

Dear Editor,

Please find below our replies to the reviewer comments and the revised version of our paper entitled “Reconstructing the annual mass balance of glacier Echaurren Norte (Central Andes, 33.5°S) using local and regional hydro-climatic data”.

We believe this revised version has improved in many aspects compared to the first version of the manuscript, and would like to thank the reviewers very much for their insightful comments and suggestions. The additions and changes in the text are marked in yellow in the attached manuscript.

In our opinion, and based on some of the points made by reviewers #2 and 3, the original manuscript needed a more detailed description on the data availability and particular characteristics of Glaciar Echaurren Norte. For this reason we have now included a closer view of the glacier to show its morphology and main characteristics (see Fig. 1C), together with a diagram showing the estimated climatology at the glacier based on data from the El Yeso meteorological station (Fig. 1D).

Another important point we would like to make is that, when compared to similar studies in other regions with a much greater quantity and quality of basic meteorological and glaciological information (e.g. Marzeion et al. 2012a), our study is clearly simpler and only capable of addressing a few basic issues regarding the glacier’s sensitivity to climate and its mass balance variations in recent decades. In this respect it is important to note that despite being the longest ongoing mass balance record in the Southern Hemisphere, the ECH data reported to the WGMS is quite limited and only includes the seasonal and annual components of the mass balance of this glacier. Many in-depth analyses necessary for a proper understanding of the energy balance or the climate sensitivity of the glacier are unfortunately hampered by this lack of data at the site. In this regards and to address the comments from reviewer #3, we now make clear that the results are based on reference-surface mass balance estimates, and include a discussion of the uncertainties involved in using this approach and the simplistic modeling adopted in our study.

In the revised version of the manuscript we have tried to better explain this situation and highlight the main objectives of the study which were a) to use a simple model to identify the first order forcings modulating the annual mass balance at ECH, and b) to reconstruct the history of annual mass balance variations of this glacier using a reliable and well-correlated regional streamflow record.

We have also trimmed several portions of the text that were not entirely relevant for our study.

More detailed assessments and on-glacier data are of course highly recommended and clearly needed in this water-scarce region. It is our intention that the manuscript highlights this need and hopefully provides an initial set of working hypotheses for future studies and glacier monitoring programs in this region.

We would like to thank you very much for your assistance in editing this manuscript, and hope it is now suitable for publication in *The Cryosphere*.

Best regards,

Mariano Masiokas,
IANIGLA-CONICET,
Mendoza, Argentina

Responses to Referees

Anonymous Referee #1

The authors applied Marzeion's basic glacier surface mass balance model on glacier Echauren Norte (which is the glacier with the longest in situ mass balance records in the central Andes of Chile and Argentina) using monthly data (precipitation and temperature) from a nearby station (El Yeso). Using this simple model, they explained 78% of the variance in the annual glacier mass balance over the 1978-2013 period and showed that precipitation is the most important factor explaining mass balance variations.

They also used regionally averaged – monthly hydroclimatic data (discharge, snowpack) obtained following Masiokas et al, 2006 and showed that these data are correlated to glacier Echauren Norte annual mass balance explaining up to 68 % of the variation since 1909. Then, they compared the long term reconstructed mass balance pattern of glacier Echauren Norte with others glaciers mass balance and glacier front chronologies and found similar trends and glaciers advances suggesting Echauren glacier is representative of the region.

The paper is clearly in the scope of “The Cryosphere” presenting an updated regional overview of the glacier mass balance changes in the glaciologically poorly known region of the Central Andes.

We thank the reviewer for the favorable opinion about our paper.

Responses to Referees

Anonymous Referee #2

The authors use Ben Marzeion's minimal model to reconstruct the mass balance of a glacier in the central Andes with the longest record of direct mass balance observations. They show that the model is capable of accurately reconstructing mass balance, and use stream-flow data to extend the modeling to the last 100 years. The paper is well written and the conclusions are generally sound, although I have a concern (see below). The discussion and conclusion sections are slightly repetitive and can be trimmed.

My concern is related to the sensitivity analysis where the mass balance changes are attributed primarily to precipitation forcing. Because the mass balance model is so simple, it is not clear that this experiment is robust. In the case of a full energy balance modeling study, there is the potential to examine uncertainties in each of the energy balance terms, and how these might influence the finding. Specifically, if the model

sensitivities to temperature and precipitation are incorrect, then the finding might be spurious.

Simply showing that the model does a good job of simulating mass balance history is not sufficient, because of the equifinality issues involved. In other words, many different combinations of temperature, precipitation and model parameter choices could produce a similar mass balance reconstruction. Each of these simulations would show a different sensitivity to temperature and precipitation forcing. I suggest that the authors remove or de-emphasize this component.

We partially agree with the reviewer in that it is possible for these simplistic sensitivity analyses to produce spurious results or similar outcomes given different combinations of model parameters and temperature and precipitation data. If assessed in isolation and looking only at the results from the annual mass balance model described in Eq. 1, this could also be true for the simple ECH model. However, the results shown in Fig. 3C indicate that holding temperatures constant and using only the precipitation variations as forcing, we can successfully reproduce the overall annual mass balance variations observed at ECH. In contrast, if we use only the temperature variations as forcing, the model does a poor job in capturing annual mass balance variations at ECH. This is the same kind of sensitivity assessment performed in Marzeion et al. (2012a), and in our opinion, it provides a first clue that precipitation is indeed playing a main role modulating this glacier's year-to-year mass balance changes.

This result is supported by additional evidence, which now includes

- a) The results from the cross-validation of the simple mass balance model, which showed that the parameters α and μ are quite stable over the entire calibration period (see lines 222-232).
- b) The strong, time-stable similarities of the annual mass balance series with the regional snowpack and streamflow records. These clear similarities also extend to the annual precipitation record from Santiago de Chile, an official station located roughly 50 km from ECH (see new Fig. 2).

These figures and correlation patterns do not mean that temperature variations are unimportant at this site, but simply suggest that variations in precipitation are likely those that ultimately define the sign and overall magnitude of the annual mass balance values at ECH.

In the context of our study, this result is important because it provides an empirical evidence in support of the use of the longer regional streamflow record (also directly modulated by variations in winter precipitation patterns in the Andes, see Fig. 2) to reconstruct the ECH mass balance series back to 1909.

In more detail, the model captures the melt process by using monthly temperature data * by a tunable melt factor. Such a model attempts to capture the influence of long-wave radiation, turbulent heat fluxes and albedo within a single term. In reality, a small, high-elevation glacier such as Glaciar Echaurren Norte must have a relatively complicated surface energy balance. I see that for example, penitentes form on its surface, indicating an important role for albedo and turbulent fluxes. Understanding the sensitivity of such a glacier to climate change (rather than reconstructing mass balance), requires

something a bit more thorough, e.g. a full-energy balance model and on-glacier observations. See for example Molg et al. 2008. International Journal of Climatology 28: 881–892 (2008).

Agreed. This is certainly the kind of studies that we would require to understand the energy balance of this glacier and fully elucidate the sensitivity of this type of glaciers to climate changes. However, as discussed in the text and mentioned above, the main objectives of our study were not to elucidate these in-depth issues for which data-intensive measurement programs would be required. Instead, given the valuable (but still limited) data available, we were interested in identifying first order forcings of the glacier mass balance variations, and then use these relationships to extend these variations back in time using other longer and well correlated records already available from this region.

We now mention the main objectives of the study in the Introduction section to clarify these points. See lines 144-159.

The paper should include a figure that shows the modelled and measured surface mass balance profiles (how b varies with elevation) so that we can get a sense of how much accumulation and melt actually occurs on Glaciar Echaurren Norte.

As mentioned above, the data reported to the WGMS is limited and only includes, for each year, the winter balance, the summer balance and the annual mass balance of Glaciar Echaurren Norte. Gathering the additional information from each measurement point and calculating and modeling mass balance profiles over the study period was not considered relevant given the main purposes of this study, which were focused on testing the ability of very simple models to capture the year-to-year changes in mass balance at ECH.

Minor comments:

Title: ‘mass balance’ (rather than balances)

Fixed

4951, Lines 8-11. See above. This finding should be de-emphasised or removed until more complete modeling is carried out.

Agreed. We have re-written this and other related portions of the text to better address this issue. See lines 33-35, and 398-408.

4952, Line 4. ‘touristic’ isn’t used by native English speakers. Replace.

Fixed. “tourist attractions” used instead of touristic.

4954, Lines 1-3. This statement about snow remaining frozen is not supported by data or a reference. It may be correct but it either needs a citation or more speculative language should be used.

Fixed. We had only one general reference to support this statement (Masiokas et al. 2006). Now we have also included a more specific study (Cara et al. in press) that shows the characteristic seasonal pattern of snow cover in the Andes at these latitudes. This pattern shows a maximum coverage during the winter months, followed by a clear decline that starts at the onset of the melting season (October-November) and reaches a minimum during the warmest months of the year (December-February).

Lines 16-20. This sentence is too complicated and needs to be rewritten.

Fixed. This now reads: “In contrast to the well known similarities between precipitation (solid and liquid) and surface runoff, the spatial and temporal patterns of high-elevation temperature records in the Central Andes of Chile and Argentina are still poorly understood.” See Lines 118-120.

4955, Line 1. Please provide elevational range of glacier.

Fixed. The elevational range and other specific characteristics of the glacier are now included in the more detailed description of the glacier (see section 2.1).

Lines 20-26. I disagree that this approach provides ‘solid evidence’ for ‘objective testing’ of the relative significance of temperature and precipitation on mass balance. See discussion above and revise this text appropriately.

Agreed. This sentence was removed and a better discussion of the limitations of the methodology is included in the text. See lines 398-408, 467-482.

4956, _ line 5. The paper would benefit from a clear list of objectives.

Fixed. See last paragraph of the Introduction. Lines 146-149, 153-159.

4957, Line 27. ‘Values’ of what?

The sentence refers to the winter mass balance values measured at ECH.

4959, Line 4. Add space ‘predictand’.

Fixed.

4966, lines 10-11. A hypothesis can not be ‘validated’. Use ‘support’ instead.

Fixed.

Responses to Referees

Anonymous Referee #3

1 General comments

This study presents an analysis of the mass balance (MB) at glacier Echaurren Norte over a longer period. Using a temperature-index MB model they first assess the sensitivity of the glacier MB to temperature and precipitation. Then they use the fact

that regional streamflow time series are well correlated to the MB at ECH in order to build a simple linear regression model and reconstruct a MB up to 1909.

The manuscript is generally well written and gathers some interesting regional data.

We thank the reviewer for acknowledging that the paper is well written, and would like to stress the fact that that no other site in the extratropical Andes (~22°-55°S) contains such a unique combination of long and complete glacier and climate records located only 10-15 km apart.

However, the efficient writing style chosen by the authors also hides some flaws and simplifications in the methodology (see comments below). The chosen methods are extremely simplistic (a fact acknowledged by the authors) while their conclusions are not. The authors' argumentation in favour of these simple tools is often qualitative and rarely backed up by references.

The use of this simplistic modeling approach was partly forced by the lack of detailed on-glacier measurements at ECH (see above), and partly motivated by our interest in finding if it was possible to successfully capture this glacier's annual mass balance variations using a simple model that only relies on monthly temperature and precipitation as input. In this sense, the key reference mentioned in several parts of the text is Marzeion et al. (The Cryosphere, 2012a), who applied the same model and sensitivity analyses to a larger glacier mass balance dataset available from the European Alps. See lines 147-149, and section 2.2.

I am surprised that the authors did not care to discuss the influence of changing glacier geometry on both the statistical and temperature-index model outputs.

Fixed. In the submitted manuscript we failed to indicate that we are reconstructing reference-surface mass balance. This is now indicated in lines 181-189, 344-351, 467-482.

Altogether I am not convinced that the presented study provides enough new material or methods to justify a publication in TC. My recommendation to the authors is to address the points below and to extend the study by including more ambitious objectives, for example by discussing the climatic drivers of the MB variability.

We have now addressed these points including a) a discussion on the use and implications of a reference-surface glacier area in the mass balance reconstruction (see previous response above), b) the cross-validation and better estimation of the simple mass balance model parameters (see lines 222-232), and c) an improved estimation of the uncertainties in the streamflow-based mass balance reconstruction and the associated uncertainties in the cumulative values back to 1909 (see lines 273-281, 291-295, 344-351).

Temperature index MB model

The authors use a variant of the well known "degree day" or "temperature index" model as described by Marzeion et al. (2012a). I am not familiar with this paper but I know the following study (Marzeion et al. 2012b) where they apply globally an extended version

of the model. In both versions of the model Ben Marzeion used monthly solid precipitation, while the present study uses total precipitation. This difference can have strong repercussions on the presented results, since temperature influences the phase of precipitation and thus the MB. In that sense, the choice of the representative altitude of the glacier for the temperature index model is also very important: Marzeion et al. 2012b uses two altitudes z_{top} and z_{tongue} to represent a glacier, while in this manuscript the representative altitude is not specified. This altitude also has a strong influence on μ .

Marzeion et al. (2012b) used two altitudes to represent their glaciers and differentiate solid from total monthly precipitation in their global study that involved many sites (255 glaciers) with different glaciological and climatological conditions. In the case of ECH and other high elevation areas in the central Andes of Chile and Argentina, it is well known that the bulk of precipitation occurs during the winter months and that the fraction of liquid precipitation is normally minimal compared to the large proportion that falls as snow.

To demonstrate this we have included a new figure that shows the seasonal cycle of temperature and precipitation at ECH extrapolated linearly from the nearby El Yeso meteorological station (Fig. 1D). This diagram shows that the peak in precipitation effectively occurs during the coldest months, and that precipitation during the warmest months (i.e. those that show mean temperatures above 0°C - December to March) only accounts for 4.8% of the annual totals at ECH. For this reason, and to avoid the additional complexity and uncertainties involved in differentiating solid from total precipitation in this glacier with such a short altitudinal distribution (see Fig. 1C), we estimate the winter balance at ECH using monthly total precipitation values from El Yeso.

The parameter μ of the temperature index model is in reality a statistical tuning parameter and must be seen as such¹: it can efficiently hide model deficiencies and must be used with care, in particular for sensitivity analyses. The authors should use cross-validation to properly assess the real accuracy of the model. The temperature index model might be a good approximation on average, but the authors should provide arguments and evidence for the usability of such a model for sensitivity analyses at the ECH glacier.

Agreed. We performed a cross-validation assessment of the simple mass balance model. This assessment also allowed the optimization of the model parameters that were adjusted to minimize the RMSE of the model at each time step. See section 2.2 of the revised manuscript for details.

Changing glacier geometry

The term “mass balance” used in this study is in fact “specific mass-balance” (Cogley et al. 2011), i.e. the MB per unit area. On decadal time scales the influence of glacier

¹ even if there are physical reasons for the temperature index model to be successful, e.g. Hock 2003

dynamics cannot be neglected. This is why the version of the MB model in Marzeion et al. 2012b (and other global studies) explicitly take glacier dynamics into account (using simple scaling laws, but still).

There are important differences between the studies of Marzeion et al. 2012a (which is the approach we use in our study) and Marzeion et al. 2012b. The first study reconstructs Alpine glacier mass balance changes using *reference-surface mass balance* estimates, whereas the second study develops *conventional glacier mass balance* reconstructions to estimate the global contribution to sea level from these mass balance changes. The analyses in Marzeion et al. 2012b necessarily require estimations of volumetric changes associated with the reconstructed changes in glacier mass balance. Therefore Marzeion et al. 2012b included a number of additional equations and parameters to explicitly account for the changes in glacier geometry at each site.

In our study we calculate reference-surface mass balances for ECH (i.e. the mass balance that would have been observed if the glacier's surface topography had not changed, see Cogley et al., 2011), and thus the estimation of the impacts of changing glacier geometry in the mass balance reconstruction were not included in the assessment.

Interestingly however, given the particular shape and hypsometry of this small cirque glacier (see Fig. 1C), the conventional and the reference-surface mass balance estimates at ECH were probably roughly similar over the relatively short periods of time evaluated here. Fig. 1C shows that over the 1975-2013 period, the glacier frontal elevation has not changed much but instead the whole glacier has thinned and seems to be disintegrating in place. In the first report on this glacier mass balance program, Peña and Narbona (1978) indicate that the main glacier body is distributed between 3650 and 3880 m asl, an elevational range that has not changed much until today. In addition, the ice mass loss over the 1975-2013 period has been around -15 m w.eq, which is well within the error bands used to calculate, for example, the elevation range and the surface topography of the glacier.

It is not clear to me how changing glacier geometry is compatible with the single linear regression model based on streamflow presented here. Interestingly, the regional streamflow time series could contain the signal of changing glacier geometry and volume, but this should be proven and discussed. Currently, I am more than skeptical about any of the absolute values of specific MB presented here, especially the ones without error bars (e.g. accumulated MB, see specific comments below).

The glacier mass balance reconstruction is also based on reference-surface estimates, and therefore the changes in glacier geometry were not considered in this case either.

We have calculated the uncertainties associated with the reconstructed cumulative series (see Fig. 4B), and have also added notes discussing these uncertainties and the implications for using these reconstructed cumulative series to derive mass balance change estimates over extended periods. See lines 344-351, 467-482. This is an important point and we thank the reviewer very much for suggesting this addition to the paper.

2 Specific comments

Title

I find that the title does not reflect the content of the manuscript. In the end the ECH is the only glacier which mass balance has been reconstructed.

Agreed. We now refer to the reconstruction of ECH in the title.

Structure

the text is sometimes repetitive. Since there are no sub-sections the logical structure is difficult to follow.

Agreed. We have now removed some repetitive sentences and have included subtitles to improve the readability of the manuscript.

P4955 “we believe that the parsimonious approach presented here provides solid evidence for objective testing of the relative significance of temperature and precipitation variables to the year-to-year variability of this glacier’s mass balance”: this does not convince me. Where are these evidences?

Agreed. We have now removed this sentence and have tried to make clear the caveats involved with these simplistic exercises (see reply to a similar comment from Referee #2 above).

P4960 L7 “indicating that up to 78% of the variance in the ECH record can be accounted for by the minimal model presented in Eq. (1)” : here cross-validation should be used to assess the real R2

Fixed. We have now cross-validated this glacier mass balance model and discuss the details and results in the text. Thanks to this exercise we have modified slightly the model parameters α (from 4.1 to 3.91) and μ (from 92 to 90.1, see section 2.2). These new parameter estimates minimize the RMSE between the observed and modeled mass balance estimates over the 1977-2012 model calibration period. See lines 222-232.

P4960 L25 “The snowpack-based mass balance reconstruction is not shown (...)” : does it even makes sense to mention the snowpack model if it is never used? The streamflow and snowpack time series seem to be highly correlated anyway.

We believe it is important to mention and show in the table the results of the snowpack-based regression model to support our assertion that the annual mass balance changes are strongly associated to changes in winter precipitation in this region.

P4960 L29 : “68% of the variance” : again, cross-validated?

Yes, this value is reached after cross-validating the estimated values obtained from the linear regression model. This is mentioned in section 2.3, lines 263-270.

P4971 L2 : “offering the possibility of reliably extending the information on glacier mass balance changes back to 1909”: and what about glacier geometry?

Glacier geometry changes are not included in the reference-surface mass balance estimates used here. See reply to related comment above.

P4961 L9 : “The year 1968 is the most prominent feature of this extended negative period and according to these results it likely constitutes the most negative mass balance year since at least 1909”: I see that MB observations show at least one more negative year (approx. 1998, El Niño?). Given the large uncertainties of this very simple statistical model and the well known property of linear regression models to dampen the variability, such precise statements cannot be formulated.

Agreed. We have removed the reference to this extreme negative mass balance year.

P4961 L13 : “an overall negative trend totalling almost -42 m.w.eq. between 1909 and 2013 (Fig. 4b)” + all numbers listed afterwards. For the cumulated time series the authors forgot to take the uncertainties into account. The accumulated values are subject to the “random walk” effect and will have a much larger spread. This uncertainty has to be quantified, for example by computing the spread of a bootstrap of random realisations.

Agreed. We have removed the reference to these estimated values and only discuss the overall patterns observed in the reconstructed ECH series. See lines 335-351, 446-465.

We have also included an improved estimation of the reconstruction uncertainty which takes into account the standard error of the regression estimate, and the standard error of the mean streamflow values used as predictors in the reconstruction model (see section 2.3 and Fig. 4A). The first error was calculated during the calibration of the model, and the second error is directly proportional to the number of individual river records used to calculate the regional average (it increases in the first decades of the record due to the decreasing number of runoff records that contribute to the regional composite).

The cumulative mass balance record now includes the estimated uncertainties calculated by propagating (adding) the reconstruction errors as we move back in time. See Fig. 4B and section 2.3 for details.

References

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1 **Reconstructing the annual mass balance of glacier Echaurren Norte (Central Andes,**
2 **33.5°S) using local and regional hydro-climatic data**

3

4 **M.H. Masiokas^{1*}, D.A. Christie^{2,3}, C. Le Quesne², P. Pitte¹, L. Ruiz¹, R. Villalba¹, B.H.**
5 **Luckman⁴, E. Berthier⁵, S.U. Nussbaumer⁶, A. González-Reyes⁷, J. McPhee⁸, G. Barcaza⁹**

6

7 ¹ Instituto Argentino de Nivología, Glaciología y Ciencias Ambientales (IANIGLA),

8 CCT- CONICET Mendoza, C.C. 330, (5500) Mendoza, Argentina

9 ² Laboratorio de Dendrocronología y Cambio Global, Instituto de Conservación Biodiversidad y

10 Territorio, Facultad de Ciencias Forestales y Recursos Naturales, Universidad Austral de Chile,

11 Valdivia, Chile.

12 ³ Center for Climate and Resilience Research (CR)², Chile.

13 ⁴ Department of Geography, University of Western Ontario, Canada.

14 ⁵ LEGOS, CNRS, Université de Toulouse, France

15 ⁶ Department of Geography, University of Zurich, and Department of Geosciences, University of

16 Fribourg, Switzerland.

17 ⁷ Departamento de Geología, Facultad de Ciencias Físicas y Matemáticas, Universidad de Chile.

18 ⁸ Departamento de Ingeniería Civil, Facultad de Ciencias Físicas y Matemáticas, Universidad de

19 Chile.

20 ⁹ Dirección General de Aguas (DGA), Santiago, Chile.

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22 * Correspondence to: mmasiokas@mendoza-conicet.gob.ar

23 Tel.: +54-261-5244264

24 Fax: +54-261-5244201

25

26 **Abstract**

27 Despite the great number and variety of glaciers in southern South America, *in situ* glacier mass
28 balance records are extremely scarce and glacier-climate relationships are still poorly understood
29 in this region. Here we use the longest (>35 yrs) and most complete *in situ* mass balance record,
30 available for glacier Echaurren Norte in the Andes at ~33.5°S, to develop a minimal glacier
31 surface mass balance model that relies on nearby monthly precipitation and air temperature data
32 as forcing. This basic model is able to explain 78% of the variance in the annual glacier mass
33 balance record over the 1978-2013 calibration period. An attribution assessment identified
34 precipitation variability as the dominant forcing modulating annual mass balances at ECH, with
35 temperature variations likely playing a secondary role. A regionally-averaged series of mean
36 annual streamflow records from both sides of the Andes is then used to estimate, through simple
37 linear regression, this glacier's annual mass balance variations since 1909. The reconstruction
38 model captures 68% of the observed glacier mass balance variability and shows three periods of
39 sustained positive mass balances embedded in an overall negative trend over the past 105 years.
40 The three periods of sustained positive mass balances (centered in the 1920s-30s, in the 1980s
41 and in the first decade of the 21st century) coincide with several documented glacier advances in
42 this region. Similar trends observed in other shorter glacier mass balance series suggest that the
43 glacier Echaurren Norte reconstruction is representative of larger-scale conditions and could be
44 useful for more detailed glaciological, hydrological and climatological assessments in this portion
45 of the Andes.

46

47 **1. Introduction**

48 The extra-tropical Andes between $\sim 23^\circ$ and 55°S contain a large number and variety of glaciers
49 ranging from small glacierets at elevations of over 6000 m in the high, arid Andes of northern
50 Chile and Argentina, to large outlet glaciers that reach the sea in the humid southwestern portion
51 of Patagonia and Tierra del Fuego. Altogether, these ice masses concentrate the largest
52 glacierized area in the Southern Hemisphere outside Antarctica and are highly valued as sources
53 of freshwater, as indicators of climatic change, as **tourist attractions, and as** environmental and
54 cultural icons in different sectors of the Andes. As reported for other mountainous areas of the
55 globe, glaciers in southern South America display a widespread retreating pattern that has been
56 usually attributed to warmer, and sometimes drier, climatic conditions in this region (Villalba et
57 al. 2003; Rignot et al. 2003; Rivera et al. 2000, 2005; Masiokas et al. 2008, 2009; Le Quesne et
58 al. 2009; Pellicciotti et al. 2014). Quantitative assessments of regional glacier mass balance
59 changes and glacier-climate relationships are, however, seriously hampered by the scarcity and
60 short length of *in situ* glacier mass balance data and **proximal** climate records within the Andes.
61 The latest publication of the World Glacier Monitoring Service (WGMS 2013) reports annual
62 mass balance measurements for seven extratropical Andean glaciers (five in Argentina, two in
63 Chile). Four of these records start in 2010 and are for small glaciers and glacierets located ca.
64 29.30°S , two records are located between 32° - 34°S and start in the mid-late 1970s, and the
65 remaining record from Tierra del Fuego (54.8°S) starts in 2001. Discontinued, short-term glacier
66 mass balance measurements (see e.g. Popovnin et al. 1999) and recent programs initiated at new
67 sites (e.g. Rivera et al. 2005; Rabatel et al. 2011; Ruiz et al. 2013) complete the network of direct
68 glacier mass balance data currently available in southern South America. Although not optimal in
69 terms of spatial coverage, arguably the single most important limitation of this network is the
70 short period of time covered by consistent, reliable records. Of the two longest mass balance
71 series mentioned above (glaciar Echaurren Norte and glaciar Piloto Este in the Central Andes, see
72 Table 1.1 in WGMS 2013), only the series from Echaurren Norte in Chile (Fig. 1A-C) provides a
73 complete record spanning more than 35 years. In fact, this series constitutes the longest direct
74 glacier mass balance record in the Southern Hemisphere (see Escobar et al. 1995a,b; DGA 2010
75 and WGMS 2013) and is thus a “reference” glacier in the WGMS global assessments. The mass
76 balance record from glaciar Piloto Este (located ca. 100 km to the north in Argentina; Fig. 1A)

77 covers the 1979-2002 period and contains several data gaps that have been interpolated using
78 various techniques (Leiva et al. 2007).

79
80 Many studies dealing with recent climate and glacier changes in southern South America have
81 pointed out the shortness, poor quality, or absence of climatic records at high elevation sites or in
82 the proximity of glaciers in the Andes (Villalba et al. 2003; Rivera et al. 2005; Masiokas et al.
83 2008; Rasmussen et al. 2007; Falvey and Garreaud 2009; Pellicciotti et al. 2014; Vuille et al.
84 2015). Given the lack of suitable data, many climatic assessments have used records from distant,
85 low elevation weather stations and/or gridded datasets to estimate conditions and recent climate
86 variability within the Andean range. It is interesting to note, however, that the amount of hydro-
87 climatic information (in particular from solid and liquid precipitation, and hydrologic variables)
88 is comparatively better for those portions of the southern Andes that support large populated
89 centers and where the water provided by the mountains is vital for human consumption,
90 agriculture, industries and/or hydropower generation. In these areas, mainly between ca. 29° and
91 42°S, local and national water resource agencies have monitored a well-maintained network of
92 hydrologic and meteorological stations for several decades (see e.g. Masiokas et al. 2006, 2010).
93 The data from the stations in this region are slowly becoming publicly available and are
94 substantially better in terms of quantity and quality than those for the less populated, more
95 inaccessible areas in southern Patagonia or in the Desert Andes of northern Chile and Argentina.

96
97 The Central Andes of Chile and Argentina between ~31° and 35°S (see Lliboutry 1998) have a
98 mean elevation of about 3500 m with several peaks reaching over 6000 m (Fig. 1A). The climate
99 of this region is characterized by a Mediterranean regime with a marked precipitation peak during
100 the cold months (April to October) and little precipitation during the warm summer season
101 (November to March; Fig. 1D). Almost all of the moisture comes from westerly Pacific frontal
102 systems, precipitating as rainfall in the Chilean lowlands and as snow in the Andes to the east
103 (Miller 1976; Aceituno 1988; Garreaud 2009). The snow accumulated in the mountains during
104 winter remains frozen until the onset of the melt season (usually October-November), producing
105 a unimodal snowmelt-dominated regime for all rivers originating on either side of the Andes at
106 these latitudes (Masiokas et al. 2006; Cara et al. in press). This relatively simple configuration
107 entails some potential benefits for the study and understanding of the hydro-climatic and

108 glaciological processes in this region: First, the strong co-variability between total rainfall
109 amounts measured in central Chile and winter snow accumulation and river discharges recorded
110 in the Andes (see Fig. 2) allows the use of a relatively limited number of station records to
111 capture the main regional hydro-climatic patterns. The strong common signal among these
112 variables also offers the possibility of inferring or reconstructing selected instrumental data (e.g.
113 winter snow accumulation, which begins in 1951) using data from other well-correlated variables
114 with a longer temporal coverage (e.g. Andean streamflow records which are available since
115 1909). Masiokas et al. (2012) used these relationships to extend Andean snowpack variations
116 using central Chile rainfall records and precipitation-sensitive tree-ring width series.

117
118 **In contrast to the well-known similarities between precipitation (solid and liquid) and surface**
119 **runoff, the spatial and temporal patterns of high-elevation temperature records in the Central**
120 **Andes of Chile and Argentina are still poorly understood.** Falvey and Garreaud (2009) presented
121 a detailed assessment of temperature trends over the 1979-2006 period along the western margin
122 of subtropical South America, reporting a notable contrast between surface cooling (-
123 0.2°C/decade) in coastal stations and a warming trend of ca. +0.25°C/decade in the Andes only
124 100-200 km inland. However, only two land stations were available with long enough records
125 above 2000 m (i.e. El Yeso and Lagunitas stations in Chile at 2475 and 2765 m, respectively), but
126 radiosonde data from the coastal station Quintero (ca. 33°S) showed comparable positive trends
127 for the free-troposphere (Falvey and Garreaud 2009). This lack of high elevation surface
128 temperature data also restricted the recent assessments of Vuille et al. (2015), who focused their
129 elevation-dependent temperature trend analyses on the region north of 18°S because data were
130 too sparse farther south.

131
132 The station El Yeso (33°40'36"S, 70°05'19"W) is located only 10 km south of glacier Echaurren
133 Norte (Fig. 1B). Mean daily and monthly temperature and total precipitation measurements from
134 this station are available since 1962 but contain several months with missing data prior to 1977
135 (temperature) and 1975 (precipitation). Since 1977, both series are practically complete and
136 updated on a regular basis. To our knowledge, in the entire extra-tropical Andes there is no other
137 operational meteorological station with such a long and complete record of temperature and
138 precipitation variations less than a few kilometres from a glacier, which moreover contains the

139 longest ongoing mass balance monitoring program in the Southern Hemisphere. This rare
140 combination of relatively long, complete climate records near a well-studied glacier site clearly
141 highlights the importance of this unique location for varied glaciological and climatological
142 investigations in the southern Andes.

143
144 In this contribution we use seasonal mass balance records from glacier Echaurren Norte plus
145 local and regionally-averaged monthly hydro-climatic data to model and reconstruct annual
146 glacier mass balance changes over the past 105 years. Since only the glacier-wide seasonal and
147 annual mass balance components are available for ECH, one of the main objectives of the study
148 was to explore the suitability of simple mass balance models that require a minimum amount of
149 input data (Marzeion et al. 2012; see also Kaser et al. 2010). Although this simplistic approach
150 provides limited insight into the intricate physical processes involved in this glacier's intra-
151 annual mass balance variations, it may, nonetheless, offer a useful starting point to address some
152 basic (yet still poorly known) questions regarding the glacier's sensitivity to climate variations.
153 We did not consider a data-intensive approach to measure and model the complex daily energy
154 and mass balance variations of this glacier (e.g. Pellicciotti et al. 2014) because of the lack of the
155 high resolution, *in situ* meteorological and glaciological measurements usually required in these
156 type of analyses. Another primary objective was to use the available, well correlated hydrological
157 records from this region (Fig. 2) to extend the ECH annual mass balance record and evaluate the
158 fluctuations of mass balance over a much longer period than that covered by regular glaciological
159 measurements. Comparisons with other shorter mass balance series and with a record of glacier
160 advances in this region suggest the resulting time series contain a discernible regional footprint.
161 Overall, we believe the findings discussed below constitute a substantial improvement in the
162 understanding of the main patterns and forcings of the glacier mass balance changes in this region
163 and provide a useful background for more detailed glacio-climatic assessments and modeling
164 exercises in this portion of the Andes.

165
166 **2 – Data and Methods**
167 **2.1. Glacier mass balance data**
168 Glaciar Echaurren Norte (33°33'S, 70°08'W; hereafter ECH) is located within a southwestern
169 oriented cirque ~50 km southeast of Santiago de Chile, in the headwaters of the Maipo river basin

170 (Fig. 1A-C). ECH provides water to Laguna Negra, a natural lake that together with the nearby El
171 Yeso artificial lake constitute crucial water reservoirs for extensive irrigated lands and for the
172 metropolitan Santiago area in Central Chile.

173
174 Mass balance measurements started at this easily accessible glacier in the austral spring of 1975
175 under the auspices of Dirección General de Aguas (DGA), the institution in charge of monitoring
176 and managing water resources in Chile. Summer and winter mass balance data at ECH have been
177 regularly measured until the present by DGA officials, and have been reported in sporadic
178 internal documents and scientific publications (Peña and Narbona 1978; Peña et al. 1995;
179 Escobar et al. 1995, 1997; DGA 2010). These records have also been reported to the WGMS,
180 from where we obtained the 1975-2012 data used in this manuscript (annual mass balance data
181 extend to 2013; see WGMS 2013 and www.wgms.ch). The glacier has thinned in the last decades
182 and presently consists of small remnants of both clean and debris-covered ice (Fig. 1C). Despite
183 this evident ice mass loss, the elevation range of the glacier has not changed much since
184 measurements started in the mid 1970s. According to Peña and Narbona (1978) and Escobar et al.
185 (1995), in the first years of the mass balance program the glacier covered an area of 0.4 km²
186 distributed over a short elevation range between ca. 3650 and 3880 m asl (Fig. 1C). As this is the
187 only area reported for this glacier, in the analyses and results below we use reference-surface
188 mass balance estimates (i.e. the mass balance that would have been observed if the glacier
189 topography had not changed over the study period; see Cogley et al. 2011).

190
191 Mass balance data from glacier Piloto Este (hereafter PIL) from 1979-2002 and shorter time
192 series from small glaciers and glacierets further north in this region are also available from the
193 WGMS database (Leiva et al. 2007; Rabatel et al. 2011; WGMS 2013; see Fig. 1A and Table 1).
194 Here we compare the cumulative annual mass balance records of these glaciers as independent
195 validation measures of the main patterns and temporal trends observed in the measured and
196 modeled mass balance series from ECH.

197 198 **2.2 Minimal glacier mass balance model**

199 A minimal model only requiring monthly temperature and precipitation data (Marzeion et al.
200 2012) was used to estimate the interannual surface mass balance variations of ECH and to

201 explore the relative importance of temperature and precipitation variability on the ECH records.
 202 In their publication, Marzeion et al. (2012) used gridded precipitation and temperature data to
 203 calibrate individual models for 15 glaciers with existing mass balance measurements in the
 204 greater Alpine region. The climate data used here come from El Yeso, a permanent automatic
 205 weather station maintained by DGA and located ca. 10 km to the south and 1200 m lower than
 206 ECH’s snout (Fig. 1B). The data are freely available at the DGA website (www.dga.cl) and
 207 contain practically complete monthly temperature and precipitation records since 1977 (only four
 208 missing months were filled using their long-term means). The mass balance model can be defined
 209 as follows:

$$210$$

$$211 \quad MB = \sum_{i=1}^{12} (\alpha P_i - \mu(\max(0, T_i - T_{melt}))) \quad (1)$$

212
 213 where MB represents the modeled annual specific mass balance of the glacier, P_i are monthly
 214 total precipitation values at the El Yeso station, and α is a scaling parameter introduced to
 215 compensate for the precipitation gradient between the elevation of this station (rounded here to
 216 2500 m) and the front of ECH (fixed at 3700 m in this analysis). T_i represents mean monthly
 217 temperatures at El Yeso extrapolated to the elevation of the glacier front using a constant lapse
 218 rate of $-0.065^{\circ}\text{C}/100\text{ m}$, and T_{melt} is the monthly mean temperature above which melt occurs. As
 219 indicated in Marzeion et al. (2012), the maximum operator ensures that melting occurs only
 220 during months with mean temperatures above T_{melt} . The parameter μ is expressed in mm K^{-1} and
 221 was introduced to translate the monthly temperature records into monthly ablation values at the
 222 glacier. In order to estimate the parameters α and μ and validate the final model, we performed a
 223 “leave-one-out” cross validation procedure (Michaelsen 1987). In this approach, ECH data for
 224 each year between 1977 and 2012 (common period between the El Yeso data and the ECH mass
 225 balance series) were successively excluded and the minimal mass balance model (Eq. 1)
 226 calibrated with the remaining values. At each step the parameters α and μ were first optimized to
 227 minimize the root mean squared error (rmse; Weisberg 1985) of the modeled values, and then
 228 used to estimate the mass balance data omitted that year. This resulted in 36 predicted values
 229 which were compared to the actual annual mass balance observations to compute validation
 230 statistics of model accuracy and error. The exercise showed that the model parameters are

231 relatively time stable: α ranged between 3.9 and 4.1 (mean value used here = 3.9), whereas μ
232 varied between 89.0 and 91.0 mm K⁻¹ (mean value used = 90.1 mm K⁻¹). The mean estimated
233 value of α indicates that accumulation at the glacier is normally about four times larger than the
234 annual precipitation recorded at El Yeso. The mean estimated value for μ is also reasonable and
235 within the range of values reported by Marzeion et al. (2012) for the 15 glaciers with direct
236 measurements in the European Alps (76-156 mm K⁻¹, see their Table 1). Finally, for the sake of
237 simplicity, we prescribed $T_{melt} = 0^{\circ}\text{C}$ as suggested in Marzeion et al. (2012).

238

239 **2.3 Glacier mass balance reconstruction**

240 In addition to modeling the interannual mass balance variations of ECH using the temperature
241 and precipitation data from El Yeso, we also used regionally representative hydroclimatic
242 indicators to extend the observed glacier mass balance record prior to 1975. The use of these
243 indicators (regionally-averaged series of mean annual river discharges; see Masiokas et al. 2006)
244 was supported by visual comparisons and correlation analyses which showed strong, statistically
245 significant positive associations not only with the winter record at ECH, but also with the annual
246 mass balance series of this glacier (Table 2 and Fig. 2). The correlation was also positive but
247 weaker between the summer component at ECH and the regional snowpack and streamflow
248 series.

249

250 The regionally-averaged record of winter snow accumulation is based on eight selected stations
251 located in the Chilean and Argentinean Andes between 30° and 37°S (Fig. 1A and Table 3). The
252 dataset has been updated from the one used by Masiokas et al. (2012) and contains the longest
253 and most complete snowpack records in this region. Prior to computing the regional average, the
254 individual series were expressed as percentages from their 1981-2010 climatology mean values.
255 A similar approach was used to develop a regional record of mean annual (July-June) streamflow
256 variations. This series was calculated using monthly data from 11 gauging stations with the
257 longest and most complete records in this portion of the Andes (Fig. 1A and Table 3). The
258 resulting snowpack and streamflow composite records cover the 1951-2014 and 1909-2013
259 periods, respectively (Fig. 2).

260

261 The glacier mass balance reconstructions are based on simple linear regression models where the
 262 predictand is the 1975-2013 ECH annual mass balance series and the predictors are, alternatively,
 263 the regional 1951-2014 snowpack and 1909-2013 streamflow records depicted in Fig. 2. Given
 264 the relative shortness of the common period between the predictor and predictand series (39
 265 years), the reconstruction models were also developed using a “leave-one-out” cross-validation
 266 procedure (Michaelsen 1987). Here, linear regression models for each year were successively
 267 calibrated on the remaining 38 observations and then used to estimate the predictand’s value for
 268 the year omitted at each step. A simple linear regression model based on the full calibration
 269 dataset (1975-2013) was finally used to reconstruct the mass balance values over the complete
 270 period covered by the regional time series. The goodness of fit between observed and predicted
 271 mass balance values was tested based on the proportion of variance explained by the regression
 272 models and the normality, linear trend, and first- and higher-order autocorrelation of the
 273 regression residuals. The uncertainties in each reconstructed mass balance value in year t ($\epsilon_{reco,t}$)
 274 were calculated integrating the standard error of the regression estimate (se_{regr}) and the standard
 275 error of the mean annual streamflow values used as predictors in the model ($se_{mean,t}$). This latter
 276 error is derived from the standard deviation of the regional record (σ) and increases as the number
 277 of contributing streamflow series (n_t) decreases back in time (see Table 3).

$$\epsilon_{reco,t} = \sqrt{se_{regr}^2 + se_{mean,t}^2}, \text{ with} \quad (2)$$

$$se_{mean,t} = \frac{\sigma}{\sqrt{n_t}} \quad (3)$$

282
 283 An independent verification of the reconstructed mass balance records was undertaken by
 284 comparing the cumulative patterns of these series with the cumulative mass balances reported for
 285 glacier Piloto Este and for other glaciers with shorter mass balance series available in this portion
 286 of the Andes (Fig. 1A and Table 1). We also compared the ECH cumulative series (observed and
 287 predicted) with a regional record of glacier advances identified during the 20th century in the
 288 Andes between 29° and 35°S. The latter record was compiled in a recent review of glacier
 289 fluctuations in extratropical South America and is based on direct observations, reports from
 290 documentary evidence, and analyses of aerial photographs and satellite images from this region

291 (see Masiokas et al. 2009). The uncertainty of the cumulative series modeled for ECH ($\epsilon_{cum,t}$)
292 were calculated by propagating (adding) the individual errors estimated for each reconstructed
293 value. That is

$$\epsilon_{cum,t} = \sqrt{\epsilon_{reco,t}^2 + \epsilon_{reco,t+1}^2} \quad (4)$$

297 3 – Results

298 3.1. Minimal glacier mass balance model

299 The 1975-2012 winter and summer values observed at ECH are depicted in Fig. 3A. The winter
300 series shows a long term mean of 2.54 m w.eq. and a larger range of variability (std. dev. 1.24 m
301 w.eq.) than the summer series, which fluctuates around a long term mean of -2.93 m w.eq (std.
302 dev. 0.72 m w.eq.). The observed and modeled annual mass balance series are remarkably similar
303 (Fig. 3B) and show a strong positive correlation ($r = 0.883$, $rmse = 0.77$ m w.eq.), indicating that
304 78% of the variance in the ECH record can be accounted for by the minimal model presented in
305 Eq. (1). Both series show similar, slightly negative linear trends and negative means (-0.35 and
306 0.34 m w.eq. for the observed and modeled series, respectively) over the 1977-2012 interval.

308 3.2. Attribution assessments

309 In order to test which climate variable (temperature or precipitation) has a stronger influence on
310 the annual mass balance variations at ECH, the glacier mass balance model was also run
311 replacing alternatively the temperature and the precipitation monthly data by their long-term
312 average values. The results from this analysis (Fig. 3C) suggest that precipitation variations
313 constitute the dominant forcing modulating annual glacier mass balance at this site. Regardless of
314 their different absolute values, the precipitation-driven estimates (blue dashed line in Fig. 3C)
315 show a strong positive correlation ($r = 0.882$) and remarkable similarities with the ECH annual
316 mass balance series (red line). In contrast, the temperature-driven estimates (dark red dashed line)
317 show a poorer correlation with the ECH record ($r = 0.240$) and a substantially lower inter-annual
318 variability which only barely follows the variations in the annual mass balance series.

320 3.3 Annual mass balance reconstruction 1909-2013

321 Fig. 4A shows the reconstruction of the ECH annual mass balance series based on the regional
322 record of mean annual streamflows. The snowpack-based mass balance reconstruction is not
323 shown as it is significantly shorter than the streamflow-based series and shows virtually the same
324 variations over their overlapping interval. The streamflow-based regression model (Table 4) is
325 able to explain 68% of the variance in the annual mass balance series over the 1975-2013 period
326 and shows no apparent sign of model misspecification, offering the possibility of reliably
327 extending the information on glacier mass balance changes back to 1909. This reconstructed
328 mass balance record is almost three times longer than the mass balance record currently available
329 at ECH and shows a strong year-to-year variability embedded within several periods of overall
330 positive or negative conditions (Fig. 4A). In particular, positive mass balance conditions were
331 reconstructed between 1914 and 1941, in the 1980s, and in the late 1990s – early 21st century. In
332 contrast, the clearest sustained period of negative mass balances occurred between the 1940s and
333 the 1970s.

334
335 The cumulative values of the streamflow-based mass balance reconstruction show a very good
336 correspondence with the observed cumulative series and an overall negative trend between 1909
337 and 2013 (Fig. 4B). Within this century-long negative trend, a prominent period of extended
338 positive mass balances can be observed between the mid 1910s and the early 1940s. The peak of
339 this extended positive period occurred in the early 1920s and reached almost 10 m w.eq. above
340 the 1909 mass balance starting value. After 1941 and during the following four decades the
341 cumulative mass balance series shows an impressive decline that is interrupted in 1980 by a ~10-
342 year long period of sustained positive conditions (Fig. 4B). Since the early 1990s and until 2013
343 the cumulative mass balance series resumes the negative tendency, only interrupted by a short-
344 lived period of positive conditions in the first years of the 21st century. It is important to note,
345 however, that ascribing absolute values to this reconstructed cumulative series is complicated and
346 should be used with caution due to the large uncertainties involved, and the fact that we are using
347 reference-surface mass balance estimates (Cogley et al. 2011). Between 1975 and 2013 the lower
348 elevation of the glacier did not change much (see Fig. 1C) and therefore the reference-surface and
349 the conventional mass balance estimates are probably roughly equivalent. However, for earlier
350 decades and without historical information on the glacier area and frontal position, it is difficult
351 to estimate the impacts of changing glacier geometry on the actual mass balance of this glacier.

352

353 **3.4 Comparison with other glacier records**

354 Examination of the main patterns in the reconstructed cumulative mass balance series shows a
355 good correspondence with a regional record of glacier advances identified in the Central Andes
356 over the past 100 years (Masiokas et al. 2009; Fig. 4C). In most cases, the glacier advances are
357 concentrated during, or soon after, the periods of sustained positive mass balances reconstructed
358 or observed at ECH. This situation is particularly clear in the 1980s and 1990s, where a large
359 number of glacier advances were identified during and/or immediately after the peak in mass
360 balances that culminated in 1989 (Fig. 4BC). Glacier advances were also identified in the 1930s,
361 1940s and 1950s likely associated with the extended period of cumulative positive mass balances
362 that culminated in the early 1940s. A few well documented advances identified in this region
363 between 2003 and 2007 may be associated with the minor peak in cumulated mass balances
364 observed at the turn of the 21st century (Fig. 4BC).

365

366 The cumulative variations in the modeled and observed mass balance series from ECH are also
367 very similar to those observed in the 1979-2002 cumulative record of PIL, providing additional
368 support for the overall reliability of the reconstructed time series (Fig. 5). The cumulative
369 tendency of PIL appears to be “smoother” than the ECH series, but still shows slightly positive or
370 near equilibrium conditions between the late 1970s and the mid 1980s followed by a sharp
371 decline until the turn of the 21st century. The cumulative series from other glaciers located further
372 north in the Pascua Lama and Cordillera de Colanguil areas (Fig. 1A and Table 1) only cover the
373 last decade or so of the ECH record. However, in all cases their overall tendency is similar and
374 markedly negative, reflecting the sustained unfavorable conditions that these ice masses have
375 endured in recent years. It is interesting to note that the smaller glaciers (Table 1 and Fig. 5) are
376 the ones consistently showing the steepest negative cumulative trends whereas the largest glacier
377 (glaciar Guanaco, with ca. 1.8 km² in 2007) shows the least negative trend.

378

379 **4 – Discussion and Conclusions**

380 Compared to other mountainous glacierized areas, the extratropical Andes in southern South
381 America contain one of the least complete networks of *in situ* glacier mass balance and high-
382 elevation climate records in the world. This scarcity of basic information in this extensive and

383 glaciologically diverse region has been highlighted on many occasions, and several recent studies
384 have attempted to overcome this limitation by estimating mass balance changes through remote
385 sensing and/or modeling approaches of varied complexity and spatial coverage (e.g. Casassa et
386 al. 2006; Radić et al. 2013; Lenaerts et al. 2014; Pellicciotti et al. 2014; Schaeffer et al. 2013,
387 2015). With such limited data availability, the few existing glacier mass balance records become
388 particularly relevant as they provide crucial information and validation measures for many
389 glaciological, climatological and hydrological analyses.

390
391 In this paper we analyzed an up-to-date compilation of the longest and most complete *in situ*
392 glacier mass balance and hydro-climatic records from the Andes between 29° and 37°S to address
393 some basic (yet poorly known) glaciological issues in this region. First, we show that it is
394 possible to estimate annual glacier mass balance changes using very simple modeling approaches.
395 Results from a minimal model requiring only monthly temperature and precipitation data (eq. 1)
396 revealed that up to 78% of the variance in the annual mass balance series between 1977 and 2012
397 could be captured simply using available records from the El Yeso station, ca. 10 km from the
398 glacier (Fig. 1A and 3B). Winter precipitation variability appears to be the dominant forcing
399 modulating annual mass balances at ECH, with temperature variations likely playing a secondary
400 role (Fig. 3C). This is particularly interesting because it contrasts with the findings in other
401 regions where the recent glacier behavior is generally more strongly related to changes in
402 temperature instead of precipitation (e.g. Marzeion et al. 2012). However, and although Peña and
403 Narbona (1978) also noted a dominant influence of the winter accumulation term on the resulting
404 annual mass balance of this glacier, the results should be assessed with caution given the
405 simplistic nature of our model and the various factors that ultimately affect the annual mass
406 balance at this site. For example, more detailed assessments should also consider the impact of
407 sublimation on the mass balance of glaciers in this high arid portion of the Andes (McDonnell et
408 al. 2013; Pellicciotti et al. 2014).

409
410 To test the reliability of the temperature records used to model the glacier mass balance series we
411 correlated the El Yeso monthly temperature record with ERA Interim gridded reanalysis
412 temperatures for the 700 mb geopotential height (roughly 3000 m asl), and also with a 0°C
413 isotherm elevation series available from central Chile (Fig. 6). The El Yeso temperature record

414 shows strong positive correlations with ERA Interim gridded data over an extensive region that
415 includes central Argentina, central Chile and an adjacent area in the Pacific Ocean (Fig. 6A). The
416 El Yeso temperature record also shows clear similarities and a positive significant correlation
417 with the 0°C isotherm elevation series over the 1977-2004 interval (Fig. 6B-C). The
418 independence of these three datasets indicates that the El Yeso mean monthly temperature data
419 are reliable and that the poor performance of this variable in the mass balance modeling exercise
420 is not related to the overall quality of the temperature series. Although this issue is beyond the
421 main purposes of this study, more complex modeling approaches are also needed to evaluate if
422 climate data at higher temporal resolution (instead of monthly values as used here) are capable of
423 capturing a larger percentage of the mass balance variations observed at ECH.

424
425 Annual mass balance variations observed at ECH can also be reproduced or estimated accurately
426 through simple linear regression using regionally-averaged winter snowpack or annual
427 streamflow records as predictors (Fig. 4A). This is due to the existence of a strong common
428 hydroclimatic signal in this region, which results in very similar inter-annual variations in winter
429 snow accumulation, mean annual river discharges, and glacier mass balance changes such as
430 those measured at ECH (Fig. 2). This simple approach allows extending the information on
431 glacier mass balance changes several decades prior to the beginning of in situ measurements
432 (back to 1909), and offers the opportunity of putting the existing glacier record in a longer term
433 perspective. Many of the extreme values reconstructed in this study have been documented in
434 historical reports and recent analyses of instrumental hydro-climatic data. For example, the
435 extreme positive values of 1914 and 1919 coincide with extremely wet winters in central Chile
436 (see e.g. Fig. 2; Taulis 1934; Masiokas et al. 2012), whereas the period with above average
437 balances centered in the 1980s or the negative conditions between the 1940s and 1970s have been
438 identified, respectively, as the snowiest and driest intervals during the instrumental era in this
439 region (Masiokas et al. 2010). Examination of the main intra- to multi-decadal patterns in this
440 extended series also indicates that the sustained negative mass balance conditions reported for
441 ECH in recent years are not unusual and were probably surpassed by more negative and longer
442 periods between the 1940s and 1970s (Fig. 4A). However, the impact of a few consecutive years
443 of negative mass balances are more serious today than several decades ago because of the low
444 volume of ice remaining and the poorer overall “health” of the glacier.

445
446 The cumulative series of the reconstructed mass balances values (Fig. 4B) shows a steep negative
447 trend that is consistent with the recent loss of ice reported for other glaciers in this region (Fig. 5;
448 Escobar et al. 1995; Rivera et al. 2000; Masiokas et al. 2009). This negative trend has been
449 temporarily interrupted by periods of sustained positive mass balances that, in most cases,
450 precede or coincide with recent glacier re-advances identified at these latitudes in the Andes
451 (Masiokas et al. 2009; Fig. 4C). The clearest example is the relationship between the peak in
452 cumulative mass balances in the mid-late 1980s and the 11 documented glacier advances in the
453 following decade. It is also interesting to note that several of the glacier events that occurred after
454 periods of positive mass balances have been identified as surges (Helbling 1935; Espizua 1986;
455 Masiokas et al. 2009; Pitte et al. in review). The well-known surges of Grande del Nevado glacier
456 (in the Plomo massif area) in 1933-34, 1984-85, and 2004-2007 are particularly noteworthy as
457 they consistently occurred near the culmination of the three periods with overall positive mass
458 balances in the 1920s-30s, in the 1980s and in the first decade of the 21st century (Fig. 4B). In
459 agreement with the progressively smaller magnitude of these peaks in the cumulative mass
460 balance series, the three Grande del Nevado surges also showed a decreasing power and
461 transferred progressively smaller quantities of mass from the upper to the lower parts of the
462 glacier. Two recent surges of Horcones Inferior glacier in the nearby Mt. Aconcagua area also
463 occurred in the mid 1980s and again between 2002 and 2006, suggesting a possible connection
464 between the development of surging events and the periods with overall positive mass balance
465 conditions in this region (Pitte et al. in review).

466
467 The fact that only limited information is available for ECH together with the use of reference-
468 surface mass balance estimates (see section 2.1) pose interesting yet complicated questions
469 regarding the applicability of this series in related glaciological and/or climatological
470 assessments. Since reference-surface mass balance variations are more closely related to changes
471 in climate than the conventional mass balance of a glacier (Cogley et al. 2011), the reconstructed
472 series discussed here is arguably more relevant to climate-change related studies rather than
473 hydrological studies. If the purpose is to evaluate the hydrological contribution of this ice mass
474 over the last century, then conventional mass balance estimates are necessarily required to take
475 the changing glacier geometry into account. In any case, and considering the relevance of the

476 observed ECH series for regional, hemispheric and global mass balance studies, a reanalysis
477 (Zemp et al. 2011) of the entire mass balance record would probably produce important
478 worthwhile information to properly assess the hydrological impact of the recent ice mass losses
479 in this semi-arid region (e.g. Ragetti et al. 2014). This issue is particularly relevant due to the
480 extended droughts experienced in recent years and the increasing socio-economic conflicts over
481 the limited water resources (almost entirely originating in the mountains) arising on both sides of
482 the Andes.

483
484 Keeping these caveats in mind, the common pattern of strongly negative mass balances, the
485 similarities with the few available glacier chronologies, and the regional nature of the predictors
486 used in the ECH reconstruction suggest that this series may nonetheless be considered
487 representative (in relative terms) of the mass balance changes during recent decades in other less
488 studied areas in this region. Reliable data from a larger number of glaciers together with
489 additional studies of the glacier-climate relationships are, however, still needed to support this
490 hypothesis and to identify, for example, the main climatic forcings behind the recent glacier
491 shrinkage observed in the Central Andes of Chile and Argentina (Masiokas et al. 2009). This is a
492 challenging issue due to several factors, including the serious lack of glacier mass balance series
493 and high-elevation climate records, the complex dynamic response of individual glaciers to
494 similar changes in climate, and the great variety of glaciers existing in this region (Pellicciotti et
495 al. 2014). The results discussed in this study offer a useful starting point to address the various
496 pending issues mentioned above and will hopefully stimulate further glaciological, climatological
497 and hydrological research in this poorly known mountainous region.

498 499 **6 – Acknowledgements**

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634

635 **Table 1.** Basic information of the glacier mass balance series used in this study. (*) Country: CL:
 636 Chile; AR: Argentina.

Name	ID in Fig. 1	Lat., Long.	Area in km² (year)	Period	Ctry*	References
Echaurren Norte	ECH	33°33'S, 70°08'W	0.226 (2008)	1975-2013	CL	DGA 2009; Barcaza (DGA); WGMS 2013
Piloto Este	PIL	32°13'S, 70°03'W	0.504 (2007)	1979-2002	AR	Leiva et al. 2007; WGMS 2013
Conconta Norte	COL	29°58'S, 69°39'W	0.089 (2012)	2008-2013	AR	Cabrera and Leiva (IANIGLA); WGMS 2013
Brown Superior	COL	29°59'S, 69°38'W	0.191 (2012)	2008-2013	AR	Cabrera and Leiva (IANIGLA); WGMS 2013
Los Amarillos	COL	29°18'S, 69°59'W	0.954 (2012)	2008-2013	AR	Cabrera and Leiva (IANIGLA); WGMS 2013
Amarillo	PAS	29°18'S, 70°00'W	0.243 (2012)	2008-2013	CL	Cabrera and Leiva (IANIGLA); WGMS 2013
Toro 1	PAS	29°20'S, 70°01'W	0.071 (2007)	2004-2009	CL	Rabatel et al. 2011; WGMS 2013
Toro 2	PAS	29°20'S, 70°01'W	0.066 (2007)	2004-2009	CL	Rabatel et al. 2011; WGMS 2013
Esperanza	PAS	29°20'S, 70°02'W	0.041 (2007)	2004-2009	CL	Rabatel et al. 2011; WGMS 2013
Guanaco	PAS	29°19'S, 70°00'W	1.836 (2007)	2004-2013	CL/ AR	Rabatel et al. 2011; Rivera (CECs); WGMS 2013

637

638 **Table 2.** Correlation analyses between the ECH mass balance series and regional hydro-climatic
 639 records. The number of observations used in each correlation test is indicated in parenthesis.
 640 Note: * (**) Pearson correlation coefficient is significant at the 95% (99%) confidence level.
 641

	Winter ECH	Annual mass balance ECH	Regional snowpack	Regional streamflow
Summer ECH	0.245 (38)	0.648** (38)	0.447** (38)	0.395* (38)
Winter ECH		0.897** (38)	0.796** (38)	0.834** (38)
Annual mass balance ECH			0.829** (39)	0.826** (39)
Regional snowpack				0.916** (63)

642
 643

644 **Table 3.** Stations used to develop regionally-averaged series of mean annual river discharges and
645 winter maximum snow accumulation for the Andes between 30° and 37°S. Mean annual
646 streamflow values refer to a July-June water year. Note: (*) The 1981-2010 climatology values
647 for each station are expressed as mm w.eq. for snowpack and as m³ s⁻¹ for streamflow. In the case
648 of the San Juan and Cachapoal rivers, the mean values used correspond to the 1981-2007 and
649 1981-2001 periods, respectively. Data sources: (DGA) Dirección General de Aguas, Chile; (DGI)
650 Departamento General de Irrigación, Mendoza, Argentina; (SSRH) Subsecretaría de Recursos
651 Hídricos, Argentina. See Masiokas et al. (2013) for further details.
652

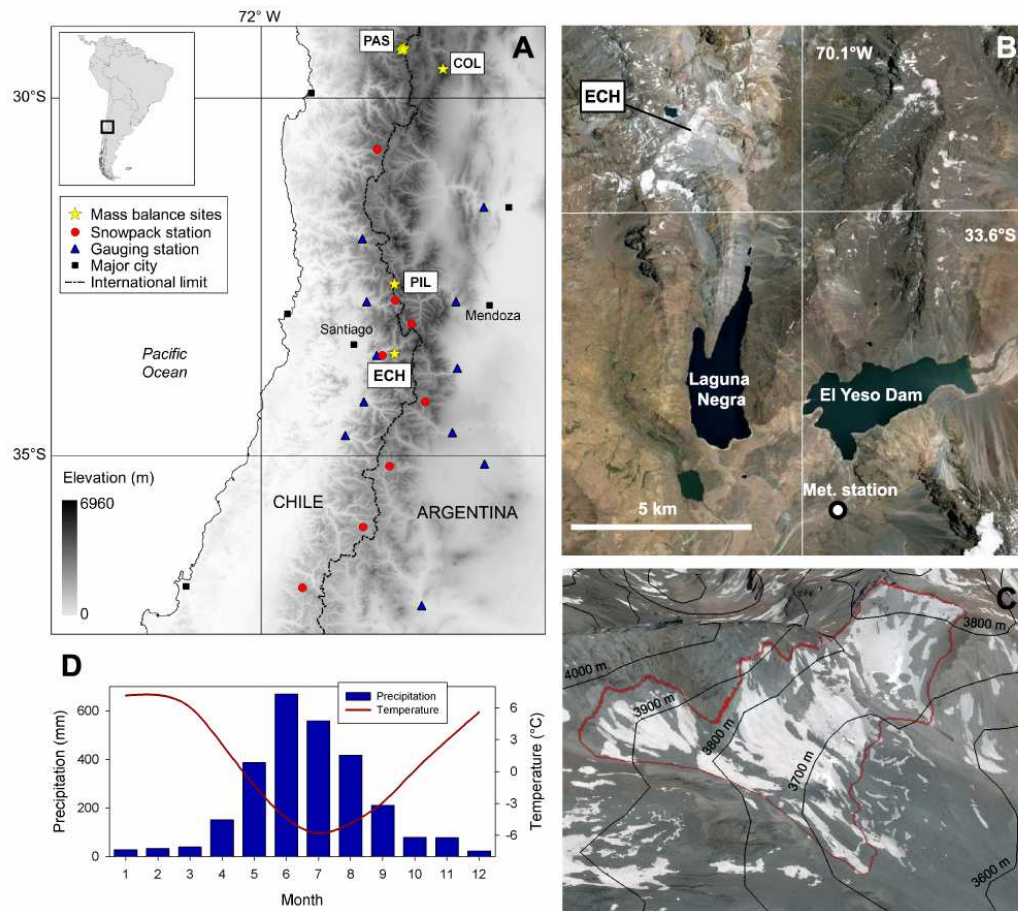
Variable	Station	Lat., Long.	Elev.	Period	1981-2010 mean*	Data source
A - Snowpack	Quebrada Larga	30°43'S, 70°22'W	3500 m	1956-2014	273	DGA
	Portillo	32°50'S, 70°07'W	3000 m	1951-2014	703	DGA
	Toscas	33°10'S, 69°53'W	3000 m	1951-2014	354	DGI
	Laguna Negra	33°40'S, 70°08'W	2768 m	1965-2014	632	DGA
	Laguna del Diamante	34°15'S, 69°42'W	3310 m	1956-2014	472	DGI
	Valle Hermoso	35°09'S, 70°12'W	2275 m	1952-2014	756	DGI
	Lo Aguirre	36°00'S, 70°34'W	2000 m	1954-2014	934	DGA
	Volcán Chillán	36°50'S, 71°25'W	2400 m	1966-2014	757	DGA
B - Streamflow (river)	Km. 47.3 (San Juan)	31°32'S 68°53'W	945 m	1909- 2007	68.2	SSRH
	Guido (Mendoza)	32°51'S 69°16'W	1550 m	1909-2013	52.4	SSRH
	Valle de Uco (Tunuyán)	33°47'S 69°15'W	1200 m	1954-2013	30.6	SSRH
	La Jaula (Diamante)	34°40'S 69°19'W	1500 m	1938-2013	35.6	SSRH
	La Angostura (Atuel)	35°06'S 68°52'W	1200 m	1948-2013	39.1	SSRH
	Buta Ranquil (Colorado)	37°05'S 69°44'W	850 m	1940-2013	154.8	SSRH
	Cuncumén (Choapa)	31°58'S 70°35'W	955 m	1941-2013	10.3	DGA
	Chacabuquito (Aconcagua)	32°51'S 70°31'W	1030 m	1914-2013	34.7	DGA
	El Manzano (Maipo)	33°36'S 70°23'W	890 m	1947-2013	123.0	DGA
	Termas de Cauquenes (Cachapoal)	34°15'S 70°34'W	700 m	1941-2001	93.6	DGA
	Bajo Los Briones (Tinguiririca)	34°43'S 70°49'W	518 m	1942-2013	53.8	DGA

653

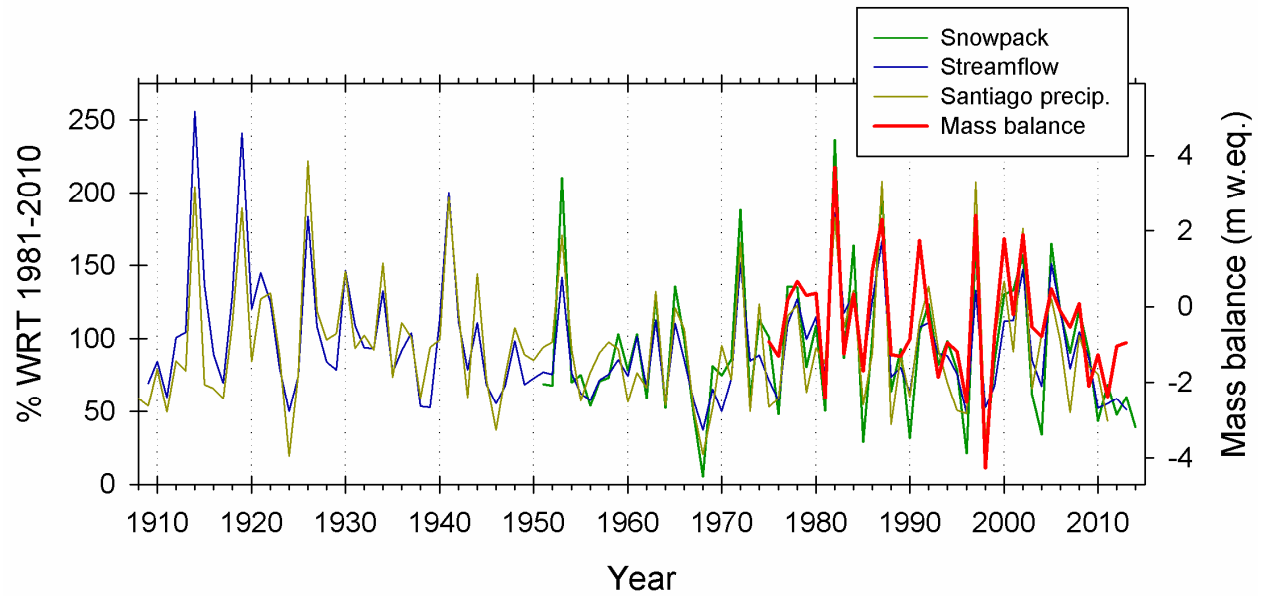
654 **Table 4.** Summary statistics for the simple linear regression models used to estimate ECH annual
655 mass balances using regional snowpack and streamflow records. Notes: (adj r^2) adjusted
656 coefficient of determination used to estimate the proportion of variance explained by regression;
657 (F) F-ratio for ANOVA test of the null hypothesis that all model coefficients are 0; (Se) standard
658 error of the estimate; (rmse) root-mean-squared error of regression. (b0) constant of regression
659 model; (b1) regression coefficient; (DWd) Durbin-Watson d statistic used to test for first-order
660 autocorrelation of the regression residuals. (Port. Q) Portmanteau Q statistic to test if high-order
661 autocorrelation in the regression residuals is different from 0. (ns) results are not statistically
662 significant at the 95% confidence level; (**) statistically significant at the 99% confidence level.
663

Predictor	Model statistics						Residual statistics		
	Adj r^2	F	Se	rmse	b0 (std. error)	b1 (std. error)	Slope	DWd	Port. Q
Snowpack	0.686	80.99**	0.889	0.911	-2.899 (0.316)**	0.026 (0.003)**	-0.003ns	2.2ns	5.7ns
Streamflow	0.682	79.49**	0.894	0.919	-4.045 (0.439)**	0.038 (0.004)**	0.006ns	2.3ns	4.9ns

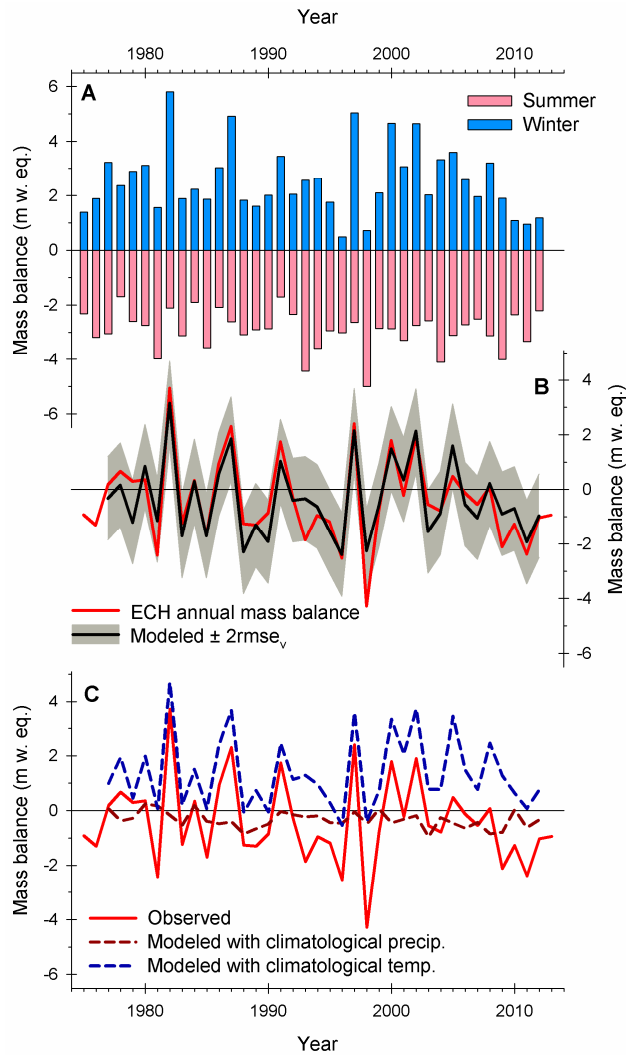
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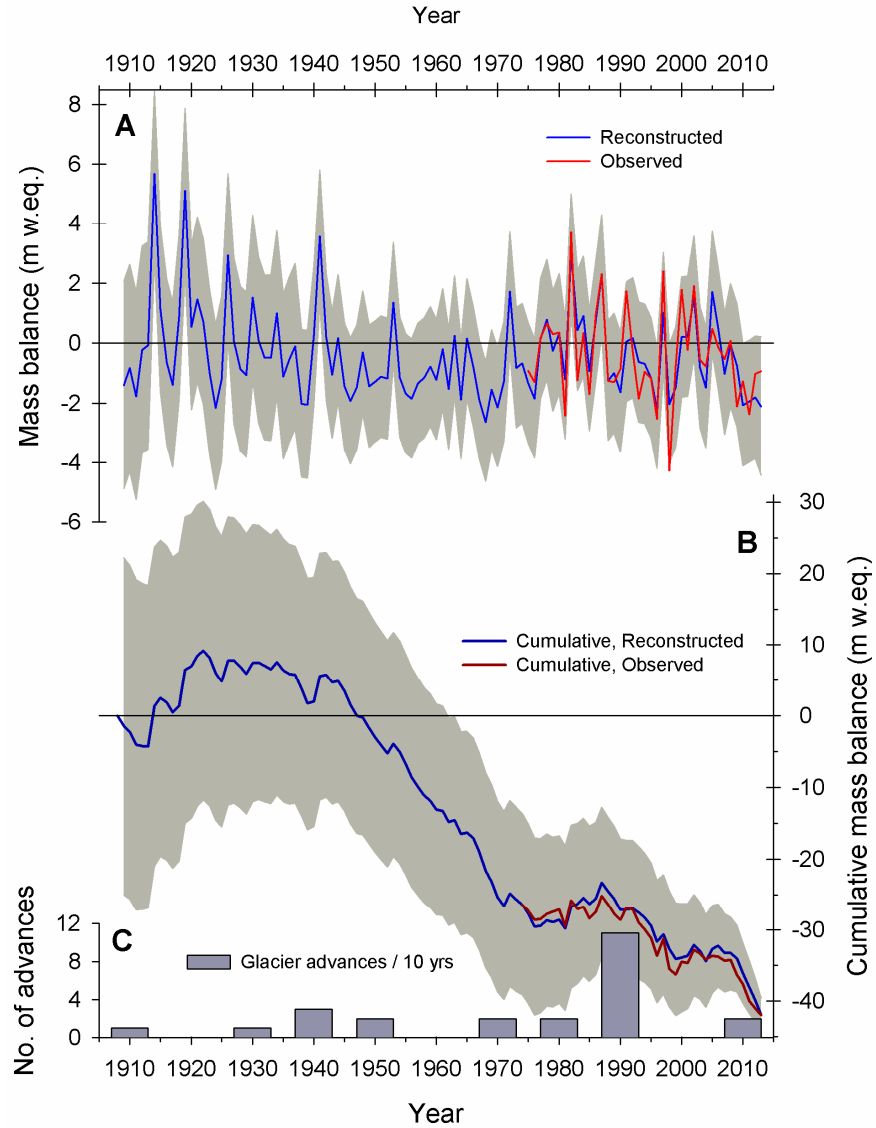
665
 666 **Figure 1. A)** Map of the Central Andes of Chile and Argentina showing the location of glaci-
 667 Echaurren Norte (ECH), glaciar Piloto Este (PIL), and several smaller glaciers with mass balance
 668 records in the Pascua Lama (PAS) and Cordillera de Colanguil (COL) areas. The locations of the
 669 snowpack and streamflow stations discussed in the text are also shown (Tables 1 and 2). **B)**
 670 General view of the El Yeso area, showing the location of ECH, El Yeso Dam, and the associated
 671 meteorological station. Laguna Negra is a natural lake that receives the meltwater from ECH.
 672 Base image acquired on January 5, 2014 and downloaded from Google Earth. **C) Closer 3D view**
 673 **of glaciar Echaurren Norte as observed in 2014 and in the early 1970s (outlined in red and based**
 674 **on Peña and Narbona 1978). Note that the glacier has remained in roughly the same position but**
 675 **has thinned markedly over the last decades. D) Seasonal variations in temperature and**
 676 **precipitation at the lower reaches of ECH (3700 m asl) extrapolated from the El Yeso**
 677 **meteorological station (see section 2.2 for details). Note that the bulk of precipitation occurs**
 678 **during the coldest months of the year (December-March precipitation only accounts for ~5% of**
 679 **the mean annual totals).**



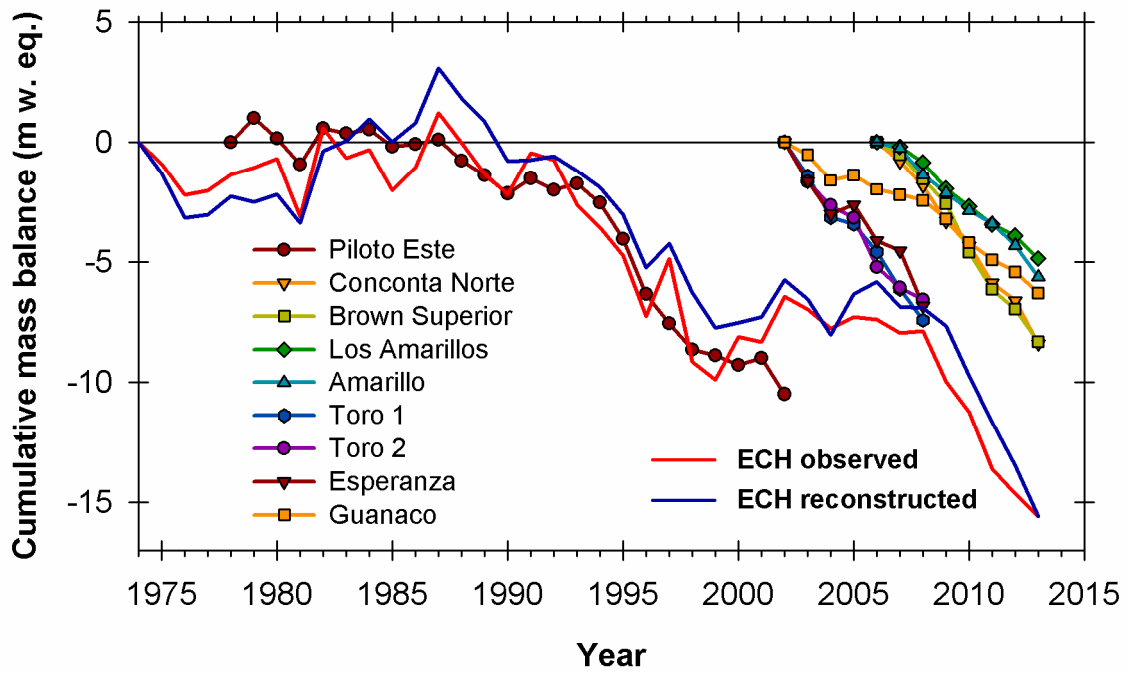
680
 681 **Figure 2.** Comparison between the annual mass balance series of ECH and regional records of
 682 maximum winter snow accumulation and mean annual river discharges in the Andes between 30°
 683 and 37°S (see Fig. 1). The regional records are expressed as percentages with respect to the 1981-
 684 2010 mean values. Variations in annual total precipitation at Santiago are also included to
 685 highlight the strong hydro-climatic signal in this region.



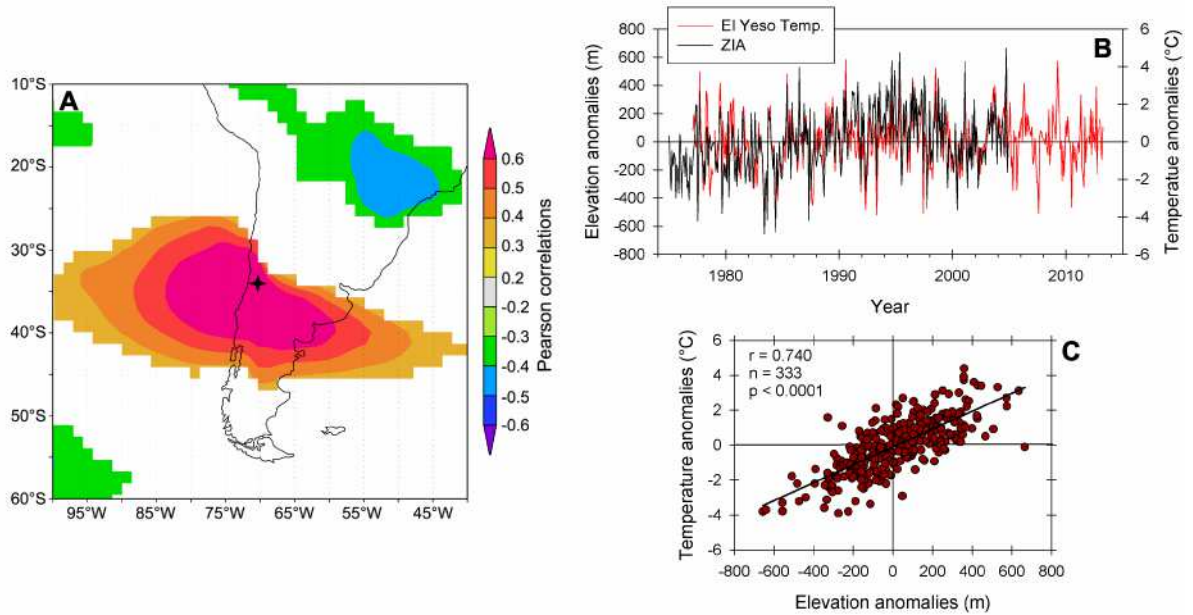
686
 687 **Figure 3.** (A) Winter and summer values observed at ECH between 1975 and 2012. (B) Annual
 688 mass balance series observed at ECH and modeled using El Yeso climate data (red and black
 689 lines, respectively). The estimated uncertainties of the modeled values (± 2 rmse) are shown with
 690 gray shading. (C) Annual mass balances observed at ECH (red line) compared to mass balances
 691 modeled using full variability in temperature but climatological monthly precipitation (dark red
 692 dashed line), and full variability in precipitation but climatological monthly temperatures (dark
 693 blue dashed line). Note the greater similarities between the observed series and the precipitation-
 694 based mass balance estimates.



695
 696 **Figure 4.** (A) Comparison between the annual mass balance record observed at ECH (red line)
 697 and the reconstructed series derived from regionally-averaged streamflow data (blue line). The
 698 estimated uncertainty of the reconstructed series ($\pm 2 \epsilon_{reco}$) is indicated by gray shading. (B)
 699 Cumulative record of the observed and reconstructed ECH mass balance series (dark red and dark
 700 blue lines, respectively). The initial value of the observed ECH cumulative record was modified
 701 to match the corresponding value in the reconstructed series. The aggregated errors in this series
 702 (see section 2.3) are also shown by gray shading (C) Glacier advances identified in the central
 703 Andes of Chile and Argentina during the past 100 years (see text for details). Events are grouped
 704 into 10-year intervals.



705
 706 **Figure 5.** Comparison between the cumulative patterns in the observed and reconstructed records
 707 from ECH and other glaciers with available direct mass balance data in the Dry Andes of Chile
 708 and Argentina (Fig. 1 and Table 1).



709
 710 **Figure 6.** A) Map showing the correlations ($p < 0.1$) between mean warm season (October-March)
 711 temperatures at the El Yeso station and gridded warm season ERA Interim mean temperatures for
 712 the 700 mb geopotential height level over the 1979-2012 period. The black star marks the
 713 location of the El Yeso station. **B)** Diagram showing variations of mean monthly temperatures at
 714 El Yeso (1977-2013) and the mean monthly elevation of the 0°C isotherm (ZIA) derived from
 715 radiosonde data from the Quintero coastal station (1975-2004). To facilitate the comparison, both
 716 series are expressed as anomalies from their mean seasonal cycles. **C)** Scatterplot of the El Yeso
 717 temperature and ZIA anomalies depicted in B. Note the positive, highly significant correlation
 718 between these two variables. ZIA data were provided by J. Carrasco from Dirección
 719 Meteorológica de Chile.
 720