Review of "Hydrological response of Andean catchments to recent glacier mass loss" by Caro et al.

Dear reviewer, in this document we present our replies (in purple) together with the changes we made to answer your comments. For each of your comments (in *Italics-black*), the original draft text is written in red color, whereas our proposed changes to the original draft text and comments are in blue color.

This study examines the hydrological response of glaciers in 786 catchments across the Andes in the period 2000-2019 by integrating meteorological data and OGGM. Similar to the comment of the Referee #1, I wonder what is the research gap / justification / novelty of this study considering the availability of observations of glacier mass balance across the Andes (especially the study published by Dussaillant et al. (2019) in NATGEO for the 2000 – 2018 period)? Talking about the hydrological response and referring to Huss and Hock (2018) NCC paper, I would expect bit more elaboration of the peak water timing in different zones of the Andes. Or is the main goal the calibration and performance evaluation of the OGGM model? If so, the study should be re-framed and re-structured in my opinion.

Reply: Dear reviewer, we sincerely value your feedback and have implemented proposed changes to the article under review. Our primary goal was to analyze the recent changes in the Andean glacier runoff while refining the parameter calibration for melting in OGGM. Additionally, we utilized this calibrated and rigorously evaluated model for a subsequent article, simulating glacier runoff projections across the Andes throughout the 21st century with particular attention to the peak water. We anticipate submitting this second article within the first month of 2024.

As per your suggestions, we have meticulously edited the current article, with a concentrated effort on improving the abstract, introduction, and conclusion sections.

L19-20: what is the meaning of these %?

Original text:

"Our results show that the glacier volume (-8.3%) and surface 20 area (-2.2%) are reduced in 93% of the catchments between the periods 2000-2009 and 2010-2019."

Edited text:

"Our results at the Andes scale show that the glacier volume and surface area were reduced by 8.3% and 2.2%, respectively, between the periods 2000-2009 and 2010-2019."

L36: but the shrinkage did not start in late 1970s, please reformulate

Original text:

“ They have been affected by a continuous shrinkage since the late 1970s, which has intensified during the last two decades (Rabatel et al., 2013; Dussaillant et al., 2019; Masiokas et al., 2020).”

Edited text:

“Continuous glacier shrinkage has been detected since the late 1970s, with intensification observed over the past two decades (Rabatel et al., 2013; Dussaillant et al., 2019; Masiokas et al., 2020).”

L73-75: please consider deleting

Original text:

“Section 2 presents the data and methods. In Section 3, we describe the glacier changes and hydrological responses at the glaciological zone and catchment scales across the Andes. In Section 4, we discuss our results and the main steps forward compared to previous research.”

Reply: We appreciate your comment; however, this paragraph introduces the main sections to the reader.

L88: surprisingly, there are no meteorological stations included for 11°N to 9°S where there are different climatological conditions compared to the rest of the study region; please comment on how this gap can impact your analysis especially in the IT zone

Original text:

“The mean monthly air temperature measurements were taken from 35 off-glacier and on-glacier meteorological stations, the latter of which are rare. The location and main properties of the meteorological stations are shown in Supplementary Table S1.”

Edited text:

“The mean monthly air temperature measurements were taken from 35 off-glacier and on-glacier meteorological stations, the latter of which are rare, located between 9 and 51°S. However, it's important to note that long-term measurements were not available northward of 9°S (the Inner tropics). To address this, data from stations located in the Outer tropics were used as a reference for temperature corrections in this zone, which could affect the performance in the estimation of calibrated parameters such as melt factor. The location and main properties of the meteorological stations are shown in Supplementary Table S1.”

L137: 12 of these 15 glaciers are located between 29°S and 39°S while only two glaciers are considered for 11°N to 29°S; please comment on how this gap can impact your analysis

Original text:

“In situ measurements of the glacier surface mass balance available for all glaciological regions (Tropical Andes, Dry Andes and Wet Andes) were collected at the hydrological year scale (dates vary according to the latitude). The location and main characteristics of the 18 monitored glaciers are shown in Supplementary Table S4.”

Edited text:

“In situ measurements of the glacier surface mass balance are available between 5°N and 55°S (across all Andean regions) at the hydrological year scale (dates vary according to the latitude). However, the Tropical Andes is represented by just two glaciers (Conejeras and Zongo glaciers), producing an underrepresentation in the evaluation of the simulated mass balance in this region. The location and main characteristics of the 18 monitored glaciers are shown in Supplementary Table S4.”

L133-134: you may consider referring to your Fig. 2 already here

Original text:

“Hugonnet et al.’s (2021) product was quantified for each glacier using the OGGM toolbox.”

Edited text:

“Hugonnet et al. (2021) product was quantified for each glacier using the OGGM toolbox (Figure 2d).”

L147: median might be more interesting than mean

Original text:

“2006). Then, we considered catchments with a glacierized surface area >= 0.01% (max = 62%, mean = 5%).”

Edited text:

“2006). Then, we considered catchments with a glacierized surface area >= 0.01% (max = 62%, mean = 5%, median = 2%).”

L158: please list these studies and summarize the main conclusions

Original text:

“We selected the La Paz (Soruco et al., 2015), Maipo (Ayala et al., 2020) and Baker (Dussaillant et al., 2012) catchments located in glaciological regions with different climatic and morphometric characteristics (Caro et al., 2021). In these catchments, previous hydro-glaciological studies have quantified the impact of glacier changes and its hydrological contribution.”

Reply: We edited this paragraph to avoid any confusion.

Edited text:

“We selected the La Paz, Maipo and Baker catchments located in glaciological regions with different climatic and morphometric characteristics (Caro et al., 2021). In the La Paz and Maipo catchments, previous hydro-glaciological studies have quantified the impact of glacier changes and their hydrological contribution. However, these studies often overlook relevant processes such as variations in precipitation, temperature corrections, and the simulation of glacier dynamics. On the other hand, in the Baker catchment, there are currently no estimations of glacier runoff contributions. These three catchments allow us to make comparisons with our regional simulations at the Andes scale using consistent data (e.g., corrected climate datasets and glacier outlines) and methods (e.g., simulating mass balance, dynamics, and glacier runoff) to verify simulation results of the same magnitude, update previous results, and provide new glacier runoff estimates. For example, it is necessary to understand what occurs during the prolonged dry period in Central Chile and Argentina.”

L173: glacier entity vs. glacier?

Original text : “using calibrated parameter values for each glacier entity individually.”

Edited text: “using calibrated parameter values for each glacier.”

L202: what are the basic properties of the NASADEM?

Original text : “glacier outlines from RGI v6.0 (RGI Consortium, 2017) and surface topography from NASADEM (Crippen et al., 2016).”

Edited text: "glacier outlines were obtained from RGI v6.0 (RGI Consortium, 2017), and surface topography data were sourced from NASADEM (Crippen et al., 2016). NASADEM has a spatial resolution of 1 arcsecond (~30m), and the data were acquired in February 2000 (NASA JPL, 2020)."

Fig. 1: please check the completeness of your workflow (e.g. the 3 catchments studies in detail); please also consider linking individual components of your workflow to the sections of the manuscript;

Original text : “Workflow per glacier simulation using OGGM between 2000 and 2019.”

Reply: In Figure 1, we present the workflow of simulation performed in each glacier. We will cite this figure in each step presented in the workflow.

Edited text: “Workflow per simulated glacier using OGGM between 2000 and 2019.”

L223: to what elevation are these numbers referring to?

Original text:

“The various glaciological regions show significant climatic differences, with contrasting extreme values between the Tropical Andes and Wet Andes in terms of mean annual precipitation (939 ± 261 mm yr-1 and 3751 ± 1860 mm yr-1, respectively) and mean annual temperature between the Dry Andes and Tropical Andes (-3.7 ± 1.4°C and 1.3 ± 0.8°C, respectively).”

Reply: All climate values are related to the mean elevation of glaciers. Considering your question, we edited the section 2.1.3 from L128 to 129

Original text :

“ The glacier extent in the RGI v6.0 is representative of the early 2000s.”

Edited text:

“The glacier extent in the RGI v6.0 is representative of the early 2000s. The analysis by catchment and glaciological region is related to the locations and elevation of these glaciers.”

L245: please consider displaying a metric quantifying the fit between observed and corrected data in Tab. S2

Reply: Thank you for your observation. We incorporated the bias between the corrected temperature of TerraClimate and the observations at each meteorological station. These values are equal to the bias presented in Figure S2.

Fig. 2: please consider incorporating also relative changes in this figure

Reply: This figure contains several maps and graphs. These show the absolute values, allowing you to directly know the loss rates of volume or area per year.

Fig. 3: maybe a boxplot everyone can read without additional explanation could work here?

Reply: We appreciate your comments and agree, however, the boxplot does not show the average or mode.

L318-320: the comparison of absolute numbers (m3/s) doesn’t tell a lot and the comparison is meaningless since these regions don’t have comparable glacier coverage; please check here and in other parts of the manuscript that the number you refer to can be compared across the zones / regions

Original text :

“In addition, the mean annual rainfall on glaciers across the Andes is 387 m3/s for the period 2000-2019. The Wet Andes has the largest amount of annual rainfall (372.7 m3/s), followed by the Tropical Andes (10.5 m3/s) and Dry Andes (4.2 m3 320 /s) with the lowest contribution of rainfall.”

Reply: One of the key messages we aim to convey here is the recognition that certain regions receive more water from rainfall on glacier surfaces than others. Specifically concerning rain on glacier surfaces, as of the current article's writing, there is no definitive understanding of the proportion of rainfall occurring during the key seasons in the Tropical, Dry, or Wet Andes. Limited estimates have been made for a handful of glaciers and a few catchments.

L333: since there is no catchment studied north from La Paz, I wonder why not to use Peruvian Río Santa catchment for which similar data are available and you refer to it in introduction?

Reply: Indeed, this could have been an option, but we do not want to multiply the examples and we chose 3 (one in each of the “main” climatic zones). La Paz was preferred as the glaciers could be relevant to 2,700,000 people in La Paz and El Alto cities.

L365-377: this part is more about the climate (changes) and doesn’t correspond with the section title; please consider moving

Reply: This article, though comprehensive, does not primarily aim to quantify variations in climate. Nevertheless, recognizing climate as the principal driver of glacier changes, we consider pertinent to incorporate this aspect. To underscore the significance of climate in influencing glacier dynamics, we believe it is fitting to provide a brief description on the subject. We would appreciate your consideration of these lines as a brief introduction, as consigning these results to supplementary materials might not fully convey their significance.

Tab. 3: please show and compare simulated and observed values

Reply: This table presents the simulation results on the scale of the three catchments. The comparison between simulations and observations was conducted at specific locations, and the results are presented in tables and figures in the supplementary materials.

L418-419: please delete

Original text:

“In this section we will discuss the relevance of the results obtained at the regional- to glacier-scale across the Andes. We will also discuss the main methodological advantages and limitations of the simulations.”

Reply: Thank you. We will delete it.

L453: please make sure that these studies appear in the list of references

Original text:

“In the Dry Andes, this correlation was high with precipitation (r = 0.8 ± 0.1) and in the Wet Andes, temperature was correlated with mass 460 balance (r = -0.7 ± 0.1) as previously observed by Caro et al. (2021).”

Reply: We included this reference.

L459-460: what is the p-value of these correlations?

Reply: We have edited lines 459-460 to include p-values in the correlations.

Edited text:

“In the Dry Andes, this correlation was high with precipitation (r = 0.8 ± 0.1, p-value < 0.05) and in the Wet Andes, temperature was correlated with mass 460 balance (r = -0.7 ± 0.1, p-value < 0.05) as previously observed by Caro et al. (2021).”

L491-495: the main findings of these studies should be summarized in the Introduction and should help you to highlight research gap you are trying to bridge with your study (see my general comment)

Original text:

“Several reconstructions of the glacier surface mass balance have been performed across the Andes (9-52°S) using a temperature index with higher mean values in the Tropical Andes (0.3-0.5 mm h-1 °C-1), than in the Dry Andes (0.3-0.4 mm h-1 °C-1) and Wet Andes (0.1-0.5 mm h-1 °C-1) (e.g., Fukami & Naruse, 1987; Koisumi and Naruse,1992; Stuefer et al., 1999, 2007; Takeuchi et al., 1995; Rivera, 2004; Sicart et al., 2008; Condom et al., 2011; Caro, 2014; Huss and Hock, 2015; Bravo et al., 2017).”

Reply: Thank you for your feedback. We have relocated this paragraph to the next paragraph in the introduction.

Original text:

“Nowadays, the availability of global glaciological products such as glacier surface elevation differences and glacier volume estimation (Farinotti et al., 2019; Hugonnet et al., 2021; Millan et al., 2022) allows for large-scale glacio-hydrological simulations with the possibility to accurately calibrate and validate numerical models at the catchment scale. In addition, models such as the Open Global Glacier Model (OGGM, Maussion et al., 2019) have been implemented to simulate the glacier mass balance and glacier dynamics at a global scale. Therefore, OGGM and the glaciological global dataset, in combination with in situ meteorological and glaciological measurements, can be used to precisely quantify the glacier retreat and its hydrological responses at the catchment scale across the Andes, while taking the related uncertainties into account.”

Edited text:

“Nowadays, the availability of global glaciological products such as glacier surface elevation differences and glacier volume estimation (Farinotti et al., 2019; Hugonnet et al., 2021; Millan et al., 2022) allows for large-scale glacio-hydrological simulations with the possibility to accurately calibrate and validate numerical models at the catchment scale. In addition, models such as the Open Global Glacier Model (OGGM, Maussion et al., 2019) have been implemented to simulate the glacier mass balance and glacier dynamics at a global scale. Therefore, OGGM and the glaciological global dataset, in combination with in situ meteorological and glaciological measurements, can be used to precisely quantify the glacier retreat and its hydrological responses at the catchment scale across the Andes, while taking the related uncertainties into account. The incorporation of in situ measurements could provide a more realistic estimation of glacier mass balance in the Andes. Currently, reconstructions of glacier surface mass balance in select locations across the Andes (9-52°S) rely on a temperature index. Notably, higher mean values are identified in the Tropical Andes (0.3-0.5 mm h-1 °C-1), compared to the Dry Andes (0.3-0.4 mm h-1 °C-1) and Wet Andes (0.1-0.5 mm h-1 °C-1) (e.g., Fukami & Naruse, 1987; Koisumi and Naruse,1992; Stuefer et al., 1999, 2007; Takeuchi et al., 1995; Rivera, 2004; Sicart et al., 2008; Condom et al., 2011; Caro, 2014; Huss and Hock, 2015; Bravo et al., 2017)."

L497-504: why not to present these findings in results section?

Original text:

"Taking these differences into account, we found a regional pattern for the melt factor using the same methodology at a monthly time step. The mean calibrated melt factor values decrease from the Tropical Andes toward the Wet Andes (TA = 0.5 ± 0.3 mm h-1 °C-1, DA = 0.6 ± 0.2 mm h-1°C-1, WA = 0.2 ± 0.1 mm h-1 °C-1) (see Table 1 and Figure 3). This geographical distribution aligns with our evaluation of the TerraClimate dataset. The lowest mean temperatures estimated in the Dry Andes imply higher factor values to reach the calibrated mass loss in the few months in which the temperatures exceed 0°C. The opposite can be observed in the Wet Andes, where low factor values are associated with a greater number of months with temperatures exceeding 0°C."

Reply: Thank you for your comment. We have relocated part of these lines in results as

Original text:

"When estimating the mass balance, it is interesting to check the calibrated melt factors (Mf) of the temperature index model in order to evaluate its possible regionalization, i.e., to evaluate the spatial coherence (see Figure 3). We obtain very similar values in contiguous zones,"

Edited text:

"When estimating the mass balance, it is interesting to check the calibrated melt factors (Mf) of the temperature index model in order to evaluate its possible regionalization, i.e., to evaluate the spatial coherence (see Table 1 and Figure 3). The mean calibrated melt factor values decrease from the Tropical Andes toward the Wet Andes (TA = 0.5 ± 0.3 mm h-1 °C-1, DA = 0.6 ± 0.2 mm h-1°C-1, WA = 0.2 ± 0.1 mm h-1 °C-1). The lowest mean temperatures estimated in the Dry Andes imply higher factor values to reach the calibrated mass loss in the few months in which the temperatures exceed 0°C. The opposite can be observed in the Wet Andes, where low factor values are associated with a greater number of months with temperatures exceeding 0°C. We obtain very similar values in contiguous zones,"

We edited L497-504 as:

"Taking these differences into account, we found a regional pattern for the melt factor using the same methodology at a monthly time step between the Tropical Andes toward the Wet Andes (see Table 1 and Figure 3). This geographical distribution aligns with our evaluation of the TerraClimate dataset."

L512-524: please consider moving to methodology

Original text:

"These differences found in the corrected TerraClimate limit the capacity of the ice/snow melting module to accurately simulate the months in which melting can occur. To account for this, the values of the thresholds used for the melting onset and for the solid/liquid precipitation phase have been adjusted. On the contrary, in the Dry Andes and Wet Andes, the corrected TerraClimate temperatures are closer to the in situ observations (mean bias = 0.2°C) and present a reliable monthly distribution. This results in model parameter values that are in better agreement with the values used in other studies. Other limitations come from RGI v6.0 because some glaciers are considered as only one larger glacier. For example, in the Dry Andes (id = 6090889690) two large glaciers, the Olivares Gamma and the Juncal Sur, form one (even larger) glacier. These glaciers could underestimate the simulated change in glacier area, limiting the performance of the volume module which depends on the glacier geometry and bedrock shape.

Furthermore, we applied different precipitation factor values in the Tropical Andes (1), Dry Andes (1.9 to 4) and Wet Andes (2.3 to 4), in order to increase the annual amplitude of the simulated mass balance. These values are in agreement with former studies, for example, similar values were used in the Dry Andes (Masiokas et al., 2016; Burger et al., 2019; Farías-Barahona et al., 2020). Values that are too high could lead to an overestimation of precipitation on some glaciers."

Reply: We appreciate the suggestion. Nonetheless, we believe that these values offer the essential context for the paragraph. This section aims to emphasize the importance of discussing precipitation values derived from climatic datasets, considering the different Andean glaciological zones.

L534-537: into the OGGM description section?

Original text:

"With regards to the structural limitations of the model, it would be relevant to distinguish between ice and snow melt when simulating the glacier melt with two melt factors. In addition, the sublimation on the glacier surface is very relevant in the Tropical Andes and DA1 (Rabatel et al., 2011; MacDonnell et al., 2013). However, the OGGM model does not incorporate these processes in glacier runoff and mass balance simulations."

Edited text:

"With regards to the structural limitations of the model, it would be relevant to distinguish between ice and snow melt when simulating the glacier melt with two melt factors. In addition, the sublimation on the glacier surface is very relevant in some glaciers located in the Tropical Andes and DA1 (Rabatel et al., 2011; MacDonnell et al., 2013). However, the OGGM model does not incorporate these processes in glacier runoff and mass balance simulations."

Reply: While we have included certain values within the methodology section, we believe that these values and their detailed descriptions are crucial for facilitating a comprehensive understanding of their significance in the simulated results. Because of that, we called this subsection "Simulation limitations".

L547: these highlighted points are neither novel nor surprising considering available in situ and remote sensing-based observations of glacier mass balance across the Andes

Original text:

"93% of the studied glacierized catchments show a decrease in glacier area between the periods 2000-2009 and 2010-2019,"

Reply: Considering all your comments we have reformulated the section Conclusion as

Original text:

"In this study, we present a detailed quantification of the glacio-hydrological evolution across the Andes (11°N-55°S) over the period 2000-2019 using OGGM. Our simulations rely on a glacier-by-glacier calibration of the changes in glacier volume. Simulations cover 36% (11,282 km^2) of their glacierized surface area across the Andes where 50% of the area corresponds to the Patagonian icefields and Cordillera Darwin that were not simulated due to specific processes such as calving and which are not accounted for in the version of glaciological model used here. In addition, we used corrected climate forcing and evaluated our simulation results at both the glacier and catchment scale using in situ observations, which are uncommon practices in regional simulations. From our results we can highlight the following:

- 93% of the studied glacierized catchments show a decrease in glacier area between the periods 2000-2009 and 2010-2019, displaying a high coherence with previous reports based, in particular, on glaciers in the Tropical Andes (Rabatel et al., 2012; Seehaus et al., 2020), Wet Andes (Rabassa 2010; Ruiz et al., 2017) and Dry Andes (Rabatel et al., 2011; Malmros et al., 2016; Farías-Barahona et at., 2020).
- The glacier runoff response to this glacier reduction has the largest percentage increase in the Tropical Andes and Dry Andes. Despite this, the largest percentage increase of glacier runoff (> 62%) estimated in

the Inner Tropic and Dry Andes 1 zones corresponds to the lowest absolute glacier runoff amounts across the Andes.

- The three selected catchments, located in contrasted climatic zones, are used to evaluate the simulations. They display consistent results with previous studies and in situ observations. The larger glacier contributions to the catchment water flows are quantified for the Baker (43%) and Maipo (36%) catchments during the summer season (January-March). On the contrary, the larger glacier contribution to the La Paz catchment (45%) was estimated during the transition season (September to November).

Lastly, our results help to improve knowledge about the hydrological responses of glaciers in a large part of the Andes through the correction of climate data, the use of the same input data and the same simulation processes as well as a strong glacier calibration applied to the glaciers. The implementation of this calibrated and evaluated model in the historical period is a prerequisite for simulating the future evolution of the Andean glaciers."

Edited text:

"In this study, we present a detailed quantification of the glacio-hydrological evolution across the Andes (11°N-55°S) over the period 2000-2019 using OGGM. Our simulations rely on a glacier-by-glacier calibration of the changes in glacier volume. Simulations cover 36% (11,282 km^2) of the glacierized surface area across the Andes where 50% of the total area corresponds to the Patagonian icefields and Cordillera Darwin that were not simulated due to specific processes such as calving and which are not accounted for in the version of glaciological model used here. The simulations were performed for the first time employing the same methodological approach, and a corrected climate forcing and parameter calibration at the glaciological zone scale throughout the Andes. Evaluation of our simulation outputs spanned both glacier-specific and catchment-scale assessments, integrating in situ observations-an unconventional approach within regional simulations. From our results we can conclude the following:

- In relation to glacier runoff composed by glacier melt and rainfall on glaciers at the catchment scale. The largest percentage of studied Andean catchments encompassing 84% of total (661 catchments) presented an increase by 12% of the mean annual glacier melt (ice and snowmelt) between the periods 2000-2009 and 2010-2019. These catchments present glaciers with higher elevation, larger size and also a lower mean annual temperature and higher mean annual precipitation compared with glaciers located in catchments that showed a decrease in glacier melt in the same period which comprise just 12% of studied catchments. Additionally, the mean annual rainfall on glaciers between the periods 2000-2009 and 2010-2019 exhibited a reduction of -2%.
- Special attention must be directed towards the Tropical and Dry Andes regions, as they exhibited the most significant percentage increase in glacier runoff between the periods 2000-2009 and 2010-2019, reaching up to 40% due to glacier melt, and 3% due to increased rainfall on glaciers over the past decade. Specifically, the Dry Andes 1 (DA1) showcased a remarkable 62% increase, while the Inner Tropic zone exhibited a 73% rise in glacier runoff in the same periods. Notably, these particular glaciological zones displayed the smallest absolute quantities of glacier runoff across the entire Andes region. The DA1 zone emerges as the most vulnerable glaciological zone to glacier runoff water scarcity in the Andes.

- Three catchments, located in contrasted climatic and morphometric zones (glaciological zones) are used to evaluate the simulations. Our results show consistency with previous studies and in situ observations. The larger glacier runoff contributions to the catchment water flows during the period 2000-2019 are quantified for the Baker (43%) and Maipo (36%) catchments during the summer season (January-March). On the other hand, the larger glacier runoff contribution to the La Paz catchment (45%) was estimated during the transition season (September to November).
- The correction of temperature and precipitation data, coupled with parameter calibration conducted at the glaciological zone scale, notably enhanced the accuracy of mass balance simulations and glacier runoff estimations. Highlighting the estimation of annual temperature lapse rates and variability in glacier mass balance through measurements to correct climate data across distinct glaciological zones. This improvement not only ensures better alignment with local observations but also establishes a more robust tool for forecasting future glacier runoff patterns in the Andes. This method stands apart from global models by specifically addressing the local climate and parameter values inherent to the Andean region.

Lastly, our results help to improve knowledge about the hydrological responses of glaciers across the Andes through the correction of inputs, calibration by glaciers and validation of our simulations considering different glaciological zones. The implementation of this model during the historical period is a prerequisite for simulating the future evolution of the Andean glaciers based on our local knowledge."

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To sum up, I'm convinced this study would benefit from (rather major) revisions regarding its structure, justification and framing in the context of the existing studies.

Reply: In response to the reviewer's suggestions, we propose to modify the article's structure to enhance the clarity about the primary goal concerning recent changes in glaciers and glacier runoff, or to address corrections and calibration. However, it's important to note that our original intention was aligned with these two goals. Consequently, we have reworked the Abstract, Introduction, and Conclusions sections to get more clear research. The Abstract and Introduction are edited as follows.

Abstract

Original text:

"The impacts of the accelerated glacier retreat in recent decades on runoff changes are still unknown in most Andean catchments, thereby increasing uncertainties in estimating and managing water availability. Here, we used a monthly time step to simulate glacier evolution and related runoff changes for 36% of the glacierized surface area of the Andes (11,282 km^2 in 786 catchments, 11°N-55°S) using the Open Global Glacier Model (OGGM) and a corrected and evaluated version of the TerraClimate dataset between 2000 and 2019. The glacier mass balance and volume were calibrated glacier-by-glacier. The simulation results were evaluated with in situ data in three documented catchments and 15 glaciers. Our results show that the glacier volume (-8.3%) and surface area (-2.2%) are reduced in 93% of the catchments between the periods 2000-2009 and 2010-2019. This glacier loss is associated with changes in climate conditions (precipitation = -9%; temperature = +0.4 ± 0.1°C) inducing an increase in the mean annual glacier melt of 12% (86.5 m^3/s) and a decrease in the mean annual rainfall on glaciers of -2% (-7.6 m^3/s). We find a regional pattern in the melt factors showing decreasing values from the Tropical Andes toward the Wet Andes. A negative mass balance trend is estimated in the three documented catchments (glacierized surface area > 8%), showing the largest mean glacier contribution during the transition season (September-November) in La Paz (Bolivia) (45%) followed by Baker (Chile) (43%) and Maipo (Chile) (36%) during the summer season (January-March). In addition, our evaluation in the monitored glaciers indicates an underestimation of the mean simulated mass balance by 185 mm w.e. yr^{-1} and a high mean correlation (r = 0.7). We conclude that the large increases in the simulated glacier melt in the Dry Andes (36%) and the Tropical Andes (24%) have helped to improve our knowledge of the hydro-glaciological characteristics at a much wider scale than previous studies, which focused more on a few select catchments in the Andes.".

Edited text:

"The impacts of the accelerated glacier retreat in recent decades on glacier runoff changes are still unknown in most Andean catchments, intensifying uncertainties in estimating water availability. This particularly affects the Outer tropics and Dry Andes, heavily impacted by prolonged droughts. Current global estimates overlook climatic and morphometric disparities among Andean glaciers, which significantly influence simulation parameters. Meanwhile, local studies have used different approaches to know glacier runoff in a few catchments. Enhanced accuracy in 21st-century glacier runoff projections hinges on corrected historical climate and calibrated parameters across diverse glaciological zones. Here, we simulate glacier evolution and related glacier runoff changes between 2000 and 2019 in 786 Andean catchments from Colombia to Tierra del Fuego (11,282 km^2 of glacierized area, 11°N-55°S) using the Open Global Glacier Model (OGGM). We also emphasize on climate correction, parameter calibration, and result evaluation within the workflow simulation. This single methodological approach considers the diverse glaciological zones in the Andes. The climate variables were corrected using in situ measurements, underlining the use of local temperature lapse rates. Meanwhile, the glacier mass balance and volume were calibrated glacier-by-glacier. The simulation results were evaluated with in situ data in three documented catchments (glacierized surface area > 8%) and monitored glaciers. Our results at the Andes scale show that the glacier volume and surface area were reduced by 8.3% and 2.2%, respectively, between the periods 2000-2009 and 2010-2019. The glacier loss during these periods is associated with a decrease in precipitation (9%) and an increase in temperature (0.4 ± 0.1°C). Glacier and climate variations have led to a 12% increase in mean annual glacier melt (86.5 m^3/s) and a decrease in mean annual rainfall on glaciers of -2% (-7.6 m^3/s) across the Andes, both variables compose the glacier runoff. The catchment scale results indicate comparable glacier runoff contribution with previous studies in the Maipo catchment (34°S, Chile). During the transition season, we suggest a larger glacier runoff contribution in the La Paz catchment (16°S, Bolivia). Additionally, we calculated for the first time the glacier runoff contribution in the Baker catchment (47°S, Chile). Furthermore, procedures by glaciological zones allow us to correct mean temperature bias up to 2.1°C and increase the amount of monthly precipitation. The related calibrated parameters, such as melt factor (for mass balance) and Glen A (for ice thickness), show strong alignment with cold/warm and dry/wet environmental conditions. "In summary, this calibrated and validated model, organized by glaciological zones and grounded in our local understanding, utilizing the same methodological approach, stands as a crucial requirement for simulating future glacier runoff in the Andes."

Introduction

Original text.

"The largest ice concentration in the southern hemisphere outside the Antarctic ice sheet is found in the Andes (RGI Consortium, 2017). Andean glaciers provide the water supply for roughly 45% of the population in the Andean countries (Devenish and Gianella, 2012) and for ecosystems (Zimmer et al., 2018; Cauvy-Fraunié and Dangles, 2019). They have been affected by a continuous shrinkage since the late 1970s, which has intensified during the last two decades (Rabatel et al., 2013; Dussaillant et al., 2019; Masiokas et al., 2020). Glacier volume loss has helped modulate river discharges, mainly in dry seasons (*e.g.*, Baraer et al., 2012; Soruco et al., 2015; Guido et al., 2016; Ayala et al., 2020).

Several studies have estimated glacier changes and their effects on hydrology using observation or modeling focused on specific Andean catchments. For instance, Huss and Hock (2018) studied 11 Andean catchments (1980-2100) and found an increase in glacier runoff in the Tropical and Dry Andes, but a more contrasted signal in the Wet Andes: no glacier runoff changes were observed in some catchments, whereas others showed a reduction or an increase. In the Tropical Andes, the glacier contribution at the annual scale was estimated to be approximately 12% and 15% in the Río Santa (9°S) and La Paz (16°S) catchments, respectively (Mark and Seltzer, 2003; Soruco et al., 2015). For the La Paz catchment, Soruco et al. (2015) found no change in the glacier runoff contribution for the period 1997-2006 compared with the longer 1963-2006 period. This was attributed to the fact that the glacier surface reduction over the time-period was compensated by their increasingly negative mass balance. In the Dry Andes, the Huasco (29°S), Aconcagua (33°S) and Maipo (34°S) catchments showed a glacier contribution comprised between 3 and 23% for different catchment sizes between 241 and 4843 km^2 (Gascoin et al., 2011; Ragettli and Pellicciotti, 2012; Ayala et al., 2020). These catchments had mainly negative glacier mass balances which were slightly interrupted during El Niño episodes (2000-2008 period), thereby reducing glacier runoff. In the Wet Andes, Dussaillant et al. (2012) estimated that some catchments in the Northern Patagonian Icefield are strongly conditioned by glacier melting. Despite this, Hock and Huss (2018) did not identify changes in the glacier runoff of the Baker catchment since 1980-2000. Given that these studies are focused on only a few catchments, these local estimations can hardly be seen as representative across the Andes, especially since glacierized catchments can be characterized by major climatic and topographic differences (Caro et al., 2021).

Nowadays, the availability of global glaciological products such as glacier surface elevation differences and glacier volume estimation (Farinotti et al., 2019; Hugonnet et al., 2021; Millan et al., 2022) allows for large-scale glacio-hydrological simulations with the possibility to accurately calibrate and validate numerical models at the catchment scale. In addition, models such as the Open Global Glacier Model (OGGM, Maussion et al., 2019) have been implemented to simulate the glacier mass balance and glacier dynamics at a global scale. Therefore, OGGM and the glaciological global dataset, in combination with in situ meteorological and glaciological measurements, can be used to precisely quantify the glacier retreat and its hydrological responses at the catchment scale across the Andes, while taking the related uncertainties into account.

Here, using OGGM, we estimate the glacier changes (area and volume) and the consecutive hydrological responses (from glacier melt [ice melt and snow melt] and rainfall on glaciers) for 786 catchments across the Andes (11°N-55°S) with a glacierized surface of at least 0.01% for the period 2000-2019. The model was run with monthly air temperature and precipitation data from the TerraClimate dataset (Abatzoglou et al., 2018) that were corrected using weather station records and mass balances measured on monitored glaciers. Our spatial analysis was performed at the catchment scale using the glaciological zones of the Andes defined in Caro et al. (2021); however, we simulated the glaciological and runoff processes at the glacier scale.

Section 2 presents the data and methods. In Section 3, we describe the glacier changes and hydrological responses at the glaciological zone and catchment scales across the Andes. In Section 4, we discuss our results and the main steps forward compared to previous research."

Edited text.

"The largest glacierized area in the southern hemisphere outside the Antarctic ice sheet is found in the Andes (RGI Consortium, 2017; Masiokas et al., 2020). Andean glaciers supply water for roughly 45% of the population in the Andean countries (Devenish and Gianella, 2012) and for ecosystems (Zimmer et al., 2018; Cauvy-Fraunié and Dangles, 2019). Continuous glacier shrinkage has been detected since the late 1970s, with intensification observed over the past two decades (Rabatel et al., 2013; Dussaillant et al., 2019; Masiokas et al., 2020). Glacier volume loss has helped modulate river discharges, mainly in dry seasons (*e.g.*, Baraer et al., 2012; Soruco et al., 2015; Guido et al., 2016; Ayala et al., 2020).

Few studies have estimated glacier changes and their effects on hydrology using observation or modeling focused on specific Andean catchments. For instance, the global-scale study by Huss and Hock (2018) comprised 12 Andean catchments (1980-2100). They defined glacier runoff as all the melt water and rainfall coming from the initially glacierized area as given by the Randolph Glacier Inventory version 4.0. and found an increase in glacier runoff in the Tropical and Dry Andes during the recent decades, but a more contrasted signal in the Wet Andes: no glacier runoff changes were observed in some catchments, whereas others showed a reduction or an increase. However, their estimations overlook the diverse climates and morphologies of Andean glaciers (Caro et al., 2021). This affects the simulation results, as they heavily rely on climate inputs and calibrated parameters. For instance, varying temperature lapse rates could result in significant disparities in glacier melt and the determination of solid/liquid precipitation on glaciers (Schuster et al., 2023). Furthermore, the selection of precipitation factor values is also crucial. Based on local studies, the glacier runoff contribution (glacier runoff relative to the total catchment runoff) in the Tropical Andes was estimated to be around 12% and 15% in the Río Santa (9°S) and La Paz (16°S) catchments, respectively (Mark and Seltzer, 2003; Soruco et al., 2015). For the La Paz catchment, Soruco et al.

(2015) found no change in the glacier runoff contribution for the period 1997-2006 compared with the longer 1963-2006 period. This was attributed to the fact that the glacier surface reduction over the time-period was compensated by their increasingly negative mass balance. In the Dry Andes, the Huasco (29°S), Aconcagua (33°S) and Maipo (34°S) catchments showed a glacier contribution comprised between 3 and 23% for different catchment sizes between 241 and 4843 km^2 (Gascoin et al., 2011; Ragettli and Pellicciotti, 2012; Ayala et al., 2020). These catchments had mainly negative glacier mass balances which were slightly interrupted during El Niño episodes (2000-2008 period), thereby reducing glacier runoff. In the Wet Andes, Dussaillant et al. (2012) estimated that some catchments in the Northern Patagonian Icefield are strongly conditioned by glacier melting. In addition, Hock and Huss (2018) did not identify changes in the glacier runoff of the Baker catchment since 1980-2000. However, these studies focused on a restricted number of catchments, employing diverse input data and methodologies over different analysis periods. As such, these local estimations may not be indicative of the broader trends across the entire Andean region. Notably, even neighboring glacierized catchments can exhibit substantial variations in climatic and topographic characteristics (Caro et al., 2021).

Nowadays, the availability of global glaciological products such as glacier surface elevation differences and glacier volume estimation (Farinotti et al., 2019; Hugonnet et al., 2021; Millan et al., 2022) allows for large-scale glacio-hydrological simulations with the possibility to accurately calibrate and validate numerical models at the catchment scale. In addition, models such as the Open Global Glacier Model (OGGM, Maussion et al., 2019) have been implemented to simulate the glacier mass balance and glacier dynamics at a global scale. Therefore, OGGM and the glaciological global dataset, in combination with in situ meteorological and glaciological measurements, considering the differences of Andean glaciological zones, can be used to precisely quantify the glacier retreat and its hydrological responses at the catchment scale across the Andes, while taking the related uncertainties into account.

Here, using OGGM, we estimate the glacier changes (area and volume) and the consecutive hydrological responses (from glacier melt [ice melt and snow melt] and rainfall on glaciers) for 786 catchments across the Andes (11°N-55°S) with a glacierized surface of at least 0.01% for the period 2000-2019. The model was run with monthly air temperature and precipitation data from the TerraClimate dataset (Abatzoglou et al., 2018) that were corrected using in situ data. Whereas the simulation procedure considered the mass balance and volume calibration. Both, corrections of climate as well as calibrations were performed considering the climatic and morphometric differences in de Andes, represented through the glaciological zones. Our spatial analysis was performed at the catchment scale using the glaciological zones of the Andes defined in Caro et al. (2021); however, we simulated the glaciological and runoff processes at the glacier scale.

Section 2 presents the data and methods. In Section 3, we describe the glacier changes and hydrological responses at the glaciological zone and catchment scales across the Andes. In Section 4, we discuss our results and the main steps forward compared to previous research."