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Carihuairazo glacier retreat and its perception in the Cunucyacu community

Retroceso del glaciar del Carihuairazo y sus implicaciones en la comunidad de Cunucyacu

David Hidalgo*[1], Christian Domínguez*[2], Marcos Villacís[3,4], Jean-Carlos Ruíz[5,6], Luis Maisincho[7], Bolívar Cáceres[7], Verónica Crespo-Pérez[8], Thomas Condom[6] and David Piedra[3]

[1] *Área de ambiente y sustentabilidad. Universidad Andina Simón Bolívar. Quito, Ecuador.*
[2] *Carrera de Ingeniería Civil. Universidad Politécnica Salesiana, 170702, Quito, Ecuador.*
[3] *Facultad de Ingeniería Civil y Ambiental, Escuela Politécnica Nacional, 170407, Quito, Ecuador.*
[4] *Centro de Investigación y Estudios en Ingeniería de los Recursos Hídricos, 170525, Quito, Ecuador.*
[5] *UMR 7619 METIS , CASE 105,Sorbonne Université, 4 place Jussieu, F-75005, Paris, France. Univiersité Grenoble Alpes.*
[6] *Insitut des Géoscience d l ´ Environnment (IGE, UMR 5001), Univ. Grenoble Alpes, IRD, CNRS, Grenoble INP, 3800, Grenoble, France.*
[7] *Instituto Nacional de Metereología e Hidrología, Quito, Ecuador.*
[8] *Instituto de Ingeniería y gestión (ING, IGE), IRD, CNRS.Universidad Grenoble Alpes, 38058, Grenoble, Francia.*

*Corresponding author: davidhidalgoponce@gmail.com y cdominguez@ups.edu.ec

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Abstract

The retreat of glaciers is a reality throughout the Andes Mountain range, especially in low-altitude mountains. One of these cases is the loss of the remaining ice mass in Carihuairazo (Tungurahua, Ecuador), which in recent years has experienced a considerable retreat. This research aims to characterize the retreat of this glacier and its implications for the nearby community (Cunucyacu) through the application of a multi-source methodology, which includes the collection of glacier aerial photographs, data from nearby meteorological stations, the use of global climate reanalysis data, interviews with community members, and mountaineers who work and frequent the area. To characterize the glacier's mass evolution, a hydroglaciological model was applied, using input data from meteorological series, and its parameters were calibrated with the photographic record of the glacier's outline. The results show a glacier loss of 99 % of its surface in 1956 (0.34 km^2) by 2021. The model successfully simulates the glacier area variation over 67 years, revealing a continuous decrease since 1978, with short periods of recovery and equilibrium, where temperature is the variable that best explains the glacier's retreat. However, the model fails to consider the effect of external factors, such as the eruption of the Tungurahua volcano that could enhance the glacier retreat. The Carihuairazo glacier is in a situation of inevitable disappearance, highlighting the vulnerabilities of communities facing this phenomenon as a consequence of climate change.

Keywords: Glacier retreat, glacier, hydroglaciological model, climate change, Carihuairazo, Cunucyacu.

Resumen

El retroceso de los glaciares es una realidad en toda la cordillera de los Andes, sobre todo en montañas de baja altitud. Uno de estos casos es la pérdida de la masa de hielo remanente en el Carihuairazo (Tungurahua, Ecuador), que en los últimos años ha experimentado un retroceso considerable. En esta investigación se intenta caracterizar el retroceso de este glaciar y su implicación en la comunidad más cercana (Cunucyacu) por medio de la aplicación de una metodología de múltiples fuentes que incluye la recopilación de aerofotografías del glaciar, datos de estaciones meteorológicas cercanas, uso de datos de reanálisis del clima global, entrevistas a miembros de la comunidad y a andinistas que trabajan y frecuentan la zona. Para caracterizar la evolución de la masa del glaciar aplicamos un modelo hidroglaciológico que usa como entrada datos de series meteorológicas y cuyos parámetros fueron calibrados con el registro fotográfico del contorno del glaciar. Como resultados se puede evidenciar una pérdida del glaciar para el 2021 equivalente al 99 % de su superficie en 1956 (0.34 km^2). El modelo logra simular la variación del área del glaciar durante 67 años, en donde se observa un decrecimiento continuo del glaciar a partir de 1978, con cortos periodos de recuperación y equilibrio, en donde la temperatura es la variable que mejor explica el retroceso del glaciar. El modelo no logra considerar el efecto de factores externos como el caso de la erupción del volcán Tungurahua que podría favorecer el retroceso del glaciar. El glaciar Carihuairazo se encuentra en una situación de inevitable desaparición y revela las vulnerabilidades de las comunidades que se enfrentan a este fenómeno como consecuencia del cambio climático.

Palabras clave: retroceso glaciar, glaciares, modelo hidroglaciológico, cambio climático, Carihuairazo, Cunucyacu.

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Orcid IDs:

Bolívar David Hidalgo Ponce: https://orcid.org/0000-0002-1430-8140
Jean-Carlos Ruíz-Hernández: https://orcid.org/0000-0002-7801-5566
Luis Maisincho: https://orcid.org/0000-0002-6078-1895
Bolívar Cáceres: https://orcid.org/0000-0002-2013-057X
Verónica Crespo-Pérez: https://orcid.org/0000-0002-8811-1965
Christian Domínguez: https://orcid.org/0000-0003-2971-7163
David Piedra: https://orcid.org/0000-0003-4435-3978
Thomas Condom: https://orcid.org/0000-0002-4408-8580
Marcos Joshua Villacís Erazo: https://orcid.org/0000-0002-4496-7323

1 Introduction

Glaciers play a significant role in the sustainability of ecosystems and the environmental balance of the regions where they are located, as in the moors (Aguilar-Lome et al., 2019; García, 2022). Glaciers act as water reservoirs, affecting all aspects related to their use, both for irrigation and consumption, in addition to their use for mining and hydroelectric generation processes (Vuille, 2013; Naranjo-Silva, 2024). The decrease in water flows associated with glacial retreat causes scarcity and generates conflicts for the rights of use between the inhabitants of mountain areas and companies that want to control access to water (Vuille, 2013). In addition to contributing to water supply, regulating the climate and maintaining a habitat for biodiversity, for Vilela (2011), they influence in the culture, identity, imaginaries and tourism.

The Carihuairazo is an extinct stratum of volcano located in the Western Cordillera of Ecuadorian Andes. The glacier contributes to several tributaries, but mainly to those located towards the eastern flank of the mountain. One of the closest populations to the glacier is the community of Cunucyacu, belonging to the parish Pilahuín, southwest of Ambato in the province of Tungurahua, in the central area of Ecuador and located north of the Carihuairazo. Currently, in the community there is a decrease in the amount of water originated in the mountain. Considering the previous studies of Cáceres and Cauvy (2015), the setback of Carihuairazo has been observed since 2003, and this process points towards its inevitable extinction (Francou et al., 2011), which could occur in the coming years. Postigo (2013) highlights the interest of knowing the impact of the glacial retreat from the perspective of the various actors involved in underlying conflicts, each of them with interests and priorities different and opposed to each other. In this sense, the testimonies and perception of different actors in this environment, as well as social agents involved with conservation experiences, are valuable.

Over the last decades, glaciers around the world have experienced a reduction in their volume (Bahr and Peckham, 1997; Basantes, 2010; Condom et al., 2011; Favier et al., 2008; Hugonnet et al., 2021). Glacial retreat is defined by Johansen et al. (2019) as the inability to store water during cooler periods and release them in the form of melt fluid during the dry season. 99 % of the world's tropical glaciers are located in the Andes (Condom et al., 2011), the same ones that have experienced a negative mass balance of $0,42 \pm 0,24$ m/year (Dussaillant et al., 2019), and there is evidence with satellite imagery and aerial photography (Basantes, 2010; Condom et al., 2011). This rapid retreat has caused global concerns about the availability of water resources, as a consequence of climate variability (French et al., 2016).

Considering the effect of climate change, there is a need to raise awareness in populations near glaciers about changes in climate patterns, and their socio-environmental consequences, since as proposed by Rhoades (2008), there is a better understanding of the urgency for adopting community mitigation and adaptation strategies that involve and favor local farmers against new climate scenarios (Pacheco-Peña et al., 2023), taking into account the need to preserve the moors as an ecosystem sensitive to glacial retreat, as pointed out by Cabrera and Romero (2013), in its qualitative assessment of the vulnerability to climate change of the main ecosystems of the Metropolitan District of Quito.

Volume changes in tropical glaciers are subject to atmospheric conditions (Favier et al., 2008; Sicart et al., 2008), glacier morphological conditions and topographic conditions (Vuille, 2013). Precipitation is stored as snow and ice, contributing to glacier mass accumulation (Favier et al., 2008). Melting is controlled by the variation of energy flows from the atmosphere, such as turbulent flow influenced by the temperature gradient between air and ice; and latent flow influenced by humidity (Sicart et al., 2008). There is also a correlation between temperature and melting in glaciers (Sicart et al., 2008). In the case of a sustained retreat of a glacier, the main feature of this phenomenon is the melting of the huge ice masses without the possibility of regenerating (Sandoval, 2021). For analyzing this phenomenon in tropical glaciers, Ramírez (2008) mentions among its main causes variations in climatic patterns such as precipitation and temperature, since, if there is no coincidence of precipitation and low temperatures, it is not possible to form permanent snow that renews and maintains the cycles of water regulation associated with glaciers. However, this is a complex multi-variable phenomenon, which is not controlled only by the amount of rainfall and temperature, but is also influenced by factors such as albedo, orientation, slope, among others. For example, ash deposition on the glacier caused by volcanic eruptions can change the albedo coefficient, altering the energy balance (Salcedo, 2019).

Various models have been developed to simulate volume variation in glaciers. The ITGG-2.0 model proposed by Juen (2006), is based on a vertical mass profile, where the density change is calculated as a function of altitude. In this model, the energy variation from altitude is based only on albedo and temperature gradients. In addition, a complete energy balance is performed including the estimation of latent and sensitive turbulent flows. On the other hand, the WEAP model proposed by Condom et al. (2011) is broader. Unlike the previous model, it does not employ a complete energy balance that considers all glacier processes, which requires detailed data and complicated calculations. Instead, the model divides the area of the basin into strips of height, some without a glacier, others with and without a glacier, and others completely with a glacier. The total volume is determined from the interactions between these bands. A more general model is the ICE-KISS model proposed by Pouget (2011), which considers a dynamic division of glaciers based on a temperature limit in the accumulation and ablation zones. In this way, sublimation and other explanatory variables are taken into account. The model uses a separation of areas of the glacier in accumulation zone and ablation zone (which is subdivided into high and low), being the main difference the temperature. In the country, several empirical and physical models have been proposed that have addressed the past and future of glaciers depending on the climate and the morphological conditions where the glacier is located. There are several models to evaluate 15th glacier of Antisana (Cáceres et al., 2006; Basantes-Serrano et al., 2016) and 12 of Antisana (Gualco et al., 2022) and a model of glacial dynamics to evaluate the state of the entire ice cap. Domínguez et al. (2012), proposed a model for the 15th glacier of Antisana.

This research aims to characterize the retreat of the Carihuairazo glacier through the use of a hydroglaciological model, a photographic record and the analysis of the influence of climatic factors and external factors. Additionally, it is intended to analyze the problems derived from the glacial retreat of Carihuairazo, considering the perception of climbers and other social agents who live or work in this area. In this sense, it is intended to confront the scientific information that validates the physical loss of the glacier thanks to hydrological and glaciological works, with the perception of some inhabitants and other social actors working in the area.

2 Materials and methods

2.1 Glacial surfaces

The area of the research corresponds to the Carihuairazo volcano and the Cunucyacu community (Figure 1), belonging to the Pilahuín parish. This community is located at an altitude of 4057 m.a.s.l. and 9.25 km from the Carihuairazo volcano. Carihuairazo is geographically located at the coordinates 1°2425S 78°4500W and reaches an elevation of 5018 m.a.s.l. It is a stratovolcano that collapsed towards the WNW (West-Northwest), located 10 km northwest of the Chimborazo volcano and 35 km from the Tungurahua volcano. The date of its last eruption is unknown, however, Clapperton (1990) points out that it may have occurred eleven thousand years ago. Rivers (Figure 1) emerge from the moors of Carihuairazo, which will irrigate arid areas of the provinces of Tungurahua and Chimborazo. This is where the Blanco River originates, which downstream joins the Colorado or Pucuyacu River, which forms the Ambato River by descending through the Chimborazo sandwaters (Moreno, 2023).

2.2 Meteorology

To characterize the glacial retreat of Carihuairazo and to know the perception of the Cunucyacu community to its extinction, we have used a methodology from multiple sources as Rhoades (2008), did in his study on the disappearance of the glacier of Cotacachi, including: repetitive photographs, data from weather stations, interviews to members of the Cunucyacu community and climbers who work and frequent the area, interviews to social actors with conservation experiences of moors since the 1970s. In this study we have collected different mea-

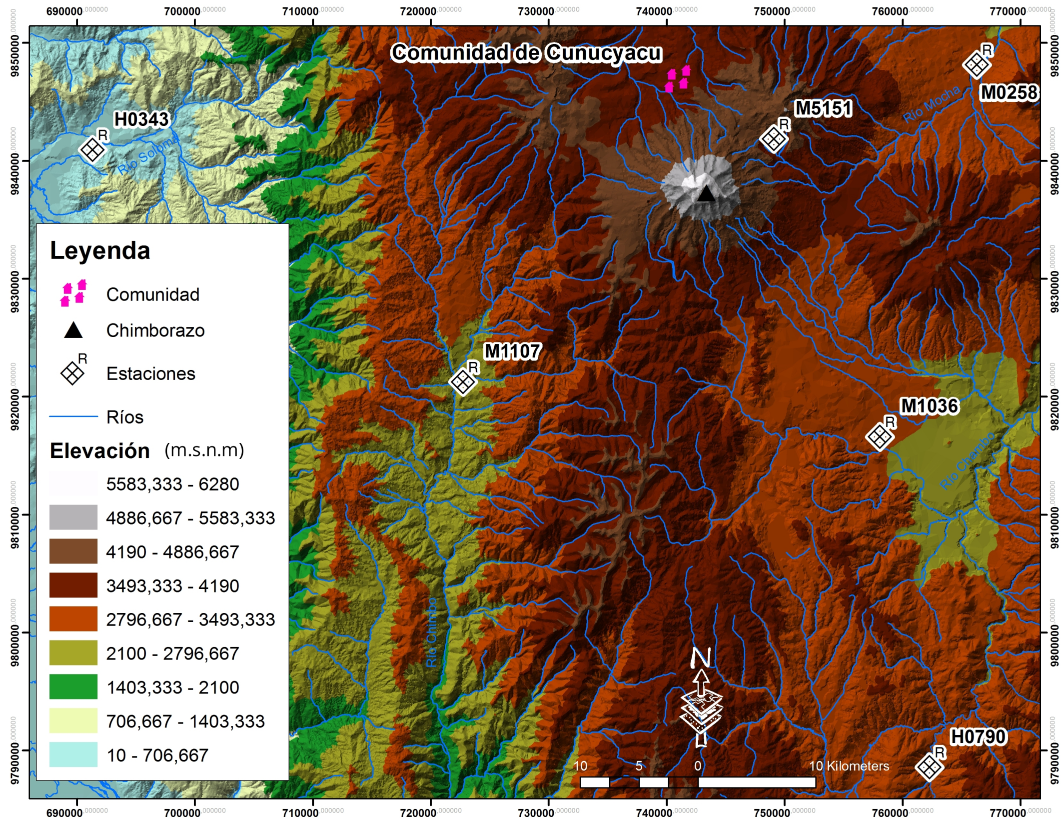

Figure 1. Map of the study area corresponding to the Carihuairazo glacier, location of the community of Cunucyacu and drainage of water sources in the community of Cunucyacu. Additionally, the location of the weather stations closest to the glacier is identified. Source: Digital Terrain Model (DTM) of Ecuador.
Source: Sigtierra Metadata Catalog.

surements of the glacier since 1956, considering the previous works ofCáceres and Cauvy (2015). This glacial contour was the reference to compare the percentage of loss until now. To complement this information, a photographic record of the mountain since the 1950s was also compiled. We also have meteorological data provided by the INAMHI (National Institute of Meteorology and Hydrology) stations closest to the study areas. Finally, to contrast the meteorological information with the perception of the population involved, as La Frenierre and Mark (2017) did in the study of the Chimborazo deglaciation, we also conducted interviews with the leaders of the community of Cunucyacu, climbers who frequent the area and social agents involved with preservation experiences. Likewise, we are interested in relating the climatic variables with the volcanic activity of Tungurahua and its influence on the evolution of the Carihuairazo glacier.

2.2.1 Glaciological data

The oldest data is the surface of the Carihuairazo glacier in 1956, which then reached an area of 0.34 km^2, from there we consider the measurements of the glacial contour made by Cáceres and Cauvy (2015); Villacis (2008) and Rosero et al. (2021). In addition, an updated measurement was made to contrast with the available measurements since its first monitoring in 2003. In the data, there is a gap of information between the year 2010 and 2015.

2.2.2 Climate data and *on-site weather* instrumentation

The meteorological data were provided by stations belonging to the National Institute of Meteorology and Hydrology (INAMHI). The "Glaciar 11 Chimborazo" station (M5151), located on the southwestern flank of the Carihuarizo at 1 km and at an altitude of 4428 m.a.s.l., was used as a reference for studying the glacier. For the treatment of temperature data station "Querochaca" (M0258) was used, located in the canton Cevallos at an altitude of 2865 m.a.s.l. The precipitation data were obtained from stations M0258, M1107 (Laguacoto) and M1036 (Riobamba Polytechnic) at a distance of 18, 35 and 28 km from station M5151, respectively. The validation and data filling process for the reference station included: homogeneity tests, linear regression and orthogonal regression, using distance as a weighting (Guijarrom, 2023).

In order to run the model from the year in which the first record of its surface is held (1956), data from the fifth generation of ERA5 reanalysis (Hersbach et al., 2020) from 1956 to 2022 were used. This information was calibrated to the observed data of the reference station by means of a statistical de-scaling from the calibration of the cumulative probability distribution of the variable with respect to a gamma distribution. From the calibration, the error corresponding to the reanalysis data was estimated.

Data on relative humidity and wind speed are scarce in these four seasons (especially for the years before 2010), for that reason data from the ERA5 reanalysis was used with their respective error (Hersbach et al., 2020).

2.2.3 Volcanic activity of Tungurahua

The Tungurahua volcano is located 35 km from Carihuairazo, its recent volcanic activity was affected with ash deposition on the glaciers of Carihuairazo and its neighbor Chimborazo. The opaque surface produced by the ash layer can affect the albedo values of ice masses, contributing to the melting process.

The eruptive process of Tungurahua began in 1999 and continued until 2016. According to reports from the Geophysical Institute of the (Instituto Geofísico de la Politécnica Nacional, 2015) and the newspaper (El Comercio, 2009, 2016). For more than 16 years, the eruption process of the Tugurahua volcano was permanent and affected several areas of the central region of Ecuador, especially the provinces of Chimborazo and Tungurahua, mainly because of the continuous emission of ash, which damaged agriculture, livestock and even involved at some point the evacuation of nearby populations.

2.3 Hydroglaciological model

The hydroglaciological model used to simulate the variation of the volume of the Carihuairazo glacier is a simplification of the model made by Piedra (2021) in Antisana. The model calculates the variation of the glacier volume monthly from an energy balance that is made with vertical profiles of the mass variation at different altitudes. Unlike other more complex models where a hydrographic basin with a glacial surface is considered and the flow produced by the non-glacial glacier assembly is estimated (Fernádez, 2018; Piedra Santillan, 2021), this model is limited to the glacier. A dynamic division of the glacier is considered for applying the model, which depends on a temperature limit in the area of accumulation and ablation. The equilibrium height line (EHL) represents the height separating the two zones (Juen, 2006).

2.3.1 Change in glacial volume

The model is applied to an annual (i) and monthly timescale (j). The relationship between volume and area of the glacier is given by the equation (Bahr and Peckham, 1997):

$$Ag_i = \left(\frac{Vg_i}{c}\right)^{1/b} \tag{1}$$

Where Ag is the area of the glacier, Vg is the volume of the glacier ab, c Vg is the calibration constants (section 2.3.5). The variation in glacial volume (ΔVg) for a given year is given by:

$$\Delta Vg_i = (\Delta Vab_i + \Delta Vac_i)\,\frac{\rho_a}{\rho_h} \tag{2}$$

Where ΔVab is the volume variation in the ablation zone, ΔVac is the volume variation in the accumulation zone, ρ_a and ρ_h are the density of water and ice, respectively.

2.3.2 Ablation zone

The ablation zone is divided into two zones with different contributions, the high (↑) and low (↓) zone, the delimitation of the zones is explained in section 2.3.4. The variation in the ablation zone is estimated from the monthly sum in one year, the total precipitation volume (Vp_{ab}), the melting volume (V_{der}) and the sublimation volume (V_{sub}):

$$\Delta Vab_i = \sum_{j=1}^{12} (Vp_{ab\,j} - V_{der\,j} - V_{sub\,j}) \quad (3)$$

Precipitation and sublimation volume are estimated by multiplying the ablation area by precipitation and sublimation height, respectively. It should be emphasized that these terms are calculated separately for their use in equation 3. The monthly sublimation was estimated with an empirical relationship considering the latent heat turbulent flow that depends mainly on wind speed and humidity (Francou et al., 2004):

$$Sn_j = a * u_j * (q_j - qs_j) \quad (4)$$

Where a is a constant for the homogeneity of the equation, u is the average monthly wind speed in m/s, q is the specific humidity and qs is the specific humidity for the ice or snow surface under melting conditions in each month. The calculation of specific humidity is based on the methodology proposed by Pouyaud et al. (1995).

For the case of the melt volume, its estimation is the sum of the melt volume in the high and low ablation zone:

$$V_{der} \uparrow\downarrow_j = F_j * M_{ab} \uparrow\downarrow_j * A_{ab} \uparrow\downarrow_j \quad (5)$$

Where F is a correction factor that depends on the variation of the incident radiation by geographic position, azimuth and slope,$M_{ab} \uparrow\downarrow$ is fusion in the high and low ablation zone, and $A_{ab} \uparrow\downarrow$ is the high and low ablation area. For the case of the Carihuairazo glacier, from the slope distribution analysis and the altimetry of the mountain, a constant slope of 25° and an azimuth of 270° have been estimated. The correction factor is estimated as the monthly incident radiation for the average incident radiation, regardless of cloud cover because no data are available. Melting is calculated as a function of temperature, where melting will only occur if the temperature in the zone is higher than the melting limit temperature:

$$M_{ab} \uparrow\downarrow_j = max\{0(a_h \uparrow\downarrow)(T_{ab} \uparrow\downarrow_j - T_{lim} \uparrow\downarrow)\} \quad (6)$$

Where a_h is the melting constant, T_{ab} is the temperature and T_{lim} is the limit temperature in the high and low ablation zone, respectively. The melting constants of each zone were calibrated (section 2.3.5). The limit temperature $T_{lim} \uparrow$ (separates the ablation zone from the accumulation zone) used has been $-1°C$ and for $T_{lim} \downarrow$(separates the ablation zone in high and low) $0,5°C$ (Favier et al., 2004; Francou et al., 2004; Pouget et al., 2017). According to Favier et al. (2004), these thresholds represent the best correlation between daily accumulated snow values and albedo variation for the case of Antisana. For the monthly case, the temperature threshold separates precipitation in liquid and solid state (Francou et al., 2004).

2.3.3 Area of accumulation

The volume variation in the accumulation zone is estimated from the difference between precipitation and sublimation, since there is no melting in this zone. The equation is as follows, where S_{ac} is sublimation in the accumulation zone and Aac is the area of the accumulation zone.

$$\Delta V_{acum\,i} = \sum_{j=1}^{12} (P_j - S_{ac\,j}) * Aac_j \quad (7)$$

2.3.4 Limit of altitudes, areas and temperatures

The limit altitudes are important variables that allow the dynamic division of the glacier in the three zones (accumulation, high and low ablation). The upper limit height (separates the accumulation and ablation zone) and the lower limit height (separates the upper and lower ablation zone) are estimated with:

$$H_{lim} \uparrow\downarrow_j = \frac{T_{lim} \uparrow\downarrow - T_{ref\,j}}{\Delta T} + H_{ref} \quad (8)$$

Where T_{ref} is the air temperature at the reference station, H_{ref} is the altitude of the reference station and ΔT is the temperature gradient relative to altitude, which is associated with variations in atmospheric circulation and relative humidity availability (Villacis, 2008). This gradient is in the order of -0,77°C,100 m^{-1} to -0,31°C,100 m^{-1} for the levels of 500 and 600 hPa (Villacis, 2008). The temperature gradient used in the model was -0,34°C,100 m^{-1}, obtained from the stations and adjusted to the glacier. This value is similar to -0,35°C,100 m^{-1} used by Pouget (2011) in the Paute basin (Ecuador).

Using the evidence of the glacier contour with the height limit of the extent, the area of the different zones of the glacier was estimated from a polynomial function with respect to elevation. Using the equation, the area of direct accumulation zone (*Aac*) and the area to the separation of the high and low ablation zone (*Aacab*) are determined. Where the areas of the high and low ablation zone are determined with:

$$Aab \uparrow_j = Aacab \uparrow_j - Aac_j \quad (9)$$

$$Aab \downarrow_j = Ag_i - Aacab \uparrow_j \quad (10)$$

Finally, the temperature in the high and low ablation zone for calculating the fusion is calculated by estimating a mean height in each zone and using a polynomial function that relates the temperature with respect to the elevation.

2.3.5 Calibration of the parameters of the glaciological model and estimation of uncertainty

The glaciological model requires four parameters for its calibration (a, b, $a_h \uparrow$, $a_h \downarrow$). Both the parameters of the glacier area-volume relationship, as well as the melting constants of each zone were calibrated using as an objective function the Nash-Sutcliffe estimator between the available annual observations of the glacier area and the model simulation from a Newton second order optimization method (Byrd et al., 1995). For calibration, calibrated weather series of the reanalysis and the values observed at the reference station were used. These parameters are called model reference parameters.

To estimate the uncertainty regarding the annual area of the glaciological model, the following procedure was performed. First, 10000 series of monthly data for each input weather variable were generated randomly. For each endpoint and each month, the value was generated randomly following a normal distribution with a mean equal to the calibrated value of the reanalysis or the observed value of the endpoint and with a standard deviation corresponding to the error between the calibrated values of the reanalysis and the observed values of the reference station. For each set of series generated, calibration of the parameters of the glaciological model was performed. Subsequently, the model was run with calibrated series of reanalysis and all calibrated parameter sets (10000) were used to demonstrate the influence of calibrated parameters in the model. Finally, the 10000 runs of the model were performed again with the different sets of weather series using the reference parameters. In this sense, it was intended to evaluate the effect of uncertainty of the input data of the model.

2.4 Community perception

The present study confronts the scientific information that validates the physical loss of the glacier thanks to hydrological and glaciological works with the perception of the communities of the area. To do this, we resorted to semi-structured interviews addressed to two members of the community of Cunucyacu. We participated in a general assembly of the whole community, we interviewed eight guides and climbers who frequently visit this mountain, in this way we recorded and compared their observations and perceptions on the retreat of the Carihuairazo glacier in the last thirty years. We also interviewed seven socio-environmental actors related to the care of the wasteland that broadened the view of this situation and its implications.

The community welcomed us at its general assembly, held on September 11, 2020. The 56 participants of this meeting expressed that their main concern regarding this phenomenon is limited to a possible decrease in visitors to the place. On the other hand, they consider that water was not lacking since the time of their grandparents, and although the retreat of the glacier is evident to them, they trust that the loss of the Carihuairazo glacier will not affect them significantly, and would have no problems in the future associated with water management in the area. Climate change and its consequences are not a relevant problem in their discussions.

Interviews were also conducted with several members of the community of Cunucyacu, such as Mr. Luis Punina, who is a community guide of Cunucyacu. The other interview was held on September 1, 2020. The other interview was held on September 11, 2020 to the five members of the community board. The interview of Mr. Segundo Enrique Punina (President of the council of the Cunucyacu community) was done on September 16, 2020. Both the community members and the eight climbers interviewed agree on the dramatic glacial retreat in Carihuairazo. Their concerns and motivations may be different but they refer to the same origin of the problem, the loss of the ice mass, leaving a serious trauma in their perception of this environment, fewer tourists, more dangers on the ascent routes, less water availability, and uncertainty about a future without glaciers in the Andes.

3 Results and discussion

3.1 Results

3.1.1 Rainfall and temperature timeseries

A good correlation was determined between the meteorological stations used in the study. The correlation coefficient reached a value of 0.67 and 0.82 for precipitation and monthly temperature, respectively. From the validation process and data filling with meteorological stations, the precipitation series was defined in the reference station from 2002 to 2017. For temperature, the series was defined from 1995 to 2012 (Figure 2). Regarding the calibration with the data of the ERA5 reanalysis, statistical de-escalation produced a reconstructed series from 1956 to 2022 for precipitation and air temperature (Figure 2). The correlation coefficient between the calibrated reanalysis series and the reference station was 0.59 and 0.74 for precipitation and temperature, respectively.

3.1.2 Climatic conditions on the glacier

The annual variation of precipitation and temperature in the study area can be seen in Figure 3. Precipitation varies between 458 and 1281 mm and the average is 770 mm. No trend can be seen in the temporal variation of precipitation (positive percentage variation factor of 3 %). The wettest years are 1983, 1984, 1994, 1998, 2008 and 2017. On the contrary, the driest years are 1961, 1962, 1986, 2003, 2009 and 2013. Regarding temperature, the average value is 0,7° and ranges from −0,3 to 1,7°C. Unlike precipitation, temperature has a clear positive trend (percentage variation factor of 137 %). Excepting 1998, the warmest year is 2013.

3.1.3 Glacier boundary between 1956 and 2021

There are barely 12 records of the contours of Carihuarizo glacier between 1956 and 2021 (Figure 4). The records are based on aerial photographs and topographic measurements, especially from 2003 onwards. There is only one previous record (1956). A downward trend in the glacier's surface area has been identified from the first estimate for the year 1956. This surface will be considered as reference for future estimates of the glacier contour for both photographic records and model outputs. By 2003, the glacier had already lost 30 % of its reference area. Unfortunately, there is an information gap between 1956 and 2003, so it cannot be observed if there were recovery periods of the glacier. By 2015, it was already recording a 90 % loss compared to 1956. In 2017 and 2021, glacial loss reaches 96 % and 99 %, respectively.

Figure 4 was elaborated thanks to the photographic archive of the mountaineer Marco Cruz, in which we show the temporal sequence of the glacial retreat in Carihuairazo. According to the definition of the Chilean National Glacier Strategy (CECS, 2009), a glacier is an ice mass of at least 0.1 km^2 in length. If we consider that in 2017 the measured area is 0.015 km^2, confirming that the remaining ice mass can no longer be considered as a glacier.

3.2 Modeling of the Carihuairazo Glacier

The model was run from 1956 to 2022 and its results can be seen in Figure 6. The model shows the recovery of the area of the glacier from 1956 to 1963, followed by a stagnation period of several years and then a significant increase between 1973 and 1976. Starting this year, the glacier is showing a continuous retreat over time, with few recovery periods. It can be observed that the model satisfactorily simulates the evolution of the glacier area until 2010. The model captures the general decreasing trend and variations in the area, including the recovery of the glacier mass in 2008. For this period, the Nash-Sutcliffe (nse) estimator is 0.82 and the mean square error (rmse) is 0.01 km^2. However, the model fails to simulate the glacier area in 2015, 2017 and 2021. Considering the whole period, the nse and rmse reach a value of 0.77 and 0,03 km^2, respectively.

The uncertainty associated with the input variables and model parameters are represented in Figure 6. The smallest range corresponds to 10000 model

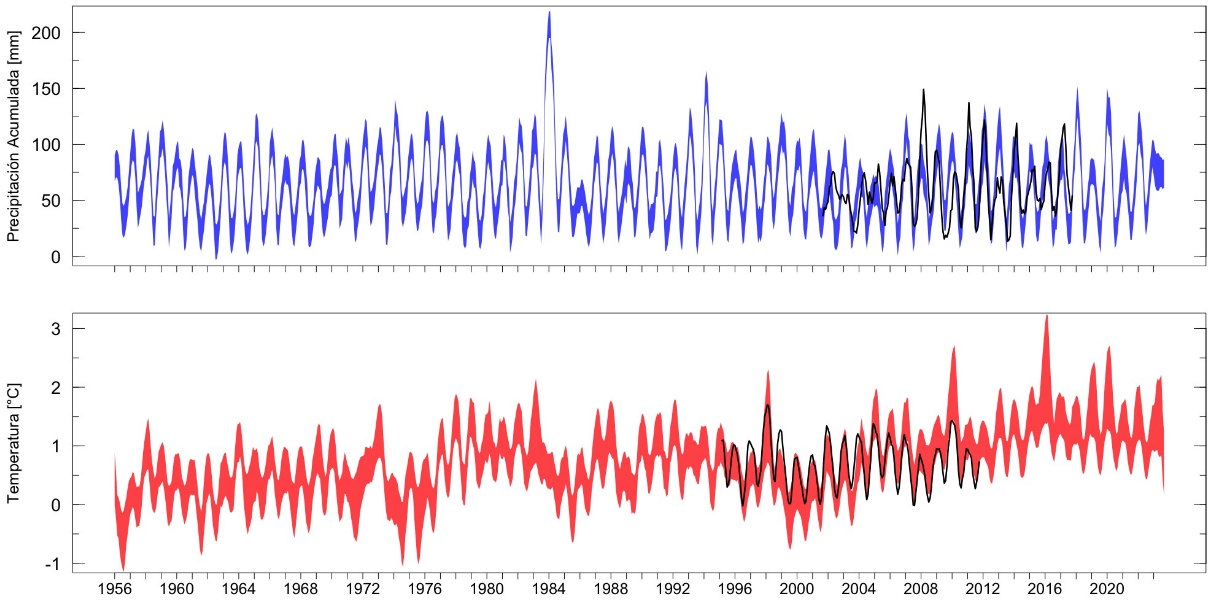

Figure 2. Monthly Precipitation (blue surface) and mean temperature (red surface) for a 95 % confidence interval in the area near Carihuairazo glacier after calibrating ERA5 reanalysis data with observations of the reference station (black line) within the period 1956 to 2022.

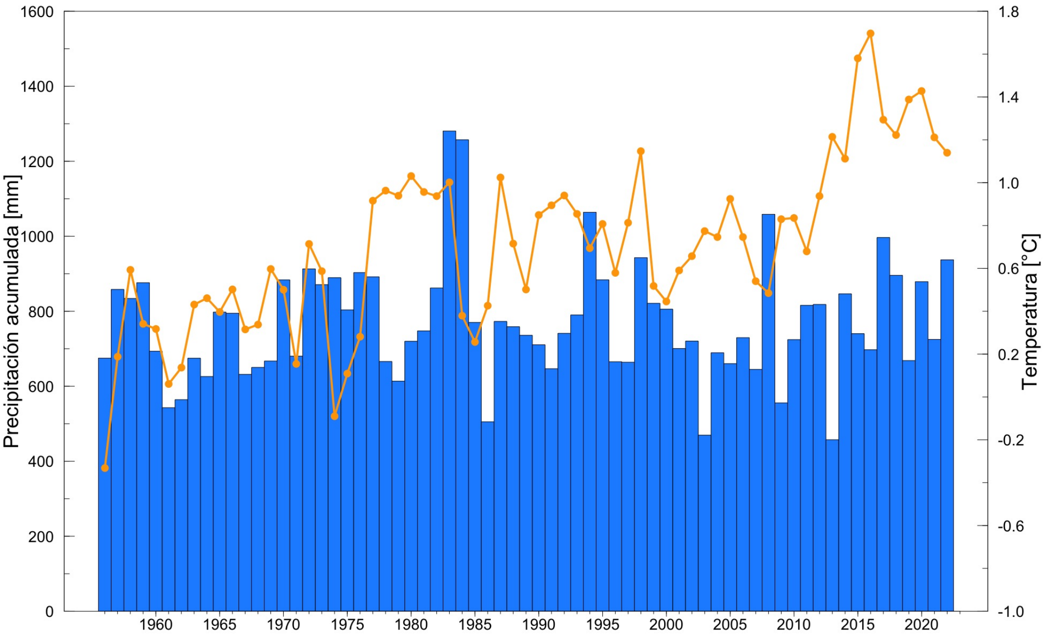

Figure 3. Accumulated precipitation (blue bars) and mean temperature (orange line) in the area near the Carihuairazo glacier in the period 1956 to 2022 obtained from the calibration of the ERA5 reanalysis data with the reference station.

simulations with changes in input variables using calibrated model reference parameters (Table 1). In this case, the band increases in size in relation to the years, and that the greatest uncertainty is seen in the last two decades. The second larger range corresponds to 10000 model simulations with calibrated parameters for each of the 10000 sets of input variables.

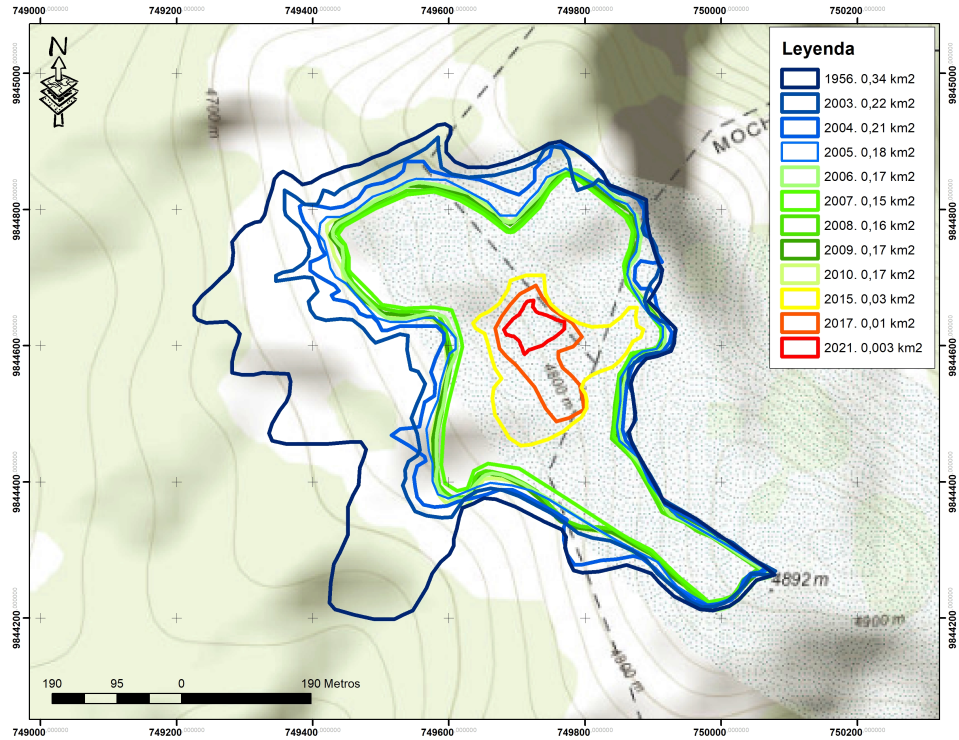

Figure 4. Map of the study area showing the evolution of the glacial retreat of Carihuairazo. The contours of the glacial surface were first measured in 1956 through aerial photographs. There are different topographic field measurements from 2003 to 2021, carried out by different research teams, which reveal the decrease of this ice mass. The blue outer contour shows the area considered as a reference recorded in 1956. On the other hand, the red polygon illustrates the last field measurement made in 2021. Source: Adaptation of Cáceres and Cauvy (2015) and Rosero et al. (2021).

In this case, it can be seen the greatest uncertainty in the first 25 years and in the last 7 years of the simulation. The range of uncertainty between the 1980s and 2010 is similar to that of the first range. Regardless of the combination, it can be seen that the model clearly simulates the loss of mass of the glacier, which increases from the second part of the 80s.

Table 1. Calibrated hydroglaciological model parameters. The range corresponds to 95 % of the 10000 values around the median.

Parameter	Range	Calibrated value
a	0.013 - 0.028	0.014
b	1.27 - 2.01	1.35
$a_h \uparrow$ [mm/month/°C]	214 - 234	218
$a_h \downarrow$ [mm/month/°C]	227 - 328	228

The model allows estimating the input and output variables of the glacier that increase and reduce the size of the glacier, respectively. Figure 7 shows these variables in the run period of the model. The predominant variable is fusion, being the highest variable in 58 % of the time. Precipitation is the highest variable on 28 occasions, being 69 % before 1980 and only on one occasion after 2000. The sublimation is low in relation to the other variables, oscillating around 100 mm of water equivalent height. In relation to the balance between inflows and outflows, there is a deficit in 61 % of the time. This explains the loss of glacier mass that is evident in the variation behavior of the glacier area, where a recovery can be observed in a few years

3.3 Discussion

3.3.1 Hydroglaciological model and influence of climatic and external factors

The hydroglaciological model was run since 1956, corresponding to the first available measurement of the glacier. To complement the data of the cli-

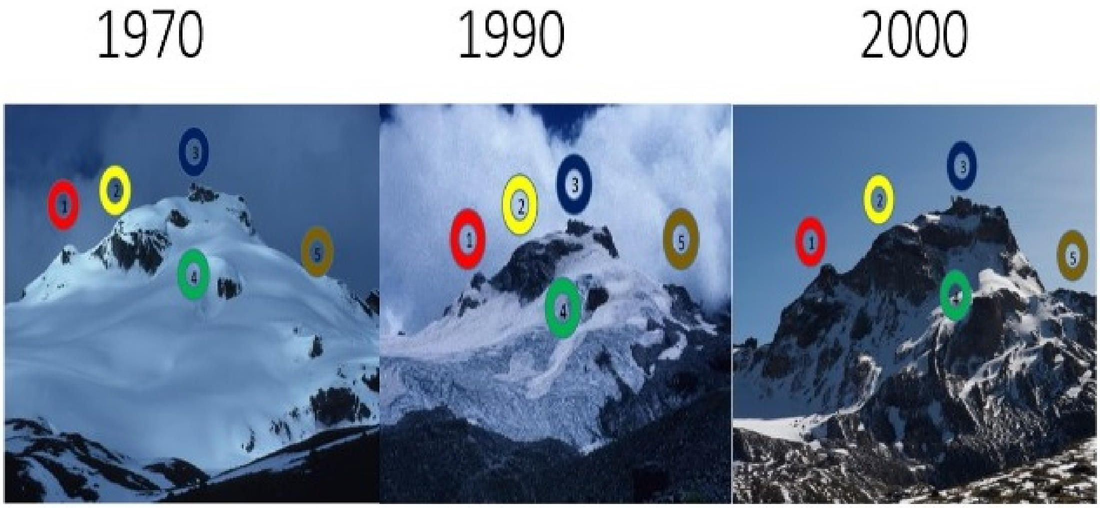

Figure 5. Photointerpretation. The images correspond to the same perspective of the central summit of Carihuairazo, from the southern flank belonging to the Marco Cruz archive. The circles of the same color show the same point on the mountain and how it has varied from the 1970s to the early 2000s. The changes in the mountains in the five reference points considered during the last decades of the 20th century can be seen. Today, the glacier can be considered practically extinct.
Source: Personal collection of Marco Cruz.

matic variables, the product of the reanalysis ERA5 was used. Reanalysis data have been used in other studies in the region such as the case of the Antisana volcano (Bradley et al., 2009; Manciati et al., 2014; Basantes-Serrano et al., 2022). Manciati et al. (2014) found that the variables of the NCEP-NCAR reanalysis (Kalnay et al., 1996) combined with data from regional stations have a good correlation with glacial mass loss. Basantes-Serrano et al. (2022) used the ERA5 reanalysis to estimate the effect of climate and topography on the variation of Antisana volume, where it was found that the reanalysis series was able to capture the seasonality of precipitation and temperature on the west side of the volcano. In this study, ERA5 reanalysis was used because it showed a better correlation with the reference station for temperature than NCEP-NCAR reanalysis.

The reconstituted temperature series presents a clear positive trend that magnified more from the year 2012. This trend is in accordance with results obtained at global (Hugonnet et al., 2021; Intergovernmental Panel on Climate Change (IPCC), 2022) and regional levels (Morán-Tejeda et al., 2016; Aguilar-Lome et al., 2019; Imfeld et al., 2021). The temperature shows an increase of 0,14$^{\circ}C$, a value similar to 0,10$^{\circ}C$ found in the Peruvian Andes (Seiler et al., 2013) and less than 0,25$^{\circ}C$ found in Ecuador (Morán-Tejeda et al., 2016). Regarding precipitation, no clear trend was found. In a study of climate trends in Ecuador,Morán-Tejeda et al. (2016) did not find a significant trend in annual precipitation in the inter-Andean region. Wet periods such as 1965-1966, 1983-1984, 1993-1994, 1997-1998 and 2008 coincide with the standardized precipitation evapotranspiration index found by Vicente-Serrano et al. (2017) in the interandean region. A clear increase in precipitation in the period 1983-1984 coincides with the extreme El Niño phenomenon in that period. However, there is no significant increase in the other extreme period of El Niño (1997-1998). This behavior coincides with the study of dry and humid extremes in the city of Quito by Domínguez-Castro et al. (2018). Dry years such as 1961-62, 1967, 1979, 1986, 1991, 2003 and 2009 coincide with the results of Vicente-Serrano et al. (2017) and Domínguez-Castro et al. (2018).

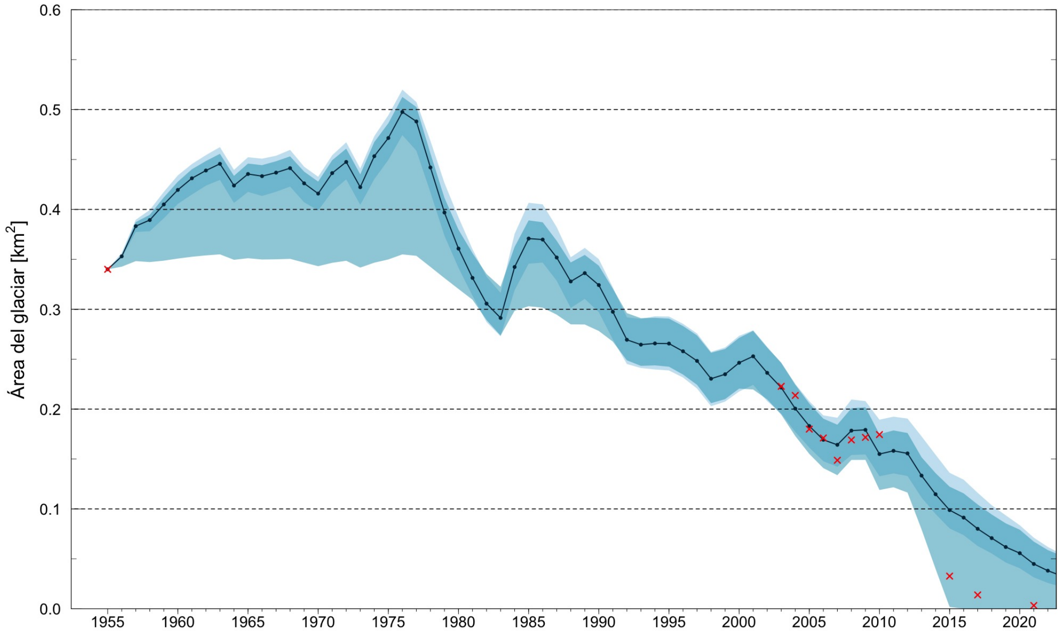

Figure 6. Variation Simulation of the Carihuairazo Glacier area (1956-2022) as a product of the hydroglaciological model. The red crosses correspond to the observed measurements of aerial photos (the first measurement in 1956 is represented in the model as the final value in 1955). The dotted dark solid line represents the model simulation with the calibrated reanalysis series. The light blue surface represents 95 % of the 10000 simulations performed with the variation of the input variables using the calibrated parameters. The dark blue surface represents 95 % of the 10000 simulations performed with the calibrated reanalysis input variables and the different parameter sets calibrated for the input variable variation. The darker blue band represents the intersection of the bands described above.

The parameters calibrated from observations of the glacier area are within typical values as evidenced in the literature (Table 1). The parameters relating the area and volume of the glacier ($a = 0{,}014$ and $b = 1{,}35$) are similar to those recommended for the study of the area-volume relationship of several glaciers of Bahr and Peckham (1997), where values of a=0.048 and b=1.36 are recommended. The parameter values obtained from the optimization of 10000 runs for different variations in the input variables reveal a large dispersion (Table 1). Bahr et al. (2015) performed a review of the area-volume relationship of glaciers for parameters a and b, and indicates that while parameter a can vary from glacier to glacier and can even change over time, the parameter should be fixed and its value should be between 1,167 and 1.5, otherwise it could cause inconsistencies in the mechanical equilibrium equations in glaciers. Grinsted (2013) also finds the value of b within this range. However, Radić et al. (2007), in a study of the evolution of 37 synthetic glaciers, found b values of 1.56 for stationary conditions, and even higher values (up to 2.90) for non-stationary conditions, concluding that parameter b is higher in warming scenarios (loss of glacial mass) and that it tends to increase with a smaller initial glacial size. This finding is in agreement with an evolution study of the small Chacaltaya glacier in Bolivia (Ramirez et al., 2001), where parameter b can be estimated from 2.05 in the period 1860-1998 from annual topographic measurements and geophysical studies carried out on the glacier. In this study, in 39 % of cases parameter b is within the range recommended by Bahr et al. (2015). In 98 % of cases, b is below 2.05. For the melting constants in the high and low ablation zone, the calibrated values are close to the values recommended by Fernández Yánez (2010), of 180 and 240 mm/month/$°C$, respectively. However, the values found are lower than the range of 284 to 434 mm/month/$°C$ used by Caro et al. (2023) in a simulation of glacier mass loss in the tropical Andean zone.

The development of the model allowed estima-

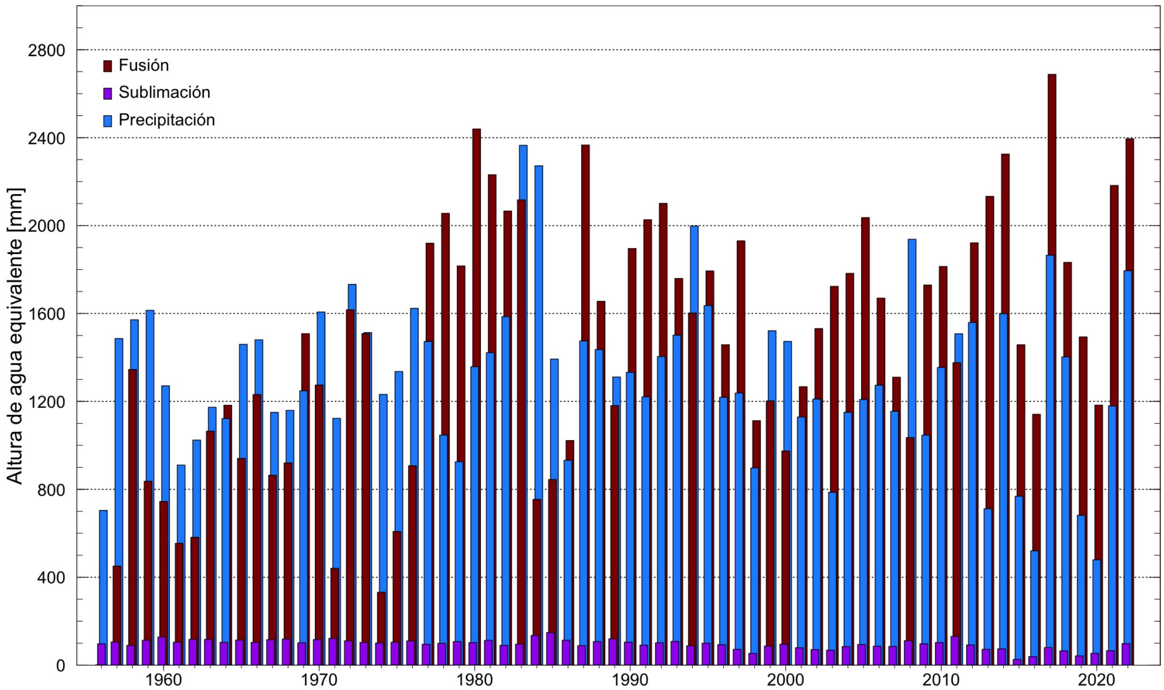

Figure 7. Annual mass balance in the Carihuairazo Glacier (1956-2022). The bars represent the variables of entry (precipitation) and exit (fusion and sublimation) that influence the mass balance of the glacier.

ting the variation in the volume of the glacier in a period of 68 years. The model shows an increase in the mass of the glacier until 1975 and later a constant loss of its mass, except for a few years (e.g. 1999-2000 and 2007-2008) where there is a slight recovery as a result of an excess in precipitation inputs or by the decrease in losses by sublimation and fusion, the last reduced by the reduction of temperature in those years. This accelerated loss of glacier volume since the late 1970s has been evident in the Andean glaciers of the tropical zone (Rabatel et al., 2013). Also, a worldwide significant decrease in the volume of glaciers has been reported since the beginning of the 21st century that coincides with the increase in sea level (Hugonnet et al., 2021). In Ecuador, a recession study of the Cotopaxi volcano glacier (Jordan et al., 2005) showed a similar behavior to that found in this study, where in the period 1956-1976 the Cotopaxi glacier maintained its mass, and subsequently suffered a 30 % retreat of its mass until 1997. In another study in the glacier of the volcano Antisana (Basantes-Serrano et al., 2022), a similar behavior can be evidenced except for the period 1956-1964, where there was a significant retreat of the glacier, and the period from 2000, where although the glacier had losses of mass, the retreat was not as significant as the period in the late 70's until 2000. This behavior differs from the retreat of the Carihuairazo glacier, where mass loss is similar between the 80s and the end of 2010. For the case of the Chimborazo volcano glacier, the closest to Carihuairazo, the loss of the glacier area between 1962 and 1997 was 57 % (Caceres, 2010), which is similar to the 48 % found in this study.

Although the model manages to successfully simulate the glacier area until 2010, it cannot reproduce the abrupt decline that occurs from 2011. Looking at the precipitation and temperature in this period, the temperature undergoes a considerable increase in 2011 to 2016, and subsequently a slight decrease (Figure 2). This variation in temperature is reflected in the decrease of the glacial area, but the loss of mass is not sufficient as seen in the observations. One factor that could explain the difference is the relationship between the volume and the area of the glacier. The model uses a constant ratio regardless of the size of the glacier. But this relationship can change especially when the area is reduced, since the influence of the topography of the mountain will be more prevalent (for example the presence of bumps or depressions). This phenomenon could be explained by the edge effect that Santos and Tellería (2006) define as "the set of processes associated with the increase of the perimeter/area relationship that occurs with the advance of fragmentation". Also, it should be considered that the reduction of the glacier mass to such a small size (less than 0.1 km^2) can produce a change in the microclimate around the glacier, producing an increase in temperature that has not been evident. For example, the small Chacaltaya glacier in Bolivia, which had an area of 0.25 km^2 at the beginning of the 1940s, has suffered a retreat to extinction. By the beginning of the 21st century, the retreat meant an outlet from the heat supply for the melting of the glacier of 10 W/m^2 (Ramirez et al., 2001), equivalent to an increase of 1,5°C.

Another factor that could be considered in the simulation of the retreat of the Carihuairazo glacier is the influence of the eruptive process of the Tungurahua volcano. Vasconez et al. (2021) determined that in November 2015, 1.83E+06 m^3 of ash were released into the atmosphere. According to this same study the average wind direction during the eruption was towards the west, northwest and southwest. This research determined that the accumulated volcanic ash reached <100 g/m^2 in the highlands of the eastern flank of Chimborazo volcano. Due to the proximity of Carihuairazo to Tungurahua volcano, the ash emanations of the volcano were deposited in the glacier, partially covering the surface of ice and snow, causing a reduction in albedo. As a result, the ability to reflect shortwave radiation to the glacier may have been diminished, favoring melting and the subsequent glacier retreat dynamics. The accumulation of ash on the glacial surface of Chimborazo and Carihuairazo from the eruptions of Tungurahua exacerbated the deglaciation process, as Cruz points out (2020, personal interview): "A high albedo will reflect up to 90% of the light energy, on the contrary, the Tungurahua ash reduced the albedo in the glaciers of Chimborazo and Carihuairazo, so that up to 80% of the light energy was absorbed by the glacier, causing the formation of large penitent fields".

La Frenierre and Mark (2017) points out that the decrease in albedo exacerbates the effect of glacial surface warming, as observed in Kilimanjaro, in West Africa, where glacial retreat has been more sensitive to the decrease in albedo, due to reduced snowfall, than to increased temperatures.

The simulation of the model, the observations of the glacier area and the record of the volcanic activity of Tungurahua have been elaborated (Figure 8) with the information collected in the meteorological stations, which relates for each year the behavior of each of these variables in order to establish a possible connection between them and the glacial retreat of Carihuairazo. In the period 2003 to 2017, it can be observed that the variation in the glacier area is mainly related to the temperature variation in both the model results and the observations. On the contrary, precipitation shows an inverse relationship in several years. Regarding the activity of the Tungurahua volcano, an attempt has been made to characterize its activity in a qualitative way. There is no obvious relationship between activity and glacial area variation, but activity may explain some differences between the model and observations.

For the period 200- 2009, despite the favorable climatic conditions for a possible considerable recovery of the glacier, the coincidence of this period with one of the most violent eruptive phases of the Tungurahua volcano, we verify only a small recovery of the Carihuairazo glacier. For the period 2010-2015, there is no significant increase in the activity of the volcano that could explain the abrupt reduction in the glacier area. In this sense, the significant retreat in the area would be more related to the edge effect in the upper part of the glacier.

3.3.2 Impacts on socioeconomic, environmental and cultural systems

An attempt has been made to characterize the impact of the glacier retreat on the Cunucyacu community. Both the community members and the climbers interviewed agree on the dramatic glacial retreat in the Carihuairazo, their concerns and motivations may be different, but they refer to the same origin of the problem, the loss of the ice mass leaves a cultural trauma in their perception of this environment. More perils on the ascent routes, less water availability, and uncertainty about a glacier-free future in the Andes. The wasteland areas are the ones that ensure the provision of water for populations at lower elevations. According to the research carried out by Buytaert et al. (2017), it was determined that the glacial contribution from Carihuairazo to the flows of the area is not representative, since it is below 4%. Although the retreat of Andean glaciers in Ecuador does not necessarily imply a decrease in water availability by itself, it is a clear indicator of the changes in conditions and temperatures of this ecosystem, and it also reveals a number of vulnerabilities associated with climate change, such as forced migration in search of better fields of cultivation, search for new water sources, better pastures, etc.

For Ana Segovia (2021, personal interview), the loss of the link with nature, specifically in the community of Cunucyacu, is due to the precarious living conditions that these people face. The lack of quality education, the distances that children have to travel to reach the community school, for example, makes that people who can afford send their children to study elsewhere, generating the conditions of future migration. One consequence of this phenomenon is that currently agriculture and livestock are managed by older adults. Segovia believes that it is also a problem of self-esteem, because it is considered that having some kind of binding belief with the mountains is wrong, not properly valued. In addition, the general perception that associates life in these areas with poverty and marginalization is very present. This uprooting of communities in front of the paramo has its interpretation in the change of land tenure, which for Luis Chicaiza (2021, personal interview) is a structural problem, since many communities were displaced from low, more productive areas, to high land, less productive for agriculture, forcing them to change land use in their search for resources for their subsistence.

As for Susana Escandón (2021, personal interview), water is one of the elements around which conflicts, knowledge, economic dynamics, etc. occur, so it is important to consider this multidimensionality of water when making comprehensive decisions about it. In this sense, it explains another way of understanding this process of disconnection, due to the decrease of resources in these territories, and which now no longer turn out to be as visible or powerful as before.

Based on the interview with Mr. Luis Punina, a local community guide, the main concern they have about the glacial retreat of Carihuairazo is the consequences in the tourist area, above even the possible implications in the availability of water for the community. Since they have the idea that visits to the sector are only due to the interest of approaching the snowy mountain, and once the glacier has disappeared, they have noticed a decrease in tourists. It is important to consider that this study has coincided temporarily with the confinement measures decreed in the context of COVID-19. At the meeting held with the community assembly on September 11, 2020, the members expressed their confidence that since the time of their grandparents, they have not lacked water, and they are confident that they will not be lacking in the future, regardless of whether the Carihuairazo glacier will disappear completely. So they show a complete disinterest in generating plans and actions that allow them to adapt to possible threats. Despite this, they have already begun to look for new sources of water supply from the Chimborazo glaciers.

Great respect for nature was one of the values rooted in the worldview of the high Andean indigenous communities, but the new generations today have a new way of understanding their environment as Mesías Usigña (2021, personal interview) points out. Factors such as religion, dispossession of arable land, migration, changes in the ways of consumption of communities and especially cities have generated inadequate living conditions around the mountains, the search for more resources has made people separate from their symbols and beliefs.

The choice we face as a society shows on the one hand the demand of care of the wasteland towards the communities for all people who benefit from it, and on the other hand is the legitimate remuneration that cities owe to communities for their conservation actions of the wasteland. It is necessary to establish the link between the urban and the rural, understand the origin of the water coming to our cities, since it will help to make visible the need for fair treatment with the communities that are responsible for the protection of the moors. It is important to value family peasant production systems, which are those that provide the cities.

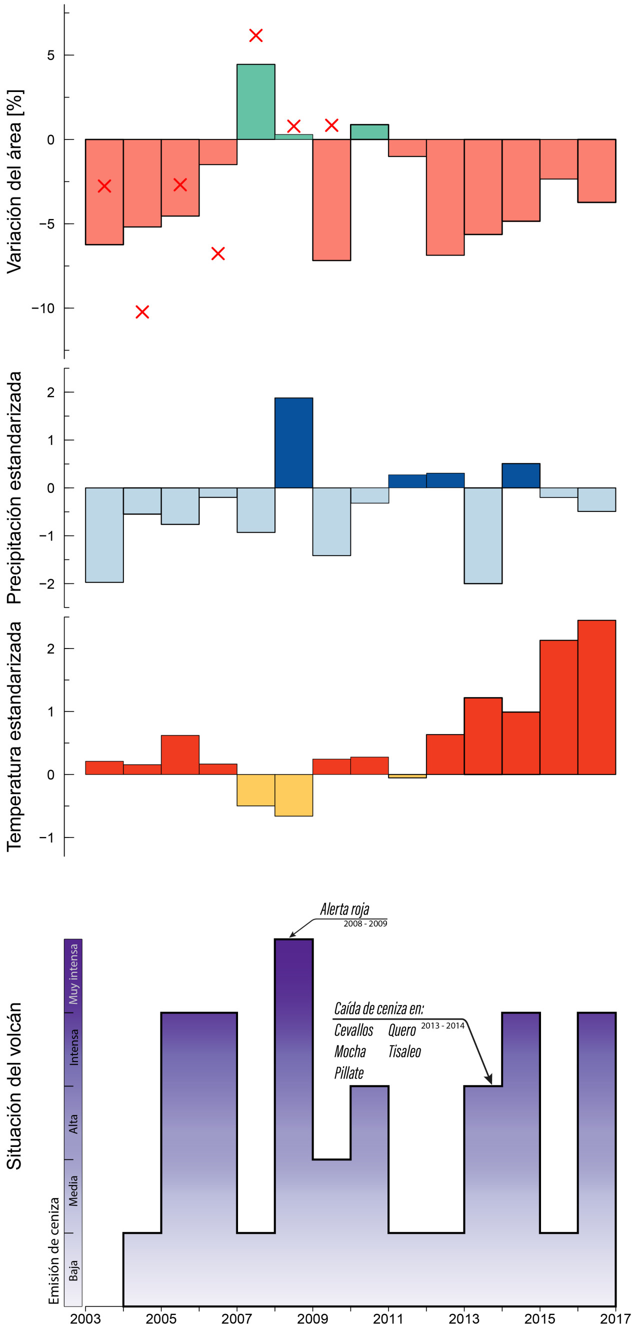

Figure 8. Relationship between the variation of the surface of the Carihuairazo glacier, precipitation, temperature and volcanic activity of Tungurahua between 2003 and 2017. The first graph shows the increase or loss of the area between each year in relation to the year 1956 (0.34 km^2), the bars correspond to the simulation of the hydroglaciological model and the red crosses to the measurements of the glacier contour (only years followed by observations were included). In the second graph, standardized precipitation is observed for each year. The third figure shows the standardized temperature in each year. The fourth graph shows the characterization of the volcanic activity of Tungurahua in relation to ash emission and point events.

Water should be considered "as a dynamizer of the peasant community organization" (Chicaiza 2021, personal interview). This perception of water as something more than just a resource, would facilitate the commitment of conservation of the sources from cities, towns and communities. Tensions around the paramo reveal deeper issues of inequality and marginalization that motivate migration processes in several aspects: land tenure, access to quality education, access to basic services, access to water of the same quality as that reaching the big cities, etc. Attempts to slow the advance of the agricultural frontier, care for water that others use, are some of the many faces of this crisis. In the last ten years, we have been able to generate data and models on the possible climate scenarios that our region could face; however, this information has not reached farmers and less so the communities that inhabit the moors, so part of this awareness process of climate change must be crossed by the democratization of climate information, which allows them to understand and adapt to the changes that are evident and that sooner or later will affect their ways of life.

Although currently indigenous communities do not specifically discuss climate change, it does not mean that they are oblivious to this reality, since for them a substantial change in their agricultural calendar is noticeable. Perhaps their discussions are more focused on issues that are considered priorities for their daily subsistence, and they will not be able to properly articulate a climate change agenda as long as their most basic needs are not met.

3.3.3 Adaptation needs, challenges and opportunities

The socio-economic context of Cunucyacu is complex, since out of its 12,218 inhabitants, 95% of the population live under poverty conditions, in an environment where not everyone has access to basic services, and do not reach to cover the basic family basket (GAD Parroquía Rural de Pilahuín, 2015). Irrigation to support crops that are not normally irrigated could become more important in the coming years due to rainfall variability. Therefore, irrigation infrastructure should enable this type of assistance, through mobile spraying or drip irrigation systems, and thus ensure food security for this population (Gobierno Provincial de Tungurahua, 2011).

We still do not fully understand the importance of glaciers in hydrological cycles, and despite this we do not have a network for monitoring and surveillance of glacial behavior in the Andes, causing serious uncertainties in the attempts to model the behavior of these ice masses and their future influence on the water supply for our fields and cities.

3.3.4 Limitations of the research

Regarding the implementation and validation of the hydroglaciological model, one of the limitations was the available measurements. There are no stations on the glacier and the nearby weather stations are rare. In addition, it is necessary to consider the uncertainty of the reconstruction of the series from the use of the ERA5 reanalysis. For this reason, there is uncertainty in the time series of the input meteorological variables used in the model that reaches an error in the estimates of the area of the glacier of 0.02 km^2. However, the main limitation is the limited number of measurements that serve to validate the model, which in this case are the measurements of the glacier area. Unfortunately, between 1957 and 2000, there is no data for the glacier area. The limited number of measurements of the glacier area generates uncertainty in the values of the calibrated parameters of the model since there may be the problem of equifinality, because there are not enough restrictions to include the uncertainty of the meteorological variables of entry. In this sense, the average error in the estimations of the area reaches 0.05 km^2 and is greater in the decades where there are no observations. However, the model manages to simulate the glacier retreat satisfactorily.

Regarding the perception of the community regarding the retreat of the glacier, the greatest limitation faced by this research was the restrictions of the COVID-19 pandemic that coincided with the time of field work. Another limitation was the community's refusal to conduct perception surveys after meetings and agreements with the community's leadership. Therefore, it was not possible to have a statistical input, to contrast with other preservation experiences of the paramo; interviews were conducted with different actors working in research tasks, water funds, leadership of indigenous organizations, private reserves and international agencies, to obtain a broader view of the socio-environmental situation of the paramos in Ecuador.

4 Conclusions

From a photographic record, community testimonies and measurements of the contour of the Carihuairazo glacier, it is concluded that the Carihuarizado glacier has experienced a significant retreat. Relative to the year 1956, the glacier has lost 97.1 % and 99.1 % of its surface area by 2017 and 2021, respectively. The use of a hydroglaciological model evidences the loss of the glacial area from the late 70s, except for a few years where a slight recovery is evident. The decline coincides with the positive trend in temperature increase over the years, this variable being the one that would have the greatest influence on the reduction of glacier volume. The model used has some limitations and cannot incorporate external factors such as ash fall from the Tungurahua volcano.

The climatic and altitude conditions to which this small mass of ice is subjected place it in a situation of inevitable extinction. Although the retreat of Andean glaciers in Ecuador does not necessarily imply a decrease in water availability by itself, because it is mainly the moors that ensure the provision of water for populations, it is a clear indicator of the changes in conditions and temperatures faced by this ecosystem.

It is necessary to persist on the need to collect meteorological information in the areas near the glaciers of the Ecuadorian Andes and to adjust models that allow predicting their behavior in the coming years to constitute a scientific basis that facilitates proposing adaptation measures.

The glacial retreat will affect some areas such as the landscape and with it there could be an impact on local tourism, but its impact on water supply will be limited, however an articulated conservation process moor - glacier, considering it as complementary elements, would allow better management of policies and actions to implement.

Finally, the scientific community must maintain links with the communities that are affected by this glacial retreat, since finally it is the people who make this reality evident beyond the behavior of the weather series.

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Author Contributions

DHP; Conceptualization, research, supervision, project administration, data processing, visualization, writing-original draft. JCRH; Data curation, writing-review and editing, research, resources, validation. LM; research, resources, writing-review and editing. BC; research, resources, writing-review and editing. VCP; research, resources, writing-review and editing. CD; Data curation, formal analysis, research, methodology, software, visualization, writing-review and editing. TC; research, resources, writing-review and editing. MV; Conceptualization, research, formal analysis, methodology, project management supervision, data processing, visualization, validation, writing-review and editing.

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