Replies to reviewer (RC2)

3rd-Apr-2026

Journal: EGUsphere (Copernicus Publications)
Manuscript ID: Egusphere-2025-3715
Title: "*Interannual relative contributions of climatic drivers and Black Carbon to glacier area retreat in Central Chile, 2000–2020*".
Autors: Karina Vallejos, Lina Castro, Álvaro Ossandon, Raúl Flores, and Felipe McCracken

We sincerely thank Anonymous Referee #2 (RC2) for the detailed and rigorous review of our manuscript. Below we provide a point-by-point response.

For clarity, each comment is labeled C1–C18. Reviewer comments are reproduced in full and formatted in italics, followed by our responses and the corresponding changes in the revised manuscript (including section, page, and line numbers where applicable).

Suggestions by Reviewer

General comments :

The manuscript "The Anthropogenic Influence on Glacier Retreat in Central Chile" by Karina Vallejos et al. employs multiple linear regression models to quantify the relative contribution of climate change and anthropogenic black carbon (BC) deposition to glacier area retreat at two glaciers (the Paloma Oeste Glacier (POG) and the Bello Glacier (BG)) in central Chile between 2000 and 2020. The study concludes that BC explains ~49% of retreat in POG, while BG retreat is predominantly climate-driven. The topic is relevant and important for hydrology and water resource management in arid/semi-arid mountain regions. However, the manuscript, in its present form, presents fundamental conceptual and methodological limitations that prevent it from meeting the scientific standards required for publication in HESS.

Major comments:

1. A major concern is the substantial overlap between the present manuscript and the previously published study by Cereceda-Balic et al. (2022), which investigated the influence of black carbon and mining-related emissions on glacier retreat in the same region of central Chile. That study combined atmospheric measurements, snow chemistry, mass balance estimates, and glacier area change, providing a comprehensive process-based analysis. In comparison, the current manuscript applies a regression-based attribution framework to a similar research question but with a more limited observational basis. The added scientific value beyond the previously published study is therefore not clearly demonstrated. Furthermore, the selection of glaciers in the present study differs from the earlier work in terms of glacier size comparability. In Cereceda-Balic et al. (2022), the glaciers were of similar surface area (3.8 km2 vs 3.6 km2), facilitating a more balanced comparison. In contrast, the glaciers analyzed here differ substantially in area (1.33 km2 vs 4.21 km2) yet are described as comparable. In general, smaller glaciers tend to exhibit faster geometric adjustment and higher relative retreat rates than larger glaciers under comparable climatic forcing. In addition, the two glaciers differ substantially in surface slope (17.6° vs 30.0°), which further affects ice dynamics, mass turnover, and sensitivity to climatic variability.

2. The title and central framing of the manuscript emphasize "Anthropogenic Influence," yet this term is not clearly or consistently defined. In practice, anthropogenic influence is treated as equivalent to black carbon (BC) deposition, while "climate change" is handled as a separate category. This conceptual separation is problematic. Anthropogenic forcing is not limited to BC. Human-induced greenhouse gas emissions have contributed substantially to regional and global climate change, which in turn exerts a strong influence on glacier mass balance and geometry (Marzeion et al., 2014). Therefore, part of the climatic signal included in the regression model may already contain anthropogenic influence. This is particularly relevant for the Central Chile megadrought discussed in the manuscript, as several studies suggest that anthropogenic climate change has likely intensified its severity and persistence (Boisier et

al., 2016). Given that the manuscript quantifies a specific percentage of "anthropogenic contribution," this conceptual ambiguity undermines the interpretation of the attribution results.

3. The choice of variables raises methodological concerns. The study uses glacier area as the response variable, yet glacier area (or length) changes are known to represent a delayed and integrative response to climatic forcing, with characteristic response times ranging from years to decades (AntarcticGlaciers.org, n.d.). This limitation becomes particularly important when comparing glaciers with substantially different surface areas, as response time and adjustment rates are strongly size-dependent. For assessing the influence of atmospheric drivers, glacier mass balance would be a more physically consistent metric, as it directly reflects accumulation–ablation processes. In addition, the selected temperature indicator—number of days below 0°C (DTbCero)—may not adequately represent variation processes. Glacier ablation is more directly related to positive degree days (PDD) or cumulative positive temperature, which have been widely used in glacier-climate sensitivity studies (Hock, 2003). Using freezing-day frequency instead of melt-relevant indices may weaken the physical interpretability of the regression results.

4. There appear to be inconsistencies in the presentation of Figures 6 and 7. According to the manuscript, Figure 6 shows in-sample fitted values, whereas Figure 7 presents results from LOOCV cross-validation. However, the BG panel appears visually identical in both figures. Since in-sample fits and cross-validated predictions should not coincide exactly, this is particularly notable given that the POG panels clearly differ between the two figures. In addition, the reliability and uncertainty of the BC dataset, which forms a key predictor in the regression framework, are not sufficiently documented.

Specific comments:

The Introduction would benefit from a clearer synthesis of previous research on anthropogenic impacts on glacier retreat, particularly regarding (i) the influence of human-induced climate change on glacier mass balance and (ii) the role of black carbon (BC) in modifying glacier albedo and melt processes. In addition, particulate matter (PM) is introduced as a relevant anthropogenic factor, but it does not appear to be analyzed or discussed in the subsequent sections.

L70-L75: Please check for grammatical errors and revise.

L85: Please add references.

1: The Study Area section would benefit from a more detailed description of the regional climatic background. In particular, a concise overview of precipitation seasonality, temperature regime, dominant circulation patterns (e.g., ENSO and PDO influences), and recent drought conditions would help contextualize the glacier variability analyzed in the manuscript.

L100-L105: The sentences state that various types of glaciers are present in the region. However, this characterization is not supported by references, and such a description has not been commonly reported in previous literature. Could the authors clarify the basis for this statement and provide appropriate references or supporting evidence? In addition, glacier characteristics appear to be described using data from 1979. Given the substantial changes in glacier geometry between 1979 and 2020, it is unclear whether these historical attributes adequately represent current glacier conditions. The authors should justify the use of 1979 data or provide updated information consistent with the study period.

Table 1: Several characteristics mentioned in the text are not fully reflected in the corresponding tables (e.g. glacier retreat pattern, mass balance, atmospheric pollution records and so on), making it difficult to verify some of the statements regarding glacier properties. In addition, the reported differences in glacier slope appear substantial (17.6 vs 30.0). Given that surface slope strongly influences glacier dynamics and mass turnover, it is unclear on what basis the two glaciers are described as similar.

In Section 2.2.4, the manuscript refers to the use of relatively coarse-resolution datasets. It is not clearly described how these data were spatially interpolated or downscaled to represent conditions over the glacier surfaces. The manuscript states that there is a lack of in situ observational data for validation.

However, Cereceda-Balic et al. (2022) reported field measurements conducted on BG, including atmospheric and snow observations.

L 116, L188, L229: These are not properly formatted.

Figure 2: The manuscript does not clearly describe the quality control and validation processes applied to the data presented in this figure (especially Surface black carbon depositation).

L200: Could you explain the reason for this approach and provide relevant references?

Section 3.2 and other parts: the inconsistent use of terminology—such as "annual precipitation," "annual accumulated precipitation," "temperature," and "days below 0"—is confusing and detracts from the clarity of the presentation. Please ensure consistent terminology throughout the manuscript.

L283: “-430 mm per decade for POG and -460 mm per decade for BG.” The manuscript reports a negative precipitation trend of approximately −430 mm per decade for POG and −460 mm per decade for BG. This magnitude appears unusually large for a semi-arid region and warrants clarification. For example, a decrease of 430 mm over a decade would correspond to approximately −43 mm per year. Could the authors clarify the mean annual precipitation values used as reference and confirm whether these trend magnitudes are correct?

Figure 5 appears to lack a clear legend explaining the symbols, colors, or model combinations shown in the panels.

Figure 7: the reported R^2 values (0.967 and 0.971) are seem to be exceptionally high.

Reference:

AntarcticGlaciers.org. (n.d.). Glacier response time. AntarcticGlaciers.org. Retrieved from https://www.antarcticglaciers.org/glacier-processes/mass-balance/glacier-response-time/

Boisier J P, Rondanelli R, Garreaud R D, et al. Anthropogenic and natural contributions to the Southeast Pacific precipitation decline and recent megadrought in central Chile[J]. Geophysical Research Letters, 2016, 43(1): 413-421.

Cereceda-Balic F, Ruggeri M F, Vidal V, et al. Understanding the role of anthropogenic emissions in glaciers retreat in the central Andes of Chile[J]. Environmental research, 2022, 214: 113756.

Hock R. Temperature index melt modelling in mountain areas[J]. Journal of hydrology, 2003, 282(1-4): 104-115.

Marzeion B, Cogley J G, Richter K, et al. Attribution of global glacier mass loss to anthropogenic and natural causes[J]. Science, 2014, 345(6199): 919-921.

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Answers from authors

C1 – Overlap with Cereceda-Balic et al. (2022) and glacier comparability

“A major concern is the substantial overlap between the present manuscript and the previously published study by Cereceda-Balic et al. (2022), which investigated the influence of black carbon and mining-related emissions on glacier retreat in the same region of central Chile. That study combined atmospheric measurements, snow chemistry, mass balance estimates, and glacier area change, providing a comprehensive process-based analysis. In comparison, the current manuscript applies a regression-based attribution framework to a similar research question but with a more limited observational basis. The added scientific value beyond the previously published study is therefore not

clearly demonstrated. Furthermore, the selection of glaciers in the present study differs from the earlier work in terms of glacier size comparability. In Cereceda-Balic et al. (2022), the glaciers were of similar surface area (3.8 km² vs 3.6 km²), facilitating a more balanced comparison. In contrast, the glaciers analyzed here differ substantially in area (1.33 km² vs 4.21 km²) yet are described as comparable. In general, smaller glaciers tend to exhibit faster geometric adjustment and higher relative retreat rates than larger glaciers under comparable climatic forcing. In addition, the two glaciers differ substantially in surface slope (17.6° vs 30.0°), which further affects ice dynamics, mass turnover, and sensitivity to climatic variability."

Response C1:

We thank the reviewer for this comment. Two issues are addressed.

Regarding the overlap with Cereceda-Balic et al. (2022): The manuscript has been revised to better articulate the novelty of our study and its methodological differences with respect to Cereceda-Balic et al. (2022).

The manuscript title has also been revised to better reflect the scope of the study: **"Interannual relative contributions of climatic drivers and Black Carbon to glacier area retreat in Central Chile (2000–2020)".**

The specific changes to the manuscript are as follows:

***Introduction** (P3, L80–86):

"While Cereceda-Balic et al. (2022) provide an in situ, site-specific attribution for OAG vs BG, our study extends and complements this evidence by analyzing an interannual 2000–2020 record and by implementing glacier-specific multivariable regression models that explicitly include large-scale climate variability (PDO and Niño 3.4) together with local meteorological drivers. This framework enables a consistent separation of climatic versus BC-related influences across years and, critically, allows us to quantify the shift in relative attribution during the onset and persistence of the Central Chile Megadrought (~2010 onward)—an aspect not addressed in the earlier study."

(P3, L90–93):

"The main objective of this study is to quantify the relative contribution of climatic and anthropogenic drivers to glacier area retreat in Central Chile using interannual multivariable regression models, and to assess how the percentage contribution of each factor influenced the reduction in glacier area between the hydrological years 2000 and 2020."

Regarding glacier size comparability and slope differences: The specific changes to the manuscript are as follows:

***2.1 Study Area** (P5, L148–158):

"In terms of slope, POG exhibits a steeper gradient than BG (30.0° vs. 17.6°). Differences in glacier geometry, including surface area and slope, may influence glacier dynamics and response times to climatic forcing (Evans, 2013), as smaller glaciers generally tend to adjust more rapidly to environmental changes. However, both glaciers share comparable elevation ranges and predominantly south-facing aspects, which are key controls on solar radiation receipt and the accumulation–ablation regime. Given these shared topoclimatic characteristics, the morphometric differences between POG and BG do not preclude a consistent assessment of their sensitivity to climatic variability and BC deposition at the interannual scale considered in the regression analysis. Furthermore, the comparability of both glaciers is supported at the regional scale by the cluster framework of Caro et al. (2021), which classified 274 glacierized Andean watersheds using machine learning methods based on climatic and morphometric variables. Both POG and BG fall within the Central Andes cluster (CA; 30–37°S), indicating that they share the same dominant climatic drivers and regional topoclimatic regime despite their morphometric differences."

C2 – Conceptual ambiguity of "Anthropogenic Influence"

"The title and central framing of the manuscript emphasize 'Anthropogenic Influence', yet this term is not clearly or consistently defined. In practice, anthropogenic influence is treated as equivalent to black carbon (BC) deposition, while 'climate change' is handled as a separate category. This conceptual separation is problematic. Anthropogenic forcing is not limited to BC. Human-induced greenhouse gas emissions have contributed substantially to regional and global climate change, which in turn exerts a strong influence on glacier mass balance and geometry (Marzeion et al., 2014). Therefore, part of the climatic signal included in the regression model may already contain anthropogenic influence. This is particularly relevant for the Central Chile megadrought discussed in the manuscript, as several studies suggest that anthropogenic climate change has likely intensified its severity and persistence (Boisier et al., 2016). Given that the manuscript quantifies a specific percentage of 'anthropogenic contribution,' this conceptual ambiguity undermines the interpretation of the attribution results."

Response C2:

We thank the reviewer for this important conceptual observation. Two issues are addressed.

Regarding the definition and scope of "anthropogenic influence": this concern was also raised by CC1. The manuscript has been revised to explicitly define the term: within the scope of this study, "anthropogenic influence" refers specifically to the deposition of light-absorbing BC from combustion sources on glacier surfaces, which reduces snow/ice albedo and enhances melt. BC is used as the primary operational proxy, justified by its well-documented radiative effects and the availability of retrospective CAMS deposition fields. Other anthropogenic factors (mineral dust from mining, SO_2-derived aerosols, land-use changes) are acknowledged as potential contributors but lie outside the direct scope of this analysis. The specific changes to the manuscript are the same as those introduced in response to CC1 and are reproduced below for completeness:

***Introduction** (P4, L101–111):

"In this study, "anthropogenic influence" refers to the impact of locally emitted combustion aerosols, represented by the deposition of black carbon (BC) on the snow surface, which reduces snow albedo and enhances melt (Flanner et al., 2007; Shi et al., 2022). In this context, the anthropogenic variable considered was surface-deposited BC, an operational indicator of the anthropogenic aerosol forcing relevant to snow and glacier melt in our analysis. This approach recognizes that BC is a well-established tracer of anthropogenic combustion processes, including transport, residential heating, mining, and industrial activities (Ramanathan and Carmichael, 2008; Gramsch et al., 2020). It is also one of the most effective light-absorbing impurities affecting snow and ice surfaces (Warren and Wiscombe, 1980; Flanner et al., 2007). Moreover, BC has been identified as the second most important anthropogenic climate forcing agent after carbon dioxide (Bond et al., 2013), and its deposition on glacier surfaces has been shown to significantly accelerate melt rates in mountain cryospheric environments, including the central Andes (Ming et al., 2009; Cereceda-Balic et al., 2022; Shi et al., 2022)."

***Section 2.2** (P7, L178–185):

"To represent local anthropogenic forcing, we selected surface-deposited Black Carbon (BC) from CAMS as an operational proxy. This choice is based on (1) the strong physical effect of BC on snow and ice albedo and melt, and (2) the availability of retrospective, spatially resolved deposition fields that allow interannual comparison. Accordingly, BC is used here as a tracer of anthropogenic particulate deposition affecting glacier surface energy balance, while other anthropogenic drivers may influence glacier retreat; their explicit quantification falls outside the scope of the present analysis. A detailed description of all data sources used in this study is provided in Table S1 in the Supplementary Material. The time series of these variables were analyzed for the hydrological years 2000 to 2020, with the hydrological year in Chile running from April 1 to March 31 of the following year."

Regarding human-induced climate change as a component of "anthropogenic influence": the reviewer raises a valid and important conceptual point. We fully agree that the separation between "climatic" and "anthropogenic" drivers in our regression framework is operational rather than physically exhaustive. The climatic predictors used in the regression — precipitation, PDD, PDO, and Niño 3.4 — may themselves contain a fraction of anthropogenic forcing, as human-induced greenhouse gas emissions have likely contributed to regional warming and to the intensification and persistence of the Central Chile Megadrought (Boisier et al., 2016; Garreaud et al., 2020; Marzeion et al., 2014). Within our framework, however, "anthropogenic influence" refers specifically to the direct radiative effect of BC deposition on glacier surface albedo — a locally mediated forcing that operates alongside, and independently from, the regional climatic signal. To clarify this interpretation, the following paragraph has been added to the Conclusions section:

***Conclusions** (P30, L680-688):

" It is important to acknowledge that the separation between 'climatic' and 'anthropogenic' drivers in our attribution framework is operational rather than physically exhaustive. The climatic predictors used in the regression (precipitation, DTb, PDO, and Niño 3.4) may themselves embed a fraction of anthropogenic forcing, given that human-induced greenhouse gas emissions have likely contributed to regional warming and to the intensification and persistence of the Central Chile Megadrought (Boisier et al., 2016; Garreaud et al., 2020; Marzeion et al., 2014). Within this study, 'anthropogenic influence' is used specifically to denote the direct radiative effect of BC deposition on glacier surface albedo —a locally mediated forcing that is physically distinct from, and additive to, the broader regional climatic signal captured by the other predictors. Accordingly, the quantified BC contribution should be interpreted as a lower bound on the total anthropogenic influence on glacier retreat, as part of the climatic signal may itself reflect anthropogenic forcing."

C3 – Use of glacier area instead of mass balance

"The choice of variables raises methodological concerns. The study uses glacier area as the response variable, yet glacier area (or length) changes are known to represent a delayed and integrative response to climatic forcing, with characteristic response times ranging from years to decades (AntarcticGlaciers.org, n.d.). This limitation becomes particularly important when comparing glaciers with substantially different surface areas, as response time and adjustment rates are strongly size-dependent. For assessing the influence of atmospheric drivers, glacier mass balance would be a more physically consistent metric, as it directly reflects accumulation–ablation processes. In addition, the selected temperature indicator—number of days below 0°C (DTbCero)—may not adequately represent variation processes. Glacier ablation is more directly related to positive degree days (PDD) or cumulative positive temperature, which have been widely used in glacier-climate sensitivity studies (Hock, 2003). Using freezing-day frequency instead of melt-relevant indices may weaken the physical interpretability of the regression results."

Response C3:

We thank the reviewer for these methodological observations. Two issues are addressed.

Regarding the use of glacier area as the response variable: The reviewer correctly notes that glacier area (or length) represents an integrated and delayed response to climatic forcing. We acknowledge this limitation. However, the use of glacier area in this study is motivated by several practical and methodological considerations.

First, continuous multi-decadal mass-balance records are not available for Paloma Oeste Glacier (POG) or Bello Glacier (BG), nor for most glaciers in Central Chile. Consequently, glacier area derived from the Landsat images represents the only variable that can be consistently reconstructed at annual resolution over the 2000–2020 period.

Second, although glacier geometry responds to climate with a lag, response times depend strongly on glacier size and thickness. Analytical and numerical studies show that glacier adjustment times are commonly approximated by the ratio between glacier thickness and ablation at the terminus

(Jóhannesson et al., 1989) and may range from decades to centuries depending on glacier geometry. In general, smaller mountain glaciers tend to adjust more rapidly to climatic perturbations than large ice masses. Conceptual models also show that glacier response times generally increase with glacier size and volume, reflecting the influence of glacier geometry on dynamic adjustment (Raper and Braithwaite, 2009). Given that both glaciers analyzed in this study are relatively small mountain glaciers, their geometric adjustment times are expected to be comparatively short, making glacier area variations suitable for evaluating interannual glacier response to climatic drivers.

Third, the objective of this study is not to resolve seasonal accumulation–ablation processes but rather to quantify the relative contribution of climatic variability and BC-related forcing to interannual glacier retreat. At this temporal scale, glacier area changes derived from remote sensing have been widely used as indicators of glacier response in mountain environments where long mass-balance series are unavailable (Rabatel et al., 2013; Malmros et al., 2016; Baradun et al., 2022; Cereceda-Balic et al., 2022).

To acknowledge this limitation more explicitly, the following paragraph has been added to the Conclusions section:

***Conclusions** (P30, L689-695):

"A first limitation is the use of glacier area as the response variable rather than glacier mass balance. While mass balance more directly reflects accumulation–ablation processes, continuous multi-decadal mass-balance records are unavailable for the glaciers studied. The use of annual glacier area derived from Landsat images, therefore, represents a pragmatic approach for evaluating interannual glacier response over the 2000–2020 period. Although glacier area represents an integrated response to climatic forcing with an associated lag, geometric response times are expected to be comparatively short given the relatively small size of both glaciers (Jóhannesson et al., 1989; Raper and Braithwaite, 2009)."

Regarding the use of DTb instead of Positive Degree Days (PDD): this comment was also raised by RC1 (C16 and C21). After careful consideration, we have decided to retain DTb (number of days with mean temperature below 0°C) rather than adopting PDD, for the following reason: DTb provides a more direct physical interpretation within our regression framework — fewer days below 0°C imply warmer conditions and greater potential for ablation. Under this definition, the sign of the regression coefficient is physically consistent and straightforward to interpret. In contrast, PDD accumulates positive temperature anomalies and would require an inverse sign interpretation in our model. To avoid confusion, the manuscript has been revised to make the DTb definition explicit and to clearly distinguish it from PDD throughout the text (Section 2.2.2, P8, L212–221).

"For the temperature variable (DTb), we analyzed the number of days per hydrological year with daily mean temperature below 0°C at the mean elevation of each glacier. This indicator was selected to evaluate whether a reduction in the number of freezing days, and therefore an increase in warmer days above the melting threshold, is associated with changes in glacier area. The time series was constructed by extrapolating daily temperature records from the reference meteorological station of each glacier to its mean elevation. This variable is physically linked to glacier melt processes, since fewer days below 0°C imply more favorable conditions for ablation. Based on these reconstructed and elevation-adjusted series, annual accumulated precipitation and DTb were calculated for each hydrological year and used as climatic predictors in the regression analysis. The use of a 0°C threshold is consistent with previous glacier-climate studies, which recognize this temperature as the melting point of ice (Vincent, 2002; Wiltshire, 2014)."

C4 – Figures 6 and 7 inconsistency

"There appear to be inconsistencies in the presentation of Figures 6 and 7. According to the manuscript, Figure 6 shows in-sample fitted values, whereas Figure 7 presents results from LOOCV cross-validation. However, the BG panel appears visually identical in both figures. Since in-sample fits and cross-validated predictions should not coincide exactly, this is particularly notable given that the POG panels clearly differ between the two figures. In addition, the reliability and uncertainty of the BC dataset, which forms a key predictor in the regression framework, are not sufficiently documented."

Response C4:

We thank the reviewer for identifying this inconsistency. Upon careful review, we confirmed that the BG panel in the original Figure 7 had been incorrectly duplicated from Figure 6, resulting in the identical appearance observed by the reviewer. This error has been corrected in the revised manuscript.

Figure 6 now presents the in-sample fitted values (simulated glacier area) versus observed values for both glaciers, while Figure 7 presents the out-of-sample predicted values obtained through Leave-One-Out Cross-Validation (LOOCV), together with the corresponding residuals. The two figures now show visually distinct point distributions, as expected given the difference between in-sample fitting and cross-validated prediction. Performance metrics (RMSE, MAPE, R^2) are reported within Figure 7 to facilitate direct interpretation of the LOOCV results.

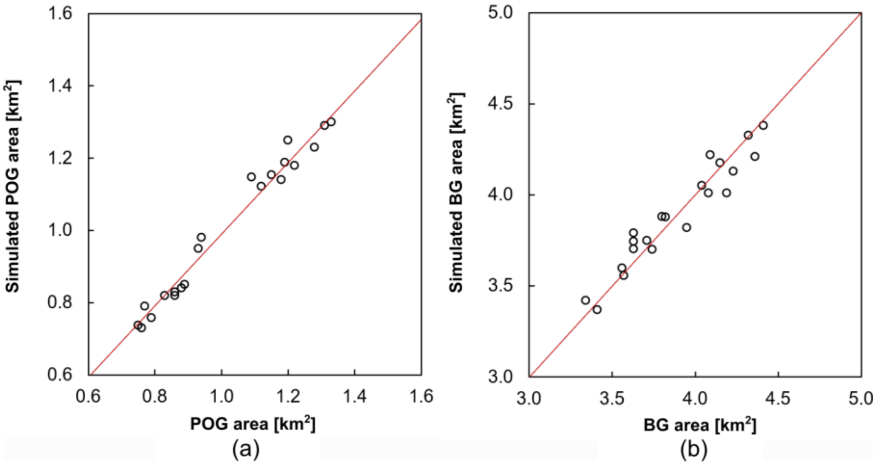
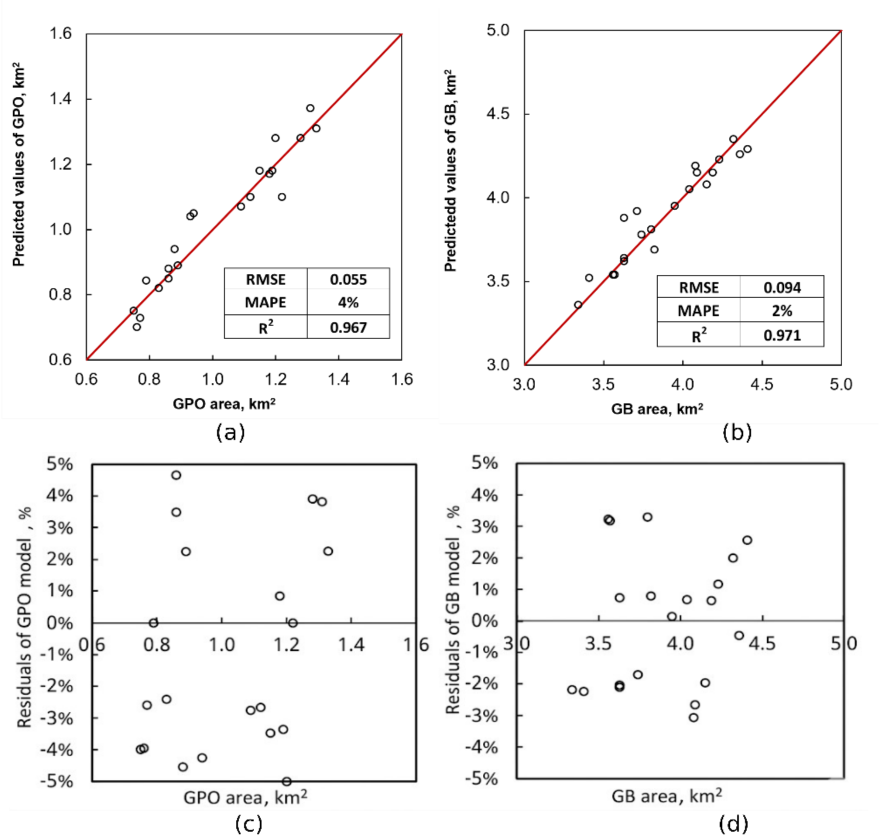


Figure 6. Glacier area simulated by MRLMs versus observed values (non-standardized). (a) BG. (b) POG.



(a) (b)

(c) (d)

Figure 7. R^2, MAPE, and RMSE values obtained through LOOCV validation applied year by year for (a) POG and (b) BG. In addition, residuals of the regression model adjusted using all effects (TE) are shown for (c) POG and (d) BG.

Regarding the reliability and uncertainty of the BC dataset, this point has been further addressed in C11. The specific changes to the manuscript are as follows:

***Section 2.2.4** (P10, L262–266): "As an indirect consistency check, field-based BC measurements conducted by Cereceda-Balic et al. (2022) on BG during 2004–2014 documented low BC surface concentrations on this glacier. Although these measurements are campaign-based and not directly comparable with the annual CAMS reanalysis fields used here, their magnitude is qualitatively consistent with the lower BC deposition values estimated for BG relative to POG. This qualitative agreement is consistent with the spatial differentiation in BC exposure captured by the CAMS dataset across the Maipo basin.

C5 – Literature synthesis and PM inconsistency

"The Introduction would benefit from a clearer synthesis of previous research on anthropogenic impacts on glacier retreat, particularly regarding (i) the influence of human-induced climate change on glacier mass balance and (ii) the role of black carbon (BC) in modifying glacier albedo and melt processes. In addition, particulate matter (PM) is introduced as a relevant anthropogenic factor, but it does not appear to be analyzed or discussed in the subsequent sections."

Response C5:

We thank the reviewer for this observation. Three issues are addressed.

Regarding the synthesis of anthropogenic impacts on glacier retreat: the Introduction has been substantially revised to provide a more explicit discussion of the role of BC in modifying glacier albedo and melt processes in the central Andes. The revised text at P3, L80–86 now reads:

"While Cereceda-Balic et al. (2022) provide an in situ, site-specific attribution for OAG vs BG, our study extends and complements this evidence by analyzing an interannual 2000–2020 record and by implementing glacier-specific multivariable regression models that explicitly include large-scale climate variability (PDO and Niño 3.4) together with local meteorological drivers. This framework enables a consistent separation of climatic versus BC-related influences across years and, critically, allows us to quantify the shift in relative attribution during the onset and persistence of the Central Chile Megadrought (~2010 onward)—an aspect not addressed in the earlier study."

P4, L105-111: "... BC is a well-established tracer of anthropogenic combustion processes (e.g., transport, residential heating, mining, industrial sources) (Ramanathan and Carmichael, 2008; Gramsch et al., 2020) and one of the most effective light-absorbing impurities affecting snow and ice surfaces (Warren and Wiscombe, 1980; Flanner et al., 2007). Moreover, BC has been identified as the second most important anthropogenic climate forcing agent after carbon dioxide (Bond et al., 2013), and its deposition on glacier surfaces has been shown to significantly accelerate melt rates in mountain cryospheric environments, including the central Andes (Ming et al., 2009; Cereceda-Balic et al., 2022; Shi et al., 2022)."

Regarding human-induced climate change and glacier mass balance: the Introduction already addresses glacier retreat in the context of regional warming and the Megadrought (Dussaillant et al., 2019; Masiokas et al., 2020; Garreaud et al., 2017, 2020; Farías-Barahona et al., 2019, 2020). To further strengthen the global context, the following sentence has been added at P2, L40-44:

"At the global scale, anthropogenic greenhouse gas emissions have been identified as the primary driver of accelerated glacier mass loss since the mid-20th century driven by increased atmospheric temperatures and changes in precipitation regimes (Marzeion et al., 2014; Zemp et al., 2019). In the central Andes, this signal is compounded by regional circulation changes associated with the ongoing Megadrought (Garreaud et al., 2020)."

Regarding PM: the mention of particulate matter (PM) in the Introduction is retained as contextual background, consistent with its documented role in albedo reduction in the region (Cereceda-Balic et al., 2018). However, PM is not analyzed as an independent predictor in this study.

The specific changes to the manuscript are as follows:

***Section 2.2** (P7, L181–183): "Accordingly, BC is used here as a tracer of anthropogenic particulate deposition affecting glacier surface energy balance, while other anthropogenic drivers may influence glacier retreat; their explicit quantification falls outside the scope of the present analysis"

C6 – Grammatical revision (L70–L75)

"L70–L75: Please check for grammatical errors and revise."

Response C6:
We thank the reviewer for this observation. The text has been carefully revised for grammatical clarity and improved flow. The primary issue concerned the sentence fragment beginning with "Glaciers are that are close to each other...", which has been rephrased accordingly.

The specific changes are detailed below:

***Introduction** (P3, L87-L90): "Glaciers in central Chile show a significant retreat, which must be evaluated with particular attention to the causes, both climatic and anthropogenic. Glaciers that are close to each other and therefore subject to similar climatic conditions differ in their retreat rates, a dynamic that does not appear to be explained by climatic factors alone (Cereceda-Balic et al., 2020; Le Quesne et al., 2009; Malmros et al., 2016)"

C7 – Missing references (L85)

"L85: Please add references."

Response C7:

We thank the reviewer for this observation. References have been added to support the statements at L85 regarding the selection of predictor variables. This passage has also been improved and better supported in the revised manuscript:

***Introduction** (P4, L99-108)**:** "The climatic variables used as predictors included the number of days with average temperatures below 0 °C (hereafter DTb), annual accumulated precipitation over the hydrological year, and the macroclimatic indices PDO and Niño 3.4. In this study, "anthropogenic influence" refers to the impact of locally emitted combustion aerosols, represented by the deposition of black carbon (BC) on the snow surface, which reduces snow albedo and enhances melt (Flanner et al., 2007; Shi et al., 2022). In this context, the anthropogenic variable considered was surface-deposited BC, an operational indicator of the anthropogenic aerosol forcing relevant to snow and glacier melt in our analysis. This approach recognizes that BC is a well-established tracer of anthropogenic combustion processes, including transport, residential heating, mining, and industrial activities (Ramanathan and Carmichael, 2008; Gramsch et al., 2020). It is also one of the most effective light-absorbing impurities affecting snow and ice surfaces (Warren and Wiscombe, 1980; Flanner et al., 2007)."

C8 – Study Area climatic background

"The Study Area section would benefit from a more detailed description of the regional climatic background. In particular, a concise overview of precipitation seasonality, temperature regime, dominant circulation patterns (e.g., ENSO and PDO influences), and recent drought conditions would help contextualize the glacier variability analyzed in the manuscript."

Response C8:

We thank the reviewer for this suggestion. The Study Area section has been expanded to provide additional climatic context, including precipitation seasonality, the regional hydrological regime, and the influence of large-scale circulation patterns such as ENSO and PDO on interannual hydroclimatic variability. A brief description of the Central Chile Megadrought (~2010 onward) has also been incorporated to contextualize recent hydroclimatic conditions.

The revised text has been added to Section 2.1 (P4-5, L125-133) of the revised manuscript as follows:

"Precipitation in central Chile is strongly seasonal, with most annual totals occurring during the austral winter (June–August), predominantly as snowfall at high elevations. Interannual hydroclimatic variability in central Chile is strongly influenced by large-scale circulation patterns, particularly ENSO and the PDO. Warm ENSO phases (El Niño) and the positive PDO phase are generally associated with wetter conditions in central Chile, whereas La Niña and negative PDO phases tend to produce drier conditions (Garreaud et al., 2009; Núñez et al., 2011). Since approximately 2010, the region has experienced the Central Chile Megadrought, a prolonged period of anomalously low precipitation linked to persistent atmospheric circulation anomalies over the southeast Pacific (Garreaud et al., 2017, 2019). This sustained drought has been identified as a key driver of recent glacier mass loss and hydrological changes in the basin."

C9 – Glacier typology and outdated inventory (L100–L105)

"The sentences state that various types of glaciers are present in the region. However, this characterization is not supported by references, and such a description has not been commonly reported in previous literature. Could the authors clarify the basis for this statement and provide appropriate references or supporting evidence? In addition, glacier characteristics appear to be described using data from 1979. Given the substantial changes in glacier geometry between 1979 and 2020, it is unclear

whether these historical attributes adequately represent current glacier conditions. The authors should justify the use of 1979 data or provide updated information consistent with the study period."

Response C9:

We thank the reviewer for this important observation. Two issues are addressed.

Regarding glacier typology, the characterization of glacier types is now explicitly supported by the most recent national glacier inventory (IPG 2022 v2; DGA), which provides a standardized and up-to-date classification of glacier types within the Maipo River basin. The corresponding reference has been incorporated into the manuscript.

Regarding the use of 1979 data, the reviewer is correct that the basin-wide descriptors previously cited from Marangunic (1979) are outdated. Accordingly, the paragraph has been fully updated using the IPG 2022 v2 inventory, which is temporally consistent with the study period.

The revised text at P5, L134–139 now reads:

"According to the Public Glacier Inventory (IPG 2022 v2), the Maipo River basin contains 1,272 glaciers, ranging in surface area from 0.001 to 24.47 km² and covering a total of 450.96 km², equivalent to 2.95% of the basin area (15,273 km²). Glaciers are distributed between approximately 2,600 and 6,370 m a.s.l. The basin includes both debris-covered and clean-ice glaciers, encompassing a variety of glacier types such as rock glaciers, valley glaciers, mountain glaciers, and glacierets. South-facing aspects dominate, whereas strictly north-facing glaciers represent about 5% of the total inventory."

C10 – Table 1 inconsistencies and slope differences

"Table 1: Several characteristics mentioned in the text are not fully reflected in the corresponding tables (e.g. glacier retreat pattern, mass balance, atmospheric pollution records and so on), making it difficult to verify some of the statements regarding glacier properties. In addition, the reported differences in glacier slope appear substantial (17.6 vs 30.0). Given that surface slope strongly influences glacier dynamics and mass turnover, it is unclear on what basis the two glaciers are described as similar."

Response C10:

We thank the reviewer for this detailed observation. Three issues are addressed.

Regarding Table 1 completeness: glacier retreat pattern, mass balance, and atmospheric pollution records were used as selection criteria for the two glaciers and are described qualitatively in the text with supporting references (Malmros et al., 2016; Cereceda-Balic et al., 2022; DGA, 2011, 2014; Ayala et al., 2016). These attributes derive from sources with incompatible temporal coverages and methodologies, making their inclusion as numeric columns in Table 1 potentially misleading. Table 1 therefore focuses on directly comparable geomorphological characteristics. To improve transparency, glacier area has been added as an additional column consistent with the IPG 2022 v2 inventory framework, as noted in the revised caption.

Table 1. Geomorphological characteristics of BG and POG. Hmin, Hmax, and Have correspond to the minimum, maximum, and mean elevations (in meters above sea level), respectively. Accumulation and Ablation Orientation indicate the predominant orientation of the accumulation and ablation zones. The glacier area is also reported as a first-order descriptor of glacier size, consistent with the IPG 2022 v2 inventory framework.

Name	Glacier Type	Basin	Sub-basin	Hmin (masl)	Have (masl)	Hmax (masl)	Accumulation Orientation	Ablation Orientation	Overall Orientation	Slope (°)	Area (km^2)
BG	Mountain glacier	Rio Maipo	Rio Yeso	3987	4439	4917	SSE	SSE	S	17.6	4.56
POG	Mountain glacier	Rio Maipo	Rio San Francisco	3704	4405	4887	S	SW	S	30	1.27

Regarding the slope difference (17.6° vs. 30.0°): we acknowledge this is substantial. However, as discussed at L148–158, glacier slope is primarily associated with flow velocity and glacier dynamics, while altitude and aspect are considered more influential determinants of glacier mass balance (Evans, 2013). Both glaciers share comparable elevation ranges and south-facing aspects — the attributes most directly linked to solar radiation receipt and accumulation–ablation partitioning. This argument has been made more explicit in the revised manuscript.

Regarding the broader comparability of POG and BG as a glacier pair: this is further supported at a regional scale by the cluster framework proposed by Caro et al. (2021), who used machine learning methods (LASSO + PAM algorithm) to classify 274 glacierized Andean watersheds based on climatic and morphometric explanatory variables of glacier area variation and mass balance. Both POG and BG fall within the Central Andes cluster (CA; 30–37°S), characterized by winter-dominated precipitation (JJA), mean annual temperatures at glacier elevation of approximately −2.7°C, and a mean glacier area variation of −30± 3% over 1955–2014 (Caro et al., 2021). This cluster-based classification confirms that, despite their differences in slope and area, both glaciers share the same dominant climatic drivers and topoclimatic regime, supporting their use as a paired comparison within a common glaciological framework. This point is also addressed in C1.

***2.1 Study area** (P5, L148–158):

"In terms of slope, POG exhibits a steeper gradient than BG (30.0° vs. 17.6°). Differences in glacier geometry, including surface area and slope, may influence glacier dynamics and response times to climatic forcing (Evans, 2013), as smaller glaciers generally tend to adjust more rapidly to environmental changes. However, both glaciers share comparable elevation ranges and predominantly south-facing aspects, which are key controls on solar radiation receipt and the accumulation–ablation regime. Given these shared topoclimatic characteristics, the morphometric differences between POG and BG do not preclude a consistent assessment of their sensitivity to climatic variability and BC deposition at the interannual scale considered in the regression analysis. Furthermore, the comparability of both glaciers is supported at the regional scale by the cluster framework of Caro et al. (2021), which classified 274 glacierized Andean watersheds using machine learning methods based on climatic and morphometric variables. Both POG and BG fall within the Central Andes cluster (CA; 30–37°S), indicating that they share the same dominant climatic drivers and regional topoclimatic regime despite their morphometric differences."

C11 – Coarse-resolution datasets and validation

"In Section 2.2.4, the manuscript refers to the use of relatively coarse-resolution datasets. It is not clearly described how these data were spatially interpolated or downscaled to represent conditions over the glacier surfaces. The manuscript states that there is a lack of in situ observational data for validation.

However, Cereceda-Balic et al. (2022) reported field measurements conducted on BG, including atmospheric and snow observations."

Response C11:

We thank the reviewer for this important observation. Two issues are addressed.

Regarding the spatial representation of coarse-resolution datasets: Precipitation and DTb time series were not spatially interpolated across the glacier surfaces. Instead, daily meteorological records from DGA reference stations were extrapolated to the mean elevation of each glacier using locally derived temperature lapse rates and precipitation–elevation gradients, calculated from the regional station network. This approach provides glacier-representative climatic forcing while avoiding artificial spatial interpolation across small glacier surfaces.

For Black Carbon (BC), we used the CAMS reanalysis product (0.1° spatial resolution; monthly data aggregated to annual means). The grid cell overlapping each glacier centroid was selected as representative. CAMS BC deposition fields have not yet been formally validated in Chile due to the lack of long-term in situ snow-BC measurements. However, previous evaluations in other regions have shown generally good correlations with ground-based observations (e.g., Prabhu et al., 2020). Given that the dependent variable in our study is annual glacier area — an integrated response at the interannual timescale — regional-scale predictors are physically consistent with the temporal scale of analysis.

The specific changes to the manuscript are as follows:

***Section 2.2.2** (P8, L200–221): "To assess the effects of climate change, time series of precipitation and temperature were analyzed for each glacier over the observation period. The meteorological stations used for this analysis are listed in Table 2 and shown in Figure 1. For BG, the reference station was Embalse El Yeso, which provided complete daily precipitation and temperature records over the study period. For POG, the reference station was Estero Yerba Loca antes Junta San Francisco, which had 30% missing data for precipitation and 27% for temperature. These gaps were filled using a regional approach based on six neighboring stations listed in Table 2. For each month, linear regressions were fit between the daily records at the reference station and those of the surrounding stations, considering elevation as an additional explanatory factor. The resulting regressions showed robust performance, with an average coefficient of determination of 0.81, ranging from 0.75 in October to 0.91 in July. Once the daily series were completed at station elevation, temperature was extrapolated to the mean elevation of each glacier using local lapse rates derived from the temperature–elevation relationship among the regional stations. Precipitation was similarly extrapolated to glacier elevation using monthly precipitation–elevation gradients calculated from the surrounding instrumental records."

Regarding Cereceda-Balic et al. (2022) field measurements: The reviewer acknowledges that Cereceda-Balic et al. (2022) conducted field-based atmospheric and snow observations on BG during 2004–2014. Although these campaign-based measurements are not temporally continuous and therefore cannot be directly incorporated into our 2000–2020 regression framework, they provide valuable qualitative context. The low BC concentrations reported for BG are consistent with the lower CAMS-derived BC deposition values estimated for this glacier relative to POG in our dataset. While a direct quantitative comparison is not possible due to methodological and temporal differences, this qualitative agreement supports the spatial differentiation in BC exposure captured by the CAMS product across the Maipo basin.

This clarification has been incorporated into Section 2.2.4 (P10, L262-266) of the revised manuscript as follows:

"As an indirect consistency check, field-based BC measurements conducted on BG by Cereceda-Balic et al. (2022) during 2004–2014 documented low BC surface concentrations on this glacier. Although these measurements are campaign-based and not directly comparable with the annual CAMS reanalysis fields used here, their magnitude is qualitatively consistent with the lower BC deposition values estimated for BG relative to POG. This qualitative agreement is consistent with the spatial differentiation in BC exposure captured by the CAMS dataset across the Maipo basin."

C12 – Formatting errors (L116, L188, L229)

"L 116, L188, L229: These are not properly formatted."

Response C12:

We thank the reviewer for identifying these formatting inconsistencies. The referenced lines have been reviewed and corrected as follows:

L116: Corrected spacing and punctuation in the sentence introducing Gramsch et al. (2020). (revised manuscript: P7, L166)

L188: Corrected citation formatting in Section 2.3 (revised manuscript: P10, 267)

L229: Standardized the list format for regression assumption (i) to ensure consistency with items (ii)–(v). (revised manuscript: P13, L326-333)

No content changes were made; corrections are purely typographical and stylistic.

C13 – Figure 2 and QC description

"Figure 2: The manuscript does not clearly describe the quality control and validation processes applied to the data presented in this figure (especially Surface black carbon deposition)."

Response C13:

We thank the reviewer for this observation. The general quality control and validation procedures applied to all datasets in Figure 2 — including temporal adjustment, homogenization, visual validation, and outlier detection — were described in detail in the revised manuscript.

The specific changes to the manuscript are as follows:

***Section 2.2** (P10-11, L268–287): "Figure 2 outlines the methodology used to quantify the interannual glacier area change of POG and BG and identify the climatic and anthropogenic variables that most influence their retreat. The workflow begins with a data-acquisition phase that gathers Landsat satellite imagery, ground-based meteorological observations, NOAA climate indices, and CAMS black carbon (BC) deposition data. All datasets were temporally aligned to the hydrological year (April 1 to March 31) to ensure that glacier area changes and predictor variables refer to the same annual window (temporal adjustment). Predictor time series were then homogenized to a common interannual resolution and checked for consistent units and time stamps across sources (homogenization). As a quality-control step, each time series and the corresponding glacier delineation outputs were visually inspected to identify discontinuities and potential processing artifacts (visual validation/manual checking). Potential outliers were flagged using robust screening and graphical inspection; flagged values were manually checked against the original inputs, and values attributable to processing artifacts were excluded to avoid undue leverage in model fitting (outlier detection and correction)."

Regarding the BC deposition data (CAMS) specifically: direct local validation was not feasible due to the absence of long-term in situ BC measurements on snow surfaces in the Chilean Andes. The CAMS reanalysis product follows the standard ECMWF quality assurance processing chain (Flemming et al., 2017; Granier et al., 2019), and previous studies have reported generally good correlations between CAMS BC data and ground-based measurements in other regions (Prabhu et al., 2020). As an indirect regional consistency check, the ~40-fold difference in mean BC concentrations between POG and BG is consistent with POG's documented proximity to active copper mining operations and with the BC transport measurements reported by Gramsch et al. (2020) for the northern Maipo basin.

This clarification has been added to Section 2.2.4 and the Figure 2 caption.

***Section 2.2.4** (P10, L258–266): "CAMS data have not yet been validated in Chile due to the lack of continuous ground-based BC measurements on snow surfaces. However, previous studies have compared CAMS BC data with ground-based measurements in other regions and have reported generally good correlations (e.g., Prabhu et al., 2020).

As an indirect consistency check, field-based BC measurements conducted by Cereceda-Balic et al. (2022) on BG during 2004–2014 documented low BC surface concentrations on this glacier. Although these measurements are campaign-based and not directly comparable with the annual CAMS reanalysis fields used here, their magnitude is qualitatively consistent with the lower BC deposition values estimated for BG relative to POG. This qualitative agreement is consistent with the spatial differentiation in BC exposure captured by the CAMS dataset across the Maipo basin."

***Figure 2 caption**: "Workflow of the methodology used to analyze the retreat of the POG and BG glaciers and identify key climatic and anthropogenic drivers. The diagram summarizes data inputs, processing steps, statistical modeling, and contribution analysis."

C14 – Methodological explanation (L200)

"L200: Could you explain the reason for this approach and provide relevant references?"

Response C14:

We thank the reviewer for this question. The selection of the image showing the largest glacier extent for each year follows established practice in glacier mapping based on optical satellite imagery (Racoviteanu et al., 2009; Paul et al., 2013; Malmros et al., 2016). Images were restricted to the late austral summer (December–March), when seasonal snow cover is minimal and glacier boundaries are more clearly exposed. When several cloud-free scenes were available within this window, the image providing the clearest glacier delineation was selected. In practice, this corresponded to the scene showing the largest mapped glacier extent after applying the NDSI classification and visual inspection. This procedure helps reduce uncertainties associated with cloud contamination, shadow effects, and transient snow patches, ensuring consistent glacier boundary detection across the study period. The corresponding clarification has been incorporated into Section 2.3.1 (P12, L295-298) of the revised manuscript.

P12, L295-298: "For each year, we selected the image showing the largest glacier extent for subsequent analysis, following standard practices in glacier mapping using optical satellite imagery, which minimizes the influence of seasonal snow and improves glacier boundary delineation (Racoviteanu et al., 2009; Paul et al., 2013; Malmros et al., 2016)."

C15 – Terminology inconsistency

"Section 3.2 and other parts: the inconsistent use of terminology—such as 'annual precipitation,' 'annual accumulated precipitation,' 'temperature,' and 'days below 0'—is confusing and detracts from the clarity of the presentation. Please ensure consistent terminology throughout the manuscript."

Response C15:

We thank the reviewer for this observation. Upon careful revision, we identified inconsistent use of terminology across the manuscript and have standardized it as follows:

The precipitation variable is now referred to consistently as "annual accumulated precipitation" throughout the manuscript.

The temperature proxy variable, previously referred to inconsistently as "temperature," "days below 0°C," or "DTbCero," is now defined at its first occurrence in Section 2.2.2 as "DTb (number of days with mean temperature below 0°C)" and used consistently as DTb thereafter — including in Sections 3.2, 3.3, Table 4, and all other instances where this variable appears as a predictor.

These corrections have been applied systematically throughout the manuscript, ensuring terminological consistency in all sections.

C16 – Precipitation trend magnitude (L283)

"L283: '-430 mm per decade for POG and -460 mm per decade for BG.' The manuscript reports a negative precipitation trend of approximately −430 mm per decade for POG and −460 mm per decade for BG. This magnitude appears unusually large for a semi-arid region and warrants clarification. For example, a decrease of 430 mm over a decade would correspond to approximately −43 mm per year. Could the authors clarify the mean annual precipitation values used as reference and confirm whether these trend magnitudes are correct?"

Response C16:

We thank the reviewer for this clarification request. The authors confirm that the reported precipitation trend magnitudes are accurate and representative of the severe hydroclimatic shift occurring in Central Chile during the study period. These values align with regional scientific datasets, most notably the CAMELS-CL record (Alvarez-Garreton et al., 2018) for the Echaurren glacier basin. Located just 3 km from the Yeso reservoir at an elevation of 3587 masl, the Echaurren basin series reveals a precipitation decline from approximately 1000 mm to 285 mm from 2000 to 2019, a trend nearly identical to the findings presented here. These observations are further corroborated by the CR2MET high-resolution gridded product (Boisier et al., 2018), which highlights the intensified precipitation deficit in this high-altitude Andean sector.

C17 – Figure 5 legend clarity

"Figure 5 appears to lack a clear legend explaining the symbols, colors, or model combinations shown in the panels."

Response C17:

We thank the reviewer for this observation. Figure 5 has been revised to include a comprehensive legend that explicitly describes all visual elements. The updated figure now includes:

- **Variable symbols**: black cells indicate that a variable is included in the model combination; white cells indicate that it is excluded.
- **Fit scale (BIC)**: a continuous grey scale is used to represent BIC values, where darker shading corresponds to lower BIC (better model fit) and lighter shading corresponds to higher BIC (poorer fit). The BIC value for each model combination is displayed on the left-hand axis.
- **Panel labels**: panel (a) corresponds to BG and panel (b) to POG.

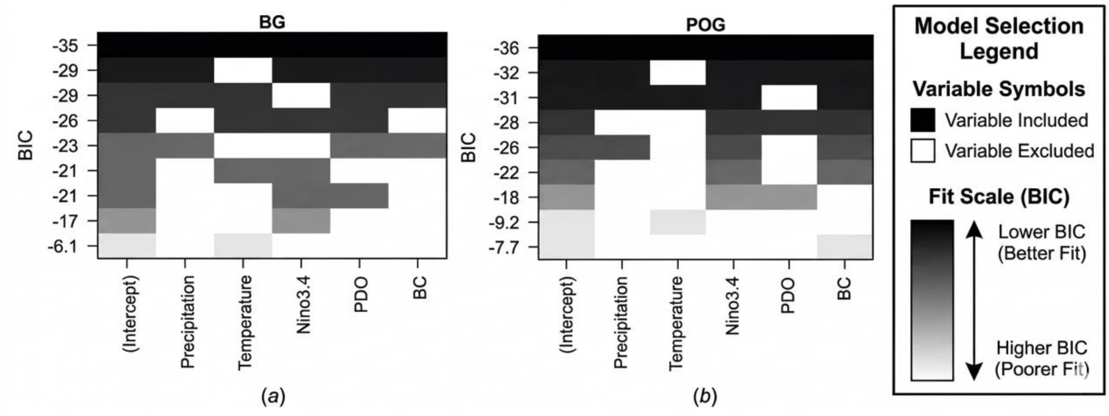


Figure 5. BIC values for selecting predictor variables to model glacier area change in an MRLM. (a) BG. (b) POG.

C18 – High R² values

"Figure 7: the reported R² values (0.967 and 0.971) seem to be exceptionally high."

Response C18:

We thank the reviewer for this observation. The authors maintain that the reported R² values (0.967 and 0.971) are technically sound and representative of the strong physical relationships captured by the models. This high performance is supported by the following evidence:

- Mathematical consistency of metrics: The high R² values are fully consistent with the low RMSE (0.055 km² for POG and 0.094 km² for BG) and the low MAPE (4.1% and 1.7%, respectively) obtained during validation.
- Rigorous variable selection: To ensure the most effective and parsimonious model, we tested multiple combinations of climatic and anthropogenic variables. The selection was based on the Bayesian Information Criterion (BIC), which identifies the optimal set of predictors while penalizing unnecessary model complexity.
- Strong explanatory signals: The high correlation is driven by the marked interannual trends of the predictors during the study period, such as the significant and sustained decline in precipitation associated with the Central Chile Megadrought and the increasing BC deposition at POG.
- Robustness via LOOCV: These metrics were verified using Leave-One-Out Cross-Validation (LOOCV), ensuring that the model maintains high accuracy even with out-of-sample data. The residuals remained consistently below 5% for both glaciers.

The high R² values should be interpreted within the context of the regression framework, which targets interannual glacier area variability rather than local microclimatic processes. Annual glacier area represents an integrated response to accumulation and ablation over multi-month to multi-year timescales, and is therefore expected to reflect low-frequency regional climatic variability strongly. Because POG and BG are relatively small glaciers, their internal spatial variability is lower than that of larger glacier systems, which may help explain why regional-scale predictors capture a substantial fraction of their interannual variability. We acknowledge that these models were calibrated for two specific glaciers and their direct transferability to other glaciers cannot be assumed.

The specific changes to the manuscript are as follows:

***Conclusions** (P30, L689–700): "Finally, some methodological considerations merit acknowledgment. A first limitation is the use of glacier area as the response variable rather than glacier mass balance. While mass balance more directly reflects accumulation–ablation processes, continuous multi-decadal mass-balance records are unavailable for the glaciers studied. The use of annual glacier area derived from Landsat images, therefore, represents a pragmatic approach for evaluating interannual glacier response over the 2000–2020 period. Although glacier area represents an integrated response to climatic forcing with an associated lag, geometric response times are expected to be comparatively short given the relatively small size of both glaciers (Jóhannesson et al., 1989; Raper and Braithwaite, 2009). In addition, the MRLMs explained more than 95% of the interannual variability, though this performance should be interpreted with caution, as regional-scale predictors and extrapolated meteorological variables may capture a substantial fraction of the variability in small glaciers without necessarily resolving local microclimatic processes. The direct transferability of these models to other glaciers in the region, therefore, remains uncertain. Finally, the glacier area time series is subject to delineation uncertainties of approximately 2–5% of the glacier extent (Paul et al., 2013), which should be considered when interpreting the results."

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