List of changes in the document

The table contains the changes associated to each reviewer's comment, where each comment is identified with the following key:

R.X.Y, where
R=Reviewer
X= Number identify the reviewer (1 or 2)
Y= Number identifying the answer as numbered in the corresponding response

Below the table we added the response to each reviewer

Response	Change in the manuscript
R.1.1	**Page 1 L.1, Page 2 L.1, Page 7 L.15-17, Page 9 L.9-13. Figure added to supplement**
R.1.2	**Changes in the manuscript: New division between discussions and conclusions.**
R.1.3	**Changes in Table 5, new figure 5, and Page 6 L.32 – Page 7 L.2**
R.1.4	**Page 5, L.25-29.**
R.1.5	**Page 4 L.22-29**
R.1.6	**Page 5 L.13-15, Page 7 L.22-27, Page 8 L.33-Page 9 L.1-2, and a figure in the supplement**
R.1.7	**Page 7 L.1-2**
R.1.8	**Page 10 L.30-35.**
R.1.9	**Page 2 L.7-17**
R.1.10	**Page 2 L.15-17**
R.1.11	**Page 4 L.6**
R.1.12	**caption Table 2**
R.1.13	**No changes**
R.1.14	**Page 5 L.5**
R.1.15	**Page 7 L.4-8**
R.1.16	**No change**
R.1.17	**No changes**
R.1.18	**Page 5 L.2-4**
R.1.19	**New figure 5**
R.1.20	**Page 10 L.27**
R.1.21	**No changes**
R.2.1	**No changes**
R.2.2	**Page 9 L.16-18**
R.2.3	**Page 3 L.30 – Page 4 L. 3**
R.2.4	**Page 4 L. 3**
R.2.5	**Figure in the supplement**
R.2.6	**no changes**
R.2.7	**Page 5 L.12-30**
R.2.8	**Page 6 L.10-14**

R.2.9	**Page 6 L.17 –19**
R.2.10	**Page 7 L.12-16**
R.2.11	**Page 7 L.28-34**
R.2.12	**Page 7 L.30 – 32**
R.2.13	**new discussion section**
R.2.14	**Page 8 L.5-12**
R.2.15	**no changes**
R.2.16	**new discussion and conclusion section**
R.2.17	**No changes**
R.2.18	**Page 5 L.26-32**
R.2.19	**Page 10 L.1-4**
R.2.20	**Page 13 L.2-8**
R.2.21	**no changes**
R.2.22	**New Table 1**
R.2.23	**new Table 3**
R.2.24	**Page 6 L.27-32**

Responses to Reviewer 1

We are very grateful with the comments provided by the anonymous Reviewer 1. It is clear that her/his comments come from a deep analysis of the work we present here. Below you will find our response to each.

Is the Rio Imperial streamflow variability representative of the entire SCC? I think it is not. Please provide evidences about this point, especially for summer. It is an important issue due the title of this paper include a large region from 35◦S to 42◦S in Chile.

R.1.1: Thanks to your observation we reassessed the sentences including the 35-42 strip and decided to modify the manuscript to "SCC ~37°-42°S". Previous studies (Rubio-Álvarez & McPhee, 2010; Muñoz et al., 2016; Lara et al, 2008) found that the Río Imperial fits better as representing the region south of 37.5, as for example a recent reconstruction of the BioBío river (~37.5°S) was similar to another built for the Puelo river (~42°S). However, we consider important to indicate that available observational datasets for the period 1980-2010 suggest that the region south of 35-42°S is a hydroclimatic cluster (see González-Reyes et al 2017), especially during the summer, our target season. The figure R1.A shows that our reconstructed streamflow (dark blue) correlates significantly (as described by the p-value) with observed streamflow of each individual station, and also each individual station correlates significantly with the composite time-series produced in our study. We will include this new analysis in the paper in order to provide further evidence on the relevance of the Río Imperial reconstruction for this region.

How an accurate calculation of natural streamflow variability can help to anticipate possible consequences in the water management? This is the justification or motivation of the analysis. My point is the following. If you proved that streamflow variance (or extremes) in the past was larger than the expected by models for the future, how this information is useful for water management? Perhaps, if droughts were more severe in the past, without a major extinction or decrease of vegetation, you can ask why we expect a major problem in the future? The major uncertainty is related to in any case with the water demand, but not with the natural or anthropogenic origin of the droughts. It is the minimum ecological discharge the variable benefited by this study? If so, I guess the water management issue is restricted to the decisions depending on this variable. Can you focus on this point?

R.1.2: We could not agree more with this assessment; the major uncertainty is related to water demand, which we don't analyze in detail here. However, we want to clarify that the main result in our work is the increasing frequency of dry summers, which is unseen in the analyzed period. In our view, this implies a new hydroclimatic scenario that might make the region more sensitive to changes in water demand, such as a possible utilization of all water rights in the watershed. In the abstract, results and discussion section we have modified the text in order to emphasize these findings. On the other hand, that our work finds some summers comparatively drier than what is seen in the available observations show, suggests that calculations of return periods can benefit from research like ours in order to produce fine-tuned statistics, specially in the determination of confidence intervals for the minimum ecological discharge. This is a statement we already have in our paper but it may be clear if we divide the section of discussion and conclusion in two, as the reviewer number 2 suggests.

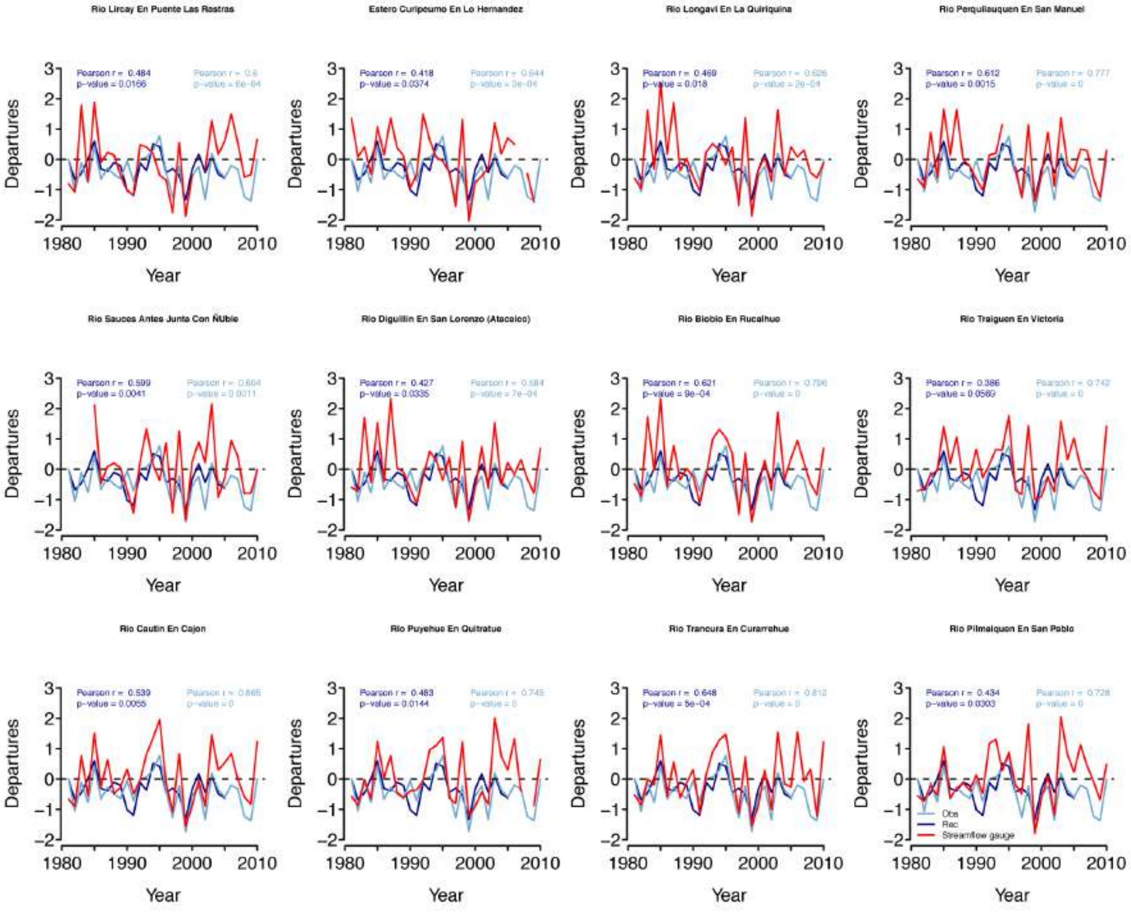

FIGURE R1.A: Comparison of available streamflow data (red), our tree-ring reconstruction (dark blue), and the composite streamflow for the period 1980-2010 (cyan).

It would have being very instructive if you were count with data until 2014 or 2015 with the aim of calculating the return period of droughts or the recurrence rate of drought events of the mega-drought mentioned in the work of Garreaud (2015). According to this author, the mentioned mega-drought 2010-14 is the largest on record. Can these statistics used in your work shows the extreme nature of the mega-drought? (at least for the instrumental record).

R.1.3: We thank you very much for your suggestion. We have decided that comparing our results with the recent developments as depicted in Garreaud et al (2015) is important and necessary. We extended our reconstruction including the period 2011-2015 ("megadrought") and found that, despite being an unprecedented dry period for the instrumental record, it does not rank as the highest in the reconstruction (see Table R1.A below). We think this finding is very interesting because a recent paper studying the megadrought on winter-spring precipitation found that the period 2011-2015 as highly unusual in the last 1000 years (Garreaud et al 2017). We also find this period as the driest of the streamflow instrumental record, but it is not too different from the period 1996-2000. In addition, in the reconstruction the 2011-2015 period ranks fifth but with an anomaly that is less than a half of the driest (1897-1901). The Figure R1.B shows that the summer reconstruction for 2011-2015 is far from the most extreme, but corroborates our main finding that dry years become more recurrent since 1980. We will update our results and discussion with these findings.

Table R1.A: Updated 5-year rankings for the instrumental and reconstructed periods

Reconstructed period (1709-2015)	Low flow		High flow	
	5-yrs	reco	5-yrs	reco
	1897-1901	-1.235	1951-1955	1.087
	1753-1757	-0.764	1829-1833	1.016
	1811-1815	-0.737	1934-1938	0.842
	1996-2000	-0.586	1834-1838	0.816
	1987-1991	-0.584	1797-1801	0.751
	2011-2015	**-0.556**	1939-1943	0.749

Instrumental period (1947-2015)				
	5-yrs	reco	5-yrs	reco
	2011-2015	**-0.778**	1955-1959	0.972
	1996-2000	-0.777	1950-1954	0.841
	2005-2009	-0.681	1965-1969	0.727
	2008-2012	-0.677	1971-1975	0.560
	1987-1991	-0.382	1976-1980	0.271
	1982-1986	-0.378	1992-1996	0.200

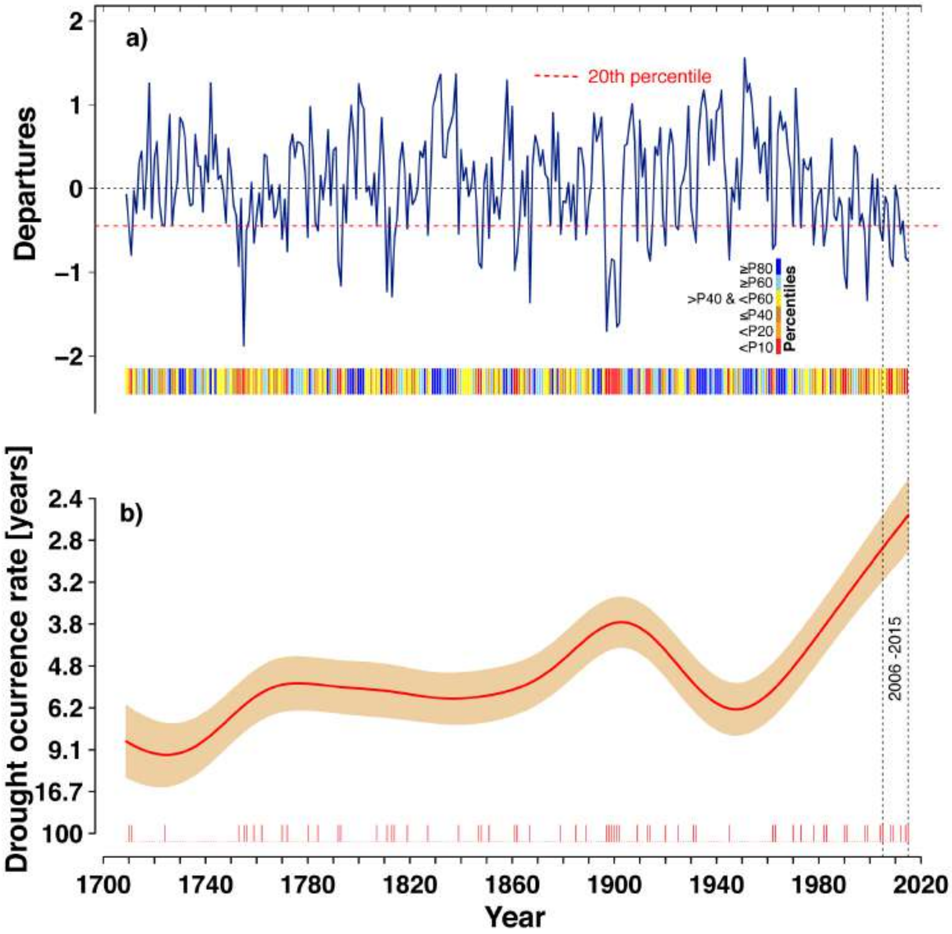

Figure R1.B: Updated calculations of departures and recurrence intervals for the period studied, including the megadrought (2011-2015).

I understand the use of the Southern Oscillation Index (SOI) instead the Niño 3.4 SST anomalies, due the longest record of atmospheric pressure data in Tahiti and Darwin. In fact, SOI is not usually used in climate studies, due its large "noise" in the intraseasonal timescale, compared to the more smoothed evolution of the SST index in the central equatorial Pacific. Anyway, I expected the used of the SOI directly calculated from stations but you used the NCEP-NCAR reanalysis. What is the justification then?

R.1.4: Thank you very much for catching this up. We will re-write these sentences since they don't make it clear we do use a SOI index built from observational data. We utilized the SOI index that begins in 1866 and is downloaded from the following link: http://www.cgd.ucar.edu/cas/catalog/climind/soi.html.

About equation (1) and Fig. 3. I am not dendronologist, so it is surprising the low covariance shared between these reconstructions, even when the samples are larger. The trees are not responding in the same way to the atmospheric forcing? (water availability for instance). This explain equation (1)... but still I need an explanation in the text for this behaviour. Looking at figure 4 (upper-left panel) the reconstruction looks good.

R.1.5: We appreciate this comment that allows us to further clarify our analysis of individual chronologies. LYV and PAG correlate positively with same-year

streamflow (0.38 and 0.43, respectively), with the streamflow of the previous year (0.53 and 0.41, respectively), and with streamflow two years before (0.3 and 0.23, respectively). Conversely, PIN shows negative correlations with previous years (-0.56 for the 1st and -0.38 for the 2nd previous year). The negative correlation for PIN is because the site is a narrow sector with recurrent fog, where atmospheric moisture and precipitation in summer may produce a relative reduction in incoming radiation and temperature; these conditions may reduce the rate of the tree-ring growth. Mundo et al (2012) already found this behavior for PIN as part of a large group of chronologies. We will include this explanation in our manuscript.

Fig. 4. It is clear from the comparison between reconstructed and observed streamflow that the reconstruction captures the low frequency but not the interannual variance, although the coherence shows a peak on 2.8 years. Based on this finding, why the authors can expect a reliable comparison with ENSO? Because it is the most important driver at interannual timescales? In fact, what is the reason for not using the Inter-decadal Pacific Oscillation instead ENSO? Why SAM? Please provide references that reinforce your thoughts about possible drivers.
R.1.6: We fully agree with the reviewer in that the reconstruction fits well with the low frequency, but we also believe it does well with the interannual variability because there are only two peaks not being captured. Figure 1 shows no peak on these years for Quepe (QUE ~1956) and Muco (MUC, ~1982) but these features are averaged-out in the composite. Thus, although our reconstruction does not capture every fluctuation of the composite time-series, it likewise evidences correspondence with observations. Nevertheless, we applied new analyses to the data. Utilizing the Blackman-Tukey spectral method (Ghil et al 2002, Figure R1.C) we see that the Río Imperial reconstruction has high frequency cycles (2-7 years) and mid-to-low frequency (> 8 years). A Multi-taper method and a Singular Spectral Analysis reveal that a ~4-year cycle captures 10% of the variance while a ~7-year cycle captures 7%. On the other hand, a 16-20-years cycle corresponds to 20%. We also performed a Continuous Wavelet Transform Analysis and found that a 16-32-years frequency is significant between 1800-1950; high frequency cycles occur along the whole period but appear more significant after 1900.

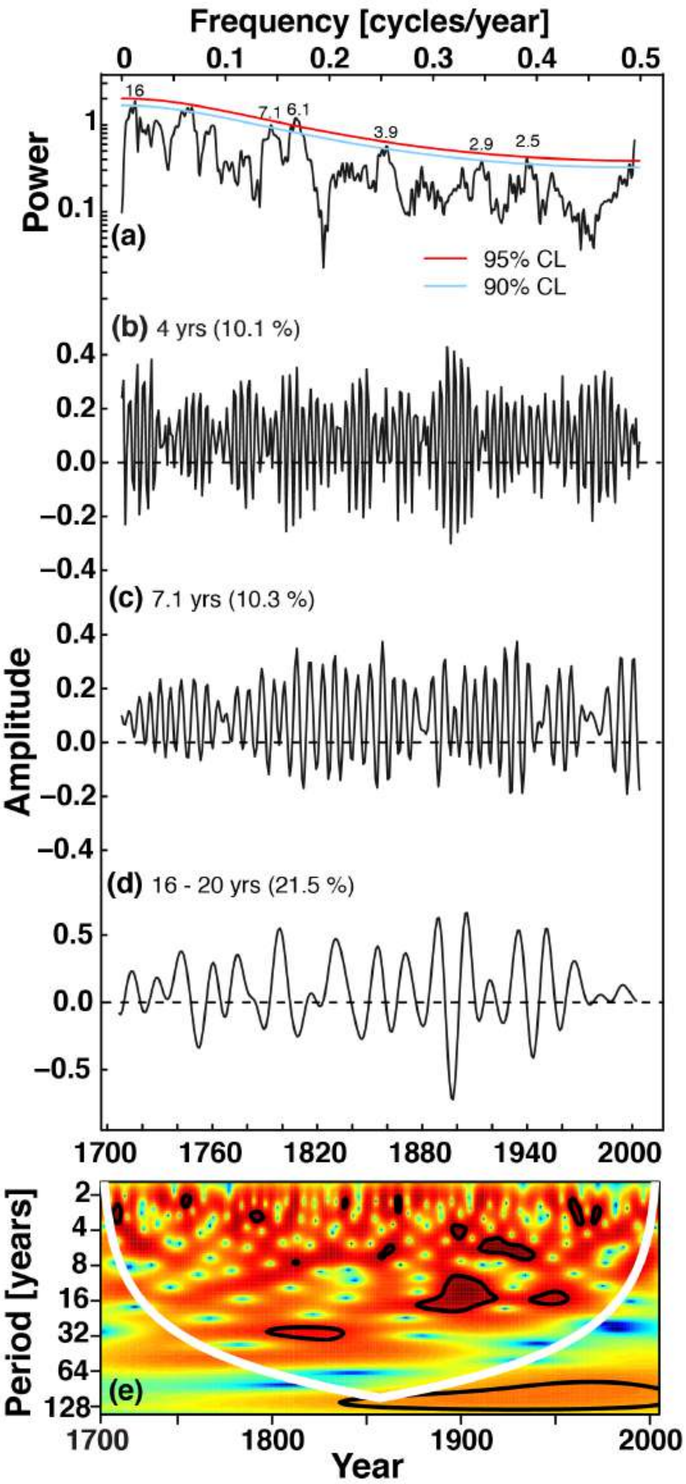

Figure R1.C: Spectral Analyses of the time-series demonstrating that it captures high frequency

Regarding ENSO, there is abundant literature correlating it with hydrological variables at the annual scale, but there is no such complete information for the summer. As we explain in our manuscript, Urrutia et al (2011) find annual discharge in the Maule river (~35°S) well correlated with ENSO, while Muñoz et al

(2016) find the BioBío river (~37°S) correlated with SAM. This was the criteria we utilized to perform these correlations. The río Imperial is south from the BioBío and our work is the first solely focused on summer dynamics. Barría et al (2017) analyzed the upper section of the BioBío dividing the year in two sections: October-March (OM) and April-September (AS). They find that PDO correlates negatively with AS runoff and positively with OM; For SAM, they find positive correlation for OM. Giving your comment and these new studies, we found no reason to not perform comparison between our time series and the IPO. We compared our time-series with the IPO reconstruction presented in Vance et al (2015) and found a statistically significant negative correlation between IPO and the 16-20-year cycle of our reconstruction (-0.38, n=295), although it looks more coherent during the 20th century (Figure R1.D). We will include these new analyses into the manuscript.

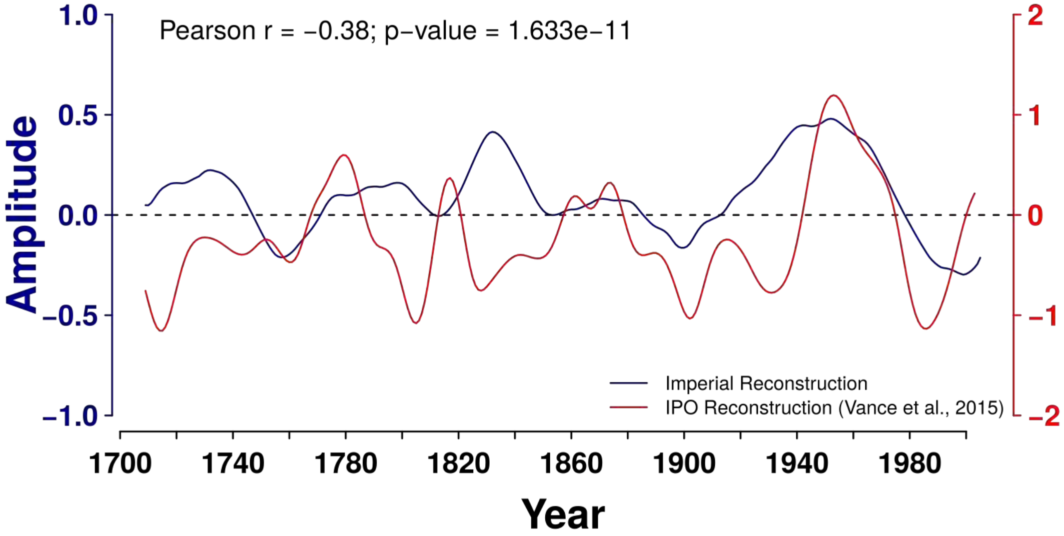

Figure R1.D: Comparison between our reconstruction and the IPO (curve inverted for readability).

Page 7, lines 25-26. The sentence is misleading, because Garreaud (2015) and Boisier et al (2016) define the mega-drought since 2010, exactly when your information stop. Have you considered the possibility of interdecadal variability? IPO changes to its positive (warm) phase at the end of 70s, changing to a negative (cold) phase ant the end of 90s. This can be seen as a negative trend since 1980... Please, provide some discussion about this possibility.

R.1.7: We agree with this comment. We reassessed that sentence and find it misleading. In our work we find that dry years are more recurrent since ~1980 and in the new version of the manuscript we highlight that this trend is previous to the mega-drought identified in Garreaud (2015) and Boisier et al (2016).

On the other hand, the positive trend of SAM can be related to any trend, even without a physical explanation. In your results, when you remove the linear trend the correlation fall to near-zero values, so what is the reason there is a relationship between SAM and streamflow at 38◦S? SAM it is just a long-term trend? Why there is not relation at other

timescale? Do you know what is controlling the SAM trend? That is a key answer to make. I think you should read the following paper:
http://www.scielo.org.mx/pdf/atm/v25n1/v25n1a1.pdf

R.1.8: We do not completely agree with this assessment. First, we believe we provide a mechanistic explanation of the influence of SAM on precipitation in the region (Page 8 L.5 to Page 9 L.5). Nevertheless, we see that the recommended paper is very helpful for us in order to improve this explanation. Second, the relation between SAM and our data is not near zero; we performed correlations using a prewhitened version of the reconstruction and observations (removing the lag-1 autocorrelation) and they are negative and statistically significant (-0.287 with p-value=0.033 and -0.290 with p-value=0.029, respectively).

Minor comments

Page 2, lines 10-11. This values were taken from the figures? If so, how accurate is that?
R.1.9: Yes, the data had been read from the figures. We reassessed that section and decided to utilize the information provided by the Atlas of Global and Regional Climate Projections of the IPCC (IPCC, 2013). We eliminated the sentence in Page 2-Lines 7-13 and replaced it with the following: “SCC is expected to undergo important climate changes. Analysis of the multi-model ensemble for the scenario RCP4.5 presented in the Atlas of Global and Regional Climate Projections (IPCC, 2013) indicates 10 to 30% reduction in spring and summer (October to March) precipitation by 2016-2035 and 2046-2065 relative to 1986-2005. The same projection forecasts 0.5 to 2°C warming for summer (December-February). Drier and warmer summers for may make SCC more vulnerable to water scarcity, given that this is the season of highest water demand in this region (Garreaud, 2015).

Page 2, lines 12-15. You have written 3 times "in this region" in few lines. I think it can be improved.
R.1.10: Thanks for catching this up. We replaced the second “in this region” for “here” and the third for “SCC”.

Page 4, line 17. Where is mentioned Table 2?
R.1.11: Thanks for finding this omission. We have mentioned the table besides Fig. 1

Table 2. What instrumental streamflow record have you used?
R.1.12: This is from the composite time-series. We have clarified this in the caption.

Page 4, line 15. I am not expert on dendronology, so I can not questioning the methodologies employed to construct the index based on three tree-ring chronologies. About equation (1), however, there is something intriguing to me. I assume that water availability affects in the same way same species of trees. Why coefficients are opposite in sign for PAG (+2.69) and LYV (-1.97) at the same time (t-1)?

R.1.13: We appreciate this comment as it allows us to provide a deeper explanation of our procedures. In order to fully understand the reasons behind this kind of multi-regression model it is important to consider that the climate signal of a given ring-width is product of climatic conditions of the same year but from previous years as well, and they can be different in certain moments and as results of different locations of the chronologies. In our study region, climatic conditions influence ring-growth in two main ways: (1) Current and previous year(s) snow accumulation on mountain areas can delay the ring's growing season, increasing the likelihood of negative correlations (and LYV is located at high elevation). (2) In high elevation sites temperature can be a limiting factor for ring-growth, this is because increase in temperature in this region is related to less moisture and rainfall, possibly producing negative correlations. Thus, PAG and LYV correspond to different landscape, one at high elevations (LYV) where some variable (e.g. temperature or seasonal snow) can explain certain portion of the correlation with hydroclimatic observations, and another at low elevations (PAG) where the relationship between ring-growth and soil moisture is more direct because for instance precipitation is always liquid. What it is important to keep in mind is that they are significantly correlated with the observational record and the statistical model is skilled in representing the streamflow variability. Muñoz et al (2016) and Lara et al (2015) are other two examples where the statistical model presents coefficients of inverse signal in the same year.

Page 4, line 24. It is written "the return period or extreme low flows..." Did you mean "the return period of extreme low flows"?
R.1.14: Yes, "of" is correct. Changed

Page 5, line 21. You defined summer ad January-February for streamflow. So, what are the previous months for rainfall and what is the value for the not simultaneous correlation"?
R.1.15: We find that your question gives us a good opportunity to further demonstrate the relevance of studying January-February streamflow. We ran correlations between observed/reconstructed streamflow with Temuco rainfall for each month of the previous year (Figure R1.E). These correlations are significant for December and February of the previous year (p-value <0.1 and <0.05, respectively) for the instrumental record. For the reconstruction, the correlation is significant for June and December (p-value <0.05).

Table 2 is analysed in page 5. I suggest to exchange numbers with table 3.
R.1.16: We do not agree with this suggestion. Table 2 follows Table 1 in the sense the Table 1 presents the instrumental record and Table 2 provides the information for the analysis of that instrumental record. Then Table 3 appears because it is about the tree-ring chronologies. If we do the change suggested, we feel the manuscript loses readability and that our line of argument weakens.

Page 5, lines 26-27. Clearly, streamflow as precipitation exhibits a positive skewness in southern Chile, which is a normal behaviour taking into account that at most, there will be no rainfall (0 mm) as the lowest values. This kind of distributions are typical also for wind speed. So, I do not understand the point of this sentence.

R.1.17: We believe this sentence is clear since it provides summary statistics corresponding to Table 2, which is about ranking streamflow extremes. We want to stress our analysis is about base-flow, which should rarely go to zero as rainfall and wind speed do.

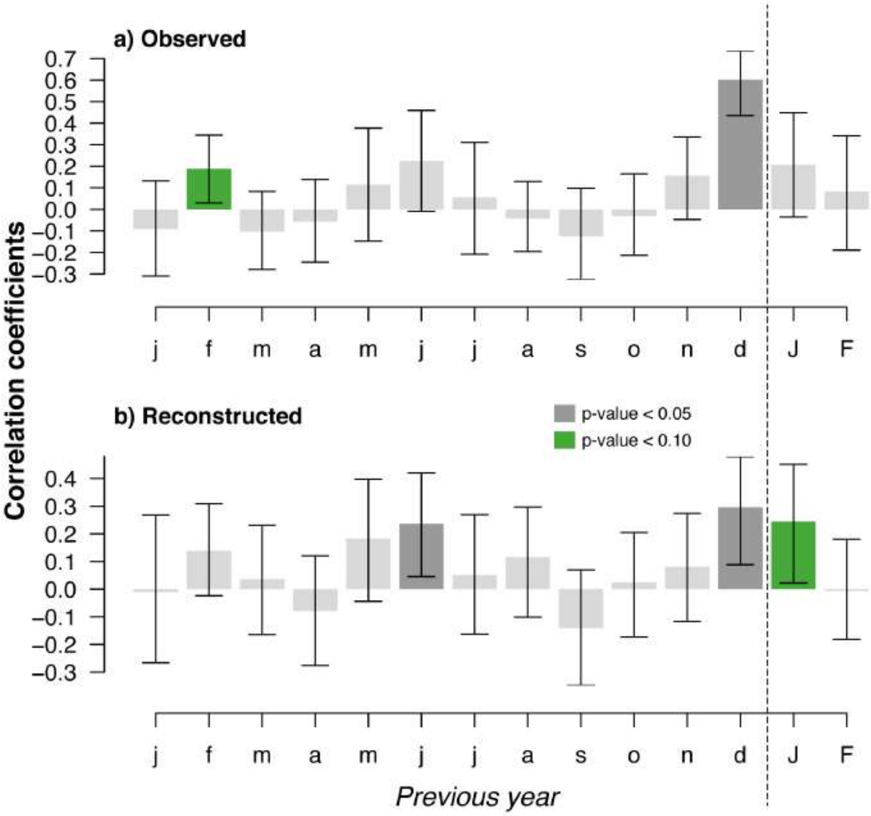

Figure R1.E: Correlation of observed/reconstructed streamflow with Temuco rainfall for each month of the previous year.

Page 6, line 8. Define VIF.

R.1.18: We will include the following definition of VIF in the method's section: The Variance Inflation Factor (VIF) evaluates the multicollinearity of the predictors; a VIF close to 1 means a low or no multicollinearity (Haan 2002) while a value above 10 is associated with multicollinearity problems between predictors (O'Brien 2007).

Fig. 4. It is very nice the percentiles at the bottom of the figure. Easy to interpret. I wonder what would be the percentile for the period 2010-2015? This information is available, why you do not have used?

R.1.19: We updated that figure (Figure R1.B) in a previous response.

Page 8, lines 33-34. The summer of 1999 is part of La Niña, not El Niño. In fact, the winter of 1998 is one of the most dry winters in instrumental record.

R.1.20: Thanks for catching this up. We are certain that winter 1998 was in fact part of a strong La Niña rather than el El Niño. We have modified the section “and the strong El Niño event of 1998” in the following: “ and a strong La Niña event in 1998-1999”.

Page 10, lines 24-25. The restriction of power supply occurred in 1996, at least in Santiago. It was different in Temuco?

R.1.21: Our reference (Fischer and Galetovic, 2001) and the Decree 287 of 1999 (available at https://www.leychile.cl/Navegar?idNorma=137602&idParte=) indicate that restrictions in energy supply were implanted across the whole Central Interconnected System in 1999, which includes Temuco.

New references

Decree 287 of 1999 (available at https://www.leychile.cl/Navegar?idNorma=137602&idParte=)

Garreaud, R. D., Alvarez-Garreton, C., Barichivich, J., Boisier, J. P., Christie, D., Galleguillos, M., LeQuesne, C., McPhee, J., and Zambrano-Bigiarini, M.: The 2010–2015 megadrought in central Chile: impacts on regional hydroclimate and vegetation, Hydrol. Earth Syst. Sci., 21, 6307-6327, https://doi.org/10.5194/hess-21-6307-2017, 2017.

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González-Reyes, Á., J. McPhee, D.A. Christie, C. Le Quesne, P. Szejner, M.H. Masiokas, R. Villalba, A.A. Muñoz, and S. Crespo, 2017: Spatiotemporal Variations in Hydroclimate across the Mediterranean Andes (30°–37°S) since the Early Twentieth Century. J. Hydrometeor., 18, 1929–1942, https://doi.org/10.1175/JHM-D-16-0004.1

Haan CT (2002) Statistical Methods in Hydrology, 2nd ed. Ames: Iowa State University Press.

IPCC, 2013: Annex I: Atlas of Global and Regional Climate Projections [van Oldenborgh, G.J., M. Collins, J. Arblaster, J.H. Christensen, J. Marotzke, S.B. Power, M. Rummukainen and T. Zhou (eds.)]. In: Climate Change 2013: The Physical Sci- ence Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

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Vance, T. R., J. L. Roberts, C. T. Plummer, A. S. Kiem, and T. D. van Ommen (2015), Interdecadal Pacific variability and eastern Australian mega-droughts over the last millennium, Geophys. Res. Lett., 42, 129–137, doi:10.1002/2014GL062447.

Responses to Reviewer 2

We truly appreciate the sincere point of view of the anonymous Reviewer 2. We found these comments very valuable, insightful and challenging at the same time. We hope we have fulfilled her/his expectations.

****The original comments appeared as one single paragraph in the file that was accessible to us. We separated the paragraph on the main ideas we believe the Reviewer was interested in.***

This manuscript is a case study for reconstruction of streamflow based on tree-ring growth data in Chile. Just to put things in perspective, and I do not mean any negativity here, there is nothing new in this particular manuscript with regard to dendrohydrology. There is almost 50 years of literature in this area; the same regression models, the same way of reconstruction, and the same variable (streamflow). The authors reconstructed summer flows, instead of annual flows, but reconstruction of seasonal variables rather than annual ones happened also several times before but perhaps not in Chile. So, from my point of view, there is not any aspect of novelty in this research. It is important to state this, at least to give the authors a chance to clarify in case I missed something, and I apologize if I did.
R.2.1: We truly appreciate your comment because it gives us the opportunity to better stress the importance of our study. This summer reconstruction is important for three main reasons: (1) Chile is one of the countries undergoing strongest precipitation decreases in the last century and (especially the region between 37° and 42°S) it is where there is more agreement among models on further reductions by the end of the 21st century (Koirala et al 2014); understanding how these changes translate into streamflow is needed in order to provide accurate information for developing adaptation and mitigation actions. (2) Although there are many studies about streamflow reconstruction, as the reviewer correctly points out, our work is different and novel relative to those because we explicitly aim to provide an evidence-based criticism of current and proposed water rights regulations and practices. As we posit in the manuscript, the Chilean model is fairly unique and has been studied at the international level for several decades, but to our knowledge this is the first time a dendrohydrological study goes into using this kind of data to discuss the implications for water resources management in detail; we hope that our study encourages other groups to begin a evidence-based discussion on these matters. (3) From a technical standpoint, reconstructing summer streamflow is challenging because relative variations (in percentages) of the average streamflow can be very large at the interannual scale. This way, as the first study focused on this season we believe our work is major step toward understanding base flow dynamics on a multi-century scale.

The section that is most interesting to read is section 4, which the authors called “Discussion and conclusion”. In this section, the authors argued hard for the utility of tree ring-based reconstruction to identify droughts that are more sever or more frequent than

those inferred from the instrumental record. This argument can be found in so many of the dendrohydrology papers published in the last decade, and again nothing here is new. However, I have a fundamental issue with the scientific foundation of the argument, and unfortunately this applies also to several other papers published in this field. The authors reconstruct almost 300 years of streamflow data and start comparing it with instrumental record of 60 years. Ob- viously, they find droughts in the 300 years with characteristics that are different from those in the 60 years, of course! But for water resources engineers, whatever you find in 300-year record MIGHT be a 300-year drought. It is unfair to compare it with the 60-year record. Engineers would fit a statistical distribution to the 60-year record, estimate 100 or 1000-year droughts, then fit a distribution to the longer reconstructed record, and again estimate whatever drought quantiles you want, then compare. Oth- erwise, engineers and water resources planners never use just the deterministic short instrumental record of flows. If you can prove, based on the analysis I suggested, that the reconstructed flows lead to significantly different frequency or severity of droughts, then you made the case about the utility of reconstruction.
R.2.2: We agree that there are several papers on reconstructions in different parts of the world. But we insist that there is very few research explicitly proposing approaches for using this information in water management such as our manuscript. In South America, there are only 7 papers published on streamflow reconstruction, a small number considering the large and complex river network across the continent. About the other criticism regarding the unfair comparison between observations and reconstruction, we fully understand the concerns of the reviewer. We want to be very clear here, we are not dismissing the importance of available records and if our writing in some ways suggests that, we assure you it was unintentional. Yes, we agree it is unfair, but it is relevant to keep in mind that the records for the last 60 years have shown important streamflow reduction (e.g. Garreaud et al 2017). We are convinced that our study provides long-term context for these recent fluctuations and our aim is to provide evidence for further discussion in both, the hydroclimatic and water management communities. Thus, our results suggest that the post-1980 period is a fairly unique dry one (for summer) in the context of the last 300 years. In the context of the instrumental record, the post-1980 period represents ~50% of the composite instrumental time-series, while it only represents ~10% of the reconstructed period; we believe this highlights the uniqueness of the post-1980 period.

Other specific points: Page 2, Lines 8-10: If you have the future projections based on the CMIP5 results, why don’t you investigate if projected future droughts are more sever/frequent than the past ones?
R.2.3: We appreciate the suggestion but our objective in the paper is to provide context for the low flows that have already occurred. The section you mention is part of our literature review. We haven’t utilized CMIP5 projections in this study but it is important to point out that Garreaud (2015) presents a figure where drought recurrence is calculated using CMIP5 output. In that document, it is clear that in the RCP8.5 droughts become more recurrent and that even by the end of the century the definition of drought becomes irrelevant. We will include this explanation in our discussion section.

Just an idea; Page 3, Line 27: How did you get the “natural regime”? Did you account for irrigation abstraction?

R.2.4: Thanks for the suggestion, in the new manuscript we supplement our explanation of natural regime with a text similar to this: In this reconstruction, we selected stations from rivers where the water has not being diverted for irrigation and hydroelectricity. The three selected stations fulfill these criteria. As matter of fact, there are two protected areas here: Reserva Nacional Malalcahuello and Parque Nacional Conguillío.

Page 3, Line 29: This sentence is not clear. How did you use the double mass curves to determine the calibration window of time?

R.2.5: Thanks for catching this up. We believe we need to improve our writing and word choice here in order to explain this idea more clearly. We utilized double mass curves to determine periods that more closely follow precipitation and thus provide us support to detect unreliable records. We eliminated records that didn't fulfill this criterion during the first few years of the time-series.

Page 4: I feel that I miss proper information about the hydroclimatology of the region. How wet or dry is it? How much is the rain and its variation? Just provide some background in- formation;

R.2.5: We appreciate your suggestion. We have included a climograph (Figure R2.A) using data from Temuco for the period 1980-2010. In this figure you can see that January and February get the lowest amounts of rainfall.

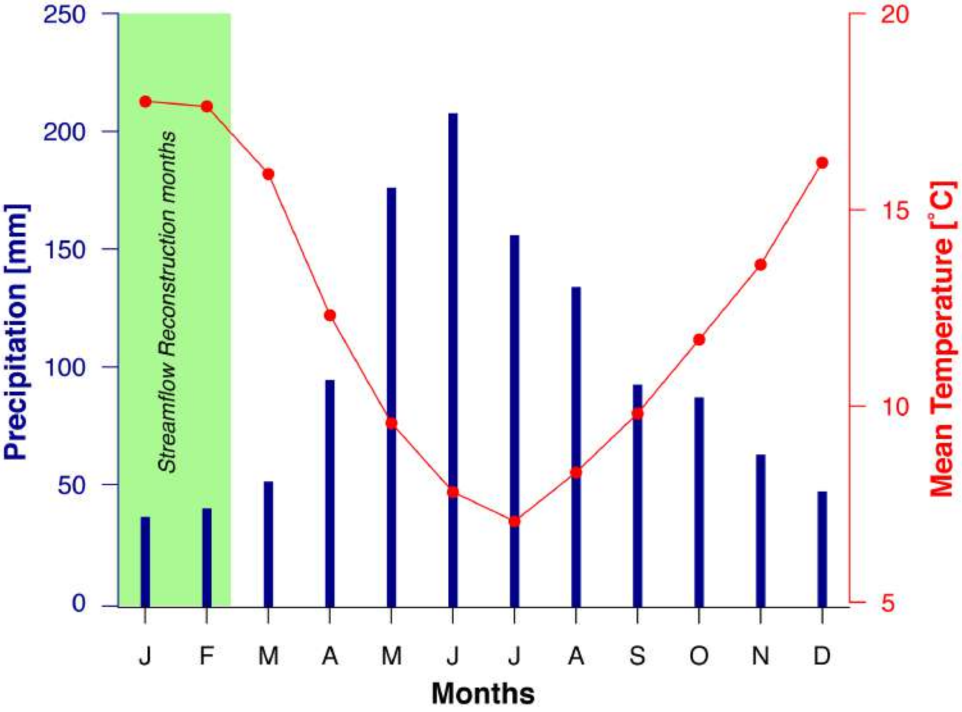

Figure R2.A: Climograph representing the conditions for Temuco for the period 1980-2010.

Changes in the manuscript: Figure in the supplement

Page 4, Line 17: You are referring to Table 3 before Table 2, please reorder the Tables;

R.2.6: We already answered this comment to the Reviewer 1: "We do not agree with this suggestion. Table 2 follows Table 1 in the sense the Table 1 presents the

instrumental record and Table 2 provides the information for the analysis of that instrumental record. Then Table 3 appears because it is about the tree-ring chronologies. If we do the change suggested, we feel the manuscript loses readability and that our line of argument weakens".

Page 4, Lines 24-26: peak over threshold is usually used for floods, but here you are doing drought analysis. Do you mean flow below threshold or something like this? You also need a reference for portion;
R.2.7: Thanks for catching this up. We will improve the description in that section. In effect, we use that method (fully described in Mudelsee 2010) to identify percentiles below the 20% during the whole reconstruction. Our objective was to determine how frequent this percentile has been in the reconstruction. This kind of analysis/representation has been utilized in papers analyzing the BioBío river (Muñoz et al 2016), PDSI reconstructions (Christie et al 2011), and in instrumental records (González-Reyes et al 2017).

Page 5, Line 25: What are these percentage numbers (54.06% and 74.12%)? Do you mean m3/s?
R.2.8: These are percentages with respect to the average flow. We have modified the text here in order to make it clear the meaning of these numbers.

Page 6, Line 2: "that" should be "than", and "here" is not clear. Do you mean your manuscript? If so, why is the reference, it is confusing;
R.2.9: Thank you for catching this up. We have modified that section (Lines 1-3) for the following: "Two of three Araucaria araucana tree-ring chronologies extended 800 years or more (PAG and LYV; Fig. 3 and Table 3), which corroborates findings from a previous study (Mundo et al 2012) on the potential of this species for providing long paleoclimatic reconstructions."

Page 6, Lines 11-17: These results are not really good (especially, RE of 0.36), I know they are typical in many dendrohydrology studies, but they should at least make the authors a bit more humble and lighten the assertion tone that is coming later in Section 4;
R.2.10: We agree with this comment. We recognize this value does not look too good; we have modified the text in order to explicitly specify that this results is good in the context of dendrohydrology. The Reduction of Error (RE) accounts for the relationship between the actual value and its estimate. This RE is however good for dendrohydrology studies. A classic paper in this field is Woodhouse (2001) about a reconstruction of streamflow in the Colorado Front Range where the RE was 0.277. In another important paper, Sauchyn et al (2015) report a RE of 0.73 for a reconstruction of the Atabasca River.

Page 6, Lines 23-24: What does this sentence mean?
R.2.11: Thanks for this question. We have modified this sentence in order to show more clearly at what temporal scale the dry years calculated from the instrumental record fit into the reconstructed streamflow: "In order to assess the uniqueness of this recent period of extreme summer streamflow, we (a) divided the tree-ring reconstruction into continuous periods of one, five, 10, and 20 years; and (b) we ranked those periods according with their departure from the mean. According to this classification, the dry period 1996-2000, one of the driest in the instrumental record, ranks fourth in the reconstruction, closely followed by 1987-1991".

Page 6, Lines 25-27: Is there any meaning for these windows of 5-year, 20-year,..etc? Of course, every time you change the window, you can get different results, but what are we supposed to learn from this?
R.2.12: We understand the concern of the reviewer and we clarify this in the new version of the manuscript. Although it is true this time windows are arbitrarily specified, our interest here is to provide context for the occurrence of extreme flows along the whole study period in way that is easier to understand for water managers. Yes, different windows will show different results, but the stress that our intention here is to provide context for the driest summers in the record. This method helps us in perform a more robust comparison between extreme years showing up in the instrumental record and those from the long-term reconstruction. We consider the use of these windows as reliable tool because have allowed us to determine the uniqueness of the post-1980 period.

Page 6, Line 27: You cannot really use reconstructed flows to comment on extremely high streamflow. Look at your Figure 4 (top left) and you will agree with me;
R.2.13: We understand this concern and that is the reason why we briefly describe high flow in that section and instead we focus on low flows. In fact, in the discussion and conclusion section we already had developed a possible explanation for this behavior based upon our results and literature review (Page 9, Lines 7-29). With the new division of sections as requested by the Reviewer 2, we have modified this section in order to better express our ideas.

Page 6, Lines 29-33: I cannot understand this portion;
R.2.14: We concur with the Reviewer this section does not read well. We have modified those lines with the following text "Since 1980, years in the lowest 20th percentile of the reconstruction have become more frequent. We calculated the return period of these low flow years in different periods of the reconstruction. We found (a) that during 1709-1750 and 1940-1960, events with streamflow below the 20th percentile had a 20-year return period; (b) a 5-year return period in 1750-1880; c) a predominantly 2 to 3-year period for 1880-1930; and d) a trend toward a 2-year return period since 1960 (Fig. 5)."

Page 7, Lines 1-5: What does this argument imply? Rain and streamflow are different! So, how did you conclude that it is a pluvial system? I think you need to elaborate;
R.2.15: We appreciate this comment, which allow us to further clarify the correlations we performed in our study. Yes, rain and streamflow are not the same, but it is important to remember that the basin we are analyzing is in a temperate climate. In this region, streamflow data clearly shows that river regime goes from nivo-pluvial regime (high elevation) to pluvio-nival and purely pluvial in lowland areas. Thus, it is expected that streamflow in lower sites are more correlated with rainfall. Thus, the correlation with the rainfall reconstruction validates the record (similarly as for the double mass curves), but it additionally demonstrates the pluvial character of the streamflow at this location and corroborates that our reconstruction is skilled in representing the hydroclimate of the region.

Pages 7-11: Almost half of the paper came under one section called Discussion and Conclusions. This is a style and format issue that does not look good. You need to include more analysis with the Results section, then not very long Discussion section, then a separate Conclusions section, this will be better.

R.2.16: Thanks for this suggestion. We have split discussion and conclusion sections, shortened the former and added some new analysis in the results according to previous suggestions by both reviewers (e.g. IPO analysis and climographs).

Page 7, Line 31: Usually trend analysis is misleading. Have you looked at the trend of the entire reconstructed record?

R.2.17: Thanks for this observation. Earlier in our research we calculated the slope for the entire record and it wasn't statistically significant. We did a new analysis considering the period 1709-2015 (according to other analyses suggested by both Reviewers) and found a non-significant slope of -0.0003. For reference, we will include this value in the first part of the results that describe findings from the tree-ring reconstruction.

Page 8, Line 5: I got confused, was that SAM work done in this study or taken from other studies?

R.2.18: We apologize if this does not read clearly in the manuscript. We will modify it in order to state more clearly that the SAM indexes have been drawn from public sources (e.g. NCAR-NCEP) and databases associated with peer-reviewed publications (e.g. Villalba et al 2012).

Page 8, Lines 10-12: On what basis was this statement made? Looking at Figure 6 and the correlation numbers does not give me the same impression that the authors have;

R.2.19: We understand the concern of the reviewer. We think this is an issue of word choice in our text; we wanted to state that the significant correlation with SAM indicates that our reconstruction captures characteristics of the regional hydroclimate. The use of the article "the" gives the impression that we are claiming that the reconstruction captures "all" features of the regional hydroclimate. We changed that statement for the following: "The tree-ring reconstruction showed a statistically significant correlation with the SAM reconstruction presented in Villalba et al. (2012), especially for the long-term trend; we consider this result confirms that our reconstruction captures characteristics of the regional hydroclimate." We have also modified the caption on Figure 6 to indicate that the asterisks represent statistical significance.

Page 11, Lines 21-24: I cannot find proof for this in the manuscript, perhaps the authors need to rewrite this;

R.2.20: We agree with your assessment. We have deleted this sentence from our manuscript.

Figure 2 (but also a general comment): On what basis was the selection of Jan-Feb only? Why not March and April too? They also seem part of the low flow season, especially that it may not be a good idea to call two months a drought; The authors also need to note that averaging the streamflow of three stations may reduce the variability in individual gauges, and make the reconstruction easier (nevertheless, the reconstruction accuracy is not high anyways). So, you need to justify this;

R.2.21: We selected January and February as representing summer because they the only two months that fall completely in this season. In the Southern Hemisphere the summer runs from December 21st to March 21st. I addition, these two months correspond to the lowest rainfall of the year, as shown in the Figure R2.A

Concerning the averaging if the individual gauges and the implications for the reconstruction, we agree with the reviewer that averaging the stations may reduce variability of individual gauges, but the objective of tree-ring reconstructions is to generate regional (for instance basin-scale) hydroclimatic time-series rather than simulate individual records (gauges). An individual gauge station can be affected by local features, but a composite time-series has more chances to average-out local particularities and thus provide a common regional signal that can be compared with the regional signal of a (or several) tree-ring chronology (ies). Despite this, we consider important to recall Figure R1.A (response to Reviewer 1) where we show that our reconstructed streamflow correlates significantly with observed streamflow of each individual station, and also each individual station correlates significantly with the composite time-series produced in our study. In addition, in the response to Reviewer 1 we further explain, citing Figure 1, that the reconstruction compares well with the instrumental records utilized for generating the composite.

Table 1: Please report the standard deviation also or better, the coefficient of variation to see the variability of each series;

R.2.22: Thank you for this suggestion. We will add the coefficient of variation to that table.

Table 3: What are those LAN and VILL in the Table title?

R.2.23: Thanks for this comment. We added the description of these chronologies in the caption of the new Table 3.

Table 4: The autocorrelation of the tree ring chronologies are quite high, and is usually transferred to the reconstructed annual flows. I find this unrealistically high for annual flows, can you comment on this and its impact on the reliability of the reconstructed flows? Can you compare it with the autocorrelation of the instrumental flows?

R.2.24: We agree with the reviewer and we believe it is important to include information on autocorrelation in the manuscript. Now in the manuscript we include the following text: “The tree-ring reconstruction presents high autocorrelation, consistent with the fact that tree-growth has a temporal memory associated with the water reserve and the soil moisture that remains and is captured by the tree. Some of the statistical procedures applied to the tree-ring chronologies are meant to minimize these effects, but it is virtually impossible to eliminate all. In our case, the autocorrelation is 0.56 to 0.49 for each individual chronology, while it is 0.248 for the reconstruction (1709-2005). This autocorrelation is still high considering that the instrumental record is essentially free from autocorrelation (-0.093)”.

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Dendrohydrology and water resources management in South-Central Chile: Lessons from the Río Imperial streamflow reconstruction

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Abstract. Streamflow in South-Central Chile (SCC, ∼~~35~~37ºS-42ºS) is vital for agriculture, forestry production, hydroelectricity, and human consumption. Recent drought episodes have generated hydrological deficits with damaging effects on these activities. This region is projected to undergo major reductions in water availability, concomitant with projected increases in water demand. However, the lack of long-term records hampers the development of accurate estimations of natural variability and trends. In order to provide more information on long-term streamflow variability and trends in SCC, here we report findings of an analysis of instrumental records and a ~~296-year~~ tree-ring reconstruction of the summer streamflow of the Río Imperial (∼37º40'S-38º50'S). This is the first reconstruction in Chile targeted at this season. Results from the instrumental streamflow record (∼1940 onwards) indicated that the hydrological regime is fundamentally pluvial with a small snowmelt contribution during spring, and evidenced a decreasing trend, both for the summer and the full annual record. The reconstruction showed that streamflow below the average characterized the post-1980 period, with more frequent, but not more intense, drought episodes. We additionally found that the recent positive phase of the Southern ~~Anular~~ Annular Mode has significantly influenced streamflow. These findings agree with previous studies, suggesting a robust regional signal and a shift to a new hydrological scenario. In this paper, we also discuss ~~the~~ implications of these results for water managers and stakeholders; we provide rationale and examples that support the need for the incorporation of tree-ring reconstructions into water resources management.

1 Introduction

Streamflow in South-Central Chile (SCC, ∼~~35~~37°S-42°S) is vital for agriculture, forestry production, hydroelectricity, and human consumption (Lara et al., 2003; Rubio-Álvarez and McPhee, 2010). With more than 55% of Chilean agriculture and forestry production delivered from this region (Instituto Nacional de Estadísticas, 2007), the drought episodes that occurred in the last few decades and the associated hydrological deficit have had damaging effects (Garreaud, 2015). These drought episodes have been linked to a significant decreasing trend in regional precipitation (Pezoa, 2003; Aravena and Luckman, 2009; González-Reyes and Muñoz, 2013), with amounts 40% below the 1901-2005 mean (Trenberth et al., 2007). ~~At the global scale, SCC corresponds to one of the regions projected to undergo major reductions in water availability. A~~ SCC is expected to undergo important climate changes. Analysis of the multi-model ensemble ~~(between 35 to 40 members) of projections from the Coupled Model Intercomparison Project phase 5 (CMIP5) using the~~ for the scenario RCP4.5 ~~scenario, posited that runoff in this region will decrease by about 10% by the period 2016-2035 relative to 1986-2005, with concomitant but less intense increases in the water balance (evaporation minus precipitation up to about 0.3 mm day^{-1}) , decrease in soil moisture (∼-3%), and relative humidity (∼-1%) (Kirtman et al., 2013). These projections are critically worrisome for summer streamflow in SCC (October to March)~~presented in the Atlas of Global and Regional Climate Projections (IPCC, 2013) indicates 10 to 30% reduction in spring and summer (October to March) precipitation by 2016-2035 and 2046-2065 relative to 1986-2005. The same projection forecasts 0.5 to 2°C warming for summer (December- February). Drier and warmer summers may make SCC more vulnerable to water scarcity, given that this ~~season~~ is the season of highest water demand in this region (Garreaud, 2015).

Current and projected increases in water demand in this region is likely a source of high uncertainty for future scenarios of water use (Lara et al., 2003). However, the lack of long-term observational records of hydrometeorological variables makes difficult the development of accurate estimations of natural variability, useful for determining the severity of the recent observed deficit in streamflow (Lara et al., 2008). Therefore, there is need to extend the observational record to better understand long-term (e.g. centuries to millennia) variability and trends in streamflow, thus providing useful information for hydrological assessment of governmental and private planning initiatives within watersheds of SCC (Lara et al., 2015; Muñoz et al., 2016).

The Río Imperial, a major river in SCC, drains an area of 12,763 km^2, extending between ∼37°40'S to ∼38°50'S (CADE-IDEPE, 2004) (Fig. 1). The river begins at the confluence between the Chol Chol and Quepe rivers, in the ninth Chilean administrative region known as “Araucanía". Summer streamflow is controlled by rainfall, as most snowmelt dominated discharge (usually occurring in late austral spring) has vanished (CADE-IDEPE, 2004). This river is currently utilized for irrigation, fishing, tourism, and transportation (in certain sections). For instance, in 2001 4% of the basin area was potentially usable for irrigation agriculture, with some projections suggesting that this proportion will grow to ∼10% (Ayala-Cabrera y Asociados, 2001). Additionally, the Río Imperial has high hydroelectric potential, ranked eleventh in the country, with 455.8 MW (Santana et al., 2014). An emerging sociohydrological problem in this basin is related to the allocation of water rights by the government: there is more streamflow allocated than the current river discharge. What seems to prevent a water availability crisis is that not all the allocated water is being exploited (Ayala-Cabrera y Asociados, 2001). Facing scenarios of water scarcity may obligate some users to fully claim their rights, likely triggering a regime shift with uncertain implications. However, the ability to ponder the possible consequences of these predicted changes is limited because accurate calculations of extreme scenarios are essential but largely nonexistent. For this reason, long-term evaluations of Río Imperial discharge are urgently needed.

Tree-ring analysis has proven to be a useful tool for supplementing available observations of streamflow. These proxy records can provide time series at yearly resolution, capable of delivering historical information on natural variability, estimations of return periods of extreme events such as droughts, and on the correlation with large-scale climatic forcings (Meko and Woodhouse, 2011; Sauchyn et al., 2011). In Chile, dendrohydrology has already been utilized for streamflow reconstruction in four major rivers: Maule (35°30’S, (Urrutia et al., 2011)), Biobío (37°10’S, (Muñoz et al., 2016)), Puelo (41°39’S, (Lara et al., 2008)), and Baker (47°40’S, (Lara et al., 2015)). To date, however, these studies have not yet been fully utilized for watershed planning and management. In order to provide more information on long-term streamflow variability and trends in SCC and thus contributing to improving water resource management in this key region for the country’s economy, here we report findings of a tree-ring based reconstruction of the summer streamflow of Río Imperial. This is the first reconstruction of streamflow in summer, the season with the highest water demand. Our research focused on expanding current understanding of long-term streamflow, thus providing more evidence on both regional coincidence among studies and seasonal/local particularities in streamflow. Therefore, our objectives were to (a) determine whether or not current summer streamflow changes in the Río imperial are unprecedented in the multi-century scale; (b) establish if the return period of extreme years of high and low streamflow has changed in the last few centuries; and (c) estimate the correlation between the multi-century variability of the Río Imperial streamflow and climate modes of natural variability such as El Niño Southern Oscillation (ENSO)~~and~~ , the Southern Annular Mode (SAM), and the Interdecadal Pacific Oscillation (IPO). Given that this is the fifth streamflow reconstruction for a Chilean river and that available results from previous studies have yet to be utilized for water resources planning, in our discussion section we also (a) summarize arguments related to physical processes that may support our summer reconstruction as a more robust time series compared to some of the previous studies, and (b) in light of our results, we evaluate strengths and weaknesses of a recently enacted method to calculate minimum ecological discharge, hoping to engage authorities, managers and stakeholders in considering proxy-data for improving water resources management and research.

2 Methods

2.1 Analysis of Instrumental Streamflow Records

In this study, January and February represent summer streamflow, the period of the year with the streamflow is closest to the river’s baseflow ~~.~~and when annual precipitation is at its lowest (Fig. S1). Streamflow during these months is sensitive to changes in soil moisture and thus summer precipitation (or the lack of) during that period or from previous months. We selected three instrumental records (Fig. 1) representing the natural streamflow regime of the mid and lower sections within the river basin (Table 1) for the period ~~1947-2010.~~ 1947-2015. These stations gauge rivers where the water has not been diverted for irrigation and hydroelectricity and are also located in two protected areas: Malalcahuello National Reserve and Conguillío National Park. Flow at downstream stations is highly conditioned by engineered structures (e.g. water intakes). We tested the “natural regime" represented by these records by conducting a correlation study between these stations and other hydroclimatic variables such as rainfall. We utilized double-mass curves to determine the length of the time series for calibration of the reconstruction model (Muñoz et al., 2016), discarding records that did not follow rainfall trends; this resulted in the elimination of a few years in the earliest section of the time series.

2.2 Reconstruction and Analysis using Tree-ring Chronologies

We built a multiple regression model relating three tree-ring chronologies from *Araucaria araucana* to records of Río Imperial's summer streamflow (Fig. 1 and Table 2). These chronologies were those showing the highest correlation with streamflow records, extracted from an initial group of 19 chronologies taken from *Araucaria araucana* (16) and *Austrocedrus chilensis* (3). We utilized the softwares ARSTAN (Cook, 1985) and COFECHA (Holmes, 1983) for standardization and dating of the tree-ring chronologies. This standardization procedure applies linear and exponential statistical models to suppress temporal auto-correlation in the series. These statistical procedures minimize the differences in tree-ring width between individual trees (e.g. due to local dissimilarities in soil moisture or differences in age) and therefore maximize our ability to retrieve the common tree-ring pattern related to the hydroclimate.

The three available instrumental records for the basin were transformed into standardized anomalies and then averaged to constitute a single composite time series (Lara et al., 2008; Muñoz et al., 2016). To obtain a valid simulation of the streamflow from the tree-ring chronologies, we employed the “leave-one-out" regression technique using the period 1947-2005 as the validation window, testing several predictors from the three tree-ring chronologies. The predictors consisted of chronologies for the growth year (t), as well as backward and forward lags of one and two years ($t-2$, $t-1$, $t+1$, and $t+2$, respectively). We found that the most robust statistical model corresponded to the following:

$$IS = 0.07 - 2.05PIN_{t+1} + 2.83LYV_t + 2.69PAG_{t-1} - 1.46PAG_{t+2} - 1.97LYV_{t-1} \qquad (1)$$

Where IS is the reconstructed summer streamflow for the Río Imperial, while PIN, LYV, and PAG correspond to the tree-ring chronologies as described in Table 3. The forward lagged time series included suggest that the statistical model has predictive skill, as shown in previous studies (e.g. Sauchyn et al. (2015a)). In this model, LYV and PAG correlated positively with same-year streamflow (0.38 and 0.43, respectively), with that of the previous year (0.53 and 0.41), and with streamflow recorded two years before (0.3 and 0.23). Conversely, PIN correlated negatively with streamflow recorded in previous years (-0.56 for the first and -0.38 for the second previous year). We conjeture that the negative correlation between PIN and the instrumental data is related to features of the sampling site, located in a narrow sector with recurrent fog, where atmospheric moisture and precipitation in summer may produce a relative reduction in incoming radiation and temperature; these conditions may reduce the rate of the tree-ring growth. Mundo et al. (2012) reported similar findings for PIN when analyzing as larger group of chronologies.

During the verification period we utilized (a) the R^2 (R^2adj) to assess the explained variance; (b) the Reduction of Error (~~ER~~RE) statistic to account for the relationship between the actual value and its estimate; (c) the F statistic for assessing the accuracy of the regression; (d) the Root Mean Square Error (RMSE) as well as the Standard Error (SE) as measures of uncertainty; (e) the Durbin-Watson test for determining the degree of auto-correlation of the residuals; and (f) the Variance Inflation

Factor (VIF) to check the possibility of multicollinearity in the regression ~~; and (f) the Durbin-Watson test for determining the degree of auto-correlation of the residuals (~~(see Ostrom (1990) for details). The Variance Inflation Factor (VIF) evaluates the multicollinearity of the predictors: a VIF close to 1 means a low or no multicollinearity (Haan, 2002) while a value above 10 is associated with multicollinearity problems between predictors (O'brien, 2007).

For studying the return period ~~or~~ of extreme low flows ~~or droughts~~ in the streamflow reconstruction, we applied the peak over threshold (POT) approach, using the low flows corresponds to a threshold ≤ 20th percentile. We also estimated the recurrence rate of drought events utilizing a kernel estimation technique with a Gaussian function and 50-yr bandwidth. The kernel-based estimation of drought recurrence allows for detection of nonlinear and non-monotonic trends without imposing parametric restrictions. Furthermore, a smooth kernel function produces more realistic estimation of drought recurrence. We calculated a confidence interval at the 95% level based on 1000 bootstrap resampling steps (Cowling et al., 1996) to estimate bias and variance properties of drought recurrence in the reconstruction. The kernel estimation, bandwidth selection, and bootstrap algorithm were computed in the free R Project platform software (R Core Team, 2016). We assessed frequency of cycles in the reconstruction by applying the following methods: Blackman-Tukey (Ghil et al., 2002), Multi-taper, Singular Spectral Analysis, and a Continuous Wavelet Transform Analysis.

We further performed a number of statistical analyses comparing observed, reconstructed streamflow time series, and other relevant hydroclimatic time series. For the period with available instrumental data (second half of the 20th century), we calculated Pearson correlations between these records and the Temuco rainfall gauge (TEM in Fig. 1; 38°46'S - 72°38'W), one of the few continuous records available in this watershed. We further analyzed the coherence of dominant periods of streamflow between the instrumental record and the tree-ring reconstruction, derived from a Singular Spectral Analysis ((Lara et al., 2015) and references herein). In addition, we compared the summer streamflow reconstruction of the Río Imperial with a November-December rainfall reconstruction of North Patagonia (Villalba et al., 1998). These chronologies are statistically independent, since the latter derives from samples extracted from *Austrocedrus chilensis*. This comparison is justified by the fact that studies in other watersheds in the SCC region have shown relatively fast response of the discharge to changes in precipitation (e.g. Zúñiga et al. (2012)). Finally, we studied the correlations between observed/reconstructed streamflow and time series representing modes of regional climate variability, namely El Niño Southern Oscillation (ENSO), the Interdecadal Pacific Oscillation (IPO), and the Southern Annular Mode (SAM). For the ENSO, we utilized the Southern Oscillation Index (SOI) ~~calculated from the NCAR-NCEP reanalysis~~ provided by the Climate Analysis Section, Climate and Global Dynamics Laboratory at NCAR[1]. This SOI is computed from monthly mean sea level pressure anomalies at Tahiti and Darwin and has became standard for climatic studies (Trenberth and Caron, 2000). Negative SOI anomalies correspond to relatively warmer conditions in the Eastern Pacific Ocean (or more El Niño-like conditions). The IPO time series is from the reconstruction presented in Vance et al. (2015). For the time series representing the activity of the SAM, we selected the Antarctic Oscillation (AAO) index, defined as the leading principal component of sea level pressure in the region south of 20°S (Thompson and Wallace, 2000) and also calculated from the NCAR-NCEP reanalysis[2].

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[1] http://www.cgd.ucar.edu/cas/catalog/climind/soi.html (last accessed 03/12/2018)

[2] For details, go to http://jisao.washington.edu/data/aao/slp/ (last accessed 04/17/2017)

3 Results

3.1 Streamflow Trends and Variability from the Instrumental Record

Our analysis of instrumental data corroborated previous studies where the regime of the Río Imperial was characterized as fundamentally pluvial with a small snowmelt contribution during spring (CADE-IDEPE, 2004). The hydrographs in Fig. 2 show that around 40% to 50% of the streamflow occurs between June and August, although at the Cautín station spring months contribute slightly more to the overall flow relative to the other stations. Conversely, summer streamflow represents 5% to 10% of the total yearly amount. We also found a high correlation, as high as 0.61 for ~~the Temuco station~~TEM, between summer discharge and rainfall of the same season as well as with rainfall observations of previous months.

All observations showed a decreasing trend since the beginning of the records, both for the annual as well as for the summer mean (Fig. 2). Four of five ~~of the~~ lowest discharge records occurred after 1995, ~~with~~ notably 1999~~being the lowest~~, whereas the five highest ~~values did so~~ are detected before 1981, with four of them before 1974 (Table 2). ~~In general, though,~~ We calculated the proportional departures of each of these years (in percentage) relative to the long term average, finding that the five lowest-flow years showed little spread, with a mean departure of 54.06% ±6.14 (1 standard deviation), ~~relative to~~ whereas for the five highest-flow ones there was more spread (74.12% ±23.49). Furthermore, the record suggested that high flow years tended to be more extreme (relative to the mean) than low flows.

3.2 Streamflow Reconstruction: Features and Interpretation

Two of three *Araucaria araucana* tree-ring chronologies extended 800 years or more (PAG and LYV; Fig. 3 and Table 3), which ~~highlights~~ corroborates findings from a previous study (Mundo et al., 2012) on the potential of this species for providing ~~longer paleoclimatic reconstructionsthat the one presented here (Mundo et al., 2012)~~long paleoclimatic reconstructions. Combining the resultant common period among the tree-ring chronologies (1606-2005) with the Expressed Population Signal (EPS) statistic yielded a 296-year (1709-2005) time series of reconstructed summer streamflow. Although the EPS for the PIN chronology was 0.85 only after 1750 (Table 4), the large number of tree-growth series in the PAG and LYV chronologies (20 and 34 by 1709, respectively, see Fig. 3) allowed for the reconstruction to begin in 1709. An EPS greater than 0.85 for a given tree-ring chronology is often assumed as proof of its reliability, because it indicates that at least 85% of the chronology variance corresponds to a common signal (Wigley et al., 1984). Additionally, the VIF for the reconstruction period had values close to 1, especially for the PAG chronology, indicating that the regression model had no problems of multicollinearity (Table 4). From Table 4 we also noted that the chronologies presented high autocorrelation, consistent with the fact that tree-growth has a temporal memory associated with trees' capacity to store carbon and water, and the uptake rate of soil moisture remaining from previous seasons and years. Some of the statistical procedures applied to the tree-ring chronologies are meant to minimize these effects, but it is virtually impossible to eliminate all. However, when calculated for the reconstruction the autocorrelation reduced to 0.25 which, although high considering that the instrumental record is essentially free from autocorrelation (-0.093), it is nevertheless better than the individual chronologies. We extended this record using the composite instrumental record and the variance of the reconstruction. This way, the reconstruction allowed us to cover and assess the hydroclimatic significance of the latest anomalous dry period detected for Central Chile (2011-2015), referred to as "megadrought" (Garreaud, 2015).

Comparison between standardized anomalies of the reconstruction ~~in relation to~~ and observations during the calibration period (~~1947-2005~~1947-2010) suggested a high reconstruction skill for summer streamflow record (Fig. 4 top-left panel). We also computed correlations between observed/reconstructed streamflow and TEM for each month of the previous year, finding significant figures for December and February of the previous year (p-value < 0.1 and < 0.05, respectively) in the case of the instrumental record; for the reconstruction, the correlation is significant for June and December (p-value < 0.05, see details in Fig S3). In addition, an analysis of coherence between dominant periods showed that both time series presented similar cycles of three, five, and 30 years (Fig. 4 top-right panel). This good performance was further corroborated with these statistics: (a) R^2adj=0.47, indicating that the regression model explained 47% of the variance in the ~~predicand~~predictand; (b) small errors, with RMSE=0.71, RE=0.36, and SE=0.66; (c) a statistically significant model as reflected by the F statistic (10.08, $p<0.0001$); while (d) the residuals were not auto-correlated (Durbin-Watson = 2.25, ~~p<~~p-value < 0.01). Previous studies have found similar performances for reconstructions in other regions of the world (e.g. Woodhouse (2001)), which lead us to assert that our reconstruction is a reliable representation of the Río Imperial's summer streamflow. Another proof is the detection of significant agreement between the reconstruction and observations for the period 1980-2010 for the region ∼35°S-42°S (Fig. S2).

~~The tree-ring reconstructionsuggested~~ We evaluated trends and frequency of extreme events for the whole reconstructed period. This analysis revealed a negative, although no statistically significant trend for the reconstruction. What we did observe was a low frequency of extreme flows, although during most of the 20th century (∼1910-1970) high flows (above the percentile 60) clustered. On the other hand, low flow periods (below the percentile 20) occurred more frequently in the late 1800s, early 1900s, and after 1980. Importantly, streamflow below the historical average characterized the post-1980 period (Fig. 4 lower panel). The application of the Blackman-Tukey method allowed us to detect high frequency cycles (2-7 years) and mid-to-low frequency (> 8 years). The Multi-taper method and the Singular Spectral Analysis revealed that a ∼4-year cycle captures 10% of the variance, a ∼7-year cycle captures 7%, while we also found a 16-20-years cycle, corresponding to 20% of the variance. This last long cycle was also found when applying a Continuous Wavelet Transform Analysis, in this case a significant 16-32-years frequency between 1800-1950; higher frequency cycles occur along the whole period but appear more significant after 1900 (Fig. S4).

In order to assess the uniqueness of this recent period of extreme summer streamflow, we ~~ranked the five most extreme high and low flows from the~~ (a) divided the tree-ring reconstruction ~~using several temporal windows:~~ into continuous periods of one, five, 10, and 20 years~~. Results~~ ; and (b) we ranked those periods according with their departure from the mean. Although somewhat arbitrary, the length of these windows are defined as a mean for providing context for the occurrence of extreme flows along the whole study period in way that is easier to understand for water managers. According to this classification, the dry period 1996-2000, one of the driest in the instrumental record, ranks fourth in the reconstruction, closely followed by 1987- 1991. Results also indicated that the lowest flow events since the mid 20th century are somewhat relevant at the five-year scale. However, the period 2011-2015 did not show low flows as extreme as other periods in the reconstruction; it only ranked high in the instrumental record. At the 10-year scale, post-1980 low discharges ranked only third and fourth. The most striking relevance of modern low flow appeared at the 20-year scale, where the period 1986-2005 ranked first, suggesting this period as the driest ~~window~~ since the beginning of the reconstruction. The same analysis for extremely high streamflow showed that the mid 20th century was persistently ranked among the five in all the timescales considered (Table 5).

~~Post-1980 was a period of frequent droughts in the~~ Since 1980, years in the lowest 20th percentile of ~~flows. We found this by dividing the time series into percentiles: this period clustered records below the 20th percentile (Fig. 5). We also distinguished four return periods of this percentile for the whole reconstruction: a)~~ the reconstruction have become more frequent. We calculated the return period of these low flow years in different periods of the reconstruction. We found (a) that during 1709-1750 and 1940-1960, events with streamflow below the 20th had a 20-year return period; (b) a 5-year ~~period between 1750 and 1880;~~ return period in 1750-1880; (c) a predominantly 2 to 3-year period for 1880-1930; ~~d) during 1940-1960 again a 20-year return period; and e) a~~ and (d) a trend toward a 2-year return period since ~~then~~ 1960. In addition, we found that since ∼1980 more droughts below the 10th percentile are also becoming more frequent (Fig. 5).

We found the Río Imperial reconstruction and the precipitation reconstruction for North Patagonia (Villalba et al., 1998) to be significantly correlated. Closer inspection of the year to year correspondence between these two reconstructions (Fig. 6a) revealed that the interannual variability was somewhat different, especially for the most negative departures in which there was ocasional coincidence. A 30-year spline filter shows the similarity at lower frequency between these two time series, although with noticeable lags (nevertheless irregular in length) between peaks and troughs, as for example in the period ∼1730-1740 (Fig. 6b). Overall, the reconstructions coincided in the number and length of high and low periods.

3.3 Streamflow Correlation with ~~the ENSO and the SAM~~Regional Climate Modes of Variability

The instrumental discharge record correlated with the ENSO and the SAM (Table 6). While summer discharge had a Pearson correlation of 0.32 with the SOI from February to March of the previous year, the coefficient was as high as -0.66 with the AAO of the previous 12 months (September to August). The AAO-streamflow correlation of streamflow with the instrumental record and tree-ring reconstruction were identical when calculated for the period September-December of the immediate previous year. This correlation was weaker (-0.3) when we removed the linear trend, indicating that a significant portion of the streamflow trend is shared with the trend in the AAO. The agreement for September-December, as well as the relatively similar correlations observed for February-March (instrumental record) and March (tree-ring), reaffirmed the previous finding about the high skill of the reconstruction to reproduce essential properties of the instrumental record. An additional confirmation of the influence of the SAM on streamflow can be observed in Fig. 6, where we found a similar correlation between a long-term reconstruction of the AAO (Villalba et al., 2012) and our streamflow reconstruction, with a statistically significant Pearson r of -0.33 for both high and low frequencies. In order to discard the possibility of a non-significant correlation, we performed further correlations between the AAO and a pre-whitened version of (a) the reconstruction and (b) the observations (removing the lag-1 autocorrelation). Results reaffirmed the negative and statistically significant correlation, with -0.287 (p-value=0.033) for the reconstruction and and -0.29 (p-value=0.029) for the observations, respectively. In the case of the IPO, we found a statistically significant negative correlation between that time series and the 16-20-year cycle of our reconstruction (-0.38, n=295), although it looks more coherent during the 20th century.

4 Discussion

The tree-ring reconstruction for the Río Imperial has revealed new information and insights on long-term streamflow variability, thus allowing for the assessment of changes in summer water availability in the SCC region, including the long-term significance of recent extreme hydrological events throughout the region. This streamflow reconstruction corresponds to the fifth ~~such~~ record for Chilean rivers, but the very first focused on summer streamflow. Some of our findings ~~coincide~~ agree with those of previous studies, which strongly suggests ~~hydrological features that characterize the region. Firstly, the~~ that our reconstruction represents well the summer hydroclimate of a large region in SCC. This is manifested by the good skill our reconstruction in simulating instrumental records along the wider region 35°S-42°S (Fig. S2), which further supports findings by González-Reyes et al. (2017), who stated that this region configures a hydroclimatic cluster.

The noticeable decreasing trend post-1980 observed in the instrumental record as well as in our reconstruction, which was to a certain extent identified in all previous reconstructions (Lara et al., 2008, 2015; Urrutia et al., 2011; Muñoz et al., 2016), ~~corroborating~~ corroborates the occurrence of an ongoing and unprecedented long-lasting ~~drought in SCC(Garreaud, 2015). Secondly, we can confirm that the driest years of the instrumental record were not the driest years of the last few centuries.~~

~~In this regard, the detection~~ summer low flow in SCC, which also includes the recent drought detected for Central Chile (Garreaud, 2015). We note that the post-1980 period represents 50% of the composite instrumental time series, while it only represents 10% of the reconstructed period; we posit this highlights the uniqueness of the post-1980 period. Thus, this period is noteworthy as the one with the lowest summer streamflow of the whole ~~reconstructed period~~reconstruction. This low flow period gradually emerged as the most acute as the time window was broadened (Table 5), despite the fact that no year during this ~~period window~~ timespan ranked high in the lowest percentile of the ~~last 296 years~~reconstruction. As shown above, the decreasing trend observed in our results has already been detected in other rivers of the region, specifically south of ∼37°30’S (Masiokas et al., 2008; Rubio-Álvarez and McPhee, 2010). The implications of this finding for water management and planning purposes are related to the ability to detect the effect of regional climate changes in the area. The increasing number of low flow years may indicate a regime shift in the summer dynamics, which can be exacerbated with predicted increased warming and precipitation reduction in SCC (Garreaud, 2015). Our results indicated a decreasing trend in summer streamflow with a smaller natural variability when compared with the rest of the ~~296-year~~ tree-ring record.

Our results additionally posited the SAM as the most influential climate mode driving the variability of the Río Imperial’s summer streamflow, especially during the second half of the 20th century. The ~~characteristics of this tree-ring reconstruction establish it~~ correlation we found between SAM and the reconstruction establishes the tree-ring time series as independent new proof of the importance of the SAM in modulating precipitation and streamflow in a large region of Central and South of Chile (Villalba et al., 2012; Muñoz et al., 2016). The SAM has been extensively described as a strong modulator of precipitation variability in SCC (Aravena and Luckman, 2009; Villalba et al., 2012; González-Reyes and Muñoz, 2013). The ~~previously~~

~~reported reconstruction of the SAM (Villalba et al., 2012) also correlated with the Río Imperial at the interannual scale but more so in terms of~~ tree-ring reconstruction showed a statistically significant correlation with the SAM reconstruction presented in Villalba et al. (2012), especially for the long-term trend~~, validating the capacity of our reconstruction to represent the~~ ; we consider this result confirms that the reconstruction of summer streamflow for the Río Imperial captures characteristics of the regional hydroclimate. The reconstruction featured in Villalba et al. (2012) contains two of the tree-ring chronologies presented in our study (PIN and LAN), in a pool of more than 1000 series developed from different species of the Southern Hemisphere. Our summer streamflow reconstruction is key in further supporting the SAM-streamflow relationship, because in this season and overall, snowmelt is a minor contributor to discharge (see Fig. 2). This makes rainfall ~~runoff~~ the principal source of water for the river. During the last 75 years or so, the SAM has been shifting to a positive phase, unprecedented in the last 1000 years (Abram et al., 2014). A positive phase means that the pressure gradient between the midlatitudes and the polar latitudes is negative, that is, more positive or less negative in the midlatitudes relative to polar latitudes. This gradient shifts the core of the southern westerly winds towards the south, limiting the effect of storm tracks over midlatitudes. In the past, the SAM has been shown to be negatively correlated with the frontal activity and hence precipitation amounts, especially for the spring season (Silvestri and Vera, 2003). Given the relatively short delay between precipitation and discharge in the region (e.g. Zúñiga et al. (2012)), this relationship may well explain the decreasing summer streamflow trend observed for the last decades, as detected in the September-December negative correlation between the AAO in relation to both instrumental records and the tree-ring reconstruction (Table 5). This way, the post-1980 trend in summer streamflow of the Río Imperial may be linked to the aforementioned positive phase of the SAM (Abram et al., 2014). More so, this close relationship could mean an unprecedented decreasing trend in summer streamflow in the Río Imperial for the last millennia. However, it is important to consider results according to Blázquez and Solman (2016) on the relationship between precipitation, frontal activity, the ENSO, and the SAM in the Southern Hemisphere. In that study, ENSO (defined as the second EOF from monthly anomalies of the 500 hPa geopotential level) correlated higher with frontal activity in spring at the interannual timescale, although the correlation was also statistically significant with the SAM (defined as the first EOF from monthly anomalies of the 500 hPa geopotential level). Blázquez and Solman (2016) also demonstrated that precipitation in SCC is significantly correlated with frontal activity. These studies suggest that the impact of the SAM on precipitation in the study area can also be associated with ENSO dynamics. For example, the low flow for the summer 1999 was concomitant with a high AAO and ~~the strong El Niño event of 1998.~~ and a strong La Niña event in 1998-1999. Recent studies have found that in-phase (e.g. positive ENSO and positive SAM) and out-of-phase occurrences of these climate modes can lead to varying strength of the associated atmospheric circulation (Fogt et al., 2011; Wilson et al., 2016), possibly controlling the intensity of their impacts on precipitation and hence streamflow. In fact, Quintana and Aceituno (2011) in a study analyzing the changes in rainfall in Central and South Central Chile found that ENSO and AAO are not independent modes of variability and rather they both affect precipitation regimes. It is also important to consider possible different seasonal effects of these modes of variability, as for example findings in Barria et al. (2017), who utilizing a 11-year moving average of a 300-year tree-ring streamflow reconstruction for the upper Biobío river determined a negative correlation between with the Pacific Decadal Oscillation (PDO) and streamflow during the snowmelt season (October-March) while a positive correlation between the SAM and that seasonal streamflow. Thus, we believe that the SAM-streamflow statistical relationship we found should be tested further in order to develop more accurate predictive models of extreme interannual dynamics. Using output from the CMIP5, Lim et al. (2016) predicted that the positive phase of the SAM will continue in some climate change projections, likely (but not certainly, given the difficulties in simulating the ENSO-SAM interactions) impacting precipitation in the midlatitudes. In this scenario, the SAM could provide more accurate statistical models of return periods.

Another relevant aspect of our reconstruction is that, like previous studies, it seemed to better represent low flow conditions rather than high flows. Urrutia et al. (2011) discussed this finding in their reconstruction of the Río Maule arguing, following Villalba et al. (1998), that this was likely a consequence of a smaller sensitivity of tree growth to precipitation above a certain threshold. However, the R^2adj of previous studies do not completely support that argument as the highest R^2adj (54%) was found in the Río Baker streamflow reconstruction (Lara et al., 2015), the southernmost and the wettest landscape of all sampled locations in Chile. In terms of R^2adj, our reconstruction ranks second (47%), followed by Biobío (45%, Muñoz et al. (2016)), while Puelo Lara et al. (2008) and Maule Urrutia et al. (2011) rank together with the lowest explained variance (42%). Notice that the two highest ranked reconstructions represent summer to fall streamflow, when the soil moisture is at its lowest in the annual cycle. Elshorbagy et al. (2016) summarized empirical and theoretical arguments to better understand, on the one hand, the physical process linking tree growth and streamflow and, on the other hand, what determines whether tree-ring reconstructions reproduce dry conditions. In that study, the authors presented data from the Oldman River Basin (∼49°40’N), a cold semi-arid watershed in western Canada. They suggested the likelihood of spurious self-correlation in the statistical models relating streamflow and tree-rings because precipitation may be considered as a confounding factor. The mechanism these authors suggested is that soil moisture modulates the relationship between tree growth and other hydrometeorological variables (e.g. evaporation or runoff), more so in areas (and perhaps seasons) where (when) soil moisture is relatively constant. Following these arguments, one should expect streamflow reconstructions to better represent years or periods of water scarcity rather than high flows. Elshorbagy et al. (2016) indeed found higher correlations between low flow and tree-ring width in the Oldman River basin. Our analysis, and the fact that the two of the previously reported reconstructions for Chile with the highest R^2adj were aimed to include summer months, suggest that reconstructions focusing on summer streamflow (at least partially as the case in Lara et al. (2015)) have physical meaning and not just statistical significance. This renders the Río Imperial reconstruction as a representative time series of summer streamflow for the last ~~296~~ 301 years, with a high capacity for capturing occurrence of dry years. However, further research is needed because the Río Puelo reconstruction (Lara et al., 2008), also aiming summer to fall streamflow, did not rank as high as our reconstruction and the one for Río Baker.

Given the crucial role that summer streamflow plays for a number of economic activities, such as agriculture and human consumption in the basin, the tree-ring reconstruction we have presented here can provide water managers and stakeholders with improved support for ~~decision making~~ decision-making and regional planning. For example, the post-1980 generalized regional decrease in streamflow, both instrumental (Rubio-Álvarez and McPhee, 2010) and reconstructed (e.g. Lara et al. (2008)), paralleled paradigmatic legal and institutional changes in national water management, whereby the policy to assign water rights (and hence rights to use a proportion of the streamflow) transited into a model “with strong private property rights, broad private economic freedoms, and weak government regulation" (*verbatim* Bauer (2004)). There is growing evidence of increasing water conflicts in SCC despite recent reform in this legal framework of water rights allocation (Bauer, 2015). Some have argued that at least part of the problem resides in the insufficient hydrological information for users, managers, and decision makers (Donoso, 1999). The relevance for water management in Chile is related to the mechanism for granting water rights, since it relies on the average river flow. By using this system, water rights have often exceeded the actual flow of rivers, specifically for the summer, forcing authorities to decree zones of water scarcity[3]. With the information obtained from tree-ring reconstructions, it is feasible for authorities to anticipate scenarios of future crises, particularly in drought cycles such as those described here. In this regard, a recently enacted (and modified) official decree defined that the minimum ecological discharge as the lowest 50% of the 95% confidence interval below the average discharge, determined from a probability distribution using a period of at least 25 years of instrumental observations[4]. The minimum ecological discharge is the current measure to determine when a given stream is so depleted that no more water rights must be allocated. Certainly, the 25-year window reflects the limited number of long-term records to reliably characterize throughout the country, ~~causing authorities to implicitly~~ obligating authorities to assume that the hydroclimatic regime of a given river is captured by a relatively short instrumental record. Interestingly, the text of the decree may likewise allow for the incorporation of tree-rings to inform the process of water rights allocation, since it actually (a) establishes the 25-year term as a minimum criteria for using available records to define the average river flow and (b) empowers the Chilean National Water Authority to incorporate other methods for river flow determination. On the other hand, this new decree defines explicitly that streamflow information has to be retrieved from an intake point, potentially limiting the use of tree-ring data because they usually represent hydroclimatic ~~varibility~~ variability at the watershed scale. We argue that information derived from the multi-centennial view of streamflow that tree-rings provide can help to better contextualize calculations from instrumental records, providing an additional “watershed" or regional perspective on water management. Our results indicated that the years of lowest discharge from the instrumental record did not classify as the most extreme droughts when contextualized in the longer tree-ring reconstruction. This suggests that, for instance, the drought in 1998-1999 was not as extreme as other events ~~from the past 296~~ in the past 301 years. Episodes such as the 1968-1969 (which in the case of the decree would need a period of at least 48 years to be detected) and 1998-1999 droughts impacted the regional economy with national repercussions, such as a 40% reduction in electricity supply (Fischer and Galetovic, 2001). Another example is the dry period after 2010 as a (Garreaud, 2015; Boisier et al., 2016), where our reconstructed streamflow indicates the that period was not as extreme as other that occurred in the last 301 years in SCC. In fact, our analysis indicates that 1996-2000 was a drier period in the reconstruction, although it only ranked fourth in Table 5. This finding implies that persistent rain deficits or meteorological droughts do not necessarily translate into extreme low streamflow because the storage capacity of certain hydrological basins can buffer these effects. We argue that, in order to understand the impacts and extent of extreme events such as droughts, tree-ring reconstructions from watersheds representing diverse hydroclimatic gradients, landcover characteristics, and geomorphometry are sorely needed.

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[3] An example of a decree for watersheds in the north of Chile can be found here https://goo.gl/S3n8d3 (last accessed 04/17/2017).

[4] See modification to decree Nº12, 2013, Ministerio del Medio Ambiente, Chile, available at https://goo.gl/uWyH9R (last accessed 04/17/2017).

5 Conclusions

The significance of our findings for planning is related to the need to consider a long-term view of the natural variability that defines the discharge regimes across the region. ~~Boisier et al. (2016) identified the period 2010-2014 as an extremely rare event of precipitation deficit (*verbatim* "megadrought") based upon statistical analyses for the period 1979-2014. However, no year in the period 2010-2014 had precipitation amounts as low as those detected in 1998-1999. Although the period 2010-2014 was not captured in our tree-ring records and our reconstruction was not intended for precipitation, the high correlation between the Temuco station and our time series allow us to infer that in a long-term view this five-year period should not depart more significantly than 1996-2000, which only ranked in the fourth place in Table 5.~~ Planning governmental responses for periods of low flow based upon the one, two, or five-year events detected in the available instrumental record may lead to ineffective mitigation actions, because those events ~~were not~~ may not be the most extreme on record. Considering the implications of our results, we assert that the extended record we have provided ~~must be utilized~~ can be utilized as a complementary source of information for water resources managers to more accurately determine the range of "worst-scenario" or "more-recurrent" droughts, thus helping the planning and implementation of more efficient mitigation policies. There are several examples where dendrohydrology has provided key information for decision-making process. Sauchyn et al. (2015b) presented an example in which a series of hydroclimatic scenarios derived from tree-ring chronologies were formally included in a government-supported hypothetical decision-making exercise where relevant stakeholders were tasked with developing adaptation measures for drought episodes. In that paper, and in the context of Canadian water policy, these authors stated that ~~dendrohydrogical~~ dendrohydrological research is a legitimate source of information for water resource planning and management. Another study, aimed to characterize long-term Athabasca River streamflow in Alberta, Canada, found that whereas a trend analysis of instrumental data depicted declining regional flows, a tree-ring reconstruction showed periods of severe and prolonged low flows not captured by the instrumental record (Sauchyn et al., 2015a)~~. This strongly suggests~~ ; suggesting that worst case scenarios estimated from historical gauge data likely underestimate the potential magnitudes of natural droughts in that region (Coulthard et al., 2016). Meko and Woodhouse (2011) described another application, where the Denver Water Board, the oldest and largest water supplier in the State of Colorado, USA, wanted to predict drought scenarios using reconstructions capable of capturing an episode ~~the~~ that occurred during the 1950s as well as other more recent droughts. Gangopadhyay et al. (2015) asserted that ~~this information can also be utilized to determine the~~ dendrohydrology can help in determining drivers of periods of extreme hydrological episodes in the Upper Colorado River basin.

The evidence presented in our study regarding the relatively dry post-1980 period, the higher frequency of droughts detected in the present for the Río Imperial relative to previous centuries, and the SAM projected to follow a positive phase leading to less precipitation altogether suggest that the regional hydrology is moving toward a new regime of more frequent (although not necessarily more intense) droughts. ~~Some of this change may be linked with recent anthropogenic climate forcing, and the detectable influence on regional precipitation trends (Boisier et al., 2016).~~ In a similar manner as documented in several recent studies targeting other regions of the world (e.g Woodhouse and Lukas (2006) and Sauchyn et al. (2015b), among others), our reconstruction of natural hydroclimatic variability of the Río Imperial can provide a valuable framework to ponder the impact of anthropogenic climate change on future hydroclimatic changes in SCC, thus leading to a prudent water resource management strategy. Furthermore, water managers could use the reconstructed flows of the Río Imperial to plan mitigation strategies for drought events with return periods of five, 10 and 20 years. As this hydrological application of dendrochronology becomes widely accepted as valid and water managers realize that this kind of historical information can guide operational strategies in the forthcoming decades (Biondi and Strachan, 2012), the possible regime shift needs to be incorporated into adaptation and mitigation plans associated with the regional impacts of future global climate changes. This will avoid, or at least mitigate, negative consequences of these changes on the management of water resources for municipal and agricultural water supplies, electrical power, ecological habitats (e.g. Carrier et al. (2013)) and impacts on the economic activities in the region as water sources become stressed.

Code and data availability. Codes and data associated with this work can be accessed by emailing the first three authors.

Competing interests. The authors declare no competing interests

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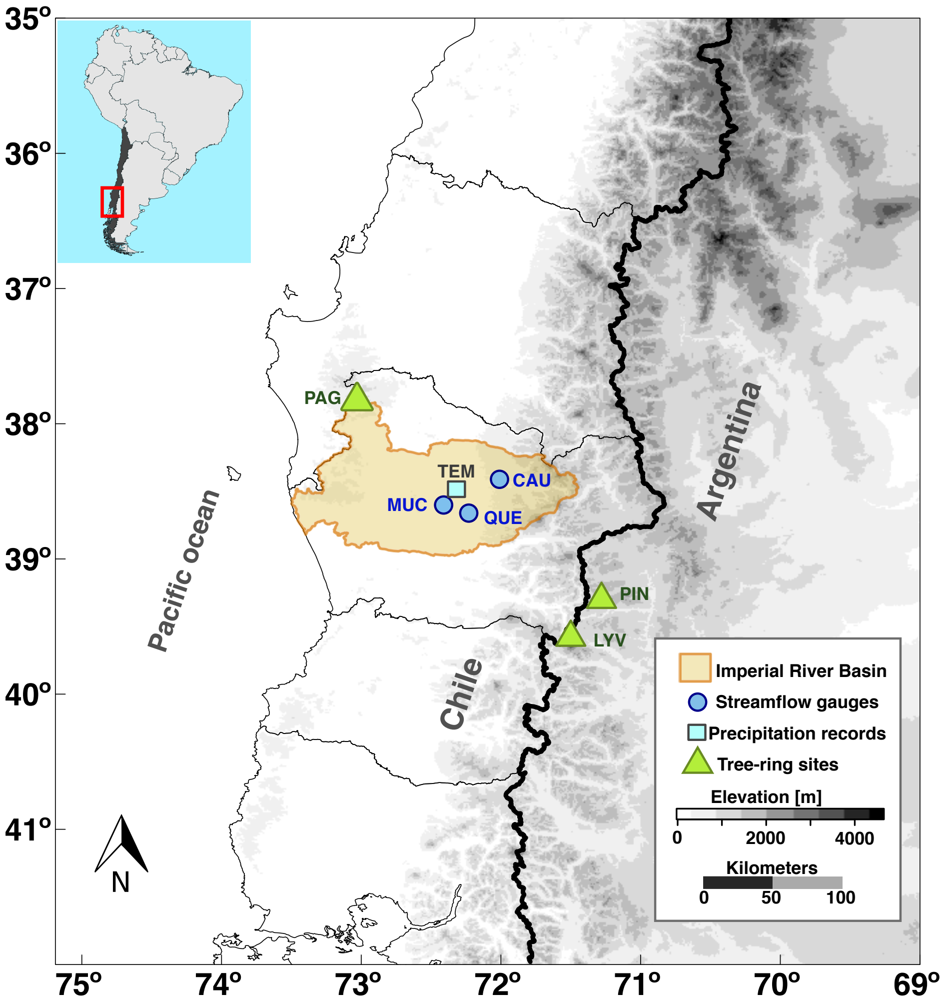


Figure 1. Map showing the Río Imperial hydrological basin in the context of the SCC region. Locations of instrumental records and tree-ring sampling sites are also included

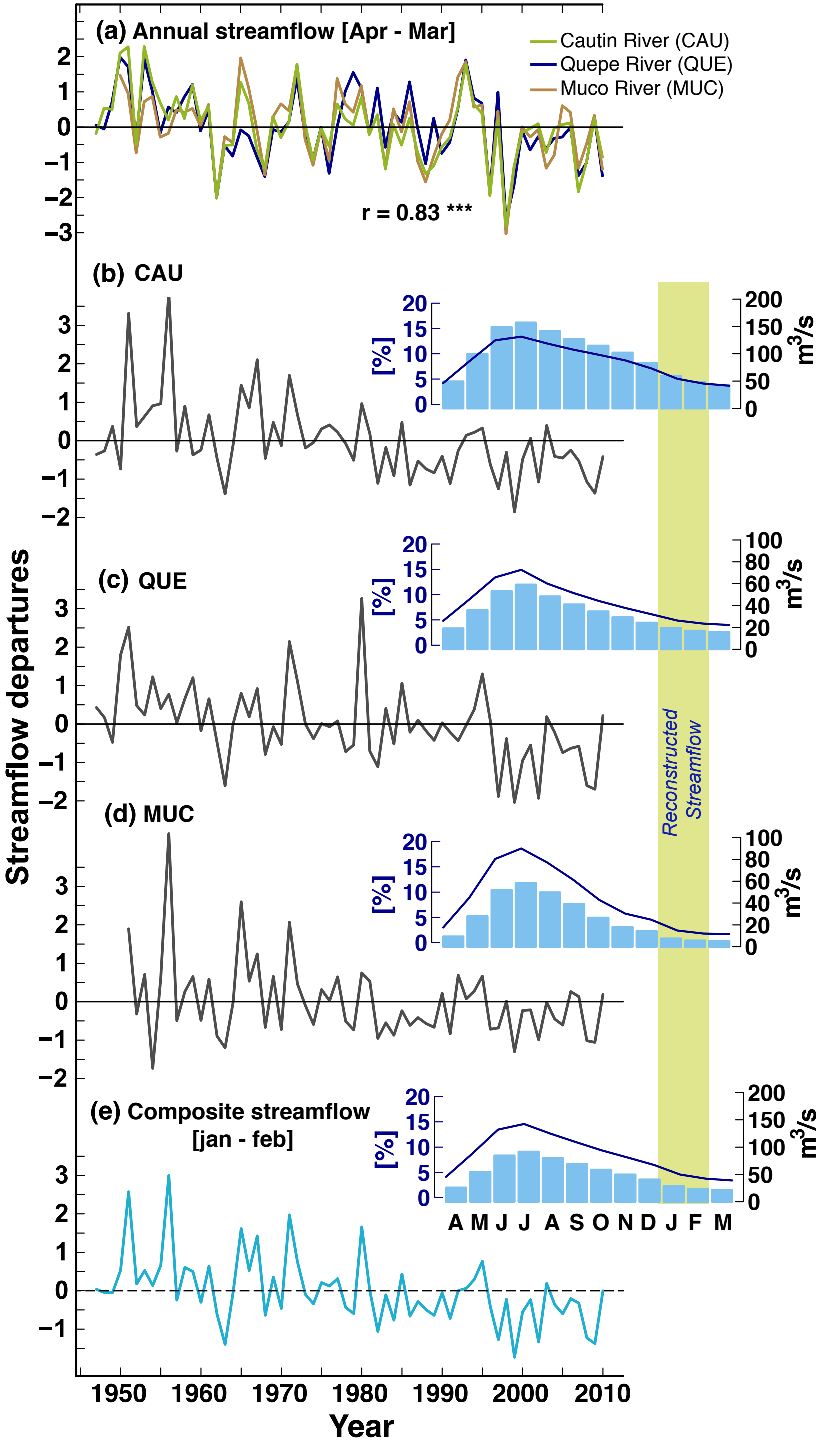


Figure 2. Hydrological regime of the instrumental records utilized in this study. These records were combined to develop a composite summer streamflow record for the period 1947-2010. The plots showing "streamflow departures" correspond to standardized anomalies for the common period of the records. The hydrographs depict the average streamflow of each month (bars) and the proportion of yearly discharge each month contributes (curves).

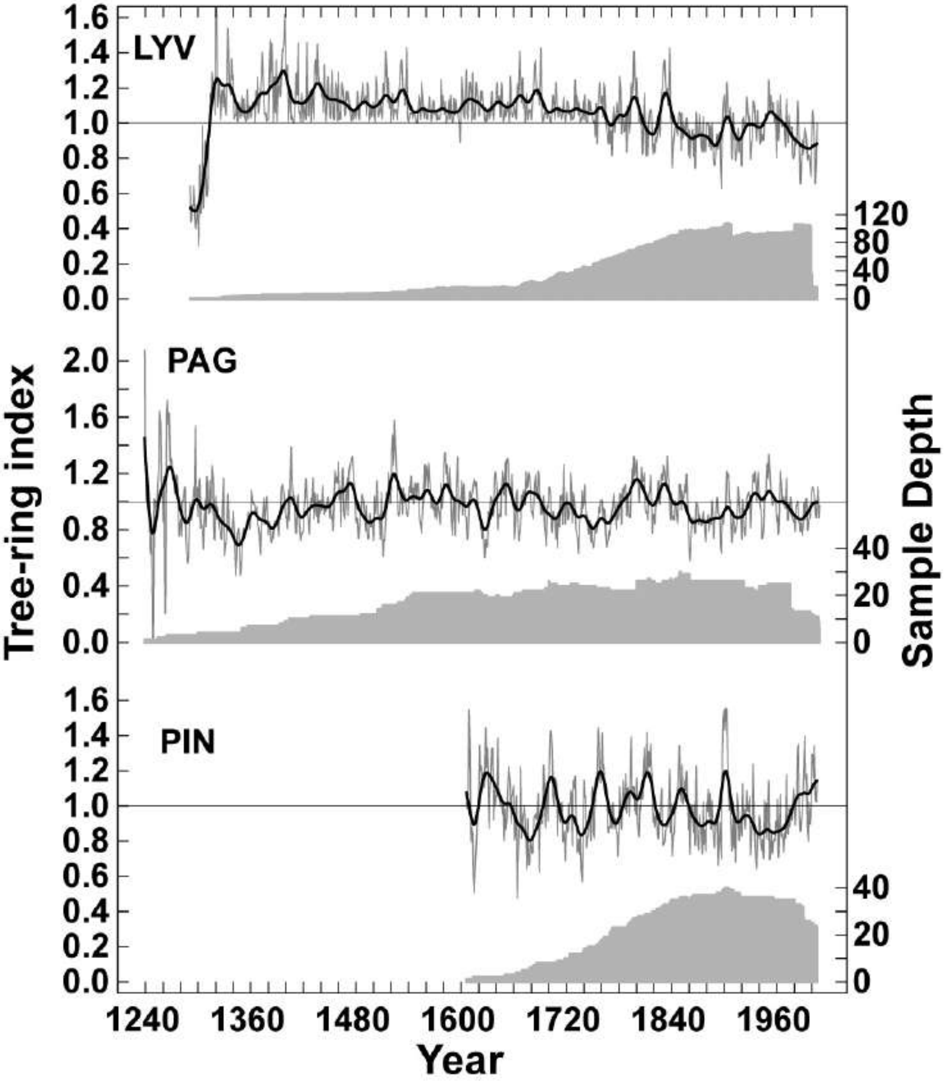
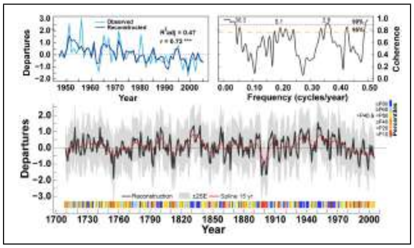


Figure 3. *Araucaria araucana* tree-ring chronologies utilized for the Río Imperial streamflow reconstruction. Gray areas represent the number of tree-growth series included in each chronology. The longest time series corresponds to the one sampled in the Nahuelbuta National Park (PAG), representing the period 1239-2009.



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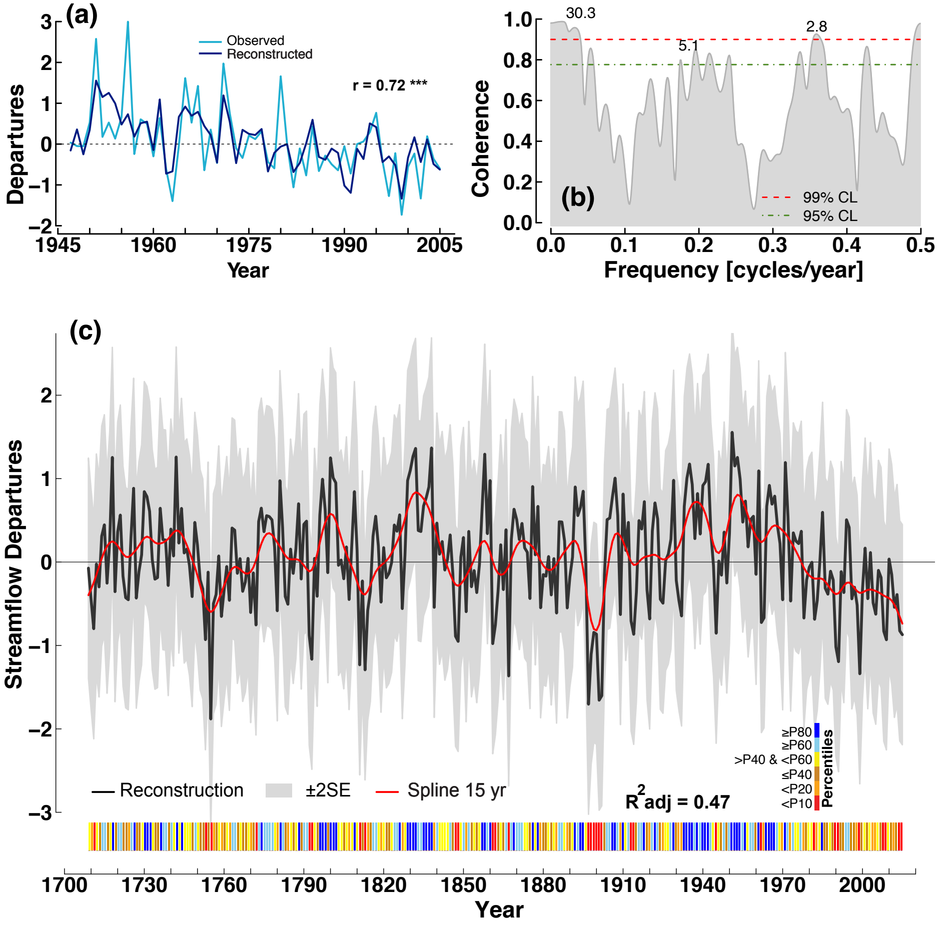
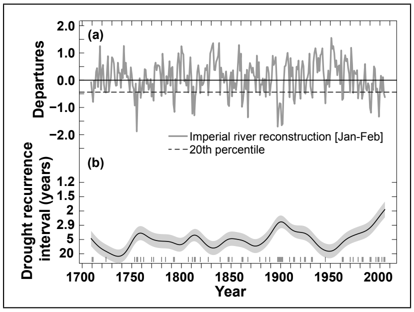


Figure 4. Summer streamflow reconstruction for the Río Imperial. The top-left panel compares standardized anomalies of observed (instrumental) streamflow and our tree-ring reconstruction. The top-right panel depicts the coherence of cycles between both time series. The lowest panel corresponds to the ~~296-year~~ streamflow reconstruction, including the envelope for the ±2 standard error (SE), a spline filter, and a classification of each year in the percentiles of the probability distribution (bottom section).



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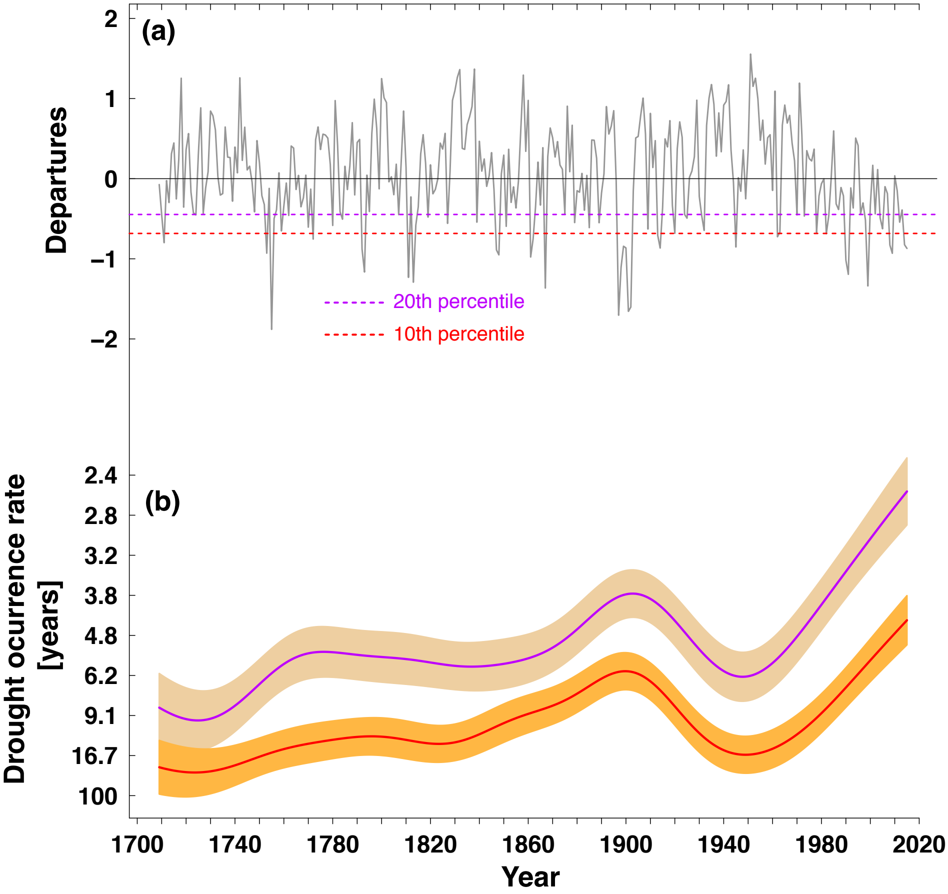

Figure 5. Summer streamflow reconstruction and the periods of low flow~~in the last 296 years~~. In (a) the 10th (red) and 20th ~~percentile is~~ (purple) percentiles are plotted over the time series. (b) shows the return period of each low flow (below the 10th and 20th ~~percentile~~percentiles) for the whole record.

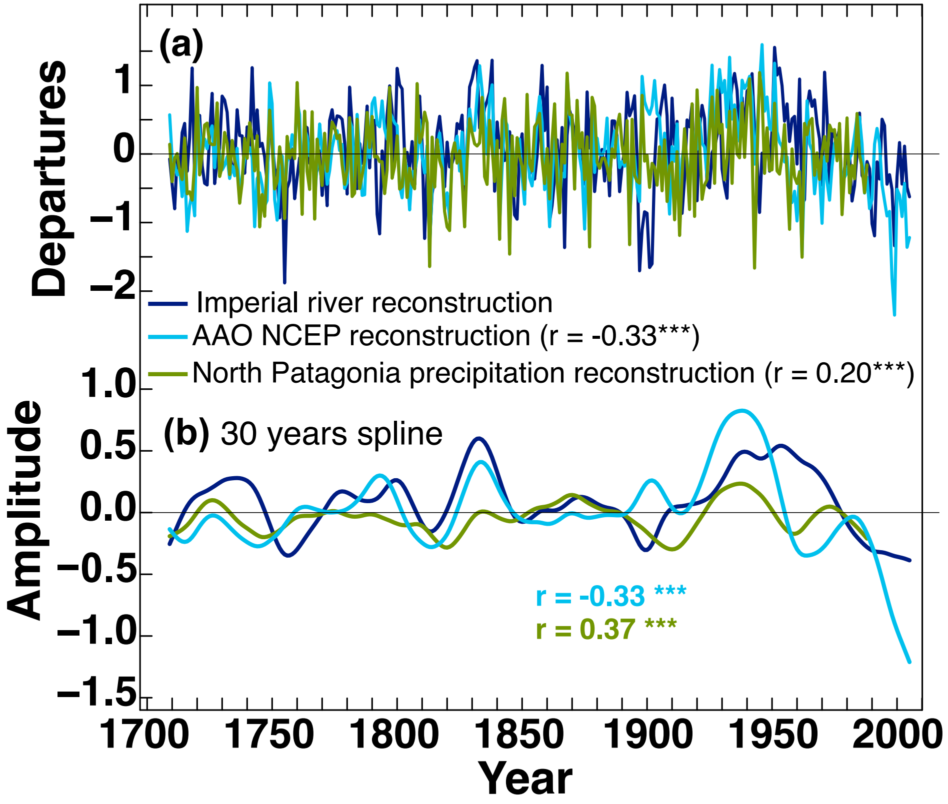

Figure 6. Comparison between the tree-ring reconstruction of Río Imperial streamflow *versus* the tree-ring precipitation reconstruction presented in Villalba et al. (1998) and the AAO tree-ring reconstruction from Villalba et al. (2012) that also utilized an index of SAM based on pressure fields from NCAR-NCEP reanalysis (Thompson and Wallace, 2000). In (a) these time series are displayed at annual resolution while (b) shows the same time series after the application of a 30-year spline filter. In both panels, the AAO index has been inverted to facilitate comparison with respect tree-ring reconstructions. Pearson correlations between the streamflow reconstruction and the other time series are included at the bottom of each panel, with asterisks representing statistically significant correlations at p-value < 0.001.

Table 1. Instrumental streamflow records utilized in this study. These records were retrieved from the Chilean National Water Authority (DGA or Dirección General de Aguas).

Name	**Latitude (S)**	**Longitude (W)**	**Period**	**Altitude (m)**	**Discharge (m^{3}s^{-1}a^{-1})**	**Coefficient of Variation**
Cautín at Rari-Ruca	38°55’	72°00’	1943-2010	425	98.1	16.43
Quepe at Vilcún	38°41’	72°13’	1946-2010	292	33.1	13.57
Muco at puente Muco	38°37’	72°25’	1951-2010	250	26.2	37.88

Table 2. Rank of the five years with highest and lowest discharges as calculated from the composite built from the instrumental record (1947-2010). Departures are expressed as percentages relative to the mean (i.e. $\%=Year_x/\bar{x}$, where $Year_x$ corresponds to the streamflow of any given year and $\bar{x}$ to the mean of the period).

Ranking	**High flow (% of the mean)**	**Low flow (% of the mean)**
1	1956 (209.8)	1999 (43.8)
2	1951 (184.1)	1963 (54.0)
3	1971 (166.8)	2009 (55.4)
4	1965 (159.8)	1997 (57.2)
5	1980 (150.1)	2008 (59.9)

Table 3. Main features of the tree-ring chronologies developed for this study. The Lanín (LAN) and Villarrica (VILL) chronologies correspond to those presented in Mundo et al. (2012) and González et al. (2005), respectively.

Location	**Code**	**Latitude (S)**	**Longitude (W)**	**Period**	**Altitude (m)**	**Source**
Pinalada Redonda	PIN	39°18’	71°17’	1606-2006	1119	Mundo et al. (2012)
Piedra del Águila	PAG	37°50’	73°02’	1239-2009	1300	Muñoz et al. (2014)
Lanín y Villarrica	LYV	39°35’	71°30’	1291-2006	1350	Composite LAN+VILL

Table 4. Statistical description of the tree-ring chronologies developed for this study. The column labelled as “EPS" depicts the year when that statistic began to be larger than 0.85.

Code	**EPS**	**Autocorrelation**	**Average sensitivity**	**VIF**
PIN	1750	0.591	0.230	1.011
PAG	1450	0.490	0.170	1.739
LYV	1525	0.566	0.206	1.724

Table 5. Rank of the five periods showing highest and lowest discharges as calculated from the tree-ring reconstruction. These periods were organized according to windows of five, 10, and 20 years. At the bottom of each period we included the highest/lowest streamflow from the instrumental record. Periods in bold represent coincidence between instrumental and reconstructed streamflow.

Period length (years)	Rank	High flow	Low flow
1	1	1951	1755
	2	1838	1897
	3	1832	1901
	4	1858	1902
	5	1940	1867
	Instrumental record	1956	1999
5	1	1951-1955	1897-1901
	2	1829-1833	1753-1757
	3	1938-1942	1811-1815
	4	1797-1801	~~**1996-2000**~~ 1996-2000
	5	1935-1939	1987-1991
	Instrumental record	1955-1959	~~**1996-2000**~~ 2011-2015
10	1	1829-1838	1896-1905
	2	1933-1942	1751-1760
	3	**1950-1959**	**1990-1999**
	4	1796-1805	1982-1991
	5	1964-1973	1810-1819
	Instrumental record	**1950-1959**	**1990-1999**
20	1	1934-1953	**1986-2005**
	2	1823-1842	1753-1772
	3	**1953-1972**	1883-1902
	4	1728-1744	1803-1865
	5	1785-1804	1843-1865
	Instrumental record	**1953-1972**	**1986-2005**

Table 6. Comparison between streamflow observations and streamflow reconstructed versus ENSO and SAM for the period 1948-2005, where “r" corresponds to the Pearson correlation coefficient

Streamflow record	**Index**	**Months**	**r**
Instrumental	AAO	Oct-Sep	-0.58
Instrumental	SOI	Feb-Mar	0.32
Instrumental	AAO	Sep-Dec	-0.54
Tree-ring	AAO	Sep-Aug	-0.66
Tree-ring	AAO	Dec-Feb	-0.50
Tree-ring	SOI	Mar	0.36
Tree-ring	AAO	Sep-Dec	-0.54