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# Hydrological Response of Andean Catchments to Recent Glacier Mass Loss

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**Abstract.** The impacts of the accelerated glacier retreat in recent decades on runoff changes are still unknown in most Andean catchments, thereby increasing uncertainties in estimating and managing water availability. Here, we used a monthly time step to simulate glacier evolution and related runoff changes for 36% of the glacierized surface area of the Andes (11,282 km$^2$ in 786 catchments, 11°N-55°S) using the Open Global Glacier Model (OGGM) and a corrected and evaluated version of the TerraClimate dataset between 2000 and 2019. The glacier mass balance and volume were calibrated glacier-by-glacier. The simulation results were evaluated with in situ data in three documented catchments and 15 glaciers. Our results show that the glacier volume (-8.3%) and surface area (-2.2%) are reduced in 93% of the catchments between the periods 2000-2009 and 2010-2019. This glacier loss is associated with changes in climate conditions (precipitation = -9%; temperature = +0.4 ± 0.1°C) inducing an increase in the mean annual glacier melt of 12% (86.5 m$^3$/s) and a decrease in the mean annual rainfall on glaciers of -2% (-7.6 m$^3$/s). We find a regional pattern in the melt factors showing decreasing values from the Tropical Andes toward the Wet Andes. A negative mass balance trend is estimated in the three documented catchments (glacierized surface area > 8%), showing the largest mean glacier contribution during the transition season (September-November) in La Paz (Bolivia) (45%) followed by Baker (Chile) (43%) and Maipo (Chile) (36%) during the summer season (January-March). In addition, our evaluation in the monitored glaciers indicates an underestimation of the mean simulated mass balance by 185 mm w.e. yr$^{-1}$ and a high mean correlation (r = 0.7). We conclude that the large increases in the simulated glacier melt in the Dry Andes (36%) and the Tropical Andes (24%) have helped to improve our knowledge of the hydro-glaciological characteristics at a much wider scale than previous studies, which focused more on a few select catchments in the Andes.

## 1 Introduction

The largest ice concentration in the southern hemisphere outside the Antarctic ice sheet is found in the Andes (RGI Consortium, 2017). Andean glaciers provide the water supply for roughly 45% of the population in the Andean countries (Devenish and Gianella, 2012) and for ecosystems (Zimmer et al., 2018; Cauvy-Fraunié and Dangles, 2019). They have been affected by a continuous shrinkage since the late 1970s, which has intensified during the last two decades (Rabatel et al., 2013; Dussaillant et al., 2019; Masiokas et al., 2020). Glacier volume loss has

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helped modulate river discharges, mainly in dry seasons (*e.g.*, Baraer et al., 2012; Soruco et al., 2015; Guido et al., 2016; Ayala et al., 2020).

Several studies have estimated glacier changes and their effects on hydrology using observation or modeling focused on specific Andean catchments. For instance, Huss and Hock (2018) studied 11 Andean catchments (1980-2100) and found an increase in glacier runoff in the Tropical and Dry Andes, but a more contrasted signal in the Wet Andes: no glacier runoff changes were observed in some catchments, whereas others showed a reduction or an increase. In the Tropical Andes, the glacier contribution at the annual scale was estimated to be approximately 12% and 15% in the Río Santa (9°S) and La Paz (16°S) catchments, respectively (Mark and Seltzer, 2003; Soruco et al., 2015). For the La Paz catchment, Soruco et al. (2015) found no change in the glacier runoff contribution for the period 1997-2006 compared with the longer 1963-2006 period. This was attributed to the fact that the glacier surface reduction over the time-period was compensated by their increasingly negative mass balance. In the Dry Andes, the Huasco (29°S), Aconcagua (33°S) and Maipo (34°S) catchments showed a glacier contribution comprised between 3 and 23% for different catchment sizes between 241 and 4843 km$^2$ (Gascoin et al., 2011; Ragettli and Pellicciotti, 2012; Ayala et al., 2020). These catchments had mainly negative glacier mass balances which were slightly interrupted during El Niño episodes (2000-2008 period), thereby reducing glacier runoff. In the Wet Andes, Dussaillant et al. (2012) estimated that some catchments in the Northern Patagonian Icefield are strongly conditioned by glacier melting. Despite this, Hock and Huss (2018) did not identify changes in the glacier runoff of the Baker catchment since 1980-2000. Given that these studies are focused on only a few catchments, these local estimations can hardly be seen as representative across the Andes, especially since glacierized catchments can be characterized by major climatic and topographic differences (Caro et al., 2021).

Nowadays, the availability of global glaciological products such as glacier surface elevation differences and glacier volume estimation (Farinotti et al., 2019; Hugonnet et al., 2021; Millan et al., 2022) allows for large-scale glacio-hydrological simulations with the possibility to accurately calibrate and validate numerical models at the catchment scale. In addition, models such as the Open Global Glacier Model (OGGM, Maussion et al., 2019) have been implemented to simulate the glacier mass balance and glacier dynamics at a global scale. Therefore, OGGM and the glaciological global dataset, in combination with in situ meteorological and glaciological measurements, can be used to precisely quantify the glacier retreat and its hydrological responses at the catchment scale across the Andes, while taking the related uncertainties into account.

Here, using OGGM, we estimate the glacier changes (area and volume) and the consecutive hydrological responses (from glacier melt [ice melt and snow melt] and rainfall on glaciers) for 786 catchments across the Andes (11°N-55°S) with a glacierized surface of at least 0.01% for the period 2000-2019. The model was run with monthly air temperature and precipitation data from the TerraClimate dataset (Abatzoglou et al., 2018) that were corrected using weather station records and mass balances measured on monitored glaciers. Our spatial analysis was performed at the catchment scale using the glaciological zones of the Andes defined in Caro et al. (2021); however, we simulated the glaciological and runoff processes at the glacier scale.

Section 2 presents the data and methods. In Section 3, we describe the glacier changes and hydrological responses at the glaciological zone and catchment scales across the Andes. In Section 4, we discuss our results and the main steps forward compared to previous research.

## 2 Data and methods

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### 2.1 Data collection and preprocessing

#### 2.1.1 Historical climate data

We used two climate datasets: the TerraClimate reanalysis and in situ measurements from meteorological stations. TerraClimate is based on reanalysis data since 1958, with a 4 km grid size at a monthly time scale, and was validated with the Global Historical Climatology Network (temperature, r = 0.95, MAE = 0.32°C; precipitation, r = 0.9, MEA = 9.1%) (Abatzoglou et al., 2018). The mean temperature was estimated from the maximum and minimum temperature whereas precipitation data is accumulated on a monthly basis. The meteorological records were compiled from Andean organizations and scientific reports (Rabatel et al., 2011; MacDonnell et al., 2013; Schaefer et al., 2017; CECs, 2018; Shaw et al., 2020; Hernández et al., 2021; CEAZA, 2022; DGA, 2022; GLACIOCLIM, 2022; IANIGLA, 2022; Mateo et al., 2022; Senamhi, 2022). The mean monthly air temperature measurements were taken from 35 off-glacier and on-glacier meteorological stations, the latter of which are rare. The location and main properties of the meteorological stations are shown in Supplementary Table S1.

#### 2.1.2 Climatic data correction and evaluation

For the temperature variable, we first quantified the local vertical annual temperature lapse rates using the in situ measurements for 33 sites across the Andes (see Table and Figure S1). Then, the TerraClimate temperature was corrected with these in situ records so that they could be used in the simulations. Last, the corrected TerraClimate temperature was evaluated via a comparison with the 34 situ data. Conversely, the precipitation variable from the TerraClimate reanalysis was scaled using the mass balance measurements for 10 monitored glaciers and was evaluated for 15 glaciers (see Tables S3, S4 and S5).

Vertical temperature lapse rates (temperature LRs) from the in situ records were estimated for each glaciological zone across the Andes as per Gao et al. (2012). The temperature LRs are presented in Figure S1. These gradients were applied to correct the raw TerraClimate temperature on the glaciers ($rTC_t$). The corrected TerraClimate temperature at the mean glacier elevation or in glacier catchments ($cTC_t$) was calculated using the following equation:

$$cTC_t = rTC_t + \Gamma * \Delta h \,, \quad (1)$$

where $\Gamma$ is the temperature LR estimated here, and $\Delta h$ is the elevation difference between a glacier inside a TerraClimate grid and the mean TerraClimate grid elevation.

Then, we assessed the $cTC_t$ in meteorological station locations (9°S-51°S) on a monthly scale, paying attention to the monthly variability in temperature as well as to the mean temperature for all the periods with data. The $cTC_t$ monthly mean variability was evaluated using the Pearson correlation coefficient, whereas the mean temperature for the whole period considered the mean difference between $cTC_t$ and the observed temperature (biases). These results are available in Table S2 and Figure S2.

In addition, the precipitation was scaled ($cTC_p$) using precipitation factors ($Pf$) for each glaciological zone across the Andes. We ran 31 simulations for 18 glaciers with mass balance measurements across the Andes using $Pf$ values between 1 and 4 taking previous studies into account (Masiokas et al., 2016; Burger et al., 2019; Farías-Barahona et al., 2020). In the end, 10 glaciers were selected (see Table S3). The goal was to find the closest simulated mass balance standard deviation in comparison with the measured mass balance standard deviation using

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different *Pf* values (Equation 2). A similar methodology was proposed by Marzeion et al. (2012) and Maussion et al. (2019). The results of the closest simulated mass balance standard deviations and associated *Pf* are presented in Supplementary Table S3. The simulated annual mass balance was evaluated on 15 monitored glaciers using a similar methodology as that for the $cTC_t$ evaluation. In addition, details such as snow/rainfall partitioning are described hereafter and in the model implementation (2.2. section).

$$Pf = \{ 1 \leq Pf \leq 4 \ : simSD_{mb} \approx obsSD_{mb} \} , \qquad (2)$$

### 2.1.3 Glacier data

**Glacier inventory**

We used version 6.0 of the Randolph Glacier Inventory (RGI Consortium, 2017) to extract the characteristics of each glacier, *e.g.*, location, area, glacier front in land or water. The RGI v6.0 was checked using the national glacier inventories compiled by Caro et al. (2021), filtering every RGI glacier that was not found in the NGI, to obtain a total glacierized surface area of 30,943 km$^2$ (filtering 633 km$^2$). The glacier extent in the RGI v6.0 is representative of the early 2000s.

**Glacier mass balance**

The mass balance datasets were comprised of the global glacier surface elevation change product of Hugonnet et al. (2021) and in situ measurements of the glacier surface mass balance since 2000 from different institutions (e.g., Marangunic et al., 2021; WGMS, 2021). Hugonnet et al.'s (2021) product was quantified for each glacier using the OGGM toolbox. Then, the geodetic mass balance estimates were obtained for every glacier of the RGI v6.0. In situ measurements of the glacier surface mass balance available for all glaciological regions (Tropical Andes, Dry Andes and Wet Andes) were collected at the hydrological year scale (dates vary according to the latitude). The location and main characteristics of the 18 monitored glaciers are shown in Supplementary Table S4.

**Glacier volume**

The global glacier ice thickness product of Farinotti et al. (2019) was used for calibrated each glacier of the RGI v6.0 in OGGM. Farinotti et al. (2019) pooled the outputs of five different models to determine the distribution of the ice thickness on 215,000 glaciers outside the Greenland and Antarctic ice sheets.

### 2.1.4 Glaciological zones and catchments

Eleven glaciological zones across the Andes were compiled from Caro et al. (2021) and all glaciers northward of the Outer Tropics were considered as zone number 12, called the Inner Tropics. To identify the glacierized area in each catchment, a spatial intersection was made between the glaciers identified in the filtered RGI v6.0 and the Level 9 HydroSHEDS catchments (Lehner et al., 2006). Then, we considered catchments with a glacierized surface area >= 0.01% (max = 62%, mean = 5%). We selected 786 catchments with a surface area between 3,236 and 20 km$^2$ across the Andes (11°N-55°S), including 13,179 glaciers with a total surface area of 11,282 km$^2$ (36% of the total glacierized surface area in the Andes).

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Calving glaciers (fresh and tide terminating, 15,444 km$^2$), primarily located in the Northern and Southern Patagonian Icefields and in the Cordillera Darwin, were not considered as the calving process is not currently implemented in this OGGM version. The glaciers that were not simulated for the internal model inconsistencies account for less than 1% of the total glacierized surface area. The other remaining 4,514 km$^2$ filtered glacierized surface area corresponds to glacierized catchments that present contradictory variations in terms of glacier volume and surface area. Only 59 km$^2$ was associated with glaciers filtered in the OT1 zone.

We selected the La Paz (Soruco et al., 2015), Maipo (Ayala et al., 2020) and Baker (Dussaillant et al., 2012) catchments located in glaciological regions with different climatic and morphometric characteristics (Caro et al., 2021). In these catchments, previous hydro-glaciological studies have quantified the impact of glacier changes and its hydrological contribution. In addition, river discharge records were collected from Soruco et al. (2015) and the CAMELS-CL project (Alvarez-Garreton et al., 2018) for Bolivia and Chile, respectively. In Bolivia, we considered the four glacierized head catchments providing water to the La Paz catchment: Tuni-Condoriri, Milluni, Hampaturi and Incachaca (discharge records from 2001 to 2007) with a total surface area of 227 km$^2$ and 7.5% of the glacierized surface area (mean elevation of 5,019 m a.s.l.). In Chile, for the Maipo catchment, we compiled records from Río Maipo at the El Manzano station (id = 5710001; 4839 km$^2$; discharge records from 1990 to 2019) and Río Mapocho at the Los Almendros catchments (id = 5722002; 638 km$^2$; discharge records from 1990 to 2019) with a glacierized surface area of 7.5% (mean elevation of 4,259 m a.s.l.). For the Baker catchment, we used the Río Baker Bajo Ñadis records (id = 11545000; 27403 km$^2$; discharge records from 2004 to 2019), considering a glacierized surface area of 8.2% (mean elevation of 1,612 m a.s.l.). Note that only the glacier contribution will be simulated.

### 2.2 Short description of the OGGM

We used the OGGM model (Maussion et al., 2019) across the Andes. OGGM is a modular and open-source numerical workflow implemented in Python that contains enough default input data to simulate the glacier mass balance and ice dynamics using calibrated parameter values for each glacier entity individually. The spatio-temporal configuration used in this study is the glacierized catchment and the monthly time step.

The required input data for running the model are as follows: air temperature and precipitation time series, and glacier outlines and surface topography for specific years. From these input data, it is possible to obtain annual outputs such as the surface mass balance, glacier volume and area and monthly glacier melt (snow and ice) and rainfall on glaciers (Figure 1). The geodetic mass balance rate and the glacier volume parameters were calibrated. First, using a glacier outline and topography, OGGM estimates the flow lines and catchments per glacier, and then the flow lines are calculated using a geometrical algorithm (adapted from Kienholz et al., 2014). Assuming a bed shape, it estimates the ice thickness based on mass conservation and shallow-ice approximation (Farinotti et al., 2017). After these numerical steps, it is possible to determine the area and volume per glacier. The mass balance is implemented using a precipitation phase partitioning and a temperature index approach (Braun and Renner, 1992; Hock, 2003; Marzeion et al., 2012). The monthly mass balance $mb_i$ at an elevation z is calculated as follows:

$$mb_i(z) = TC_{p\,i}^{snow}(z) * P_f - M_f * max(cTC_{t\,i}(z) - T_{melt}, 0), \quad (3)$$

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Where $TC_{p\,i}^{snow}$ is the TerraClimate solid precipitation before being scaled by the precipitation correction factor ($P_f$), $M_f$ is the glacier's temperature melt factor, $cTC_{t\,i}$ is the monthly corrected TerraClimate temperature, and $T_{melt}$ is the monthly air temperature above which ice melt is assumed to occur (from 0°C to 2.1 °C). $TC_{p\,i}^{snow}$ is calculated as a fraction of the total precipitation ($cTC_p$ ) where 100% is obtained if $cTC_{t\,i}$ <= $T_i^{snow}$ (between 0-2.1°C) and 0% if $cTC_{t\,i}$ >= $T_i^{rain}$ (between 2-4.1 °C), using a linear regression between these temperature thresholds to obtain the solid/liquid precipitation fraction. Here, $M_f$ was calibrated for each glacier individually using the previously described glacier volume change datasets (Hugonnet et al., 2021). The calibrated parameter values are summarized by glaciological zone in Table 1.

**Table 1. Calibrated parameter values used in the glacier mass balance and volume simulations across the Andes (11°N-55°S) during the period 2000-2019**

| Region | Zone | Mass balance parameter values | | | | | | Volume parameter |
|---|---|---|---|---|---|---|---|---|
| | | Temperature LR [ºC/m a.s.l.] | Precipitation factor [-] | Mean melt factor [mm mth$^{-1}$ ºC$^{-1}$] | Temperature for melt onset [ºC] | Temperature at start of snowfall [ºC] | Temperature at start of rainfall [ºC] | Glen A inversion |
| | IT | | | 434 | | | | 2.4 10$^{-23}$ |
| Tropical Andes | OT2 | -0.0066 | 1 | 284 | 2.1 | 2.1 | 4.1 | 6.3 10$^{-24}$ |
| | OT3 | | | 432 | | | | 1.2 10$^{-23}$ |
| | DA1 | -0.0082 | 2.8 | 418 | | | | 2.4 10$^{-25}$ |
| Dry Andes | DA2 | -0.0065 | 1.9 | 479 | | | | 1.3 10$^{-23}$ |
| | DA3 | -0.0063 | 4 | 299 | | | | 2 10$^{-24}$ |
| | WA1 | -0.0051 | 4 | 103 | | | | 1.7 10$^{-23}$ |
| | WA2 | | 4 | 118 | 0 | 0 | 2 | 1.9 10$^{-23}$ |
| | WA3 | | | 152 | | | | 6 10$^{-24}$ |
| Wet Andes | WA4 | -0.0063 | 2.3 | 128 | | | | 1.3 10$^{-23}$ |
| | WA5 | | | 179 | | | | 1 10$^{-23}$ |
| | WA6 | | | 139 | | | | 1.5 10$^{-23}$ |

### 2.2.1 Model setup, calibration and validation

We ran the model for each glacier and then the results per catchment were aggregated for each of the 786 catchments along the Andes (including the three selected test catchments for a detailed analysis).

The input data are as follows: the corrected monthly TerraClimate precipitation ($cTC_p$ ) and temperature ($cTC_t$ ), glacier outlines from RGI v6.0 (RGI Consortium, 2017) and surface topography from NASADEM (Crippen et al., 2016). Model outputs such as the surface mass balance and glacier volume were calibrated (Table 1 and Figure 2). The calibration procedure was applied per glacier to match the simulated mass balance 2000-2019 to the geodetic mass balance product from Hugonnet et al. (2021). The simulated glacier volume was calibrated using Farinotti et al.'s (2019) product at a glaciological zone scale to fit the Glen A parameter. In addition, it was assumed that the glacier outlines of all glaciers were made for the year 2000. For instance, in the case of glaciers for which the

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outline was delimited based on data acquired before or after 2000, this area was considered for the simulations starting in 2000.

Last, the simulated mass balance was evaluated in comparison with in situ mass balance observations (Marangunic et al., 2021; WGMS, 2021). Although the OGGM outputs are in calendar years and the observations are in hydrological years, we consider it essential to evaluate the interannual performance (Pearson correlation, p-value, variance, RMSE and bias from average difference) and the cumulative mass balance since the year 2000.

Figure 1 summarizes the simulation workflow, as well as the results obtained for each glacier in each catchment.

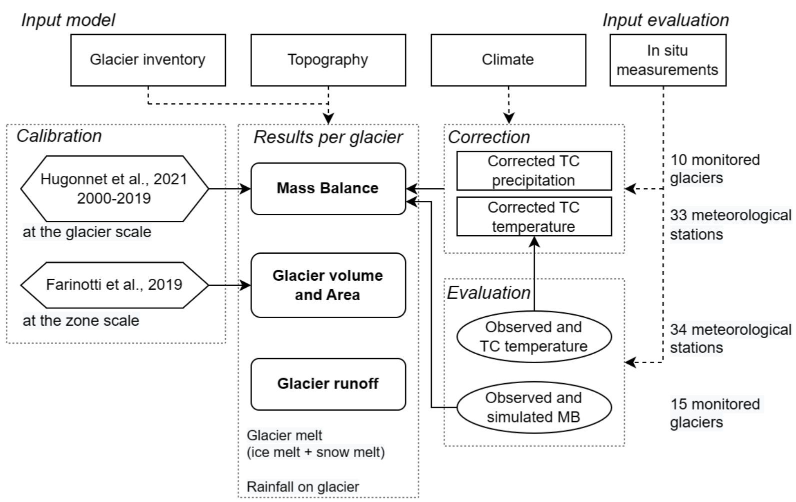


**Figure 1. Workflow per glacier simulation using OGGM between 2000 and 2019. Two groups of input data were used: one to run the model and the second to correct/evaluate the TerraClimate temperature (cTCt) and precipitation (cTCp). Then, the mass balance and glacier volume were calibrated. Lastly, results such as the cTCt and glacier mass balance were evaluated at 34 meteorological stations and on 15 glaciers with mass balance observations.**

## 3 Results

### 3.1 Climatic changes on glaciers across the Andes during the period 2000-2019

The climate associated with 786 Andean glacierized catchments (11°N-55°S) presents a mean corrected TerraClimate temperature (cTCt) of -0.2 ± 2.2°C and a mean annual corrected TerraClimate precipitation (cTCp) of 2699 ± 2006 mm yr$^{-1}$ between 2000 and 2019. The various glaciological regions show significant climatic differences, with contrasting extreme values between the Tropical Andes and Wet Andes in terms of mean annual precipitation (939 ± 261 mm yr$^{-1}$ and 3751 ± 1860 mm yr$^{-1}$, respectively) and mean annual temperature between the Dry Andes and Tropical Andes (-3.7 ± 1.4°C and 1.3 ± 0.8°C, respectively). Certain glaciological zones highlight very negative and positive mean annual temperature values such as DA2 (-4.8°C) and WA2 (1.9°C) and lower and higher cumulative precipitation values such as DA1 (447 mm yr$^{-1}$) and WA5 (6075 mm yr$^{-1}$). Meanwhile, the climate change between the periods 2000-2009 and 2010-2019 across the Andes shows a

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cumulative precipitation decrease of -9% (-234 mm yr$^{-1}$) and a mean annual temperature increase of 0.4 ± 0.1°C. Precipitation is decreasing primarily in the Dry Andes (-256 mm yr$^{-1}$; -23%) and Wet Andes (-337 mm yr$^{-1}$; -9%), and increasing in the Tropical Andes (44 mm yr$^{-1}$; 5%), whereas the temperature is increasing between 0.3-0.4°C in all regions. At the glaciological zone scale, only the Tropical Andes and DA1 (12%) show a cumulative increase in precipitation, whereas a larger decrease in precipitation is found in DA2 (-32%) and DA3 (-27%). The mean annual temperature increases in all zones, especially the Inner Tropics (+0.6°C) followed by WA3 (+0.5°C). A summary of the climate changes by glaciological zone is presented in Table 2.

Our cTCt evaluation is statistically significant (p-value < 0.01) at 32 meteorological stations with a mean temperature bias of 0.4°C and a mean correlation of 0.96. The regional results show a larger bias in the Tropical Andes (mean = 2.1°C, four stations) with a meteorological station mean elevation of 4,985 m a.s.l., where cTCt cannot represent the mean monthly temperature amplitude. However, cTCt well represents the maximum temperatures in spring/summer and the minimum temperatures in winter. The lowest bias is observed in the Wet Andes and Dry Andes. The Wet Andes, with a meteorological station mean elevation of 813 m a.s.l., shows good results in terms of reproducing the mean monthly temperature amplitude in most stations, with a minimum correlation higher than 0.86. In the Dry Andes, with a meteorological station mean elevation of 3,753 m a.s.l. (18 stations) and bias of 0.2°C, the cTCt reproduces the mean monthly temperature amplitude very well. However, in some stations such as La Frontera and Estrecho Glacier (29°S), the mean cTCt is warmer than 6°C, whereas in other stations such as El Yeso Embalse (33.7°S) and Cipreses glacier (34.5°S), the mean cTCt is colder than 6°C. The detailed cTCt evaluation can be found in Tables S1 and S3 and Figure S2 of the Supplementary Materials.

### 3.2 Glaciological changes across the Andes during the period 2000-2019

The annual mass balance and glacier dynamics per glacier are simulated by taking 36% of the total glacierized surface area across the Andes (11°N-55°S) into account to obtain the glacier area and glacier volume at an annual time scale, as well as the glacier runoff (glacier melting and rainfall on glaciers) at a monthly time scale. In more detail, over 85% of the glacierized surface area in the Dry Andes (18°S-37°S) and 79% in the Tropical Andes (11°N-18°S) is considered, which corresponds to 11% (3,377 km$^2$, in 321 catchments) of the total glacierized area of the Andes. For the Wet Andes (37°S-55°S), 29% of the glacierized surface area in the region is considered, which corresponds to 26% (7,905 km$^2$, in 465 catchments) of the total area in the Andes (see the distribution of the catchments in Figure 2a). The simulated lower glacierized surface area in the Wet Andes results from the filtering out of the numerous calving glaciers found there.

Between the periods 2000-2009 and 2010-2019, the glacier volume and area in the Andean catchments decreases by -8.3% (-59.1 km$^3$) and -2.2% (-245 km$^2$), respectively, associated with a negative mean annual mass balance of -0.5 ± 0.3 m w.e. yr$^{-1}$ (Figure 2d). A decrease in glacier volume and surface is seen in 93% of the catchments (n = 724) whereas 7% of the catchments (n = 65) present an increase in glacier volume and surface. The loss in glacier volume (Figure 2b) is largest (-47.8 km$^3$, -9%) in the Wet Andes, followed by the Tropical Andes (-5.9 km$^3$, -7%) and Dry Andes (-5.4 km$^3$, -6%). Similarly, a larger decrease in the glacier surface area (Figure 2c) is observed in the Wet Andes (-144.4 km$^2$, -2%), followed by the Tropical Andes (-55.5 km$^2$, -4%) and lastly the Dry Andes (-45.2 km$^2$, -3%). As expected, the correlation between both glacier change variables is consistent at the zone scale, showing a positive correlation between the changes in area and volume (r = 0.9).

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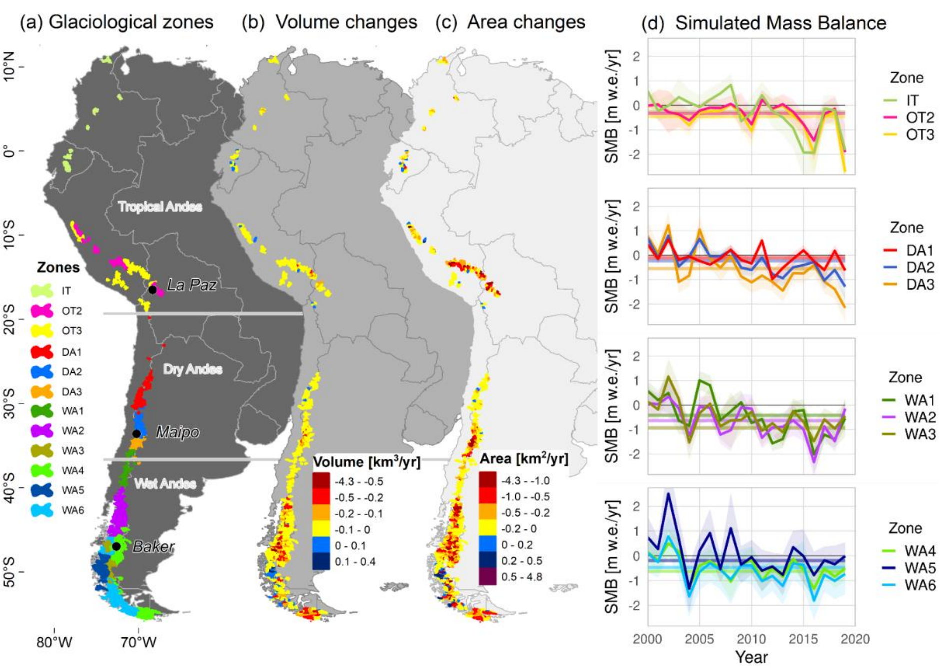


**Figure 2. Recent glacier changes across the Andes. The glacier changes are comprised of the mean annual differences between the periods 2000-2009 and 2010-2019 per catchment (n = 786). (a) It shows the distribution of the glaciological zones (11°N-55°S), followed by the (b) volume and (c) area changes at the catchment scale. The (d) annual simulated mass balances are presented in each glaciological zone (the shaded areas are the standard deviation), where the straight lines correspond to the mean geodetic mass balance (2000-2019) estimated by Hugonnet et al. (2021).**

When estimating the mass balance, it is interesting to check the calibrated melt factors ($M_f$) of the temperature index model in order to evaluate its possible regionalization, i.e., to evaluate the spatial coherence (see Figure 3). We obtain very similar values in contiguous zones, with the lowest values found in the Wet Andes (mean below 179 mm mth$^{-1}$ ºC$^{-1}$), followed by the Tropical Andes (mean below 434 mm mth$^{-1}$ ºC$^{-1}$), and the Dry Andes (mean below 479 mm mth$^{-1}$ ºC$^{-1}$). The largest melt factor values are found in the Dry Andes where the DA2 zone (mean = 479 mm mth$^{-1}$ ºC$^{-1}$) presents the lowest mean temperatures across the Andes (-4.8°C between 2000-2019). The lowest melting factor values are calibrated in the Wet Andes where zone WA1 (mean = 103 mm mth$^{-1}$ ºC$^{-1}$) shows high mean temperatures (1.8°C between 2000-2019). Despite this, a lower correlation between the melt factors and mean temperature for the 2000-2019 period is estimated ($r = -0.5$; p-value = 0.08). Conversely, the correlation between the melt factors and mean precipitation for the 2000-2019 period is high ($r = -0.8$; p-value = 0.002).

To test our results we evaluated the simulated mass balance in 15 monitored glaciers (Tables S4 and S5 and Figure S3). The in situ data show a mean negative mass balance (-832 ± 795 mm w.e. yr$^{-1}$) between 2000 and 2019 greater than our mean simulated mass balance (-647 ± 713 mm w.e. yr$^{-1}$) in the same glaciers. The evaluation results give a mean Pearson correlation of 0.67 (except for Agua Negra, Ortigas 1, Guanaco and Amarillo glaciers, which shows either no correlation or a negative correlation) with an underestimation of the mean simulated mass balance

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of 185 mm w.e. $yr^{-1}$ (bias); 40% of the glaciers present a correlation equal to or greater than 0.7. In terms of the best results by glaciological region, in the Tropical Andes, the Conejeras glacier has a high correlation (r = 0.9) and bias (1104 mm w.e. $yr^{-1}$), whereas in the Dry Andes, the Piloto Este, Paula, Paloma Este and Del Rincón glaciers display a high correlation (r >= 0.8) and a mean bias of 351 mm w.e. $yr^{-1}$. In the Wet Andes, the Mocho-Choshuenco and Martial Este glaciers show a moderate correlation (r = 0.5) and a lower overestimation of the simulated mass balance (-118 mm w.e. $yr^{-1}$). Model limitations are observed in the Zongo glacier (r = 0.3 and bias = -224 mm w.e. $yr^{-1}$) in the Tropical Andes. In the Dry Andes, no correlation is observed in the three monitored glaciers (Guanaco, Amarillo and Ortigas 1); this is mainly because sublimation, an ablation process that is not represented in the model, is dominant for these glaciers.

The details of the glacier changes in the 786 Andean catchments, which are larger in the Wet Andes followed by the Tropical Andes and then the Dry Andes, are available in the Supplementary Materials. The simulated mass balance evaluation for the 15 glaciers can be found in Figures S4 and S5 of the Supplementary Materials.

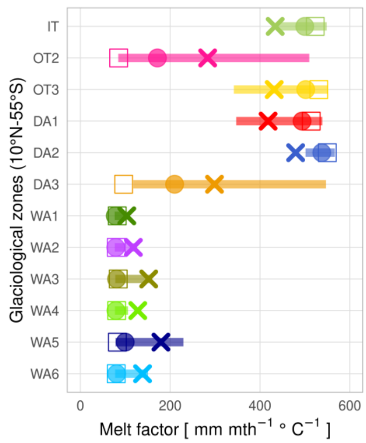


**Figure 3. Statistics for the calibrated melt factors per glacier at the glaciological zone scale across the Andes. This figure shows the mean (x), median (circle), mode (square), and percentile 25 and 75 (lines) values for 13,179 glaciers.**

### 3.3 Changes in glacier runoff across the Andes during the period 2000-2019

Due to glacier changes across the Andes, high glacier runoff variations are observed from glacier melt and rainfall on glaciers (Figure 4). The mean annual glacier melt in all catchments for the period 2000-2019 was 696 $m^3/s$. At the regional scale, the Wet Andes shows the largest mean annual glacier melt in the Andes (583.5 $m^3/s$), followed by the Dry Andes (59.9 $m^3/s$) and then the Tropical Andes (52.7 $m^3/s$). However, if we look at the mean annual glacier melt changes between the periods 2000-2009 and 2010-2019, we see an increase of 12% (86.5 $m^3/s$) across the Andes, where 84% (n = 661) of catchments show an increase and 12% (n = 95) of them present a decrease. As Table S6 shows, an increase in glacier melt is observed in catchments with a higher glacier elevation, larger glacier size, lower mean temperature and higher mean precipitation compared with catchments that show either a decrease

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in glacier melt or no changes at all. These latter catchments also show the largest decrease in precipitation (-10 to -14%).

The mean annual glacier melt changes show the largest percentage increase in the Tropical Andes (40%, 21 $m^3/s$), followed by the Dry Andes (36%, 21.7 $m^3/s$), and the Wet Andes (8%, 4.8 $m^3/s$). In addition, significant differences are observed for the different zones: for instance, the Inner Tropics in the Tropical Andes presents the largest increase (73% with only 4.1 $m^3/s$), followed by DA1 (62% with only 1.8 $m^3/s$) in the Dry Andes. In the Wet Andes, the larger percentage of increase in the mean annual glacier melt changes is observed in WA5 (14% with 4.1 $m^3/s$), showing a lower percentage in comparison with the Inner Tropics and DA1 zones, however, its absolute increase in glacier melt is equal to or greater than 4.1 $m^3/s$. These results per glaciological zone are summarized in Table 2. Related to the previously described glacier changes (see Section 3.2) between the periods 2000-2009 and 2010-2019, at the glaciological zone scale, we logically find a high negative correlation between the glacier melt and glacier volume changes in the Tropical Andes and Dry Andes (r = -0.9) and the Wet Andes (r = -1).

In addition, the mean annual rainfall on glaciers across the Andes is 387 $m^3/s$ for the period 2000-2019. The Wet Andes has the largest amount of annual rainfall (372.7 $m^3/s$), followed by the Tropical Andes (10.5 $m^3/s$) and Dry Andes (4.2 $m^3/s$) with the lowest contribution of rainfall. In terms of the changes in the mean annual rainfall on glaciers between the periods 2000-2009 and 2010-2019, we observe a reduction of -2% (-7.6 $m^3/s$) across the Andes, showing a reduction in 41% of the catchments (n = 322) whereas the largest proportion of the catchments (51%, n = 403) show an increase. Table S6 shows that the catchments with the larger increase of rainfall on glaciers are concentrated in the same latitude range as the catchments with an increase in glacier melt. These catchments have similar glacier elevations and glacier sizes. The catchments that do not show changes in rainfall on glaciers are concentrated in the Dry Andes region, where the rainfall contributes less to the glacier runoff volume.

At the glaciological region scale, the mean annual rainfall on glaciers decreases in the Wet Andes (-3%, 10.1 $m^3/s$), but increases in the Tropical Andes (23%, 2.4 $m^3/s$) and Dry Andes (3%, 0.1 $m^3/s$). In addition, large differences are observed in the glaciological zones (Table 2): e.g. DA1 in the Dry Andes has the largest percentage increase (106% with only 0.2 $m^3/s$), followed by IT (74% with only 0.4 $m^3/s$) in the Tropical Andes. In the Wet Andes, the larger increase (in percent) in the mean annual rain on the glaciers is observed in WA5 (6.6% with 2.1 $m^3/s$). Other zones such as WA2 and WA6 show large absolute reductions (-11.7 $m^3/s$ and -4.5 $m^3/s$, respectively).

The changes in glacier melt and rainfall on glaciers observed in the Tropical Andes, Dry Andes and Wet Andes are summarized in Table 2, and are available for the 786 Andean catchments in the Supplementary Materials.

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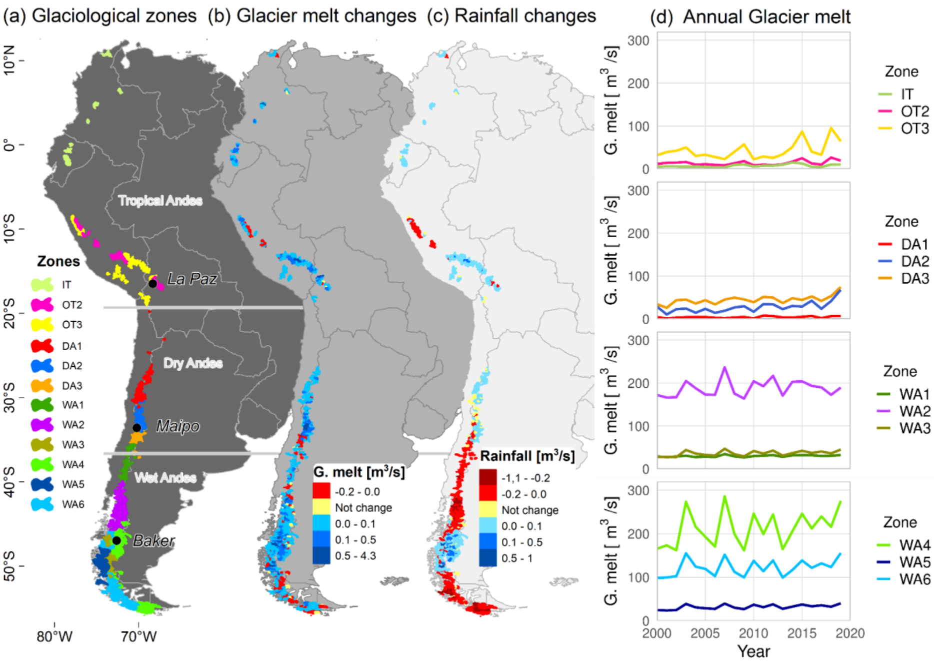


**Figure 4. Recent glacier runoff components across the Andes. The total glacier melt and rainfall on glaciers are comprised of the mean differences between the periods 2010-2019 and 2000-2009 per catchment (n = 786). (a) It shows the distribution of the glaciological zones (11°N-55°S), followed by (b) glacier melt and (c) rainfall on glaciers at the catchment scale. The (d) total annual glacier melt is presented in each glaciological zone.**

**Table 2. Mean annual changes in glacier area and volume, glacier runoff and climate between periods 2000-2009 and 2010-2019 at the glaciological zones scale across the Andes (11°N-55°S)**

| Region | Zone | Change in surface area [km$^2$] (%) | Change in volume [km$^3$] (%) | Change in glacier melt [m$^3$/s] (%) | Change in rainfall on glaciers [m$^3$/s] (%) | Simulated area [km$^2$] and percentage in total glacierized area (%) | cTCt change [°C] | cTCp change [mm yr$^{-1}$ (%)] |
|---|---|---|---|---|---|---|---|---|
| Tropical Andes | IT | -5.8 (-3) | -0.7 (-8) | 4.1 (73) | 0.4 (74) | 191 (88) | 0.6 | 81 (7.1) |
| | OT2 | -19.3 (-4) | -1.2 (-8) | 2.8 (23) | 0.3 (10) | 437 (77) | 0.3 | 19 (2) |
| | OT3 | -30.4 (-3) | -4 (-7) | 14.1 (40) | 1.6 (25) | 1149 (81) | 0.4 | 43 (5.2) |
| Dry Andes | DA1 | -5.2 (-2) | -0.4 (-4) | 1.8 (62) | 0.2 (106) | 218 (93) | 0.3 | 50 (11.9) |
| | DA2 | -7.4 (-1) | -2 (-4) | 11.3 (59) | 0.1 (14) | 770 (76) | 0.3 | -269 (-32) |
| | DA3 | -32.6 (-5) | -3 (-8) | 8.5 (23) | -0.1 (-3) | 613 (97) | 0.3 | -629 (-27.2) |

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| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Wet Andes | WA1 | -7 (-3) | -1.1 (-8) | 1.7 (6) | -1.6 (-13) | 237 (93) | 0.3 | -937 (-18.3) |
| | WA2 | -41.2 (-3) | -11.6 (-13) | 10.7 (6) | -11.7 (-9) | 1550 (91) | 0.4 | -454 (-8) |
| | WA3 | -4.9 (-1) | -3 (-7) | 4.4 (14) | 1.1 (5) | 469 (4) | 0.5 | -161 (-4.4) |
| | WA4 | -72 (-2) | -21.4 (-9) | 15.3 (8) | 4.4 (5) | 3746 (57) | 0.4 | -96 (-5.1) |
| | WA5 | 4.5 (1) | -0.3 (-1) | 4.1 (14) | 2.1 (7) | 378 (15) | 0.4 | -407 (-6.5) |
| | WA6 | -23.9 (-2) | -10.5 (-8) | 7.7 (7) | -4.5 (-5) | 1524 (32) | 0.3 | -382 (-10) |

### 3.4 Hydro-glaciological behavior at the catchment scale during the period 2000-2019

In this section, we focus on three Andean catchments: La Paz (16°S, Tropical Andes), Maipo (33°S, Dry Andes) and Baker (47°S, Wet Andes) (see locations in Figure 2 or 4), where previous glaciological observations and simulations of glacier evolution and water production have been carried out, and in situ records are also available. Detailed results for each of the 786 catchments and glaciers included are available in the dataset provided in the Supplementary Material.

#### 3.4.1 Glaciological variations in the selected catchments: La Paz (16°S), Maipo (33°S) and Baker (47°S)

Figure 5 shows the annual mass balance in the three catchments (2000-2019). The mean over the study period is negative, and there is a negative trend for the annual values toward 2019. For instance, for the Maipo catchment, we estimate a mean annual mass balance of -0.29 ± 0.14 m w.e. yr$^{-1}$, a slightly more negative balance in the Baker catchment (-0.47 ± 0.19 m w.e. yr$^{-1}$), whereas the glaciers in the La Paz catchment show a greater loss of -0.56 ± 0.19 m w.e. yr$^{-1}$. In addition, when considering the annual mass balance values, it is possible to note differences between the catchments. The La Paz catchment shows mostly negative annual mass balance values over the whole period, while in the Baker and Maipo catchments the mass balances are predominantly negative after 2004 and 2009, respectively. Considering the total area and volume changes per catchment in the periods 2000-2009 and 2010-2019, an overall reduction is observed in each of the three catchments. For the La Paz catchment, considering 86% (14 km$^2$) of glacierized area in 2000 (mean glacierized elevation of 5,019 m a.s.l.) and 20 glaciers, the glacierized surface area and volume decrease by -7% (-1 km$^2$) and -11% (-0.1 km$^3$), respectively. For the Maipo catchment, with a larger percentage of simulated glacierized surface area in 2000 (99%, with mean elevation of 4,259 m a.s.l.) and a greater number of glaciers (n = 225), the area and volume decrease by -1% (-4.2 km$^2$) and -5% (-1 km$^3$), respectively. For the Baker catchment, which contains the largest glacierized surface area of the three catchments in 2000, we simulated 66% of this glacierized area (1514 km$^2$, with mean elevation of 1,612 m a.s.l.) and 1805 glaciers: this area shrank by approximately -2% (-36.7 km$^2$), losing close to -11% (-9.3 km$^3$) of its volume. These results are summarized in Table 3.

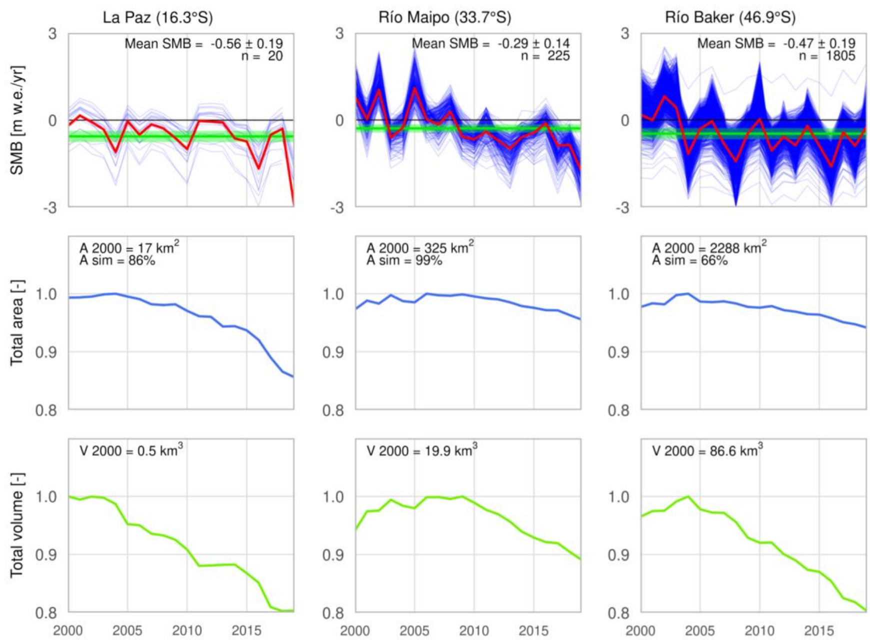


**Figure 5. Recent specific mass balance, surface area, and volume variations in the La Paz, Maipo, and Baker catchments from 2000 to 2019. The first row shows the mass balance for each simulated glacier (blue line), as well as the weighted mean mass balance per catchment (red line). The mean geodetic mass balance and its error for the period 2000-2019 are also presented (green bar). The second row presents the total glacierized area per catchment (blue line). The total area from RGI v6.0 and the simulated area percentage are also presented. The last row exhibits the total volume per catchment (green line). The surface area and volume have both been normalized to make it easier to compare the evolution between the catchments.**

#### 3.4.2 Hydrological contribution of glaciers in the selected catchments: La Paz (16°S), Maipo (33°S) and Baker (47°S)

The La Paz, Maipo, and Baker catchments display large climatic and glaciological differences over the period 2000-2019. For instance, contrasting cumulative precipitation amounts can be found between the Baker and La Paz catchments (2224 ± 443 mm yr$^{-1}$ and 791 ± 100 mm yr$^{-1}$, respectively), while the La Paz and Maipo catchments present the maximum difference in mean annual temperature (1.4 ± 0.5°C and -4.1 ± 0.5°C, respectively) (Figure 6). At a seasonal scale, precipitation in the Maipo and Baker catchments is concentrated in autumn and winter (April-September), even if the latter catchment also has a significant amount of precipitation in summer. Conversely, precipitation in the La Paz catchment mainly occurs in spring and summer (October to March). In addition, the La Paz and Baker catchments are characterized by the warmest temperatures (>0°C) in spring and summer; the warmest temperatures for the Maipo catchment occur in summer. Changes in the climatic conditions are observed between 2000-2009 and 2010-2019. For instance, a decrease in cumulative precipitation is observed in the Maipo (-30%, -454 mm yr$^{-1}$) and Baker catchments (-2%, -52 mm yr$^{-1}$), but an increase can be seen in the

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La Paz catchment (4%, 30 mm yr$^{-1}$). The mean annual temperature increases in the three catchments (+0.5°C in La Paz and Baker, +0.4°C in Maipo).

The glacier runoff simulation, which considers the glacier melt (ice and snow melt) and rainfall on glaciers (liquid precipitation), shows strong differences between the catchments (Figure 6). Over the period 2000-2019, the glaciers in the Baker catchment have the highest mean annual glacier melt (94 ± 19.6 m$^3$/s), followed by those in the Maipo (15.1 ± 4.2 m$^3$/s) and La Paz catchments (0.5 ± 0.2 m$^3$/s). The rainfall on glaciers contributes 30% to glacier runoff in the Baker catchment (41 ± 10.1 m$^3$/s); a lower value is found in the La Paz catchment with 17% (0.1 m$^3$/s) followed by the Maipo catchment with 5% (0.8 ± 0.3 m$^3$/s), which is the lowest contribution of rainfall on glaciers in these catchments. The simulations of glacier runoff changes between the periods 2000-2009 and 2010-2019 for the three catchments show an increase in glacier melt and rainfall on glaciers. The largest relative increase in mean annual glacier melt is observed in the Maipo with 37% (4.7 m$^3$/s), followed by the La Paz with 21% (0.09 m$^3$/s) and the Baker catchments with 10% (9 m$^3$/s). Meanwhile, the largest relative increase in the mean annual rainfall on glaciers is observed in the La Paz catchment (15%, 0.01 m$^3$/s), followed by the Baker catchment (11%, 4.3 m$^3$/s) and lastly the Maipo catchment (2%, 0.02 m$^3$/s). The results for the glacier melt and rainfall on glaciers are summarized in Table 3.

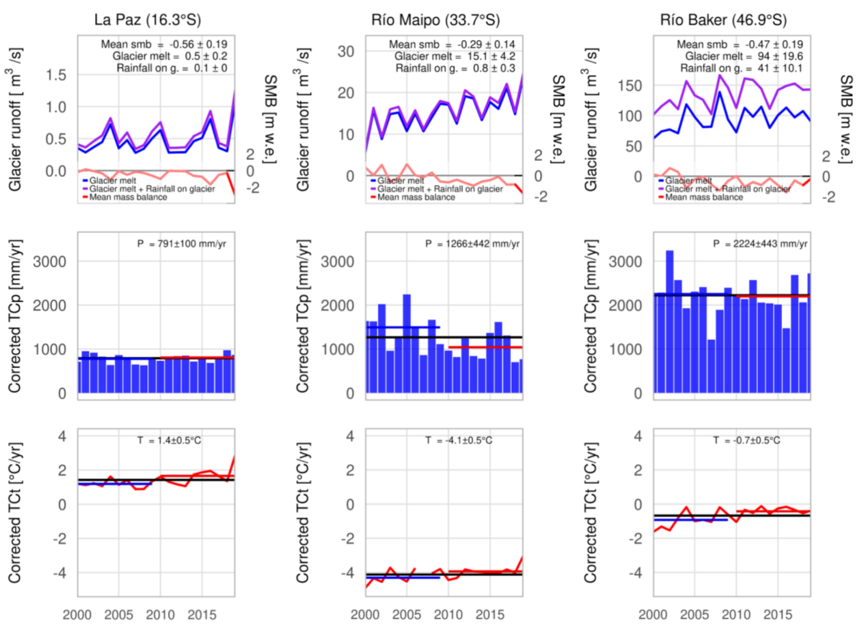


**Figure 6. Hydro-glaciological responses and climate variations in the La Paz, Maipo and Baker catchments from 2000 to 2019. The first row presents the mean annual glacier runoff (purple line = ice melt+snow melt+rainfall on glaciers), the mean annual glacier melt (blue line = ice melt+snow melt), and the annual mass balance (red line). The other rows show the mean total annual precipitation and mean annual temperature with the mean annual amount for the periods 2000-2019 (black line), 2000-2009 (blue line) and 2010-2019 (red line).**

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In Figure 7, at a mean monthly temporal scale for the period 2000-2019, the glacier melt simulation presents a short maximum during summer (January-February) in the Maipo and Baker catchments. In contrast, peaks in the La Paz catchment are extended during spring and summer (November-March) highlighting the so-called transition season (between September and November) where there is a low amount of rainfall on glaciers and glacier melt progressively increases. In the Baker catchment, melting begins earlier in September while in Maipo it begins later (November). The interannual variability of glacier melt over the periods 2000-2009 and 2010-2019 shows a larger contribution from the glacier in the period 2010-2019 for the Maipo catchment. Furthermore, the simulated rainfall on glaciers is larger mainly during the summer season in all catchments, with more rainfall in the La Paz catchment (December to February) after the transition season.

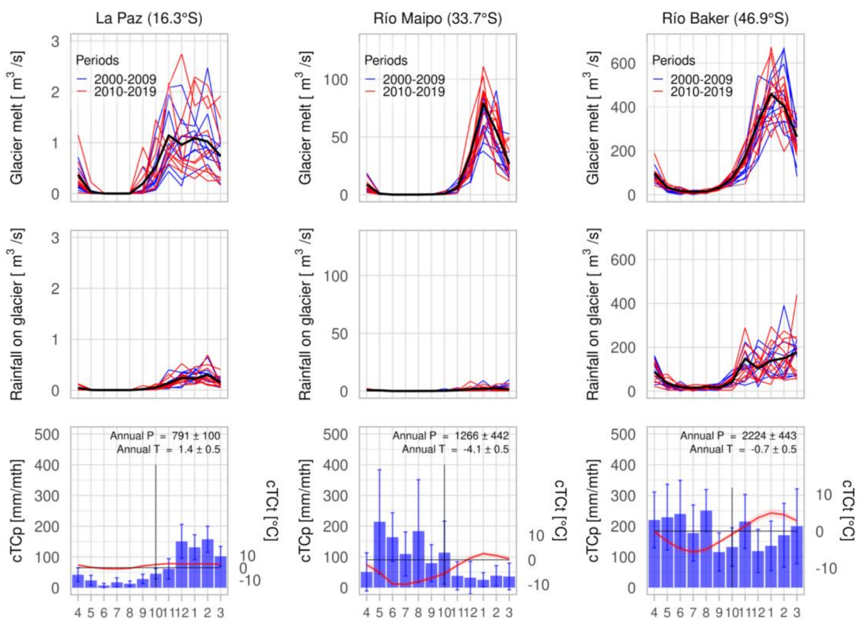


**Figure 7. Monthly hydro-glaciological responses and climate variations in the La Paz, Maipo and Baker catchments from 2000 to 2019. The first and second rows present the mean monthly glacier melt and rainfall on glaciers (black line) and the mean amounts per year during the periods 2000-2009 (red lines) and 2010-2019 (blue lines). In the last row, the climographs show the mean monthly precipitation (blue bars) and temperature (red line) for the period 2000-2019.**

For the mean annual discharge measurements in each catchment and the mean annual simulated glacier runoff (glacier melt and rainfall on glaciers) between 2000-2019 (Figure 8), we estimate that the largest glacier contribution is in the Baker catchment (24%), followed by the La Paz (22%) and Maipo catchments (14%), where all catchments present a similar proportion of glacierized surface area (7.5% to 8.2%). If we consider the summer season only (January to March), the glacier contribution is highest in the Baker catchment (43%), followed by the Maipo (36%) and La Paz catchments (18%), where the larger percentage of glacier melt is found in the Maipo catchment (34%) and the larger percentage of rainfall on glaciers is displayed in the Baker catchment (12%).

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Unlike the Maipo and Baker catchments, which present a maximum glacier contribution in the summer season, the La Paz catchment shows the largest glacier contribution (45%) in the transition season (September to November).

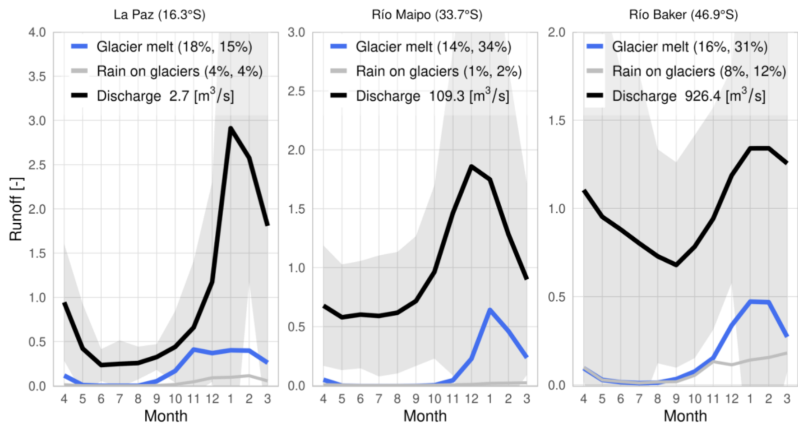


**Figure 8. Monthly simulated glacier runoff (glacier melt + rainfall on glaciers) and discharge measurements in the La Paz, Maipo, and Baker catchments from 2000 to 2019. The results for the glacier melt (blue lines) and rainfall on glaciers calculations (gray) are presented, as well as the discharge measurement (black line) and its standard deviation (gray area). The mean annual glacier contribution (as a percentage) and the mean glacier contribution (as a percentage) from January to March are shown in parentheses. The values are normalized by the mean river discharge.**

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**Table 3. Hydro-glaciological and climatic changes between the periods 2000-2009 and 2010-2019 for the three selected catchments**

| Region | Catchment | Change in surface area [km$^2$] (%) | Change in volume [km$^3$] (%) | Contribution of the annual glacier melt [m$^3$/s] (%) | Contribution of the annual rainfall on glaciers [m$^3$/s] (%) | Total simulated glacierized area [km$^2$] (%) | cTCt change [°C] | cTCp change [mm yr$^{-1}$] (%) |
|---|---|---|---|---|---|---|---|---|
| TA | La Paz | -0.96 (-6.7) | -0.1 (-11.5) | 0.09 (21.3) | 0.01 (15.3) | 14.4 (86) | 0.5 | 30 (4) |
| DA | Maipo | -4.2 (-1.3) | -1 (-5) | 4.7 (37) | 0.02 (2.2) | 353.9 (99) | 0.4 | -454 (-30) |
| WA | Baker | -36.7 (-2.4) | -9.3 (-10.7) | 9 (10) | 4.3 (11.2) | 1514 (66) | 0.5 | -52 (-2) |

## 4 Discussion

In this section we will discuss the relevance of the results obtained at the regional- to glacier-scale across the Andes. We will also discuss the main methodological advantages and limitations of the simulations.

420 ### 4.1 Comparison with previous studies across the Andes

Hock and Huss (2018) studied 11 Andean catchments across the Andes (1980-2000 and 2010-2030) and estimated an increase in glacier runoff in the Tropical Andes (Santa and Titicaca catchments) and the Dry Andes (Rapel and

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Colorado catchments). Our results are consistent with these estimates. We show an increase in glacier melt by 40% and 36% in both regions, respectively, between the periods 2000-2009 and 2010-2019. However, in the Wet Andes, Hock and Huss (2018) did not estimate any changes in glacier runoff on the western side of the Andes (Biobio catchment), and instead found a decrease (Río Negro catchment) and an increase (Río Santa Cruz catchment) in glacier runoff on the eastern side of the Andes. Our results for this region show an increase in glacier melt by 8% and a decrease in rainfall on glaciers by -3%.

Based on local reports in the Tropical Andes, the catchment associated with the Los Crespos glacier (id = 6090223080) on the Antisana volcano shows a small decrease in the glacier area of -1% between the periods 2000-2009 and 2010-2019, which is in agreement with Basantes-Serrano et al. (2022). Their study estimated that almost half of the glacier area (G1b, G2-3, G8, G9 and G17) had a positive mass balance during the period 1998-2009 with the largest glacier presenting a mass balance of 0.36 ± 0.57 m w.e. $yr^{-1}$, in agreement with our mass balance estimation at the catchment scale of 0.2 ± 0.5 m w.e. $yr^{-1}$ (2000-2009). However, in this region, the corrected TerraClimate temperature cannot reproduce the magnitude of the monthly temperature variation (see Figure S2). This limits the effectiveness of the parameter values used in the model to accurately simulate the melting onset and the amount of solid/liquid precipitation. Furthermore, the mass balance simulation is performed through the temperature index model which does not take the sublimation process into account; and in addition, it runs at a monthly time step thereby limiting the relevant processes that occur hourly. On the other hand, the catchments that contain the Zongo glacier (id = 6090629570) and the Charquini glacier (id = 6090641570) display results that are consistent with the observations (Rabatel et al., 2012; Seehaus et al., 2020; Autin et al. 2022). In addition, our simulated mass balance evaluation on the Zongo glacier shows a low bias (-0.2 m w.e. $yr^{-1}$) with regard to the observations. In the Dry Andes, the catchments associated with the Pascua Lama area (id = 6090836550 and id = 6090840860), the Tapado glacier (id = 6090853340) and the glaciers of the Olivares catchment (id = 6090889690) show consistent results in terms glaciological variations in comparison with the observations (Rabatel et al., 2011; Malmros et al., 2016; Farías-Barahona et at., 2020; Robson et al., 2022). In the Wet Andes, the catchments associated with the Chilean side of the Monte Tronador (id = 6090945100) and the Martial Este and Alvear glaciers in Tierra del Fuego (id = 6090037770) show results that are consistent with previous reports (Rabassa 2010; Ruiz et al., 2017). Despite this, it is possible that our methodology could overestimate precipitation in some catchments; for example, the cumulative precipitation associated with the Nevados de Chillán catchment (id = 6090916140) was estimated at 4023 mm $yr^{-1}$.

At the glaciological region scale, previous studies have reported a large decrease in the percentage of glacier area in the Tropical Andes by -29% (2000-2016) (Seehaus et al., 2019; 2020), followed by the Dry Andes between -29 and -30% (Rabatel et al., 2011; Malmros et al., 2016) although for a longer time-period. In the Wet Andes, Meier et al. (2018) reported a -9% decrease in the glacier area (1986–2016). Our simulations are consistent with these observed glacier area reductions. In addition, Caro et al. (2021) estimated a similar trend across the Andes between 1980-2019 (Tropical Andes = -41%, Dry Andes = -39%, Wet Andes = -24%). On the other hand, we found high correlations between the mean annual climatic variables and annual mass balance. In the Dry Andes, this correlation was high with precipitation (r = 0.8 ± 0.1) and in the Wet Andes, temperature was correlated with mass balance (r = -0.7 ± 0.1) as previously observed by Caro et al. (2021). These correlations between precipitation or temperature with the annual mass balances for each catchment across the Andes can be reviewed in Table S7 and Figure S5 of the Supplementary Materials.

### 4.2. Comparison of our results with previous studies in the three selected catchments

In the La Paz catchment, Soruco et al. (2015) evaluated the mass balance of 70 glaciers (1997-2006) and their contribution to the hydrological regime. In the present study, we simulated a less negative mass balance (-0.56 ± 0.19 m w.e. $yr^{-1}$ *vs.* -1 m w.e. $yr^{-1}$) considering a largest glacierized area due to the use of RGI v6.0 (with 14.1 $km^2$ in comparison to 8.3 $km^2$). Our estimation of the mean annual glacier runoff (22%) is larger than the previous estimation close to 15% (Soruco et al., 2015). This may be due to the fact that we have considered a warmer 2010-2019 period than the one observed in Soruco et al. (2015). Unlike the previous report, we estimated a larger glacier contribution during the wet season (26%, October to March) and increasing in the transition season (45%, September to November). This increase in glacier contribution given by the model agrees with the larger glacier mass loss observed by Sicart et al. (2007) and Autin et al. (2022) during this season. In the Maipo catchment, we identified a slightly smaller glacierized area (325 $km^2$ for the year 2000, -14%) compared with Ayala et al. (2020) because they considered rock glaciers from the Chilean glacier inventory. In addition, we observed a more negative mass balance after 2008, coinciding with the mega-drought period characterized by a decrease in precipitation and an increase in temperature (Garreaud et al., 2017). The hydrological response to this negative mass balance trend is an increase in glacier runoff since 2000 that is concentrated between December and March. Our mean annual glacier contribution estimation close to 15%, reaching 36% in summer (January-March), is close to Ayala et al.'s (2020) estimation (16% at the annual scale for the period 1955-2016). It is difficult to compare our results given here with previous studies in the Maipo and La Paz catchments, as any comparison is limited by the use of different input data and models, as well as spatial resolution, time step and calibration processes. Lastly, in the Baker catchment, Dussaillant et al. (2012) stated that catchments associated with the Northern Patagonian Icefield (NPI) are strongly conditioned by glacier melting. In this respect, Hock and Huss (2018) did not identify glacier runoff changes between the periods 1980-2000 and 2010-2030, they only considered 183 $km^2$ of the glacierized area (-12% until 2020), whereas we estimated a 10% and 11% increase in glacier melt and rainfall on glaciers, respectively, taking a larger glacierized area (1514 $km^2$; -2% until 2020) into account. The relevance of the rainfall on glaciers with regards to the glacier runoff estimated here is close to 30% (including glaciers from east of NPI to the east) which is confirmed by Krogh et al. (2014), who estimated that over 68% of the total precipitation at the catchment scale in east NPI (León and Delta catchments) corresponds to rainfall.

### 4.3 Melt factor values distributed across the Andes

Several reconstructions of the glacier surface mass balance have been performed across the Andes (9-52°S) using a temperature index with higher mean values in the Tropical Andes (0.3-0.5 mm $h^{-1}$ $°C^{-1}$), than in the Dry Andes (0.3-0.4 mm $h^{-1}$ $°C^{-1}$) and Wet Andes (0.1-0.5 mm $h^{-1}$ $°C^{-1}$) (e.g., Fukami & Naruse, 1987; Koisumi and Naruse, 1992; Stuefer et al., 1999, 2007; Takeuchi et al., 1995; Rivera, 2004; Sicart et al., 2008; Condom et al., 2011; Caro, 2014; Huss and Hock, 2015; Bravo et al., 2017). However, these studies considered different scales, both spatially (from stakes to a catchment scale) and temporally (from hourly to monthly), as well as different in situ and fixed (literature) melt factor values for the snow and ice temperature index. Taking these differences into account, we found a regional pattern for the melt factor using the same methodology at a monthly time step. The mean calibrated melt factor values decrease from the Tropical Andes toward the Wet Andes (TA = 0.5 ± 0.3 mm $h^{-1}$ $°C^{-1}$, DA = 0.6 ± 0.2 mm $h^{-1}$ $°C^{-1}$, WA = 0.2 ± 0.1 mm $h^{-1}$ $°C^{-1}$) (see Table 1 and Figure 3). This geographical distribution aligns with our evaluation of the TerraClimate dataset. The lowest mean temperatures estimated in the

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Dry Andes imply higher factor values to reach the calibrated mass loss in the few months in which the temperatures exceed 0°C. The opposite can be observed in the Wet Andes, where low factor values are associated with a greater number of months with temperatures exceeding 0°C.

### 4.4 Simulation limitations

Limitations in the simulations result from different sources: (1) the quality/accuracy of the input data; (2) the calibration of the precipitation and melt factors; and (3) the model itself, including its structure and the processes that are not represented. Regarding the evaluation of the corrected TerraClimate temperature using meteorological observations in the Tropical Andes, the corrected TerraClimate data do not reproduce either the low monthly temperature amplitude or the higher temperature in specific months which have a mean bias of 2.1°C (e.g. Llan_Up-2 9°S, Zongo at glacier station 16°S). These differences found in the corrected TerraClimate limit the capacity of the ice/snow melting module to accurately simulate the months in which melting can occur. To account for this, the values of the thresholds used for the melting onset and for the solid/liquid precipitation phase have been adjusted. On the contrary, in the Dry Andes and Wet Andes, the corrected TerraClimate temperatures are closer to the in situ observations (mean bias = 0.2ºC) and present a reliable monthly distribution. This results in model parameter values that are in better agreement with the values used in other studies. Other limitations come from RGI v6.0 because some glaciers are considered as only one larger glacier. For example, in the Dry Andes (id = 6090889690) two large glaciers, the Olivares Gamma and the Juncal Sur, form one (even larger) glacier. These glaciers could underestimate the simulated change in glacier area, limiting the performance of the volume module which depends on the glacier geometry and bedrock shape.

Furthermore, we applied different precipitation factor values in the Tropical Andes (1), Dry Andes (1.9 to 4) and Wet Andes (2.3 to 4), in order to increase the annual amplitude of the simulated mass balance. These values are in agreement with former studies, for example, similar values were used in the Dry Andes (Masiokas et al., 2016; Burger et al., 2019; Farías-Barahona et al., 2020). Values that are too high could lead to an overestimation of precipitation on some glaciers. However, to confirm that the precipitation factor produces realistic precipitation values, we adjusted the standard deviation of the simulated mass balance to the observed mass balance, a method similar to that proposed in Marzeion et al. (2012) and Maussion et al. (2019). On the other hand, the uncertainty of the calibrated melt factors come from the climate and geodetic mass balance datasets used to run and calibrate the model, respectively. Because of the monthly temperature variability, the upper threshold defines the melting onset and determines the number of months in which it occurs. Meanwhile, the geodetic mass balance defined the maximum melting per glacier in a given period. Based on our evaluation of the corrected TerraClimate temperature and simulated mass balance, we found a true seasonal melting distribution, associated with a mean underestimated mass balance of 185 mm w.e. $yr^{-1}$ that was highly correlated with the in situ data (r = 0.7).

With regards to the structural limitations of the model, it would be relevant to distinguish between ice and snow melt when simulating the glacier melt with two melt factors. In addition, the sublimation on the glacier surface is very relevant in the Tropical Andes and DA1 (Rabatel et al., 2011; MacDonnell et al., 2013). However, the OGGM model does not incorporate these processes in glacier runoff and mass balance simulations.

## 5 Conclusion

In this study, we present a detailed quantification of the glacio-hydrological evolution across the Andes (11°N-55°S) over the period 2000-2019 using OGGM. Our simulations rely on a glacier-by-glacier calibration of the changes in glacier volume. Simulations cover 36% (11,282 km$^2$) of their glacierized surface area across the Andes where 50% of the area corresponds to the Patagonian icefields and Cordillera Darwin that were not simulated due to specific processes such as calving and which are not accounted for in the version of glaciological model used here. In addition, we used corrected climate forcing and evaluated our simulation results at both the glacier and catchment scale using in situ observations, which are uncommon practices in regional simulations. From our results we can highlight the following:

- 93% of the studied glacierized catchments show a decrease in glacier area between the periods 2000-2009 and 2010-2019, displaying a high coherence with previous reports based, in particular, on glaciers in the Tropical Andes (Rabatel et al., 2012; Seehaus et al., 2020), Wet Andes (Rabassa 2010; Ruiz et al., 2017) and Dry Andes (Rabatel et al., 2011; Malmros et al., 2016; Farías-Barahona et at., 2020).
- The glacier runoff response to this glacier reduction has the largest percentage increase in the Tropical Andes and Dry Andes. Despite this, the largest percentage increase of glacier runoff (> 62%) estimated in the Inner Tropic and Dry Andes 1 zones corresponds to the lowest absolute glacier runoff amounts across the Andes.
- The three selected catchments, located in contrasted climatic zones, are used to evaluate the simulations. They display consistent results with previous studies and in situ observations. The larger glacier contributions to the catchment water flows are quantified for the Baker (43%) and Maipo (36%) catchments during the summer season (January-March). On the contrary, the larger glacier contribution to the La Paz catchment (45%) was estimated during the transition season (September to November).

Lastly, our results help to improve knowledge about the hydrological responses of glaciers in a large part of the Andes through the correction of climate data, the use of the same input data and the same simulation processes as well as a strong glacier calibration applied to the glaciers. The implementation of this calibrated and evaluated model in the historical period is a prerequisite for simulating the future evolution of the Andean glaciers.

**Code and data availability**

Data per glacier in this study is available at https://doi.org/10.5281/zenodo.7890462

**Supplement link**

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**Author contributions**

AC, TC and AR were involved in the study design. AC wrote the model implementation and produced the figures, tables and first draft of the manuscript. NC contributed to the model implementation. AC and NG carried out the data curation and TerraClimate temperature evaluation. AC performed the first level of analysis, which was improved by input from TC, AR, NC, FS. All authors contributed to the review and editing of the manuscript.

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## References

Abatzoglou, J. T., Dobrowski, S. Z., Parks, S. A., and Hegewisch, K. C. TerraClimate, a High-Resolution Global Dataset of Monthly Climate and Climatic Water Balance from 1958-2015. Sci. Data 5, 1–12. https://doi:10.1038/sdata.2017.191, 2018.

Alvarez-Garreton, C., Mendoza, P. A., Boisier, J. P., Addor, N., Galleguillos, M., Zambrano-Bigiarini, M., Lara, A., Puelma, C., Cortes, G., Garreaud, R., McPhee, J., and Ayala, A.: The CAMELS-CL dataset: catchment attributes and meteorology for large sample studies – Chile dataset, Hydrol. Earth Syst. Sci., 22, 5817–5846, https://doi.org/10.5194/hess-22-5817-2018, 2018.

Autin, P., Sicart, J. E., Rabatel, A., Soruco, A., and Hock, R. Climate Controls on the Interseasonal and Interannual Variability of the Surface Mass and Energy Balances of a Tropical Glacier (Zongo Glacier, Bolivia, 16° S): New Insights From the Multi-Year Application of a Distributed Energy Balance Model. Journal of Geophysical Research: Atmospheres, 127(7), https://doi.org/10.1029/2021JD035410, 2022.

Ayala, Á., Farías-Barahona, D., Huss, M., Pellicciotti, F., McPhee, J., and Farinotti, D. Glacier Runoff Variations since 1955 in the Maipo River Basin, Semiarid Andes of central Chile. Cryosphere Discuss. 14, 1–39. https://doi:10.5194/tc-2019-233, 2020.

Baraer, M., Mark, B. G., Mckenzie, J. M., Condom, T., Bury, J., Huh, K.-I., et al. Glacier Recession and Water Resources in Peru's Cordillera Blanca. J. Glaciol. 58 (207), 134–150. https://doi:10.3189/2012JoG11J186, 2012.

Basantes-Serrano, R., Rabatel, A., Francou, B., Vincent, C., Soruco, A., Condom, T., and Ruíz, J. C.: New insights into the decadal variability in glacier volume of a tropical ice cap, Antisana (0°29′ S, 78°09′ W), explained by the morpho-topographic and climatic context, The Cryosphere, 16, 4659–4677, https://doi.org/10.5194/tc-16-4659-2022, 2022.

Bravo, C., Loriaux, T., Rivera, A., & Brock, B. W. Assessing glacier melt contribution to streamflow at Universidad Glacier, central Andes of Chile. Hydrology and Earth System Sciences, 21(7), 3249-3266. https://doi.org/10.5194/hess-21-3249-2017, 2017.

Braun, L. N. and Renner, C. B. Application of a conceptual runoff model in different physiographic regions of Switzerland. Hydrol. Sci. J. 37(3), 217-231. 1992.

Burger, F., Ayala, A., Farias, D., Shaw, T. E., MacDonell, S., Brock, B., et al. Interannual Variability in Glacier Contribution to Runoff from a High-elevation Andean Catchment: Understanding the Role of Debris Cover in Glacier Hydrology. Hydrological Process. 33 (2), 214–229. https://doi:10.1002/hyp.13354, 2019.

Caro A, Condom T and Rabatel A. Climatic and Morphometric Explanatory Variables of Glacier Changes in the Andes (8–55°S): New Insights From Machine Learning Approaches. Front. Earth Sci. 9:713011. https://doi: 10.3389/feart.2021.713011, 2021.

Caro, A. Estudios glaciológicos en los nevados de Chillán. Santiago: University of Chile. [thesis], 2014

Cauvy-Fraunié, S., and Dangles, O. A Global Synthesis of Biodiversity Responses to Glacier Retreat. Nat. Ecol. Evol. 3 (12), 1675–1685. https://doi:10.1038/s41559-019-1042-8, 2019.

CEAZA, datos meteorológicos de Chile [data set], http://www.ceazamet.cl/, 2022.

CECs. Meteorological data measured by Centro de Estudios Científicos, 2018.

Condom. T., Escobar, M., Purkey, D., Pouget J.C., Suarez, W., Ramos, C., Apaestegui, J., Zapata, M., Gomez, J. and Vergara, W. Modelling the hydrologic role of glaciers within a Water Evaluation and Planning System (WEAP): a case study in the Rio Santa watershed (Peru). Hydrol. Earth Syst. Sci. Discuss., 8, 869–916. https://doi:10.5194/hessd-8-869-2011, 2011.

Crippen, R., Buckley, S., Agram, P., Belz, E., Gurrola, E., Hensley, S., Kobrick, M., Lavalle, M., Martin, J., Neumann, M., Nguyen, Q., Rosen,P., Shimada, J., Simard, M., Tung, W. NASADEM Global Elevation Model: Methods and Progress. The International Archives of thePhotogrammetry, Remote Sensing and Spatial Information Sciences XLI-B4, 125–128. (20), 2016.

Devenish, C., and Gianella, C. Sustainable Mountain Development in the Andes. 20 Years of Sustainable Mountain Development in the Andes - from Rio 1992 to 2012 and beyond. Lima, Peru: CONDESAN, 2012.

DGA, datos de estudios hidroglaciológicos de Chile [data set], https://snia.mop.gob.cl/BNAConsultas/reportes, 2022.

Dussaillant A., Buytaert W., Meier C. and Espinoza F. Hydrological regime of remote catchments with extreme gradients under accelerated change: the Baker basin in Patagonia. Hydrological Sciences Journal,Volume 57, https://doi.org/10.1080/02626667.2012.726993, 2012.

Dussaillant, I., Berthier, E., Brun, F., Masiokas, M., Hugonnet, R., Favier, V., et al. Two Decades of Glacier Mass Loss along the Andes. Nat. Geosci. 12 (10), 802–808. https://doi:10.1038/s41561-019-0432-5, 2019.

Farías-Barahona, D., Wilson, R., Bravo, C., Vivero, S., Caro, A., Shaw, T. E., et al. A Near 90-year Record of the Evolution of El Morado Glacier and its Proglacial lake, Central Chilean Andes. J. Glaciol, 66, 846–860. https://doi:10.1017/jog.2020.52, 2020.

Farinotti, D., Huss, M., Fürst, J. J., Landmann, J., Machguth, H., Maussion, F., et al. A consensus estimate for the ice thickness distribution of all glaciers on Earth. Nat. Geosci. 12, 168–173. https://doi: 10.1038/s41561-019-0300-3, 2019.

https://doi.org/10.5194/egusphere-2023-888
Preprint. Discussion started: 23 May 2023


Farinotti, D., Brinkerhoff, D. J., Clarke, G. K., Fürst, J. J., Frey, H., Gantayat, P., ... & Andreassen, L. M. How accurate are estimates of glacier ice thickness? Results from ITMIX, the Ice Thickness Models Intercomparison eXperiment. The Cryosphere, 11(2), 949-970, https://doi.org/10.5194/tc-11-949-2017, 2017.

Fukami, H. and Naruse, R. Ablation of ice and heat balance on Soler glacier, Patagonia. Bull. Glacier Res. 4, 37–42, 1987.

Gao L., Bernhardt M. and Schulz K. Elevation correction of ERA-Interim temperature data in complex terrain. Hydrol. Earth. Syst. Sci. 16(12): 4661–4673, https://doi: 10.5194/hess-16-4661-2012, 2012.

Garreaud, R. D., Alvarez-Garreton, C., Barichivich, J., Boisier, J. P., Christie, D., Galleguillos, M., LeQuesne, C., McPhee, J., and Zambrano-Bigiarini, M.: The 2010–2015 megadrought in central Chile: impacts on regional hydroclimate and vegetation, Hydrol. Earth Syst. Sci., 21, 6307–6327, https://doi.org/10.5194/hess-21-6307-2017, 2017.

Gascoin, S., Kinnard, C., Ponce, R., Lhermitte, S., MacDonell, S., and Rabatel, A.: Glacier contribution to streamflow in two headwaters of the Huasco River, Dry Andes of Chile, The Cryosphere, 5, 1099–1113, https://doi.org/10.5194/tc-5-1099-2011, 2011.

GLACIOCLIM, Données météorologiques [data set], https://glacioclim.osug.fr/Donnees-des-Andes, 2022.

Guido, Z., McIntosh, J. C., Papuga, S. A., and Meixner, T. Seasonal Glacial Meltwater Contributions to Surface Water in the Bolivian Andes: A Case Study Using Environmental Tracers. J. Hydrol. Reg. Stud. 8, 260–273. https://doi:10.1016/j.ejrh.2016.10.002, 2016.

Hernández, J., Mazzorana, B., Loriaux, T., and Iribarren, P. Reconstrucción de caudales en la Cuenca Alta del Río Huasco, utilizando el modelo Cold Regional Hydrological Model (CRHM), AAGG2021, 2021

Hock, R. Temperature index melt modelling in mountain areas. Journal of Hydrology, 282(1-4), 104-115. https://doi.org/10.1016/S0022-1694(03)00257-9, 2003.

Hugonnet, R., McNabb, R., Berthier, E. et al. Accelerated global glacier mass loss in the early twenty-first century. Nature 592, 726–731. https://doi.org/10.1038/s41586-021-03436-z, 2021.

Huss, M. and Hock, R. A new model for global glacier change and sea-level rise, Front. Earth Sci., 3, 54, https://doi.org/10.3389/feart.2015.00054, 2015.

Huss, M. and Hock, R. Global-scale hydrological response to future glacier mass loss, Nature Climate Change, 8, 135–140, https://doi.org/10.1038/s41558-017-0049-x, 2018.

IANIGLA, datos meteorológicos [data set], https://observatorioandino.com/estaciones/, 2022.

Kienholz, C., Rich, J. L., Arendt, A. A., and Hock, R.: A new method for deriving glacier centerlines applied to glaciers in Alaska and northwest Canada, The Cryosphere, 8, 503–519, https://doi.org/10.5194/tc-8-503-2014, 2014.

Koizumi, K. and Naruse R. Measurements of meteorological conditions and ablation at Tyndall Glacier, Southern Patagonia, in December 1990. Bulletin of Glacier Research, 10, 79-82, 1992.

Krögh, S.A., Pomeroy, J.W., McPhee, J. Physically based hydrological modelling using reanalysis data in Patagonia. J. Hydrometeorol. http://dx.doi.org/10.1175/JHM-D-13-0178.1, 2014.

Lehner B, Verdin K, Jarvis A. Hydrological data and maps based on Shuttle elevation derivatives at multiple scales (HydroSHEDS)-Technical Documentation, World Wildlife Fund US, Washington, DC, Available at http://hydrosheds.cr.usgs.gov, 2016.

https://doi.org/10.5194/egusphere-2023-888
Preprint. Discussion started: 23 May 2023


MacDonell, S., Kinnard, C., Mölg, T., Nicholson, L., and Abermann, J. Meteorological drivers of ablation processes on a cold glacier in the semi-arid Andes of Chile, The Cryosphere, 7, 1513–1526, https://doi.org/10.5194/tc-7-1513-2013, 2013.

Malmros, J. K., Mernild, S. H., Wilson, R., Yde, J. C., and Fensholt, R. Glacier Area Changes in the central Chilean and Argentinean Andes 1955-2013/14. J. Glaciol. 62, 391–401. https://doi:10.1017/jog.2016.43, 2016.

Marangunic C., Ugalde F., Apey A., Armendáriz I., Bustamante M. and Peralta C. Ecosistemas de montaña de la cuenca alta del río Mapocho, Glaciares en la cuenca alta del río Mapocho: variaciones y características principales. AngloAmerican - CAPES UC, 2021.

Mark, B. and Seltzer, G. Tropical glacier meltwater contribution to stream discharge: A case study in the Cordillera Blanca, Peru. J. Glaciol, 49(165), 271-281. https://doi:10.3189/172756503781830746, 2003.

Marzeion, B., Jarosch, A. H., and Hofer, M.: Past and future sea-level change from the surface mass balance of glaciers, The Cryosphere, 6, 1295–1322, https://doi.org/10.5194/tc-6-1295-2012, 2012.

Masiokas, M. H., Christie, D. A., Le Quesne, C., Pitte, P., Ruiz, L., Villalba, R., et al. Reconstructing the Annual Mass Balance of the Echaurren Norte Glacier (Central Andes, 33.5° S) Using Local and Regional Hydroclimatic Data. The Cryosphere 10 (2), 927–940. https://doi:10.5194/tc-10-927-2016, 2016.

Masiokas, M. H., Rabatel, A., Rivera, A., Ruiz, L., Pitte, P., Ceballos, J. L., et al. A Review of the Current State and Recent Changes of the Andean Cryosphere. Front. Earth Sci. 8 (6), 1–27. doi:10.3389/feart.2020.00099, 2020.

Mateo, E. I., Mark, B. G., Hellström, R. Å., Baraer, M., McKenzie, J. M., Condom, T., Rapre, A. C., Gonzales, G., Gómez, J. Q., and Encarnación, R. C. C.: High-temporal-resolution hydrometeorological data collected in the tropical Cordillera Blanca, Peru (2004–2020), Earth Syst. Sci. Data, 14, 2865–2882, https://doi.org/10.5194/essd-14-2865-2022, 2022.

Maussion, F., Butenko, A., Champollion, N., Dusch, M., Eis, J., Fourteau, K., et al. The open global glacier model (OGGM) v1.1. Geoscientific Model. Develop. 12, 909–931. https://doi:10.5194/gmd-12-909-2019, 2019

Millan, R., Mouginot, J., Rabatel, A. et al. Ice velocity and thickness of the world's glaciers. Nat. Geosci. 15, 124–129. https://https://doi.org/10.1038/s41561-021-00885-z, 2022.

Rabassa, J. El cambio climático global en la Patagonia desde el viaje de Charles Darwin hasta nuestros días. Revista de la Asociación Geológica Argentina, 67(1), 139-156, 2010.

Rabatel, A., Bermejo, A., Loarte, E., Soruco, A., Gomez, J., Leonardini, G., Vincent, C., and Sicart, J. E.: Relationship between snowline altitude, equilibrium-line altitude and mass balance on outer tropical glaciers: Glaciar Zongo – Bolivia, 16◦ S and Glaciar Artesonraju – Peru, 9◦ S, J. Glaciol., 58, 1027–1036, https://doi:10.3189/2012JoG12J027, 2012.

Rabatel, A., Castebrunet, H., Favier, V., Nicholson, L., and Kinnard, C. Glacier Changes in the Pascua-Lama Region, Chilean Andes (29° S): Recent Mass Balance and 50 Yr Surface Area Variations. The Cryosphere 5 (4), 1029–1041. https://doi:10.5194/tc-5-1029-2011, 2011.

Rabatel, A., Francou, B., Soruco, A., Gomez, J., Cáceres, B., Ceballos, J. L., et al. Current State of Glaciers in the Tropical Andes: A Multi-century Perspective on Glacier Evolution and Climate Change. The Cryosphere 7, 81–102. https://doi:10.5194/tc-7-81-2013, 2013.

Ragettli, S., and Pellicciotti, F. Calibration of a Physically Based, Spatially Distributed Hydrological Model in a Glacierized basin: On the Use of Knowledge from Glaciometeorological Processes to Constrain Model Parameters. Water Resour. Res. 48 (3), 1–20. https://doi:10.1029/2011WR010559, 2012.

RGI Consortium. Randolph Glacier Inventory - A Dataset of Global Glacier Outlines, Version 6. Boulder, Colorado USA. NSIDC: National Snow and Ice Data Center, https://doi.org/10.7265/4m1f-gd79, 2017.

Rivera, A. Mass balance investigations at Glaciar Chico, Southern Patagonia Icefield, Chile. PhD thesis, University of Bristol, UK, 303 pp, 2004.

Robson, B. A., MacDonell, S., Ayala, Á., Bolch, T., Nielsen, P. R., and Vivero, S. Glacier and rock glacier changes since the 1950s in the La Laguna catchment, Chile, The Cryosphere, 16, 647–665, https://doi.org/10.5194/tc-16-647-2022, 2022.

Ruiz, L., Berthier, E., Viale, M., Pitte, P., and Masiokas, M. H. Recent geodetic mass balance of Monte Tronador glaciers, northern Patagonian Andes, The Cryosphere, 11, 619–634, https://doi.org/10.5194/tc-11-619-2017, 2017.

Schaefer M., Rodriguez J., Scheiter M., and Casassa, G. Climate and surface mass balance of Mocho Glacier, Chilean Lake District, 40°S. Journal of Glaciology, 63(238), 218-228, https://doi:10.1017/jog.2016.129, 2017.

Seehaus, T., Malz, P., Sommer, C., Soruco, A., Rabatel, A., and Braun, M. Mass balance and area changes of glaciers in the Cordillera Real and Tres Cruces, Bolivia, between 2000 and 2016. J. Glaciol, 66(255), 124-136. https://doi:10.1017/jog.2019.94, 2020.

SENAMHI, datos hidrometeorológicos de Perú [data set], https://www.senamhi.gob.pe/?&p=descarga-datos-hidrometeorologicos, 2022.

Shaw, T. E., Caro, A., Mendoza, P., Ayala, Á., Pellicciotti, F., Gascoin, S., et al. The Utility of Optical Satellite Winter Snow Depths for Initializing a Glacio-Hydrological Model of a High-Elevation, Andean Catchment. Water Resour. Res. 56 (8), 1–19. doi:10.1029/2020WR027188. 2020.

Sicart, J. E., P. Ribstein, B. Francou, B. Pouyaud, and T. Condom. Glacier mass balance of tropical Zongo Glacier, Bolivia, comparing hydrological and glaciological methods, Global Planet. Change, 59(1), 27– 36, 2007.

Stuefer, M. Investigations on Mass Balance and Dynamics of Moreno Glacier Based on Field Measurements and Satellite Imagery. Ph.D. Dissertation, University of Innsbruck, Innsbruck, 1999.

Stuefer, M., Rott, H. and Skvarca, P. Glaciar Perito Moreno, Patagonia: climate sensitivities and glacier characteristics preceding the 2003/04 and 2005/06 damming events. J. Glaciol., 53 (180), 3–16. https://doi: 10.3189/172756507781833848, 2007.

Soruco, A., Vincent, C., Rabatel, A., Francou, B., Thibert, E., Sicart, J. E., et al. Contribution of Glacier Runoff to Water Resources of La Paz City, Bolivia (16° S). Ann. Glaciol. 56 (70), 147–154. https://doi:10.3189/2015AoG70A001, 2015.

Takeuchi, Y., Naruse R. and Satow K. Characteristics of heat balance and ablation on Moreno and Tyndall glaciers, Patagonia, in the summer 1993/94. Bulletin of Glacier Research, 13, 45-56, 1995.

WGMS. Global Glacier Change Bulletin No. 4 (2018-2019). Michael Zemp, Samuel U. Nussbaumer, Isabelle Gärtner-Roer, Jacqueline Bannwart, Frank Paul, and Martin Hoelzle (eds.), ISC (WDS) / IUGG (IACS) / UNEP / UNESCO / WMO, World Glacier Monitoring Service, Zurich, Switzerland, 278 pp. Based on database version https://doi.org/10.5904/wgms-fog-2021-05, 2021.

Zimmer, A., Meneses, R. I., Rabatel, A., Soruco, A., Dangles, O., and Anthelme, F. Time Lag between Glacial Retreat and Upward Migration Alters Tropical alpine Communities. Perspect. Plant Ecol. Evol. Syst. 30, 89–102. https://doi:10.1016/j.ppees.2017.05.003, 2018.