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Original Article

Association of ENSO and Long-Term Climatic Trends with Glacier Area Variation in Los Nevados National Natural Park

Relación entre el fenómeno ENOS y las tendencias climáticas a largo plazo con la variación de la superficie de los glaciares

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Spanish version

Abstract

Introduction: Tropical glaciers are sensitive to climate variability and global warming. In Colombia, they exhibit a clear trend toward area reduction, although interannual fluctuations are strongly linked to the El Niño-Southern Oscillation (ENSO).
Objective: This study quantifies the relative contribution of global climate change and the ENSO phenomenon to the variability of glaciers and snow cover in the Ruiz, Santa Isabel, and Tolima mountains within Los Nevados National Natural Park.
Methodology: Climate data (1982–2024) and the Multivariate ENSO Index (MEI.v2) were analyzed using statistical trend and variability tests. Glacier and snow areas were mapped from 24 Landsat images (1986–2023) through the Normalized Difference Snow Index (NDSI), supervised classification, and QGIS. Linear regression models were used to separate the long-term effect of climate change from the interannual influence of ENSO.
Results: ENSO explained 78.2–84.8% of the interannual variability in glacier area, while climate change contributed 15.2–21.8%. All glaciers showed statistically significant negative trends. T
Conclusions: Although ENSO dominates short-term fluctuations, climate change drives long-term retreat. The warm phase of ENSO can accelerate glacier melting when combined with global warming. These results provide key inputs for water resource management in the Colombian Coffee Axis region.

Keywords: tropical glaciers, glacier retreat, NDSI, Landsat, Colombian Andes, Los Nevados National Natural Park, ENSO variability.

Resumen

Introducción: Los glaciares tropicales son sensibles a la variabilidad climática y al calentamiento global. En Colombia, muestran una clara tendencia a la reducción de su superficie, aunque las fluctuaciones interanuales están estrechamente relacionadas con el fenómeno El Niño-Oscilación del Sur (ENOS).
Objetivo: Este estudio cuantifica la contribución relativa del cambio climático global y del fenómeno ENOS a la variabilidad de los glaciares y la capa de nieve en las montañas Ruiz, Santa Isabel y Tolima, dentro del Parque Nacional Natural de Los Nevados.
Metodología: Se analizaron datos climáticos (1982-2024) y el Índice Multivariante ENSO (MEI.v2) mediante pruebas estadísticas de tendencia y variabilidad. Se utilizaron modelos de regresión lineal para separar el efecto a largo plazo del cambio climático de la influencia interanual de ENSO.
Resultados: Según el análisis de descomposición de la pendiente de las series temporales observadas, previstas y residuales, el componente residual atribuido al fenómeno ENOS representó entre el 78,2 % y el 84,8 %, mientras que la contribución atribuible al efecto del cambio climático osciló entre el 15,2 % y el 21,8 %.
Conclusiones: Aunque el ENOS domina las fluctuaciones a corto plazo, el cambio climático impulsa el retroceso a largo plazo. Si la ocurrencia simultánea de fases El Niño y el calentamiento acelerado genera efectos compuestos sobre la pérdida glaciar constituye una pregunta abierta que requiere análisis estadístico de interacción explícito. Estos resultados proporcionan información clave para la gestión de los recursos hídricos en la región del Eje Cafetero colombiano.

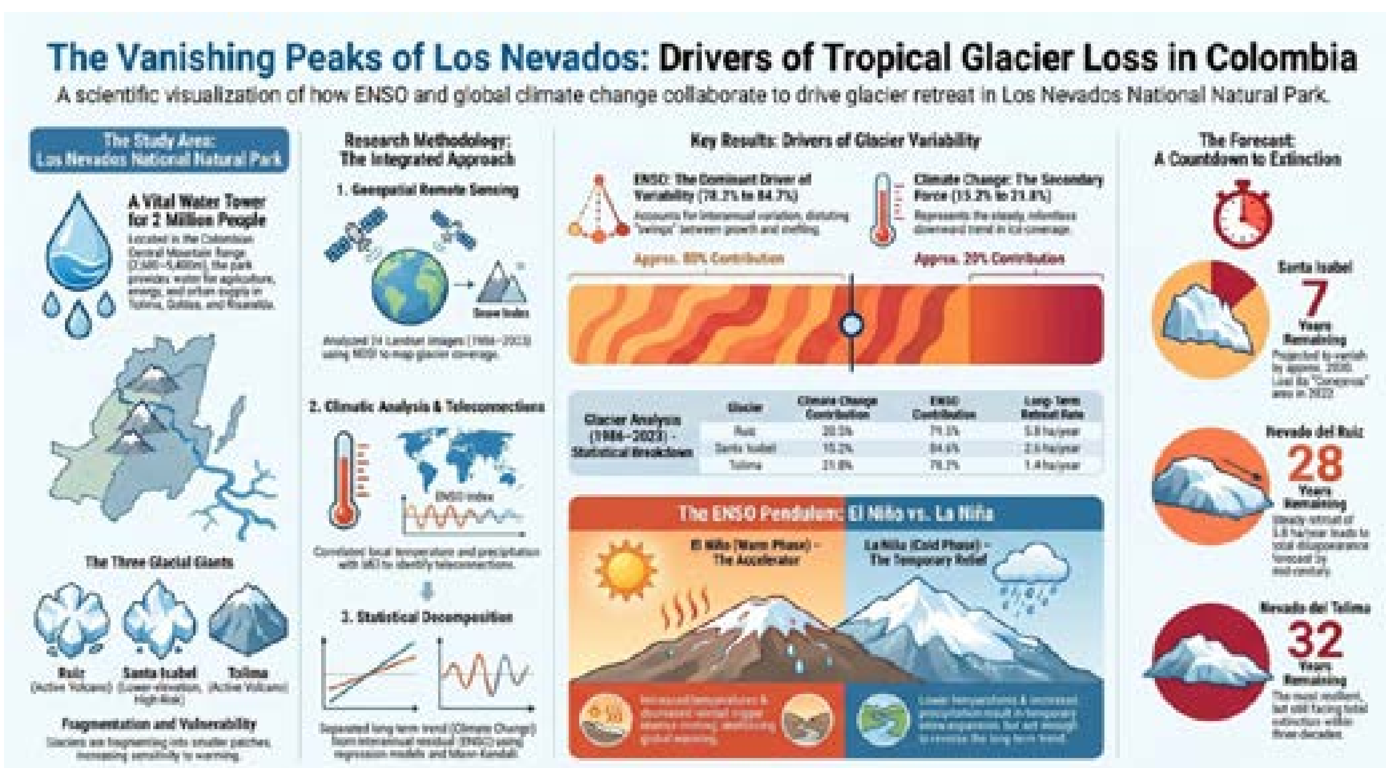
Palabras clave: glaciares tropicales, retroceso glaciar, NDSI, Landsat, Andes colombianos, Parque Nacional Natural Los Nevados, variabilidad ENSO.

Why was it done?
Tropical glaciers are ecosystems that are highly sensitive to climate variability and global warming. In Colombia, the glaciers of Los Nevados National Natural Park show a general trend of shrinking area, although they experience significant interannual fluctuations associated with the El Niño-Southern Oscillation (ENSO) phenomenon. This study aims to quantify the relative contribution of global climate change and ENSO to the variability of glacier and snow cover.

What were the most relevant results?
The ENSO phenomenon accounted for the majority of the interannual variability in the three glaciers, whilst climate change plays a secondary role in this variability. All three glaciers (Ruiz, Santa Isabel and Tolima) showed statistically significant negative trends. Projections indicate that, considering only the effect of climate change, the Santa Isabel glacier could disappear by 2026, the Ruiz glacier in 28 years and the Tolima glacier in 32 years.

What do they contribute?
This study provides a methodological tool based on remote sensing and statistical modeling to distinguish the effects of ENSO and climate change on tropical glaciers. The results are useful for water resource planning and management.

Graphical Abstract



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Introduction

Several authors consider tropical glaciers to be indicators of climate change and climate variability (2). They are important because they supply fresh water to various river basins, which serve as sources of water for different ecosystems and socio-economic activities (1). Several authors consider that tropical glaciers can be regarded as indicators of climate variability and change due to their sensitivity to the balance between ablation and accumulation (3), (2), (4). The equatorial location of tropical glaciers makes them sensitive to global climate change, as well as local conditions such as altitude, slope, local climate, and exposure to solar radiation facilitating their retreat dynamics (5).

The Andes Mountain range is the longest mountain range in the world, stretching nearly 7,000 kilometers across seven countries on the continent. The Andes provide water to nearly 75 million people and their snow-capped peaks serve important functions such as regulating surface water flows, cloud formation, and precipitation, as well as being part of the atmosphere–ocean circulation (6). Most of the glaciers over the mountain range are in Peru, while they are scarce in other parts due to low precipitation. In addition to being a source of supply for different populations, the water flows that originate from the snow – capped peaks are used for energy production and agricultural production. According to some statistics, approximately 44% of the Andean population lives in high-mountain areas. Colombia is no exception to this, as 41.5% of the country's population lives in the Andean region, where 55% of the country's urban areas are in the mountain range. For this reason, knowledge of the dynamics of high-mountain ecosystems is important both from the point of view of their conservation and preservation, and from the point of view of appropriate land management to meet human needs for ecosystem services whilst preserving ecosystem functionality.

Some of these high-mountain ecosystems are glacial peaks. Colombia currently has six glaciers: Sierra Nevada de Santa Marta, Sierra Nevada de El Cocuy, Nevado del Ruiz, Nevado de Santa Isabel, Nevado del Tolima y Nevado del Huila. (7). According to inventories conducted by the Institute of Hydrology, Meteorology and Environment Studies (IDEAM) and other researchers in the field (8, 9), it is confirmed that in recent decades there has been an estimated annual retreat rate of 1–3%, indicating their imminent disappearance in the medium term (4). According to (10), eight snow-capped peaks have disappeared in the last century, and the next peak to disappear is Santa Isabel. The area known as Conejeras disappeared as a result of the El Niño phenomenon in 2022 and because it lies at an altitude of less than 5,000 meters above sea level.

This is significant because the country's glaciers area sources of water supply and give rise to various river systems. The melting of these glaciers can lead to water shortages, changes in water regulation, impacts on low – flow river levels, reduced water availability, the risk of flash floods, or ecosystem disturbances (11). This scenario encompasses all the snow–capped mountains in the country (12). From a water resources engineering perspective, the projected disappearance of these glaciers has direct implications for flow regulation, water supply infrastructure, and deficit risk planning. The Chinchiná River, sourced from Nevado del Ruiz, supplies approximately 434,000 inhabitants of Manizales; the Combeima and Saldaña rivers, fed by Nevado del Tolima, are the primary water sources for much of the department of Tolima. The gradual reduction of glacial

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contribution — estimated at up to 25% of dry-season flow in Andean basins (5) — will require updating hydraulic infrastructure design criteria and anticipating seasonal deficit scenarios in the medium term. Despite the relevance of this dynamic, a detailed analysis is not conducted to contribute to understanding how the phenomenon of global climate change and the macro climatic event ENSO affect variations in glacial area, considering that the latter, being a tropical glacier, is sensitive to interannual variations in precipitation and temperatures caused by the cold and warm phases of the ENSO event.

The study hypothesis that year-on-year variations in snow-covered area are influenced not only by the effects of global warming, but also by ENSO events. For this reason, this study analyzes glacier-area variation in Nevado del Ruiz, Nevado de Santa Isabel, and Nevado del Tolima between 1986 and 2023, and evaluates its association with long-term climatic trends and ENSO-related interannual variability.

The results of this analysis, as well as the projection of the life of the glaciers, can serve as input for territorial and water resource planning entities to carry out research related to the effect of glacial melt on the availability and variability of water in glacial basins in order to project their conservation and sustainable use of water.

Materials and Methods

Description of the study area

Los Nevados National Natural Park is situated in Colombia’s Central Mountain Range, between the departments of Caldas, Risaralda, Quindío and Tolima. It includes the Nevado del Ruiz, Nevado de Santa Isabel, Nevado del Tolima glaciers (12). The protected area of Los Nevados National Natural Park is located approximately between: Latitude: 4°36′ N and 4°57′ N, Longitude: 75°12′ W and 75°30′ W. The El Nevado del Ruiz lies within the altitude range of 4,800 to 5,321 meters above sea level; the Nevado de Santa Isabel extends from 4,700 to 4,935 meters above sea level; and the Nevado El Tolima - from 4,800 to 5,215 meters.

The Protected Area was created in 1974 to help conserve globally important ecosystems such as three of the remaining glaciers in the country, super-paramo ecosystems, paramo, high Andean wetlands and high Andean forests (13).

The park covers eight main volcanoes: Santa Rosa, Quindío volcano, Santa Isabel Glacier, El Cisne, Cerro Bravo, Cerro Machín, Tolima Glacier, and Ruiz Glacier, with the last three being active (14). The location of the PNN is presented in (Figure 1).

This National Park produces and regulates multiple environmental goods and services for the Coffee Axis ecoregion. In terms of water supply, it meets the needs of more than two million people in the coffee area and important rice and cotton-growing regions in the department of Tolima. Its protection and conservation become a key element for socio – environmental development and a connecting axis for regional conservation initiatives (15).

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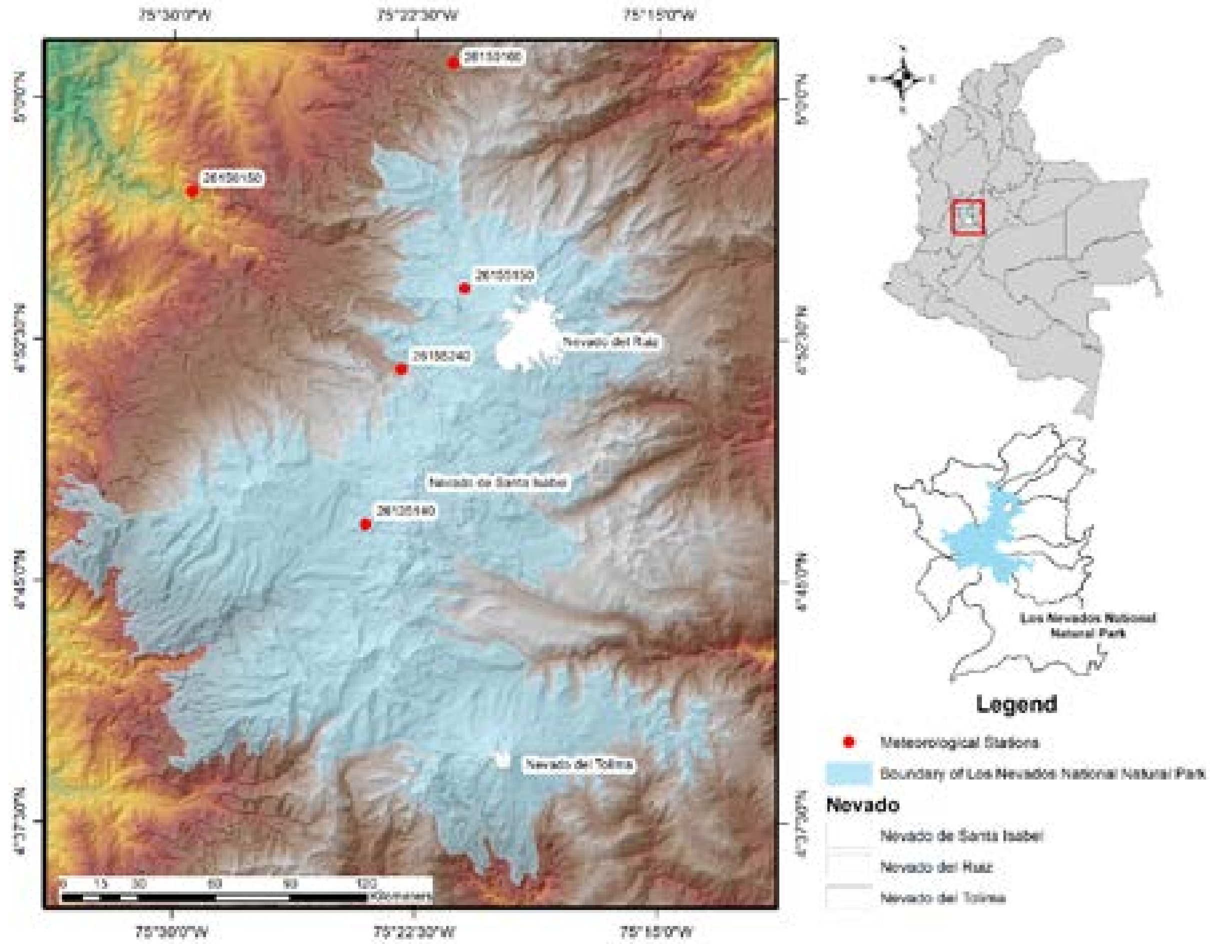

Figure 1. Location of the PNN Los Nevados and the weather stations used in the study. Source: own elaboration.

Although some national experts in the field confirm that the retreat of Colombian glaciers is irreversible (16), it is important to study them to understand their dynamics and conclude on their sensitivity to climate change and the ENSO phenomenon to project their future scenario with greater certainty. The proposed study allows for the separation of these two forcing factors on the contraction of the glacial area. In this way, it will be known how much the effect of climate change influences this negative trend and project the "life" of the glacier, as well as identify whether the interannual variations of the glacier are sensitive to the ENSO phenomenon, whose incidence is demonstrated in different strategic ecosystems of the country (17). The results of this study provide direct inputs for hydraulic engineers and water resource planners: the separation of ENSO and climate change contributions allows projecting glacier-sourced flow scenarios under different climatic phases, supporting the design of storage infrastructure, drought contingency plans, and long-term water allocation frameworks for the glacierized basins of the Colombian Coffee Axis.

Methodological steps

The methodology designed to assess the association of climate change and the El Niño-Southern Oscillation (ENSO) phenomenon on temporal variation in glacier area is divided into three main blocks: climatic analysis, geospatial analysis, and the integration of the two analyses, which allows one to reach the results. The methodological steps are presented graphically in the following figure.

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The gray color corresponds to the steps associated with geospatial analysis, blue corresponds to climatic studies, and turquoise corresponds to the integration of the previous two analyses.

As seen in (Figure 2), the process begins with obtaining the inputs. Among the climatological information are time series of total precipitation and temperatures from meteorological stations located near the glaciers to the snow – capped mountain (18). The series of the MEI index (19), which characterizes the ENSO phenomenon, is downloaded from the NOAA Physical Sciences Laboratory website (20). The geospatial information relates to the Landsat satellite images available for free on the United States Geological Survey website (21).

In this study, the selection of satellite images was limited by the high cloud cover present for most of the year, caused by the passage of the Intertropical Convergence Zone. Therefore, since it was not possible to obtain the complete set of satellite images for every month of every year, the images corresponding to certain dates within each period were considered representative for the entire year. This limitation may lead to confusion between seasonal snow and glacier cover and, as a result, overestimate the contribution of the ENSO event to the interannual variation in glacier areas on snow-capped mountains.

In addition, these data are supplemented by statistics on glacier areas, corresponding to (7) in the years when quality satellite images will not be available to allow for remote sensing of the glacier cover. The accuracy of remote sensing was assessed using a confusion matrix, calculating the overall accuracy (greater than 70%) and Cohen's Kappa coefficient, with a value of 80% or higher.

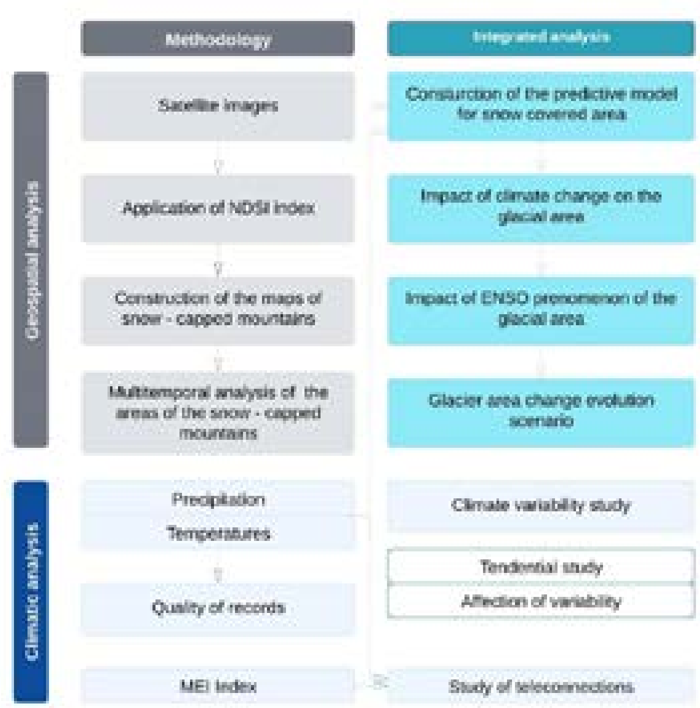

Figure 2. Methodology to evaluate the impact of climate change and the ENSO phenomenon on the temporal variations of glacial areas. Source: own elaboration.

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When collecting the inputs, the climatic analyses and satellite imagery are carried out. Initially, the climate data underwent a quality check, which included reviewing missing data, checking for consistency, and identifying outliers using box plots (22).

Following this analysis, a variability analysis was carried out. The study of climate series variability consists of analyzing homogeneity by average value and variance, as well as constructing teleconnections with the Multivariate ENSO Index (MEI) (23) that identifies the manifestation of the ENSO event. The study operates under the hypothesis that the effect of global climate change is reflected in the climate series, mainly in the emergence of a statistically significant trend and in the change of variability patterns of these (24).

Normally, the trend in temperature series is increasing (25), while the type of trend, in response to climate change, in rainfall records is different in various areas of the country (26). To determine whether the trend is statistically significant, the t-test was used with a significance level of 0,05 to assess the slope pf the linear regression in precipitation and temperature climate series, a method that has proven effective in climate studies (27). On some occasions, the effect of climate change of variability of the main climatic parameters. For this reason, the records of precipitation and average temperatures were analyzed for changes in variability using Fisher's test. After conducting these analyses, we can conclude whether there is evidence that climate change is affecting the regional climate, which may possibly have repercussions on the dynamics of the glaciers.

In addition to global climate change, there are other climatic phenomena whose influence on the Colombian climate has been widely documented in various studies. Among these, the North Atlantic Oscillation (NAO) stands out, and especially the ENSO phenomenon, whose influence on climatic variables in Colombia has proven to be predominant over other events.

In this study, it is assumed that the residuals of the precipitation and temperature series – once the trend effect associated with climate change is discounted – mainly correspond to the influence of ENSO. Therefore, these residuals were correlated with the multivariate index MEI, which characterizes the intensity and presence of this climatic phenomenon. The obtained coefficient of determination reflects the percentage of variability of the climatic series explained by the ENSO, while the p – value allows us to assess the statistical significance of that correlation (28).

After conducting climate analyses, the geospatial information is interpreted, which includes identifying the surface area covered by glaciers and snow in satellite images. This step was carried out using the normalized difference snow index NDSI (29), which is defined based on the type of Landsat satellite images as follows:

$$Landsat\ 4-7, NDSI = \frac{(Band_2 - Band_5)}{(Banda_2 + Banda_5)} \quad (1)$$

$$Landsat\ 8-9, NDSI = \frac{(Band_3 - Band_6)}{(Band_3 + Band_6)} \quad (2)$$

Values greater than 0.0 in the indices used indicate the presence of snow cover, while values equal to or less than 0.0 correspond to other types of surface cover. Once the glacial and snow areas have been identified, the raster files are vectorized using a geographic information system (30), thus

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allowing us to obtain, for each analyzed year, the interannual series of the area covered by glaciers. The study aims to evaluate the variation in snow cover, including glacial and snow surface areas, and to determine which part of this interannual variation is due to the effects of global climate change and which part is associated with the ENSO phenomenon. For this reason, the NDSI index was initially used to assess snow/non-snow cover. The results were then subjected to supervised editing using a combination of green visible and shortwave infrared (SWIR) bands to adjust the remote sensing graphic outputs to the two covers of the ecosystem.

As in the case of climatic series, it is assumed that the statistically significant trend observed in these series is attributable to the effect of global climate change, in turn, the residual component is associated with the influence of macroclimatic events, with the ENSO phenomenon having the greatest relative weight. The significance of the trends was assessed using the t-test. The choice of this test is justified by its suitability for analyzing short time series that do not necessarily follow a normal distribution.

Finally, to separate the influence of climate change and the ENSO phenomenon on the glacial areas of the snow – capped mountains, the scheme presented in Table 1 is applied. For its implementation, regression models were initially constructed between the series of glacier coverage areas and the average temperature of the weather station closest to each glacier. Given that temperature series are affected by climate change, the study considered that the predicted glacier area series is the result of global climate change, while the residual term, obtained as the difference between the area values observed by remote sensing and the predicted series, is the result of the ENSO phenomenon. In this way, for each snow – capped mountain, three series of glacier areas were obtained: observed, forecasted, and residual. For each of these, linear trend lines and their respective slopes were plotted. The percentage of climate change's impact on glaciers was defined using the relationships between the slopes shown below.

Table 1. A decision algorithm was developed to identify the contributions of climate change and the (ENSO) phenomenon to glacial areas of snow-capped mountains.

A_{obs_i}	$A_{i\ pro}$	$A_{res\ i}$	Contribution		Conclusion
	Forecasted area trend	Residual area trend	Climate change	ENSO	
Negative trend in the glacier area	<0	<0	i_{pre}/i_{obs}	i_{res}/i_{obs}	Both factors influence the decrease of the glacial area
	<0	>0	100	0	Climate change affects the decrease of glacial area
	>0	<0	0	100	The ENSO phenomenon affects the decrease of glacial area
i –	trend				

Source: own elaboration.

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Where:

i_{pre} – slope of the series constructed according to the predictive model

i_{obs} – slope of the observed series of the glacial area

i_{res} – slope of residual series

This makes it possible to identify the extent to which the variation in glacier surface area is due to global climate change and the extent to which it is due to the El Niño-Southern Oscillation phenomenon (ENSO) phenomenon contributes to it. Furthermore, this analysis allows us to determine the surface area lost by glaciers due to climate change using a linear regression equation. Knowing the annual loss of glacial area and its current size allows us to calculate the expected time until complete disappearance. We can then compare these forecasts with previous national-level studies that consider not only the effect of climate change, but also the general trend and the effects of other climatic phenomena that may affect interannual variability.

Based on all the methodological steps presented above, answers were given to the following questions: Does the glacier layer show a significant trend toward a decrease in glacier area? To what extent do the dynamics of the glacier depend on global climate change and the ENSO phenomenon? In how many years is the total loss of the three glaciers expected, considering only the effect of global climate change? Finally, to evaluate the sensitivity of the glacier area to the regime of the main climate variables, such as precipitation and temperature.

Results

Below are the results related to climate analysis, remote sensing, and the impact of climate change and the ENSO phenomenon on the glaciers of PNN Los Nevados.

In the region of the park, there is a limited number of weather stations with a sufficient recording period for conducting climate variability studies. The most recent stations began their measurements in 2018, and some stations are suspended or under maintenance due to the adverse effects of the eruptions of the Ruiz volcano in 2023. Five meteorological stations with records between 1982 and 2024 were identified for the study area. Stations 26155240 – PNN Nevados, 26155150 – Las Brisas, and 26135140 – Laguna have data on precipitation and temperature, while stations 26150160 – La Esperanza and 26150150 – Papayal only record precipitation data. The location of these stations is shown in the (Figure 1).

Time series of climate variables result from various macroclimatic phenomena. The effects of these phenomena are reflected in climate variability across different timescales. The study considered that the existence of an annual trend is associated with the effects of global climate change, and that interannual variability is due to a set of phenomena such as ENSO (31). which has the greatest impact on interannual climate variability in Colombia.

In the national context, according to the length of historical series, the identification of interannual cyclicity does not appear to be possible. For this reason, the historical series of precipitation and average annual temperatures were analyzed for their dependence on climate change and the ENSO

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event. Climate change is reflected in the change of mean values and variability (t-tests and Fisher tests) (32), while the incidence of ENSO is determined as the correlation between the residual term of the historical series versus the average value of the annual MEI index. The results of the analysis of homoscedasticity (F-test) and homogeneity (t-test) are presented in Table 2.

Table 2. The analysis of homoscedasticity (F-test) and homogeneity (t-test) for the temperatures.

Code	t-test (P- value)	F-test (P – value)
26155150	0.002	0.010
26135140	0.002	0.408
26155240	0.008	0.012

As can be seen from the previous summary, two out of the three stations confirmed that, during the study period, the variance of temperatures has changed. Reviewing the variance values, it has increased at both stations. All temperature records indicate a statistically significant upward trend. To summarize, in the park area, average temperatures have increased, accompanied by greater temporal variability.

In contrast, the analysis of the annual total precipitation series reveals a less uniform pattern. The results of the variability and homogeneity tests es presented in Table 3.

Table 3. The analysis of homoscedasticity (F-test) and homogeneity (t-test) for the temperatures.

Code	t-test (P- value)	F-test (P – value)
26135140	0.25	0.21
26150150	0.53	0.26
26150160	0.16	0.20
26150240	0.27	0.00
25155150	0.07	0.02

These results show that, in two of the five evaluated stations, there is a statistically significant change in the variance of precipitation, suggesting a decrease in its temporal variability. However, the remaining stations did not show significant changes in either variance or mean. Furthermore, the trend analysis confirms that none of the precipitation series exhibit statistically significant increasing or decreasing trends over time.

Based on these results, it is concluded that the mean temperature series do exhibit a clear influence of global climate change, reflected in the sustained increase in their average values. In contrast, the total annual precipitation series do not show significant changes, which aligns with findings reported by previous national studies. These studies indicate that the impact of climate change on precipitation in Colombia is not as pronounced as that observed in the thermal regime (33).

The effect of global warming is evident in a rise in average temperatures, with an increase of 0.14 °C every 10 years, alongside greater variability. The effect on annual precipitation is unclear, as no weather station identified a statistically significant trend and only two stations reported a decrease in variability in their readings.

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To find the relationship between climatic variables and the ENSO phenomenon, the trends was extracted from the average temperature series, leaving the residual term. This term was correlated with the annual mean values of the MEI index, while the precipitation series, not showing a statistically significant trend, were directly correlated with the climatic index.

The residual term of the temperature series is directly related to the MEI index, where positive values of the index correspond to the warm phase (El Niño) of the phenomenon, indicating an increase in mean temperatures with an average gradient of 0.06 °C for every 0.1 unit change in the MEI climate index. The precipitation shows an inverse relationship with total annual precipitation: the warm phase produces a decrease with an average gradient of around 20 mm of total annual precipitation for every 0.1 unit change in the climate index between stations. A numerical summary of the constructed teleconnections is presented in Table 4.

Table 4. Correlation between climatic variables and the ENSO index.

Climatic variable	**Parameter**	**Code**				
		26135140	**26150150**	**26150160**	**26150240**	**26155150**
Total annual precipitation	R^2	0.23	0.18	0.19	0.005	0.20
	P-value	0.0006	0.0035	0.0023	0.102	0.002
Average temperature	R^2	0.29			0.29	0.27
	P-value	0.0002			0.0002	0.0004

Source: own elaboration.

As shown in Table 2.20 % of the interannual precipitation pattern is dependent on the ENSO phenomenon, with only one station, code 26150240, not showing a statistically significant correlation with this climate event. All temperature records confirmed that an average of 29% of the interannual temperature pattern is dependent on ENSO.

The next methodological step was to identify the areas corresponding to the glacial layers and analyze their interannual variability. To this end, a total of 23 satellite images were collected, mostly from the Landsat mission, the information for which is detailed below. Landsat Level 1 and Level 2 satellite images (uncorrected and with atmospheric correction) have the same spatial resolution of 30 meters. Table 5.

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Table 5. Information on the satellite images used in the study.

N	Year	Image code	N	Year	Image code
1	1986	LT05_L1TP_009057_19860908_20200917_02_T1	13	2002	LE07_L2SP_009056_20020726_20200916_02_T1
2	1987	LT05_L2SP_009057_19870114_20201014	14	2003	LE07_L1TP_009057_20030307_20200916_02_T1
3	1988	LT04_L2SP_009057_19881023_20200957	15	2006	LE07_L1TP_009056_20060923_20200914_02_T1
4	1989	LT04_L2SP_009057_19890807_20200986_02_T1	16	2010	LE07_L1TP_009057_20100105_20200971_02_T1
5	1990	LT04_L1TP_009057_19900725_20200915_02_T1	17	2011	LE07_L1TP_009057_20110905_20200910_02_T1
6	1991	LT05_L1TP_009057_19911211_20200974_02_T1	18	2013	LE07_L1TP_009057_20130724_20200917_02_T1
7	1993	LT05_L1TP_009056_19930215_20231210_02_T1	19	2014	LC08_L2SP_009057_20141226_20200910_02_T1
8	1995	LT05_L2SP_009057_19950917_20231216_02_T1	20	2019	LC08_L1TP_009057_20190903_20200826_02_T1
9	1996	LT05_L2SP_009056_19960802_20200911_02_T1	21	2020	LC08_L1TP_009057_20200109_20200823_02_T1
10	1997	LT05_L2SP_009056_19970906_20200909_02_T1	22	2021	LC08_L2SP_009056_20211213_20211222_02_T1
11	1999	LT05_L2SP_009057_19990710_20240118_02_T1	23	2023	LC08_L2SP_009056_20231203_20231209_02_T1
12	2000	LE07_L2SP_009057_20000821_20200918_02_T1			

Source: own elaboration.

After applying remote sensing analysis using the NDSI index and supervised classification analysis, the areas of snow and glacier coverage were calculated, and the information is presented in (Figure 3). The overall accuracy was 89% and the mean Kappa coefficient was 75%. For the years 1986, 1993 and 2019, perfect accuracy was achieved, with overall accuracy values of 100% and a Kappa coefficient of 1.0. For the years 1990, 2000, 2006 and 2023, lower accuracy was obtained due to topographical conditions; in none of the satellite images did false positives exceed 11%.

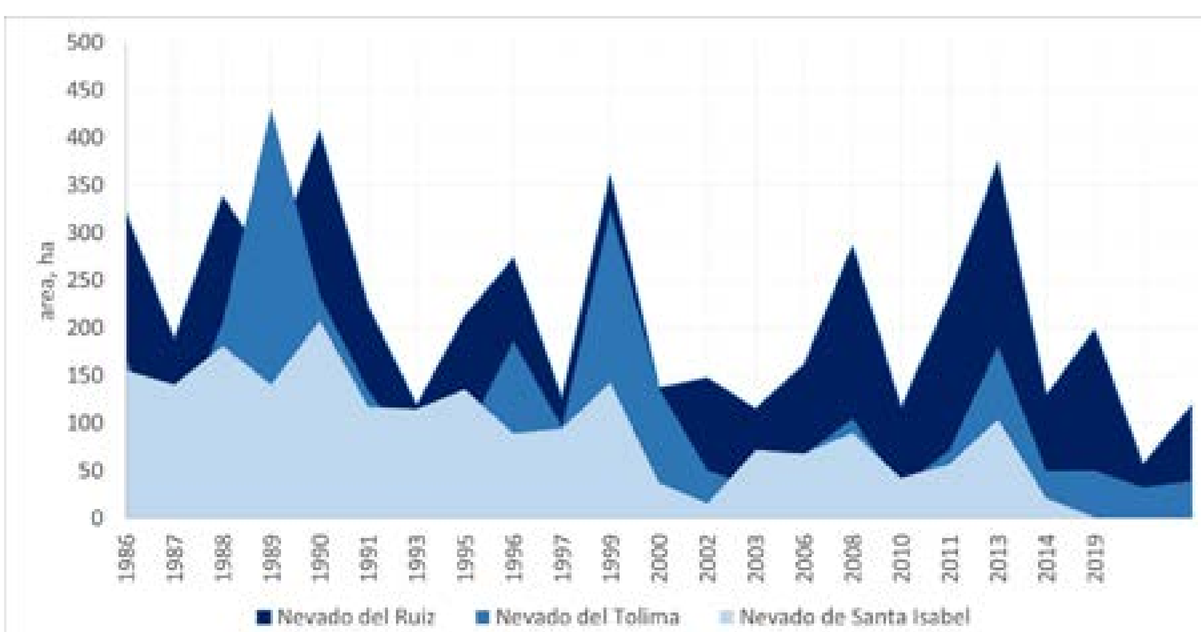

Figure 3. Interannual variation of the glacial areas of the snow – capped mountains. Source: own elaboration.

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As can be seen in (Figure 3), all areas show a decreasing trend. To evaluate whether these are statistically significant, the t test was applied, presenting the following P – values: El Ruiz –0,019, Santa Isabel – 0,00023, Tolima – 0,0026, which indicates that all trends are negative and statistically significant and, indeed, there is a decrease in glacial layers associated with global climate change.

For Nevado Santa Isabel, the results show a sustained trend of glacier area reduction between 1986 and 2019, with a more pronounced decrease starting in 2000, suggesting a phase of accelerated retreat. The linear regression fit indicates an average loss of approximately 4,6 ha/year. The model has a standard error of the estimate on the order 50 – 60 ha, indicating a high dispersion of data around the estimated trend and reflecting the interannual variability typical of glacier systems. Based on the model projection, it is estimated that the glacier would reach an area close to zero around 2026. However, when considering the prediction interval – directly influenced by the model error – there is a range of uncertainty suggesting that disappearance could occur approximately between 2015 and 2035. This wide range of variation evidence both climate variability and the limitations of the linear model in representing nonlinear processes in the final stages of glacier degradation. Overall, these results indicate that the glacier is in a terminal phase, with a high probability of disappearance in the short term, possibility associated with the increase in temperature and changes in precipitation patterns. The linear model is appropriate for Nevado Santa Isabel because the glacier is already in a terminal phase, with very little remaining area and a highly significant negative trend ($p = 0.00023$). When a glacier approaches zero extent, linear and non-linear models converge in their projection of disappearance date, making the choice of functional form inconsequential for the main conclusion. Additionally, the limited number of observations ($n = 23$) constrains the use of more complex models without risk of overfitting.

For the El Ruiz snowcap, the results show a general trend of decreasing snowcap area between 1986 and 2021, with an approximate loss rate of between 2,0 and 2,5 ha/year. Nevertheless, the behavior of the time series shows high interannual variability, with significant fluctuations that include both abrupt increases and decreases in glacier area. According to forecasts, it is estimated that the area covered by snow could reach between 150 and 180 hectares in around 28 years. However, the prediction interval is wide, ranging from values close to zero to over 300 ha, reflecting considerable uncertainty associated with climate variability and the nonlinear nature of the process. In this context, there is no clear evidence of an imminent disappearance of the glacier, but rather a highly variable behavior that suggests a system in a condition of instability, possibly influenced by interannual climate fluctuations and changes in accumulation and melting patterns.

For the Nevado del Tolima, the results show a sustained trend of decrease in the snow – covered area between 1986 and 2021, with a loss rate of approximately 3,5 to 4,0 ha/year. The behavior of the series shows a marked reduction starting in 2000, followed by a recent phase characterized by low and relatively stable values, which suggests a progressive decline of the glacier system. Based on the projection, it is estimated that the glacier and snow areas area could be between 10 and 30 ha around the year 2030. However, the prediction interval is wide, ranging from values close to zero to approximately 150 – 180 ha, reflecting the uncertainty associated with interannual variability and the non – linear nature of the process. Overall, these results suggest that the glacier and snow areas are in an advanced phase of reduction, with a high probability of continuing to decrease

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and eventually disappear in the medium term, although it still presents fluctuations that prevent defining an exact point of collapse.

The study hypothesizes that (10) these variations are associated with the cold and warm phases of the ENSO event. As an example, the years 1997 and 1999 can be considered. In 1997, the warm phase of ENSO (El Niño) occurred with an average MEI index value of 1.23. This phase in Colombia manifests as a decrease in rainfall and an increase in temperature, producing the ablation of land cover in the ecosystem. From the second half of 1998 to the first half of 2011, a strong La Niña event occurred, with an average MEI index value of – 1.24 for 1999. This manifested as increased rainfall and decreased average temperatures. This shift in climate variability resulted in a significant expansion of snow and glacial cover. The above indicates a research hypothesis on the sensitivity of ecosystem cover to the ENSO phenomenon.

The following figure shows a map of the spatiotemporal reduction in ice and snow cover in the study area. Figure 4.

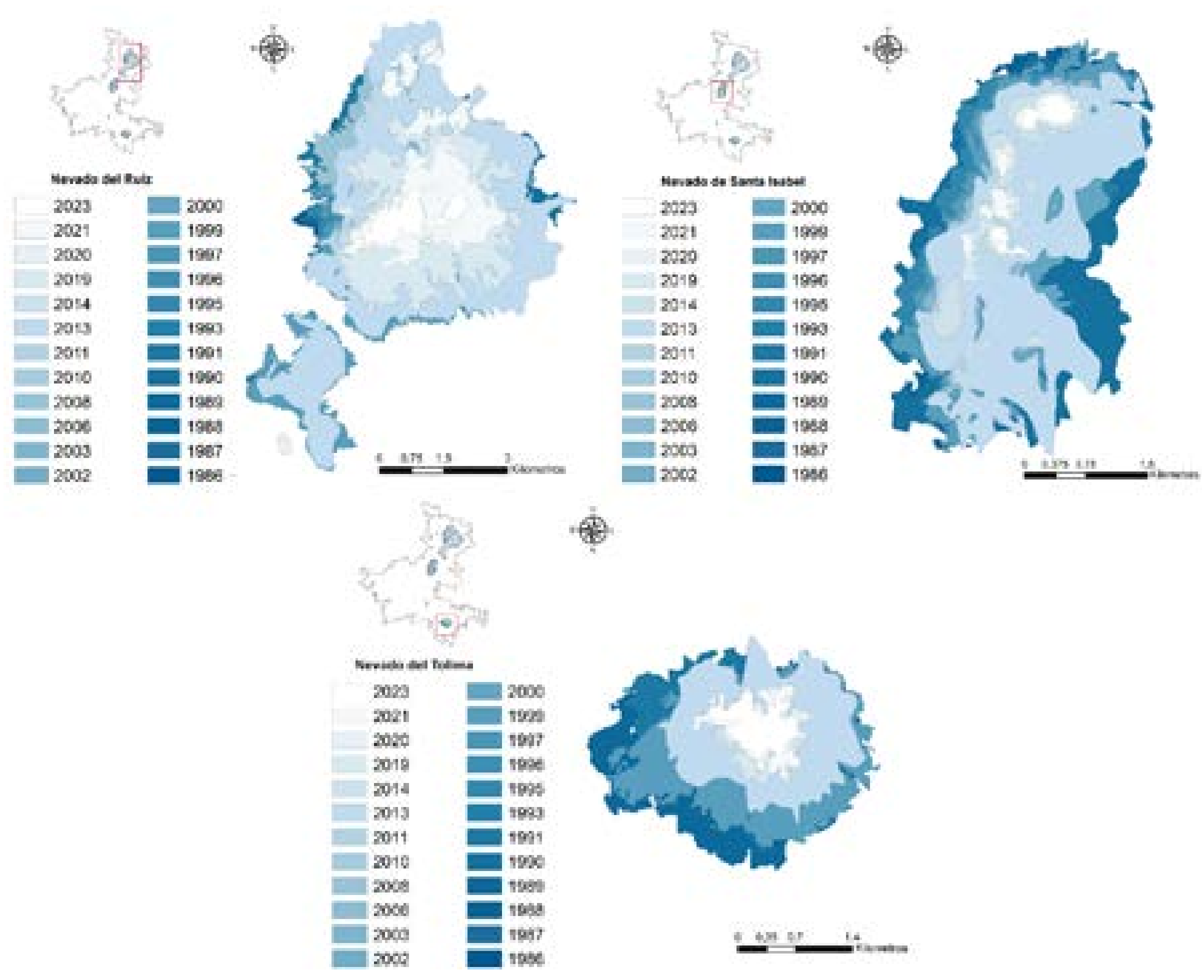

Figure 4. Reduction of Glacier Layers in the Nevados of the Los Nevados National Natural Park (1986-2023): a) Nevado del Ruiz, b) Nevado de Santa Isabel, c) Nevado del Tolima. Source: own elaboration.

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In addition to the reduction in glacier area, a visual analysis clearly reveals the fragmentation of snow-capped mountains into smaller patches, a process that increases their exposure to warming by reducing thermal mass and increasing the surface-to-volume ratio (34),(35). Despite this overall retreat trend, the series shows pronounced non-seasonal interannual fluctuations that the study attributes to ENSO forcing. The next analytical step was therefore to quantify how much of the observed rate of area change is driven by long-term climate change versus ENSO variability, using the slope decomposition scheme described in Table 4. The results are presented in Table 6. Note that these percentages reflect each factor's contribution to the observed rate of area change — not the fraction of variance explained (R^2), which is a methodologically distinct metric.

Table 6. Percentage contribution of climate change and the ENSO phenomenon to the variation in the glacial layer of snow–capped mountains.

Glacier	Slope (absolute) the observed, forecast and residual series for glacier and snow cover areas (ha/year)			% contribution	
	Observed area	Forecast area	Residual area	Climate change	ENSO
Ruiz	28.1	5.8	22.31	20.5	79.5
Santa Isabel	17.4	2.6	14.74	15.2	84.8
Tolima	6.6	1.4	5.12	21.8	78.2

Source: own elaboration.

Where:

i_{pre} – slope of the series constructed according to the predictive model

i_{obs} – slope of the observed series of the glacial area

i_{res} – slope of residual series

The percentage contribution of climate change to the variation in area is calculated by dividing the slope of the predicted line by that of the observed line, whilst the contribution of the ENSO phenomenon is estimated as the slope of the residual series relative to the observed series of areas.

As can be seen from the results obtained, in all cases the percentage contribution of the ENSO phenomenon to the interannual variability in glacier area is greater than that of global climate change, ranging from 78.2% to 84.7%, whilst the impact of global warming varies between 15.2% and 21.8%. This indicates that, although glacier ablation and expansion account for a significant proportion of their variability, they are dependent on the ENSO event. This indicates that, although glacier ablation and expansion account for a significant portion of their variability and depend on the ENSO event. The onset of the cold phase (La Niña) results in an increase in glacier area, while the onset of the warm phase (El Niño) results in a decrease in glacier area.

The methodology applied in the study can be regarded as one of the ways of assessing the impact of global warming and ENSO events on the interannual variability of glacial areas, based on the

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hypothesis that the effects of global climate change are reflected in the emergence of a linear trend in hydroclimatic time series. However, it is recommended that non-linear simulation models be explored for forecasting purposes.

In the proposed model, the prediction of snow-covered area associated with the effects of global warming depends on the mean air temperature. Although this climatic variable includes the effects of climate change and the ENSO event, its use is justified because it is the main variable controlling the process of glacier ablation as a consequence of global warming, whilst the ENSO event is reflected in the dynamics of contraction and expansion not only through mean temperatures, but also through other climatic variables such as solar radiation, solid and liquid precipitation, and the energy balance. Furthermore, the ENSO event does not govern long-term climate trends, but rather controls annual fluctuations, introducing interannual climate oscillations.

Two methodological considerations merit discussion. First, since ENSO influences mean temperature (R^2=0.27–0.29, Table 2), using temperature as the sole predictor of glacier area may partially capture ENSO signal, introducing multicollinearity. However, given that the long-term warming trend in the temperature series is statistically significant and independent of ENSO phase, temperature is treated here as the primary expression of climate change forcing on glacier dynamics. Second, precipitation was not included as a predictor variable because none of the precipitation series showed a statistically significant trend, meaning it does not carry a long-term climate change signal. Its interannual variability is instead captured through the residual term, which is attributed to ENSO.

Discussion

From the above, it can be concluded that the three snow-capped mountains that make up the national natural park exhibit high variability in their glacier and snow cover areas. The analysis showed that 15.2–21.8% of this variation is associated with the effects of global warming and 78.2–84.8% with the El Niño-Southern Oscillation (ENSO) phenomenon, the latter being the main driver of variation in these areas.

However, not only global warming influences the decline in glacier cover, but the warm phase of the ENSO phenomenon also produces greater ablation of snow – capped mountains through increased temperatures and lower rainfall. The El Niño phase therefore causes a significant retreat of glaciers on its own; to determine whether it interacts synergistically with the long-term warming trend and results in a non-additive loss of glaciers, an explicit analysis of the interactions between ENSO and climate is required. Future studies should test this interaction using mass-balance observations, higher-frequency satellite data, and distributed climate records.

The results are consistent with previous findings on the link between glacier area variability and ENSO. The warm phase (El Niño) drives ablation while the cold phase (La Niña) promotes expansion, a pattern documented across the tropical Andes (4, 36). Vuille et al. (37) identify ENSO as one of the main drivers of interannual variability in Andean snowfields, and Francou et al. (36) — working on inner tropical glaciers in Ecuador — report that over 50% of variance in mass balance is explained by ENSO intensity, a figure broadly consistent with the slope decomposition results obtained here for the Colombian glaciers.

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The thawing process could have implications for water supply from glacial catchments, low-flow rates and water regulation services. For example, the Chinchiná River basin originates from the El Ruiz Glacier, which is one of the sources of water supply for the city of Manizales, which has a population of approximately 434,000. The Combeima and Saldaña rivers originate from the El Tolima Glacier, which are the main regional water sources for the department of Tolima. However, these types of studies that evaluate the effect of the melting of Colombian glaciers are scarce (38), due to the insufficient and absent network of hydrological stations that make this type of analysis impossible.

Given the vulnerability of the glaciers analyzed, it is necessary to carry out hydrological monitoring of the rivers—which are sources of water supply—and to study the effects of glacial melt on water supply, low-flow rates and water regulation. Some studies estimate that glaciers contribute up to 25% of dry-season streamflow in Andean basins (5). For the glacierized basins of PNN Los Nevados, this implies that the progressive loss of glacial area will reduce base flows in rivers such as the Chinchiná, Combeima, and Saldaña — directly affecting water supply for over two million people in the Coffee Axis region and the department of Tolima. Water resource engineers and planners should anticipate deficit scenarios in the medium term, prioritize hydrological monitoring of these basins, and revise storage infrastructure design criteria to account for the declining glacial contribution.

The collection of data and the methodological approach used reveal certain limitations in this type of study. These include the following:

1. The low temporal resolution of freely available satellite imagery does not allow for the analysis of seasonal variations in glacier and snow cover;

2. The high cloud cover present in most satellite images acts as an obstacle to obtaining a robust sample of geospatial data.

3. The absence of weather stations within the snow-capped mountain areas: for this reason, records from the weather stations closest to the snow-capped mountains were consulted. However, their representativeness of the local climate of the snow-capped mountains may be limited and may not necessarily reflect the climatic variability present in the study area.

4. Limitations of the linear model: the study tested the hypothesis regarding the linear effects of climate change on snowpack ablation. This introduced uncertainty into the results obtained. For this reason, it is recommended that the use of non-linear multivariate models be considered in studies of snowpack dynamics.

Conclusions

From the analyses previously conducted, it is concluded that the regional climate is sensitive to global climate change and the ENSO event. The effect of climate change is reflected in an increase in average temperatures with a positive gradient around 0.14 °C for every 10 years, along with an increase in variability. The effect on annual precipitation is not evident, and none of its records confirmed a statistically significant trend, with only two stations indicating a decrease in variability

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in their values. The analysis of teleconnections with the ENSO event confirms a clear dependence of the regional climate on this macroclimatic phenomenon, where the warm phase (El Niño) generates an increase in mean values, and the cold phase (La Niña) results in a decrease in temperature, with a gradient of 0.06 °C for every 0.1 unit of the MEI index. Unlike the uncertain impact of climate change on rainfall patterns, this variable reacts clearly to the ENSO phenomenon. The relationship between precipitation and the MEI index is inverse, such that for every 0.1 increase in the MEI index, precipitation decreases by 20 mm. In other words, the cold phase of the phenomenon (La Niña) leads to an increase in rainfall, whilst the warm phase (El Niño) leads to a decrease.

Under the proposed residual-based approach, approximately 80% of the interannual component was associated with ENSO-related variability, and approximately 20 % depends on the effects of global change. The El Niño phase produces an increase in temperatures and, consequently, ablation of the glacial layer, while the La Niña phase results in an increase in this layer. Climate change is associated with a constant melting process of the glacial layer with statistically significant trends. These allowed for the evaluation of the ablation gradient for each of the glaciers as follows: Ruiz – 2.0 to 2.5 ha/year, Santa Isabel – 4.6 ha/year, and Tolima – 3.5 – 4.0 ha/year. These results are consistent with various existing national studies that raise alarms regarding the effects of global climate change on the imminent disappearance of these ecosystems (10).

The study shows that glacier retreat is following a persistent downward trend and that year-to-year fluctuations appear to be linked to the ENSO phenomenon.

The results of this research can be considered as a basis for studying the effects of glacial melt on the availability and variability of water in glacial basins to project water availability for different human uses and conservation of their ecosystem integrity.

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CrediT authorship contribution statement

Conceptualization - Ideas: Yulia Ivanova, Julián David Castellanos . Data curation: Yulia Ivanova, Julián David Castellanos . Formal analysis: Yulia Ivanova, Julián David Castellanos, Luisa Fernanda Yustres Quintero. Investigation: Yulia Ivanova, Julian David Castellanos. Methodology: Yulia Ivanova, Julian David Castellanos. Project Management: Yulia Ivanova. Resources: Yulia Ivanova. Software: Yulia Ivanova, Julián David Castellanos. Supervision: Yulia Ivanova. Validation: Yulia Ivanova, Julián David Castellanos. Writing - original draft - Preparation: Yulia Ivanova, Julián David Castellanos. Writing - revision and editing -Preparation: Yulia Ivanova, Julián David Castellanos.

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doi: 10.25100/iyc.v28i2.15786

References

1. Qin D. y Ding Y. Key Issues on Cryospheric Changes, Trends and Their Impacts. Advances in Climate Change Research, 2010; 1(1):1-10

https://doi.org/10.3724/SP.J.1248.2010.00001

2. Calizaya E., Laqui W., Sardón S., Calizaya F., Cuentas O., Cahuana J., Mindani C. y Huacani W. Snow Cover Temporal Dynamic Using MODIS Product, and Its Relationship with Precipitation and Temperature in the Tropical Andean Glaciers in the Alto Santa Sub-Basin (Peru). Sustainability 2023, Vol. 15, Page 7610, 2023; 15(9):7610,

https://doi.org/10.3390/su15097610

3. Collier E., Mölg T. y Sauter T. Recent Atmospheric Variability at Kibo Summit, Kilimanjaro, and Its Relation to Climate Mode Activity. Journal of Climate, 2018; 31(10):3875-91,

https://doi.org/10.1175/JCLI-D-17-0551.1

4. Rabatel A., Francou B., Soruco A., Gomez J., Cáceres B., Ceballos J.L., Basantes R., Vuille M., Sicart J.E., Huggel C., Scheel M., Lejeune Y., Arnaud Y., Collet M., Condom T., Consoli G., Favier V., Jomelli V., Galarraga R., Ginot P., Maisincho L., Mendoza J., Ménégoz M., Ramirez E., Ribstein P., Suarez W., Villacis M. y Wagnon P. Current state of glaciers in the tropical Andes: A multi-century perspective on glacier evolution and climate change. Cryosphere, 2013; 7(1):81-102,

https://doi.org/10.5194/tc-7-81-2013

5. UNESCO El Atlas de Glaciares y Aguas Andinos: el impacto del retroceso de los glaciares sobre los recursos hídricos. 2018

https://unesdoc.unesco.org/ark:/48223/pf0000266209

6. UNESCO, Schoolmeester T., Johansen K.S., Alfthan B., Baker E., Hesping M. y Verbist K. El Atlas de Glaciares y Aguas Andinos: el impacto del retroceso de los glaciares sobre los recursos hídricos. 2018; :1-72.

https://unesdoc.unesco.org/ark:/48223/pf0000266209

7. Ideam informe del estado de los glaciares colombianos 2020 2 Coordinación técnica Fotografías de portada. 2020, https://www.ideam.gov.co/sites/default/files/prensa/boletines/2025-05-20/4_iegc_2020_informe_del_estado_de_los_glaciares_colombianos_2020.pdf

8. Ceballos J. y Tobón E. Glaciares colombianos: evolución reciente y estado actual. Boletín de Geología, 2007; 29(2):143-51,

https://revistas.uis.edu.co/index.php/revistaboletindegeologia/article/view/461

9. IDEAM Report on the Status of Colombian Glaciers (Informe del estado de los glaciares Colombianos). Bogotá D.C: 2025.

https://www.ideam.gov.co/file-download/download/public/17092

doi: 10.25100/iyc.v28i2.15786

10. IDEAM Ideam presenta el sexto informe del estado de los Glaciares Colombianos 2023 [Internet]. 2023 [10 Jun. 2025]. Disponible en:

http://archivo.ideam.gov.co/web/ecosistemas/investigacion-publicaciones

11. Marulanda Aguirre A., Fonseca Tobasura O.A., Vélez Upegui J.J. y Arboleda O.D.C. Hydrological study of the potential effects of the melting of Nevado del Ruiz glacier on urban growth zones in Manizales, Colombia. Hydrological Sciences Journal, 2016; 61(12):2179-92,

https://doi.org/10.1080/02626667.2015.1090574

12. Bolaño-Ortiz T.R., Díaz-Gutiérrez V.L., Vélez-Pereira A.M., Vergara-Vásquez E.L. y Camargo-Caicedo Y. Snow Albedo Reduction in the Colombian Andes Mountains Due to 2000 to 2020 Saharan Dust Intrusions Events. Water 2023, Vol. 15, Page 3150, 2023; 15(17):3150,

https://doi.org/10.3390/w15173150

13. PNN Parque Nacional Natural El Cocuy - Parques Nacionales Naturales de Colombia [Internet]. 2024 [10 Jun. 2025]. Disponible en:

https://www.parquesnacionales.gov.co/nuestros-parques/pnn-el-cocuy/

14. Vásquez Vásquez V.Hugo. y Serrano G. M.A.. Las áreas naturales protegidas de Colombia. 2009; :696,

https://catalogo.humboldt.org.co/cgi-bin/koha/opac detail.pl?biblionumber=8414&shelfbrowse_itemnumber=29931

15. PNN Restauración ecológica en páramos del Parque Nacional Natural de Los Nevados. Manizales [Internet]. 2010 [10 Jun. 2025]. Disponible en:

https://www.parquesnacionales.gov.co/nuestros-parques/parque-nacional-natural-los-nevados/

16. Rekowsky I., Bremer U. y Veettil B. Variations in glacier area in Colombia and Venezuela between 1985 and 2015, using remote sensing data | Request PDF. 2018;

https://www.researchgate.net/publication/329943939_Variations_in_glacier_area_in_Colombia_and_Venezuela_between_1985_and_2015_using_remote_sensing_data

17. Román-Cuesta R.M., Carmona-Moreno C., Lizcano G., New M., Silman M., Knoke T., Malhi Y., Oliveras I., Asbjornsen H. y Vuille M. Synchronous fire activity in the tropical high Andes: An indication of regional climate forcing. Global Change Biology, 2014; 20(6):1929-42,

https://doi.org/10.1111/gcb.12538

18. IDEAM Query and download hydrometeorological data using ArcGIS Web Application [Internet]. 2025 [10 Jun. 2025]. Disponible en:

http://dhime.ideam.gov.co/atencionciudadano/

doi: 10.25100/iyc.v28i2.15786

19. Hsu Y.-C., Liao Y.-C., Fu K.-H., Tseng I.-F. y Lee C.-P. The Relationship Between the Sea Surface Temperature Variability Within the Southwest Atlantic Ocean and Multivariate ENSO Index. ISOPE International Ocean and Polar Engineering Conference, 2013; :97-103,

https://onepetro.org/ISOPEIOPEC/proceedings-abstract/ISOPE13/ISOPE13/ISOPE-I-13-428/15480

20. NOAA Multivariate ENSO Index Version 2 (MEI.v2) [Internet]. 2025 [10 Jun. 2025]. Disponible en:

https://psl.noaa.gov/enso/mei/

21. USGS USGS.gov Science for a changing world [Internet]. 2024 [10 Jun. 2025]. Disponible en:

https://www.usgs.gov/

22. INEI, Mendoza S., Abad P., Huapaya E. y Huerta L. Guía para la presentación de gráficos estadísticos. 2009

23. Chen S. y Zha X. Effects of the ENSO on rainfall erosivity in the Fujian Province of southeast China. Science of The Total Environment, 2018; 621:1378-88,

https://doi.org/10.1016/j.scitotenv.2017.10.090

24. Manrique-Cantillo A.P., Morales-Acuña E. de J., Linero-Cueto J.R., Manrique-Cantillo A.P., Morales-Acuña E. de J. y Linero-Cueto J.R. Variability, cycles, and trends of mean air temperature north of Colombia. Atmósfera, 2024; 38:327-50,

https://doi.org/10.20937/ATM.53265

25. Robledo-Buitrago D.A., Polanco-Puerta M.F., Luque-Villa M. De, Mesa-Caro M. y Calder-Ricardo C.A. Climate Change Trends in Colombia: A Case Study in Facatativá, Cundinamarca. International Journal of Sustainable Development and Planning, 2021; 16(3):535-42,

https://doi.org/10.18280/ijsdp.160314

26. Ruiz D., Martinson D.G. y Vergara W. Trends, stability and stress in the Colombian Central Andes. Climatic Change, 2012; 112(3-4):717-32.

https://doi.org/10.1007/s10584-011-0228-0

27. Broomandi P., Galán-Madruga D., Satyanaga A., Hamidi M., Ledari D.G., Fathian A., Sarvestan R., Janatian N., Jahanbakhshi A., Bagheri M., Karaca F., Al-Dousari A. y Kim J.R. Variability of Middle East springtime dust events between 2011 and 2022. Air Quality, Atmosphere and Health, 2024; 17(6):1341-60

https://doi.org/10.1007/s11869-024-01510-9

28. Jiang X., Holbrook N.J., Marshall A.G. y Love P.T. Quasi-Biennial Oscillation influence on Australian summer rainfall. npj Climate and Atmospheric Science, 2024; 7(1):1-14,

https://doi.org/10.1038/s41612-023-00552-7

doi: 10.25100/iyc.v28i2.15786

29. Bolaño-Ortiz T.R., Diaz-Gutiérrez V.L. y Camargo-Caicedo Y. ENSO and Light-Absorbing Impurities and Their Impact on Snow Albedo in the Sierra Nevada de Santa Marta, Colombia. Geosciences 2020, Vol. 10, Page 437, 2020; 10(11):437,

https://doi.org/10.3390/geosciences10110437

30. QGIS Spatial without Compromise · QGIS Web Site [Internet]. 2024 [10 Jun. 2025].

https://www.qgis.org/

31. Poveda G. La hidroclimatología de colombia: una síntesis desde la escala inter-decadal hasta la escala diurna. Revista de la Academia Colombiana de Ciencias Exactas, Físicas y Naturales, 2004; 28(107):201-21,

https://doi.org/10.18257/raccefyn.28(107).2004.1991

32. Lewis S.C. y King A.D. Evolution of mean, variance and extremes in 21st century temperatures. Weather and Climate Extremes, 2017; 15:1-10,

https://doi.org/10.1016/j.wace.2016.11.002

33. Cerón W.L., Andreoli R. V., Kayano M.T., Canchala T., Ocampo-Marulanda C., Avila-Diaz A. y Antunes J. Trend Pattern of Heavy and Intense Rainfall Events in Colombia from 1981-2018: A Trend-EOF Approach. Atmosphere 2022, Vol. 13, Page 156, 2022; 13(2):156,

https://doi.org/10.3390/atmos13020156

34. Banerjee S., Sati V.P., Almazroui M. y Chakraborty S. Spatio-Temporal Assessment of Areal Fragmentation and Volume of Snow Cover in the Central Himalaya. Earth Systems and Environment, 2024

https://doi.org/10.1007/s41748-024-00469-y

35. Ghosh S., Pandey A.C., Nathawat M.S., Bahuguna I.M. y Ajai Contrasting Signals of Glacier Changes in Zanskar Valley, Jammu & Kashmir, India Using Remote Sensing and GIS. Journal of the Indian Society of Remote Sensing, 2014; 42(4):817-27

https://doi.org/10.1007/s12524-014-0368-6

36. Francou B., Vuille M., Favier V. y Cáceres B. New evidence for an ENSO impact on low-latitude glaciers: Antizana 15, Andes of Ecuador, 0°28′S. Journal of Geophysical Research Atmospheres, 2004; 109(18)

https://doi.org/10.1029/2003JD004484

37. Vuille M., Francou B., Wagnon P., Juen I., Kaser G., Mark B.G. y Bradley R.S. Climate change and tropical Andean glaciers: Past, present and future. Earth-Science Reviews, 2008; 89(3-4):79-96,

https://doi.org/10.1016/j.earscirev.2008.04.002

38. Ruiz D., Moreno H.A., Gutiérrez M.E. y Zapata P.A. Changing climate and endangered high mountain ecosystems in Colombia. Science of the Total Environment, 2008; 398(1-3):122-32,

https://doi.org/10.1016/j.scitotenv.2008.02.038

doi: 10.25100/iyc.v28i2.15786