Replies to reviewer (RC1)

3rd-Apr-2026

Dear Anonymous Referee #1,

Attached please find our responses to your review comments on the manuscript:

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 #1 (RC1) for the constructive and detailed review. Below we provide a point-by-point response.

For clarity, each comment is labeled C1–C27. 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

This paper presents an extensive analysis of causes of glacier area retreat over two morphologically and climatically similar glaciers in Central Chile with different retreating rates. The differences in retreating rates are attributed to reduced ice albedo due to higher black carbon concentrations in the fast-retreating glacier, which is located nearby anthropogenic mining activities. The authors build multilinear regression models to estimate annual glacier area change based on climatic and anthropogenic variables. Most of the analyses presented are robust, and the presentation of results is clear (with some exceptions which I elaborate below). The paper is generally well written, well structured, and easy to follow. However, I have important concerns regarding the novelty and framing of the study, as well as the presentation and interpretation of some of the results.

In its current form, the paper does not sufficiently articulate the novelty with respect to the study from Cereceda-Balic et al. (2022) titled "Understanding the role of anthropogenic emissions in glaciers retreat in the central Andes of Chile", which is a very similar title to the title of this paper. Both studies compare the glacier retreat rates from the same glacier (Bello Glacier), to the retreat rates from a glacier located near a mining area (Olivares Alpha Glacier in Cereceda-Balic, and Paloma Oeste Glacier in this study, which are located a few km away from each other). The results in terms of attribution of glacier retreat to black carbon compared to climatological factors are therefore very similar between the two studies.

In my opinion, this paper presents two main novelties that the authors need to put more value on, with some caveats. The first one is the incredibly high performance of a simple multilinear regression model in predicting glacier area variability based on some rather simple climatic variables and indices (explaining up to 95% of glacier area variability). The second one is the shift from black carbon dominated glacier area change to climate dominated glacier area change with the onset of the Chilean Megadrought. The current title and main messages of the paper do not sufficiently articulate these novelties. Furthermore, in its current form the paper focuses on glacier area retreat alone and lacks discussion on the implications of the findings beyond the impact of anthropogenic activities on glacier area retreat (for instance, hydrological implications). A revised paper would be more suitable within the aims and scope of another EGU journal such as The Cryosphere and I therefore do not recommend publication in HESS in its current form.

Main comments:

Data availability: The authors should comply with the journal data policy (https://www.hydrology-and-earth-system-sciences.net/policies/data_policy.html), making data available or clearly explaining why that is not possible. In any case the data for reproducing the figures must be made available. There is no indication of where the meteorological data can be found, other than "Data provided on request" in the data availability section. Authors obtained records for PDO and El Niño from NOAA but only point to the general NOAA website, and not the actual data records. The same occurs for atmospheric composition data, pointing only to the Copernicus Atmosphere website but not the specific dataset used.

Section 2.2.2: The use and postprocessing of meteorological data is unclear. The authors present a table with the weather stations in the area (Table 3), but then it seems that only two weather stations are used (Lines 145-146), while additional weather stations were used for gap filling. There are no details about this gap filling. What data series were filled, how, and how many gaps were there? In line 143-144 “precipitation data were extrapolated from nearby meteorological stations”; what does this mean? How was it extrapolated? Same with temperature in line 148 “extrapolating to the glacier elevation” does this mean lapse rates were applied, and what values were applied?

Some of the methods outlined in Figure 2 are not clearly described in the text (e.g., temporal adjustment, homogenization, visual validation, outlier detection-correction, manual checking).

L272: “At the current rate of retreat, POG could disappear in just over 10 years.” This statement should be removed, or evidence should be shown. Where does the estimation of 10 years come from? Judging from the trend lines in Figure 3, it does not seem like either glacier will disappear within 10 years, and this is assuming the Megadrought will continue.

Throughout the results and discussion section, the authors write statements with trend values based on the 20-year time series available. In many cases, the trend values presented refer only to the 10 years of Megadrought period from 2010 to 2020. The values of these trends are therefore very high, and large affected by the Megadrought period. The authors should apply caution throughout the manuscript in presenting these as significant trend values, given that 10 years is not enough for climatological trends to be significant, especially as they could easily be reversed if the Megadrought would stop. Instead, these should be presented as rates or changes within the 10-year period, with clear explanations that these are clearly affected by the Megadrought period and not necessarily long-term climate trends. Examples of this are in line 281-289.

Figure 4: These should be presented as time series (line plots with time on the x-axis), instead of boxplots.

I believe there is an error in the calculation of the Mean Absolute Percent Error (MAPE). Based on Figures and Tables, I think the authors did not multiply the MAPE by 100, to make it a percentage. This is especially clear in Figure 9, where a RMSE of 0.75 km2 corresponds to a 4% error. With the area of the glacier being < 4 km2, I think this is wrong. This then affects the results and discussion presenting the model with tiny errors, such as in line 349 (“The MAPE remains below 0.1%”).

It is an incredibly good result that the multilinear regression models explain up to almost 97% (Fig. 7a) of the variability in glacier area. However, it seems difficult to believe that a simple model can explain such a high variability of the glacier area. The temperature and precipitation data are not observed on the glacier but extrapolated from nearby stations. The two climate variables used are large-scale climate indices which I assume have a coarse resolution (not stated in the paper). The Black Carbon variable has a 0.1 degree resolution. All seem too coarse to capture the effect of these variables at the location of the glaciers, given their small sizes. Nevertheless, the authors should clearly discuss this almost perfect predictive performance. Is this performance possible to extrapolate to other glaciers in the region? If so, that would be great and could lead to a follow-up study, or a reframing of this study, to investigate regional variability in glacier area change with a simple model. If not, it could be that the model is overparameterized for these glaciers. Or perhaps the fact that these are relatively small glaciers has an influence on the results? Further detailed discussions on this matter should be provided. Furthermore, the dependent variable (observed glacier area) must have some uncertainty associated to it, but this is also not discussed or presented.

Other comments:

- L53: “changes experienced by the Cryosphere”. Does this mean globally? Then a few more references of global studies should be included.
- L73: “does not appear to be explained by glaciological factors alone”. What are the glaciological factors? Do the authors mean climatological?
- L80: -1.2% AND -0.6% of what? Melt rates or glacier area?
- L103: Isn’t there a more modern inventory than the one in 1979? With strong glacier retreat, I would guess these numbers may have changed.
- Table 1: Would be good to add area of the glacier as a column.

- L149-151: Please use Positive Degree Days (PDD), instead of DTbCero. PDD is a more common variable in climate studies, and is even the variable used in the two papers that are cited to justify the use of DTbCero (e.g. Vincent 2002 and Wiltshire 2014).
- Table 2: I think this table could move to an appendix or Supplement.
- L189: The use of the word "evaluate" here is not clear what is referring to.
- L236: Is leaving one year out enough for a cross validation in this case? As the data series are 20 years.
- Figure 3: Remove [yyyy] from the labels. Regarding the colourbar of years: while the current colour scale is useful to identify single years, I think here it would be more useful or impactful to have a continuous colour scale that shows how the glacier is retreating through time.
- Table 5: Temperature should be PDD and not temperature, and the value should therefore be negative. Otherwise the positive correlation indicates that more temperature leads to larger glacier area. Please also make cm2 and Km2 a superscript for 2.
- Figure 9: Are the R2 values or RMSE for these models only presented in Figure 9? If so, I suggest combining these figures.
- Table 6: Should 2004 be 2007 in the middle bottom of the table?
- L355: The difference between standardized and unstandardized is not entirely clear to the reader, making the difference between Figure 6 and 7 not clear either. What is the difference between predicted and simulated glacier area?
- L373: What is an "equivalent decrease in winter temperatures" compared to an increase in BC? As these variables are difficult to compare, equivalent here is ambiguous.
- Figure 9: Does KGE make sense for this evaluation?
- Figure 10: I think this is an interesting impactful figure and should be a more focal point of the study.

Citation: https://doi.org/10.5194/egusphere-2025-3715-RC1

Answers from authors

C1 – Novelty relative to Cereceda-Balic et al. (2022)

In its current form, the paper does not sufficiently articulate the novelty with respect to the study from Cereceda-Balic et al. (2022) titled "Understanding the role of anthropogenic emissions in glaciers retreat in the central Andes of Chile", which is a very similar title to the title of this paper. Both studies compare the glacier retreat rates from the same glacier (Bello Glacier), to the retreat rates from a glacier located near a mining area (Olivares Alpha Glacier in Cereceda-Balic, and Paloma Oeste Glacier in this study, which are located a few km away from each other). The results in terms of attribution of glacier retreat to black carbon compared to climatological factors are therefore very similar between the two studies.

Response C1:

We thank the reviewer for this observation. As the reviewer points out, both studies focus on glaciers in Central Chile that share similar geographic and climatic settings; however, they exhibit contrasting retreat rates and employ distinct methodological approaches. While Cereceda-Balic et al. (2022) provide process-based evidence from field campaigns in a specific point (BC/PM measurements, snow chemistry, and albedo) and a mining-specific attribution for the Olivares Alpha Glacier over the 2004–2014 period, our study offers a complementary, longer-term attribution framework spanning 2000–2020. Specifically, we developed glacier-specific multivariable attribution models that explicitly incorporate large-scale climate variability (PDO and Niño 3.4) alongside local meteorological forcings. This enables a unified statistical separation of climatic versus pollution-related influences on glacier area retreat. This approach allows us to: (i) quantify the relative contributions of surface BC deposition and climatic drivers for each glacier; (ii) contrast the BC-related contributions between the paired glaciers; and (iii) evaluate how the relative importance of BC shifted before and during the Central Chile Megadrought.

To address the reviewer's concern regarding potential overlap and to better reflect the scope of our findings, we have revised the manuscript title to: **"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."

C2 – Framing of main novelties (Model performance & Megadrought shift)
In my opinion, this paper presents two main novelties that the authors need to put more value on, with some caveats. The first one is the incredibly high performance of a simple multilinear regression model in predicting glacier area variability based on some rather simple climatic variables and indices (explaining up to 95% of glacier area variability). The second one is the shift from black carbon dominated glacier area change to climate dominated glacier area change with the onset of the Chilean Megadrought. The current title and main messages of the paper do not sufficiently articulate these novelties. Furthermore, in its current form the paper focuses on glacier area retreat alone and lacks discussion on the implications of the findings beyond the impact of anthropogenic activities on glacier area retreat (for instance, hydrological implications). A revised paper would be more suitable within the aims and scope of another EGU journal such as The Cryosphere and I therefore do not recommend publication in HESS in its current form.

Response C2:
Thank you for this comment. We appreciate you highlighting these two novel aspects of our work. Accordingly, we have revised the abstract to better reflect these contributions and incorporate your suggestions.

***Abstract**:
"Glaciers across the Andes have retreated significantly since the mid-20th century, driven by both regional climatic forcing and local anthropogenic pollution. Notably, certain glaciers under similar meteorological conditions exhibit contrasting retreat rates that cannot be explained solely by climatic factors. Focusing on the Maipo River basin (central Chile), we compare the Paloma Oeste Glacier (POG) and the Bello Glacier (BG), which share comparable climatic and geomorphological settings yet show divergent area-loss trends. We developed glacier-specific multivariable linear regression models to attribute interannual glacier area variability (2000–2020) to a parsimonious set of drivers: annual accumulated precipitation, days with mean temperature below 0 °C (DTb), surface black carbon (BC) deposition, and the large-scale climate indices PDO and Niño 3.4. Despite their simplicity, the models demonstrate high predictive skill, explaining up to ~95% of the observed interannual variability. Attribution analysis indicates that glacier area changes are particularly sensitive to BC and Niño 3.4, while the BC sensitivity in POG is substantially higher than in BG, consistent with its more pronounced retreat. Between 2000 and 2020, 49% of the area retreat of POG is explained by BC pollution, whereas 97% of BG's retreat is explained by climatic effects (climate change and climate variability). Furthermore, we identify a marked shift in the drivers of retreat during the Central Chile Megadrought (2010–2020). Before the Megadrought, BC was the dominant driver of retreat in POG (53%), whereas during 2010–2020 climatic effects became dominant (61%) and the relative BC contribution decreased to 39%. These findings underscore the spatiotemporally variation in the influence of climatic and pollution-related factors on glacier retreat, highlighting how sustained drought conditions can shift the primary mechanisms of glacier mass loss."

Main comments:

C3 – Data availability
Data availability: The authors should comply with the journal data policy (https://www.hydrology-and-earth-system-sciences.net/policies/data_policy.html), making data available or clearly explaining why that is not possible. In any case the data for reproducing the figures must be made available. There is no indication of where the meteorological data can be found, other than "Data provided on request" in the data availability section. Authors obtained records for PDO and El Niño from NOAA but only point to the general NOAA website, and not

the actual data records. The same occurs for atmospheric composition data, pointing only to the Copernicus Atmosphere website but not the specific dataset used.

Response C3:
The data used in this study are available from the following public sources:

- Climate Indices (Niño 3.4 and PDO): Monthly time series for the Niño 3.4 and Pacific Decadal Oscillation (PDO) indices were obtained from the National Oceanic and Atmospheric Administration (NOAA) Physical Sciences Laboratory (PSL) at https://psl.noaa.gov/data/climateindices/list/.
- Meteorological Data: Precipitation and temperature records were obtained from the Chilean Water Directorate (Dirección General de Aguas, DGA) through its public portal https://snia.mop.gob.cl/extraerData/ (or alternatively https://snia.mop.gob.cl/BNAConsultas/reportes). The specific time series were constructed by merging records from the Yeso Embalse and Estero Yerba Loca meteorological stations.
- Atmospheric Composition (Black Carbon): Monthly anthropogenic Black Carbon emission data were obtained from the Copernicus Atmosphere Monitoring Service (CAMS) Global Anthropogenic Emissions Inventory, version 4.2 (CAMS-GLOB-ANT v4.2). These data represent surface-level emissions and were retrieved from the Atmosphere Data Store (ADS) at: https://ads.atmosphere.copernicus.eu/datasets/cams-global-emission-inventories?tab=overview.

A detailed description of all data sources has been added as Table S1 in the Supplementary Material. The Data Availability section of the revised manuscript has been updated accordingly.

C4 – Section 2.2.2: meteorological processing (stations, gap filling, extrapolation)
Section 2.2.2: The use and postprocessing of meteorological data is unclear. The authors present a table with the weather stations in the area (Table 3), but then it seems that only two weather stations are used (Lines 145-146), while additional weather stations were used for gap filling. There are no details about this gap filling. What data series were filled, how, and how many gaps were there? In line 143-144 "precipitation data were extrapolated from nearby meteorological stations"; what does this mean? How was it extrapolated? Same with temperature in line 148 "extrapolating to the glacier elevation" does this mean lapse rates were applied, and what values were applied?

Response C4:
We appreciate the reviewer's request for clarification. The meteorological data processing was conducted as follows:

- **Data Continuity and Gap Filling:**
  - **Embalse El Yeso Station (Reference for Bello Glacier):** This station had 0% missing data for both precipitation and temperature at the daily scale for the study period; therefore, no gap filling was required.
  - **Estero Yerba Loca Station (Reference for POG):** This station presented 30% missing data for precipitation and 27% for temperature. These gaps were filled using a regional approach with six neighboring stations (listed in Table 3).

- **Methodology:** For each month, a linear regression was established between the daily data from the reference station and the neighboring stations, considering elevation as a factor. The correlations were robust, with an average R^2 of 0.81 for all regressions (ranging from $R^2 = 0.75$ in October to $R^2 = 0.91$ in July).

- **Extrapolation to Glacier Elevation:**
  - **Temperature:** Once the daily series at the station elevation were completed, they were extrapolated to the mean elevation of each glacier (Bello and POG). This was done by calculating a local lapse rate based on the temperature-elevation relationship derived from the regional stations.
  - **Precipitation:** Similarly, precipitation was extrapolated to the mean glacier elevation using the monthly precipitation-elevation gradients calculated from the instrumental records of the surrounding stations.

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. 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)."

C5 – Figure 2: methods not clearly described in text

Some of the methods outlined in Figure 2 are not clearly described in the text (e.g., temporal adjustment, homogenization, visual validation, outlier detection-correction, manual checking).

Response C5:

We thank the reviewer for this observation. We have improved the Figure 2 explanation (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. This step is followed by a preprocessing stage where interannual time series for glacier area and the aforementioned predictors are derived through a data harmonization process and a quality control workflow (Fig. 2, light blue boxes). 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). The subsequent stage involved an exploratory analysis of the independent variables to identify climatic trends and potential multicollinearity. Afterward, for each glacier, a multiple linear regression model (MLRM) was fitted to the glacier area using a parsimonious set of predictors—including indicators of climate change, climate variability, and anthropogenic pollution—selected during the exploratory phase. This stage is central to the study, as it enables the attribution of glacier area variations to specific drivers. Finally, a suite of statistical tests was applied to verify regression assumptions and validate the proposed MLRMs. While the primary models integrated all selected variables, individual MLRMs were also implemented for each predictor to isolate and evaluate their specific effects."

C6 – L272: statement about disappearing in ~10 years

L272: "At the current rate of retreat, POG could disappear in just over 10 years." This statement should be removed, or evidence should be shown. Where does the estimation of 10 years come from? Judging from the trend lines in Figure 3, it does not seem like either glacier will disappear within 10 years, and this is assuming the Megadrought will continue.

Response C6:
Thank you for this valuable observation. We agree that the original statement was insufficiently supported by the data presented in the text. In response, we have replaced this general projection with a more rigorous estimate based on the observed retreat rates. Specifically, we re-calculated the projected timeline by extrapolating the intensified rates recorded during the Central Chile Megadrought. We have updated the manuscript with justification for our findings in P15-16, L379-383.

P15-16, L379-383:

"However, during the Megadrought period, these retreat rates intensified, reaching -0.35 km² per decade for POG and -0.60 km² per decade for BG. In all cases, the rate of change is negative and statistically significant ($p\text{-value} < 0.05$) for both glaciers. A simple linear extrapolation of the 2000–2020 area-loss rate (0.56 km² over 20 years) suggests a characteristic timescale on the order of two decades for POG to lose the majority of its remaining area, provided that post-2010 retreat rates persist."

C7 – Use of "trend" for Megadrought period (10 years)
Throughout the results and discussion section, the authors write statements with trend values based on the 20-year time series available. In many cases, the trend values presented refer only to the 10 years of Megadrought period from 2010 to 2020. The values of these trends are therefore very high, and large affected by the Megadrought period. The authors should apply caution throughout the manuscript in presenting these as significant trend values, given that 10 years is not enough for climatological trends to be significant, especially as they could easily be reversed if the Megadrought would stop. Instead, these should be presented as rates or changes within the 10-year period, with clear explanations that these are clearly affected by the Megadrought period and not necessarily long-term climate trends. Examples of this are in line 281-289.

Response C7:
We thank the reviewer for this observation. We agree that the term 'trend' can be misleading when applied to 10- or 20-year periods, as these timescales may reflect decadal variability rather than long-term climatological shifts. Following your suggestion, we have performed a comprehensive revision of the manuscript, replacing 'trend' with 'rate of change' or 'retreat rate' where appropriate. Furthermore, we have clarified throughout the text that the accelerated rates observed between 2010 and 2020 are specifically associated with the Central Chile Megadrought and should be interpreted as such, rather than as permanent long-term trends.

C8 – Figure 4: boxplots should be time series
Figure 4: These should be presented as time series (line plots with time on the x-axis), instead of boxplots.

Response C8:
We thank the reviewer for this valuable suggestion. Following this recommendation, Figure 4 has been completely revised and the original boxplots have been replaced by annual time series (line plots with time on the x-axis) for all variables included in the analysis. This new representation allows a clearer visualization of temporal trends, interannual variability, and detected change points (Mann–Kendall and Pettitt tests), which are explicitly discussed in Section 3.2 (Exploratory Data Analysis). The updated Figure 4 is now presented as a four-panel time series (precipitation, DTb, macroclimatic indices, and BC deposition), improving the interpretation of the temporal evolution of the drivers considered in the MRLM.

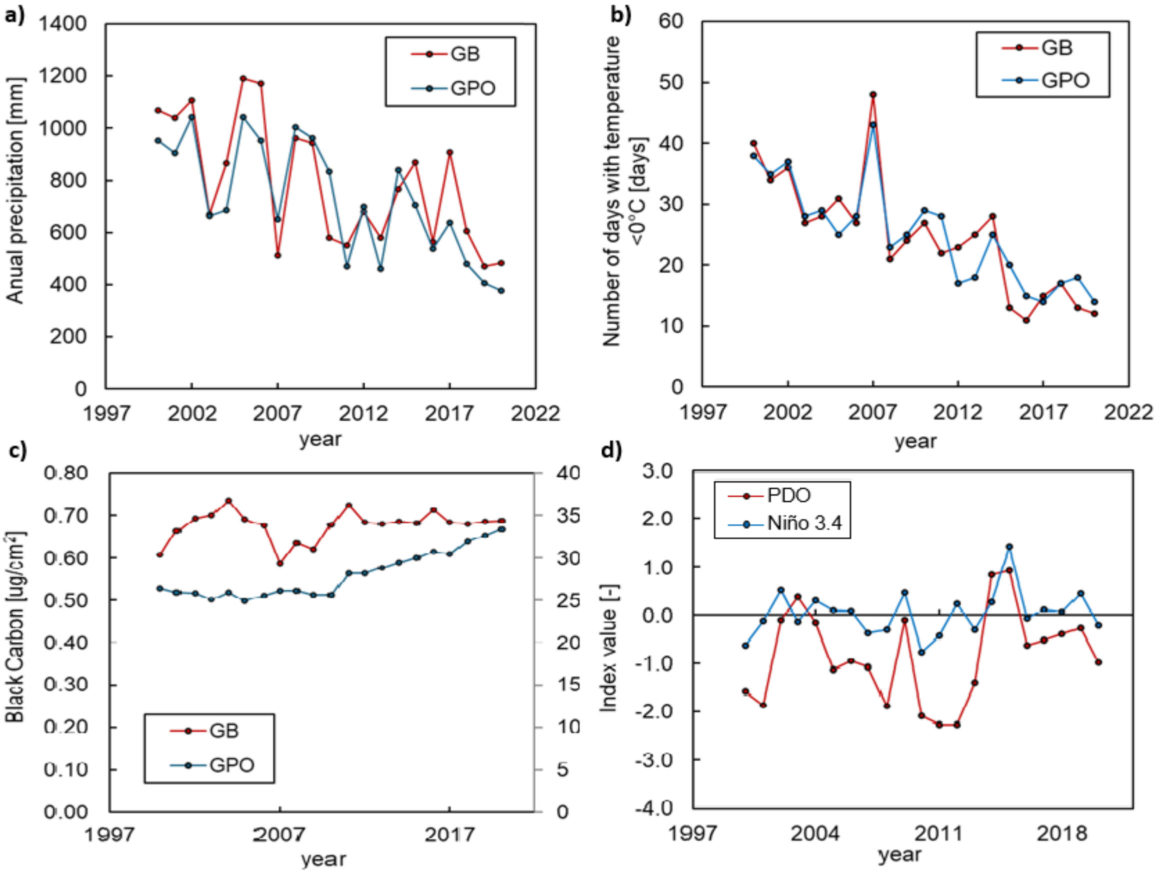

Figure 4. Annual time series of the variables included in the regression model for POG and BG (2000-2020). (a) Annual accumulated precipitation [mm]. (b) DTb [days]. (c) BC concentration on snow for POG and BG, expressed in [μg·cm2]. (d) Macroclimatic indices: Niño 3.4 (May–September average) and PDO (August–October average).

C9 – MAPE calculation error (missing ×100)

I believe there is an error in the calculation of the Mean Absolute Percent Error (MAPE). Based on Figures and Tables, I think the authors did not multiply the MAPE by 100, to make it a percentage. This is especially clear in Figure 9, where a RMSE of 0.75 km2 corresponds to a 4% error. With the area of the glacier being < 4 km2, I think this is wrong. This then affects the results and discussion presenting the model with tiny errors, such as in line 349 ("The MAPE remains below 0.1%").

Response C9:

We thank the reviewer for this careful observation regarding the Mean Absolute Percentage Error (MAPE) reporting. We acknowledge that an editorial inconsistency occurred in the transcription of these values. Specifically, the values presented in the original Figures and Tables (e.g., 0.041 and 0.017) were calculated as absolute decimal fractions (proportions) rather than percentages. Consequently, the statement in line 34-'The MAPE remains below 0.1%'-is incorrect, as the percentage symbol was added without multiplying the base fraction by 100. Based on the reported RMSE of 0.055 km2 for POG and 0.094 km2 for BG, the actual Mean Absolute Percentage Errors for the best-fitting models are 4% and 2%, respectively. These values are physically consistent with the residuals shown in Figures 7c and 7d, which range between +-5%. We have updated the manuscript, including Figure 7, Figure 9, and the corresponding discussion, to ensure all error metrics are consistently reported as percentages (%).

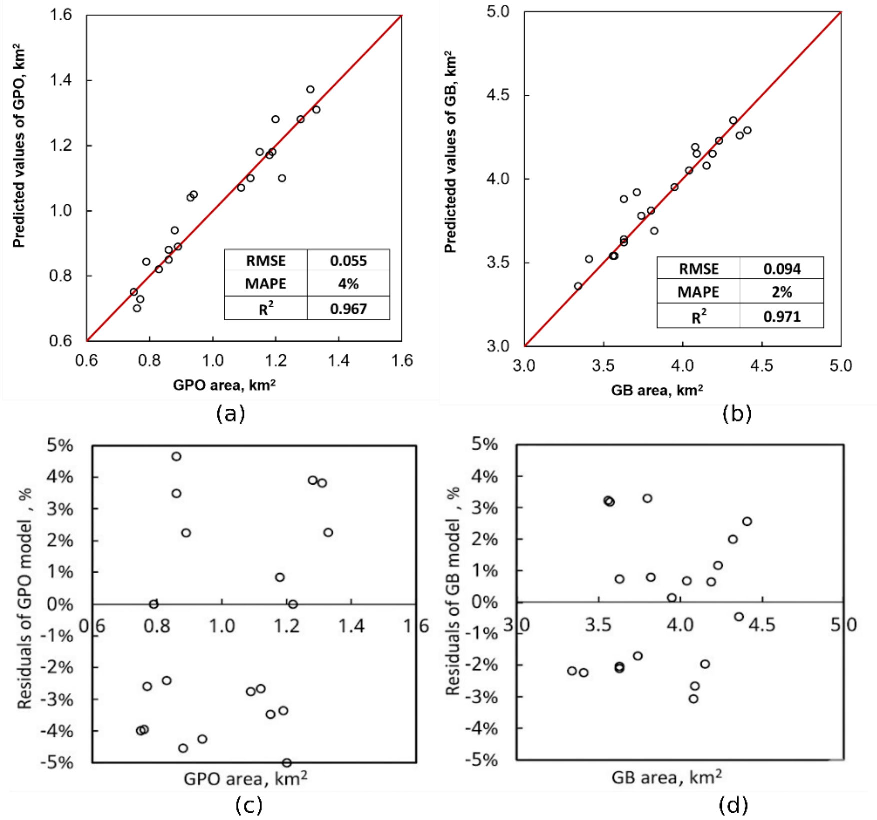

Figure 7. R^2, MAPE, and RMSE values obtained through LOOCV validation applied year by year for (a) POG and (b) BG. In addition, residuals of the regression model adjusted using all effects (TE) are shown for (c) POG and (d) BG.

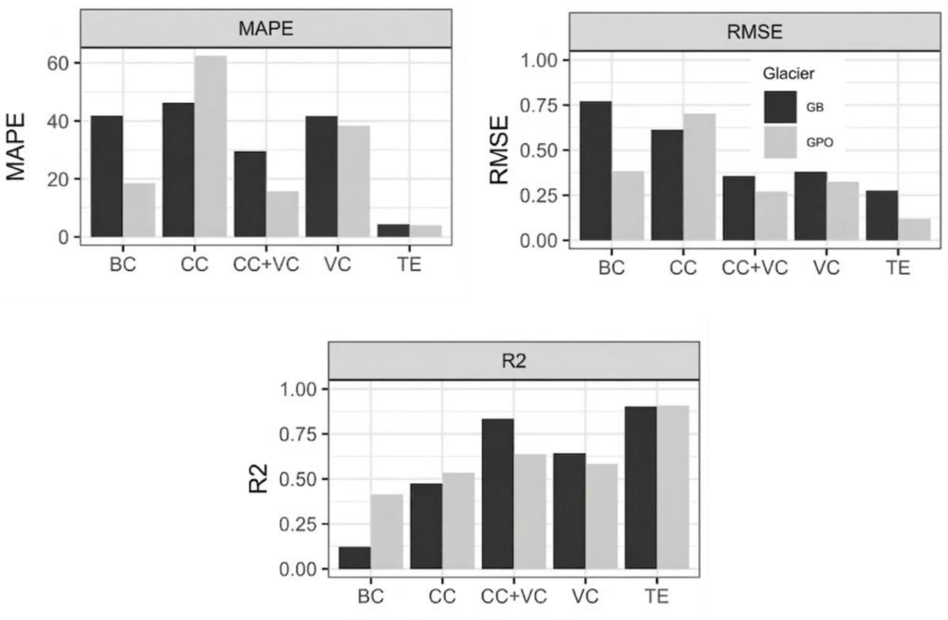

Figure 9. Goodness-of-fit metrics (MAPE, RMSE, and R^2) for regression models fitted using the variables included in each case study (BC, CC, CC+VC, VC, and TE), with results shown separately for BG and POG.

C10 – High R² / plausibility, scale mismatch, overparameterization, transferability, uncertainty in area
It is an incredibly good result that the multilinear regression models explain up to almost 97% (Fig. 7a) of the variability in glacier area. However, it seems difficult to believe that a simple model can explain such a high variability of the glacier area. The temperature and precipitation data are not observed on the glacier but extrapolated from nearby stations. The two climate variables used are large-scale climate indices which I assume have a coarse resolution (not stated in the paper). The Black Carbon variable has a 0.1 degree resolution. All seem too coarse to capture the effect of these variables at the location of the glaciers, given their small sizes. Nevertheless, the authors should clearly discuss this almost perfect predictive performance. Is this performance possible to extrapolate to other glaciers in the region? If so, that would be great and could lead to a follow-up study, or a reframing of this study, to investigate regional variability in glacier area change with a simple model. If not, it could be that the model is overparameterized for these glaciers. Or perhaps the fact that these are relatively small glaciers has an influence on the results? Further detailed discussions on this matter should be provided. Furthermore, the dependent variable (observed glacier area) must have some uncertainty associated to it, but this is also not discussed or presented.

Response C10:
We thank the reviewer for highlighting these important points. We agree that the high explanatory power of the MRLMs requires careful interpretation, particularly given the different spatial scales of the predictor variables. In our framework, annual glacier area represents an integrated response to accumulation and ablation processes over multi-month to multi-year timescales. Therefore, it is expected to reflect low-frequency regional climatic variability more strongly than short-lived local meteorological fluctuations. Within this context, Niño 3.4 and PDO represent large-scale modes of climate variability that influence regional temperature and precipitation, while BC deposition provides a physically meaningful radiative forcing through snow and ice darkening. Although BC is available at relatively coarse spatial resolution (0.1°), it captures the regional structure and intensity of pollution exposure, including the marked contrast between the two glaciers. In addition, because POG and BG are relatively small glaciers, their internal spatial variability is expected to be lower than that of larger glacier systems, which may help explain why extrapolated meteorological variables and regional-scale predictors are able to capture a substantial fraction of their interannual area variability. We emphasize that the regression models are not intended to resolve local microclimatic processes at the glacier scale, but rather to provide an interannual attribution framework for the dominant climatic and pollution-related controls on glacier area variability. Accordingly, the high R² values should be interpreted in that context, rather than as evidence that all local-scale processes are explicitly resolved. Regarding transferability, we acknowledge that these models were calibrated for two specific glaciers and their direct application to other glaciers in the region cannot be assumed. Differences in glacier geometry, elevation range, and local environmental conditions may affect model performance, and further work would be needed to test their broader regional applicability. Finally, we acknowledge that the observed glacier area contains uncertainty associated with Landsat-based delineation, including the influence of seasonal snow, shadow, and classification thresholds. Following previous studies, these uncertainties are typically on the order of 2–5% of the glacier extent (Paul et al., 2013). For POG (minimum area ~0.77 km²) and BG (minimum area ~3.61 km²), this corresponds to uncertainties of approximately 0.02–0.04 km² and 0.07–0.18 km², respectively, which are small relative to the interannual variability captured by the models.

These limitations have been incorporated into the Conclusions section of the revised manuscript (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."

Other comments:

C11 – L53: Cryosphere context (global vs regional)
L53: "changes experienced by the Cryosphere". Does this mean globally? Then a few more references of global studies should be included.

Response C11:
We thank the reviewer for this observation. We have revised the manuscript to specify that the statement refers to global cryosphere changes and have added relevant global-scale references to support this context.

The specific changes to the manuscript are as follows:

***Introduction** (P2–3, L62–64):

"Several studies propose that changes observed in the global cryosphere in recent years are due to climate change (Rivera et al., 2006; Raina, 2009; Migliavacca et al., 2015; Valdés-Pineda et al., 2014; Masiokas et al., 2020; Dussaillant et al., 2019; IPCC, 2021)."

C12 – L73: "glaciological factors" wording
L73: "does not appear to be explained by glaciological factors alone". What are the glaciological factors? Do the authors mean climatological?

Response C12:
We thank the reviewer for pointing this out. The term "glaciological" was imprecise in this context. We have corrected the manuscript to read "climatic factors", which reflects the intended meaning and is consistent with the terminology used throughout the revised manuscript.

The specific changes to the manuscript are as follows:

***Introduction** (P3, L89):

"[...] does not appear to be explained by **climatic factors** alone."

C13 – L80: Percentage clarification
L80: -1.2% AND -0.6% of what? Melt rates or glacier area?

Response C13:
We thank the reviewer for this clarification request. We have revised the manuscript to explicitly state that –1.2% and –0.6% refer to annual glacier area retreat rates over the study period.

The specific changes to the manuscript are as follows:

***Introduction** (P4, L97-98):

"BG, both located in central Chile but with different relative area change rates between 2000 and 2020: –1.2% and –0.6%, respectively."

C14 – L103: Glacier inventory update
L103: Isn't there a more modern inventory than the one in 1979? With strong glacier retreat, I would guess these numbers may have changed.

Response C14:
We thank the reviewer for this valuable suggestion. We reviewed the glacier inventory and updated the manuscript accordingly. The text now references the most recent Public Glacier Inventory (IPG 2022 v2) instead of Marangunic (1979).

The specific changes to the manuscript are as follows:

* **Section 2.1** (P5, L134–139):
"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."

C15 – Table 1: Add glacier area column
Table 1: Would be good to add area of the glacier as a column.

Response C15:
We thank the reviewer for this suggestion. A glacier area column has been added to Table 1 based on the IPG 2022 v2 inventory.

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

C16 – PDD terminology instead of DTbCero
L149-151: Please use Positive Degree Days (PDD), instead of DTbCero. PDD is a more common variable in climate studies, and is even the variable used in the two papers that are cited to justify the use of DTbCero (e.g. Vincent 2002 and Wiltshire 2014).

Response C16:
Thank you very much for this valuable comment. We appreciate the reviewer's concern regarding the interpretation of the temperature variable. In our analysis, the temperature-related predictor was not intended to represent air temperature itself, nor Positive Degree Days (PDD), but rather the number of days per hydrological year with daily mean temperature below 0°C at the mean glacier elevation. We selected this variable because it provides a more direct interpretation of the relationship with glacier area in our framework: fewer days below 0°C imply warmer conditions and, consequently, a greater possibility of glacier melting and area reduction. To avoid confusion, we have revised the manuscript to make this definition explicit and to distinguish this metric clearly from PDD.

The revised text reads as follows (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)."

C17 – Table 2 to Supplement
Table 2: I think this table could move to an appendix or Supplement.

Response C17:
We thank the reviewer for this suggestion. Table 2 has been moved to the Supplementary Material (Table S2), and all references to it in the main text have been updated accordingly.

C18 – L189: "evaluate" wording
L189: The use of the word "evaluate" here is not clear what is referring to.

Response C18:
We thank the reviewer for this comment. The wording at line 189 has been revised for clarity. The sentence now reads:

P10, L268-269:

"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."

C19 – Cross-validation robustness (LOOCV)
L236: Is leaving one year out enough for a cross validation in this case? As the data series are 20 years.

Response C19:
We thank the reviewer for this comment. We used leave-one-out cross-validation (LOOCV) because it is a standard and efficient approach for small-sample regression problems, where preserving as much data as possible for model fitting is critical. In our case, LOOCV allows each annual observation to be evaluated as an independent holdout while the model is trained for the remaining years, thereby providing a robust assessment of prediction consistency across the full record. Leaving out larger subsets of data (e.g., blocks of years) could compromise model parameterization given the limited sample size. In the revised manuscript, we clarify that LOOCV is used as a first-level robustness check, complemented with additional validation analyses (e.g., temporal split and regime-based validation separating pre- and post-Megadrought periods) to better assess model stability under different hydroclimatic conditions.

The specific changes to the manuscript are as follows:

P13, L336-337: "This approach is particularly suitable for small-sample regression problems, as it allows each observation to be used as an independent validation case while preserving the maximum number of data points for model calibration."

C20 – Figure 3 formatting
Figure 3: Remove [yyyy] from the labels. Regarding the colourbar of years: while the current colour scale is useful to identify single years, I think here it would be more useful or impactful to have a continuous colour scale that shows how the glacier is retreating through time.

Response C20:
We thank the reviewer for this suggestion. The labels in Figure 3 have been revised to remove the "[yyyy]" notation as recommended.

Regarding the colorbar issue, we appreciate the reviewer's suggestion to use a continuous color scale to emphasize glacier retreat through time. However, we consider it preferable to retain the year-by-year color differentiation because glacier area loss has not occurred uniformly over the study period. In several sectors, retreat has been more pronounced during specific years rather than as a smooth, gradual progression. For example, in POG, localized depletion is evident in 2006, whereas the spatial patterns observed in 2019 and 2020 differ. For this reason, preserving discrete annual colors allows the temporal variability and the non-uniform character of glacier retreat to be represented more clearly.

C21 – Table 5: PDD sign & unit formatting
Table 5: Temperature should be PDD and not temperature, and the value should therefore be negative. Otherwise the positive correlation indicates that more temperature leads to larger glacier area. Please also make cm2 and Km2 a superscript for 2.

Response C21:
Thank you very much for this valuable comment. We appreciate the reviewer's concern regarding the interpretation of the temperature variable. In our analysis, the temperature-related predictor was not intended to represent air temperature itself, nor Positive Degree Days (PDD), but rather the number of days per hydrological year with daily mean temperature below 0°C at the mean glacier elevation (DTb). We selected this variable because it provides a more direct interpretation of the relationship with glacier area in our framework: fewer days below 0°C imply warmer conditions and, consequently, a greater possibility of glacier melting and area reduction. Under this definition, the observed sign of the correlation is consistent with the physical interpretation of the variable.
To avoid confusion, we have revised the manuscript to make this definition explicit and to clearly distinguish this metric from PDD. In addition, we have corrected the notation of units throughout the manuscript by formatting cm^2 and km^2 with superscript exponents.

A similar response was provided in comment C16 (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)."

C22 – Figure 9: Combine R^2/RMSE presentation
Figure 9: Are the R2 values or RMSE for these models only presented in Figure 9? If so, I suggest combining these figures.

Response C22:
We thank the reviewer for this suggestion. If we understand the reviewer correctly, the comment refers to the possibility of merging figures that present model performance metrics such as R^2 and RMSE. However, Figure 9 is not redundant with other figures in the manuscript.

Figure 7 presents the performance metrics of the final integrated model (TE), whereas Figure 9 shows the results of a sensitivity analysis based on regression models fitted using different subsets of predictors (BC, CC, VC, CC+VC, and TE). This allows the individual and combined contributions of each driver to be evaluated independently.

Therefore, Figure 9 provides complementary information rather than duplicating results already presented, and has been retained as an independent figure. In addition, following the reviewer's suggestion, KGE has been removed and the results have been reordered to improve clarity. The new presentation order is: BC, CC, CC+VC, VC, and TE.

C23 – Table 6-year correction
Table 6: Should 2004 be 2007 in the middle bottom of the table?

Response C23:
We thank the reviewer for catching this error. The year has been corrected from 2004 to 2007 in Table 5 of the revised manuscript.

C24 – Standardized vs unstandardized models
L355: The difference between standardized and unstandardized is not entirely clear to the reader, making the difference between Figure 6 and 7 not clear either. What is the difference between predicted and simulated glacier area?

Response C24:
We thank the reviewer for this comment. To clarify this point, we have improved the explanation in the revised manuscript (P21, L484–489):

"It is worth noting the distinction between Figures 6 and 7: Figure 6 presents the non-standardized model fit — glacier area simulated by the MRLMs against observed values — reflecting in-sample performance using the full dataset. Figure 7, in contrast, shows the predicted LOOCV values, where each annual estimate is obtained by a model trained without that particular year. This distinction is important when interpreting model skill: in-sample fit (Figure 6) reflects how well the model reproduces the calibration data, while LOOCV (Figure 7) provides a more conservative and realistic assessment of predictive performance."

C25 – "Equivalent decrease" ambiguity
L373: What is an "equivalent decrease in winter temperatures" compared to an increase in BC? As these variables are difficult to compare, equivalent here is ambiguous.

Response C25:
We thank the reviewer for pointing out this ambiguity. We agree that the original phrasing was unclear. The sentence has been revised to clarify that the comparison is based on standardized coefficients (i.e., one standard deviation changes), which provide a dimensionless measure of relative sensitivity within the model. The revised text explicitly states that this comparison is intended only to rank the relative influence of the predictors and does not imply a physically equivalent perturbation between BC and DTb.

To clarify this point, we have improved the explanation at P22, L511-516:

"Furthermore, the sensitivity analysis based on the standardized model suggests that a one standard deviation increase in BC concentration is associated with a larger change in glacier area than a one standard deviation change in DTb. This comparison is made in standardized units and is intended only to rank the relative sensitivities of the predictors within the model, rather than to imply a physically equivalent perturbation between variables. Although the model was not designed for predictive purposes, these results help identify which factors may carry greater relative weight in future glacier evolution under environmental changes, reinforcing the need to mitigate local pollution sources."

C26 – KGE metric appropriateness
Figure 9: Does KGE make sense for this evaluation?

Response C26:

We thank the reviewer for the observation regarding the suitability of the Kling-Gupta Efficiency (KGE) for this evaluation. We agree that while KGE is a robust metric for hydrological modeling, it is not the most appropriate tool for assessing a multivariable linear regression model. Consequently, we have updated Figure 9 by removing the KGE panel. The revised figure now focuses on traditional regression metrics, including the Coefficient of Determination (R2), Root Mean Square Error (RMSE), and Mean Absolute Percentage Error (MAPE).

C27 – Figure 10 prominence
Figure 10: I think this is an interesting impactful figure and should be a more focal point of the study.

Response C27:
We thank the reviewer for this valuable comment. We agree that Figure 10 is one of the most integrative and impactful results of the study, as it synthesizes the temporal shift in the relative importance of climatic drivers and BC in explaining glacier area retreat before and after the onset of the central Chile Megadrought. In the revised manuscript, we have expanded the discussion of Figure 10 to give it greater prominence and to better emphasize its contribution to the main findings of the study. In particular, we clarify that after 2010 the relative

contribution of climatic forcing increased in both glaciers, while the BC contribution remained glacier-dependent and continued to be substantial in POG.

See revised text at P27-28, L603-632:

"Further evidence of a change in glacier retreat dynamics emerges from the period-based evaluation of model behavior before and after 2010 (Figure 10). The breakpoint detected in the residuals (RMSE) of the CC+CV models for both POG and BG suggests that the onset of the central Chile Megadrought marked a shift in the variables governing glacier area loss. This shift is consistent with the persistently drier and warmer conditions reported for central Chile (Garreaud et al., 2020), which altered the hydroclimatic setting under which both glaciers evolved. The RMSE comparison between periods (Figure 10a) provides additional insight into this transition. In BG, RMSE decreased after 2010, indicating that climatic predictors increasingly well explained glacier retreat during the Megadrought. This result supports the interpretation that, for BG, glacier area loss became increasingly controlled by regional climatic forcing during prolonged drought. In contrast, POG exhibited a higher RMSE after 2010, suggesting that its response became more complex and less fully captured by the fitted relationships. This behavior reflects the combined influence of intensified climatic forcing and the continued presence of high BC deposition.

Figure 10b shows that the relative contribution of climatic drivers increased in both glaciers after 2010. In POG, the share of retreat attributed to climatic effects (CC+CV) rose from 47% during 2000-2009 to 61% during 2010-2020, while the contribution of BC decreased from 53% to 39%. In BG, where BC exposure is much lower, climatic effects already dominated before 2010 (94%) and became even more decisive after 2010 (97%), whereas the BC contribution remained marginal, decreasing from 6% to 3%. These results indicate that the Megadrought strengthened the role of hydroclimatic forcing in glacier retreat across both study sites, although the magnitude of the anthropogenic pollution signal remained glacier-dependent.

For POG, the reduction in the relative contribution of BC after 2010 should not be interpreted as evidence that pollution ceased to be important. Rather, it indicates that under the more severe climatic conditions of the Megadrought, the explanatory weight of temperature and precipitation forcing increased more rapidly than that of BC. Thus, BC remained a relevant driver of retreat in POG, but its relative importance diminished because climatic stress intensified during the second period. In BG, by contrast, the low contribution of BC throughout the record confirms that glacier retreat has been governed primarily by climatic forcing, with only a minor anthropogenic pollution effect.

These findings align with Farias-Barahona et al. (2020), who reported that shifts in precipitation and temperature patterns during the Megadrought were correlated with accelerated glacier retreat in the central-southern Andes. Our results similarly indicate that, after 2010, climatic effects emerged as the primary driver of glacier retreat in the study region, even for glaciers with substantial exposure to pollutants, such as POG. Overall, these findings reinforce the conclusion that, since the onset of the central Chile Megadrought, climatic conditions have become the dominant driver of glacier retreat in central Chile, even in glaciers where black carbon pollution continues to exert a significant influence."

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