yr}^{-1}$ (Las Termas UAV-SRTM, 2000–2024), $\pm 0.17 \text{ m w.e. yr}^{-1}$ (Pléiades-SRTM, 2000–2025), and $\pm 0.01 \text{ m w.e. yr}^{-1}$ (ASTER-SRTM, 2000–2018).

3.6 Hydroclimate Data

Precipitation data were sourced from CR2 (<https://explorador.cr2.cl/>, last access: 23 September 2025) for two meteorological stations nearest the Nevados de Chillán complex, Las Trancas and Diguillín, located approximately 10 and 18 km aerial distance and 1366 m and 1899 m below the complex, respectively. Maximum and minimum monthly temperature data were obtained from the DGA's Diguillín meteorological station, while no temperature data was available for the Las Trancas station. Monthly streamflow data were also provided for the Diguillín station. Monthly precipitation data were summed to compute cumulative annual precipitation for the Las Trancas and Diguillín meteorological stations. Monthly streamflow data were similarly summed to compute cumulative annual discharge for the Río Diguillín station. Daily minimum and maximum temperature data were averaged to derive mean daily temperature. From these, three temperature time series were generated representing minimum, mean, and maximum values.

Temperature, precipitation, and streamflow were analyzed on monthly, seasonal, and annual timescales for the full record. Hydroclimatic trends were quantified using Sen's slope estimator (Sen, 1968), which is robust to outliers, missing values, and non-normal distributions that commonly characterize climatic and hydrological time series. Sen's

slope computes the median of all pairwise slopes between observations,

$$\hat{\beta} = \text{median}\left(\frac{x_j - x_i}{j - i}\right), \text{ for } j > i, \quad (8)$$

yielding a distribution-free estimate of the monotonic trend magnitude. Trends were evaluated over the full record and separately for pre- and post-2000 periods to enable comparison with glacier mass balance changes. Statistical significance of trends was assessed using the nonparametric Mann–Kendall test (Mann, 1945; Kendall, 1948), following Burkey (2006) via the *pymanuskendall* package in Python. Significance was evaluated at the 95 % level ($p < 0.05$).

3.7 Geospatial and Topographic Analysis

The relationship between glacier surface elevation change (Δh) and topographic variables (mean elevation, slope, and aspect) was assessed at the glacier scale using Spearman rank correlation as the primary statistical test, appropriate given the non-normal distribution of elevation change data. Pearson correlation coefficients are also reported for comparison. Spatial autocorrelation of pixel-level elevation change within glacier boundaries was characterized using Global Moran's I and Local Moran's I (LISA) statistics, implemented using the *PySAL esda* library with a rook contiguity spatial weights matrix. Statistical significance was evaluated at the 95 % confidence level ($p < 0.05$) using 499 permutations.

4 Results

4.1 DEM co-registration and error calculation

By co-registering the IGM, ASTER, UAV, and Pléiades DEMs to the SRTM DEM, we reduce geolocation errors and thus improve the accuracy of our elevation change and mass balance calculations (Shean et al., 2023). Post-co-registration median signed error and NMAD were calculated for each DEM over stable off-glacier terrain (Table 2). All DEMs achieved median errors within ± 0.2 m after co-registration, confirming successful vertical alignment across all epochs.

4.2 Glacier elevation change

Glaciers thinned on average across the entirety of the Nevados de Chillán complex, and all analysis periods (Fig. 3). For the Las Termas subcomplex, mean thinning increased when using the 2019 glacier polygons versus the 2000 glacier polygons, whereas the opposite was true for the Cerro Blanco subcomplex and the complex as a whole.

Glacier loss was greatest near the tongue of each glacier, showing a relationship between greater glacier thinning and lower elevation. Between 2000 and 2019, the glaciers situated on the saddle between the Cerro Blanco and Las Termas subcomplexes (Puerto los Baños) disappeared entirely

(Fig. 3). Positive elevation change shown in blue on Fig. 3a–c likely corresponds to lava lobes from eruptions during that period (1954–2000), the formation of the Arrau crater, or persistent seasonal snow at the time of imaging, rather than glacier thickening (Dixon et al., 1999; Naranjo et al., 2008). Given that we were unable to survey the northeastern aspect of the complex with UAV, the melt dynamics of those glaciers are constrained by the Pléiades and ASTER DEMs only. Glacier thinning was observed across the full complex in both satellite datasets. On the Cerro Blanco subcomplex, elevation decrease was greatest on the southern and western faces, with slightly less thinning observed on the northern and eastern faces. A similar pattern was observed on the Las Termas subcomplex, where the southern and western faces showed the greatest elevation decrease.

Mean and median glacier thinning on the Cerro Blanco subcomplex exceeds that on the Las Termas subcomplex across all periods (Fig. 3). Furthermore, ice loss from 2000–2024 (UAV-SRTM) for the two subcomplexes far exceeds that measured from 1954–2000 for the whole complex, indicating an increase in the rate of mass loss post-2000 for these glaciers. This acceleration is further corroborated by the full-complex estimates, which show -0.61 ± 0.06 m w.e. yr^{-1} from 2000–2018 (ASTER-SRTM) and -0.60 ± 0.38 m w.e. yr^{-1} from 2000–2025 (Pléiades-SRTM), both substantially more negative than the 1954–2000 whole-complex estimate of -0.42 ± 0.20 m w.e. yr^{-1} .

We analyzed the relationship between elevation change (Δh) and pixel topographic variables (aspect, slope, and elevation), and found that these topographic factors explained up to 12 % of observed elevation change (Pléiades (2025) – SRTM (2000), $\rho^2 = 0.12$, $p = 0.07$), with no correlation reaching statistical significance ($p > 0.05$ in all cases), meaning that most of the variation is controlled by other factors (Appendix B). Spearman rank correlation was used as the primary statistical test given the non-normal distribution of elevation change data, with Pearson correlation reported for comparison. While topographic patterns vary by glacier subcomplex and by year, topographic variables had a very small and insignificant effect on glacier surface elevation change overall. We also observed significant ($p = 0.001$) spatial autocorrelation in pixels with elevation change, calculating Global Moran's I values for the glacier elevation change raster layers ranging from a minimum of 0.71 to a maximum of 0.96. Using Local Moran's I analysis, we found a high degree of spatial clustering of elevation change across all epochs, though the nature of clustering varied by period (Appendix C). For the 2000–2025 Pléiades epoch, 97.4 % of pixels fell within significant clusters, of which 93.4 % were high-high clusters (HH), indicating that high mass loss pixels are overwhelmingly surrounded by other high-mass-loss pixels, consistent with spatially uniform thinning across the complex in the recent period. For longer-term epochs (1954–2000, 1954–2025), significant clusters were predominantly low-low (LL, ~ 10 %), reflecting spatially coherent low-loss

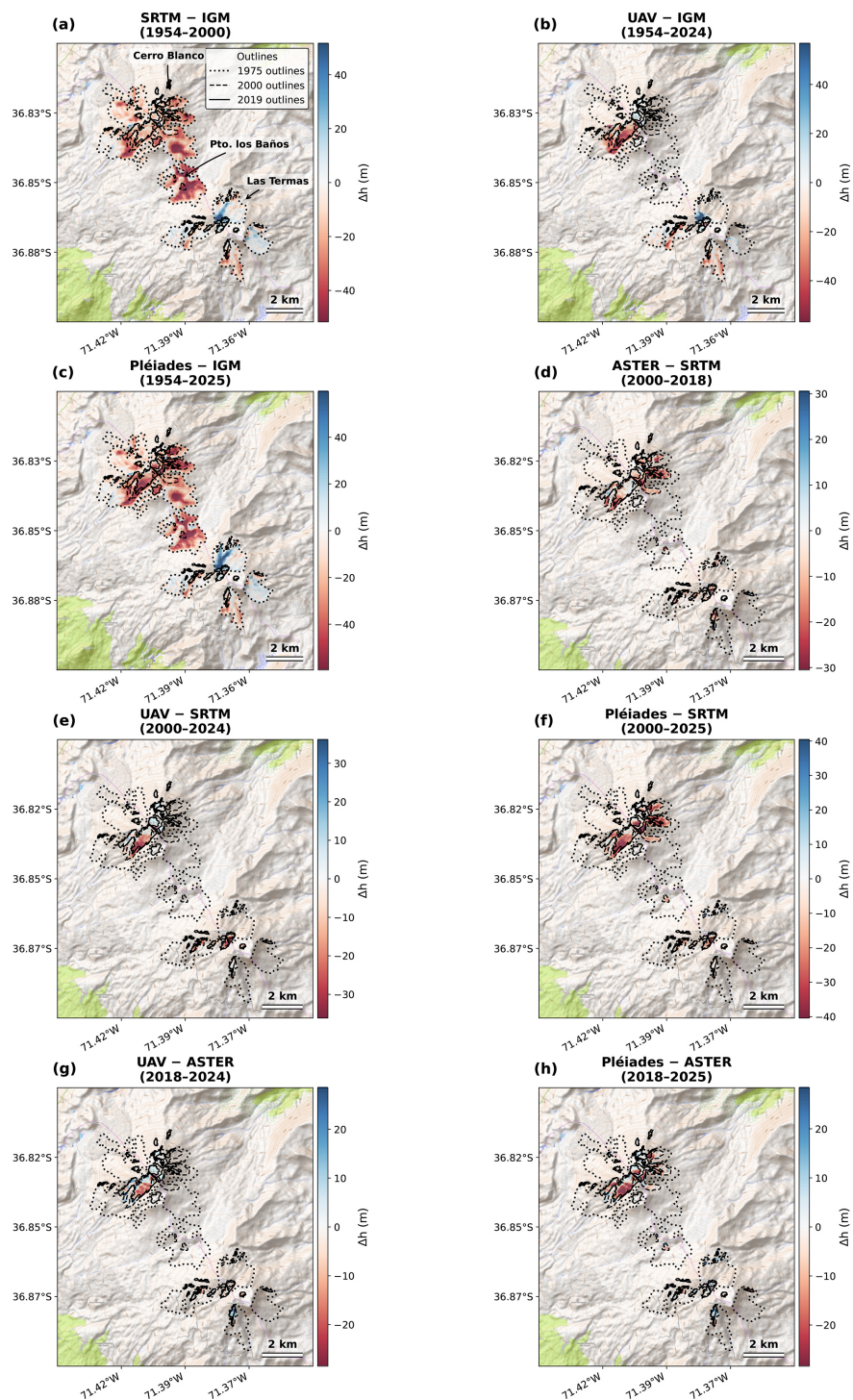


Figure 3. Glacier elevation change (m) of the Cerro Blanco and Las Termas subcomplexes on Nevados de Chillán. Glacier outlines are shown for 1975 (dotted), 2000 (dashed), and 2019 (solid). (a) 1954–2000 elevation changes for the entire glacier complex derived from the IGM topographic map and SRTM DEM, (b) 1954–2024 elevation changes for Cerro Blanco and Las Termas subcomplexes constrained by UAV flight extent, derived from UAV surveys and the IGM DEM, (c) 1954–2025 elevation changes for the entire complex derived from the IGM DEM and Pléiades DEM, (d) 2000–2018 elevation changes for the entire complex derived from ASTER and SRTM DEMs, (e) 2000–2024 elevation changes for UAV-surveyed glaciers relative to SRTM 2000, (f) 2000–2025 elevation changes for the entire complex derived from Pléiades and SRTM DEMs, (g) 2018–2024 elevation changes for UAV-surveyed glaciers relative to ASTER 2018, (h) 2018–2025 elevation changes for the entire complex derived from Pléiades and ASTER DEMs. Panels (a) and (c) are clipped to the 1975 glacier inventory; all other panels are clipped to 2000 or 2019 glacier perimeters to reflect the DEM dates. Basemap: © OpenTopoMap contributors.

Table 2. Post-co-registration median signed error and NMAD for each DEM over stable off-glacier terrain.

DEM	<i>N</i> stable pixels	Median dh (m)	NMAD (m)
IGM 1954	38 941	0.154	11.13
ASTER 2018	7 048 792	0.189	5.84
Cerro Blanco UAV 2024	1225	0	11.18
Las Termas UAV 2024	12 311	0	4.64
Pléiades 2025	54 806	0	3.63

areas corresponding to higher-elevation accumulation zones. In other words, glacier elevation loss on Nevados de Chillán is spatially coherent, and the spatial organization of mass loss has shifted from localized preservation within accumulation zones in the long-term record to near-uniform thinning across glacier surfaces in the most recent period.

We also observed the impact of glacier outline choice (2000 vs. 2019) on measured glacier elevation change (Fig. 4). Our primary mass balance estimates use the mean area approach following Zemp et al. (2019), which accounts for glacier area change and reduces sensitivity to outline choice. For the full Nevados de Chillán complex, mean elevation differences were nearly identical between inventories and not significant (Pléiades 2000–2025: $\Delta\text{median} = +0.49$ m, Cohen's $d = 0.057$, $p = 0.23$). The Las Termas subcomplex showed slightly greater glacier thinning using 2019 outlines, but the difference was negligible and not significant ($\Delta\text{median} = -0.69$ m, Cohen's $d = 0.102$, $p = 0.17$). In contrast, the Cerro Blanco subcomplex showed a small but statistically significant difference ($\Delta\text{median} = +2.50$ m, Cohen's $d = -0.183$, $p = 0.022$), though the effect size remains negligible ($|d| < 0.2$). These results demonstrate that mass balance estimates for smaller subcomplexes are more sensitive to the choice of glacier inventory, while the overall complex is largely unaffected.

4.3 Mean Mass Balance of Nevados de Chillán Complex

For the full complex, mean annual specific mass balance was -0.42 ± 0.20 m w.e. yr^{-1} from 1954–2000, and accelerated to -0.60 ± 0.38 m w.e. yr^{-1} from 2000–2025 (Pléiades) and -0.61 ± 0.06 m w.e. yr^{-1} from 2000–2018 (ASTER), both significant. We used the mean area approach for mass balance calculations following Zemp et al. (2019), with the 1975 glacier inventory (DGA, 2011) serving as the reference outline for 1954-based epochs given that a reliable earlier reference outline was not available. The Cerro Blanco subcomplex had a mean annual specific mass balance of -0.70 ± 0.38 m w.e. yr^{-1} (2000–2025, Pléiades) and -0.54 ± 0.30 m w.e. yr^{-1} (2000–2024, UAV), indicating broad agreement between the two independent datasets. The Las Termas subcomplex had a mean annual specific mass balance of -0.48 ± 0.17 m w.e. yr^{-1} from 2000–2024 (UAV), which is significant, while the Pléiades-derived esti-

mate of -0.30 ± 0.38 m w.e. yr^{-1} for 2000–2025 falls within the range of measurement uncertainty. The discrepancy between the two estimates likely reflects differences in point density and spatial coverage, as the UAV-derived DEM benefits from centimeter-scale measurements resampled to 30 m, yielding more reliable elevation values over the complex terrain of the Las Termas subcomplex than the Pléiades stereo product. The Las Termas subcomplex showed a slower mass loss rate from 2018–2024 (-0.32 ± 0.19 m w.e. yr^{-1}) compared to 2000–2018 (-0.49 ± 0.07 m w.e. yr^{-1}), though this difference does not exceed the combined measurement uncertainty (± 0.20 m w.e. yr^{-1}). Figure 5 summarizes mass balance and error estimates for all time periods within both the 2000 and 2019 glacier outlines.

Mean glacier thinning of the Cerro Blanco subcomplex far exceeded that of the Las Termas subcomplex. For the 1954–2024 period, Cerro Blanco lost an average of -28.0 ± 4.4 m in elevation (Fig. 3). For Las Termas, the most reliable cumulative estimate is -11.6 ± 4.7 m over 2000–2024, as the 1954-based Las Termas value carries large uncertainty due to the limited coverage of the 1975 glacier inventory over this subcomplex. The relatively higher measurement error of the 1954 IGM DEM means the 1954–2000 contribution to total ice loss cannot be precisely partitioned for either subcomplex. This epoch yields a slightly positive but statistically insignificant mean mass balance ($+0.06 \pm 0.20$ m w.e. yr^{-1} for SRTM–IGM), which we attribute to the geometric mismatch between the large 1975 Las Termas polygons (4.99 km^2) and the much smaller current glacier footprint (0.45 km^2), resulting in inclusion of recently deglaciated terrain in the mean area calculation. This estimate is therefore excluded from trend analysis.

The mass balance of Glaciar Nevado, the largest glacier on Nevados de Chillán, was calculated for the 1954–2000 and 2000–2024/2025 sub-periods (DGA, 2011; 2014; 2022). Individual glacier-level estimates for 1954-based epochs are not available as the 1975 inventory predates the fragmentation of the complex into the discrete glacier units identified in the 2000 and 2019 inventories, reflecting the much greater ice extent at that time. From 2000–2018, the ASTER-derived mean annual mass balance of Glaciar Nevado was -0.50 ± 0.04 m w.e. yr^{-1} , increasing to -0.54 ± 0.30 m w.e. yr^{-1} from 2000–2024 (UAV) and -0.72 ± 0.38 m w.e. yr^{-1} from 2000–2025 (Pléiades)

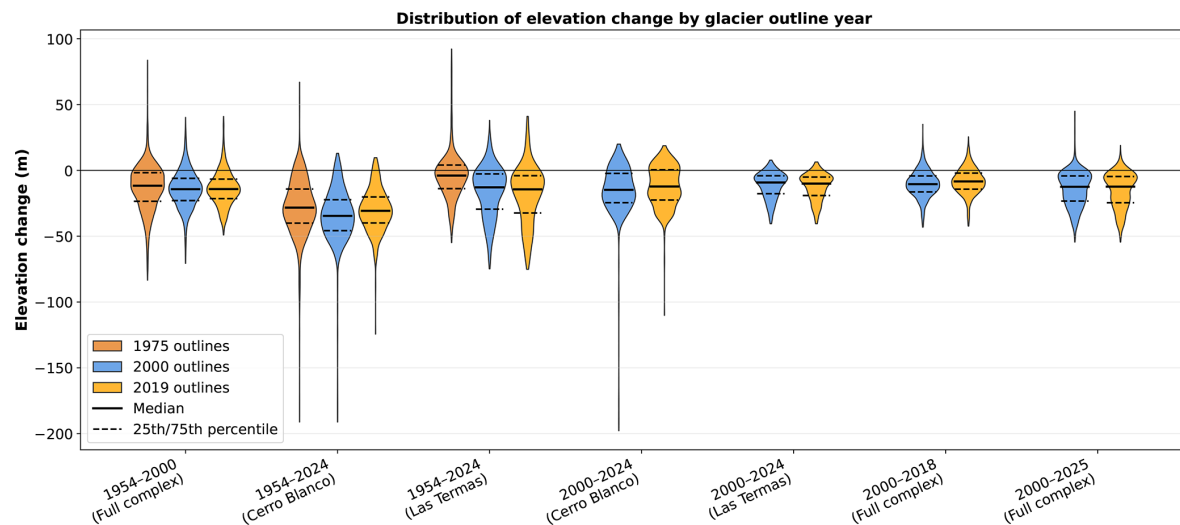


Figure 4. Distribution of glacier elevation change by glacier outline (1975, 2000, and 2019) for the Cerro Blanco and Las Termas subcomplexes and the entire Nevados de Chillán complex with median, 25th and 75th percentiles plotted.

(Fig. 5). The close agreement between these three independent estimates increases confidence in the reported mass loss signal. These results suggest an increasing rate of glacier mass loss over time. The magnitude of glacier loss from 1954–2000 for the whole complex was within the range of measurement uncertainty. Mass loss was significant across all 2000-based epochs for both the Cerro Blanco subcomplex and Glaciar Nevado. The Las Termas Pléiades-derived 2000–2025 estimate (-0.30 ± 0.38 m w.e. yr^{-1}) was also within measurement uncertainty, however the UAV-derived estimate (-0.48 ± 0.17 m w.e. yr^{-1}) and the 2018–2024 ASTER-UAV estimate (-0.55 ± 0.06 m w.e. yr^{-1}) confirm significant and accelerating mass loss at Las Termas.

In summary, mean annual specific mass balance accelerated significantly over time for the Cerro Blanco subcomplex and Glaciar Nevado, with clear post-2000 intensification relative to the 1954–2000 baseline. The 1954–2000 whole-complex mass balance of -0.42 ± 0.20 m w.e. yr^{-1} exceeds 2σ and is statistically significant, indicating measurable glacier mass loss even in the pre-2000 period. The most robust signals of post-2000 acceleration are the ASTER 2018 and Pléiades 2025 full-complex estimates, which agree closely at -0.61 ± 0.06 and -0.60 ± 0.38 m w.e. yr^{-1} respectively. Las Termas mass loss rates showed variability between sub-periods but remained consistently negative across all 2000-based epochs.

4.4 Hydroclimatic Trends

We found that annual cumulative precipitation decreased by an average of -19.00 mm yr^{-1} ($p = 0.022$) at the Diguillín meteorological station, and by -48.90 mm yr^{-1} ($p < 0.001$) at the Las Trancas station over the full record (Fig. 6D and E). The rate of decline accelerated markedly after 2000, with

precipitation decreasing at -79.2 mm yr^{-1} ($p = 0.001$) at Diguillín and -116.8 mm yr^{-1} ($p < 0.001$) at Las Trancas.

Maximum, minimum, and mean temperature were analyzed for the Diguillín station alone (Fig. 6A, B, C), since no temperature data were available for Las Trancas. Average annual minimum daily temperatures increased by 0.029 °C yr^{-1} ($p < 0.001$) and average annual mean daily temperatures increased by 0.023 °C yr^{-1} ($p < 0.001$) (Fig. 6A and B). Average annual maximum temperatures showed no significant trend over the full record, though post-2000 maximum temperatures increased at 0.086 °C yr^{-1} ($p = 0.053$) (Fig. 6C).

To assess whether hydroclimatic trends were better characterized by a sudden shift or continuous monotonic change, we applied both the E-Divisive multiple changepoint algorithm (James and Matteson, 2015) and segmented (piecewise linear) regression (Pilgrim, 2021). The E-Divisive method detects changes in the joint distribution of multivariate time series using permutation testing, while segmented regression identifies the year at which the rate of change accelerated most significantly. Neither method detected a statistically robust breakpoint in any series, confirming that the observed hydroclimatic trends are better described as continuous monotonic acceleration rather than abrupt regime shifts. Trend analysis therefore relies solely on Sen's slope and Mann–Kendall tests as described in Sect. 3.6. Streamflow was also analyzed for the Diguillín station, with cumulative annual streamflow decreasing by -32.40 m³ s⁻¹ yr^{-1} ($p = 0.01$) over the full time series. Analysis of post-2000 cumulative annual streamflow indicated dramatic reductions, with streamflow decreasing by -213.10 m³ s⁻¹ yr^{-1} ($p = 0.001$), representing a > 550 % increase in the rate of streamflow decline.

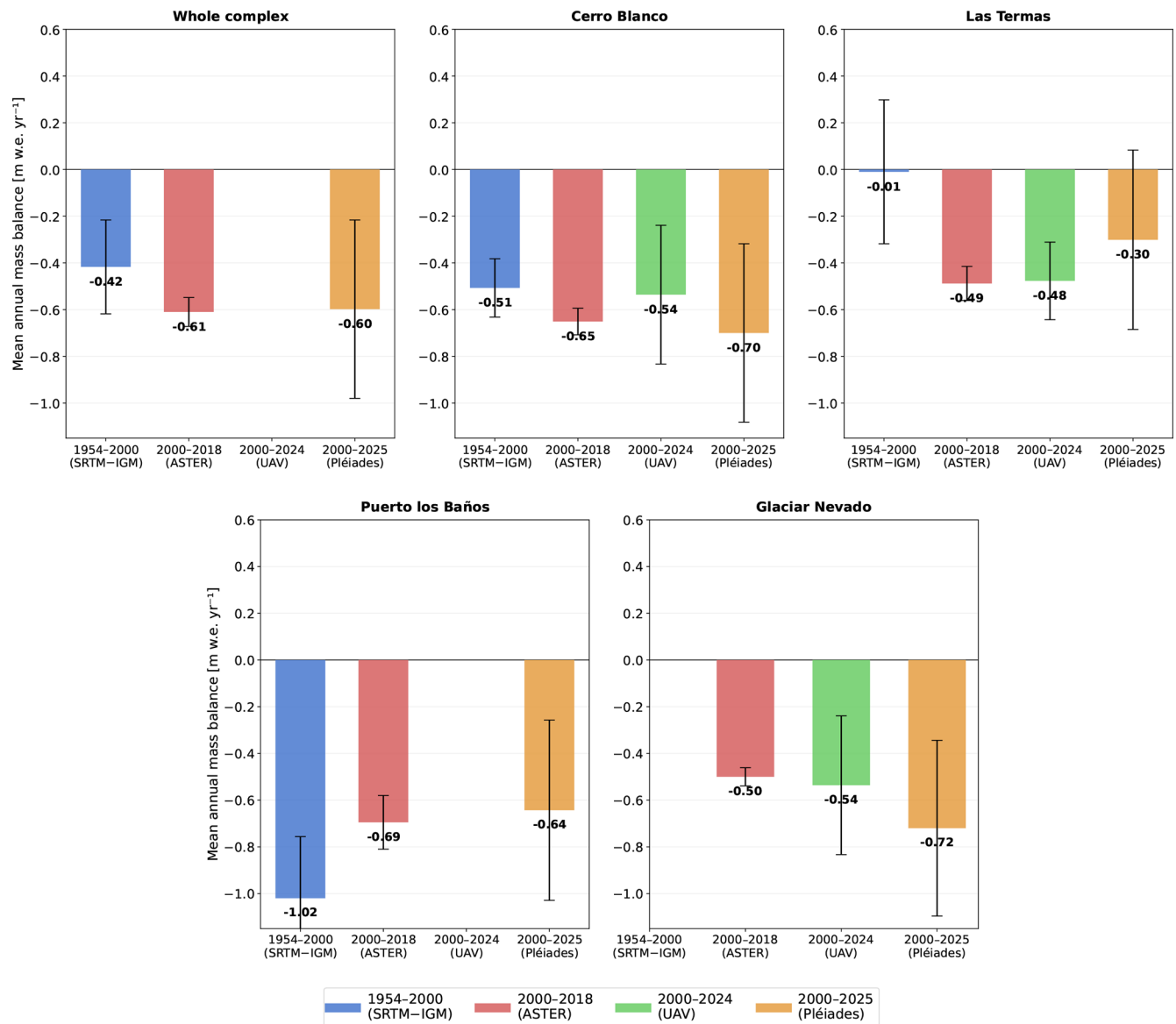


Figure 5. Mean annual specific mass balance (m w.e. yr^{-1}) for the Nevados de Chillán glacier complex across all subcomplexes and observation periods. Panels show results for the whole complex, Cerro Blanco subcomplex, Las Termas subcomplex, Puerto los Baños subcomplex, and Glaciar Nevado. Four epochs are shown where data are available: 1954–2000 (SRTM-IGM, blue), 2000–2018 (ASTER, red), 2000–2024 (UAV, green), and 2000–2025 (Pléiades, orange). UAV-derived estimates are available only for Cerro Blanco and Las Termas subcomplexes; the 1954–2000 estimate is available only at the whole-complex level due to the spatial extent of the 1975 glacier inventory. Error bars represent propagated uncertainty following Rolstad et al. (2009) and Hugonnet et al. (2022). Values within the range of measurement uncertainty ($|\text{MB}| < 1\sigma$) are not considered statistically significant.

In addition to annual trends, we analyzed changes in summertime (January–March; JFM) temperature (Fig. 7), precipitation (Fig. 8), and streamflow (Fig. 9). Minimum daily temperatures all increased significantly over the full record in all three months (January: $+0.054\text{ }^{\circ}\text{C yr}^{-1}$, $p < 0.001$; February: $+0.054\text{ }^{\circ}\text{C yr}^{-1}$, $p < 0.001$; and March: $+0.039\text{ }^{\circ}\text{C yr}^{-1}$, $p = 0.011$). Mean daily temperatures also increased significantly across all three months (January: $+0.047\text{ }^{\circ}\text{C yr}^{-1}$, $p < 0.001$; Febru-

ary: $+0.042\text{ }^{\circ}\text{C yr}^{-1}$, $p < 0.001$; March: $+0.031\text{ }^{\circ}\text{C yr}^{-1}$, $p = 0.002$). Maximum daily temperatures increased significantly in January ($+0.036\text{ }^{\circ}\text{C yr}^{-1}$, $p = 0.019$), February ($+0.037\text{ }^{\circ}\text{C yr}^{-1}$, $p = 0.027$), and March ($+0.038\text{ }^{\circ}\text{C yr}^{-1}$, $p = 0.011$) over the full record. Post-2000 warming rates accelerated substantially for January and March maximum and mean temperatures (January T_{max} : $+0.189\text{ }^{\circ}\text{C yr}^{-1}$, $p = 0.007$; March T_{max} : $+0.260\text{ }^{\circ}\text{C yr}^{-1}$, $p = 0.019$; January T_{mean} : $+0.134\text{ }^{\circ}\text{C yr}^{-1}$, $p = 0.036$), while post-2000

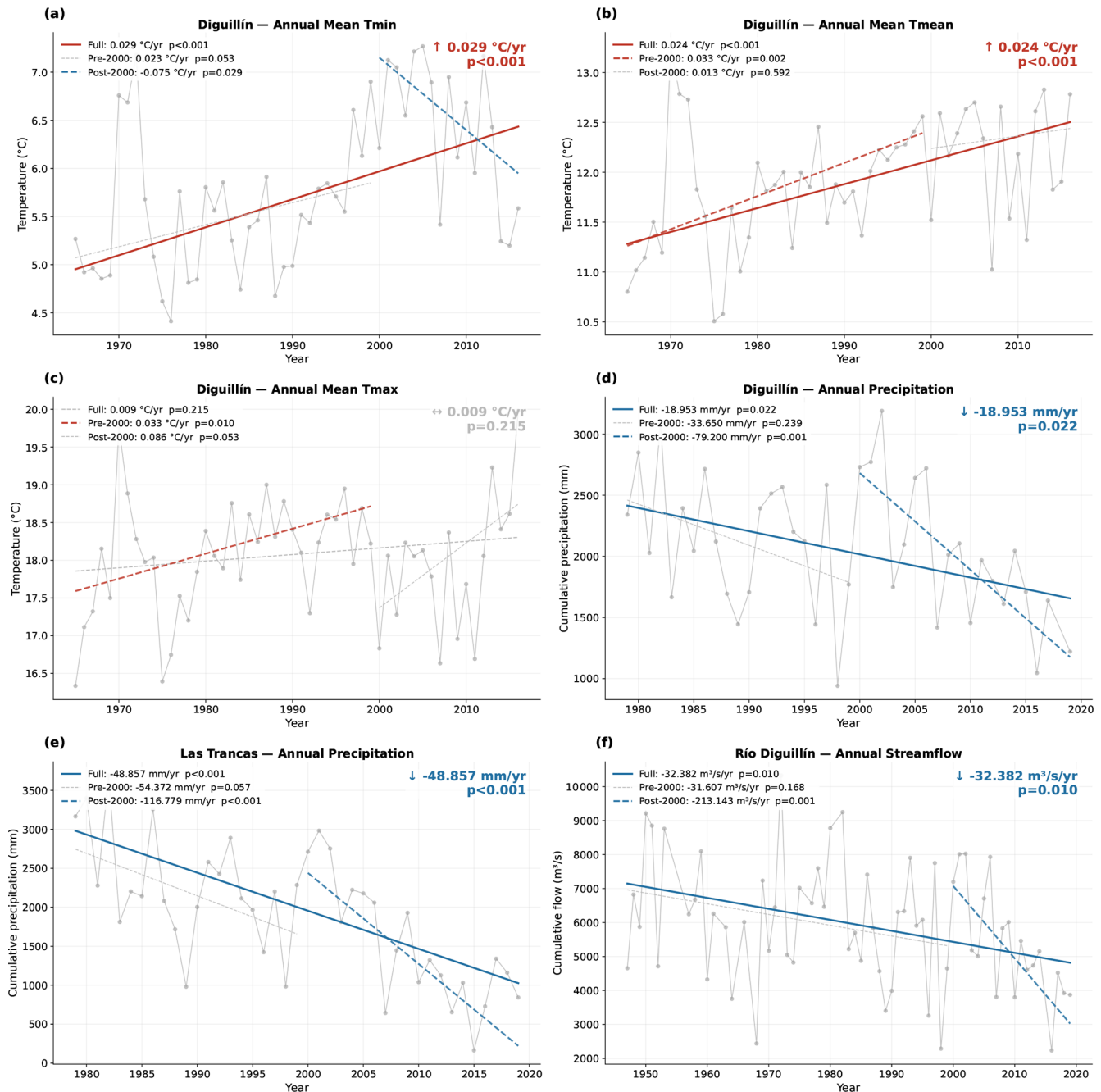


Figure 6. Sen's slope trend analysis of annual mean temperature (T_{min} , T_{mean} , T_{max}), cumulative precipitation, and cumulative streamflow at the Diguillín and Las Trancas meteorological stations. Trend lines are colored red (significant increase), blue (significant decrease), or grey dashed (non-significant). Pre- and post-2000 trends are shown as dashed lines where significant.

minimum temperature trends were not significant for any month.

Summertime (JFM) precipitation trends were mixed between stations (Fig. 8). At Las Trancas, JFM cumulative precipitation declined significantly over the full record (-2.39 mm yr^{-1} , $p = 0.019$), suggesting a measurable drying signal in the ablation season at the higher-elevation sta-

tion nearest the glaciers. At Diguillín, the summertime trend was negative but did not reach the significance threshold used in this study (-1.37 mm yr^{-1} , $p = 0.076$). This contrasts with the stronger and significant annual precipitation decline at both stations, indicating that the drying signal is primarily concentrated in the accumulation season rather than the ablation season.

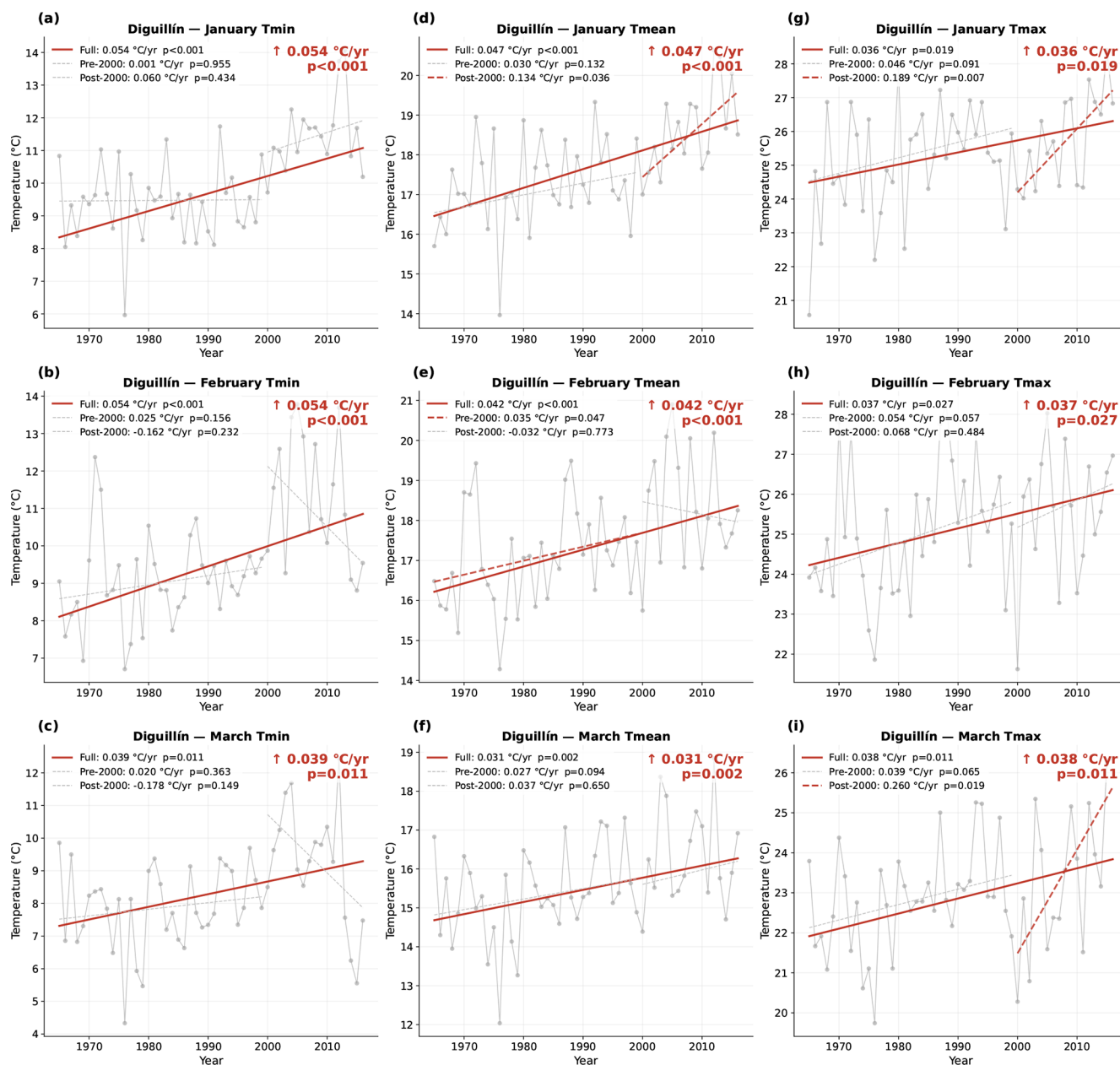


Figure 7. Sen's slope trend analysis of monthly summertime (JFM) minimum, mean, and maximum daily temperature at the Diguillín meteorological station. Trend lines are colored red (significant increase), blue (significant decrease), or grey dashed (non-significant). Pre- and post-2000 trends are shown as dashed lines where significant.

January streamflow decreased significantly over the full study period (Fig. 9A), and post-2000 February and March streamflow also decreased significantly (February: $-0.211 \text{ m}^3 \text{ s}^{-1} \text{ yr}^{-1}$, $p = 0.002$; March: $-0.117 \text{ m}^3 \text{ s}^{-1} \text{ yr}^{-1}$, $p = 0.012$) (Fig. 9B and C). February and March represent the months when seasonal snow has typically melted off, meaning that significant post-2000 decreases in streamflow during these months could be a result of decreased glacier melt.

Significant increases in post-2000 JFM maximum and mean temperatures (Fig. 7), and post-2000 decreases in February and March daily streamflow (Fig. 9B and C), may be related to the accelerating post-2000 glacier loss observed in this paper. Increasing summertime temperatures accelerate glacier melt, consistent with the increasingly negative glacier MB calculations observed across the complex. The decrease in post-2000 February and March streamflow (Fig. 9B and C) could indicate that the glaciers on Nevados de Chillán passed peak water, meaning that despite their increasing rate

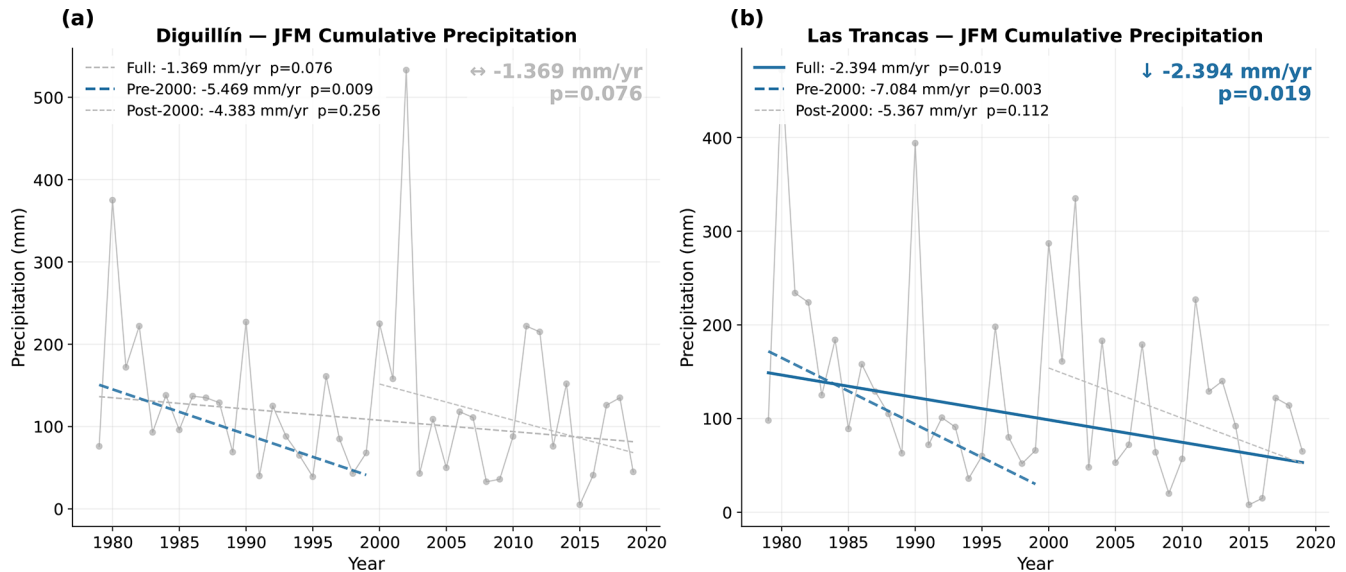


Figure 8. Sen's slope trend analysis of cumulative summertime (JFM) precipitation at the Las Trancas and Diguillín meteorological stations. Trend lines are colored blue (significant decrease) or grey dashed (non-significant). Pre- and post-2000 trends are shown as dashed lines where significant.

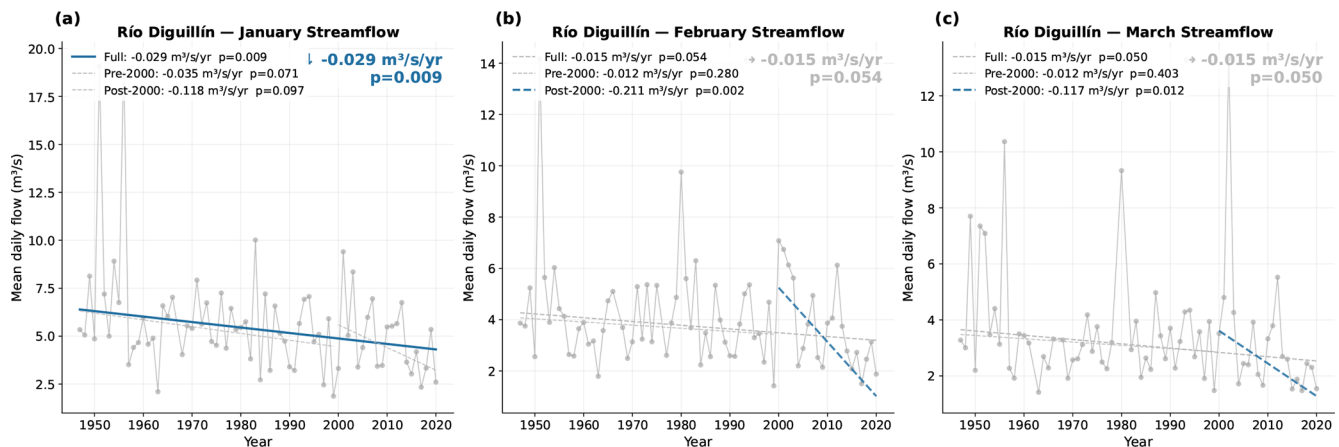


Figure 9. Sen's slope trend analysis of monthly summertime (JFM) mean daily streamflow at the Río Diguillín station. Trend lines are colored blue (significant decrease) or grey dashed (non-significant). Pre- and post-2000 trends are shown as dashed lines where significant.

of glacier mass loss over time, post-2000 streamflow contributions have decreased (Huss and Hock, 2018). However, an in-situ or modeling analysis of glacier melt contributions would be necessary to confirm this attribution, as declining streamflow is likely also attributable to seasonal precipitation trends.

5 Discussion

5.1 Findings and Implications

This study reports a negative MB trend across the entire Nevados de Chillán complex over the full study

period. For the full complex, mass loss accelerated from $-0.42 \pm 0.20 \text{ m w.e. yr}^{-1}$ (1954–2000) to $-0.60 \pm 0.38 \text{ m w.e. yr}^{-1}$ (2000–2025), corroborated by the ASTER 2018 estimate of $-0.61 \pm 0.06 \text{ m w.e. yr}^{-1}$ (2000–2018). While these results provide the first geodetic MB study of the full Nevados de Chillán complex, previous work by the DGA reports the mass balance of Glaciar Nevado from 2021–2022 and 2023–2024 (DGA, 2022, 2024). Our multi-decadal trends are substantially smaller in magnitude than short-term estimates reported by the DGA for 2021–2022 and 2023–2024, which were derived from four ablation stakes and partial (40%–60%) glacier UAV LiDAR coverage. The DGA's single-year measurements suggest extreme annual losses ($\sim -8 \text{ m}$

w.e. in 2021–2022 and ~ -7 m in 2023–2024), whereas their LiDAR estimates ranged from pronounced thinning (-5.37 m) to near-zero balance ($+0.02$ m), the latter likely reflecting an above-average snowfall year. In this case, the larger magnitude of the DGA's values likely stems from differences in temporal scale (single-year vs. this study's multi-decadal analysis), spatial coverage (40 %–60 % versus full glacier coverage), and limitations of spatial interpolation of point-scale measurements, whereas our record captures multi-decadal averages over the full complex. Here, we observed localized thinning of -40 to -60 m from 2000–2024 (Fig. 3), confirming that multi-meter annual losses can occur but do not represent long-term trends. Overall, the results from our complex-wide long-term glacier analysis are more consistent with regional geodetic studies across the southern Andes, suggesting that Nevados de Chillán's glaciers are responding in line with broader regional patterns.

Regional-scale geodetic glacier MB studies generally align more closely with our findings at Nevados de Chillán than the short-term DGA analyses described above. The Nevados de Chillán complex is included in broader studies conducted by Dussaillant et al. (2019), Braun et al. (2019), Zemp et al. (2019), and Hugonnet et al. (2021). Dussaillant et al. (2019) measured a mass balance ranging from -0.31 ± 0.19 m w.e. yr^{-1} in the Central Andes and -0.57 ± 0.22 m w.e. yr^{-1} in Northern Patagonia, between 2000–2018, with Nevados de Chillán located near the transition from the Central Andes to Northern Patagonia. We measured a mass balance of -0.61 ± 0.06 m w.e. yr^{-1} for Nevados de Chillán over the same period, indicating strong agreement between our studies. Braun et al. (2019) reported mass balance of just -0.05 ± 0.09 m w.e. yr^{-1} over 2000–2011/15 for the Chilean Lakes District (~ 35 – 42° S) (well below our results for 2000–2018), also encompassing the study area, whereas Zemp et al. (2019) reported the most negative mass balance of -1.18 ± 0.38 m w.e. yr^{-1} for 2006–2016 over the Southern Andes (approximately double our 2000–2018 measurement). Hugonnet et al. (2021) calculated a geodetic mass balance estimate of -0.67 ± 0.15 m w.e. yr^{-1} for the Southern Andes from 2000–2019, which is nearest to our post-2000 mass balance calculations for the Nevados de Chillán complex (-0.60 ± 0.38 m w.e. yr^{-1} from 2000–2025 and -0.61 ± 0.06 m w.e. yr^{-1} from 2000–2018). Nevados de Chillán lies within the study areas of these regional assessments, and our mass balance estimates are generally consistent with the ranges reported at the regional scale, despite differences in temporal coverage, glacier extent, and methodology, including whether area change is considered. The range of estimates across these studies reflects differences in spatial coverage, temporal period, and methodology, reinforcing the value of multiple independent assessments in identifying consensus rates of glacier change.

The results presented in this paper and others highlight the strong spatial variability of glacier mass balance in the Andes, emphasizing that local studies like ours are essential

for accurately constraining basin- and glacier-scale changes. Mountain-to-mountain variability, differences in observational methods, and temporal coverage all significantly influence mass balance estimates, making site-specific analyses critical for understanding glacier response and for informing local hydrological management. Long-term local geodetic records such as the one presented here remain comparatively rare in the Andes, despite the critical importance of glacier meltwater for downstream water security. Regional-scale studies necessarily aggregate across heterogeneous glacierized environments, masking the sub-complex spatial variability evident at Nevados de Chillán where volcanic geothermal forcing, eruption-driven debris deposition, and aspect-controlled solar radiation create local mass loss patterns that can diverge substantially from regional means. Site-specific long-term records are therefore essential both for understanding the local drivers of glacier change and for informing the water resource management decisions of downstream communities who depend on meltwater from these glaciers.

Though spatially and temporally heterogeneous, south-central Chile is experiencing both warming and drying trends on average as indicated by detailed analyses performed by Schumacher et al. (2020) and Lagos-Zúñiga et al. (2024) and supported by the analyses herein. The trends observed for the Las Trancas and Diguillín stations are in line with precipitation decreases and temperature increases observed in previous studies. For example, Martínez-Retureta et al. (2021) found similar trends from 1976–2016 in the Muco basin to the south of the study area. Climate change, in addition to the negative Pacific Decadal Oscillation phase and the El Niño phase, are all shown to contribute to the observed warming and drying trends (Boisier et al., 2016; Cordero et al., 2024; Garreaud et al., 2017). In particular, the Central-Andes Mega Drought caused accelerated decreases in mean annual precipitation (Boisier et al., 2016). Caro et al. (2024) found that climate presents higher explanatory power than topographic variables in the Andes, with precipitation exerting the strongest control on glacier mass balance. We found that annual cumulative precipitation decreased significantly at both stations over the full record (Diguillín: -19.0 mm yr^{-1} , $p = 0.022$; Las Trancas: -48.9 mm yr^{-1} , $p < 0.001$), with the rate of decline accelerating markedly after 2000 (Diguillín: -79.2 mm yr^{-1} ; Las Trancas: -116.8 mm yr^{-1}).

Average annual minimum and mean temperatures increased significantly for the Diguillín station near Nevados de Chillán (Fig. 7), while trends in average annual maximum temperatures were not significant (Fig. 6). We found that January, February, and March maximum, minimum, and mean monthly temperatures are increasing substantially for the station nearest to Nevados de Chillán over the full study period (Fig. 7). Post-2000 mean and maximum monthly temperature increases have accelerated in January and March at Diguillín (Fig. 7D, G, F, and I). Caro et al. (2024) also found that temperature increases have accelerated in recent years compared to historic temperature regimes, though over a different pe-

riod than our analysis, finding that mean annual temperatures increased by 0.3 °C from 2010–2014, compared to 1979–2014. In addition to a shift in precipitation from snowfall to rainfall, extreme droughts are increasing in south-central Chile (Poveda et al., 2020).

The analysis herein indicated that streamflow decreased over the full study period (Fig. 6F), with significant reductions in post-2000 February and March streamflow and annual cumulative discharge (Figs. 9B and C, 6F). This decline is consistent with the glaciers on Nevados de Chillán having passed peak water, meaning that meltwater contributions are now decreasing despite accelerated mass loss (Huss and Hock, 2018). Although rising summertime (JFM) temperatures (Fig. 7) have increased the rate of vertical melt (m w.e. yr^{-1}), the glaciers have lost substantial surface area and total ice volume, so a faster rate of thinning is occurring over a much smaller ice reservoir. As a result, the total volume of melt available for runoff decreases, even while the calculated mass balance becomes more negative. McCarthy et al. (2022) and Ragettli et al. (2016) found that Juncal and Maipo catchments in central Chile, which contribute water to Santiago, have passed peak water. A similar in-situ or modeling analysis of glacier melt contributions for our study area would be necessary to confirm that streamflow reductions are attributable to glacier mass loss, as opposed to other hydrological inputs, but our findings suggest that glacier retreat has progressed to a stage where declining ice volume has begun to reduce relative meltwater contributions to streamflow.

Another potential attribution for glacier mass patterns on Nevados de Chillán is volcanic activity. It is yet unknown whether ice-lava interaction and/or the impact of thin deposition of volcanic tephra decreasing the albedo of glacier surface have impacted glacier melt on the Nevados de Chillán complex. Volcanic activity on the Las Termas subcomplex increased dramatically from 2016–2019 (Global Volcanism Program, 2022). More recently, from June–October 2022, over 1000 explosive volcanic events were reported from the Nicanor crater on the Las Termas subcomplex (Global Volcanism Program, 2022). Some of these events triggered pyroclastic flows and avalanches, as well as substantial debris deposition on glacier surfaces (Novoa Lizama et al., 2025). Debris cover is a rapidly developing area of glacier research. In the case of thin and/or discontinuous debris, ablation typically increases due to the lower albedo of debris (rock, sand, dust, or ash) compared to snow and ice (Brock et al., 2007). The decreased albedo causes an increase in the ratio of radiation absorbed to reflected, causing an increase in glacier surface melt (Rivera et al., 2006; Wigmore and Mark, 2017; Rounce et al., 2021; Rossini et al., 2023). Given the similar flow topography of pyroclastic and lahar deposits, and debris-covered glaciers, it is difficult to tell from remote imagery whether some glaciers on the Las Termas subcomplex are now debris-covered or have disappeared altogether. Future work should be done to determine the extent of debris

cover on Nevados de Chillán and the impact on glacier mass balance.

5.2 Limitations and Assumptions

The availability of glacier outlines for 1975, 2000, and 2019 provided three reference datasets for mass balance calculation. For 1954-based epochs, mean glacier area was computed as the arithmetic mean of the 1975 (DGA, 2011) start area and the 2000 (DGA, 2014) end area following the mean area approach following Zemp et al. (2019), as the 1975 inventory represents the closest available approximation to the 1954 ice extent. For 2000-based epochs, the arithmetic mean of the 2000 (DGA, 2014) and 2019 (DGA, 2022) areas was used. While these inventories provide the best available approximation of glacier area for each epoch, they do not capture continuous area change over time, meaning that mean annual mass balance estimates remain reliant primarily on vertical ice thinning measurements. Future studies would benefit from exploring glacier mass balance on finer time resolutions to isolate the impacts of volcanic eruptions, tectonic uplift, anthropogenic climate change, and regional climate variability on interannual glacier mass balance.

The reliance on five DEMs to reconstruct seven decades of glacier mass balance does not illuminate interannual fluctuations (Rabatel et al., 2017). Thus, our calculation of mean annual mass balance from total estimated mass balance should be used with caution (Rabatel et al., 2017). This approach, however, is widely accepted for geodetic mass balance estimates of mountain glaciers, given the scarcity of DEM products for these regions (e.g. Fariás-Barahona et al., 2019). Similar studies show high agreement between geodetic measurements from remotely sensed DEMs and in-situ MB measurements (Beraud et al., 2023). Thus, remotely sensed DEMs provide an excellent option to compute glacier-wide mass balance in the absence of detailed in-situ measurements.

While differencing DEMs enabled the calculation of glacier mass balance, estimating geodetic mass balance relied on the established estimation of mean glacier density of 850 kg m^{-3} , rather than accounting for variations in density across glacier area and time (Huss, 2013; Fariás-Barahona et al., 2019). However, Huss (2013) indicated that errors inherent to ice density assumptions decrease with longer-scale geodetic studies. In the case of this study, our 70-year analysis period far exceeds the suggestion by Huss (2013) of > 5–10 years to reduce mean glacier density estimation error.

Another limitation of this study is that only the western/southwestern glaciers were surveyed in 2024 with the UAV campaign, due to logistical and weather limitations. The addition of the Pléiades 2025 DEM addresses this limitation for full-complex mass balance from 2000–2025, providing coverage of all 28 inventoried glaciers. However, UAV-derived subcomplex-level estimates for 2000–2024 remain available for only 11 of the 28 inventoried glaciers. Mass balance from

1954–2000 and 2000–2024 was only compared for these 11 glaciers for the sake of consistency, whereas complex-wide mass balance was computed for 1954–2000, 2000–2018, and 2000–2025.

The existing studies on Nevados de Chillán exclusively focus on the clean ice glaciers, failing to account for the presence of debris cover which is evident on the complex, and is likely due to both rock slides and eruptions from the Las Termas subcomplex depositing volcanic ash, tephra, and other debris on the glacier surfaces (Zenteno, 2008; Caro, 2014). Frequent eruption events make it particularly difficult to distinguish pyroclastic and lahar deposits from debris-covered glaciers. Due to the difficulty in accurately delineating current debris-covered glacier extent, in addition to the difficulty of distinguishing snow patches from glacier ice, we did not estimate current glacier extent. By relying on the 2019 glacier outline as our most recent glacier area, we likely overestimated post-2019 glacier area, resulting in a conservative estimate of recent glacier mass loss. Additionally, this geodetic mass balance approach measures the ground surface height within the 2000 and 2019 glacier boundaries without accounting for debris thickness, meaning that results may underestimate glacier loss where the actual glacier surface is covered by debris.

An additional limitation of this study is due to the active volcanic and tectonic activity on Nevados de Chillán, as it pertains to our comparison of DEMs. First, in 2010 an 8.8 moment magnitude (M_w) earthquake in the neighboring region of Maule caused plate subsidence in the Chilean central valley, and uplift in the Andes Mountain range of up to 20 cm, from 33 to 40° S (Li et al., 2017). In effect, our 2018, 2024, and 2025 DEMs are subject to additional uncertainty after co-registration due to possible uplift of the Nevados de Chillán volcanic complex. Given that a strong glacier melt signal was measured post-2000 in this study, the effect of tectonic uplift on our DEMs would imply that we may underestimate recent glacier melt. Additionally, studying the most recent active period of Nevados de Chillán from January 2016–2023, Novoa Lizama et al. (2025) reported that there was a period of either no change or slight topographic subsidence during the first three years of the eruption, with a maximum subsidence of 0.8 cm yr^{-1} measured. This period was followed by significant uplift from 2019–2022, with stations ranging from a total observed vertical displacement of $\sim 5\text{--}25 \text{ cm}$ (Novoa Lizama et al., 2025). This recent uplift was attributed to increased magma flow from a deeper to a shallower reservoir (Novoa Lizama et al., 2025). Importantly, this implies that surface elevation presented in our post-2000 DEMs may further underestimate glacier surface elevation decrease. To summarize, both earthquake and volcanic activity in the study area have likely resulted in a net uplift of between $\sim 0\text{--}45 \text{ cm}$ in Nevados de Chillán's topography since the year 2000.

Although the assumptions discussed above introduce some uncertainty, because tectonic uplift and supraglacial debris deposition likely contributed to increases in surface elevation, the reported estimates of mean glacier loss should be considered conservative, potentially underrepresenting the true extent of glacier volume loss. This finding highlights the challenging nature of applying glacier mass balance analyses to glacierized volcanic environments. These settings are rarely considered in the existing literature, emphasizing both the novelty of this study and the need for further research focused on glaciers in volcanic regions.

6 Conclusion

This study provides the first long-term geodetic mass balance record for the glaciers of the Nevados de Chillán volcanic complex in south-central Chile, directly addressing the need to quantify how glacier mass loss has evolved in this region. Our 71-year record shows that glaciers across the complex have experienced sustained and accelerating mass loss since 1954, with greater losses on the Cerro Blanco subcomplex than on Las Termas. From 1954–2000, the full complex lost ice at a mean rate of $-0.42 \pm 0.20 \text{ m w.e. yr}^{-1}$. Losses intensified significantly after 2000, reaching $-0.60 \pm 0.38 \text{ m w.e. yr}^{-1}$ from 2000–2025 (Pléiades), corroborated by the ASTER 2018 estimate of $-0.61 \pm 0.06 \text{ m w.e. yr}^{-1}$ for 2000–2018. From 2000–2024, the Cerro Blanco subcomplex lost mass at $-0.54 \pm 0.30 \text{ m w.e. yr}^{-1}$ and Las Termas at $-0.48 \pm 0.17 \text{ m w.e. yr}^{-1}$. The Las Termas subcomplex showed a lower mass loss rate from 2018–2024 ($-0.32 \pm 0.19 \text{ m w.e. yr}^{-1}$), though this difference does not clearly exceed the combined measurement uncertainty ($\pm 0.20 \text{ m w.e. yr}^{-1}$). These results illustrate that recent glacier retreat is not uniform across the complex and that glacier loss has accelerated since 2000.

By establishing the magnitude and spatial variability of glacier mass loss at Nevados de Chillán, the work herein provides a benchmark against which future change can be assessed and offers a necessary foundation for understanding downstream implications. This study found that declining summertime streamflow coincided with accelerated glacier loss, however, quantifying the contribution of glacier melt to river discharge remains a key task for future studies. Our results clarify the rate at which glacier volume is disappearing on Nevados de Chillán, providing critical data to support water management and drought mitigation efforts.

Appendix A

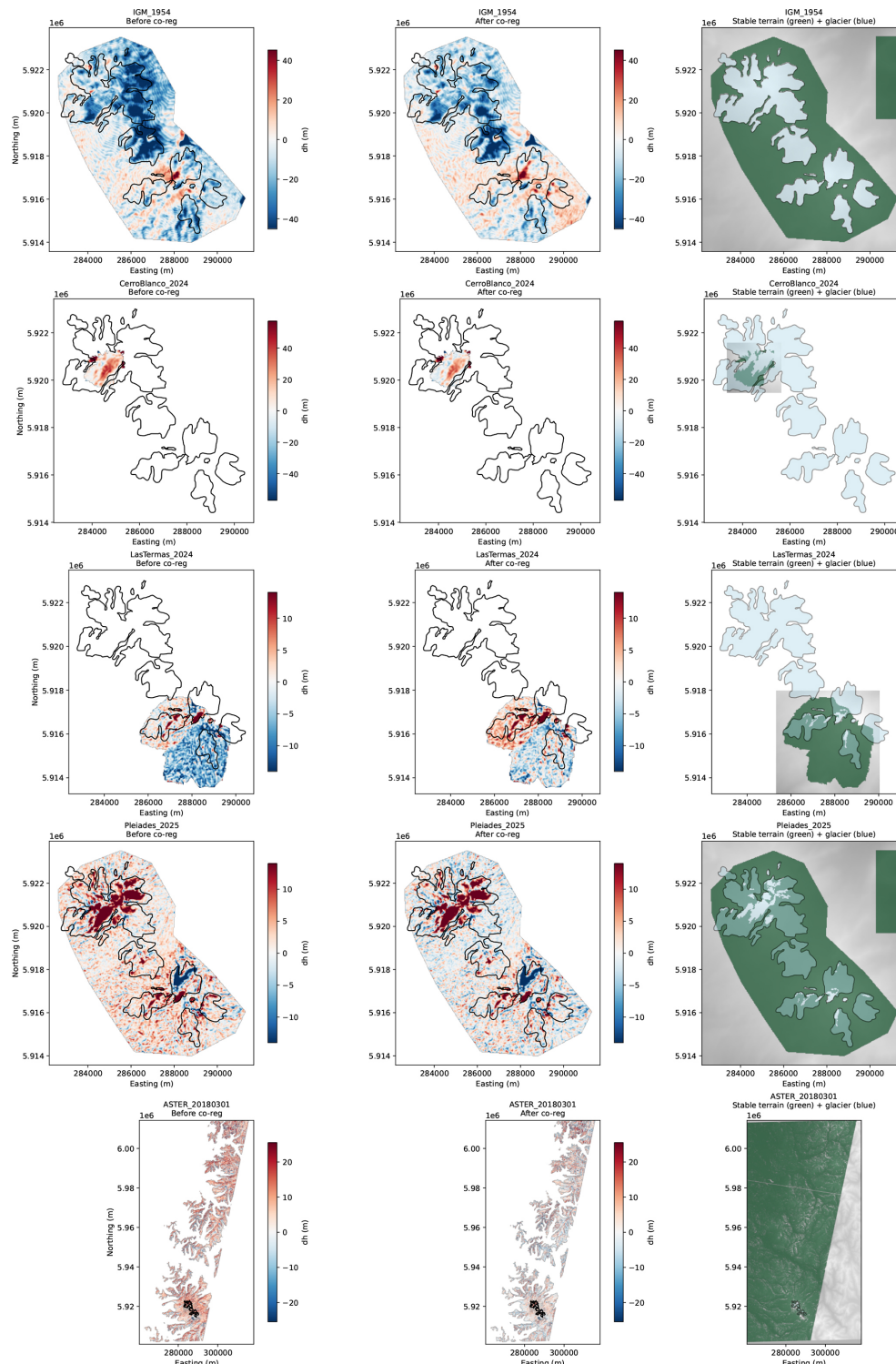


Figure A1. Co-registration quality control maps for all DEMs co-registered to the SRTM 2000 reference. For each DEM, three panels are shown: elevation difference (dh) before co-registration (left), elevation difference after co-registration (center), and stable terrain used for co-registration (green) overlaid on the reference DEM with glacier areas shown in blue (right). Rows show IGM 1954, Cerro Blanco UAV 2024, Las Termas UAV 2024, Pléiades 2025, and ASTER 2018. Basemap: © OpenTopoMap contributors.

Appendix B

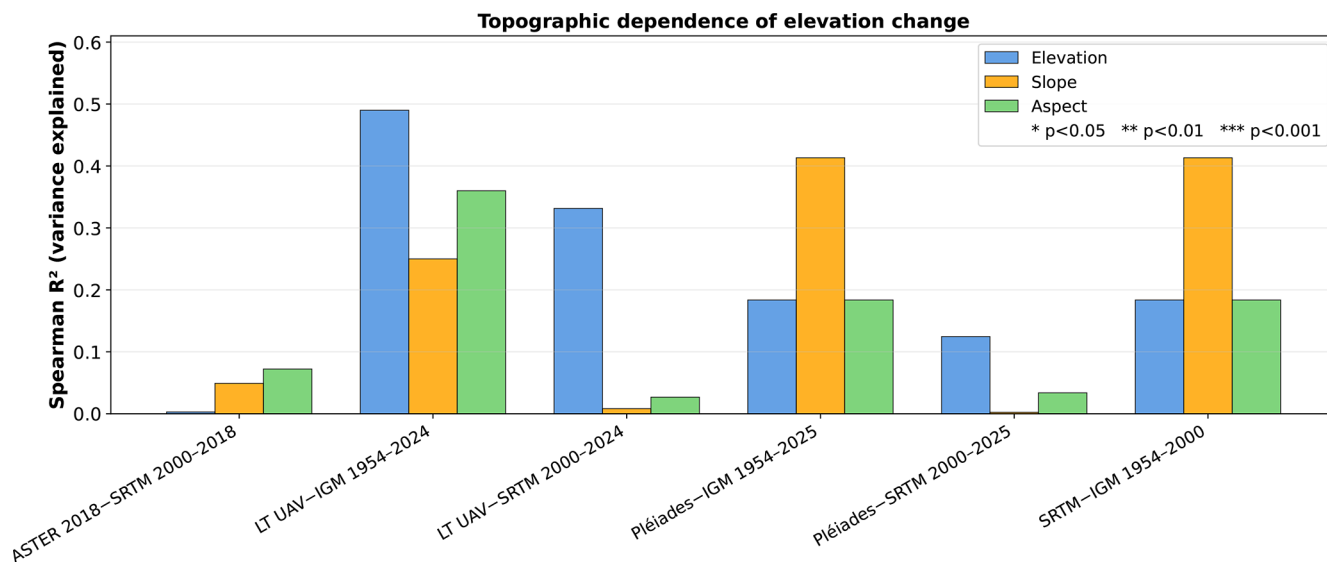


Figure B1. Spearman rank correlation (R^2) between glacier-scale mean elevation change (Δh) and topographic variables (mean elevation, slope, and aspect) across all epochs and subcomplexes. No correlations reached statistical significance ($p > 0.05$ in all cases), suggesting that topographic variables are weak predictors of glacier mass loss at Nevados de Chillán, consistent with dominant volcanic and radiation forcing at this complex.

Appendix C

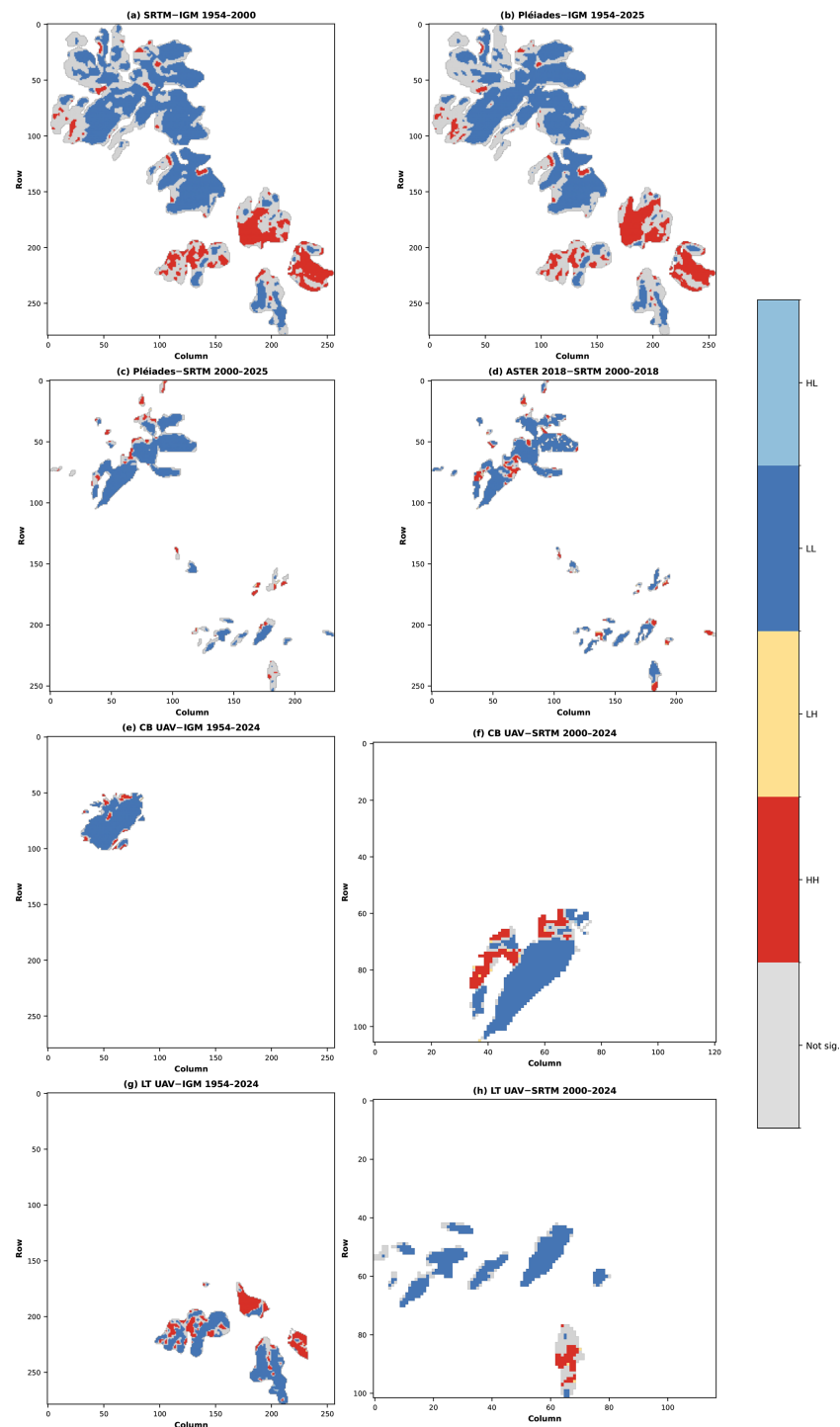


Figure C1. Global and Local Moran's I analysis of spatial autocorrelation in glacier elevation change (Δh) across all epochs. Global Moran's I values (range 0.71–0.96, $p = 0.001$ in all cases) confirm significant positive spatial autocorrelation across all epochs. Local Moran's I (LISA) maps show the spatial distribution of significant clusters: high-high (HH, red) indicates areas of high mass loss surrounded by high mass loss; low-low (LL, blue) indicates areas of low mass loss surrounded by low mass loss; low-high (LH) and high-low (HL) indicate spatial outliers. Non-significant pixels are shown in grey.

Code and data availability. The data and code utilized in this paper can be found at <https://github.com/millie-spencer/Seven-Decades-Glacier-Loss-Nevados-Chillan> (last access: 17 August 2026) and are hosted at: <https://doi.org/10.5281/zenodo.21987345> (Spencer, 2026).

Author contributions. MS, RC, EM, and AF designed the field-work plan. MS and RC carried out the fieldwork and processed the UAV images. AF provided the IGM DEM and advised research methodology. JB postprocessed the Pléiades DEM obtained from the Chilean Water Authority (DGA) under the Chilean Transparency Act. PM advised on hydroclimate analysis. MS developed model code and performed DEM analysis with assistance from ET. MS produced the figures and prepared the manuscript with contributions from all co-authors.

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

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