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LETTER

Surface temperature variability in a tropical Andean summit: influence of ENSO, elevation, and slope direction

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Abstract
Tropical Andean ecosystems are critical for biodiversity conservation and water regulation. Climate change is affecting these ecosystems, but research at high altitudes is still scarce. We aim to understand the complex relationships between surface temperatures and seasons, El Niño Southern Oscillation phenomenon (ENSO), elevation, and slope direction, using novel *in situ* monitoring data in Northern South America (i.e., Cocuy National Park, Colombia). We analyzed hourly surface temperature data recorded from 2011 to 2019 at four summits between 4050 and 4400 m elevation, collected using self-logging thermometers as part of the Global Observation Research Initiative in Alpine Environments (GLORIA) Andes network. Furthermore, we assessed temperature trends and differences in relation to elevation, season, slope, and ENSO. Contrary to other regional results, surface warming in these summits did not increase with altitude i.e., no local evidence of elevation-dependent warming (EDW). Even more, minimum and maximum temperatures exhibited contrasting trends: minimum and maximum temperatures increased over time at the lowest elevation, while minima increased and maxima decreased at the highest elevation. Also, lower elevations warmed faster during the dry season. Surface temperatures were weakly correlated with the Oceanic Niño Index (ONI), and the other El Niño indices (1+2, 3 and 4). Given that the ONI index reflects both the effects of El Niño and La Niña, we observed that during La Niña there was a significant intensification of warming for minimum temperatures and cooling for maximum temperatures at the highest elevation. Slope orientation played an important role. Contrary to what other studies have found, minimum temperature trends on slopes exposed to predominant winds (i.e., northeasterlies) were significantly different (warmer) from the leeward slopes (cooler). These findings underscore the need for continued research and monitoring to better understand microclimate variability and heterogeneity in these complex topographic regions. Such efforts are essential for improving climate model accuracy and guiding effective natural resource management in the face of a changing climate.

Introduction

Climate change is one of the main threats to mountainous ecosystems worldwide. These regions, covering about 25% of the land surface, are crucial for providing numerous environmental services, including drinking water for ca. 40% of the population (Rahbek *et al* 2019). However, there are also potential impacts on these ecosystems including reduced biodiversity, habitat loss, declining snowpacks, and retreating glaciers (Chimborazo *et al* 2022, Pepin *et al* 2022).

Studying the climate in these mountainous ecosystems is complex because there is high local variability due to topography, slope, aspect, land cover and exposure (Navarro-Serrano *et al* 2020). Many studies have suggested that warming rates in mountains are elevation-dependent (Palazzi *et al* 2019, Rottler *et al* 2019, You *et al* 2020, Miller *et al* 2021, Pepin *et al* 2022). However, this relation is not always positive, since higher elevations do not consistently experience more rapid warming (Toledo *et al* 2022). Globally, and particularly in extratropical regions, minimum temperatures have shown a greater increase with elevation compared to maximum temperatures. This suggests that different mechanisms may be driving changes in daytime and nighttime temperatures (Rangwala *et al* 2016, Toledo *et al* 2022). In general, evidence shows a rapid increase in temperature in the cryosphere due to snow-albedo feedback, although other factors such as changes in cloud cover and soil moisture also play an important role (Pepin *et al* 2015, 2022).

One of the best-known cases of elevation dependent warming (EDW) is in the Tibetan Plateau, where rapid warming is evident since the 20th century (Lu *et al* 2010, You *et al* 2020). However, EDW patterns are not consistent. Wei and Fang (2013) found positive warming of 0.318 °C decade^{-1} in the whole region, based on data from 144 stations from 1961–2010; but this trend has been gradually decreasing. Lu *et al* (2010) found that high-altitude areas in the plateau (below 5000 m) are less sensitive to warming than low-altitude areas, both in speed and intensity of the warming. The uncertainty in the EDW pattern is greater in tropical mountains because they are not as studied as the Northern Hemisphere or mid-latitude mountains (e.g., Palazzi *et al* 2019, Williamson *et al* 2020, Hu and Hsu 2023, Pandey *et al* 2024, Zhao *et al* 2024). Besides, warming with elevation in tropical mountains could be more pronounced due to the stronger albedo feedback, the reduced seasonal variation in snowline elevation and the more dominant cloud feedback and latent heat release present at these locations (Pepin *et al* 2015, Byrne *et al* 2024).

High-altitude climate data is scarce, thereby studies usually use models rather than observations (Rangwala *et al* 2016, Zhang 2018, You *et al* 2020). Despite significant advancements, climate models often fall short in capturing the complexities of high-altitude environments (Lembrechts *et al* 2019). In contrast, *in situ* monitoring provides a better representation of the highly complex spatiotemporal weather conditions and air temperature patterns (Thornton *et al* 2022). This challenge is compounded by the insufficient number of meteorological stations in mountainous, particularly in the Tropics, to accurately capture climate variability (Navarro-Serrano *et al* 2020, Newell *et al* 2022).

The Andes Mountains are the world's largest continental mountain range (Espinoza *et al* 2020). Within these mountains, the Tropical Andes are considered a biodiversity (Myers *et al* 2000) and a climate hotspot (Nogués-Bravo *et al* 2007). The surface temperature has risen by 0.68 °C between 1939 and 2008, reflecting an average increase of 0.1 °C per decade. (Vuille *et al* 2008). In one of the most representative Colombian ecosystems, the *páramo*, a tropical high-altitude tundra above 3000 m.a.s.l, there has been a temperature increase of 0.6 °C to 1.3 °C decade^{-1} (Ruiz *et al* 2008).

In the tropical mountains, high elevation temperatures are modulated by the El Niño Southern Oscillation phenomenon (ENSO) (Sarachik and Cane 2011). ENSO is the primary driver of climate variability on interannual timescales, especially in the tropical Pacific, which directly influences atmospheric circulation and temperature patterns in the Andes (Bedoya-Soto *et al* 2019, Reboita *et al* 2021). Therefore, EDW could also be influenced by ENSO, due to changes in clouds, atmospheric water vapor, and the increase in freezing level heights (Diaz *et al* 2014). A study by Toledo *et al* (2022), using climate model data, reported a positive EDW in both the tropics and subtropics for maximum temperatures, probably due to changes in the shortwave radiation related to the presence of snow. However, for the minimum temperatures, the tropics presented a negative EDW trend, explained by changes in longwave radiation. These changes could also be explained by the stronger warming trend in daytime compared with nighttime temperatures (Aguilar-Lome *et al* 2019).

In the context of local climate variability, another key factor is the slope. However, slope direction dependent warming (hereafter: SDDW), has not been widely studied worldwide. In the Andes, warming has been higher in the western side than in the eastern (Vuille *et al* 2003), due to enhanced easterly winds and wind subsidence on those slopes (Chimborazo *et al* 2022). In other parts of the world, such as the Kilimanjaro, the northeast slope was warmer on average compared to the southwest slope, and these differences were up to 4 °C–5 °C (Pepin *et al* 2017).

Despite these findings, tropical mountains remain largely understudied. Given their conservation value, unique topography, and limited *in situ* climate data, understanding climate variability in these regions is crucial for managing natural resources and anticipating climate change impacts on biodiversity and water regulation. The North Andean Cordillera in Colombia encompasses a significant portion of these ecosystems and faces threats from climate and land cover changes. Therefore, this study aims to understand: (1) How does surface temperature vary in Colombia's tropical Andean summits over different timescales (from hourly to

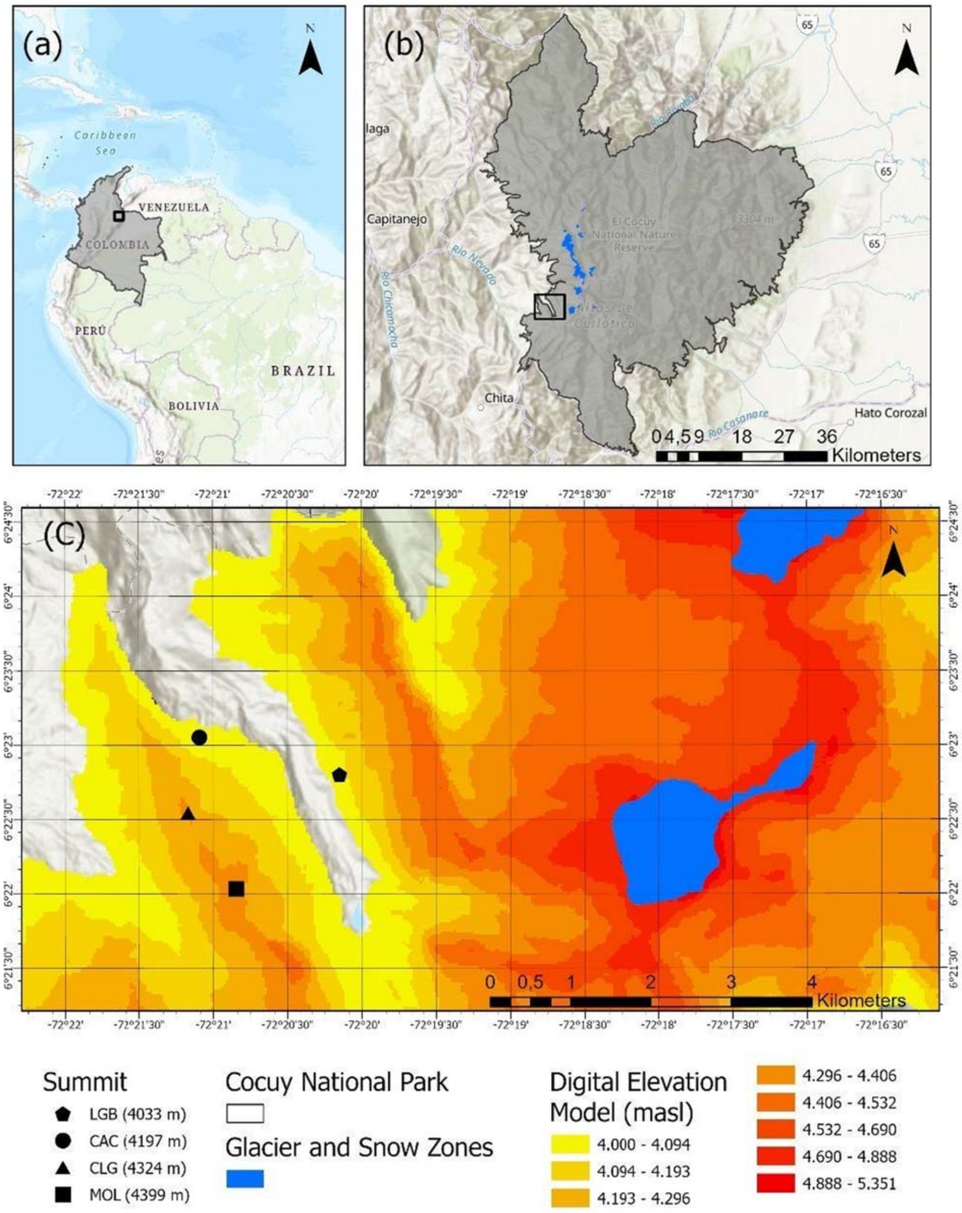

Figure 1. Study site. (a) Colombia. (b) Cocuy National Park location. (c) Elevation map with the four summits (LGB, CAC, CLG, MOL) and areas covered with glacier (more than 3 km from our summits). Source: Paramo's delimitation ministry of environment and sustainable development Colombia 2021.

multiannual)? (2) How does temperature variability relate to ENSO, season, and elevation? (3) How is temperature variability linked to slope direction?

Materials and methods

Study area

The Sierra Nevada de El Cocuy is a National Park (PNN Cocuy), spanning the Departments of Boyacá, Casanare, and Arauca in Colombia (6.402° N, 72.345° W) (Molano *et al* 2022) (figures 1(a), (b)). One of its key ecosystems is the páramo, represented by herbaceous vegetation, with average temperatures below 10 °C and they present a strong diurnal temperature range, cloudy skies, foggy days, high UV radiation, and strong winds (Ruiz *et al* 2008). According to data from the Institute of Hydrology, Meteorology and Environmental Studies (IDEAM), the eastern portion of the range is unimodal, with one dry season and one rainy season (IDEAM *et al* 2017, Urrea *et al* 2019). Maximum precipitation occurs between June and August (López-Moreno *et al* 2014).

Data

We used data from the 'Global Observation Research Initiative in Alpine Environments (GLORIA)' Andes network (https://redgloria.condesan.org/homeen/), which studies climate change impacts in high mountain ecosystems, collecting data on plant biodiversity and climate. All GLORIA sites follow a standardized multi-summit approach for easy comparability between study sites (Carilla *et al* 2018, Llambi *et al* 2022, Cuesta *et al* 2020, 2023).

In the PNN Cocuy, the GLORIA site was installed in 2010 and has four summits at different elevations: Lagunillas Bajo (LGB, 4033 m), Camino Alto del Conejo (CAC, 4197 m), Cerro Lagunillas (CLG, 4324 m) and Cerros del Molino (MOL, 4399 m) (figure 1(c); https://redgloria.condesan.org/sitios-piloto/parque-nacional-el-cocuy/). At these summits, there is no permanent snow cover; hail may occasionally fall, but it does not form a permanent, lasting ice cover. Temperature has been recorded using GeoPrecision Mlog-5W (accuracy of at least ± 0.1 °C at 0 °C with a resolution of 0.01 °C; temperature logged every hour; Ettlingen, Germany) located at ground level, without direct exposure to sun, wind, or rain, sheltered beneath rocks or hidden among vegetation clumps. These sensors have a long lifespan, lasting between five and ten years on a single battery. Although four loggers have been placed in each summit, one in each of the four cardinal points, according to GLORIA protocol (Pauli *et al* 2015), in our comparison we only used the northern sensor, as it had continuous data from September 2011 to March 2019 (Supplementary information). However, we double-checked trends by comparing to other sensors in the same summit, which showed the same temperature patterns in the recorded temperature range. For exploring the differences in surface temperature between the four slopes, we chose LGB as it was the only summit with a continuous 10-year record for the four sensors. For tropical Andean mountain summits, an unprecedented large amount of more than 500,000 data was compiled and synthesized in this study, representing data collected at the four summits of PNN Cocuy, Colombia (Sanchez 2025).

Data analysis

Data processing was done using the interquartile method for removing outliers (Dash *et al* 2023). We removed only the superior limit (data points falling above $Q3 + 1.5 * IQR$), due to the occasional values higher than 20 °C–25 °C, which we considered as errors based on previous páramo studies (Ruiz *et al* 2008, Sanchez *et al* 2018). These outliers were not present in the minimum temperatures. To characterize the climate, hourly to decadal maximum and minimum temperatures were analyzed. Daily temperature minima and maxima were first derived by selecting the lowest and highest hourly values recorded each day, ensuring a consistent and standardized approach before further analysis. To assess the differences between seasons, the dry season was considered from December to March, and the wet season as the rest of the months. The dry season in this region does not imply an absence of precipitation but rather a period of significantly lower rainfall. This seasonal variability plays a crucial role in shaping ecological processes, hydrological dynamics, and local climatic conditions (Lazo *et al* 2019, Patiño-Gutiérrez *et al* 2024).

Climate and ENSO relations were analyzed using multiple indices that capture different expressions of the phenomenon, including the Oceanic Niño Index (ONI), which is based on a 3-month rolling average of sea surface temperature anomalies in the central Pacific (Glantz and Ramirez 2020). According to the National Oceanic and Atmospheric Administration (NOAA), El Niño conditions occur when ONI is $+0.5$ °C or higher, while La Niña occurs when ONI is -0.5 °C or lower. We also considered Niño 1+2, Niño 3 (Canonical El Niño), Niño 4 (El Niño Modoki), and Niño 3.4, as they are known to produce different atmospheric responses in the Andes (Reboita *et al* 2021). To better understand the ENSO-temperature relationship, we performed a lagged correlation analysis between ONI and surface temperatures at 1-month, 3-month, and 6-month lags, as the ENSO signal often manifests with a delay in high-altitude tropical regions (Córdoba-Machado *et al* 2016, Sayol *et al* 2022). The strength of these relationships was quantified using the Spearman correlation coefficient. Additionally, we incorporated the Monthly Arctic Oscillation (AO) as an additional climate driver that may influence temperature variability (Chen *et al* 2024). We also tested the relationship with the Antarctic Oscillation (AAO), but there was no significant correlation with temperature variability at the study site, likely due to its equatorial location (results not shown).

A linear regression was performed using monthly temperature values, with elevation and date as predictors to determine overall warming trends. Statistical significance was assessed using a t-test. Diurnal temperature range (DTR) was calculated as the difference between the monthly mean maximum temperature and the monthly mean minimum temperature. Additionally, warming trends for minimum and maximum temperatures were analyzed separately using linear regression on monthly mean temperatures across seasons and ENSO phases. Differences between summits and slopes under varying conditions (dry/wet seasons, El Niño/La Niña) were tested using a Kruskal–Wallis test and post-hoc Dunn test due to non-normal data. Correlations between slopes (in LGB) and summits were evaluated with Spearman's rank coefficient. All the analyses were performed in R (R studio team 2020) and a list of all the packages used can be found in the

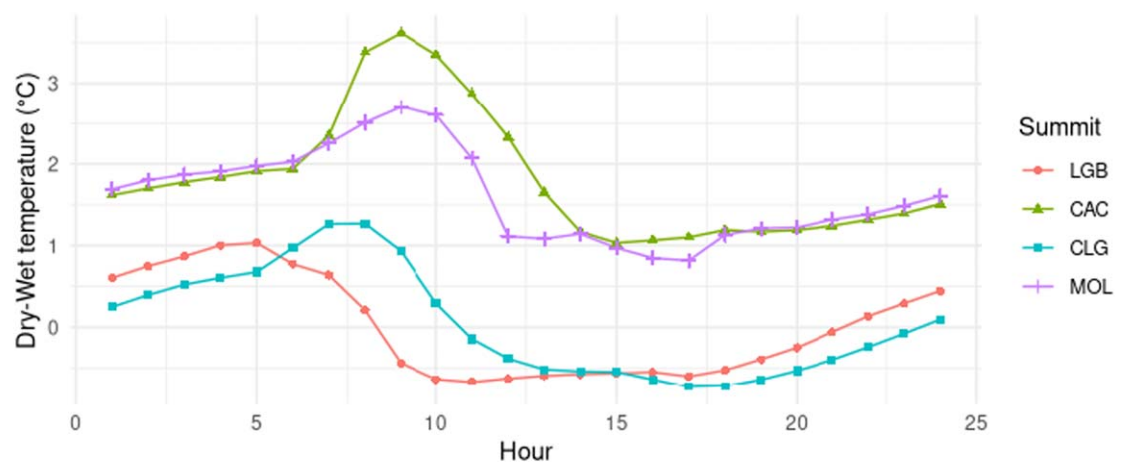

Figure 2. Differences in hourly temperatures between the dry and wet seasons, for the four summits (LGB, CAC, CLG, MOL) (local time, GMT-5). The largest differences between dry and wet seasons occurred during the daytime (6 AM to 3 PM) across all summits, though each summit exhibited distinct peaks during this period. The summits are presented in ascending order of elevation.

supplementary material. We highlight that the temperature trends presented in this study, including changes in minimum and maximum temperatures as well as diurnal temperature range (DTR) focus on climate variability rather than long-term climate change, given the $\leqslant$ 20-year study period. However, studying microclimatic heterogeneity, even with shorter-term data, is key to predict and understand the impacts of climate change at different scales (Zandonai *et al* 2024).

Results

Temperature variation from hourly to decadal scales

In analyzing temperature dynamics across summits, variations in daily temperature differences between the dry and wet seasons were observed, particularly at the higher-elevation sites (figure 2). Long term monthly temperature showed distinct trends in minimum and maximum temperatures (figure 3). In general, maximum temperatures increased in all summits, except at the highest summit (MOL). Minimum temperatures were not consistent across summits, with two summits (CAC and CLG) showing an increase and two others (LGB and MOL) showing a decrease. Average temperature trends were non-significant except for LGB, which showed an increase of 1.15 °C decade^{-1} ($p < 0.05$, table S2). Minimum temperatures exhibited a significant increasing trend in LGB (1.04 °C decade^{-1}, $p < 0.05$; table S1) and MOL (3.15 °C decade^{-1}, $p < 0.05$; table S1), with MOL consistently having the lowest minimum temperatures and LGB the highest. However, CAC and CLG showed decreasing trends for minimum temperatures (−1.74 °C decade^{-1}, and −0.40 °C decade^{-1} respectively; table S1). Conversely, maximum temperatures generally showed an increasing trend for all summits (LGB 1.96 °C decade^{-1}, CAC 2.12 °C decade^{-1}, CLG 3.12 °C decade^{-1}, $p < 0.05$; table S1), except MOL, which exhibited a significant decreasing trend (−5.39 °C decade^{-1}, $p < 0.05$; table S1). Minimum temperatures showed less variability over time and across the summits, compared to maximum temperatures (figure 3, table S1). After removing the seasonal cycle, the regression analysis of temperature anomalies showed that the overall trends remained consistent, confirming the robustness of our findings (figure S1).

The correlations between the four summits are generally moderate to high (figure 3, table S5), with stronger correlations observed for maximum compared to minimum temperatures. However, MOL exhibits weaker correlations, particularly for maximum temperatures, suggesting that while the variability across slopes is comparable, their time evolution differs significantly at these scales. Additionally, Diurnal Temperature Range (DTR, maximum minus minimum temperatures) exhibited significant increasing trends in LGB, CAC and CLG, whereas a significant decreasing trend was observed in MOL (figure S2, table S3). There were also significant differences in the DTR between LGB and all the other summits ($p < 0.05$, table S4).

Relationships between temperature variability and the ENSO, season, and elevation

The impact of ENSO, represented by the ONI index and other Niño indices (Niño 1+2, Niño 3, and Niño 4), on monthly mean temperature was low ($r < 0.5$) across all summits. Specifically, for ONI, this low impact was consistent across all lag scenarios (0-month, 1-month, 3-month, and 6-month lags) (figure S3). Similarly, the Arctic Oscillation (AO) index showed no significant impact on temperature variability (figure S4). Correlations with Niño 1+2, Niño 3, and Niño 4 were weak and non-significant for most summits, except for LGB and MOL, where weak but significant correlations were observed for some Niño types (figure S5). However, when averaging the ONI index during the

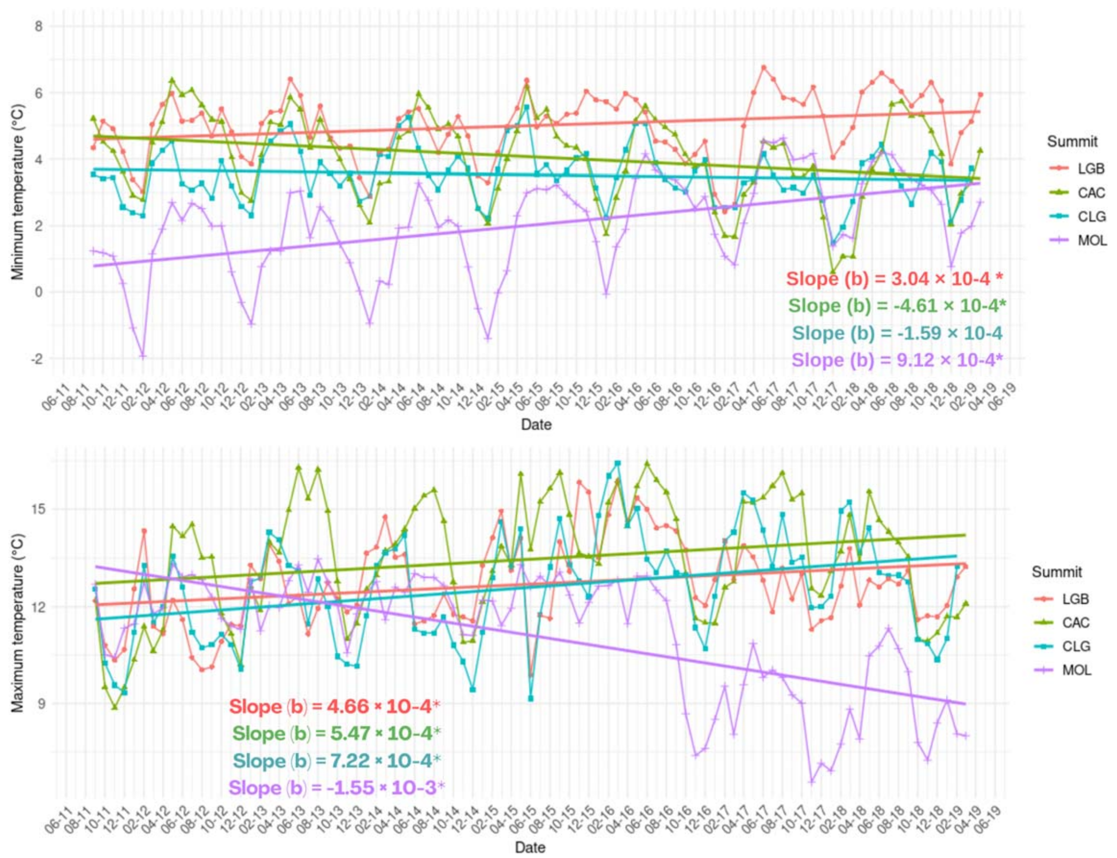

Figure 3. Monthly minima (upper panel) and monthly maxima (lower panel) temperature variation in the four summits (LGB, CAC, CLG, MOL). The *x*-axis displays data at two-month intervals. Regression slopes are indicated (units: °C day^{-1}). Statistically significant slopes ($p < 0.05$) are depicted by an asterisk (*) and specific slope and p-values can be found in table S1. The summits are presented in ascending order of elevation.

study period (2011–2019), we found a positive value of +0.13, suggesting a slight dominance of El Niño conditions during this time. Differences in average temperatures between summits were significant for both maximum and minimum temperatures, except between LGB and CLG (maximum temperatures; figure 4(A), table S6). During the dry season, LGB temperatures ranged from 7 to 13 °C, while MOL ranged from 3 °C to 6 °C (figure 4(B)). In the wet season, LGB had a higher temperature range, especially compared to MOL (7 °C to 14 °C versus 2 to 6 °C, respectively). MOL presented the lowest temperatures, especially in the dry season (figure 4(B)). Differences between summits were significant during both seasons ($p < 0.05$; table S7).

Warming trends for minimum and maximum temperatures, categorized by seasonal (dry/wet) and ENSO (El Niño/La Niña) conditions, are summarized in figure 5. Trends were calculated separately for each category using monthly temperature data to assess how temperature changes vary under different climatic conditions. At LGB, consistent warming was observed in both minimum and maximum temperatures during the dry season, while no significant trends were found during the wet season or ENSO. At MOL, minimum temperatures showed significant warming across all conditions except El Niño, whereas maxima consistently cooled, with stronger cooling during El Niño than La Niña. CAC displayed significant trends under most conditions (figure 5, table S8). In contrast, at CLG, minimum temperatures showed significant cooling for the overall dataset and the dry season, while maxima displayed significant warming across all conditions except El Niño (figure 5, table S8). At mid-elevations, like CAC and CLG, cooling for minimum and warming for maximum temperatures were less pronounced during the dry season, but intensified during La Niña, reflecting significant differences between all data and these conditions (figure 5, table S9).

The altitudinal temperature gradient showed a negative slope, decreasing by ca.°C-0.007°C per meter (-7 °C km^{-1}, $p < 0.001$) (figure S6), consistently for both minimum and maximum temperatures (figure 4(A)). However, elevation-dependent warming trends were not significant ($p > 0.05$), with rates of -1.61 °C $decade^{-1}$ km^{-1} for average temperatures, -14.13 °C $decade^{-1}$ km^{-1} for maxima, and 4.28 °C $decade^{-1}$ km^{-1} for minima. Temperature differences between LGB and MOL varied over time, with a slight decrease during the dry season and an increase from 2 to 3 °C during the wet season (slope = 0.02 °C $month^{-1}$, $p = 0.06$). This suggests LGB temperatures rose significantly faster during the dry season, while MOL temperatures decreased (figure 6).

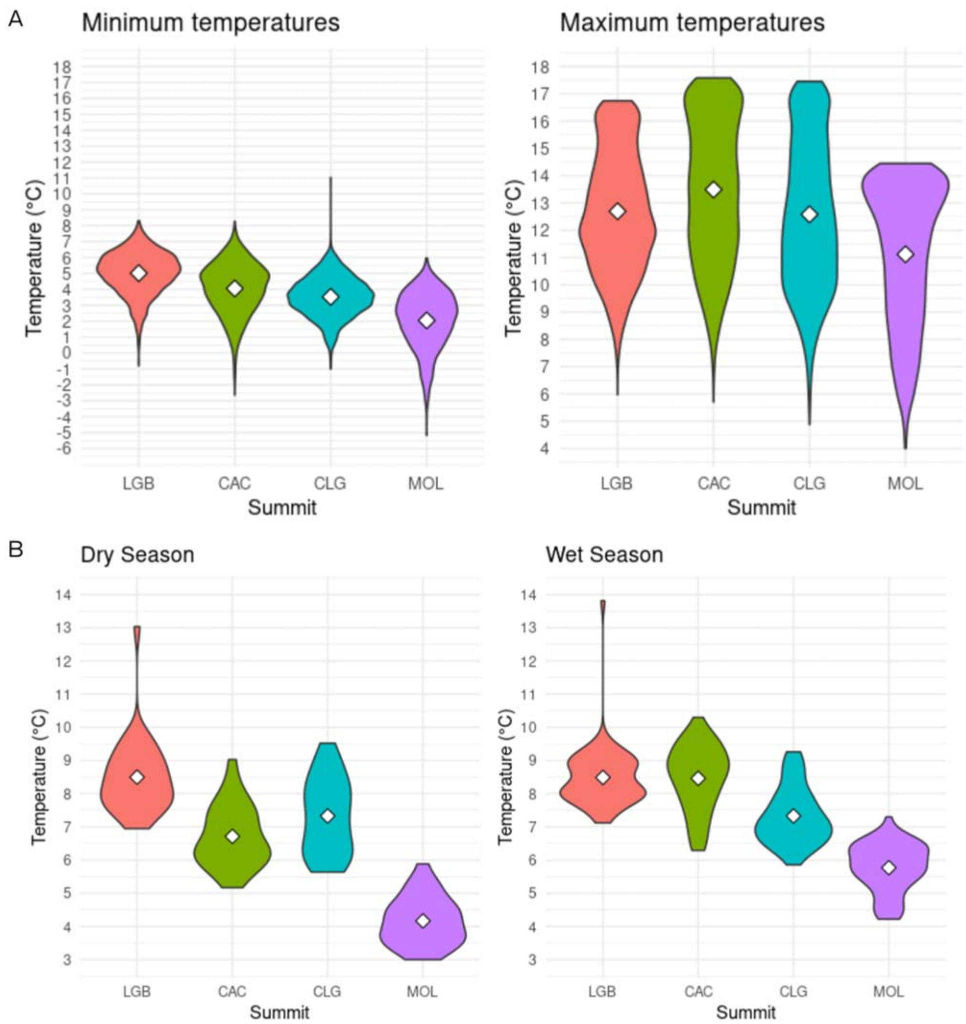

Figure 4. (A). Mean temperature differences between minimum and maximum temperatures in the four summits (LGB, CAC, CLG, MOL). Maximum temperatures tend to have a broader range than the minimum, with LGB consistently being warmer than MOL (mean minimum temperature ≈ 5 °C, mean maximum ≈ 13 °C.) (B). Mean temperature differences between the dry and wet seasons for the four summits (LGB, CAC, CLG, MOL). Diamonds show the mean temperature for each summit. Minimum temperatures are significantly different between LGB-CAC, LGB-CLG and LGB-MOL and maximum temperatures between LGB-CAC and LGB-MOL ($p < 0.05$; table S6). All summit temperatures were significantly different between the dry and wet season (Table S7). The summits are presented in ascending order of elevation.

Temperature variability and slope direction relation

Minimum and maximum temperatures showed distinct trends among slopes in SDDW (figure 7). For the minima, the N and E slopes exhibited increasing trends (2.8 °C decade^{-1} and 1.47 °C decade^{-1} respectively, $p < 0.05$), while S and W showed a decreasing trend (−1.88 °C decade^{-1} and −0.67 °C decade^{-1}, $p < 0.05$; table S10). For the maxima, N, S, and E slopes increased (0.205 °C decade^{-1}, 0.12 °C decade^{-1}, 1.18 °C decade^{-1}, respectively, $p < 0.05$), whereas the W slope decreased significantly (−1.05 °C decade^{-1}, $p < 0.05$; table S10) (figure 7). Correlations between slopes were higher for N-E ($r = 0.17$) than W-S ($r = 0.04$), though both were significant ($p < 0.05$; table S11). Significant differences were observed among slopes under all conditions (dry/wet seasons, El Niño/La Niña), except during the wet season (table S12). Notable differences included E-S, N-S, and S-W ($p < 0.05$) for combined data, the dry season, and El Niño, while E-W and S-W differed significantly during La Niña ($p < 0.05$; table S12).

Comparing minimum and maximum temperatures across seasons and El Niño/La Niña for each slope at LGB, significant differences ($p < 0.05$, table S13) were found for the maxima. For the minima, no significant differences were observed between all data and La Niña ($p > 0.05$, table S13). However, a significant cooling trend in minimum temperatures was found during the dry season and La Niña on the S-facing slope. Additionally, maximum temperatures showed a significant cooling trend during the wet season and La Niña on the W slope, with more cooling of minimum temperatures in the dry season. In contrast, warming trends were more pronounced on the N and E slopes during El Niño (table S14, figure S6).

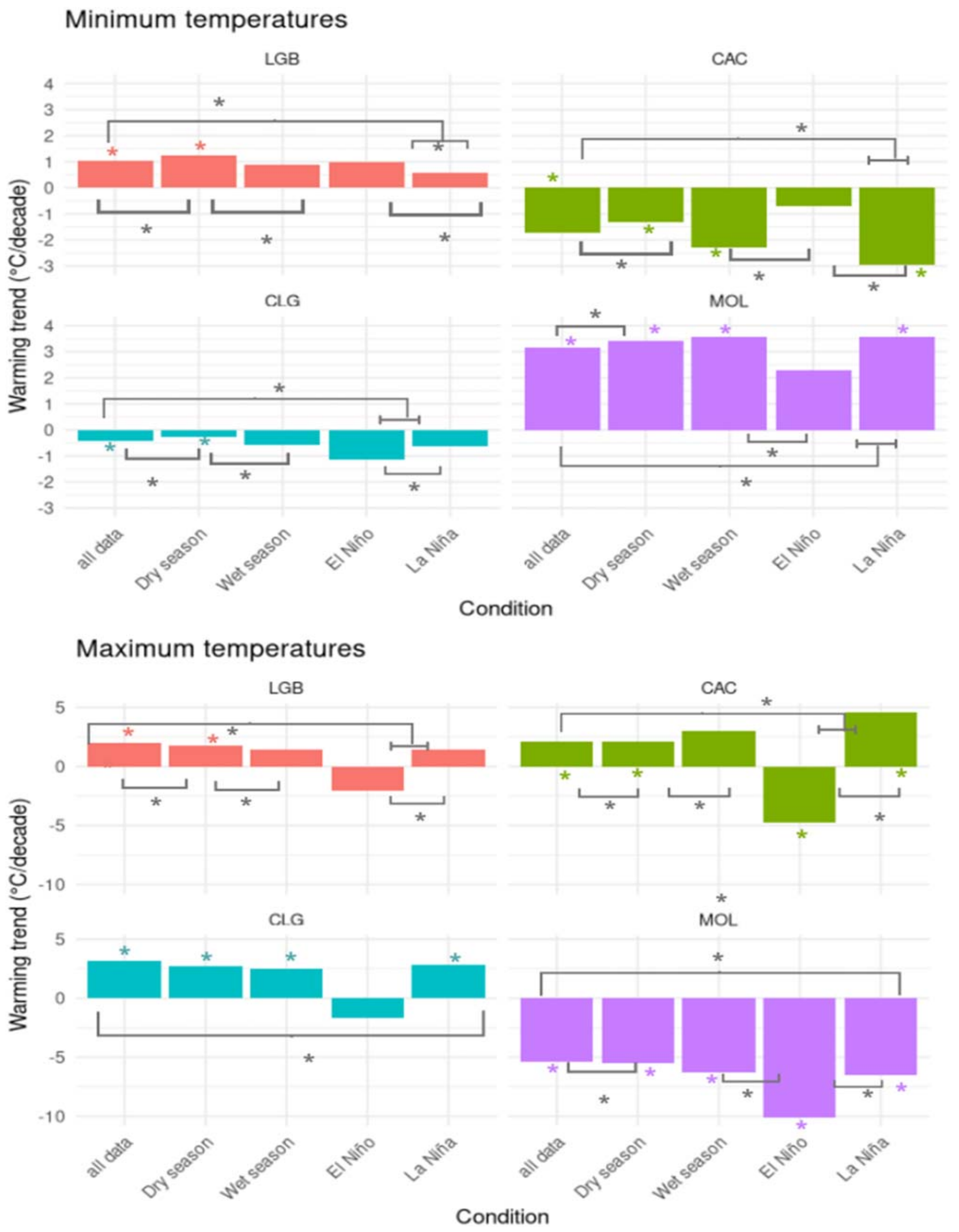

Figure 5. Changes in warming trends for minimum and maximum temperatures for the seasons (dry and wet) and ENSO (El Niño and La Niña) between summits (LGB, CAC, CLG, MOL). Monthly temperature data were grouped into seasonal and ENSO categories, and trends were calculated separately for each condition. Significant differences ($p < 0.05$) between groups are depicted by an asterisk (*) and details are found in table S9. Color asterisks show significant trends ($p < 0.05$) within each specific group; values can be found in table S8.

Discussion

Surface temperature variability in the tropical Andean summits of Colombia, particularly in PNN Cocuy, showed distinct patterns across elevations. Minimum temperatures increased in both LGB and MOL, while maximum temperatures increased in LGB but decreased in MOL (figure 3). Despite being less than 400 meters apart, temperature trends varied widely (from −5 to 3 °C decade^{-1}), contrasting with previous páramo ecosystem trends of 0.6 to 1.3 °C per decade (Ruiz *et al* 2008). However, the average trend of 1.15 °C decade^{-1} at the lowest elevation aligned more closely with those previous values. This discrepancy is likely due to air/surface temperature variability and the proximity of glaciers, where microclimates are warming more rapidly, especially in tropical and Southern Hemisphere mountains (Marta *et al* 2023).

Maximum temperatures showed about 20% more variability than minimum temperatures, likely due to differences in solar radiation and cloud cover (figure 3). From 1981 to 2020, cloud cover explained over 83% of the changes in diurnal temperature range (DTR) across global land areas (Ruiz *et al* 2008, Zhong *et al* 2023). The increased variability in maximum temperatures may also be linked to the reduced cooling effect of soil moisture,

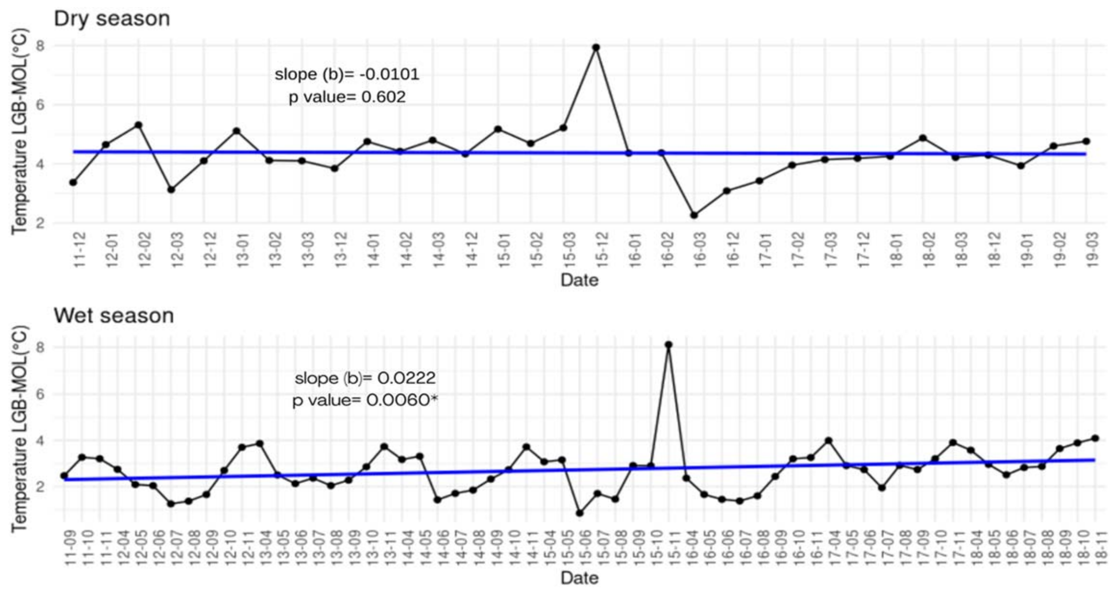

Figure 6. Average temperature differences for the dry (upper panel) and wet (lower panel) seasons, between the lower and higher elevation summits (LGB minus MOL). Slopes are in units: °C/month and the statistical significance ($p < 0.05$) is shown by an asterisk (*).

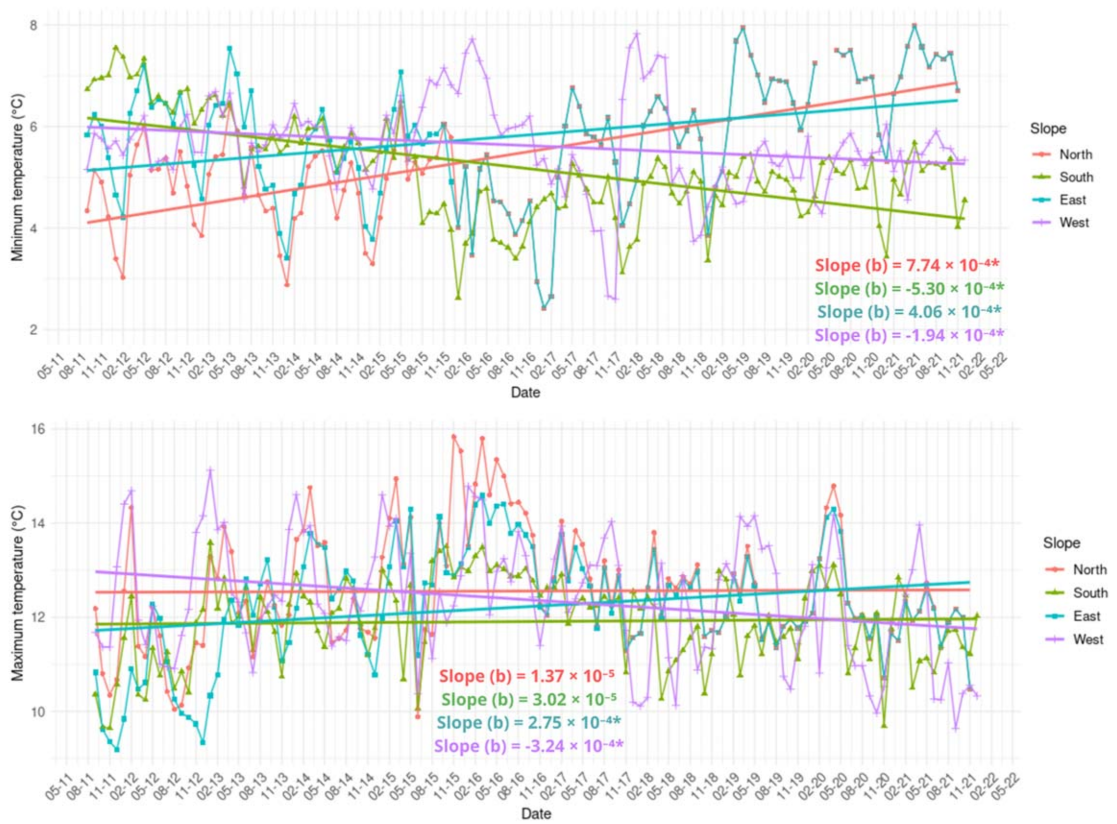

Figure 7. Monthly minimum (upper panel) and monthly maximum (lower panel) temperature variation in the four slope directions (north, south, east and west) at LGB summit. The *x*-axis displays data at three-month intervals for improved readability. Regressions are in units: °C/day. Statistically significant slopes ($p < 0.05$) are depicted by an asterisk (*). Specific slope and p-values can be found in table S7.

which contributes to faster warming (Zhong *et al* 2023). Additionally, daytime temperatures increased more than nighttime temperatures in most of our summits, likely due to lower specific humidity and precipitation, potentially leading to heat stress on fauna and flora (Cox *et al* 2020). Temperature differences between dry and wet seasons varied significantly, with lower altitudes warming more during the wet season. However, in regions with unimodal regimes, wet seasons have been shortened by 60.3% of the tropics and by 64.8% of these areas the season's timing has shifted, alongside decreased precipitation (Guo *et al* 2022).

A contrasting trend was observed at the highest summit (MOL), where minimum temperatures increased more than maximum temperatures, suggesting that nights are warming faster than days (figure 3). This is likely due to higher humidity and cloud cover, which reduce the diurnal temperature range. This pattern aligns with global observations of nighttime warming exceeding daytime warming by 0.25 °C, which has significant implications for plant phenology and carbon processes (Cox *et al* 2020). The warming asymmetry is primarily driven by reduced shortwave radiation during the day due to cloud cover, leading to cooler daytime temperatures, while longwave radiation re-emission at night causes warming. Soil moisture also plays a critical role in this asymmetry, particularly in the tropics (Cox *et al* 2020).

Warming asymmetries, where temperature differences between minima and maxima exceed 3 °C, have been reported in the Tibetan Plateau and parts of the Andes (Cox *et al* 2020). At high elevations (around 4500 m), this phenomenon is more pronounced, particularly due to extensive cloud cover at night. The impacts observed on the Tibetan Plateau primarily affect plant growth, phenology shifts (Cox *et al* 2020), and ectotherms (Speights and Barton 2019). The rising nighttime temperatures offer thermal refuge, allowing organisms to recover from daytime heat, potentially driving shifts in species distributions to higher altitudes (Cox *et al* 2020). The cooling trend at MOL (figure 3) aligns with less warming observed at higher elevations in the tropics since 1979 (Wigley *et al* 2006) and may be linked to a global warming hiatus, as noted in recent Andes studies (Vuille *et al* 2015). A local high-elevation microclimate at MOL can run counter to the broader Andean warming trend. Several complex feedbacks specific to the MOL summit may be occurring, including snow-albedo and surface energy balance feedbacks, katabatic winds, water vapor and cloud interactions, soil moisture trends and associated latent heat fluxes, localized shading effects, or even subtle changes in vegetation cover (see Pepin *et al* 2015, Byrne *et al* 2024). For example, a microclimate with increased daytime snow cover and reduced cloudiness—leading to greater outgoing shortwave and longwave radiation—during the 2011–2019 period at the highest summit (MOL) could help explain the contrasting negative trend in maximum temperatures. However, confirming this hypothesis would require dedicated modeling efforts and/or additional instrumentation, which are beyond the scope of the present study.

In Colombia, ENSO plays a crucial role in shaping hydroclimatic variability, with its effects shaped by the country's tropical condition and complex Andean topography (Vega *et al* 2024). ENSO phases strongly regulate rainfall patterns, with El Niño bringing prolonged droughts, heat waves, and forest fires, whereas La Niña leads to severe storms, landslides, and floods (Poveda *et al* 2020). ENSO also affects soil moisture and causes anomalies in vegetation, influencing evapotranspiration patterns (Poveda *et al* 2011). Higher elevation areas also face unique challenges, including frequent frost events during dry seasons due to intense nighttime radiative cooling and low cloud cover (Poveda *et al* 2020). Despite these broad-scale influences, the relationship between ENSO and surface temperature variability in the tropical Andean summits of PNN Cocuy appears to be complex.

The weak correlation between ENSO indices and surface temperature variability (figures S3, S4 and S5) suggests that local and regional factors, such as slope orientation and microclimatic conditions, may mediate its effects. The lack of significant findings regarding ENSO's impact could also stem from the relatively short period of analysis (2011–2019), which limits our ability to fully capture the interdecadal variability of the ENSO-temperature relationship. Moreover, the Eastern Andes is impacted later and more weakly by the ENSO signal (Poveda *et al* 2011), which could further explain the weak correlation in this region. This may explain why warming during El Niño/La Niña was non-significant at the lowest summit (LGB) and why there were no significant differences in minimum temperatures at the highest summit (MOL). Interestingly, maximum temperatures at MOL cooled more during El Niño than La Niña, while minimum temperatures increased more during La Niña. The absence of significant differences in minimum temperatures indicates that local factors—such as persistent cloud cover, moisture levels, or wind patterns—may play a more dominant role in temperature dynamics in these mountainous regions (Lundquist and Cayan 2007).

Our analysis revealed a significant altitudinal temperature gradient, of ca. 7 °C per kilometer, higher than the standard adiabatic lapse rate of 6 °C (Fitzgerald and Kirkpatrick 2020) and the 4.5 °C of other mountainous regions (Dutra *et al* 2020). Nevertheless, elevation-dependent warming in maximum and minimum temperatures was non-significant, suggesting that local factors such as topography, wind patterns, or cloud cover changes may influence temperature trends independently of elevation (Lundquist and Cayan 2007). Contrasting results in Andean EDW studies include Toledo *et al* (2022), who found a negative EDW in minimum temperatures and a positive trend in the maxima, likely due to differing methodologies, such as climate simulations for future projections. Vuille and Bradley (2000) reported a negative EDW in the Andes, with reduced warming but no cooling. In Colombia, an EDW has been reported, but no warming rate has been estimated (IDEAM, PNUD, MADS, DNP, Cancillería 2017), likely due to biases from using average temperatures from climatological stations. Byrne *et al* (2024) estimated a surface air temperature trend from 0.0089 to 0.018 K $decade^{-1}$ km^{-1}, in the tropics and the subtropics, while Chimborazo *et al* (2022) reported a positive warming rate of 0.08 K $decade^{-1}$ km^{-1} in Ecuador. These numbers are smaller than the

-1.61 K decade^{-1} km^{-1} reported in this study, likely due to the use of climate models versus observed data and the broader spatial and temporal scales considered in those studies.

The analysis of SDDW showed that temperature trends were influenced by whether the slope faced northeast or southwest, likely due to factors such as cloud cover and solar geometry (Pepin and Lundquist 2008). The predominant easterly winds in Cocuy, shifting to northerly winds at times (Murcia *et al* 2017), likely explain the correlations between the N and E slopes. These winds may enhance heating on the east-facing slopes by moving clouds and mist (Pepin and Lundquist 2008). Pepin *et al* (2017) found similar trends in Kilimanjaro, where NE slopes warmed faster due to earlier direct sunlight, coupled with lower humidity. Interestingly, in contrast with Vuille *et al* (2003) and Chimborazo *et al* (2022), the west-facing slope exhibited a significant decrease in maximum temperatures, which could be explained by differences in solar exposure, wind patterns, and moisture retention. López-Moreno *et al* (2022) observed similar trends in Cocuy glaciers, where east-facing slopes experienced greater ice loss, while west-facing slopes saw increased ice cover, likely due to higher humidity. This could cause species to migrate to higher elevations or seek thermal refuge there. Feldmeier *et al* (2020) observed that species may move towards locations that are either cooler or warmer, depending on their thermal preferences. For instance, the alpine salamander and the common lizard in the Swiss Alps exhibited upward shifts in elevation as well as northward shifts in aspect, with the latter being associated with cooler conditions.

Conclusion

This study significantly contributes to understanding Elevational Dependent Warming (EDW) and its broader climatic impacts in the Andes, with a focus in Colombia—an understudied region. By examining spatial heterogeneity in alpine environments, it highlights how short-term temperature variability can differ between closely spaced elevations and mountain slopes, revealing the complexities of climatic patterns in tropical high-altitude ecosystems. These findings are invaluable for managing vulnerable ecosystems, where surface temperature is a key factor in environmental research and water management (Aguilar-Lome *et al* 2019, Zandonai *et al* 2024). However, effectively modeling microclimates across large areas remains a challenge due to limited data in tropical mountainous regions. Continuous monitoring, including energy fluxes and humidity (Rangwala and Miller 2012), is essential. Additionally, understanding short-term temperature variation, such as diurnal temperature range (DTR), is vital, as it influences species distribution and the elevational range of vascular plants (Gallou *et al* 2023). This knowledge is critical for developing strategies to mitigate the impacts of climate change in this region.

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Data availability statement

The dataset used in this study is publicly available on Zenodo at https://doi.org/10.5281/zenodo.15265047. It includes surface temperature measurements from the four summits and slope orientations in the PNN Cocuy. Any additional information is available upon request. Data will be available from 15 June 2025.

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