Glacier runoff variations since 1955 in the Maipo River Basin, semiarid Andes of central Chile

Response to reviewers

Reviewers: Black font

Authors: Blue font

We thank both reviewers for evaluating our article, for highlighting the relevance of our study, as well as for their useful feedback and comments. We have responded to all the questions raised by the reviewers, and provided a detailed justification where we did not perform the suggested changes.

We summarize the main changes in our manuscript below:

1. As suggested by reviewer 1, we have added a new table (Table 4) that summarizes glacier mass balance and runoff contribution per sub-catchment in the historical period (1955-2016), and in the period when glaciers have reached an equilibrium with the current climate (last 20 years of the committed ice loss scenarios).
2. As the two reviewers pointed out that the model was validated against few field data, we have added a new sub-section (S3) called "Additional model validation" to the supplementary material. The sub-section compares model results against i) streamflow records and intermediate sections of the Maipo River and ii) a 40-year time series of SWE manual measurements. We found that our simulations compare well with these point-scale observations. This new section has thus strengthened our article.
3. We found that some of the scripts that analysed the results from TOPKAPI-ETH and the extrapolation methodology used a number of 558 km^2 for total glacierized area in 1955, instead of 532 km^2, which is the correct number. The number of 558 km^2 was also used twice in the text. After correcting the scripts, some numbers changed in the text and in some plots (figures 2, 7, 8, 9c and 10), but all the changes are small and do not affect our conclusions.
4. We have improved figures 1, 3 and 6, following suggestions from both reviewers.
5. A number of small changes have been performed in the text, following suggestions from both reviewers.

Please see our detailed responses below.

Response to reviewer 1 (Francisca Bown)

The study examines the glacier mass balances for the upper Maipo, central Chile, between years 1955 and 2000/13 and the corresponding melting water contributions to runoff over that period. This is done by physically-based modelling of selected glaciers and its extrapolation to the entire basin. The approach has been tested abroad and now adapted for the Andes setting for a period that concurs the largest observed retreat rates in historical times. Input glaciological data are two main glacier inventories separated by 48 years, originated from very different type of sources, resolution, precision, etc, but properly corrected and processed for the purposes of direct comparison as best as possible. These were complemented to Digital Elevation Models (DEMs) of same dates, distributed ice thicknesses obtained from modelling & geodetical balances, and several types of hydro-meteorological datasets (mostly downscaling reanalysis and remotely-sensed data i.e. input local observations are limited). Extrapolations (spatially and temporarily), calibrations and verifications are careful.

We thank the reviewer for her thorough evaluation of our article, and for her useful suggestions and comments. We have responded to all the questions raised by the reviewer. Please see our detailed responses below.

It is clear, however, that lack of direct radar measurements and AWS data over glaciers must have committed the results at some extent. This is particularly true when authors raised datasets discrepancies and provide sublimation estimates without in situ verification. In that sense, TOPKAKI-ETH would require more field measurements than applied for an optimal hydrological simulation.

We very much agree with the reviewer that more field data would be useful and they could reduce the uncertainty in our results. In particular, more field data can be useful to better constrain our estimates of precipitation and temperature at remote high-elevation areas (such as Tupungatito Volcano or the Upper Maipo sub-catchment), and improve the simulation of some specific processes, such as elevation changes due to ice flow, the impact of supraglacial debris on glacier melt, or long-term ice albedo changes.

The reason why we did not use more field data however is that these are not widely available in the region. However, to alleviate the difficulties posed by the lack of a basin-wide set of data described in the previous paragraph, we have made a consistent effort to derive most of the Topkapi-ETH parameters from data collected in previous field campaigns in this region, starting in 2008. The datasets collected in those campaigns consisted of ablation stakes, distributed snow depth measurements, on-glacier meteorological records, terrestrial cameras, and others, that we have used in previous studies to force models of variable complexity that we now fully exploit in this study (Pellicciotti et al., 2008; Ragettli and Pellicciotti, 2012; Ayala et al., 2016, 2017a, 2017b; Burger et al., 2019). In particular, we use the previous, field-based modelling to calibrate several TOPKAPI-ETH parameters, such as melt factors, albedo decay rates, and parameters controlling the snow gravitational distribution. These previous studies have also shown that many of the parameters required by the model are fairly stable, in the sense that they can be extrapolated from one glacierized area to another with a reasonable degree of confidence (Ayala et al., 2017b; Burger et al., 2019). We thus indirectly use a relatively (for the region) large amount of field data to inform the model and calibrate its parameters. In relation to sublimation, Corripio (2003) and Ayala et al. (2017a, 2017b) estimated its daily and seasonal rates at several sites across the semiarid Andes, and we use these estimates as a reference in our study.

In the revised version, we include these ideas in section 6.3 (lines 578-586):

“Although our study has benefited from a series of new meteorological and glaciological datasets presented for the Southern Andes in recent years (Cortés and Margulis, 2017; Álvarez-Garretón et al., 2018; Farías-Barahona et al., 2019a), the lack of field data in the Maipo River Basin is something that needs to be taken into account in glacio-hydrological modelling studies in the region, particularly at high-elevation, remote sites. In this study, we alleviate the difficulties posed by the lack of basin-wide field data, and its impact on the TOPKAPI-ETH results, by deriving most of the model parameters from data collected in previous field campaigns in this region, starting in 2008 (Pellicciotti et al., 2008; Ragettli and Pellicciotti, 2012; Ayala et al., 2016). These previous studies have also shown that many of the parameters required by the model are fairly stable, in the sense that they can be extrapolated from one glacierized area to another with a reasonable degree of confidence (Ragettli et al., 2014; Ayala et al., 2017b; Burger et al., 2019).”

In relation to the two specific datasets mentioned by the reviewer (radar data and on-glacier AWSs), we note that radar data from the Glacier Thickness Database (GlaThiDa) (Gärtner-Roer et al., 2014) are used as validation for our ice thickness estimates for Volcán Tupungatito and Marmolejo glaciers (lines 162-165). We also notice, with respect to the reviewer’s appropriate comment on lack of on-glacier AWSs, that a glacio-hydrological model such as TOPKAPI-ETH applied at the large scale of the entire Maipo basin cannot be forced with on-glacier data, as these represent the atmosphere in the glacier boundary layer and would result in incorrect estimates of all the remaining hydrological components in the non-glacierised sections of the catchment.

Ice volume and runoff values and trends are given in reasonable orders of magnitude and complement former studies in the region. The authors raised that typical increasing or decreasing phases of peak water cannot be observed over the period 1955-2016, however there is a bulk of facts (i.e. areal and ice volume losses, negative mass balances and elevation changes, observed runoff trends and conservative committed ice losses up to year 2100) that suggests this peak is hidden somewhere within 2000-10.

Based on our data and results, we think that there is not enough evidence to identify a clear peak water in our study period. Since glacier runoff is defined as the summed contributions of rain, snowmelt and ice melt over the areas defined by the glacierized areas in 1955, peak water is not only connected to ice melt, but also to the annual variability of precipitation. Given the humid years in the 1980s and the large values of ice melt in the 1990s, we believe that glacier runoff in the 2000s was actually lower than that in the previous decades (see Figure 9c). In addition, we think that the exact occurrence of peak water will depend also on future changes (e.g. more precipitation or more ice melt), which are not addressed in our article.

These arguments have been summarized in our conclusion “b” (lines 617-619) as:

“Instead of a clear peak water, we identify a decreasing sequence of runoff maxima that can be linked to both a decrease in precipitation since the 1980s and a reduction of ice melt. The exact occurrence of peak water will depend also on future changes (e.g. more precipitation or more ice melt), which are not addressed in our article”

In contrast, authors argue a possible transient equilibrium with climate of some glaciers to justify some short periods of positive/neutral mass balances, hyphotesis which is not really supported.

To our knowledge, short periods of positive/neutral mass balance in this region are well documented in the literature. Although glaciers in the semiarid Andes have been retreating for several decades, the direct mass balance measurements at Echaurren Norte Glacier, and the latest geodetic mass balance studies point to near-neutral glacier mass budgets in that decade. We have summarised this evidence in the table below.

Summary of glacier mass balance results in the Central Andes for the 2000-2013 period

Domain	Type of data	Value	Period	Source
Echaurren Norte Glacier	Glaciological mass balance	+0.2 m w.e. yr^{-1}	2000-2009	World Glacier Monitoring Centre (WGMS)
Echaurren Norte Glacier	Geodetic mass balance	+0.54±0.40 m w.e. yr^{-1}	2000-2009	Farías-Barahona et al.(2019)
Central Andes	Geodetic mass balance	+0.17±0.23 m w.e. yr^{-1}	2000-2009	Dussaillant et al. (2019)
Bello Glacier	Model simulations	–0.01±0.09 m yr^{-1}	2000-2013	Burger et al. (2019)
Yeso Glacier		–0.03±0.09 m yr^{-1}		

Apart from that, the study is clearly explained from beginning to end, it is a well- structured & written manuscript. Figures, tables and supplementaries are generally all informative and of appropriate visual quality, but with some improvements and clarifications I would recommend. I particularly missed a table providing mass balance and runoff values per each sub-basin, which would make more explicit and/or highlight possible influence of factors such as elevation range and latitude.

This is a very useful suggestion and we include the suggested table in the revised version of the article (Table 4):

Table 4: Simulated glacier mass balance and runoff in the sub-catchments compared with their main characteristics

Basin	Mean elev. (m a.s.l.)	Mean lat. (°S)	Glacierized area in 1955 (km^2)	Average annual glacier mass balance in 1955-2016 (m w.e. yr^{-1})	Runoff contribution in 1955-2016 (*) (mm w.e. yr^{-1})		Runoff contribution in the committed ice loss scenarios (mm w.e. yr^{-1})	
					Total	Ice melt	Total	Ice melt
Olivares	3698	33.3	111	–0.26 ± 0.07	34.1 ± 7.9	15.8 ± 3.6	22.5 ± 6.1	5.4 ± 1.5
Colorado	3755	33.4	152	–0.10 ± 0.07	53.2 ± 12.2	16.1 ± 3.7	42.7 ± 11.5	6.4 ± 1.7
Yeso	3303	33.7	65	–0.09 ± 0.07	21.5 ± 4.9	7.5 ± 1.7	17.1 ± 4.6	3.6 ± 1.0
Volcán	3392	33.8	86	+0.04 ± 0.07	24.2 ± 5.6	7.7 ± 1.8	20.0 ± 5.4	3.5 ± 1.0
Upper Maipo	3182	34.0	111	–0.03 ± 0.07	41.8 ± 9.6	12.6 ± 2.9	33.4 ± 9.0	4.4 ± 1.2

Maipo River Basin	3175	33.6	532	–0.09 ± 0.07	176.9 ± 40.7	65.5 ± 15.1	138.6 ± 37.4	25.8 ± 7.0

(*) From the areas defined by the 1955 glacier outlines, but normalized by the Maipo River Basin area

The study settled the hydrological role of glaciers together with those of snow and rain, both on annual and seasonal basis. This is helpful in current times when concerns on water security are quite high and general public receives distorted information from environmental NGOs. It additionally provides the main forcing factors of hydrological trends and predicts the decreasing glacier buffer capacity even at the conservative scenario. By themselves, these points suggest an important impact in the scientific community, likely for stakeholders and decision makers as well. There are much more strengths than weaknesses that make this manuscript suitable for going from TCD into TC after very minor editing.

We thank again the reviewer for her positive comments about our article. Please see our responses to the specific comments and technical corrections below.

SPECIFIC COMMENTS

Lines 23-26: "If glaciers in the basin were in equilibrium with the climate of the last two decades, their volume would be reduced to 81±38% of the year 2000 volume, and glacier runoff during dry periods would be 61±24% of its maximum contribution inthe period 1955-2016, considerably decreasing the drought mitigation capacity of the basin". This sentence refers an optimistic scenario based on minimum ice volumetric loss and minimum decrease of glacier runoff contribution, but it is rather confusing and probably needs improvement in redaction, probably in a way like this or similar: "Assuming conservative ice losses of 81% under a constant climate...glacier runoff during dry periods..."

We apologise if the wording was confusing. In fact, we are neither assuming any ice loss (as in the sentence suggested by the reviewer) nor is the value of 81% resulting from assuming a constant climate. We have changed these sentences to (lines 24-26):

"Glaciers in the Maipo River Basin will continue retreating because they are not in equilibrium with the current climate. In a hypothetical constant climate scenario, glacier volume would reduce to 81±38% of the year 2000 volume, and glacier runoff would be 78±30% of the 1955-2016 average. This would considerably decrease the drought mitigation capacity of the basin."

Lines 83-84: "Unrealistic" mentioned several times seems awkward.

To avoid word repetition, we have reworded some of the sentences that included the idea of "unrealistic projections".

- (lines 536-537): "We stress that these estimates do not correspond to a realistic future scenario, but are an indication of the glacier changes that past climate will produce in any case." is changed to "We stress that these estimates are an indication of the glacier changes that past climate will produce in any case."
- Captions of figures 9 and 10: "The committed ice loss scenarios do not represent a realistic projection for the future, and we use the years of 2000 to 2100 in the x-axis for visual purposes only" is changed to "For visual purposes, we present the committed ice loss scenarios using the period 2000-2100 in the x-axis."

Lines 127-128: Inventories error assignments of 5 (year 2000) and 10% (year 1955) seem rather arbitrary. Can you explain better?

We have now extended the explanations using these sentences (section 3.1, lines 130-133):

"In this study, we assign an error of 5% to the year 2000 inventory, which is a common choice for glacier inventories (Paul et al., 2013), and has been used for this inventory in particular (Barcaza et al., 2017). As the inventory of 1955 suffers from additional errors (such as the presence of snow patches that likely made the interpretation of glacierets difficult, and the use of Lliboutry maps to fill missing areas), we assume an error of 10% for that year."

Lines 161-173: When calculating ice thicknesses in 1955 based on Huss and Farinotti complemented to geodetic balances 1955-2000 and area-volume ratio, there is an intrinsic assumption of no basal melting. I think this could be mentioned.

We agree with the reviewer. We have now added the following sentence (section 3.2, lines 184-186):

"In the calculation of glacier volumes, we implicitly assume that no basal melting takes place. The error introduced by neglecting this process is much less than the uncertainty associated with the ice thickness estimates and the geodetic mass balance."

Lines 176-177: Uncertainty of 15% in average for 1955, 2000 and 2013? 1955 is clearly more uncertain, maybe you could clarify.

Thanks for noting this. The uncertainty of 15% in total ice volume is only for 2000. The uncertainty in the total ice volume in 1955 and 2013 is larger because it includes the uncertainty from the geodetic mass balance. We have changed this to (lines 181-186):

"For the total ice volume of the investigated basin, we assume an uncertainty of 15% in year 2000. (…) The uncertainty in the total ice volume in 1955 and 2013 is larger than in 2000 since it also includes the uncertainty from the geodetic mass balances."

Lines 179-203: Is there any particular reason why fluviometric data elsewhere available upstream El Manzano was not used for feeding or verifying the model results?

This is a very useful comment. We used only the Maipo en El Manzano streamflow gauge because we focused on the glacier runoff contributions at the scale of the entire catchment. To extend the verification of the model as suggested by the reviewer, a new sub-section ("Additional model validation") is included in the supplementary information of the revised version. In this sub-section, we add new figures and tables showing the verification of the model at i) six intermediate streamflow gauges, and ii) the Laguna Negra snow monitoring site, at which the Chilean Directory of Water Resources (DGA) have measured annual near-maximum SWE for several decades. Due to its length (5 pages), this new sub-section is included at the end of this document.

Lines 204-212: Modis datasets used in calibration of snow processes have minor resolution than the model output. Something to say about that?

The MODIS datasets are used only for the calibration of snow parameters in the basin-wide model, which has a spatial resolution of 1 km. The 1-km model resolution is actually lower than that of the MODIS datasets (500 m) and that of the SWE reconstruction (180 m). In any case, all datasets and results are aggregated at the catchment scale and we used basin-wide values in the model calibration. We think that given the large size of the Maipo River Basin, the differences in spatial resolution will not strongly affect the parameter calibration.

We have now provided more details (section 4.1.2, lines 282-284):

"The calibration of the Maipo River Basin model was performed for the period April 2003 to March 2016, and consists of two steps: (i) the snow parameters are varied in order to fit SCA and SWE aggregated at the scale of the entire basin from the MODIS and CAMELS-CL datasets (section 3.4), …"

Lines 237-240: "To calculate ice melt under supra-glacial debris we also use the ETI model but with reduced melt factors (see section 4.1.3). Although TOPKAPI-ETH includes a melt module..." I understand it, but be aware there is a bias. Debris impact on melt can be variable depending on thickness, mineralogy, etc.

To account for this comment, we have added the next sentence (lines 258-260):

"As a result of our assumptions, we expect that some of the spatial patterns of glacier ablation induced by the spatial variability of supraglacial debris thickness are not accurately represented in our simulations."

Lines 282-287: Because of different conditions of elevation ranges, air humidity, winds, etc, among 5 sub-basins, I disagree with the representativeness of 34 mm/yr of sublimation, at least in the case of the higher ones.

We agree with the reviewer about the large spatial variability of surface sublimation. Please note that the 34 mm yr^{-1} correspond only to a basin average of discarded snow and that we do not assume that the value applies to all five sub-basins individually. In general, we estimate about 688 mm yr-1 (~2 mm day^{-1}) in the areas above 5000 m a.s.l., which is in agreement with estimates derived from energy balance models in the region (Corripio, 2003; Ayala et al., 2017a, 2017b).

To be more precise about this topic, we have added the following sentences:

(Section 4.1.2, lines 313-314) "As elevation decreases south, the discarded snow varies from about 121 mm w.e. yr^{-1} over the Colorado sub-catchment to about 10 mm w.e. yr^{-1} over Upper Maipo."

(Section 4.1.3, lines 341-343) "However, as these models are calibrated on volume loss (thus including both losses by sublimation and melting), it can be assumed that glacier response is well captured, but the portioning of hydrological fluxes (sublimation versus runoff) is unconstrained."

I think authors should raise there is a limitation of SWE information from Landsat.

We think that we have not been clear enough in our text. Please consider that SWE does not come directly from Landsat but from inversion of snowmelt calculations from re-analysis using Landsat images as boundaries. We have now included the following sentence (section 3.4). Note that the sentence also addresses the limitation of the Landsat based SWE product (lines 219-225):

"The SWE reconstruction was obtained from a data assimilation framework that integrates a land surface and depletion model, the assimilation of Landsat imagery, and the Modern Era Retrospective Analysis for Research and Applications (MERRA) reanalysis as a forcing dataset (Cortés et al., 2016; Cortés and Margulis, 2017). Although not all physical processes are included in the assimilation process (for example, blowing snow sublimation), the dataset has been validated at several sites across the Southern Andes (Cortés et al., 2016; Cortés and Margulis, 2017), and it should provide a good estimate of snow on the ground that can be used for hydrological modelling.

Lines 288: "...and is in the order of the model uncertainties (see Figure 2)." You mean 34 mm/yr in comparison to 49.9 mm of RMSE? Please clarify.

Yes. We have now included the number 49.9 in that sentence (section 4.1.2, lines 311-313):

"…, which is similar to the estimates of sublimation amounts for this region (Corripio, 2003; Ayala et al., 2017a, 2017b), and is in the order of the model uncertainties (49.9 mm w.e. in Figure 2a)."

Lines 317-319: "We suspect that this is an expression of the fact that some of the processes not included in TOPKAPI-ETH (namely permafrost, sublimation, snow dynamics or geothermal fluxes) may play a role governing the mass balance of these glaciers". Then it is partially contradictory to this sentence: "...which is a reasonable estimate of sublimation amounts for this region...".

We apologise if we have not been clear in any of those two sentences.

The second sentence refers to the amounts of snow that we remove from the simulations of the Maipo River Basin at the end of each year. We recall that the 1-km resolution simulations of the Maipo River Basin do not consider glaciers. Given the amount and location at high-elevation sites of the removed snow, we think is reasonable to attribute them (at least partly) to sublimation losses. In contrast, the first sentence refers to the models for the individual glaciers, where sublimation is not included.

In relation to neglecting sublimation in the individual models, we include the following sentence in section 4.1.3 (lines 339-343):

"In contrast to the model setup for the entire Maipo River Basin, in this setup we do not perform any corrections to account for sublimation or other mass removal apart from melt. However, as these models are calibrated on volume loss (thus including both losses by sublimation and melting), it can be assumed that glacier response is well captured, but the portioning of hydrological fluxes (sublimation versus runoff) is unconstrained."

Lines 333-335: "Interestingly, several of the glaciers show a positive or near-neutral mass balance over the entire period, which might be an indication that these glaciers have already retreated close to a new equilibrium." This seems to contradict evidence of glacier mass balances in the entire Andes.

We have extended the arguments that might explain the positive or near-neutral mass balance using the following sentence (section 4.1, lines 366-370):

"Interestingly, several of the glaciers show a positive or near-neutral mass balance over the entire period, which might be an indication that these glaciers have already retreated close to a new equilibrium. However, this is not the general trend (as shown by the average values in Figure 4) and it is limited to some specific cases where glaciers have retreated to elevations above the basin-average ELA, or have been covered by thick debris."

Lines 410: Authors report an important and larger ELA elevation than reported in Carrasco et al (2005). It should be highlighted.

We thank the reviewer for this very good comment and pointing out these numbers. We realized that we wrote a different number in the text (370 m and 66 m decade^{-1}) than in Figure 6 (239 m and 39 m decade^{-1}). The correct numbers are those in Figure 6, i.e. +239 m (39 m decade^{-1}) in the study period. The numbers in the text correspond to an earlier version of our calculations.

In the revised version, we also highlight the differences of our results from those of Carrasco (Section 5.1, lines 449-450):

"These estimates of the ELA change are larger than those calculated by Carrasco et al. (2005), who estimated an increase in the elevation of the 0°C isotherm of about 160 m for central Chile in the period 1975-2001."

Lines 419-410: "In general, glaciers in southern catchments show more positive mass balance than those in northern catchments." This occurs despite elevations are much lower. Any explanation other than precipitation?

This is a very good comment. As shown in Figure 1, the southern catchments (Yeso, Volcán and Upper Maipo) contain a larger proportion of debris-covered and rock glaciers than those in the north (particularly Olivares catchment), which together with precipitation differences can explain the more positive or neutral mass balances.

We have briefly added this (section 5.1, lines 460-461):

"This can be explained by larger precipitation amounts and a higher proportion of both debris-covered and rock glaciers."

Lines 424-440: This is the core of this research. It compares the contributions of ice, snow and rain in annual and summer basis. Is the 3% decrease of glacier summer contribution (entire study period versus current drought) a possible indication peak water was already reached?

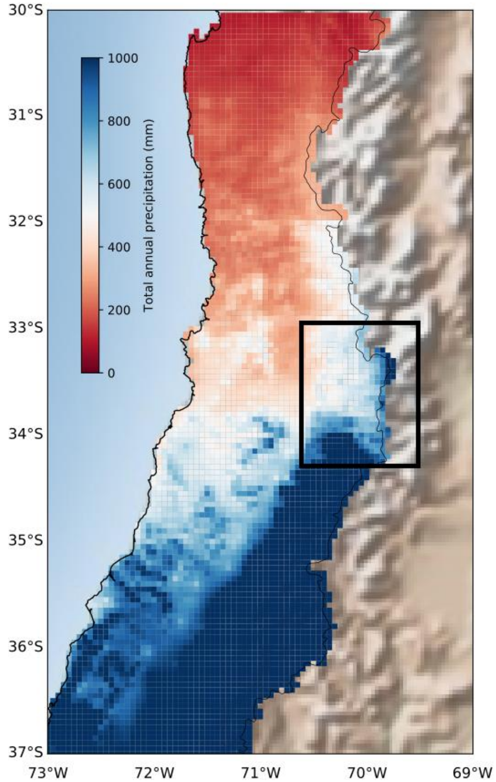
Yes, we think that that 3% decrease can be an expression of peak water. However, note that glacier runoff provides 59±23% of the summer runoff in the catchment, and that a 3% decrease is far smaller than the range of the inter-annual variability (23%). We think that a decrease in glacier runoff is more evident in figures 9c and 10.

Lines 441-455 & Figure 9c: Maybe a "realistic" projection could have complemented this analysis.

Yes, we agree that more realistic projections that are forced by global climate simulations should be made for this catchment. However, this study focuses on understanding past changes. Please see also the reply to the main comment (number 1) of reviewer 2.

Lines 481-485: As raised by the authors, difference in mass balances among sub-basins can depend on many climatic and morphological factors, however it is doubtful that precipitation increases that much in semiarid Andes to lead positive mass balances in southern basins. Unless there is data enough to support this statement.

Please note that, according to the CR2 dataset (DGA, 2017), precipitation differences between the northern and southern sub-catchments are in fact very large: up to about 100%, as shown in the next figure.



Annual precipitation from the CR2 product (DGA, 2017). The black frame shows the area where the Maipo River Basin is located.

TECHNICAL CORRECTIONS

Line 164: “ a meaningful 1955 ice thicknesess...” Delete “a”

We have deleted “a”.

Lines 256-261: I think this sentence repeats information from section 3.3.

Not exactly. While in section 3.3 we present the data, in section 4.1.2 we provide more details about how the data are used.

Lines 514-542 Uncertainties of modelling I particularly find this could have been assessed in summary at the end of methods section.

We agree with the reviewer that in its present form, the location of this section was not the best (also noticed by the other reviewer). Our aim is to provide an integrated discussion of the uncertainties of our results within this section. Therefore, we prefer to keep the information at its current location, but we have improved its embedding. We do so by incorporating results from the previous sections, and comments from both reviewers.

Figure 1 (a): Maipo outline may be better recognised if Chile and Argentina are just outlined (without color filling);

We have deleted the colour filling and kept only the outlines of the two countries.

(b) debris-free areas could be coloured in blue because white is difficult to distinguish over yellow;

We noted that the yellow colour of the Volcán sub-catchment corresponded to an old version of that figure. In the revised version, Volcán is coloured in dark orange. Because of this change, we keep the debris-free areas coloured in white. In any case, we improve the visibility of this figure by making some additional changes.

(c) I would recommend sub-basins labels to be horizontally oriented with brackets, so far I cannot tell where are the boundaries between them;

We have oriented the labels horizontally, but we do not clearly see the advantage of using brackets. Please note that there is no clear boundary between the sub-catchments, because the latitude of the glaciers overlap.

(d) Why Volcán label and number of glaciers are in light grey?

The colour should be light blue. We have checked again the colours.

Legend Figure 1: "a) Maipo River Basin next to the city of Santiago, in central Chile; (b) the basin outlet and the sub-catchments, rivers, main glaciers, and hydro-meteorological stations..." These are not all glaciers, nor the 26 modelled glaciers, just main ones.

We have added the term "main glaciers", as suggested by the reviewer.

Please see the new figure 1 below.

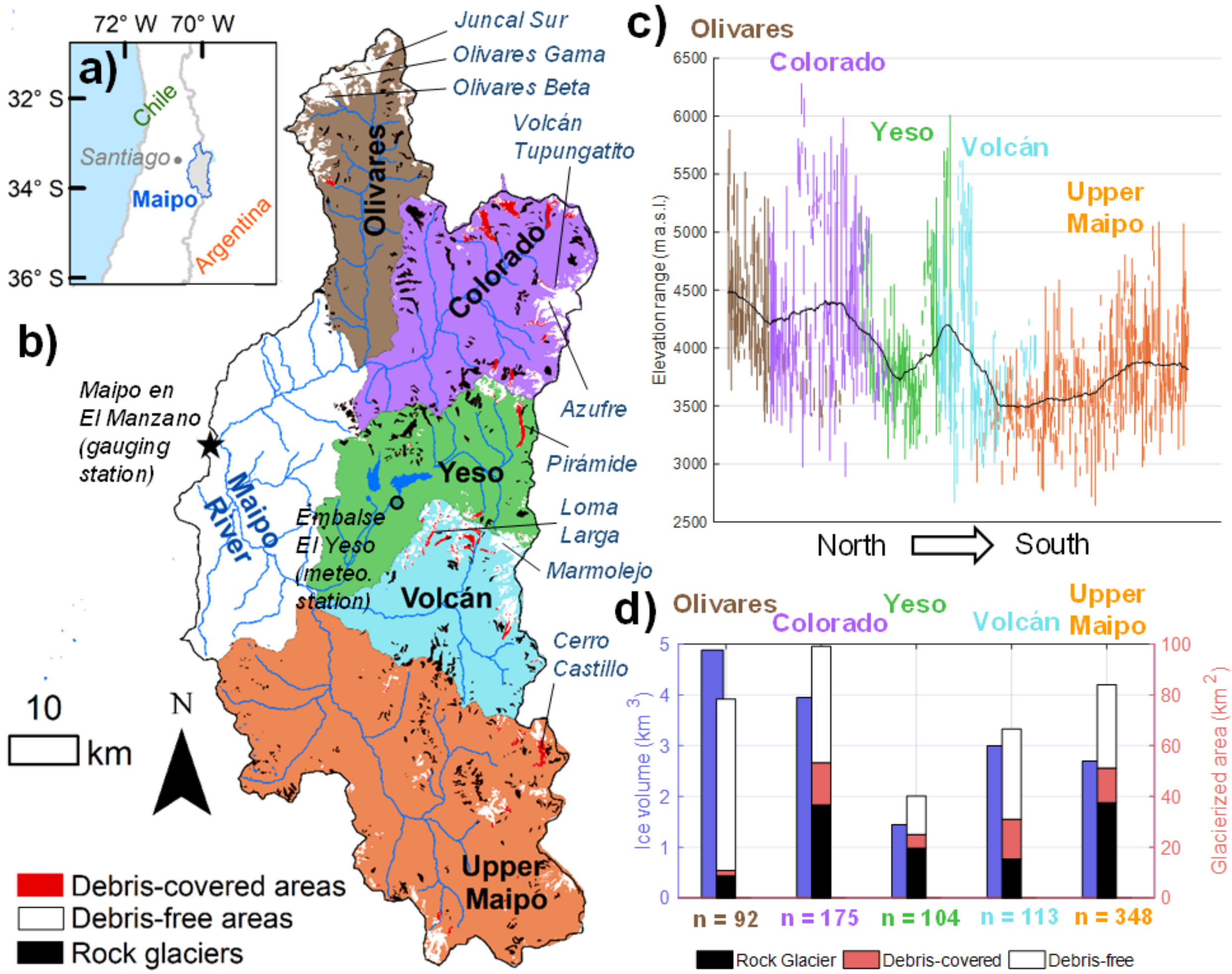


Figure 1: a) Maipo River Basin next to the city of Santiago, in central Chile; (b) the basin outlet and the sub-catchments, rivers, main glaciers, and hydro-meteorological stations; (c) the elevation range of every glacier in the basin as a function of the average latitude (arbitrary scale) in each sub-catchment, and the mean elevation (black line); (d) estimated total ice volume using the method developed by Huss and Farinotti (2012) (left axis), and glacierized area (right axis) in each sub-catchment. The surface and glacier type (debris-free, debris-covered or rock glacier), as well as the number of glaciers in each sub-catchment are indicated.

Figure 2 (a): It is Cortes et al 2016 or Cortes and Margulis 2017? Please clarify.

We thank the reviewer for noting this. The correct reference is that of Cortés and Margulis (2017).

Figure 3. I am not sure if this is necessary (instead they could be shown in Figure 1(a). In any case, glaciers in white are difficult to distinguish over yellow. Maybe blue is more appropriate. Name of main glaciers could be added.

As Figure 1a already contains large amounts of information, we would prefer to keep Figure 3 in the article. We have changed the yellow colour of Volcán sub-catchment and use blue for selected glaciers. As suggested by the reviewer, we have added the name of the main glaciers. Please see the new Figure 3 below.

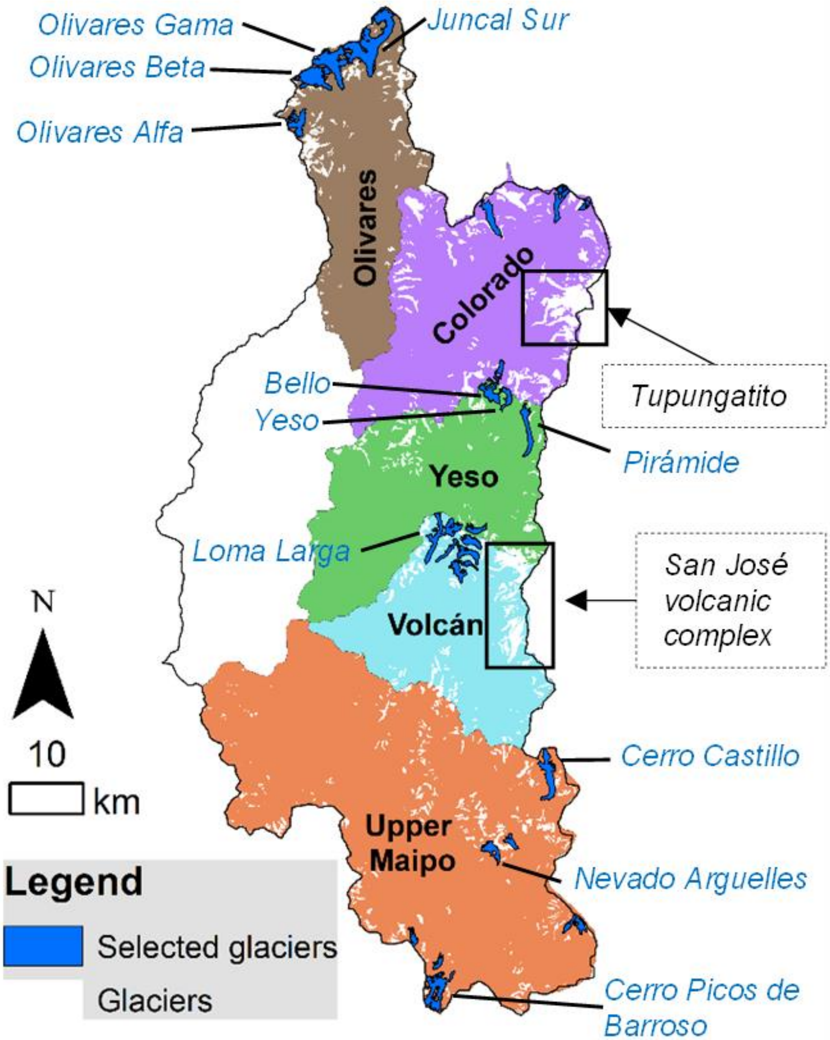


Figure 3: Location of the 26 glaciers modelled with TOPKAPI-ETH. The glaciers' names are given in light blue font. The two black boxes highlight the volcanic areas on which some large glaciers were discarded from the modelled sample.

Response to reviewer 2

This article aims to quantify the evolution of the glaciers and the runoff since 1955 in an Andean Chilean catchment using the TOPKAPI-ETH hydro-glaciological model. This study is very interesting and could help for water management in this region. Nevertheless, some issues have to be resolved before publication in the TC journal (see below).

We thank the reviewer for his/her thorough evaluation of our article, for highlighting the relevance of our study, as well as for his/her useful feedback and comments. We have responded to all the questions raised by the reviewer. In the few cases where we did not perform the suggested analyses or simulations, we have provided a detailed justification.

1. I am not convinced by the long term simulations that use a 'stationary climate' during two decades. By nature, climate is non stationary and an important decadal variability is observed in this region for the different climate variables (for instance the precipitation). The simulations provided here can be a first approach but simulations based on future climate projections should be made. This is important if one consider that this kind of study is oriented to water resource management (as state in various places in the article).

We agree with the reviewer about the importance of climate variability for glaciers and water management, particularly in this region where a large inter-annual climatic variability has been observed. We also agree that projections forced by global climate simulations should be made for this catchment. However, the focus of this study is *on past changes* in glacier and hydrological response, with the aim to understand their drivers. As noted in the text (e.g lines 84, 445, 492, 575, 859 and 867), the committed ice loss scenarios presented in this study are not meant to represent future projections. Rather, they are used for i) understanding how far the glaciers are from an equilibrium after the climatic changes that took place in the period 1955-2016, and ii) providing a baseline for the future changes in hydrology that the basin will experience in any case, i.e. even in the hypothetical case that climate change was to stall. Such committed ice loss scenarios have been increasingly used in the glaciological literature (e.g. Mernild et al., 2013; Christian et al., 2018; Marzeion et al., 2018; Zekollari et al., 2019), but have not been used for hydrological implications so far.

It is for these reasons that we have not performed future simulations. In the revised version, in addition to the limitations already stated in the text, we clearly highlight the aims of our committed ice loss scenarios in the Introduction section (lines 82-87).

"Additionally, we estimate glacier changes under synthetic scenarios of committed ice loss, in which air temperature, precipitation and cloudiness are assumed to stay at their current levels until the end of the century. We use these scenarios for i) understanding how far the glaciers are from an equilibrium after the climatic changes that took place in the period 1955-2016, and ii) providing a baseline for the future changes in hydrology that the basin will experience in any case, i.e. even in the hypothetical case that climate change was to stall. They are thus highly conservative and do not correspond to a realistic projection for the future."

2. The methodology to calculate volume and surface glacier variations in relation with the climate is confused. More details should be done (time step, kind of processes, basal sliding, etc....).

The reviewer most likely refers to the methods described in section 4.2 "Extrapolation". In this section, we extrapolate the mass balance of the 26 selected glaciers to all glaciers in the catchment using the methods developed by Huss (2012) for the European Alps. These balances are then used to calculate volume and area variations by means of volume-area scaling.

The method consists of a statistical extrapolation that does not consider any specific physical process (such as basal sliding) explicitly. Such processes are indirectly considered in the uncertainty associated with parameter "c" of the volume-area scaling relation, as explained by Bahr et al. (2015): "...basal sliding and other boundary conditions cannot change the scaling exponent as discussed above, but these boundary conditions could have a very important influence on the random distribution of c.".

To clarify these issues, we include these changes in the revised version (Section 4.2):

- We add the word "annual" in the method description to clarify that these calculations have an annual time step.
- In relation to the processes mentioned by the reviewer, we include this sentence (lines 398-400): "The uncertainty in parameter c should indirectly account for the different boundary conditions (such as basal sliding or surface geometry) that are found at each glacier (Bahr et al., 2015)."

3. Concerning the precipitation used in the model, a clear explanation on how the discrimination phase between solid and liquid is done is missing.

This information was included in lines 225-226 but might have not been clear enough. In the revised version, we write (section 4.1.1, lines 241-243):

"The model simulates snowfall at a given grid cell when precipitation occurs and air temperature is below a threshold parameter. If air temperature is above that threshold, precipitation is considered as rain."

The calibrated values of the precipitation threshold parameter are given in Table 1. The values are 0°C for the individual glaciers and 2°C for the Maipo River Basin to account for the different spatial resolutions and extents of the different models.

I don't understand why an additional meteorological station is used here. Only one station is not adequate to the size of the catchment.

There seems to be a misunderstanding here. As explained above, we do not use a single station to discriminate between snowfall and rain but rather use the temperature at each grid cell at the time of the precipitation event. If the reviewer refers to the extrapolation of air temperature from the Embalse El Yeso station, we have added the following sentence (section 6.3, lines 574-577):

"An additional simplification in the meteorological distribution is the extrapolation of air temperature from one single station. Nevertheless, we are confident that air temperature variability is well constrained over the catchment, because it usually correlates well over long distances, daily lapse rates are derived from the basin-wide CR2 temperature dataset, and the timing of snow disappearance is well simulated by TOPKAPI-ETH."

A correction is made on the raw precipitation but details should be given concerning the methodology used.

We have added the following details in relation to the precipitation correction (section 4.1.2, lines 297-299):

"We obtain a precipitation correction factor by manually fitting the observed and modelled curves of SCA and SWE, and at the same time closing the water balance of the basin. We obtain a value of +50%."

To improve the justification of this relatively large value, in addition to the errors originated from the reanalysis data (already discussed in the original manuscript), we include undercatch as a possible explanation (lines 295-297):

"Although the CR2 precipitation product corrects the ERA-Interim values by comparing them with ground data, these data are available only below 3000 m a.s.l. in this region, and have not been corrected for gauge undercatch (DGA, 2017), which can also contribute to the underestimation of precipitation at the highest elevations (Rasmussen et al., 2012)."

Finally how does the model compute the sublimation?

This is a very good question. We think that our explanations might have not been clear enough. Surface sublimation is not computed in the TOPKAPI-ETH model. To avoid confusion, this is now clearly stated in the model description of the revised manuscript (Section 4.1.1, line 254):

"TOPKAPI-ETH does not compute sublimation."

Additionally, we have extended the discussion of the issues caused by neglecting sublimation in the simulations for the entire Maipo River Basin (section 4.1.2, lines 306-315):

"An additional aspect of model simplifications identified during the model calibration is that air temperature over areas above 5000 m a.s.l. (about 5% of the basin) is most of the time lower than the air temperature threshold parameter for melt onset, generating large snow accumulation that is not seen in the SWE reconstruction product. As snow on this high-elevation areas is in reality removed by wind transport and sublimation, we reset the SWE in the model to zero at the beginning of each hydrological year. Although this implies that the model is not strictly mass-conserving, we verify that the discarded snow is in average 34 mm yr^{-1} over the entire basin (or 688 mm yr^{-1} = 1.9 mm d^{-1} over the areas above 5000 m a.s.l.), which is a reasonable estimate of sublimation amounts for this region (Corripio, 2003; Ayala et al., 2017a, 2017b), and is in the order of the model uncertainties (49.9 mm w.e. in Figure 2a). As elevation decreases south, the discarded snow varies from about 121 mm w.e. yr^{-1} over the Colorado sub-catchment to about 10 mm w.e. yr^{-1} over Upper Maipo."

In the setup for the individual glaciers, we add the following comment (section 4.1.3, lines 339-343):

"In contrast to the model setup for the entire Maipo River Basin, in this setup we do not perform any corrections to account for sublimation or other mass removal apart from melt. However, as these models are calibrated on volume loss (thus including both losses by sublimation and melting), it can be assumed that glacier response is well captured, but the portioning of hydrological fluxes (sublimation versus runoff) is unconstrained."

4. For the snow cover evolution, no in-situ data is provided. Does such data exists? If yes, a comparison between the simulations of the snow cover with TOPKAPI and CAMEL-CL models should be made. Please give more details concerning the CAMEL-CL product (resolution, etc...).

Our simulation of SWE in the catchment has been calibrated and validated using the SWE reconstruction of Cortés and Margulis (2017), included in the CAMELS-CL database. In the revised version, we provide more details about these products.

Section 3.4 (lines 217-225):

"These basin-scale SWE estimates were aggregated by Álvarez-Garretón et al. (2018) from a daily gridded SWE reconstruction for the Andes Cordillera generated by Cortés and Margulis (2017) at a 180-m resolution. The SWE reconstruction was obtained from a data assimilation framework that integrates a land surface and depletion model, the assimilation of Landsat imagery, and the Modern Era Retrospective Analysis for Research and Applications (MERRA) reanalysis as a forcing dataset (Cortés et al., 2016; Cortés and Margulis, 2017). Although not all physical processes are included in the assimilation process (for example, blowing snow sublimation), the dataset has been validated at several sites across the Southern Andes (Cortés et al., 2016; Cortés and Margulis, 2017), and it should provide a good estimate of snow on the ground that can be used for hydrological modelling."

To further extend the validation of our model results, we add a new sub-section in the supplementary material ("Section S3: Additional model validation"). There, we include the comparison of direct measurements and simulated values of SWE at the DGA (Chilean Water Directory of Water Resources) monitoring site of Laguna Negra. Due to its length (5 pages), the new sub-section is given at the end of this document.

5. Recent studies underlined the importance of groundwater in mountainous catchments. Here in the model, it seems that no water flux into the ground exists. This cannot be true. Subterranean water fluxes may have an importance for the future of water resources.

We are aware that several studies have been uncovering the role of groundwater, both in sedimentary and in fractured rock systems, in mountainous catchments. TOPKAPI-ETH does indeed simulate sub-surface water fluxes (possibly our description at lines 245-248 of the original manuscript was too brief as to be noted), albeit in a simpler way than many dedicated groundwater models. Since we focus mainly on the snow and ice mass balance components of the water cycle, and given that we are able to validate the simulation of these components independently, we believe that the uncertainty associated with groundwater fluxes should not affect significantly the conclusions of our work. Additionally, the comparisons with observed streamflow in our work are conducted at stations located in narrow gorges with rock outcroppings, where subsurface fluxes should be minimum compared with surface river flow.

6. Please define 'glacier runoff'.

Glacier runoff is defined as the sum of rain, snowmelt and ice melt generated in the areas defined by the glaciers outlines in 1955. We acknowledge that this was stated relatively late in our article (lines 367-368). In the revised version, we provide this definition in the Introduction (Section 1, line 81).

7. If the model is oriented to be used for water management (as stated in the lines 544-547), please give results for daily simulations. What is the agreement between the simulations and the observations at daily time-step?

In the revised version, we provide an evaluation of simulated streamflow at a daily time step. However, since daily streamflow records at the outlet are not corrected for water extractions or the operation of the Embalse El Yeso dam (in opposite to the monthly records we used for calibration), we do not provide a direct comparison. Instead, we provide a comparison based on flow-duration curves. As suggested by reviewer 1, we also provide a comparison of model results with streamflow records at intermediate gauges.

All this information is included in the new sub-section of “Additional model validation” in the supplementary information of the article (also included at the end of this document).

8. I think that all the sections 6.3, should be moved at the beginning of the result section.

Reviewer 1 raised a similar comment. Section 6.3 aims at providing an integrated discussion of the uncertainties in our results, and we therefore prefer to improve the text rather than reshuffle its location. We do so by incorporating results from the previous sections, and comments from both reviewers.

Specific comments:

Abstract – line 14: please precise the time step of the simulated runoff

We have added this information (line 18):

“TOPKAPI-ETH is run at a daily time step using…”

Abstract – line 20: please precise the latitude range

We have added this geographical information (lines 14-15):

“We investigate glacier runoff in the period 1955-2016 in the Maipo River Basin (4 843 km2, 69.8-70.5°W, 33.0-34.3°S), semiarid Andes of Chile.”

Abstract – Please precise if the glacier area’s changes are taking into account in the model

TOPKAPI-ETH does take into account glacier area changes. To make this more explicit, we have added this sentence (lines 16-17):

“We model the mass balance, area and volume changes, and runoff contribution of 26 glaciers with the physically-oriented and fully-distributed TOPKAPI-ETH glacio-hydrological model, and extrapolate the results to the entire basin.”

This is also better explained in the model description of the revised version (section 4.1.1, lines 264-265):

“Negative annual mass balances can result in glacier area reductions, but no area increases due to positive mass balances are prescribed. Area changes are applied at the end of March.”

Line 81: “....estimate glacier changes....” please precise if it is surface, volume or both ?

In this line of the revise version we write (lines 79-81):

“Our main objective is to reconstruct glacier changes (area and volume) during the last six decades in one of the main catchments of the semiarid Andes, the Maipo River Basin, analyse the role of glaciers in the regional hydrology, and identify the main trends in glacier runoff.”

Line 95: “...., to which it provides most of the drinking water…” please specify the percentage (give a quantity).

We have now specified the percentage (lines 96-97):

“The basin is located in central Chile (~33°S, ~70°W), to the east of the Chilean capital city, Santiago (Figure 1a), to which it provides about 70% of its drinking water (DGA, 2004).”

Line 125: If I understand well, the outlines taken in 1955 are used for the year 2000 ? If the answer is yes, it is certainly not true. Please add more details.

We did not use the 1955 outlines for the year 2000. The year 2000 is the year the SRTM DEM refers to. We intersected that DEM with the outlines of the national glacier inventory, which was derived using images from 2003.

We have now explained this as (lines 127-128):

"For consistency with the DEM obtained from the Shuttle Radar Topography Mission (SRTM), we assume that the outlines in the national inventory from 2003 are also valid for 2000"

Lines 191-194: "....for the years 2004-2016....." How do you do before 2004?

This procedure is explained in the next paragraph of the article (lines 206-209):

"Values for air temperature gradients and cloud transmissivity in the study periods without information from CR2 and the Chilean solar radiation database (1955 to 1978 and 1955 to 2003, respectively) are randomly selected from a pool of values recorded in the same day of the year in the periods with available information."

Line 221: The model is "physically-oriented", so how do you do with the land cover and land use changes over the last decades? Please indicate clearly that in the article. If the changes are important, this should be taken into account in the model.

We thank the reviewer for this very good comment. We agree with the reviewer that land cover and land use changes can impact the hydrological simulations.

In the original article we explain how land use was derived in section 3.4 (lines 213-214):

"For modelling evapotranspiration and sub-surface water fluxes, we generate land use and soil types maps, respectively. The land use maps are extracted from the National Forest Corporation (CONAF) database (CONAF, 2013),…"

Unfortunately, to our knowledge, there are no data available to evaluate meaningful changes in land cover. We have now included that information (section 3.4, 230-232):

"To our knowledge, there are no enough detailed datasets to evaluate changes in land use throughout the study period, and we keep land use and soil types constant in our simulations."

Line 245: "....but no area increases due to positive mass balance are prescribed." This is not a valid statement as it is possible to observe glacier's advances. So if the model is "physically-oriented" this should be changed.

TOPKAPI-ETH has been defined as "physically-oriented" because it represents the main glacio-hydrological processes with the most relevant variables of each process. Examples are the ETI model for snow and ice melt (Pellicciotti et al., 2005), and the SnowSlide model for gravitational distribution of snow (Bernhardt and Schulz, 2010). Glacier advances are particularly difficult to model because they require an explicit simulation of ice flow, requiring information on ice rheology, basal sliding and internal deformation. The explicit simulation of ice flow would increase the computational cost to an extent that is not compatible with the purposes of this particular modelling exercise. Alternatively, ice flow models applicable to the basin scale have emerged only very recently (e.g. Zekollari et al., 2019), and are not included in TOPKAPI-ETH for the time being.

However, the deviations associated with positive glacier area and volume changes are implicitly taken into account by assuming an uncertainty in the volume-area scaling parameter "c". In any case, apart from some glacier advances in the 1980s and 2000s (Masiokas et al., 2016), no generalized or long-term advance phase has been documented in this region, so neglecting this process has a limited effect. Please see also our reply to comment 2.

In all this part, the time-step should be precised.

In the revised version we include:

- The time steps at which the model can be run when describing the model (Section 4.1.1, line 239)
  "…can be run at different spatial and time steps (typically hourly or daily),"
- The time step we used (daily) in our setups
  - (Section 4.1.2, lines 274-275): "The model is run continuously from 1955 to 2016 at a daily time step."
  - (Section 4.1.3, line 325): "The models are run at a daily time step starting in the year 1955,…"

In the model, the selected calibration and validation periods are unclear.

We have added these periods (section 4.1.2):

"The calibration of the Maipo River Basin model was performed for the period April 2003 to March 2016, and…"

"…, we use the period April 1984 to March 2003 for model validation."

Furthermore, details should be given concerning the snowfall/rainfall discrimination (T◦threshold ?).

Please see our reply to comment 3.

I don't understand why the ERA-interim and MERRA products are not tested in the model. Please explain why.

In our study, we use the CR2 products of precipitation and air temperature, which were computed using a statistical downscaling of ERA-Interim variables (lines 182-188, given here below). On the other hand, the SWE product is a reanalysis obtained through a combination of an energy balance model forced with MERRA, with data assimilation of Landsat snow cover. We operate under the assumption that the downscaled products are a better representation of the local conditions than ERA-interim and MERRA can be, as most of the local meteorological information have been used for downscaling CR2. A further validation of ERA-Interim and MERRA is beyond the scope of this study.

This information is present in the manuscript (Section 3.3, lines 190-196):

"The CR2 daily precipitation product was generated by means of a statistical downscaling of precipitation and moisture fluxes from the ERA-Interim reanalysis. The downscaling procedure is based on multiple linear regressions with topographic parameters, which were calibrated with quality-controlled precipitation records. The CR2 temperature product was obtained using near-surface temperature from ERA-Interim and land surface temperature (LST) from the Moderate Resolution Imaging Spectroradiometer (MODIS), by means of multiple regression models using LST as the explanatory variable and validated with local observations."

Line 315: What is the criterion "to fit the geodetic mass balances…"?

We have now specified the criterion as (section 4.1.3, lines 335-339):

"Glacier-wide mass balance is considered as fitted when the difference between the simulated and observed balance is smaller than a certain threshold. We find that choosing a threshold equal to half of the uncertainty in the geodetic mass balance allows for reliable simulations while keeping an acceptable computation time. The uncertainty of the geodetic mass balances is 3.2 and 1.2 m w.e. for the periods 1955-2000 and 2000-2003, respectively. "

Line 366 – 367: Please rewrite this sentence, unclear.

We change the original sentence: "The uncertainty in glacier runoff is estimated at each year as proportional to that calculated for glacier volume." into "At a particular year, the uncertainty in glacier runoff is estimated as a fraction of the same variable. That fraction is the same as that between glacier volume and its uncertainty in that year."

Fig. 1: please specify in the legend how the total ice volume is obtained

We include this information in the new caption of Figure 1:

"… (d) estimated total ice volume using the method developed by Huss and Farinotti (2012)"

Fig.6: you should add the uncertainty for each curve.

We have added an uncertainty band for the extrapolation of mass balance to the entire basin (Figure 6c). We did not do it for the external data (precipitation and temperature from CR2 products, and Echaurren Norte mass balance from DGA), because uncertainty is not provided in the datasets. The uncertainty in the mass balance of the sub-catchments is shown in the new Table 4 (suggested by reviewer 1). Please see the new Figure 6 below.

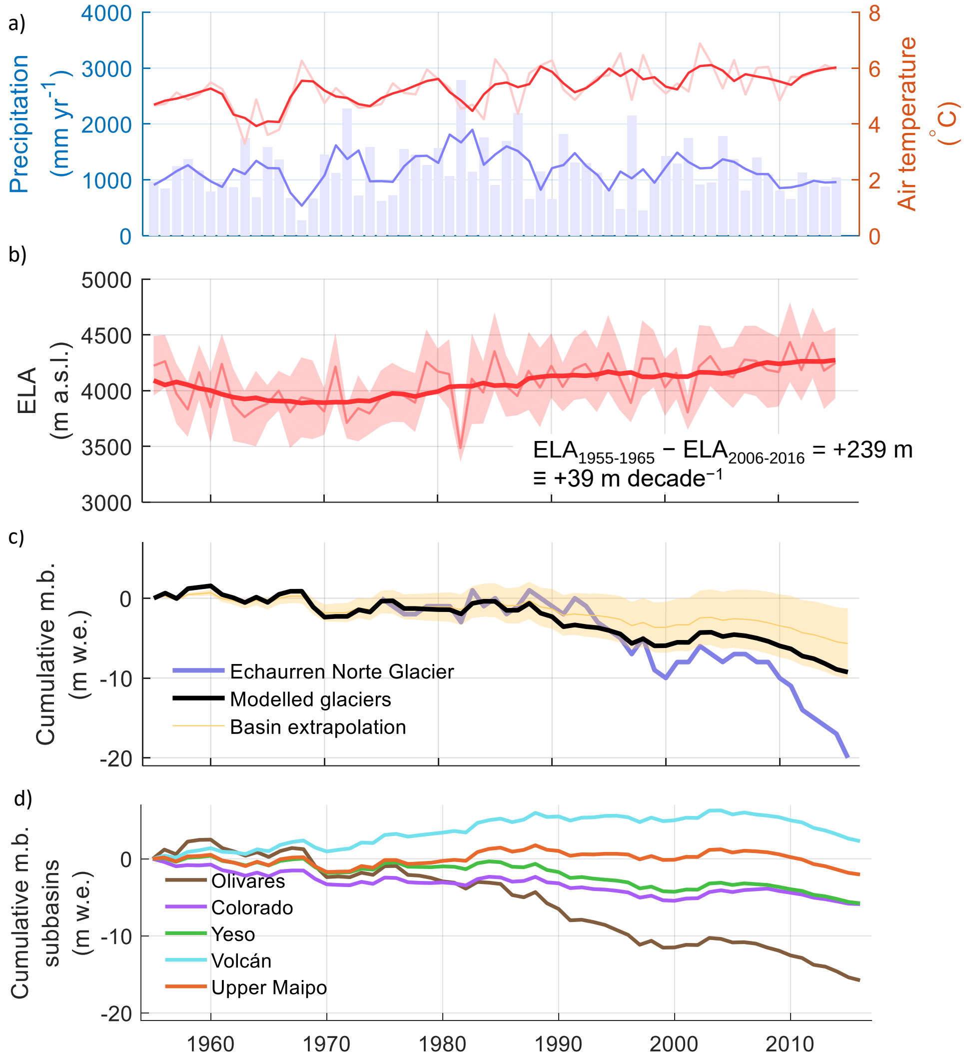


Figure 6: Variability of meteorological and glaciological variables in the Maipo River Basin over the period 1955-2016. (a) Air temperature and precipitation with a 3-year moving mean, (b) equilibrium line altitude (ELA), (c) cumulative glacier mass balance for the modelled glaciers (simulated with TOPKAPI-ETH), the entire basin (extrapolation) and its associated uncertainty, and the measurements on Echaurren Norte Glacier, and (d) cumulative glacier mass balance for each sub-catchment. In b), the difference between the ELA in the last 10 years (2006-2016) and the first 10 years (1955-1965) of the study periods is indicated, as well as the equivalent ELA increase rate. The shadowed area in (b) shows the standard deviation of the elevation of grid cells with a mass balance between –0.1 m w.e and 0.1 m w.e.

Fig. 7: Where is the subterranean part ?

In TOPKAPI-ETH, subsurface and groundwater flux components are routed and added to the total flow at every sub-catchment closing point. As such, they are considered in the total flow volumes and compared against river streamflow observations. In general, as these gauging stations are placed at locations where much of the overall basin flow is captured, there is not a major subterranean component to flow. Please see also our response to comment 5.

Please indicate the evolution of glacier volume and glacier area.

This information is found in Figure 9 and we don't think that repeating it here would be beneficial.

Fig. 8: In the figure 7, you indicate Rain = 3% and in the figure 8 you indicate Rain : 29+/-8 % , why?

While Figure 7 shows the runoff contribution from the area that was glacierized in 1955, Figure 8 shows the runoff contribution in the entire Maipo River Basin.

Tab. 1: Please indicate the tested ranges for each parameter and the references associated.

We have now provided the ranges and references. Note that we used ranges for only some of the parameters. For the rest of the rest of the parameters we used typical values from the literature since they showed good performance.

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New supplementary information for the article

Section S3: Additional model validation

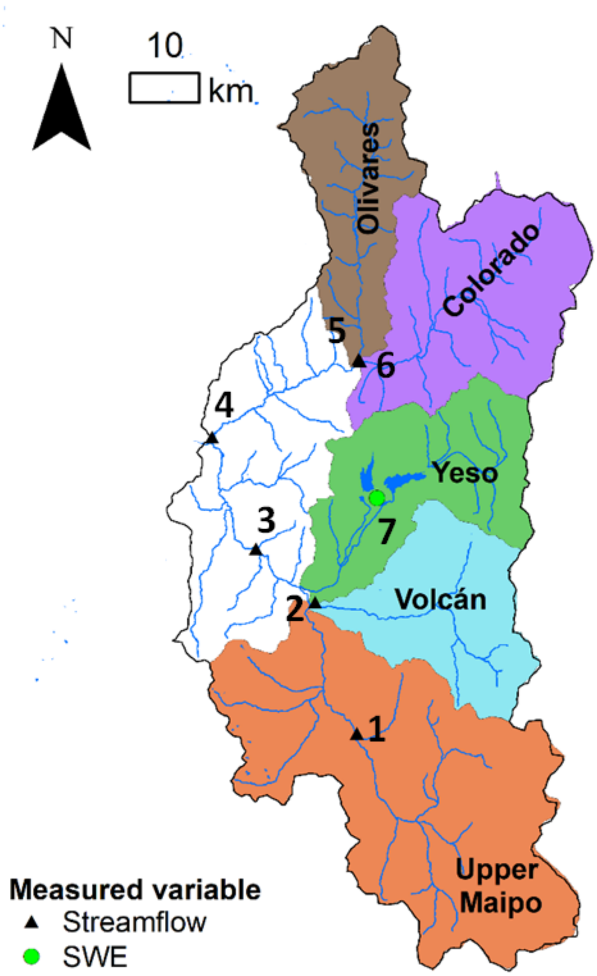
We present additional model validation using two datasets: i) six streamflow gauges at intermediate locations of the main catchment, and ii) SWE direct measurements at the Laguna Negra monitoring site of the DGA. The SWE measurements consist of 50 data points measured in the period 1969-2007. While Figure S2 shows the location of the gauges and Laguna Negra in the Maipo River Basin, figures S3 to S7 and Table S3 show results of the validation.

While our simulations of SWE at Laguna Negra compare well to the observations (Fig. S6-S7), this is not always the case for the streamflow values. This is partly because there are many water diversions that subtract water from the Maipo River and its tributaries, and some of the available streamflow records at intermediate gauges have not been corrected for these water extractions. However, considering that no specific calibration of the sub-surface parameters for the intermediate river sections was performed, results of the model validation are in general satisfactory at both monthly (Tab. S3 and Fig. S3-S4) and daily (Fig. S5) time scales.

Table S3: Results of the model validation at streamflow gauges at the monthly scale

Gauge	Time period	Average streamflow ($m^3 s^{-1}$)	Nash-Sutcliffe (NS)	Root Mean Square Error (RMSE) ($m^3 s^{-1}$)	Mean Bias (BIAS) (%)
Río Maipo en Las Hualtatas	1979-2013	32.3	0.63	15.6	-11.2
Río Volcán en Queltehues	1955-2015	8.1	0.61	6.1	-22.0
Río Maipo en San Alfonso	1955-2015	73.0	0.60	35.8	-12.2
Río Colorado antes junta río Olivares (*)	1978-2016	11.3	0.49	9.9	23.9
Río Olivares antes junta río Colorado (*)	1978-2016	6.0	0.26	7.0	-4.8
Río Colorado antes junta río Maipo (*)	1955-2015	30.3	0.26	17.4	19.6

(*): Available streamflow observations are not corrected for water extractions



Number	Name
1	Río Maipo en Las Hualtatas
2	Río Volcán en Queltehues
3	Río Maipo en San Alfonso
4	Río Colorado antes junta río Olivares
5	Río Olivares antes junta río Colorado
6	Río Colorado antes junta río Maipo
7	Laguna Negra

Figure S2: Location of intermediate streamflow gauges and the Laguna Negra snow monitoring site

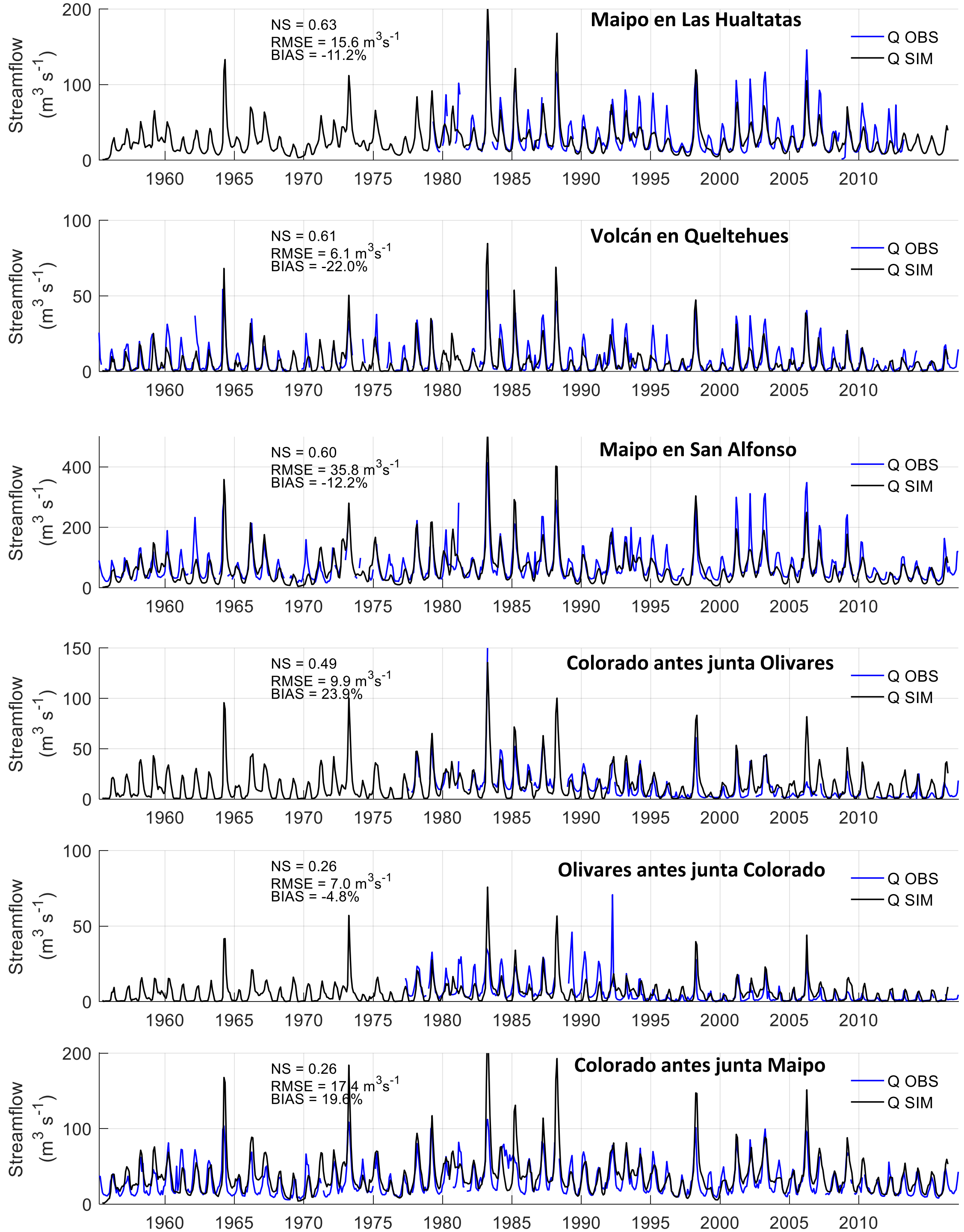


Figure S3: Validation of model results at six intermediate streamflow gauges. Monthly time series.

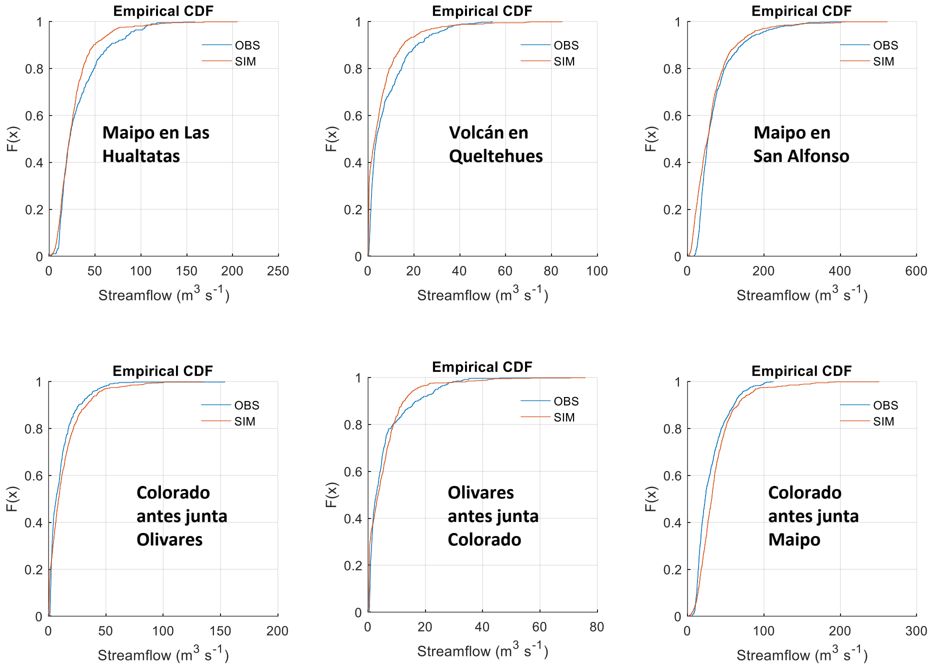


Figure S4: Validation of model results at six intermediate streamflow gauges. Flow-duration curves of monthly time series.

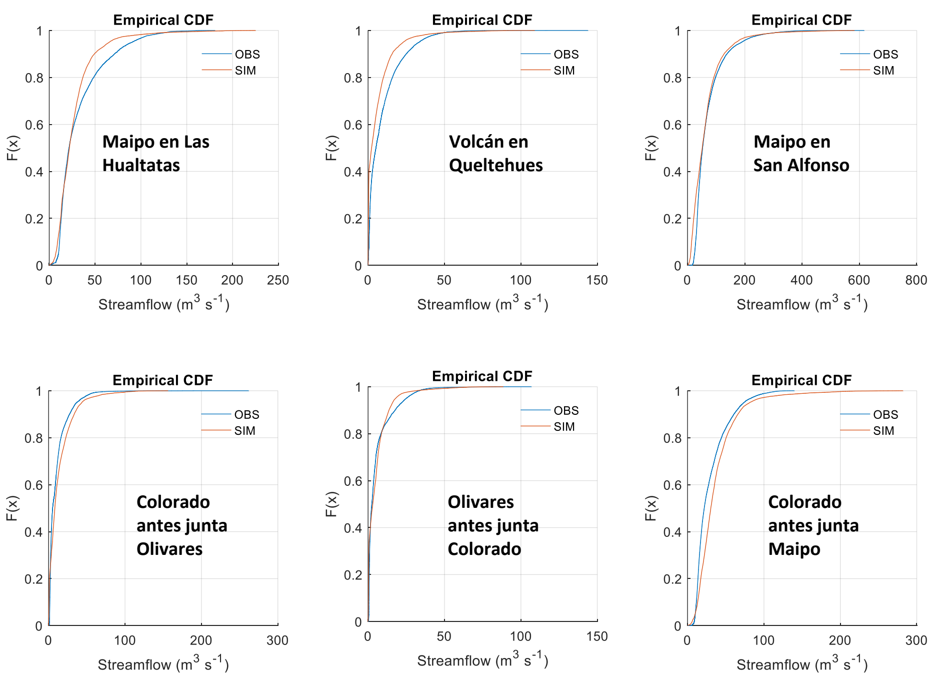


Figure S5: Validation of model results at six intermediate streamflow gauges. Flow-duration curves of daily time series.

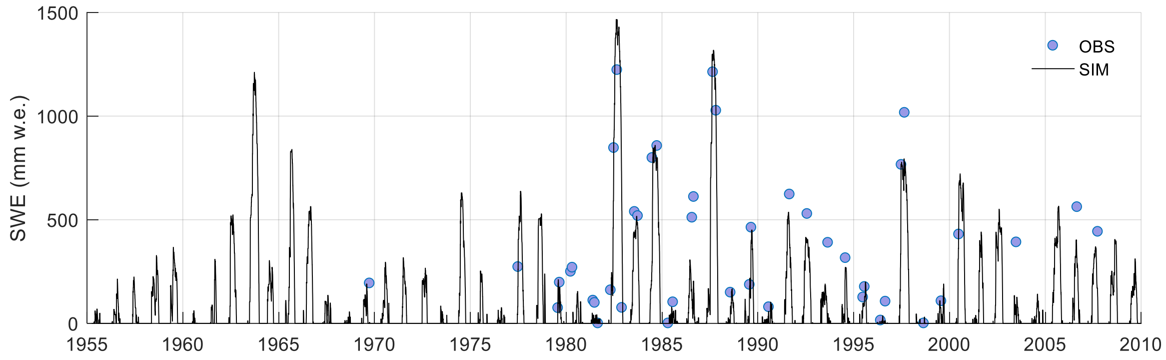


Figure S6: Validation of model results using SWE manual measurements at Laguna Negra (33.67°S, 70.11°W). The SWE measurements consist of 50 data points measured in the period 1969-2007. Daily time series of simulated values against observations.

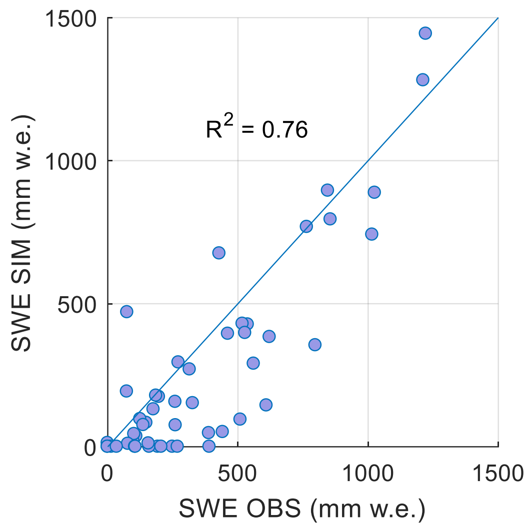


Figure S7: Validation of model results using SWE manual measurements at Laguna Negra (33.67°S, 70.11°W). The SWE measurements consist of 50 data points measured in the period 1969-2007. Scatter plot of observations and simulated values at the time of the measurements.

Glacier runoff variations since 1955 in the Maipo River Basin, semiarid Andes of central Chile

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Abstract. As glaciers adjust their size in response to climate variations, long-term changes in meltwater production can be expected, affecting the local availability of water resources. We investigate glacier runoff in the period 1955-2016 in the Maipo River Basin (4 843 km^2, 69.8-70.5°W, 33.0-34.3°S), semiarid Andes of Chile. The basin contains more than 800 glaciers covering 378 km^2 (inventoried in 2000). We model the mass balance and runoff contribution of 26 glaciers with the physically-oriented and fully-distributed TOPKAPI-ETH glacio-hydrological model, and extrapolate the results to the entire basin. TOPKAPI-ETH is run at a daily timestep using several glaciological and meteorological datasets, and its results are evaluated against streamflow records, remotely-sensed snow cover and geodetic mass balances for the periods 1955-2000 and 2000-2013. Results show that glacier mass balance had a general decreasing trend as a basin average, but with differences between the main sub-catchments. Glacier volume decreased by one fifth (from 18.6±4.5 to 14.9±2.9 km^3). Runoff from the initially glacierized areas was 177±25~~186±27~~ mm yr^{-1} (~~17~~16±7% of the total contributions to the basin), but it shows a decreasing sequence of maxima, which can be linked to the interplay between a decrease in precipitation since the 1980s and the reduction of ice melt. ~~If glaciers in the basin were in equilibrium with the climate of the last two decades,~~ Glaciers in the Maipo River Basin will continue retreating because they are not in equilibrium with the current climate. In a hypothetical constant climate scenario, glacier ~~their~~ volume would reduce~~be reduced~~ to 81±38% of the year 2000 volume, and glacier runoff ~~during dry periods~~ would be 78±30% of the 1955-2016 average~~61±24% of its maximum contribution in the period 1955-2016,~~. This would considerably decrease~~decreasing~~ the drought mitigation capacity of the basin.

1 Introduction

Most glaciers on Earth have retreated due to global atmospheric warming during the 20th century (Zemp et al., 2019). Glaciers that are still out of balance with the present climate are committed to lose part of their mass in the coming decades, even without further warming (Zemp et al., 2015; Marzeion et al., 2018), and major changes in their meltwater production can be anticipated (Bliss et al., 2014; Huss and Hock, 2018; IPCC, 2019). In the absence of precipitation changes, a temporary increase of meltwater generation from a retreating glacier occurs as a consequence of higher air temperatures and enhanced ablation, but after this transient phase, melt amounts decrease due to the reduction of the available snow, firn and ice volumes (Jansson et al., 2003). The period in which the annual melt volume reaches its long-term maximum has been termed "peak water" (Gleick and Palaniappan, 2010; Baraer et al., 2012). Global-scale studies indicate a large heterogeneity in the geographical distribution of peak water; while several catchments in Himalaya and Alaska are expected to increase their glacier runoff due to the enhanced ablation in the next decades and reach a maximum at some point of the 21st century, other regions in the world, such as the semiarid Andes, Central Europe and Western Canada, have already reached a regional maximum, and thus glacier runoff will only decrease in the future (Bliss et al., 2014; Huss and Hock, 2018). While these studies provide global trends that are key for macro-regional assessments, studies focusing on the catchment-scale can provide more specific information about local hydro-glaciological changes to communities and stakeholders for the generation of mitigation and adaptation strategies. Additionally, catchment-scale studies place glacier runoff in the context of other components of the water cycle, and evaluate the impacts of glacier changes on downstream areas.

In this study, we focus on glacier changes and their impacts on long-term glacier runoff contribution in the semiarid Andes. Melt water originated in the Andes are key for Chile and the western areas of Argentina, as it represents the main source for drinking water, agriculture, industry, mining and ecosystems. The climate of this region is characterized by its strong inter-annual variability of precipitation linked to periodic atmosphere-ocean variations over the Pacific Ocean (Montecinos and Aceituno, 2003; Falvey and Garreaud, 2007) and a sustained air temperature increase during the last decades (Carrasco et al., 2005; Burger et al., 2018). A few studies have estimated the present (Ragettli and Pellicciotti, 2012; Ayala et al., 2016; Burger et al., 2019) and future (Ragettli et al., 2016; Huss and Hock, 2018) glacier runoff contribution in the semiarid Andes, but its past variations have not been analysed in detail, mostly due to the lack of long-term glaciological data. As future climate scenarios anticipate a decrease in glacier runoff (e.g. Ragettli et al., 2016), the question of whether peak water has already occurred still remains open. The assessment of long-term changes in glacier runoff is particularly useful for water planners, because it provides reference information for the role of glacier meltwater in river flows, and the impacts that can be anticipated in the absence of its contribution.

Glaciers in the semiarid Andes underwent a major retreat in the 20th century (Le Quesne et al., 2009; Malmros et al., 2016), and the last two decades (Braun et al., 2019; Dussaillant et al., 2019). Historical documents, aerial photographs, and dendrochronological studies suggest that the general retreat trend started around the mid-19th century, but it has been interrupted by occasional periods of positive mass balance accompanied by glacier advances (Le Quesne et al., 2009; Masiokas et al., 2009). Masiokas et al. (2016) performed a reconstruction of the annual mass balance of Echaurren Norte Glacier (3650-3900 m a.s.l.) since 1909 using a simple glacier mass-balance model forced with monthly precipitation and air temperature. The model was verified against streamflow records and direct mass balance measurements on the glacier, where the first mass balance monitoring programme in the Southern Andes started in 1975. Masiokas et al. (2016) found a general retreat interrupted by three periods of sustained positive mass balances in the 1920-30s, 1980s and 2000s. The latter, positive or balanced mass budget in the semiarid Andes in the 2000-2009 period has been recently verified by geodetic mass balances (Braun et al., 2019; Dussaillant et al., 2019; Farías-Barahona et al., 2019b), and has been supported by independent modelling results (Burger et al., 2019). As the findings by Masiokas et al. (2016) are based on a relatively simple model applied to only one glacier at low elevation (<4000 m a.s.l.), they cannot be extrapolated to other glaciers. This is especially true due to the large spatial variability of response times and retreat rates reported for this region (Malmros et al., 2016). Thus, a more detailed analysis based on the specific characteristics of each glacier is needed to complement these results and estimate regional changes of ice volume and glacier runoff. From a climatic perspective, glacier retreat in the semiarid Andes has been driven by a general temperature increase and modulated by a strong temporal variability of precipitation. Air temperature showed an increasing trend of about 0.25°C decade^{-1} in the period 1979-2006 (Falvey and Garreaud, 2009), mostly explained by a spring and autumn warming (Burger et al., 2018), which can be used to explain an increase of the 0°C isotherm and the regional Equilibrium Line Altitude (ELA) (Carrasco et al., 2005, 2008). Precipitation, on the other hand, exhibited an average decrease of –65 mm (–7.1%) decade^{-1} in the period 1979-2016 (Boisier et al., 2016), although with a large inter-annual and -decadal variability (Montecinos and Aceituno, 2003).

Our main objective is to reconstruct glacier changes (area and volume) during the last six decades in one of the main catchments of the semiarid Andes, the Maipo River Basin, analyse the role of glaciers in the regional hydrology, and identify the main trends in glacier runoff. Glacier runoff is defined as the water originating from ice melt, snowmelt and rain over a given glacier. Additionally, we estimate glacier changes under synthetic scenarios of committed ice loss, in which air temperature, precipitation and cloudiness are assumed to stay at their current levels until the end of the century. We use these scenarios for i) understanding how far the glaciers are from an equilibrium after the climatic changes that took place in the period 1955-2016, and ii) providing a baseline for the future changes in hydrology that the basin will experience in any case, i.e. even in the hypothetical case that climate change was to stall. ~~Such a scenario can be used to compute the minimum changes that glaciers will experience due to past changes of the climate.~~ They are thus highly conservative and do not correspond to a realistic projection for the future. The calculation of glacier changes and runoff contribution is carried out for a subset of the largest glaciers using the physically-oriented and fully-distributed TOPKAPI-ETH glacio-hydrological model (Ayala et al., 2016; Ragettli et al., 2016), and the resulting mass balances are extrapolated to the entire basin (Huss, 2012). We set up the glacier model using glacier inventories, Digital Elevation Models (DEMs) and estimates of ice thickness, and we force it with a combination of local meteorological stations and reanalysis data for precipitation, air temperature and solar radiation. The model is calibrated and validated using remotely-sensed snow cover, streamflow records, and geodetic mass balances covering the periods 1955-2000 and 2000-2013 (Braun et al., 2019; Farías-Barahona et al., 2019a).

2 Study area

The study focuses on the headwaters of the Maipo River Basin (for simplicity we hereafter refer to these areas as the Maipo River Basin). The basin is located in central Chile (~33°S, ~70°W), to the east of the Chilean capital city, Santiago (Figure 1a), to which it provides about 70% of most of its drinking water (DGA, 2004). The basin outlet is the Maipo en El Manzano gauging station, which roughly marks the boundary between rural mountain areas and Santiago urban districts. The selected basin has an area of 4 843 km^2, its elevation ranges from 850 to 6570 m above sea level (a.s.l.), and more than 800 glaciers covering about 378 km^2 (7.8% glacierized) were inventoried in 2000 (Barcaza et al., 2017). The Maipo River and its tributaries are the primary source for drinking water, agriculture, hydropower, and industry in the region, which concentrates about 40% of the country's population. The region has a Mediterranean-type climate, with a strong seasonality characterized by cold and wet winters, and hot and dry summers. Average precipitation in Santiago was 308 mm yr^{-1} in the period 1950-2018, but values as low as 69 mm yr^{-1} and as high as 712 mm yr^{-1} have been registered, with a coefficient of variation of 0.45. Recurrent droughts have been reported since the beginning of hydro-meteorological records. Precipitation amounts are, in general, larger towards the south and towards higher elevations. An early study estimated that glacier runoff in the Maipo River Basin represents about 34% of the total discharge in February, and up to 67% during summer months of dry years, such as 1968-1969 (Peña and Nazarala, 1987).

There are five major sub-catchments in the study area, from north to south: Olivares, Colorado, Yeso, Volcán and Upper Maipo (Figure 1b). According to the national Chilean inventory (Barcaza et al., 2017) (described in next section), the highest glacierized sites are in the Olivares and Colorado sub-catchments, with mean elevations between 4200 and 4500 m a.s.l., and some glaciers reaching elevations higher than 5500 m a.s.l. (Figure 1c). The Upper Maipo sub-catchment, on the other hand, has the lowest-lying glaciers, with mean elevation varying between 3500 and 4000 m a.s.l., and several glaciers reaching elevations below 3000 m a.s.l. (Figure 1c). Glacierized areas vary from 40 km^2 in the Volcán sub-catchment to 99 km^2 in Colorado. Upper Maipo has the largest number of individual glaciers (348), and most of them correspond to low-elevation, rock and debris-covered glaciers (Figure 1d). In general, glacier size tends to decrease towards the south, with the largest glaciers being located in Olivares (Juncal Sur, Olivares Gama, and Olivares Beta glaciers), and on the slopes of Tupungatito and Marmolejo volcanoes (Volcán Tupungatito, Azufre and Marmolejo glaciers) in the Colorado sub-catchment. Another series of relatively large glaciers corresponds to debris-covered ones, such as Pirámide, Loma Larga, and Cerro Castillo glaciers.

3 Data

3.1 Geographic and topographic information

Glacier outlines are extracted from the national Chilean inventory (Barcaza et al., 2017) and the Marangunic inventory (Marangunic, 1979). While the information for the Maipo River Basin in the national inventory was produced using two satellite images from the Landsat Enhanced Thematic Mapper ETM+ of 2003, the Marangunic inventory was mostly based on aerial photographs taken in 1955 during a national geodetic programme, and maps presented by Lliboutry (1956) for the few missing areas. For consistency with the DEM obtained from the Shuttle Radar Topography Mission (SRTM)~~ for the year 2000~~, we assume that the outlines ~~derived from~~in the national inventory from 2003 are also valid for 2000~~that year~~. Additionally, the glacierized areas in the national inventory that are not identified as such in 1955 (mostly rock glaciers and debris-covered areas) are added to the 1955 inventory. In this study, we assign an error of 5% to the year 2000 inventory, which is a common choice for glacier inventories (Paul et al., 2013), and has been used for this inventory in particular (Barcaza et al., 2017)~~ (Paul et al., 2013), and we double this value for the year 1955 inventory~~. As the inventory of 1955 suffers from additional errors (such as the presence of snow patches that likely made the interpretation of glacierets difficult, and the use of Lliboutry maps to fill missing areas), we assume an error of 10% for that year. Based on the resulting inventories, we estimate that the total glacier area changed from 532~~558~~ km^2 in 1955 to 378 km^2 in 2000 (–28.9~~32.3~~%), and that the number of individual glaciers decreased from 861 to 854. Although some small glaciers might have effectively disappeared, the decreasing trend in the total number of glaciers is also balanced by the fragmentation of large glaciers, such as the Olivares Alfa glacier complex, into several smaller units (Malmros et al., 2016).

In addition to the glacier inventory, we generate a mask of debris-covered glacier areas from the same Landsat images that were used to produce the Chilean glacier inventory. For this, we use the semi-automatic method based on band ratio segmentation of TM4 and TM5 Landsat bands (Paul et al., 2004), and we manually correct the results using Google Earth imagery. For the year 1955, we maintain the same debris-cover maps as in the 2000-2010 period, i.e. assuming that no major changes have occurred in the extension of debris cover, but we delete small debris-covered areas on the upper glacier areas.

In our analyses, we use the DEMs for years 1955, 2000 and 2013, and the geodetic mass balance datasets for the periods 1955-2000 and 2000-2013, calculated by Farías-Barahona et al. (2019a) and Braun et al. (2019). While the DEMs for 2000 and 2013 correspond to a part of the products generated in the study of Braun et al. (2019) for the entire South-American Andes, the DEM for 1955 and the geodetic mass balance for the period 1955-2000 was produced in the study of Farías-Barahona et al. (2019a), who extended the period of analysis of Braun et al. (2019) for the Maipo River Basin. Here, we provide a brief description of the derivation of these datasets, but more details are included in the supplementary information. The 1955 DEM was calculated from digitized 50-m contour lines of the 1:50’000 official Chilean cartography product, which was also obtained from the 1955 geodetic programme. While the DEMs for the year 2000 were extracted from the SRTM product, the DEM of Maipo River Basin for 2013 was derived from TanDEM-X post-processed products (which for this region correspond to the year 2013). The DEMs were co-registered following Nuth and Kääb (2011). Errors from the geodetic mass balances were assessed over stable ground, and calculated using a standard error propagation procedure, including typical error sources such as radar penetration signal. Two glaciers (San Francisco and Mirador del Morado) were discarded from the geodetic mass balance, because the original SRTM product was not available for those areas (only the void-filled product). As rock glaciers exhibit changes that are smaller than the estimated uncertainties, they were also discarded from the geodetic mass balance.

3.2 Ice thickness

Distributed glacier ice thickness in 2000 is estimated for all individual glaciers using the method of Huss and Farinotti (2012) with the glacier outlines and the SRTM DEM. Standard model parameters are used except for glaciers classified as debris-covered or rock glaciers. For these two types of ice bodies, the parameter prescribing ice flux is substantially reduced to obtain thicknesses comparable to the direct thickness observations on the debris-covered Pirámide Glacier and its neighbouring rock glaciers (DGA, 2012). The obtained ice thickness estimates compare well with Ground Penetrating Radar (GPR) measurements (DGA, 2014) on Volcán Tupungatito (1685 data points) and Marmolejo (1544 data points) glaciers extracted from the Glacier Thickness Database (GlaThiDa) (Gärtner-Roer et al., 2014), for which we find a Root Mean Square Error (RMSE) of 9.8 and 8.5 m, respectively.

Once the distributed ice thickness is calculated for every glacier for the year 2000, we use the geodetic mass balance in the period 1955-2000 to estimate the ice thickness distribution in 1955. In this procedure, we find the problem that for some grid cells showing a positive elevation change from the geodetic mass balance for the 1955-2000 period, the ice thickness in year 2000 is too small, resulting in an inferred negative thickness. To avoid this, and obtain ~~a~~ meaningful 1955 ice thicknesses that are consistent with both the geodetic mass balance and the glacier inventory, we assign the year 2000 ice thickness to 1955 in these grid cells and add the estimated positive elevation change. In this way, we obtain a corrected ice thickness value in 2000 for 4.8% of the glacierized area. As no geodetic mass balance was calculated for rock glaciers they are assumed to have the same thickness in 1955 as in year 2000. A similar result was found in the study of Bodin et al. (2010) for rock glaciers near Santiago. Finally, to calculate the 1955 ice thickness of small glaciers that are not included in the year 2000 inventory, we use the 1955 glacier areas from the glacier inventory and a scaling relation to calculate mean ice thickness ($\bar{h}$) as a function of the glacier area (S), and assume average thickness to be valid for every grid cell in these glaciers:

$$\bar{h} = c \cdot S^{\gamma-1}, \quad (1),$$

where γ=1.357 and c=28.5 are standard parameters in the area-volume scaling theory (Chen and Ohmura, 1990).

At the basin-scale, we find a total ice volume of 18.6±4.1 km^3 and 16.1±2.4 km^3 for 1955 and 2000 (a change of −13.8%), respectively. Based on the geodetic mass balances for period 2000-2013, we estimate a total ice volume of 15.2±3.2 km^3 for year 2013 (a change of −18.4% relative to 1955). For the total ice volume of the investigated basin, we assume an uncertainty of 15% in year 2000. This is between the values estimated by Huss and Farinotti (2012) for regional totals (~12%), and the value estimated by Farinotti et al. (2017) for individual glaciers (~21%). The uncertainty in the total ice volume in 1955 and 2013 is larger than in 2000 since it also includes the uncertainty from the geodetic mass balances. In the calculation of glacier volumes, we implicitly assume that no basal melting takes place. The error introduced by neglecting this process is much less than the uncertainty associated with the ice thickness estimates and the geodetic mass balance.

3.3 Hydro-meteorological data

Precipitation and temperature data for the period 1979-2016 are derived from daily gridded products developed by the Centre for Climate and Resilience Research in Santiago, Chile (CR2, www.cr2.cl). These products were generated for a national water balance study led by the Chilean directorate of water resources (DGA) (DGA, 2017; Álvarez-Garretón et al., 2018). The CR2 daily precipitation product was generated by means of a statistical downscaling of precipitation and moisture fluxes from the ERA-Interim reanalysis. The downscaling procedure is based on multiple linear regressions with topographic parameters, which were calibrated with quality-controlled precipitation records. The CR2 temperature product was obtained using near-surface temperature from ERA-Interim and land surface temperature (LST) from the Moderate Resolution Imaging Spectroradiometer (MODIS), by means of multiple regression models using LST as the explanatory variable and validated with local observations. For our study, while the CR2 precipitation product is linearly interpolated from its original resolution (0.05°) to the spatial resolutions of our glacio-hydrological models (1 km and 100 m, see sections 4.1.2 and 4.1.3) to generate monthly average maps, the CR2 temperature product is used to generate basin-scale daily temperature lapse rates.

Daily cloud transmissivity of solar radiation is calculated from the Chilean solar radiation database (http://www.minenergia.cl/exploradorsolar/) for the period~~years~~ 2004-2016 at the location of Embalse El Yeso meteorological station, which is placed close to the centroid of the Maipo River Basin, and assumed to be uniform over the catchment. The solar radiation database was derived using reanalysis data to force a radiative transfer model for clear-sky solar irradiance and an empirical model based on satellite data for cloudy conditions (Molina et al., 2017).

In addition to the information from the CR2 products, we use local records of air temperature and precipitation from Embalse El Yeso and Quinta Normal (located in Santiago) meteorological stations, respectively, as a base for extrapolating these variables during the period 1955-1978 (see sections 4.1.2 and 4.1.3). Values for air temperature gradients and cloud transmissivity in the study periods without information from CR2 and the Chilean solar radiation database (1955 to 1978 and 1955 to 2003, respectively) are randomly selected from a pool of values recorded in the same day of the year in the periods with available information. Finally, streamflow data for the Maipo River Basin are available as monthly mean records at the gauging station of Maipo en El Manzano. These time series were already corrected for extractions and reservoirs to approximate the natural flow in the study of CONIC-BF (2008).

3.4 Additional datasets

To calibrate and validate the snow processes in the study area, we use two products: (i) post-processed MODIS snow-cover area (SCA), downloaded from an online platform (http://www.dgf.uchile.cl/rene/MODIS/) that automatically calculates SCA from MODIS Terra and Aqua satellites products at a spatial resolution of 500 m in several Chilean river basins, and (ii) daily basin-scale snow water equivalent (SWE) estimates for the period 1984-2014, extracted from the Chilean version of the Catchment Attributes and Meteorology for Large Sample Studies (CAMELS-CL) database (http://camels.cr2.cl/). These basin-scale SWE estimates were aggregated by Álvarez-Garretón et al. (2018) from a daily gridded SWE reconstruction ~~product~~ for the Andes Cordillera generated by Cortés and Margulis (2017) at a 180-m resolution~~et al. (2017)~~. The SWE reconstruction was obtained from a data assimilation framework that integrates a land surface and depletion model, the assimilation of Landsat imagery, and ~~at a 180-m resolution using a data assimilation framework of~~ the Modern Era Retrospective Analysis for Research and Applications (MERRA) reanalysis ~~and Landsat imagery~~as a forcing dataset (Cortés et al., 2016; Cortés and Margulis, 2017). Although not all physical processes are included in the assimilation process (for example, blowing snow sublimation), the dataset has been validated at several sites across the Southern Andes (Cortés et al., 2016; Cortés and Margulis, 2017), and it should provide a good estimate of snow on the ground that can be used for hydrological modelling.

For modelling evapotranspiration and sub-surface water fluxes, we generate land use and soil types maps, respectively. The land use maps are extracted from the National Forest Corporation (CONAF) database (CONAF, 2013), and the same maps are used to estimate the spatial distribution of soil types in the basin. For simplicity, and due to the absence of more detailed data, we define only two soil types based on the presence or absence of vegetation. The vegetated soil type dominates areas at low elevations and close to streams, whereas the no-vegetated one dominates on mountain slopes. To our knowledge, there are no enough detailed datasets to evaluate changes in land use throughout the study period, and we keep land use and soil types constant in our simulations.

4 Methods

4.1 TOPKAPI-ETH

4.1.1 Model description

TOPKAPI-ETH is a physically-oriented, fully distributed, glacio-hydrological model that was adapted from a rainfall-runoff model (Ciarapica and Todini, 2002) to simulate snow cover evolution and glacier mass balance in high-mountain areas. The model has been used successfully in the semiarid Andes (Ragettli et al., 2014; Ayala et al., 2016), the Alps (Fatichi et al., 2014, 2015) and the Himalaya (Ragettli et al., 2013, 2015), can be run at different spatial and time steps (typically hourly or daily), and it is well-suited for long-term simulations (Ragettli et al., 2016).

TOPKAPI-ETH is forced with time series of precipitation, air temperature and cloud transmissivity of solar radiation. The model simulates snowfall at a given grid cell when precipitation occurs and air temperature is below a threshold parameter. If air temperature is above that threshold, precipitation is considered as rain. When snow accumulation exceeds a slope-dependent threshold of a given grid cell (snow holding depth, S_{hd}), excess snow is moved to a lower grid cell based on the SnowSlide gravitational transport model (Bernhardt and Schulz, 2010):

$$S_{hd} = SGR_C \cdot e^{SGR_a \cdot SLP}, \qquad (2),$$

where SGR_C (m) and SGR_a are empirical parameters and SLP is the slope of the grid cell. Snow and ice melt is calculated with the Enhanced Temperature-Index (ETI) model (Pellicciotti et al., 2005), depending on the net solar radiation and near-surface air temperature:

$$M = \begin{cases} SRF \cdot S_{in} \cdot (1-\alpha) + TF \cdot T_a, & T_a > T_T \\ 0, & T_a \leq T_T \end{cases}, \qquad (3),$$

where M is melt (mm h^{-1}), SRF is the shortwave radiation factor (mm m^2 h^{-1} W^{-1}), S_{in} is the incoming shortwave radiation (W m^{-2}), α is surface albedo, TF is the temperature factor (mm h^{-1} °C), T_a is air temperature (°C), and T_T is the air temperature threshold parameter for the onset of melt (°C). TOPKAPI-ETH internally converts the units of the ETI variables and parameters to a daily time~~-~~step. TOPKAPI-ETH does not compute sublimation. To calculate ice melt under supra-glacial debris we also use the ETI model but with reduced melt factors (see section 4.1.3). Although TOPKAPI-ETH includes a melt module that accounts for debris thickness in the computation of sub-debris ice melt, we did not to use it due to the lack of debris thickness information in the region, and the large uncertainties that are present in large-scale estimates of debris thickness (Rounce and McKinney, 2014; Schauwecker et al., 2015). As a result of our assumptions, we expect that some of the spatial patterns of glacier ablation induced by the spatial variability of supraglacial debris thickness are not accurately represented in our simulations.

Once snow accumulation and melt are integrated to calculate the annual glacier surface mass balance, TOPKAPI-ETH translates it to elevation changes at the end of each hydrological year (from April to March) by means of the Δh-approach (Huss et al., 2010). This is done by using the originally-proposed, glacier-size dependent parameters (cf. Fig 3b in Huss et al. (2010)). Negative annual mass balances can result in glacier area reductions~~At the end of March, if the annual mass balance was negative the model performs a reduction of glacier area~~, but no area increases due to positive mass balances are prescribed. Area changes are applied at the end of March. While snow melt over a non-glacierized grid cell is added to the respective soil layers, snow and ice melt over glaciers are added to a conceptual water reservoir for each glacier, which releases its water by means of a linear reservoir equation (Jansson et al., 2003). In non-glacierized grid cells, the model simulates subsurface water flow, evapotranspiration, and water routing (Ciarapica and Todini, 2002).

4.1.2 Model setup for the Maipo River Basin

We setup an instance of the TOPKAPI-ETH model for the entire Maipo River Basin at a spatial resolution of 1 km that does not include glaciers. Glaciers and their runoff contribution are accounted for separately in the next section, but their ice melt contribution is included in this section for the calibration of the sub-surface parameters. The objective of the 1-km resolution setup for the entire Maipo River Basin is to simulate snowmelt and rain, which account for the largest runoff volumes in the basin, at a resolution that allows for multiple model runs and the automatic calibration of the sub-surface flow parameters. The model is run continuously from 1955 to 2016 at a daily time~~-~~step.

We spatially distribute daily precipitation over the basin using monthly mean maps derived from the CR2 precipitation product. The spatial distribution is made from basin-averaged precipitation extracted from the CAMELS-CL database (Álvarez-Garretón et al., 2018) for the period 1979-2016, and from Quintal Normal station for the period 1955-1978. Daily mean air temperature is extrapolated from Embalse El Yeso using basin-scale daily temperature lapse rates (see section 3.3). Periods with no direct information of daily mean air temperature at Embalse El Yeso are filled using correlation with records of daily extreme temperatures at the same station (mainly the period 1962-1977) or at Quinta Normal station (1955-1979).

The calibration of the Maipo River Basin model was performed for the period April 2003 to March 2016, and consists of two steps: (i) the snow parameters are varied in order to fit ~~basin-scale~~ SCA and SWE aggregated at the scale of the entire basin from ~~against~~ the MODIS and CAMELS-CL datasets~~products~~ (section 3.4), and (ii) the parameters controlling sub-surface fluxes are varied in order to fit monthly mean streamflow records at Maipo en El Manzano. While parameters in step (i) are manually calibrated and largely correspond to default values from previous studies using TOPKAPI-ETH, parameters in step ii) are automatically calibrated minimizing three different evaluation metrics (Nash-Sutcliffe (NS), Root Mean Squared Error (RMSE), and mean bias (BIAS)). As the SWE reconstruction data are available starting on 1984, we use the period April 1984 to March 2003 for model validation.

During the calibration procedure, we find that the use of the precipitation amounts derived from the CR2 product leads to an underestimation of SCA and SWE over the basin area, and streamflow at the basin outlet. This underestimation of precipitation by the CR2 product was already identified by Álvarez-Garretón et al. (2018) when analysing runoff ratios across Chile, and attributed to a limitation of satellite-derived precipitation estimates over high-elevation areas. Similar results have been found in this region using a regional climate model driven by ERA-Interim (Bozkurt et al., 2019), and the MERRA reanalysis (Cortés et al., 2016). Although the CR2 precipitation product corrects the ERA-Interim values by comparing ~~contrasting~~ them with ground data, these data are available only below 3000 m a.s.l. in this region, and have not been corrected for gauge undercatch (DGA, 2017), which can also contribute to the underestimation of precipitation at the highest elevations (Rasmussen et al., 2012). We obtain a precipitation correction factor by manually fitting the observed and modelled curves of SCA and SWE, and at the same time closing the water balance of the basin. We obtain a value of +50%~~In our study, to fit the seasonal average curves of SCA and SWE, and close the water balance of the basin, we correct the precipitation derived from the CR2 product~~

~~by 50%~~. This correction generates precipitation amounts in the order of 3 to 4 times larger than that registered on low-lying areas. This value is larger than those estimated by previous studies on the west side of the semiarid Andes (Falvey and Garreaud, 2007; Viale et al., 2011; Cortés et al., 2016), which estimated that the orographic effect results in a precipitation enhancement in the order of 2 to 3. The spread of precipitation amounts estimates over the semiarid Andes (and in general over mountain areas) is in fact large, and previous hydrological studies have performed different types of corrections to close the water balance at the basins' scale (Vicuña et al., 2011; Ragettli and Pellicciotti, 2012; Burger et al., 2019).

An additional aspect of model simplifications ~~problem~~ identified during the model calibration is that air temperature over areas above 5000 m a.s.l. (about 5% of the basin) is most of the time lower than the air temperature threshold parameter for melt onset, generating large snow accumulation that is not seen in the SWE reconstruction product. As snow on this high-elevation areas is in reality removed by wind transport and sublimation, we reset the SWE in the model to zero at the beginning of each hydrological year. Although this implies that the model is not strictly mass-conserving, we verify that the discarded snow is in average 34 mm yr^{-1} over the entire basin (or 688 mm yr^{-1} = 1.9 mm d^{-1} over the areas above 5000 m a.s.l.), which is similar to the estimates ~~a reasonable estimate~~ of sublimation amounts for this region ~~–~~(Corripio, 2003; Ayala et al., 2017a, 2017b)~~(Corripio, 2003; Ayala et al., 2017a)~~, and is in the order of the model uncertainties (49.9 mm w.e. in ~~see~~ Figure 2a). As elevation decreases south, the discarded snow varies from about 121 mm w.e. yr^{-1} over the Colorado sub-catchment to about 10 mm w.e. yr^{-1} over Upper Maipo.

Figure 2 shows the results of the model calibration for daily time series of SWE (Figure 2a), monthly time series of streamflow (Figure 2b), and seasonal variations of SCA (Figure 2c), SWE (Figure 2c) and streamflow (Figure 2d). The final calibrated snow parameters for this setup are shown in Table 1, whereas values for the sub-surface flux parameters are shown in the supplementary information (Table S1). The quality metrics for snow and streamflow variables show very good results in both the calibration and validation periods. Extreme values are well captured, except for the humid winter of 1988, in which the model underestimates snow accumulation and streamflow.

4.1.3 Model setup for individual glaciers

In addition to the basin-scale model, we set up an instance of TOPKAPI-ETH for each one of the glaciers larger than 1 km^2 in the catchment (about 59 glaciers). These instances have a spatial resolution of 100 m, which is more adequate to simulate the processes governing glacier mass balance. The domain of these models runs correspond approximatively to the smallest catchment that contains the 1955 glacier extent of each glacier. The models are run at a daily time~~-~~step starting in the year 1955, and are then re-started in 2000 using the topographic and geographic information from that year. The models are forced using daily precipitation at the location of the centroid of each glacier, linearly interpolated from basin-averaged precipitation (including the 50% precipitation correction) (Álvarez-Garretón et al., 2018), and assumed uniform over each corresponding domain. Air temperature is extrapolated from the Embalse El Yeso meteorological station using a constant air temperature gradient equal to the environmental lapse rate (-6.5 °C km^{-1}). For the study period in which no CR2 precipitation products are available, the Quinta Normal and Embalse El Yeso stations are used.

We choose a set of model parameters typically used in the literature for this region (Ragettli and Pellicciotti, 2012; Ayala et al., 2016; Burger et al., 2019) for all individual glacier models and keep parameter calibration at a minimum level. For each glacier, we vary only the ETI model parameters within ranges suggested in the literature (Finger et al., 2011; Ragettli and Pellicciotti, 2012; Ayala et al., 2017b) to fit the glacier-wide mass balance as derived from the geodetic mass balances. Glacier-wide mass balance is considered as fitted when the difference between the simulated and observed balance is smaller than a certain threshold. We find that choosing a threshold equal to half of the uncertainty in the geodetic mass balance allows for reliable simulations while keeping an acceptable computation time. The uncertainty of the geodetic mass balances is 3.2 and 1.2 m w.e. for the periods 1955-2000 and 2000-2003, respectively. In contrast to the model setup for the entire Maipo River Basin, in this setup we do not perform any corrections to account for sublimation or other mass removal apart from melt. However, as these models are calibrated on volume loss (thus including both losses by sublimation and melting), it can be assumed that glacier response is well captured, but the portioning of hydrological fluxes (sublimation versus runoff) is unconstrained. A summary of literature-derived and calibrated parameters for the individual models is shown in Table 1. Within each model, melt factors for debris-covered areas are fixed to 25% of the values for debris-free areas. The 25% factor is estimated from the comparison between melt rates on debris-free and debris-cover sites on Piramide, Bello and Yeso glaciers in the Estero del Yeso catchment (Ayala et al., 2016; Burger et al., 2019), a sub-catchment of the Maipo River Basin.

Although we set up a TOPKAPI-ETH model for all glaciers with an area above 1 km^2 in 2000 (equivalent to 59 glaciers), we find that staying within the selected ranges for the ETI parameters only allows to fit the geodetic mass balances in 26 cases. Among the discarded glaciers, about half of them are smaller than 3 km^2, and the rest correspond to those lying on the slopes of the Tupugatito Volcano and San José volcanic complex (Volcán Tupungatito, Azufre, and Marmolejo glaciers). We suspect that this is an expression of the fact that some of the processes not included in TOPKAPI-ETH (namely permafrost, sublimation, snow dynamics or geothermal fluxes) may play a role governing the mass balance of these glaciers. However, it might also be related to local deficiencies in the spatial distribution of air temperature and precipitation. No rock glaciers are included in this subset of glaciers. The location and main properties of the 26 modelled glaciers in comparison with those of the total sample are shown in Figure 3 and Table 2, respectively. The simulated glaciers are spread over the entire basin, and their mean elevations are in the middle range of the total sample. Glaciers smaller than 1 km^2, from which 85% correspond to rock glaciers or glacierets, are less-well represented by the sample of 26 glaciers. The sample of 26 glaciers is mostly oriented towards south (aspect > 90°) and does not include the steepest glaciers. In Figure 3, we also highlight the areas with the discarded large glaciers on Tupungatito Volcano and San José volcanic complex.

The results of the calibration of the TOPKAPI-ETH models for the 26 modelled glaciers are shown in Figures 4a (period 1955-2000) and 4b (2000-2013). The calibration results are very good for both periods with area-weighted RMSEs of 1 and 0.2 m w.e. for the 1955-2000 and 2000-2013 periods, respectively. These errors are well within the uncertainty bounds of the geodetic mass balance. Figure 4c shows the resulting cumulative glacier mass balance for all simulated glaciers, their area-weighted average, and the comparison with the glaciological mass balance measured on the Echaurren Norte Glacier since 1975. The fastest declining line of the sample corresponds to the Olivares Alfa Glacier, which has been previously identified as one of the glaciers with the largest retreating rates in the basin (Malmros et al., 2016). Interestingly, several of the glaciers show a positive or near-neutral mass balance over the entire period, which might be an indication that these glaciers have already retreated close to a new equilibrium. However, this is not the general trend in the basin (as shown by the average values in Figure 4) and it is limited to some specific cases where glaciers have retreated to elevations above the basin-average ELA, or have been covered by thick debris.

4.2 Extrapolation

We extrapolate the mass balance of the 26 modelled glaciers to the entire basin based on the methodology described by Huss (2012). In that work, a set of in-situ glacier mass balance measurements for Switzerland were used to calculate the mass balance of all glaciers in the European Alps. Here, we calculate the annual surface mass balance B (m w.e.) of glacier g in year y with:

$$B(g,y) = \bar{B}(g,p) + \Delta B(s,y), \qquad (4),$$

where $\bar{B}(g,p)$ is the average annual mass balance in the study period p, and $\Delta B(s,y)$ is the glacier annual mass balance anomaly in the sub-catchment s, where glacier g is located. While $\bar{B}(g,p)$ is extracted from the geodetic mass balance, $\Delta B(s,y)$ is derived from the TOPKAPI-ETH simulations. Equation (4) is applied to the periods 1955-2000 and 2000-2013 by calculating $\bar{B}(g,p)$ from the geodetic mass balance. The term $\Delta B(s,y)$ is calculated as the anomaly of annual mass balance of simulated glaciers located in the sub-catchment s for each study period, i.e.:

$$\Delta B(s,y) = B(g^{*,s},y) - \bar{B}(g^{*,s},p), \qquad (5),$$

where $g^{*,s}$ is the subset of modelled glaciers $(*)$ in sub-catchment s.

The time series of annual mass balance $B(g,y)$ are then used to estimate the volume changes of each glacier throughout the study periods. Glacier areas (S) are updated due to negative changes in glacier volume (V) (we do not prescribe increases of glacier area due to positive annual mass balance) by means of the area-volume scaling formula:

$$S = \left(\frac{V}{c}\right)^{\frac{1}{\gamma}}, \qquad (6),$$

where γ and c are the scaling parameters. In line with recommendations of the volume-area scaling theory (Bahr et al., 2015), the parameter γ is kept constant in all periods at a value of 1.357, and we let c to vary in order to fit the total glacier volume in the basin in years 1955 and 2000 (calculated in section 3.2). Parameter c is calculated as 28.1 for 2000 (this value is also used afterwards), but a value of 21.1 is the one that fits best to our estimates of ice thickness in 1955. In between these two years we use a linear interpolation of c.

In the calculation of area and volume evolution, we account for the uncertainties in the annual mass balance, inventoried glacier areas in 1955 and 2000, and the parameter c, by disturbing each variable with a random variation. These random variations are 1000 realizations of three normal probability distributions of mean 0 and standard deviations equivalent to the typical errors of each variable. From the uncertainties in the geodetic mass balance, we estimate a typical error in the annual mass balance of 0.08 m w.e. yr^{-1} for the period 1955-2000 and 0.13 m w.e. yr^{-1} for 2000-2016. Based on Paul et al. (2013), we assign a 5% error to the area of each glacier in the year 2000 inventory, and we double this value for the 1955 inventory. The error for the parameter c is calculated in order to match the uncertainty in our ice thickness estimates, and results in a value of 4.1. The uncertainty in parameter c should indirectly account for the different boundary conditions (such as basal sliding or surface geometry) that are found at each glacier (Bahr et al., 2015).

Glacier runoff, including all its components (i.e. ice melt, snow melt and rain), is extrapolated directly from the TOPKAPI-ETH results for the 26 modelled glaciers to the rest of the glacierized areas, and do not depend on the extrapolated time series of glacier mass balance. At a particular year, the uncertainty in glacier runoff is estimated as a fraction of the same variable. That fraction is the same as that between glacier volume and its uncertainty in that year. ~~The uncertainty in glacier runoff is estimated at each year as proportional to that calculated for glacier volume.~~ As in Huss and Hock (2018), we compute~~define~~ glacier runoff as the water originating from the initially glacierized area (1955 in our case), i.e. independent of the glacier area in a particular year. This allows the evaluation of changes in total headwater runoff due to glacier retreat. However, in our study we also evaluate specific variations of the ice melt component. Throughout the manuscript, glacier runoff and its components are presented as normalized by the area of the entire Maipo River Basin.

4.3 Committed ice loss estimates

We estimate the committed glacier ice loss caused by the temperature increase in the last decades by conducting a set of ten additional TOPKAPI-ETH simulations, and by extrapolating them using the same analysis as described in the previous section. The additional simulations are run under different synthetic climate scenarios in which the climate of the last two decades is stochastically repeated for a 100-year period. The meteorological inputs are built by repeating 1-year long blocks of the input variables (precipitation, temperature and cloud transmissivity) corresponding to a randomly selected year between 1993 and 2016 (23 years). We select this period because air temperature was relatively stable in the basin, and precipitation showed the characteristic inter-annual variability of this region.

While the anomaly term $\Delta B(s, y)$ is calculated in the same way as for the period 1955-2016 (i.e. from the TOPKAPI-ETH simulations), as no geodetic mass balances are available for the synthetic scenarios, we calculate $\bar{B}(g, p)$ using two different approximations depending on glacier size. For glaciers that are larger than the size of the smallest modelled glacier (1.1 km^2), we use a multiple linear regression of the mass balance of the modelled glaciers in each scenario with their topographic parameters in year 2000:

$$\bar{B}(g,p) = a_1 \cdot x_1 + \cdots + a_n \cdot x_n \quad (7),$$

where a_i are calibrated coefficients and x_n are topographic parameters. In average for the 10 synthetic scenarios, the best results are given by glacier area, median glacier elevation, percentage of debris cover, mean sky view factor, and mean aspect. Together, these five variables explain 52% of the total variance, which is in the range of the original application of this methodology (Huss (2012) obtained 35% using three variables and 51% using six). Results of this procedure are summarized in Table 3. For glaciers smaller than 1.1km^2, we use the average mass balance of modelled glaciers in the corresponding sub-catchment. As in the 1955-2016 period, rock glaciers are assumed to have a balanced mass budget. Once the time series of mass balance for the 10 synthetic scenarios are calculated, we compute area and volume evolution of each glacier, and their associated uncertainties, using the same methodology as for the 1955-2016 period.

5 Results

Figure 5 and Table S2 (in the supplementary information) present a summary of the simulations in this study. In the period 1955-2016, we conduct the TOPKAPI-ETH simulations for the Maipo River Basin (SIM-1A) and the 26 modelled glaciers (SIM-1B), and the extrapolation for all glaciers (SIM-1C). Using the synthetic meteorological time series derived to calculate the committed ice loss, we conduct 10 additional TOPKAPI-ETH simulations for the Maipo River Basin (SIM-2A) and the modelled glaciers (SIM-2B), which are then also used for extrapolation (SIM-2C).

5.1 Glacier changes and runoff contribution in the period 1955-2016

In Figure 6, we present the temporal variability of precipitation (a), air temperature (a), the equilibrium line altitude (ELA) (b) and cumulative mass balance (c and d) in the Maipo River Basin since 1955. While the large inter-annual variability of the basin's mean precipitation (Figure 6a, blue bars) directly relates to the El Niño Southern Oscillation (ENSO) phenomenon, a 3-year moving average of this variable exposes a sequence of dry (e.g. 1967-1969, 2010-2016) and wet periods (e.g. 1978-1987 and 2000-2008). This sequence has been related to other climatic indices, such as the Pacific Decadal Oscillation (PDO) or the Interdecadal Pacific Oscillation (IPO) (Boisier et al., 2016; González-Reyes et al., 2017). From 2010 on, precipitation has decreased due to a severe drought across Chile (Garreaud et al., 2017). Air temperature over the basin shows a sustained increase in the long-term, but with relatively stable values since the mid-1990s. Since the 1960s, air temperature has increased in about 2°C. Figure 6b shows the annual and decadal variability of the ELA of the 26 modelled glaciers. The ELA is calculated as the average elevation of all grid cells with an annual mass balance of ±10 cm, and the estimated range (in light red) corresponds to the standard deviation. Since the 1960s, the elevation of the ELA has increased by ~~370~~ 239 m, or ~~66~~ 39 m per decade. These estimates of the ELA change are larger than those calculated by Carrasco et al. (2005), who estimated an increase in the elevation of the 0°C isotherm of about 160 m for central Chile in the period 1975-2001.

Figures 6c and 6d integrate the results of TOPKAPI-ETH and the extrapolation procedure. Figure 6c presents the cumulative surface mass balance of glaciers in the Maipo River Basin since 1955, including the 26 glaciers modelled with TOPKAPI-ETH, and the remaining glaciers in the basin for which extrapolation was used. The cumulative mass balance shows a decreasing trend interrupted by short periods of positive or near-neutral mass balance, with a more negative final value for the 26 modelled glaciers than for all glaciers in the basin. The more negative value for modelled glaciers might be caused by their larger area in comparison to the rest of the glaciers, as large glaciers have shrunk more extensively (Malmros et al., 2016). For comparison with the long-term glacier mass balance reference in the region, we include the direct measurements on Echaurren Norte Glacier, which presents a more negative trend, most likely due to its low elevation (3650 to 3900 m a.s.l.). In Figure 6d, we present the surface mass balance of glaciers in each sub-catchment, where relatively large differences can be seen. In general, glaciers in southern catchments show more positive mass balance than those in northern catchments. This can be explained by larger precipitation amounts and a higher proportion of both debris-covered and rock glaciers. Most notably, glaciers in Olivares show the most negative mass balance throughout the study period, whereas those in Volcán present a positive mass balance until the mid-2000s. However, after the start of the current drought in 2010, negative glacier mass balances dominate across the entire Maipo River Basin. The information included in Figure 6d, is summarized in Table 4, which shows the simulated glacier mass balance in each sub-catchment for the 1955-2016 period. For comparison, we include the mean elevation, mean latitude and the 1955 glacierized area of each sub-catchment.

In Figure 7 we show the variations of glacier runoff and its components (ice melt, snow melt and rain) in the initially glacierized areas over the period 1955-2016. While the annual and summer inter-annual variability is presented in Figure 7a and 7b, Figure 7c presents the average seasonal curve and the percentage of each contribution. The summer period is chosen as January to March. Glacier runoff was 177±25~~186±27~~ mm yr^{-1} over the entire period and shows a sequence of three decreasing maxima (1968-1969, mid-1980s, and end of 2000s). Glacier runoff peaked at 245±62~~257±64~~ mm yr^{-1} during the severe drought of 1968-1969 (the driest hydrological year in record) and it averages 158±27~~166±30~~ mm yr^{-1} during the current drought (2010-2016). Figure 7a shows that the inter-annual variability of ice melt is very large (with a coefficient of variation of 0.57), and its share in total glacier runoff can vary from less than 10% (as in 1982-1983, 1997-1998, and 2002-2003) to more than 90% (as in 1968-1969). Except for 1968-1969, snow melt on this areas is consistently the largest runoff contributor at the annual scale, but the contribution during summer is very variable. In Figure 7c, we show the summary of runoff contributions at the annual scale. Runoff contribution is dominated by snowmelt (60%), with ice melt representing 37% of the annual total. Rain represents about 3%, but these amounts have increased since 1955 (Figures 7a and 7b).

In Figure 8, we quantify the role that glacier runoff has played in the entire Maipo River Basin over the study period. At the annual scale, glaciers provide 16~~17~~±7% of the total runoff, but this contribution can increase up to ~~60~~59±23% in summer. In

1968-1969, the runoff contribution from the 1955 glacier areas provided ~~51~~49% of the annual runoff, and almost 100% during summer. During the current drought, glacier runoff has represented 17% of the annual runoff and 55~~57~~% of summer runoff. The value of 17% during the current drought is close to the average value over the entire study period.

5.2 Glacier changes and runoff contribution for the committed ice loss scenarios

Figure 9 presents the evolution of glacier volume (a), area (b), and runoff (c) in the Maipo River Basin, in the past period (1955-2016) and the committed ice loss scenarios. To assess the changes of glacier area and volume we use the values estimated for the year 2000 as reference, whereas for glacier runoff we use the average in the period 1955-2016. As mentioned above, the committed ice scenarios do not represent a realistic projection for the future, and we use the years of 2000 to 2100 in the x-axis for visual purposes only. Glacier area and volume varied by –35±5% (from 532±53 to 347±27 km^2)~~–38±5% (from 558±56 to 347±27 km^2)~~ and –20±14% (from 18.6±4.5 to 14.9±2.9 km^3) in the period 1955-2016, respectively and if glaciers were in equilibrium with the current climate, the glacier area and volume would reduce to 79±18% and 81±38% of the 2000 values, respectively. The uncertainty in glacier area and volume derived from our calculations (blue bands) reduces from 2000 on, due to the higher accuracy that we assign to the year 2000 inventory and DEM. In the committed ice loss scenarios, uncertainty starts on similar levels as that in 2000, but as the scenarios differentiate from each other, the uncertainty increases towards the end of the simulation period. In Figure 9c presents glacier runoff from the initially glacierized areas normalized by the area of the Maipo River Basin. Glacier runoff in the committed ice loss scenario decreases quickly until a relatively steady value is reached at 78±30~~79±33~~% of the average glacier runoff in the 1955-2016 period. This value is equivalent to 61±21~~4~~% of that in the 1968-1969. Uncertainty bounds in Figure 9c are proportional to those of the glacier volume.

As the large precipitation inter-annual and inter-decadal variability could mask the runoff trends associated only with the reduction of glacier volume, in Figure 10 we present the variability of ice melt in the period 1955-2016 and the committed ice loss scenarios. For this figure, we use the maximum value of ice melt in the period 1955-2016 as reference, which corresponds to the hydrological year 1968-1969. Although also ice melt shows a very large inter-annual variability, it is clear that the maximum values have decreased over the last decades (see maximum values in 1968-1969, 1990-1991, and 2011-2012). We estimate that if glaciers reached equilibrium with the current climate, the peaks would be considerably lower than those in the 1955-2016 period. In this equilibrium situation, the peaks are close to 40% of the largest ice melt runoff contribution in the past (1968-1969). The information presented in Figures 9c and 10 is also summarized in Table 4. In that table, we present the average glacier runoff contribution per sub-catchment for the 1955-2016 period and the last twenty years of the committed ice loss scenarios.

6 Discussion

6.1 Glacier changes

Our results indicate that the total glacier volume in the Maipo River Basin decreased in about one fifth in the period 1955-2016. The cumulative glacier mass balance in the Maipo River Basin shows variations that are similar to those registered on Echaurren Norte Glacier. These variations consists of a general decreasing trend, concurrent with an increase of the ELA (Carrasco et al., 2005, 2008), which has been interrupted by periods of slightly positive or neutral mass balance. Since the mid-1980s, there has been a strong mass loss, interrupted only by a positive period in the beginning of the 2000s. In fact, from 2000 on, we observe a 10-year period with positive or nearly neutral mass balance. This was also described by glaciological observations (Masiokas et al., 2016) and geodetic mass balances (Braun et al., 2019; Dussaillant et al., 2019). Following this period, strongly negative mass balances have been observed (Masiokas et al., 2016; Burger et al., 2019), concurrent with a severe drought in central Chile, unprecedented in extension and duration (Garreaud et al., 2017). For the period before 1975, when the mass balance measurements on Echaurren Norte Glacier started, we compare our results to the reconstruction obtained by Masiokas et al. (2016). The latter estimated a strongly negative mass balance in the period 1955-1975, whilst we obtain a nearly neutral mass balance between 1955 and 1968, and a more negative balance from 1968 to 1975. These differences might either correspond to differences between the basin-averaged mass balance and that on Echaurren Norte Glacier, or be a consequence of the different methodologies between our study and that of Masiokas et al. (2016). While Masiokas et al. (2016) relies on the correlation between hydro-meteorological records and the measured surface mass balance on Echaurren Norte, our model is calibrated to the geodetic mass balances.

The different trends of glacier mass balance in the sub-catchments of the Maipo River Basin are an expression of the diverse climatic and morphological characteristics that dominate across the basin. For example, the positive and near-neutral glacier mass balances in Volcán and Upper Maipo might be related to higher precipitation towards the south, or that several glaciers have retreated close to a new equilibrium state. Within the Olivares sub-catchment, the geodetic mass balance is in line with the large areal changes found by Malmros et al. (2016). This might be explained by a strong imbalance of the large glaciers in that catchment, and/or by the impacts of nearby mining activities (Los Bronces and Andina mines), especially dust deposition on Olivares Alfa Glacier and its neighbour glaciers. However, more specific studies addressing albedo changes are necessary to obtain more conclusive results.

Our estimates of committed ice loss show that glaciers will continue to shrink if the climate remains stable, with an estimated committed ice loss of 20% relative to the volume in the year 2000 (30% relative to 1955). We stress that these estimates ~~do not correspond to a realistic future scenario, but~~ are an indication of the glacier changes that past climate will produce in any case. Future projections under emission scenarios will certainly show more dramatic reductions of glacier area and volume. In the context of future projections, we highlight that most projections for glacier changes in the Central Andes (Marzeion et al., 2012; Radić et al., 2014; Huss and Hock, 2015) are included in the macro-region of the “Southern Andes”, which also contains the Patagonian Ice Fields. Future projections of glacier changes in the region are thus strongly influenced by these large ice masses, with their peculiar climate, and physical processes (e.g. calving) that are not representative of the small mountain glaciers along the semiarid Andes (Mernild et al., 2015).

6.2 Glacier runoff

Despite the reduction of glacier volume in the period 1955-2016, our estimates of glacier runoff do not show (Figure 8 and 9c) the typical increasing or decreasing phases of peak water observed or projected for other catchments across the world (Baraer et al., 2012; Farinotti et al., 2012). This result is similar to that obtained by Casassa et al. (2009), who did not find significant trends in an analysis of Maipo streamflow records. Peaks in glacier runoff have reduced their magnitude over the last decades as a combination of a decrease in precipitation (Boisier et al., 2016) and the reduction of ice volume, but it is difficult to identify if there was an increasing phase of glacier runoff in the period 1955-2016.

We suggest that the strong inter-annual and inter-decadal climatic variability observed in the semiarid Andes (Montecinos and Aceituno, 2003; Masiokas et al., 2006; Falvey and Garreaud, 2007) is also transferred to the glacier runoff time series, modifying or masking the typical trends associated with glacier retreat. Once an extended time period is considered (in this case a committed ice loss scenario, Figure 9c), peak water emerges more clearly. Huss and Hock (2018) estimated that glacier runoff in the Rapel River Basin (south of the Maipo River Basin) experiences peak water in the current decade (2010-2020), but their analyses also show a strong inter-annual glacier runoff variability from 1980 to 2010. This makes peak water evident only when compared to the future projections under different emission scenarios, in which the glacier runoff is considerably lower than present levels.

6.3 Uncertainties in the modelling of glacier changes in data-scarce regions

We identify four main sources of errors and uncertainties in our study: (i) the glaciological datasets, i.e. the geodetic mass balance, glacier outlines, ice thickness and debris cover areas, (ii) the spatial distribution of meteorological inputs, (iii) modelling limitations in TOPKAPI-ETH, and (iv) limitations of the extrapolation methodology.

In general, the uncertainties of the elevation changes and glacier properties are well quantified and explicitly stated in the confidence bounds of the geodetic mass balance (Figure 9). However, a few properties were not explicitly quantified, such as the ice content in rock glaciers, which is in fact a key problem in the semiarid Andes (Schaffer et al., 2019). Due to this, there might be an overestimation in the ice content due to the presence of rock glaciers. In the future, more geophysical measurements to acquire information on ice content in rock glaciers of the semiarid Andes (e.g. Croce and Milana, 2002) could improve the estimates of runoff generation from these landforms.

The accuracy in the spatial distribution of meteorological inputs is particularly difficult to evaluate, and it likely corresponds to a major source of uncertainty, especially precipitation. This is because of the relatively sparse network of meteorological stations installed in the basin, the difficulties of atmospheric models to represent precipitation processes over the Andes (Bozkurt et al., 2019), and the underestimation of satellite-based precipitation products over high-elevation areas (Álvarez-Garretón et al., 2018). However, the indirect evaluation of precipitation amounts through snow cover products and the basin's water balance increase the confidence in the results of this study. An additional simplification in the meteorological distribution is the extrapolation of air temperature from one single station. Nevertheless, we are confident that air temperature variability is well constrained over the catchment, because it usually correlates well over long distances, daily lapse rates are derived from the basin-wide CR2 temperature dataset, and the timing of snow disappearance is well simulated by TOPKAPI-ETH.

Although our study has benefited from a series of new meteorological and glaciological datasets presented for the Southern Andes in recent years (Cortés and Margulis, 2017; Álvarez-Garretón et al., 2018; Farías-Barahona et al., 2019a), the lack of field data in the Maipo River Basin is something that needs to be taken into account in glacio-hydrological modelling studies in the region, particularly at high-elevation, remote sites. In this study, we alleviate the difficulties posed by the lack of basin-wide field data, and its impact on the TOPKAPI-ETH results, by deriving most of the model parameters from data collected in previous field campaigns in this region, starting in 2008 (Pellicciotti et al., 2008; Ragettli and Pellicciotti, 2012; Ayala et al., 2016). These previous studies have also shown that many of the parameters required by the model are fairly stable, in the sense that they can be extrapolated from one glacierized area to another with a reasonable degree of confidence (Ragettli et al., 2014; Ayala et al., 2017b; Burger et al., 2019). ~~In relation to TOPKAPI-ETH, it has been shown that the parameterizations of snow accumulation and ablation included in TOPKAPI-ETH work well for wind-sheltered locations (Ayala et al., 2017b). However~~In addition, the representation of processes driving the mass balance at some specific sites requires more fundamental work, and additional parameterizations or more physically-based representations are required. Such sites correspond mainly to sublimation-dominated sites above 5500 m a.s.l., where we had to correct our simulations of snow depth and the temperature-index modelling is inaccurate (Ayala et al., 2017a, 2017b), debris-covered areas with complex distributions of debris thickness (Burger et al., 2019), or steep glacierized slopes such as the volcanoes in the Maipo River Basin.

As the average rates of annual mass balance in the 1955-2016 period are calculated from the geodetic mass balance, the long-term glacier changes derived from the extrapolation methodology should be well simulated, but the year-to-year variations of mass balance depends on the representativity of the modelled glaciers. As discussed by Huss (2012), a low representativity of the reference glaciers could lead to large errors in the mass balance of individual glaciers and years, but these errors should be lower at the mountain-range scale and over long time periods. In the committed ice loss scenarios, the uncertainty of glacier changes is higher because it also relies on the multiple linear regression analysis. In any case, we explicitly accounted for the uncertainties in the extrapolated mass balance (are least partly) by means of the random perturbation described in section 4.2.

7 Conclusions

We have reconstructed the changes that glaciers in the Maipo River Basin experienced over the last six decades, with a focus on glacier runoff and the impacts of its long-term variations on the basin's hydrology. These results add a missing piece to the current hydro-climatological knowledge of the semiarid Andes, and can be useful for water managers and stakeholders to develop adaptation or mitigation strategies. Although some uncertainties still remain, our results successfully take into account a number of independent datasets, including snow cover area variations, snow water equivalent reconstructions, streamflow records, glacier inventories and geodetic mass balances.

Our main conclusions are as follows:

a. Over the period 1955-2016, the total glacier volume in the Maipo River Basin has decreased by 20±14% (from 18.6±4.5 to 14.9±2.9 km^3), respectively. In agreement with other studies, our results show that the cumulative glacier mass balance over the study period had a general decreasing trend, interrupted by short periods of positive or near-neutral mass balance. This might be an indication that some glaciers temporarily retreated to a new equilibrium state. Strongly negative mass balance have dominated since the start of the current drought in 2010. Despite the general trend, there are important differences between the glacier mass balances of the sub-catchments, with the southern sub-catchments (Volcán and Upper Maipo) showing positive or near-neutral mass balances until 2000, and the Olivares sub-catchment showing a strongly negative mass balance over the entire period.

b. The average glacier contribution to runoff in the Maipo River Basin – i.e. the runoff contribution from liquid precipitation, snowmelt and icemelt from the areas that were glacierized in 1955 – was 177±25~~186±27~~ mm yr^{-1} in the period 1955-2016. Instead of a clear peak water, we identify a decreasing sequence of runoff maxima that can be linked to both a decrease in precipitation since the 1980s and a reduction of ice melt. The exact occurrence of peak water will depend also on future changes (e.g. more precipitation or more ice melt), which are not addressed in our article. Glacier runoff has decreased since the severe drought of 1968-1969, when glacier runoff peaked at 245±62~~257±64~~ mm yr^{-1} (~~51~~49% of the basin's total runoff). During the current drought, which started in 2010, the contribution was 158±27~~166±30~~ mm yr^{-1} (17% of the total runoff).

c. If climate was to stabilize at the level of the past two decades, we estimate a committed glacier ice mass loss of 19±38%. This would cause glacier runoff to reduce by 22±30~~21±33~~% when compared to the 1955-2016 average, or by 39±21~~4~~% when compared to 1968-1969. Based on these numbers, we anticipate that the future capacity of the basin to mitigate severe droughts will be reduced.

Our results shed light on the glacier runoff evolution in the semiarid Andes, and complement recent studies that assessed regional-scale glacier changes (Braun et al., 2019; Dussaillant et al., 2019). Some topics deserving further attention that should be addressed are the drivers behind the positive mass balance in the southern catchments (Volcán and Upper Maipo), the processes governing mass balance on glaciers on active volcanoes, the possible anthropogenic impacts on glaciers in the

Olivares sub-catchment, and the quantification of the hydrological role of rock glaciers. Whilst our simulations of committed ice loss provide estimates of the minimum changes that glaciers will experience due to past changes of the climate, future studies driven by climate model simulations and emission scenarios should provide more realistic projections for the future of the region’s glaciers.

Data availability

Data used in this study are available upon request to the authors.

Author contributions

AA designed the study with contributions from DF and DFB, and performed the calculations with TOPKAPI-ETH and the extrapolation method. DFB calculated the geodetic mass balances. MH calculated the ice thicknesses for 2000. All co-authors provided scientific advice during the study. AA prepared the manuscript with contributions from all co-authors.

Competing interests

The authors declare that they have no conflict of interest.

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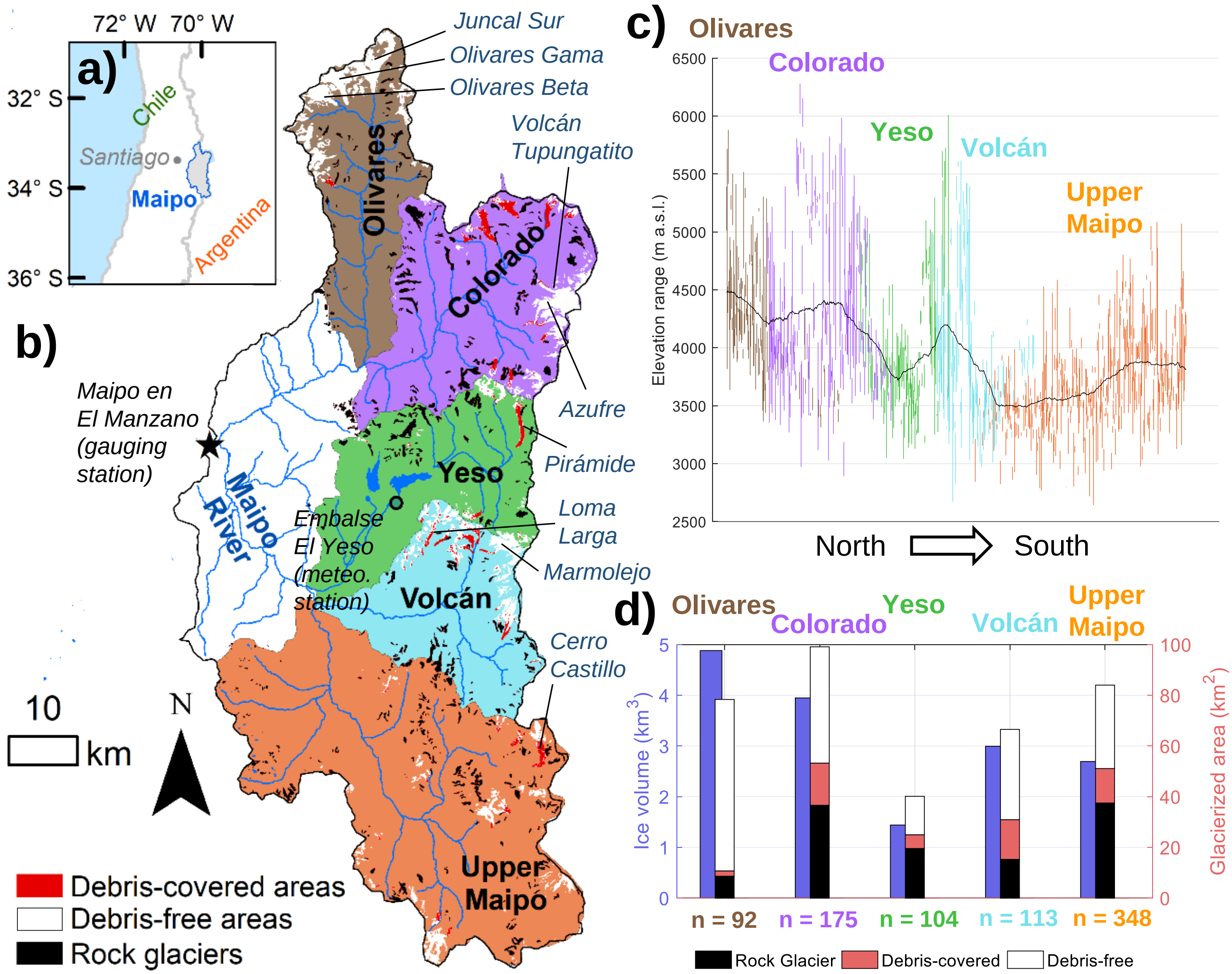

Figure 1: a) Maipo River Basin next to the city of Santiago, in central Chile; (b) the basin outlet and the sub-catchments, rivers, glaciers, and hydro-meteorological stations; (c) the elevation range of every glacier in the basin as a function of the average latitude (arbitrary scale) in each sub-catchment, and the mean elevation (black line); (d) estimated total ice volume using the method developed by Huss and Farinotti (2012) (left axis), and glacierized area (right axis) in each sub-catchment. The surface and glacier type (debris-free, debris-covered or rock glacier), as well as the number of glaciers in each sub-catchment are indicated.

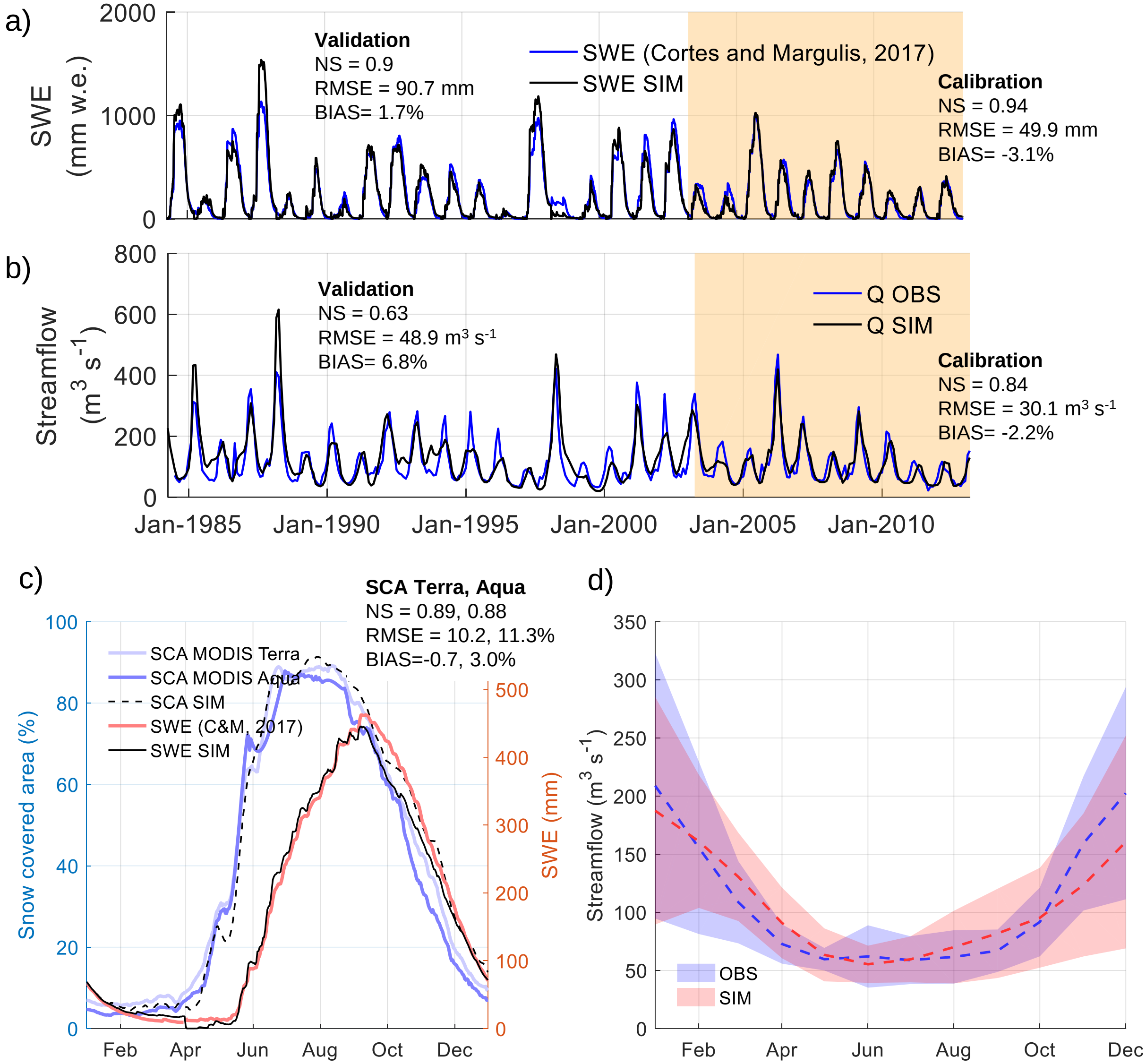

Figure 2: Results of the calibration of the TOPKAPI-ETH model for the Maipo River Basin. (a) Simulated SWE against results of Cortés and Margulis (2017)~~et al. (2016)~~, (b) Simulated and observed monthly streamflow at the basin outlet. In (a) and (b) the light orange area indicates the calibration period. (c) Average seasonal variability of simulated and observed SCA from Aqua and Terra missions and SWE from Cortés and Margulis (2017) ~~et al. (2016)~~ in the calibration period, (d) average seasonal variability of simulated and observed streamflow in the calibration period. The coloured areas in (d) correspond to the observed and simulated standard deviations from the inter-annual variability. Model metrics are indicated for the calibration and validation periods and correspond to NS: Nash-Sutcliffe coefficient, RMSE: Root Mean Square Error, and BIAS: average bias.

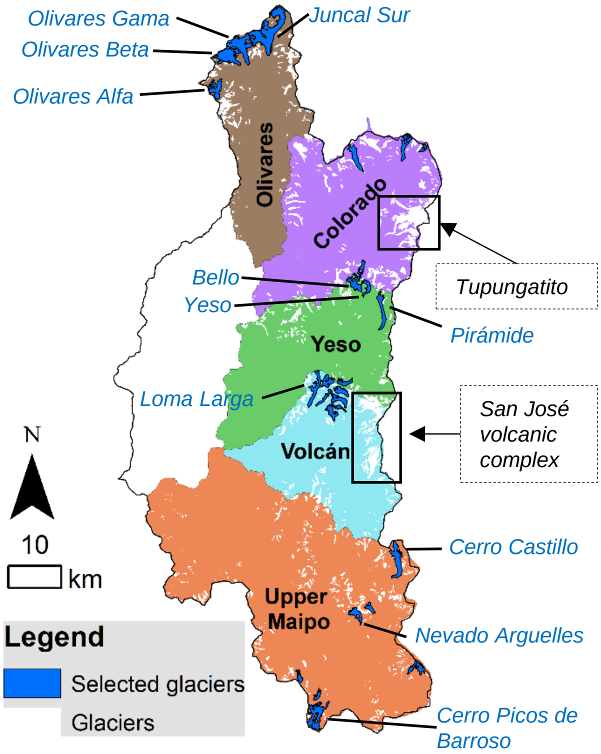

Figure 3: Location of the 26 glaciers modelled with TOPKAPI-ETH. We highlight the volcanic areas on which some large glaciers were discarded from the modelled sample. We include the name of the main glaciers in this sample.

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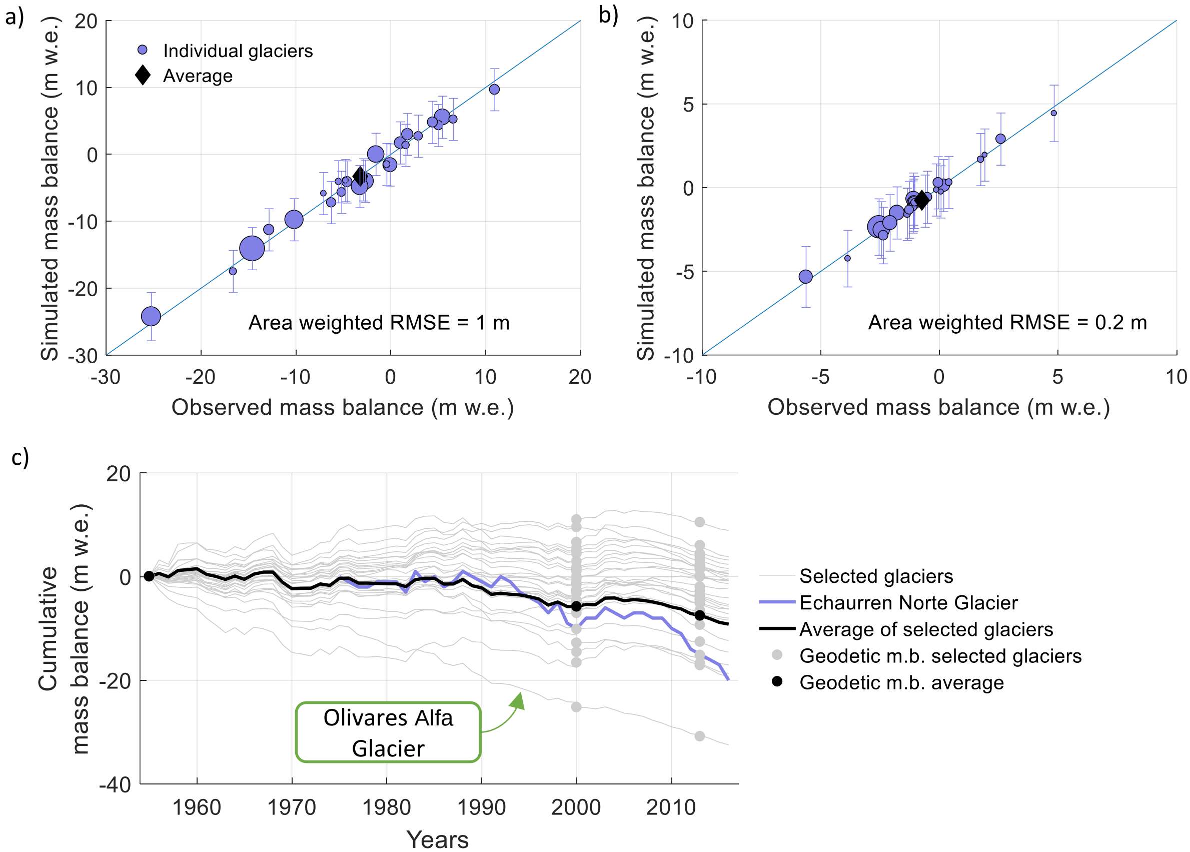

Figure 4: Results of the calibration for the 26 modelled glaciers. Glacier-averaged mass balance (blue circles) simulated with TOPKAPI-ETH and observed from geodetic mass balances in the period (a) 1955-2000 and (b) 2000-2013. The area-weighted average of all glaciers is indicated with black diamonds. The blue bars show the uncertainty of the geodetic mass balances, (c) Cumulative 1955-2016 mass balance for each modelled glacier (grey lines), the area-weighted average of all glaciers (black line) and the mass balance measured on Echaurren Norte Glacier (blue line). The geodetic mass balances for each modelled glacier is indicated with a circle. The curve corresponding to the fastest retreating glacier of the sample, Olivares Alfa Glacier, is labelled.

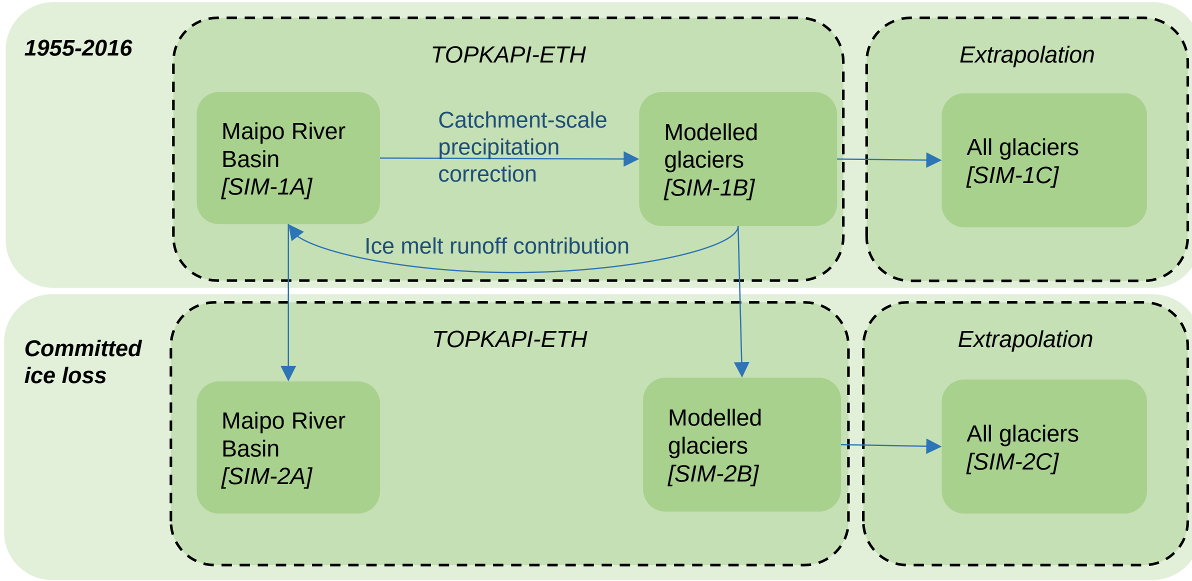

Figure 5: Organization of the simulations. The two main boxes indicate the time period of the simulations (1955-2016 and committed ice loss scenario), the boxes with a dashed outline indicate the method used (TOPKAPI-ETH or extrapolation), and the smallest boxes indicate the spatial domain (Maipo River Basin, modelled glaciers, and all glaciers). The arrows indicate outputs that are used in other methods or domains. The codes in brackets (e.g. SIM-1A) correspond to the simulation codes defined in Table S1.

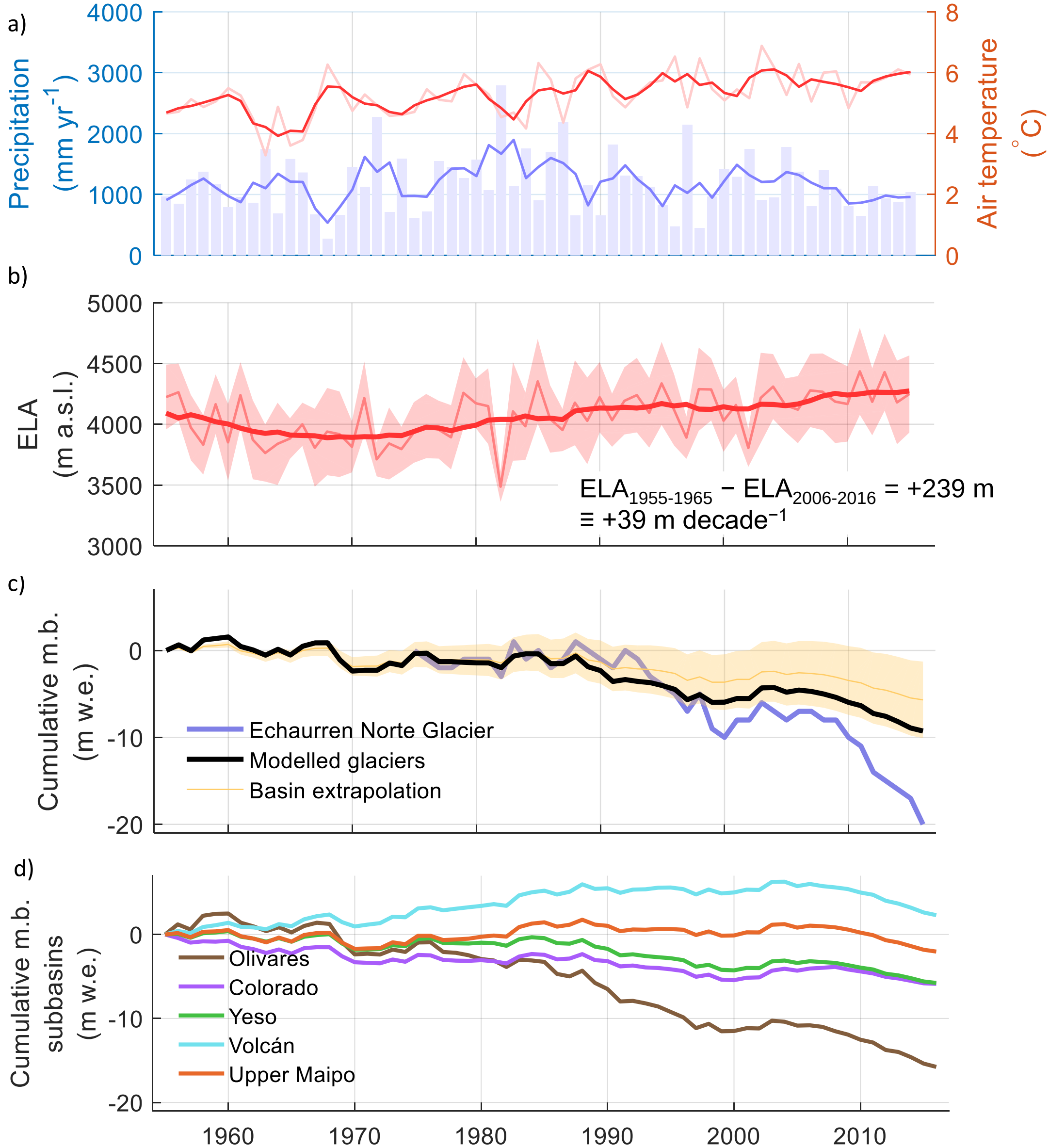

Figure 6: Variability of meteorological and glaciological variables in the Maipo River Basin over the period 1955-2016. (a) Air temperature and precipitation with a 3-year moving mean, (b) equilibrium line altitude (ELA), (c) cumulative glacier mass balance for the modelled glaciers (simulated with TOPKAPI-ETH), the entire basin (extrapolation) and its associated uncertainty, and the measurements on Echaurren Norte Glacier, and (d) cumulative glacier mass balance for each sub-catchment. In b), the difference between the ELA in the last 10 years (2006-2016) and the first 10 years (1955-1965) of the study periods is indicated, as well as the equivalent ELA increase rate. The shadowed area in (b) shows the standard deviation of the elevation of grid cells with a mass balance between –0.1 m w.e and 0.1 m w.e.

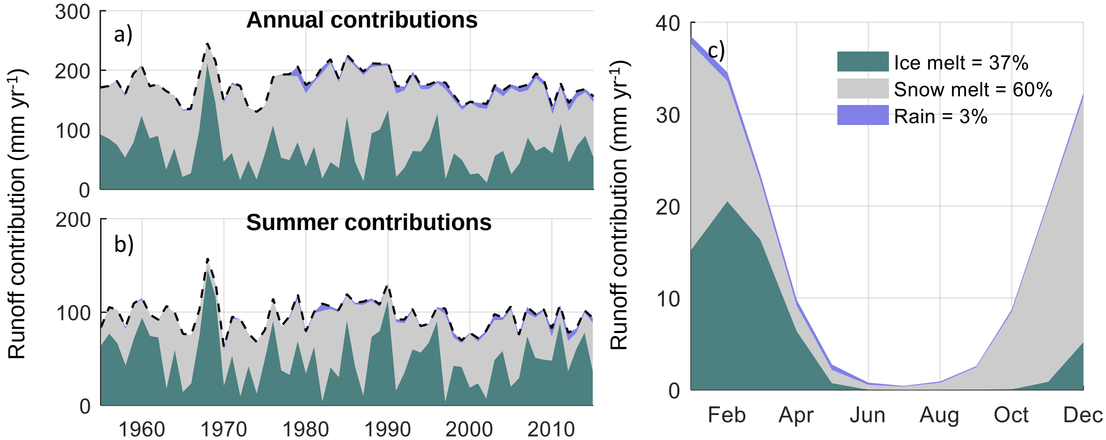

Figure 7: Runoff contribution from ice melt, snow melt and rain from the headwater regions defined by the 1955 glacierized areas. The units are normalized by the Maipo River Basin area. (a) Total annual contribution, (b) summer contribution, and (c) seasonal average contribution. The percentage of each contribution over the period 1955-2016 are indicated next to the legend.

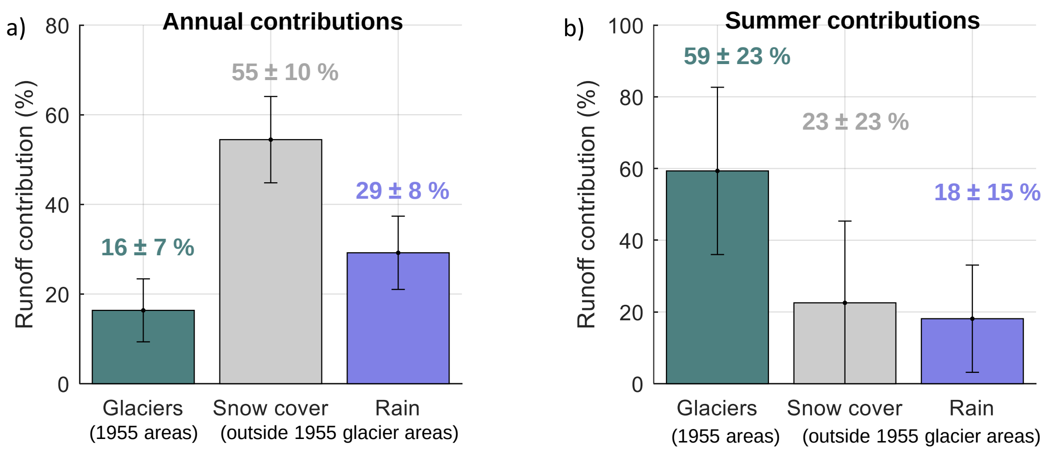

Figure 8: Partition of runoff contribution in the Maipo River Basin in the period 1955-2000. The contributions are computed for the headwater regions defined by the 1955 glacierized areas (the sum of ice melt, snow melt and rain), and snow melt and rain outside those areas. The plus/minus symbol refers to the inter-annual variability. (a) Annual, and (b) summer contribution.

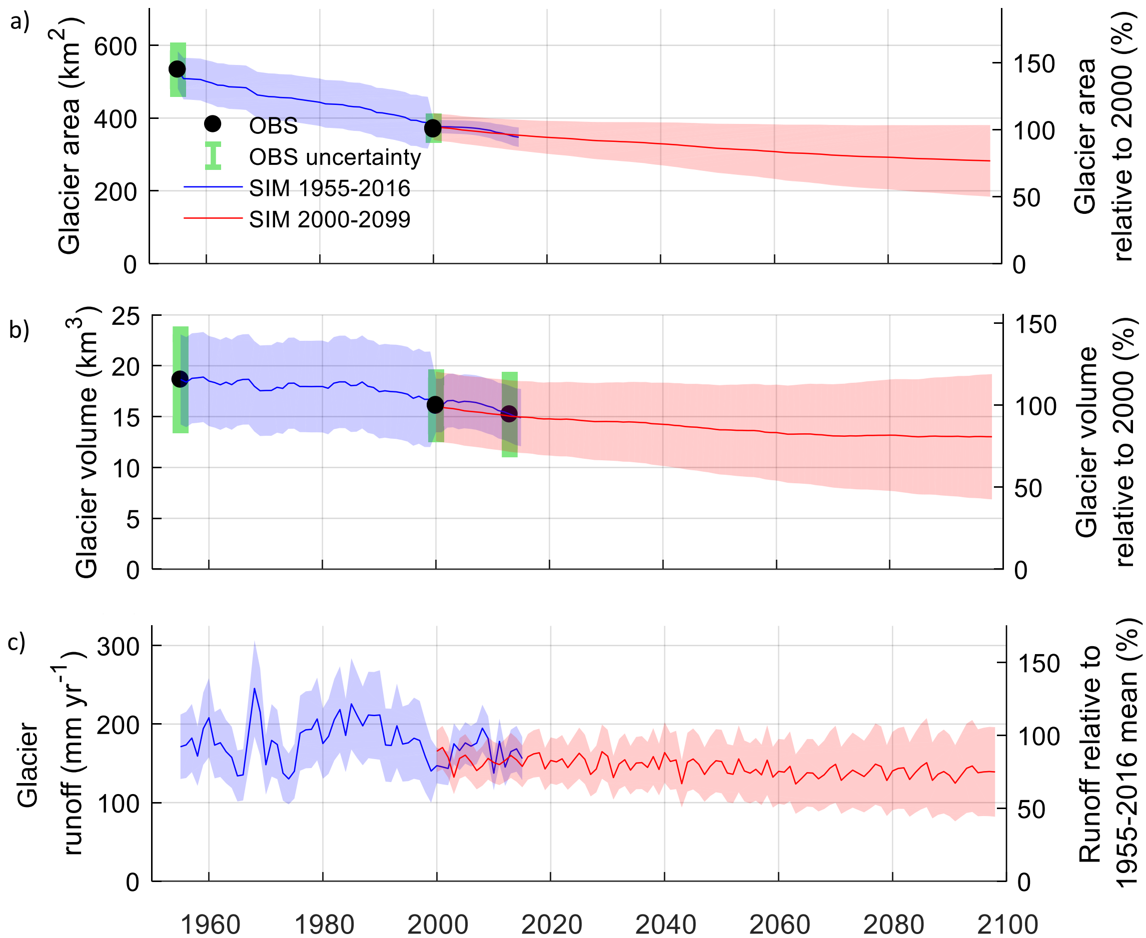

Figure 9: Variations in (a) ice volume, (b) glacierized areas, and (c) glacier runoff in the Maipo River Basin for the past period (1955-2016) and the committed ice loss scenarios assuming a constant climate. In a) and b) we use results from the glacier inventories, and the combination of ice thickness estimates and geodetic mass balances, respectively, as observations of glacier area and volume. Glacier runoff in (c) is computed for the Maipo River Basin (i.e. runoff units are normalized by the basin area). While the uncertainty bars of the observations are shown in green, that of the simulations are shown in blue for the 1955-2016 period and in red for the committed ice loss scenarios. For visual purposes, we present the committed ice loss scenarios using the period 2000-2100 in the x-axis.~~The committed ice scenarios do not represent a realistic projection for the future, and we use the years of 2000 to 2100 in the x-axis for visual purposes only.~~

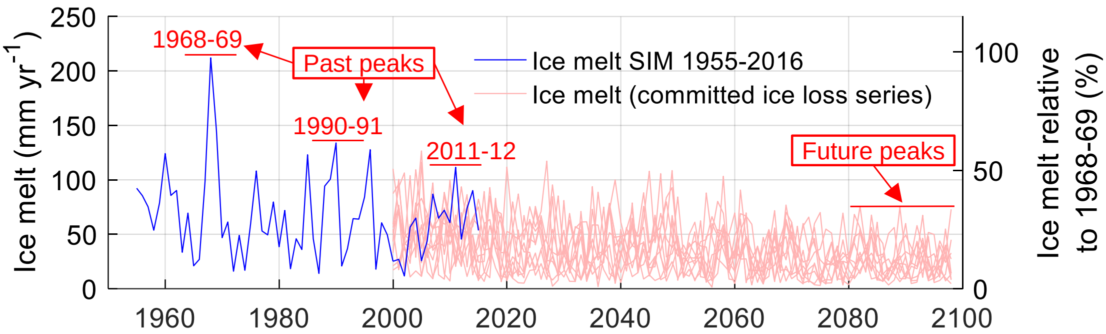

Figure 10: Variations in ice melt in the Maipo River Basin for the past period (1955-2016, in blue) and each one of the ten committed ice loss scenarios (light red). The peaks of ice melt over the past period and those at the final decade of the committed ice loss scenarios are highlighted in red. On the right axis, we set the ice melt estimated for the severe drought of 1968-1969 as 100%. Ice melt is computed for the Maipo River Basin (i.e. runoff units are normalized by the basin area). For visual purposes, we present the committed ice loss scenarios using the period 2000-2100 in the x-axis.~~The committed ice scenarios do not represent a realistic projection for the future, and we use the years of 2000 to 2100 in the x-axis for visual purposes only.~~

Table 1: Parameters in TOPKAPI-ETH's snow and ice modules for the 1955-2016 time period. The tested ranges of some parameters are given in parentheses.

Module	Parameter	Symbol	Calibrated value – Simulation: Individual glaciers	Calibrated value – Simulation: Maipo River Basin	Units	References for the selected values and ranges
Snow accumulation and gravitational transport	Snow/rain threshold	P_T	0 (0-3)	2 (0-3)	°C	Typical ranges for this variable
	Snow holding capacity parameter 1	SRF_C	250	250	m	Ragettli and Pellicciotti (2012)
	Snow holding capacity parameter 2	SRF_a	0.172	0.172	-	
ETI model	Shortwave radiation factor	SRF	0.002-0.014~~0~~	0.009~~0~~ (0.002-0.014)	mm m^2 h^{-1} W^{-2}	Pellicciotti et al. (2008), Ragettli and Pellicciotti , Ayala et al. (2016, 2017b)
	Air temperature factor	TF	0-0.4 (0.01-0.05)	0.01 (0.01-0.05)	mm h^{-1} °C	
	Air temperature threshold for the onset of melt	T_T	0 (0-3)	1 (0-3)	°C	
Sub-debris ice melt	Shortwave radiation factor	SRF_d	0.25*SRF	-	mm m^2 h^{-1} W^{-2}	Ayala et al. (2016), Burger et al. (2019)
	Air temperature factor	TF_d	0.25*TF	-	mm h^{-1} °C	
	Albedo debris	α_{debris}	0.16	-		
Surface albedo	Albedo of fresh snow	α_1	0.83 (0.80-0.95)	0.90 (0.80-0.95)		Cuffey and Paterson (2010)
	Decay of snow albedo	α_2	0.11	0.11		Brock et al. (2000), Ragettli and Pellicciotti (2012)
	Ice albedo	α_{ice}	0.3	-		Cuffey and Paterson (2010)

Table 2: Morphological properties of the 26 glaciers modelled with TOPKAPI-ETH

Property	**Range for modelled glaciers**	**Total range**
Area (km^2)	1.1 – 21.3	0.01 – 21.3
Mean elevation (m a.s.l.)	3313 – 4526	2801 – 6174
Slope (°)	10.2 – 26.6	6.3 – 60.7
Aspect (southing) (°)	90.4 – 178.9	1.1 – 179.6
Debris coverage (%)	0 – 95	0 – 100

Table 3: Results of the multiple regression analysis for the committed ice loss scenario simulations

Property	**Fraction of explained variance of the model (%)**	**Sign of the mass balance dependence**
Area (km^2)	42.1	–
Median elevation (m a.s.l.)	18.2	+
Percentage of debris cover (%)	17.1	+
Sky view factor (%)	15.6	+
Aspect (southing) (°)	7.0	+

Table 4: Simulated glacier mass balance and runoff in the sub-catchments compared with their main characteristics

Basin	Mean elevation (m a.s.l.)	Mean latitude (°S)	Glacierized area in 1955 (km^2)	Average annual glacier mass balance in 1955-2016 (m w.e. yr^{-1})	Runoff contribution in 1955-2016 (*) (mm w.e. yr^{-1})		Runoff contribution in the committed ice loss scenarios (*) (mm w.e. yr^{-1})	
					Total	Ice melt	Total	Ice melt
Olivares	3698	33.3	111	–0.26 ± 0.07	34.1 ± 7.9	15.8 ± 3.6	22.5 ± 6.1	5.4 ± 1.5
Colorado	3755	33.4	152	–0.10 ± 0.07	53.2 ± 12.2	16.1 ± 3.7	42.7 ± 11.5	6.4 ± 1.7
Yeso	3303	33.7	65	–0.09 ± 0.07	21.5 ± 4.9	7.5 ± 1.7	17.1 ± 4.6	3.6 ± 1.0
Volcán	3392	33.8	86	+0.04 ± 0.07	24.2 ± 5.6	7.7 ± 1.8	20.0 ± 5.4	3.5 ± 1.0
Upper Maipo	3182	34.0	111	–0.03 ± 0.07	41.8 ± 9.6	12.6 ± 2.9	33.4 ± 9.0	4.4 ± 1.2
Maipo River Basin	3175	33.6	532	–0.09 ± 0.07	176.9 ± 40.7	65.5 ± 15.1	138.6 ± 37.4	25.8 ± 7.0

(*) From the areas defined by the 1955 glacier outlines, but normalized by the Maipo River Basin area