Climate Dynamics

Streamflow variability in the Chilean Temperate-Mediterranean climate transition (35°S-42°S) during the last four hundred years inferred from tree-ring records.

--Manuscript Draft--

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Abstract:

As rainfall in South-Central Chile has decreased in recent decades, local communities and industries have developed an understandable concern about their threatened water supply. Reconstructing streamflows from tree-ring data has been recognized as a useful paleoclimatic tool in providing long-term perspectives on the temporal characteristics of hydroclimate systems. Multi-century long streamflow reconstructions can be compared to relatively short instrumental observations in order to analyze the frequency of low and high water availability through time. In this work, we have developed a Biobío River streamflow reconstruction to explore the long-term hydroclimate variability at the confluence of the Mediterranean-subtropical and the Temperate-humid climate zones, two regions represented by previous reconstructions of the Maule and Puelo Rivers, respectively.

In a suite of analyses, the Biobío River reconstruction proves to be more similar to the Puelo River than the Maule River, despite its closer geographic proximity to the latter. This finding corroborates other studies with instrumental data that identify 37.5°S as a latitudinal confluence of two climate zones. The analyzed rivers are affected by climate forcings on interannual and interdecadal time-scales, Tropical (El Niño Southern Oscillation; ENSO) and Antarctic (Southern Annular Mode; SAM). Longer cycles found, around 80-years, are well correlated only with SAM variation, which explains most of the variance in the Biobío and Puelo rivers. This cycle also has been attributed to orbital forcing by other authors. All three rivers showed an increase in the frequency of extreme high and low flow events in the 20th century. The most extreme dry and wet years in the instrumental record (1943-2000) were not the most extreme of the past 400-years reconstructed for the three rivers (1600-2000), yet both instrumental record years did rank in the five most extreme of the streamflow reconstructions as a whole. These findings suggest a high level of natural variability in the hydro-climatic conditions of the region, where extremes characterized the 20th century. This information is particularly useful when evaluating and improving a wide variety of water management models that apply to water resources that are sensitive to agricultural and hydropower industries.

Reviewer #1

Using a set of tree-ring chronologies, the authors developed a new Biobio River streamflow reconstruction for the period 1500 - 2003. By comparative analysis of this reconstruction and those of the Maule and Puelo Rivers, the authors characterized the patterns of streamflow variability in these three rivers during the past 400 years (1599 - 1999), and examined their relationships with ENSO and AAO. The information obtained from this study is useful for evaluation of current streamflow status in the context of a longer time scale, and for understanding their climatic forcings. The manuscript is well-written. **I recommend acceptance with minor revision**. I only have a few suggestions listed in the comments to authors.

Response: We incorpored all the suggestions in the text and explained in the tables below.

Reviewer #2

General Comments:
The authors reconstructed the Biobio River in south-central Chile creating the longest streamflow reconstruction in the region. Their reconstruction was further compared to two previous reconstructions to assess the nature of climate dynamics in a region that changes from a temperate-humid climate to a Mediterranean-subtropical climate. Further, the reconstruction was analyzed for drought and pluvial events and correlations with oceanic-atmospheric climate drivers.
I considered this to be a valuable analysis but some revisions are required to address three major issues prior to publication:

1) justify the use of the composite flow record or re-do the reconstruction with the gage best correlated to tree growth (further comments below),

2) remove or re-frame the analysis of annual to 3-year drought events because of the moderate explanatory power of the model (further comments below), and

3) include correlation values and levels of significance with climate forcings because they appear to be weak from wording in the discussion (further comments below).

A few odds and ends- The introduction could be shortened. While the detail is appreciated, some of it is unnecessary for the reader to understand the importance of the paper. The figures are well done overall. Small language issues but otherwise well-written

Response: We incorpored all the suggestions in the text and explained in the tables below.

P2L35- have not has	Changed
P2L45- found not founded	Changed
P2L44- acronyms not defined before use	incorporated
P4L151- Structure of questions is odd. Write in sentence form and number?	Reworked as sentence

P5L165- This sentence is unnecessary- "Figure 1 shows the three watersheds, the streamflow stations, and the location of the tree-ring collection sites used in the reconstructions." It's more of a figure caption. Incorporate in paragraph better.	Sentence deleted
P5L177- end of autumn?	Incorporated
P5L195- so the reconstructions used a composites of flow gages in each basin? This should be justified. Did the previous studies use the composite. If so, why? I'm wondering how this will affect detection of drought and pluvial because App 3 show reduced variability in the composite series. The use of the composite might also cause a reduction in the variance explained in the reconstruction model. I would pick a gage that has the strongest relationship with tree growth, suggesting that the same inputs (precipitation) and outputs (runoff) are affecting both in a similar way. Mixing the rain and snow dominated gages probably muddles this relationship. Or reconstruct each gage separately. Also, how were station data filled?	We incorporate the explanation of type of instrumental record used in the three reconstructions. Also, we explain how the stations data were filled.
P6L236- "applied utilized"? Pick one.	changed
P6L243- you already told us about the chronology composed of other sites. Cut this phrase.	Phrase changed
P7L259- what is the verification period? Is it the same as the calibration period? What was the RE calculated on?	Changed by calibration. We include a paragraph explaining the importance of the RE to assess the predictive capacity of the model.
P7L264- you already told us about the VIF above.	Changed. Deleted from here and moved to the chronologies description
P7L284- delete "of".	deleted
P8L301- delete "and the reconstructions"	Deleted
P9L334- I would recommend a figure in the actual flow units in the manuscript or appendix	We do not consider this information relevant considering that the Biobio river has a big current flow, because both Maule and Biobio reconstructions were made using small streams in these basins, given the large parts of these basins are very intervened by restitutions and deviations of the streams. Also, the goal of this research is to compare the variability and not the quantities.

P9L337- This section on statistics does not present anything but the adj r2 value. Please add the values for the other tests or put in a table.	We added the statistics of the Biobio reconstruction in the caption of the Figure 2.
P9L343- combine this sentence with the next paragraph.	We put both paragraphs together.
P9L358- I would caution against using single-year or even 3-year event analysis in a reconstruction that explains 45% of the instrumental record. In instances of moderate explained variance, the strength of the reconstruction is more in the low-frequency trends than individual years. This is especially the case with the use of a composite flow record that reduced the instrumental variability. I would consider removing this analysis and focusing on low-frequency (decadal or longer). You might be able to keep the discussion about frequency of annual to 3-year drought but cut the discussion of specific years.	We are agree with these and we will incorporate this comment into the discussion section, but we think it is very important to keep this sentence about the single years given the coincidence of the dry years in two of the three rivers reconstructed. In addition, these years have been found in articles in preparation about the fire regime and would be reported here in order to support the dry condition in the region showed by others approximations. We also included a new figure in the appendices to describe longer coincidences in the three reconstructions.
P10L396- use SAM or AAO consistently throughout manuscript.	We changed this throughout the manuscript
P10L403- an 83-year (also on L410).	changed
P10L404- how significant? P-value? I do see some r values in figure 5. In this paragraph or anywhere in the Results section, you must include statistics for any correlation, relationship, or suggestion of significance. Check this thoroughly. I suspect that many of the relationships are moderate at best. While there may be a relationship, I'm guessing that the explanatory power of the climatic forcings is weak. If so, what does this say about your model and the interpretation of paleoclimate dynamics.	The 83-year cycle was identified in the Multi-taper Method spectral analysis (Apendix 6). The sentence was changed also. All the correlations in the complete text were included with the significance levels (p values).
P10L408- similarities?	changed
P11L450- slightly doesn't mean much. Was it significant?	We included the values of the correlations and its significance level in all the sections of the text
P12L460- corroborant? Word choice.	changed

P12L461- in the hydroclimate of the SPD?	We changed this throughout the manuscript. Southern Pacific Domain SPD
P11L473- new paragraph needed. Also, awkward transition.	changed
P12L462- 5% explained variance by SAM suggests that it is not a dominant driver of streamflow. Same goes for the low explained variance for the other cycles. So what is the dominant driver? Perhaps the low variance explained in the reconstruction is causing. I'm not convinced that ENSO and AAO relationships are fully flushed out. Visually, I can see the relationship but not statistically.	We re-focused the sentence, including a less categorical description of the influence of each forcing (ENSO, SAM). Also we added new information about the explanation of the long-term cycles associated to orbital forcings.
P13L516- don't use roman numerals, please.	Was changed throughout the manuscript

Figures

Fig. 1- Nice figure.	Thanks
Fig. 5- I'm not sure how useful this figure is because the overlay of multiple time series in A, B, and C makes it difficult to read. The correlation values are useful though.	We changed this figure in order to not overlap multiple series, and are leaving only the best correlations between rivers and forcings.

Appendix

App 3- What are the r values in panel A? Are these correlations with the composite? Also, shown not shows.	We include the explanation in the panel A. about the correlation main. Changed
App 4- Do you really need to show information about chronologies used at other sites? These should have been published with the previous papers.	This is necessary because the reader can compare the sites of each reconstruction and identify the statistics for a better understanding of the independence of the predictors and the quality of the tree-ring records. Also, in the previous revision there was a suggestion by one of the reviewers about this.
App 7- could be cut because it is not discussed much.	We kept this in the appendix because it helps to support the discussion with respect to the change in the 20th century.

Reviewer #3

I repeat my earlier comment that this is an interesting paper that provides a new long streamflow reconstruction at an important climate transition zone in Chile and compares the results with 400 year-long tree-ring based reconstructions from two adjacent river systems. This is important science that needs to be published and the results have significant implications for regional hydrologic and climatological studies.

The paper has significantly changed from the earlier version with new material on the relationship between the streamflow reconstructions and long proxy reconstructions of climate forcing functions, supplementing the discussion based on the instrumental records. Material has also been added on the changing recurrence intervals of extreme events. However, the calculation of recurrence intervals needs to be clearer in order to evaluate Figure 3. In my view there needs to be more detailed discussion and analysis of the new reconstruction itself with Appendix 5A and 5C included in the main text.

R: We Added the reconstruction to the main text, improved the discussion and the analyses. We explained in detail every change made to the tables.

Also the comparative analysis of the three reconstructions could be more focused. What specifically is the contribution of each of many comparative analyses in this paper, e.g. figs 3, 5 and appendices 7 and 8? The results in these figures and their significance need to be explored in more depth.

The authors have addressed the question of the independence of the tree-ring based reconstructions of streamflow. However, as both the ENSO and AAAO reconstructions are tree-ring based, this should also be considered.

R: We used ENSO and AAO reconstructions from tree-rings from the northern and southern hemisphere, and also provided instrumental data corroboring the relationships.

The paper also lacks a formal conclusion. Perhaps the present discussion section could be labelled discussion and conclusions with the subheadings specifically addressing the questions raised in lines ca 151-155.

R: We added a main conclusion incorporing the goals of the study.

As previously there are many minor errors in English and places where the text needs some clarification. Many of these are listed in the detailed comments below.

I think the paper is improved but still needs some additional material. **I would suggest it needs minor revision** and correction of many of the minor points listed below

Response: We incorpored all the suggestions in the text and explained in the tables below.

33 rephrase as rainfall… has decreased, local communities….	incorporated
35 have not has	Changed
36 useful tools	incorporated
37 new is redundant	changed
45 found	incorporated
45 what about e.g. PDO or equivalent, you would not expect long-term cycles to correlate with ENSO	We didn't find long cycles (80-year) in the reconstructions of ENSO and PDO. We only found this 80-year cycle in the SAM reconstruction. Also, we incorporated other potential explanation
49 common between what	changed
50 the most extreme wet years in the instrumental records for Maule and Puelo do not rank in the top 5 of the reconstructions nor do most of the 10 year mean extremes. This section needs reworking.	Section re-worked
69 why delicate? The balance between … demand for… creates?	changed
76 70% of hydroelectric or 70% of the power?	Hydroelectric power
81 is recognized?	changed
85-6 rephrase? Reduced water availability has resulted in ……..	Re-worked
89 indicates… over this region	incorporated
92 it = what? Rephrase. If these trends continue the stresses on water supply will be further exacerbated by ….	Re-worked
93-4 Rephrase- Water deficits for dams and hydroelectric plants in the last few years have resulted in ….produced	Re-worked
96 Rephrase- In some cases hydroelectric………	Re-worked
100 There is a water … in S-C Chile that is ….	Re-worked
108 the PDO type fluctuations may also be significant see Masiokas et al J.Hydromet. 11, 2010 fig 4	Incorporated in the paragraph
109 ENSO is considered…..	Changed
115 delete the before climatic	deleted
117 how do the climate zones define the watershed? Rephrase.	Re-worked

121-2 there is a single precipitation regime but two components of the hydrologic regime because the upper catchment is dominated by snowmelt from the high Andes whereas the lower elevations receive rainfall inputs directly.	Re-worked
127 … because streamflow records are relatively short (less than 60…)	incorporated
129-33 Simplify. Available instrumental records may be too short to predict…. accurately	Incorporated
134 tree rings or tree-ring reconstructions	incorporated
136 Such studies provide important ……	Changed
141-6 is all this information on the Maule relevant here?	We shortened the sentence, gave less details about the number of hydroelectric plants in the Maule River watershed but provided the information because this basin is very important in Chile.
146 et seq. revise. The Biobio situated at the …… and between the Maule and Puelo watersheds allows…..	Re-worked
153 lowest flows rather than driest	changed
154 relationships exist?	Changed
161 Watersheds	Changed
162 larger not the bigger	Changed
165-6 delete sentence	Deleted
177 end of	incorporated
177 first pulse of what ?	changed
178 …and during austral…	Incorporated
180-1 not clear. The comments relate to the position of the stream gauges with respect to the local precipitation regime but surely there is a snowmelt contribution to streamflow even at these downstream sites. These comments seem to imply there is no snowmelt component to the Biobio flows.	Section re-worked
185-6 are the Biobio gauges natural or regulated flows?	Section re-worked
190-1 See previous comment - is there any indication of the proportion of the Biobio flow is snowmelt derived	Section re-worked
195 station records	Changed
216 new paragraph?	changed
219 delete non-destructively	Deleted
232 between chronologies or between series within a chronology? This sentence is redundant anyway- delete.	deleted

236 delete applied	deleted
242-4 not clear- different measures (monthly seasonal, annual) of streamflow of the Biobio were correlated with all the predictor chronologies?	Section re-worked
246 common period of what records?	Response incorporated into the paragraph
250 And the actual relationship? perhaps the equation should be inserted here ?	We did not understand which actual relationship. We do not consider the equation necessary here
256 observed record?	Changed
260 estimated value?	Changed
267 there is no evaluation of the quality of the reconstruction or discussion of, for example the figure in Appendix 3A. In particular this shows that the extreme high and low flows are underestimated. Although this is not unusual it is worthy of comment as evaluation of high and low flows over the entire record is carried out later in the paper.	We included the figure in the paper (Fig. 2) and discussed the extreme flows underestimated in the Biobio reconstruction in the results section
273 i.e. the Puelo reconstruction is only for the summer, snowmelt, period which, surprisingly is less than half the annual flow volume. How significant is this when comparing the reconstructed flow patterns?	We incorporated a paragraph to clarify this topic in the methods section.
276 is there any documentation of this difference? what is the snowmelt contribution to the Biobio?	We added documentation about this difference. There is not information about the contribution of the Biobío River published. Some modelling studies in a small sub-basin of the Biobío have shown that snowmelt dynamics are relevant in the cycle, but the authors do not estimate the contribution of the snowmelt (Sther et al. 2009)
276 tree series?	changed
277 used in both reconstructions	Changed
277 more detail perhaps. The two composite chronologies share different combinations of tree series- what proportion (number) of trees are found in the two composite chronologies?	We added the number of trees shared by the two reconstructions.
284 delete of … analyzed over a common…	Changed

285 using data expressed as consecutive one, two or three year periods for the entire record. These values were converted to percentiles of the flow duration curve and the 20th and 10th percentiles used to identify severe and extreme drought events.	incorporated
Question was the same flow duration curve used for each or were different flow duration curves defined for each parameter? - clearly the 10th percentile of the annual flows would differ from the 10th percentile of three-year mean flows.	The 10th percentile is the same for one or three-year mean flows, but there is a different number of events in both cases. That is why the curves are very different for one and three consecutive years.
288 estimates of what? Recurrence intervals?	We included a better explanation of this in the text.
288-93 needs better explanation and justification.	We incorporated a better explanation and justification in the method section.
307 how independent is the ENSO reconstruction from the hydrological reconstructions?	The ENSO reconstruction is completely independent. There are not trees shared by the streamflow reconstructions and the ENSO reconstruction.
308 first mention of the PDO? Justification for this reconstruction?	We have included the importance of PDO in the Introduction, especially related with its influence over the Mediterranean climate documented by Masiokas et al 2010.
330-1 redundant? Begin para with…. The Biobio reconstruction……	Changed
332 calibration rather than common? Why is this figure not in the paper?	Changed. Now the figure is in the paper as Fig. 2.
329-42 This section reports the testing of the quality of the Biobio reconstruction but never actually discusses or describes the reconstruction itself.	The purpose of this article is to use this reconstruction to compare its hidrocliamtic varibility with other two reconstructions located to the north and south of the Biobio River reconstruction. In the last review of this article, the reviewers have indicated to us that we had to decide if the paper must be focused on the

	Biobio reconstruction or in the comparison of the three rivers in the long-term perspective. We have re-written the article taking the second option, that is why we focused on the comparison of the streamflow variability of the three reconstructions using the Biobio river as the middle point of the latitudinal gradient and located in the temperate-mediterranean climate transition. The majority of the results have been focused from the Biobio perspective with respect to the other two rivers.
346-7 is this the only comment on figs 2A and B?	We included a new paragraph to explain more details about this figure.
350 to the greater relative importance	changed
352 the hydrograph clearly shows a snowmelt peak which is radically different than the rainfall regime. The correlations for the lowest site are fairly restricted. Perhaps an additional comment here?	We think the explanation is clear in the text, and pretty similar to the reviewer comment.
354 delete the before time	changed
358 delete against	deleted
360 reconstructed not recorded?	changed
361 But where does 1940 rank in the instrumental record? The wettest instrumental year does not rank in the top 5 for 2 of the reconstructions- no comment on this?	We included these coments
362-3 where are these data?	The data is in the Table 2.
366-7 1944-53 is only ranked in the top 5 in the Puelo where it is 5th however 1936-1945 and 1946-55 rank 1 and 2 in the Biobio but only 1935-44 is found in the Maule. The text here rather glosses over these differences and it is a quite superficial analysis	We incorporated the comments and a new detailed paragraph describing these topics in the article--increasing the explanation of the wettest five-years and the decadal periods in results section.
369-70 invert the sentence, instrumental first and then reconstructions.	changed
371 the Puelo has 4!	changed

385 drought events	changed
383 how do you reconstruct a moving drought recurrence interval?	This method has been well explained in the methods section and also the method is mentioned in the captions of the Figure 4.
383-90 again I find this rather superficial	We added a new paragraph to best explain this section.
395 You use the Niño3.4 data as a measure of ENSO variability. This does not mean that ENSO is only temperatures as your text suggests.	We have changed the sentence including the atmospheric change asociated to the sea temperature changes in the tropical Pacific.
397-400 although correct, these statements are very superficial. For example what is the best correlation for the Puelo and Biobio with ENSO? The results for AAO largely reflect the common trend (see Villalba et al 2012) but relationship with ENSO is not reported here, and, though not as great as the AAO could be quite important.	Section re-worked. The correlations between El Niño 3.4 variability in the same months, and the Maule, Biobío and Puelo reconstructions in the instrumental period, were $r = 0.44$, $r = 0.10$ and $r = 0.06$ ($p < 0.1$), respectively. The best relationships in the three reconstructions for the instrumental period are showed in the Figure 5.
407 found also 409,410	changed
410 found in this analysis or also found in the previously published accounts of these reconstructions?	found in the previously published accounts of these reconstructions
413 cryptic comment in brackets. Why not begin para with Wavelet analyses (Appendix 7) show that…….	incorporated
421 in Chile?	Changed
423 delete existing	Deleted
426 that have proved	changed
429 hydrometric records where?	We included the complete information about the period and the place where the study took place.
433 what specifically do they suggest? Did they actually say anything about Biobio? Delete phrase before Lara- replace with Lara et al (2008) also note a…..	incorporated
435 are consistent with? = has similar	changed
438 replace with ….There is a strong relationship between…..	incorporated

439 these forcings result in P and T anomalies that vary geographically across Chile	Incorporated
440 SAM is considered to be ….	Changed
443 are common	Changed
444 what does increased in frequency mean here?	We clarified the text about the increase in the short-term cycles between 2-6 years.
445 what did Fowler et al describe- an increase in frequency of ENSO or the Maule reconstruction?	We clarified this in the text. Fowler is referring to an increase in the variability of the ENSO and the cycles in the 2-6 years band.
446 especially	changed
449 which part of Fig 5?	Fig.5A
451 a correlation here perhaps?	We included the correlations and the significance levels.
459 found	Changed
460 corroborating	Changed
461 what is hydroclimatic SPD?	We defined this before, but we added the complete sentence in all the cases where it was mentioned.
461-4 rephrase	We changed this paragraph, incorporating more details and explanaition about the cycles.
465 reorder Toggweiler (2009) has described……	reordered
470 which study? Our?	Changed
472 influence on… the temperate	Incorporated
473 rephrase. The reconstructions of …. show ….	Changed
477 also showed by Lara et al 2008	incorporated
477 identified in the SAM…	changed
483 Reconstructions	Changed
484 testing or modelling?	Changed
486 delete through.	deleted
489 one and two-year droughts?	changed
491 rephrase…. and a similar increase was seen in	incorporated
493-4 reorder…. flows in the three was ca 5 years at the end….. century but was variable throughout the record with return intervals of greater than 10 years in places (ref to Figure?)	Changed and completed with new information. Figure 4.
495 seen not showed.	Changed

497 reorder.. The most intense…in 1681 in the Biobio….., whereas 1998	Changed
500 events	incorporated
501 where is the evidence for this? You only discuss ENSO with respect to the Maule?	We added a paragraph in the results section related with the Table 2 and the ENSO extreme events and its coincidences with the three streamflow records.
502 were these also El Niño years?	These years were La Niña years. The information was added to the text.
497-507 perhaps needs to discuss ENSO effects in more detail	We have incorporated more details about the specific years of EL Niño and La Niña and the effects of the ENSO activity in the latitudinal gradient in the region.
508 are we talking decades here or ten year periods?	Ten-years period. It was corrected in the text.
508-13 This needs to be rewritten. The first sentence is incorrect (see table 2 Biobio pluvial and Puelo droughts) and the remaining points could be made more clearly.	We added the instrumental period for each reconstruction in order to clarify that the most extreme 10-years period occurred out of the hydro-measurement knowing about these rivers. Also, we improved the complete sentence.
513 rephrase- The relative wetness of the earlier 320th century is also shown……	Changed
514 why is Neuquen not mentioned earlier?	The Neuquen River was not mentioned earlier because this study is restricted to the comparison of the three reconstructions in a latitudinal gradient of Chile, and the Neuquen River is in a different climate and shares some chronologies with the Biobío reconstruction. Here it is mentioned only to support the fact that the 20th century was wet in the fort half on a regional scale.
517 increasing low is awkward= progressively lower?	changed

518 see also Villalba et al 2012	We added this study and improved the sentence with other studies about the same topic.
519 et seq. Why is this analysis not sooner?	We moved this analysis from the discussion to the last part of the results.
521 1994-2003 reconstructed or measured? Clarify. Why not compare reconstructed vs reconstructed? I don't see the point of these diagrams. Surely they simply indicate that earlier droughts were stronger than those experienced during the instrumental record?	We clarify this in the text (using only reconstructed data). We changed the before analyses and now we use only reconstructed data. We removed the diagrams.
526-9 This is a very weak conclusion given the extensive earlier justification for the study	We improved the conclusion
533 Support was provided by; the Inter-……..	Incorporated
571-4 delete. Duplicate	Deleted
585 ER not ED	changed
599 complete authorship?	Completed
621 TT not T.T	Changed
646 complete authorship?	Completed
663-4 MK TW and HF	Changed
691 200 or 2000?	200 is correct
702 WH, VT, delete &	Deleted
735 Jouzel	changed

Figures

Figure 1 Precipitation records are not identified on Fig 1 and there are some discrepancies. The Biobio precipitation on Fig 1 is from Temuco but Los Angeles is used in Appendix 3a. The precipitation for the Puelo basin is listed as Puerto Montt but all three stations in the diagram are too far to the east to be Puerto Montt	Precipitation records are included in Fig. 1. The Biobio precipitation record is from Los Angeles, Temuco was wrong. The Puerto Montt precipitation station was added to the Fig. 1
F 3 watersheds in south- central Chile (delete intervening text)	Deleted
F 5 move bracket to end of sentence.	Changed
Figure 2 are the filtered plots in Fig 2a and B identical?	The splines 2A and 2B are the same. The smoothing spline on the Fig. 2A and 2B are the same. Fig. 2B is just the spline of 25 yrs from the reconstructions.
Is the scale of the Biobio reconstruction different?	Only the Maule scale is different
The caption should indicate the base period for departures - is it the reconstructed mean or the instrumental mean?	The period used for transforming value reconstructions Z (Departures) is 1599 to 1999.
F 20 delete of years, shown not showed. (twice)	Changed
F21 spline	Changed
F21 filter is fitted to each	Changed
F22 what parameters are plotted here? Annual precipitation vs the annual discharge?	We changed the sentence for a better understanding of which parameters correlate.
Figure 3 over what intervals are these recurrence rates calculated. Is it a running interval or e.g. discrete 25 or 50 year blocks? How are these graphs interpreted?	This is well explained in the method section. They are interpreted as the temporal changes in the recurrence of extreme events along the reconstructions. The extreme events are defined by the years where the flows are lower than the percentile 10th and 20th.

F36 Individual years above the 20th percentile are shown at the base of Figs A, D and G.	We included this suggestion.
F45-6 The best fit seasonal data for each reconstruction are shown	Incorpored
F62 the AAO reconstructions have been inverted (i.e. for both not just Villalba?)	For both. Changed
Tables	
T1 1 basins not basin	Changed
T1 2 coastal precipitations stations are Nirvilo (Maule)…etc	Changed
T1-3 the Andean stations were… respectively and Puelo Lake in Argentina is represents conditions east of the Andes	Changed
T2-1 decadal = 10 contiguous years	Changed
Appendices	
A3 1 used to develop the	
A3 3 shown not shows, panels not panel	changed
A4 2 location of chronology sites are shown….. however, the chronology sites are not specifically identified by code on Fig 1	We added this information in the figure 1
Notes	
A4 2 move RHP to the next line and delete were	Changed
A4 3 composite chronology from three sites	Changed
A4-6 tree-ring	Changed
A5-2 between which series?	Between observed and reconstructed series
A5-5 smoothing spline?	Smoothing spline
A7 2 what is the 95%?	95% of significance. It was
A 8 2 long term instrumental or reconstructed average? Are these annual data if so should be bar graphs not a continuous curve.	We deleted this Appendix and incorpored the information in the text.

Valparaiso, Jan 014 2015.

Dr. Jean-Claude Duplessy
Executive Editor - Climate Dynamics Journal

Dear Editor,

Please find enclosed our manuscript entitled, “Streamflow variability in the Chilean Temperate-Mediterranean climate transition (35°S-42°S) during the last four hundred years inferred from tree-rings records,” authored by Ariel A. Muñoz, Alvaro González-Reyes, Antonio Lara, David Sauchyn, Duncan Christie, Paulina Puchi, Ricardo Villalba, Isadora Toledo, Isabella Aguilera-Betti, Rocío Urrutia, Ignacio Mundo, Paul R Sheppard, Daniel Stahle, Paul Szejner, Carlos LeQuesne and Jessica Vanstone.

We incorporated the majority of the reviewers' suggestions and comments. All of the corrections can be found detailed in the attached document. These incorporated corrections have improved the manuscript substantially.

We consider this article to be an original contribution of international interest for your journal. Here we describe the streamflow variability in South-Central Chile (35°S - 42°S) through a precipitation gradient in a long-term context comparing three streamflow reconstructions from tree-rings records. We are re-submitting this article after incorporating the observations from the last revision of the Climate Dynamics reviewers.

Considering the IPCC calculations, the south-central Chile is one of the most dynamic places in terms of precipitation variability. This area has been defined as a transition zone between the Mediterranean zone to the north and the wet temperate zone to the south. This geographic area has a second highest population in Chile, after the capital Santiago, and additionally is responsible for 54% of the nation’s agricultural production and 58% of forestry. This zone is also crucial to the generation of electricity for the “Sistema Interconectado Central” Chilean electric grid system, which supplies 92% of the Chilean population with energy.

During recent decades (1980-2010), multiple droughts have affected south-central Chile. Their consequences have been expressed especially in a reduction of water availability for economic activities and human consumption. The climate variability in the south-central Chile has become an important research focus in the last two decades, because the shortness of the hydroclimatic register makes it difficult to assess current water variability in the long-term perspective. In this context, we believe that the hydroclimatic reconstructions discussed in this study, developed using tree rings from the temperate-Mediterranean transition, allow the identification of regional patterns that affect the Maule, Biobio, and Puelo rivers as well as differential patterns that affect only some of these rivers. According to these reconstructions, the 20th century contained important annual and multi-annual anomalies for all three rivers. However, the trend of reduced flows during the 20th century was only seen in rivers south of 37.5°S, representing part of a multi-decadal cycle shared by the rivers south of this parallel. High latitude forcings (AAO) appear to explain this variation better than tropical-latitude forcings such as ENSO.

For these reasons, we think this study can improve the understanding of climate variability in one of the most important areas in Chile, serving as a basis for future research on climate change adaptation.

Sincerely,

Dr. Ariel A. Muñoz

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Streamflow variability in the Chilean Temperate-Mediterranean climate transition (35°S-42°S) during the last four hundred years inferred from tree-ring records.

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Abstract

As rainfall in South-Central Chile has decreased in recent decades, local communities and industries have developed an understandable concern about their threatened water supply. Reconstructing streamflows from tree-ring data has been recognized as a useful paleoclimatic tool in providing long-term perspectives on the temporal characteristics of hydroclimate systems. Multi-century long streamflow reconstructions can be compared to relatively short instrumental observations in order to analyze the frequency of low and high water availability through time. In this work, we have developed a Biobío River streamflow reconstruction to explore the long-term hydroclimate variability at the confluence of the Mediterranean-subtropical and the Temperate-humid climate zones, two regions represented by previous reconstructions of the Maule and Puelo Rivers, respectively.

In a suite of analyses, the Biobío River reconstruction proves to be more similar to the Puelo River than the Maule River, despite its closer geographic proximity to the latter. This finding corroborates other studies with instrumental data that identify 37.5°S as a latitudinal confluence of two climate zones. The analyzed rivers are affected by climate forcings on interannual and interdecadal time-scales, Tropical (El Niño Southern Oscillation; ENSO) and Antarctic (Southern Annular Mode; SAM). Longer cycles found, around 80-years, are well correlated only with SAM variation, which explains most of the variance in the Biobío and Puelo rivers. This cycle also has been attributed to orbital forcing by other authors. All three rivers showed an increase in the frequency of extreme high and low flow events in the 20th century. The most extreme dry and wet years in the instrumental record (1943-2000) were not the most extreme of the past 400-years reconstructed for the three rivers (1600-2000), yet both instrumental record years did rank in the five most extreme of the streamflow reconstructions as a whole. These findings suggest a high level of natural variability in the hydro-climatic conditions of the region, where extremes characterized the 20th century. This information is particularly useful when evaluating and improving a wide variety of water management models that apply to water resources that are sensitive to agricultural and hydropower industries.

Keywords: Biobío River, streamflow reconstructions, Southern Annular Mode, hydroclimate variability.

Introduction

The balance between the supply and demand for water in the world's important river basins creates an increased interest in the vulnerability of water supplies used in agriculture, industry, hydroelectricity, domestic use and urban growth (Meko & Woodhouse 2011). Water availability has been recognized as one of the primary limits to future economic growth in many regions of the world (Arnell et al. 2001; Viviroli et al. 2003), including the mining and the agriculture industries in Chile. In South-Central Chile (35°S to 42°S: Fig. 1) water availability is vitally important for agricultural, forestry, hydroelectricity and domestic consumption (Lara et al. 2003; Rubio-Álvarez & McPhee 2010). Over 50 hydroelectric complexes in this region supply more than 70% of the hydroelectric power to the Chilean electric grid ("Sistema Interconectado Central", SIC). Although over 60% of Chileans live in this geographic region, the SIC supplies energy to 92% of the country's population (CDEC-SIC 2011). Additionally, South-Central Chile is responsible for more than 55% of the nation's agriculture and forestry production (INE 2009; CDEC-SIC 2011). This region constitutes the northern portion of the Valdivian Ecoregion of the northern Patagonian Andes (35°S - 48°S), which is the primary area of temperate forest in South America and is recognized as one of the Earth's most threatened ecosystems by the Global 200 Initiative (Olson & Dinerstein 2002), due to the high endemism in the region and the intensity of anthropogenic threats and climate change (Villagrán & Hinojosa 1997; Myers et al. 2000; Echeverría et al. 2006).

A series of drought episodes over the last few decades has affected South-Central Chile. Reduced water availability has resulted in land-use changes, economic activities and stresses on human consumption of water (Lara et al. 2003), which has led the Chilean government to invest millions of dollars in mitigation measures (MINAGRI 2011). Instrumental climatic information indicates a marked decrease in precipitation over this region and a temperature increase in the higher elevations of the Andes (CONAMA 2006; Garreaud et al. 2009; Falvey & Garreaud 2009). Furthermore, changes in the elevation of the 0ºC isotherm and glacial recession in the region are related to the temperature changes (Carrasco et al. 2005; Masiokas et al. 2008). If these trends continue, the stresses on water supply will be further exacerbated by the increase in demand (Lara et al. 2003). Given these climate trends, water deficits for dams and hydroelectric plants in the last few years produced electrical rationing, changes in daylight savings time schedules and cost increases for residents and industry. In some cases hydroelectric companies have reduced stream discharges in order to maintain dam functions, depriving downstream users of water rights, generating conflicts between these two interests (Donoso & Cancino 2010). In Chile, unlike most countries, water rights are privately owned, generating a supply and demand market that will likely be stressed in the future if water availability continues to decrease (Bauer 1995; Donoso & Cancino 2010). This is a water availability issue in South-Central Chile that is likely to become even more complex as the water resources demand intensifies, generating a high level of uncertainty in the future (Lara et al. 2003).

In South-Central Chile there is a climatic zone transition between a Mediterranean climate-type in the north (35°S - 38°S), with 3-4 dry months, and a wet-temperate climate south of 40°S without distinctly defined dry months (Miller 1976; Pezoa 2003). This climatic transition results from the latitudinal gradient, the seasonal position of the Southern Pacific Anticyclone and the synoptic climatology of the westerlies, which on a global scale are affected by the El Niño Southern Oscillation (ENSO) and the Southern Annular Mode (SAM) also known as the Antarctic Oscillation (AAO; Garreaud et al. 2009; Villalba et al. 2012). ENSO is considered the principal influence on interannual precipitation variability in the northern latitudes of the transition (35°S - 40°S; Rutllant & Fuenzalida 1991), while the climatic effect of the SAM increases southward to 40°S (Garreaud et al. 2009; Aravena & Luckman 2009). The effect of the Pacific Decadal Oscillation (PDO) has been also documented in the hydro-climate of the region, especially in snowpack and streamflow records in the 30°S - 37°S latitudinal range (Masiokas et al. 2010). Even though the effects of ENSO and SAM are better reflected in the climate of mid and high latitudes respectively, their influence affects extensive regions of Chile (Vuille & Milana 2007). The limits of the climatic influence of these large-scale climate anomalies in the South American Southern Pacific domain is an important subject of study in the region, especially with respect to the extreme events, water availability and wildfire activity (Lara et al. 2008; Holz et al. 2012; Holz & Veblen 2012).

The Biobío watershed (~ 37°S - 38°S) has been described as the place where the confluence of the Mediterranean and temperate climate occurs (Kottek et al. 2006). This large watershed provides important habitat for many plant and animal species. As a result of the last glaciation of the Southern Andes, this small geographic range hosts the highest diversity of temperate tree species found in South America (Villagrán & Hinojosa 1997). The Biobío River is characterized by two components of the hydrological regime. The upper catchment is dominated by snowmelt from the high Andes, while the lower elevations, as the Central Valley and the Coast Range, receive rainfall inputs directly. The watershed contains important water bodies (i.e.: Laja Lake) and ten hydroelectric plants that together supply 46% of the hydropower energy generated by the SIC, making this watershed the most important in the country in terms of hydro energy production (CDEC-SIC 2011).

Incorporating long-term information about streamflow variability in decision making processes is crucial, because streamflow records in South-Central Chile are relatively short (less than 60 years on average) (Rubio-Álvarez & McPhee 2010), as well as and the high level of uncertainty in future water availability (CONAMA 2006). Also, the projections of water use in irrigation, hydroelectricity and domestic consumption are a primary concern (Lara et al. 2008; Urrutia et al. 2011). Available instrumental records may be too short to predict the streamflow variability with accuracy (Woodhouse & Lukas 2006; Mundo et al. 2012), which is very important in hydrological forecasts, hydraulic infrastructure design and water use planning. Tree-ring reconstructions provide a lengthy proxy for the natural variability in precipitation and streamflow (Woodhouse et al. 2006; Lara et al. 2008; Meko & Woodhouse 2011; Sauchyn et al. 2011). Such studies provide important information for water management identifying flow regimes and changes in the water availability in rivers like the Colorado River in the United States and the South Saskatchewan River in Canada (Woodhouse & Lukas 2006, Axelson et al. 2009). In Chile, streamflow reconstructions have been developed for the Maule (36°S), the Puelo (42°S) and the Baker (47°S) rivers in Chilean Southern Pacific. The Maule River watershed is the second most important in terms of hydropower production (28%: CDEC-SIC, 2011) and hosts an important zone of domestic and export agriculture in Chile (INE 2009). The Puelo River is part of a bi-national watershed between Chile and Argentina. A valuable aquaculture industry constitutes the third largest industrial export of Chile. In order to better understand the variability of water resources over long periods of time we developed an annual (hydrological year: April - March) streamflow reconstruction for the Biobío River situated at the confluence of the Temperate and Mediterranean climate regions of Chile and between the Maule and Puelo watersheds, allowing a spatio-temporal comparison of streamflow in three important watersheds along a gradient between 35°S and 42°S (Fig. 1). Patterns of variability in the three reconstructions shared over a period of 400 years and enabled us to address the following objectives:

1) Determine the changes in the recurrence of annual and multiannual lowest flows (intense drought) during the last four centuries in these rivers.

2) Assess if the driest period during the recent decades is part of the natural climate variability during the last centuries.

3) Assess the relationships between the reconstructions and large-scale climate forcings and how they vary along the latitudinal gradient (35°S - 42°S).

Methods

Study Area

The study area (Fig. 1) covers the region between 35°S - 42°S along the western slope of the Andes. The three watersheds analyzed are located within this range: the Maule, Biobío and Puelo River Watersheds. The Maule watershed is the second largest in the Mediterranean climate zone (Fig. 1, Table 1). The Biobío watershed is the larger basin and the third largest watershed in Chile, lying in the Mediterranean-Temperate transition. This climatic zone has been described as Temperate with a Mediterranean influence. The Puelo watershed has the smallest area, is located in Chile and Argentina and lies in a wet temperate oceanic climate zone. The main land uses in the three watersheds are included in Appendix 1. The Maule River watershed has the highest percentage of land dedicated to agriculture, in contrast to the Puelo River watershed, which is mainly covered by native forests, snowfields and glaciers. The Biobío watershed contains an intermediate level of native forests, agriculture lands and glaciers when compared to the other two watersheds. However this watershed has a larger area dedicated to fast-growing exotic tree species plantations, which is an intensively water-demanding type of land use (Little et al. 2009).

Instrumental streamflow data

The three watersheds have mixed flow regimes with inputs from melting snow/ice melting and rainfall. High precipitation at the end of autumn and through most of winter (May-July) forces the first pulse of water. Snow and ice melting in the Andes at the end of spring and during austral summer (November-January) provides a second pulse in flow. Summer precipitation is low and sporadic. The three reconstructions (Maule, Biobío and Puelo Rivers) were developed using data from flow stations registering both snowmelt and precipitation (Fig. 1). More source precipitation to the Puelo River falls as snow than the other rivers, principally due to the low elevation of 0ºC isotherm in winter. In order to reconstruct the natural variability of the flows in the Maule, Biobío and Puelo rivers, gauges were selected that have no diversions of water for irrigation or hydroelectricity. This requires leaving out data from parts of the river that have higher volume flows closer to the coast. Given the importance of agriculture and hydroelectricity in these watersheds, many streams are subject to diversion. The characteristics of the stations used to construct the Biobío River instrumental streamflow time-series are shown in Appendix 2.

The annual streamflow series for the Biobío River is capturing principally the rain regime within the watershed. This can be observed in its hydrograph and the less marked melting supply in spring months compared with the Maule and Puelo rivers (Fig. 1). The average elevation of the station records used in the reconstruction of the Maule, Biobío and Puelo Rivers is 290, 205, 314 m a.s.l, respectively. More details about the stations used to reconstruct the Maule and Puelo Rivers can be found in Urrutia et al. (2011) and Lara et al. (2008), respectively.

Following the procedures of the Maule and Puelo reconstructions, to reconstruct Biobío River streamflow, we used station records that were previously homogenized, validated, and completed for any missing data by Rubio-Álvarez & McPhee (2010). Gaps in monthly data were filled by a combination of annual flow correlations and monthly distribution coefficients differentiated by wet, normal, and dry water years (Rubio-Álvarez & McPhee 2010). Additionally, the confidence in these records was evaluated using a double mass curve with precipitation data from Los Angeles City, close to the river basin. This analysis indicated anomalous values prior to 1943, which were removed from further analyses. As a result the annual (water year: April-March) instrumental streamflow record for the Biobío Rivers spanned the period

1943-2004. The stations used in the reconstruction of the Biobío River are shown in Appendix 3 with their relationship with Los Angeles' precipitation. There were high levels of positive correlation between the four stations used in the composite series for the Biobío River, reaching significance levels of 99% and correlation coefficients above 0.60 in all four cases (Appendix 3). The three reconstructions used composite records from three to five gauges (see Lara et al. 2008; Urrutia et al. 2011; Appendix 3). Especially in the case of the Maule and Biobío rivers, the gauge selected has flows of small magnitude compared with the size of the watershed, which can be affected by high variability. The composite instrumental record allows to maximization of the regional streamflow signal of each basin, reducing the variability of the small watersheds.

Tree-ring data

A set of 25 tree-ring chronologies of *Araucaria araucana* and *Austrocedrus chilensis* sampled near to the Biobío watershed was used to select the best possible predictors for the Biobío streamflow reconstruction. From this pool of 25 chronologies, five were selected, one of which is comprised of trees from three different site chronologies. The characteristics of the selected chronologies are given in Appendix 4, including a Variation Inflation Factor (VIF) and the correlation among chronologies. These statistics evaluate the multicollinearity that exists between the predictors in a reconstruction. Values of VIF close to 1 indicate a low or null multicollinearity (Haan 2002). Values of VIF above 10 indicate multicollinearity problems between predictors (O'Brien 2007). VIF statistics for the Biobío tree-ring chronologies range from 1.13 to 1.61. The Maule and Puelo reconstructions utilized principal components derived from tree-ring chronologies. The regression model and the VIF were calculated using the Matlab and Minitab software, respectively.

Similar procedures and common dendrochronological methods to recover and process two cores per tree were used for the Maule, Biobío and Puelo Rivers. More information on the chronologies used in the reconstructions of the Maule and Puelo Rivers there is in Urrutia et al. (2011) and Lara et al. (2008), respectively. Core samples were extracted from trees using increment borers and samples were mounted and sanded to a fine polish. Following Schulman's convention (1956) for the Southern Hemisphere, annual rings were assigned to the year in which ring formation started. The samples were visually cross-dated and the exact calendar year of each growth ring was assigned. Ring widths were measured with 0.001 mm precision under a stereoscopic microscope (50x). The raw ring-width measurements were then submitted to the quality control program COFECHA (Holmes 1983). The growth series were standardized using the program ARSTAN (Cook 1985) to maximize the effect of climate and remove the effect of age and forest disturbance on ring widths. The chronologies were standardized by conservative methods of detrending using a negative exponential curve or cubic spline function that removed 50% of the variability in growth while retaining 50% of the frequency at no greater than two-thirds of the length of the series (Cook & Kairiukstis 1990). The standardized ring-width series were averaged for each site using a mean value function that minimizes the effect of outliers (Cook & Kairiukstis 1990), producing dimensionless stationary index data with a defined mean of 1.0 and relatively constant variance. The Expressed Population Signal (EPS) measures the strength of the common signal among the tree-ring series in a chronology over time and quantifies the degree to which it represents a hypothetically perfect chronology (Wigley et al. 1984). To calculate the EPS, we used a 50-year window with an overlap of 25 years between adjacent windows. We utilized the common 0.85 threshold to denote a good level of common signal fidelity between trees and used only those portions of the chronologies as predictors in the reconstruction.

Reconstructing Biobío River streamflow

All selected chronologies had significant correlations with the annual Biobío instrumental streamflow series (water year April-March, average correlation r = 0.58). To reconstruct the Biobío streamflow the tree-ring chronologies were used as predictors during a common period of the chronologies where the EPS statistic exceeded 0.85 (1500-2004). The annual (April-March) instrumental Biobío streamflow data series was used as the predictand (Shapiro-Wilk *W*= 0.987; p = 0.734). The inflation of variance related to the decrease in sample size was minimized with this procedure (Wigley et al. 1984). A stepwise multiple regression model using five predictors from five different chronologies at year t=0, t+1, t+2 was applied to develop the Biobío streamflow reconstruction.

The entire common period (1943-2003) of the composite streamflow record was used to calibrate the tree-ring model utilizing the “leave-one-out” cross-validation procedure (Michaelsen, 1987; Meko, 1997). In this approach each observation is successively withheld a model is estimated on the remaining observations, and the omitted observation is predicted. At the end of this procedure, the time series of predicted values assembled from the deleted observations is compared with the observed records to compute the validation statistics of accuracy and error model. The proportion of variance explained by the regression or adjusted R^2 (R^2adj) was used to evaluate the quality of fit between the observed and predicted streamflow values. In the calibration period, reduction of error (RE) was used, which is a rigorous measure of the relationship between a value in a series and its estimated value. The theoretical limits of the RE range from a maximum of 1 to negative infinity. Any positive value indicates that the model has some predictive capacity (Fritts et al. 1991; Hughes et al. 2011). As additional measures of regression accuracy, we also computed the F-value of the regression and the Reduction of Error (RE) statistic over the verification period. As a measure of reconstruction uncertainty we computed the root-mean-square error (RMSE) statistic and the Standard error (SE). Residual autocorrelation was evaluated using the Durbin-Watson test (Ostrom 1990).

Comparing the streamflow reconstructions of the Maule, Biobío and Puelo Rivers

The reconstructions have certain methodological differences. Composite streamflow station data represent a water year composed of 12 months from April to March for both the Maule and Biobío Rivers, and a 6-month period (December-May) for the Puelo, where the reconstructed period represents around 30% of the total annual discharge. The summer–fall (December–May) observed streamflow record is significantly correlated with the annual (April–March) flow (r=0.70, P>0.99 for the 1943–1999 period). This correlation results from the persistence in streamflow records favored by the mixed pluvial-nival regime of the Puelo River (Lara et al 2008). This correlation results from the persistence in streamflow records favored by the mixed pluvial-nival regime of the Puelo River (Lara et al. 2008). The source regimes differ between systems, with the Maule and Puelo rivers having higher amounts of snowmelt in the spring and summer, representing a more marked rain-to-snow regime, while stations along the Biobío River mainly receiving rainfall at lower elevations within the watershed (Fig. 1). The hydrological regime of the Biobío River is a mix of rainfall and snowmelt in the headwaters of the Principal Cordillera and exclusively rainfall in the Central Depression and Coastal Cordillera (Tolorza et al. 2014). On the other hand, the Maule and Puelo rivers share only 13 trees from a composite chronology (Cuyin-Manzano site) of four chronologies used in each reconstruction. These data do not interfere with for an independent interpretation of the Maule and Puelo River reconstructions. The predictors used for the Biobío River reconstruction were completely independent of the other two streamflow reconstructions (Appendix 4). Correlations were calculated between the instrumental and reconstructed streamflow data for all three rivers. Correlation maps were also used to compare relationships between precipitation and streamflow reconstructions.

The drought recurrence intervals were analyzed over a common period (1599-1999 years) for each reconstruction using data expressed as consecutive one, two and three-year periods for the entire record.

These values were converted to percentiles of the flow duration curve and the 20th and 10th percentiles used to identify severe and extreme drought events (Meko & Woodhouse 2011). These occurrence rates were evaluated by creating an event time series and based on 20th and 10th percentiles thresholds, representing severe and extreme drought events, respectively. To assess the occurrence rate of severe and extreme droughts (low flow) along the reconstructions, we employed a kernel estimation technique (Mudelsee et al. 2004). This method allows the detection of non-linear and non-monotonic trends and does not impose parametric restrictions. The estimation of temporal changes of the extreme event recurrence intervals of low flows was computed using a 60-year bandwidth. The Kernel functions estimate the probability of occurrence of one specific event (i.e., droughts) in a moving window. In order to better interpret these estimates, confidence bands at the 95% level were obtained from 1000 bootstrap re-sampling steps (*see* Christie et al. 2011). This routine was run in the R-project platform (R-core team 2015) and using the package "Paleofire" (Blarquez et al. 2014).

Spectral analyses were used to identify the distinct oscillatory variability in the reconstructions and the large-scale modes of climate variability (ENSO and SAM). The Multi-Taper Method (MTM; Mann & Lees 1996) was used to identify the cycles that explained significant proportions of variance using Continuous Wavelet Transform analysis (Grinsted et al. 2004) to compare the temporal variability of these cycles. The decomposition of the reconstructions' oscillatory modes, explaining most of the variance, was developed using Singular Spectral Analysis (SSA) (Vautard & Ghil 1989). Correlation analysis was used to identify the relationship between each reconstruction and large-scale modes of climate variability (ENSO and SAM). For evaluation of the large-scale climatic forcings, we used the measurements of Sea Surface Temperature (SST) from the Niño-3.4 region (N3.4) as an indicator of ENSO behavior (Trenberth 2007), and the Antarctic Oscillation (AAO; http://www.jisao.washington.edu/aao/) to represent the SAM variability. Autoregressive (AR) modeling was used to pre-whitened each reconstruction time-series in order to eliminate the effect of first-order autocorrelation on the indices. To evaluate the entire periods of the reconstructions and their relationship with the large-scale forcings, we compared the oscillatory modes of the river reconstructions with climate forcing reconstructions of ENSO (Li et al. 2013), PDO (Biondi et al. 2001) and SAM (Zhang et al. 2010; Villalba et al. 2012).

Results

Streamflow reconstructions in the Temperate-Mediterranean climate transition zone

We developed a streamflow reconstruction for the Biobío River, located in the transition of the mediterranean and temperate climates. The Biobío reconstruction model efficiently replicated the flow variability during the entire calibration period ($r^2_{adj} = 0.45$) (1943-2003; Fig. 2A). In some cases, extreme high values (e.g., 1950 and 1973) and extremely low values (e.g., 1968 and 1998) in the instrumental record were not exactly replicated in the model, with extreme flow values being underestimated (Fig. 2A). The instrumental and reconstructed streamflow series showed spectral coherence between the interannual, 2-6 year, and interdecadal cycles of nearly 30 years (Fig. 2B). The Biobío River reconstruction covers the period 1500-2003 and is the longest streamflow reconstruction published in the Southern Pacific domain. (SPD) (Fig. 2C). Calibration and verification statistics for the multiple regression analysis demonstrated a high capacity to reconstruct water year variability. The linear model explained 45% of the variation in the instrumental record, with strong results when subjected to cross validation, reaching positive values in error reduction (RE) and significant F statistic values ($p<0.001$). Standard error (SE) and the root mean squared error (RMSE) were relatively small. Residuals were distributed normally, without evidence of autocorrelation according to the Durbin-Watson statistic (DW close to 2) and the Portmanteau test (Q) (Fig. 2). The values of VIF for all predictors were close to 1, indicating low or null multicollinearity (Appendix 4).

The Maule, Biobío and Puelo River reconstructions share 400 years (1599-1999) of streamflow variability in the Mediterranean and Temperate climate transition (Fig. 3A). This allows an analysis of climate variability in an important latitudinal moisture gradient in western South America. The three streamflow reconstructions showed similarities in the high and low frequency band (Fig. 3A, B), which is strongly related to the frontal precipitation patterns in the Southern Pacific domain (SPD). In the three reconstructions, the first part of the 20th century showed high levels of flows followed by a declining level of the flows during the second part of this century. Also, the three reconstructed records showed extreme flows in the second part of the 17th century, which were most expressed in the Biobio and Puelo Rivers (Fig. 3A). The low frequency of the flows was also most marked in these last rivers (Fig. 3B).

The three reconstructions replicate precipitation variability well, with higher correlations in the areas where the watersheds are located, demonstrating their ability to represent the spatio-temporal variability of the hydrological conditions in the study area. However, this relationship weakens towards the south (Fig. 3C), most probably related to the greater relative importance of snowmelt in the hydrological cycle in the Puelo River and a less defined seasonality of precipitation in the southern part of the precipitation gradient (Fig. 1, 3).

Extreme events in the streamflow variability of the Maule, Biobío and Puelo rivers through time

The reconstructed recurrence of high and low flow events provides managers with a long-term proxy perspective on the relatively short instrumental record of severe drought and flood recurrence. We selected the five highest and lowest single-year, 5-year and decadal positive (wettest) and negative (driest) anomalies from each reconstruction and the instrumental record (Table 2). The Maule, Biobío and Puelo Rivers reconstructed 3, 4 and 2 of the five wettest years during the 20th century, respectively (Table 2). In all three reconstructions the year 1940 ranked in the top five wettest years suggesting a regional pattern of high moisture, only in the Maule River was this year notable in the instrumental record. The wettest instrumental year does not rank in the top five for two of the reconstructions (Table 2). The analysis of 5 and 10-year periods confirmed that many of the highest flows of the last four centuries occurred during the first half of the 20th century, a pattern repeated in all three reconstructions, and most pronounced in the Biobío reconstruction (Table 2). The highest 5-year anomalies of the instrumental record ranked third and fifth in the Biobío River and Puelo River reconstructions, respectively. The 1944-1948 period was the wettest in the Biobío River and the fifth in the Puelo River, both in the beginning of the instrumental period of these rivers (Table 2). The 20th century included two, four, and two of the five wettest 5-year periods in the Maule, Biobío, Puelo rivers, respectively (Table 2). The decade 1944-1953 ranked as the highest decadal flow period of the three rivers in the instrumental period, but this decade was ranked only in the top five in the Puelo reconstruction, where it was 5th of the five wettest decades in the reconstructed period (Table 2). However, 1936-1945 and 1946-1955 rank first and second in the Biobio River, respectively. Only 1935-1944 was found as the thirst of the five wettest periods in the Maule reconstruction (Table 2).

In both the Biobío and Puelo River reconstructions 1681 was the most severe drought year of the last four centuries. The year 1998 was the most severe drought in instrumental record for the Biobío and Puelo Rivers, and ranked as the fifth, fourth and second most severe single-year drought reconstructed for the Maule, Biobío and Puelo Rivers, respectively (Table 2). The Maule and Puelo Rivers had four of the five most severe reconstructed drought years in the 20th century. The Biobío River reconstruction revealed prolonged dry periods in the second half of the 17th century (Appendix 5), where three of the five lowest values of this reconstruction occurred (Table 2). Comparing 5-year periods indicates that two of these driest periods happened during the 20th century in the three reconstructions. The period 1995-1999 ranked as the lowest 5-year flow period of the instrumental record for the Maule and Biobío Rivers, while the period 1996-2000 was the lowest one in the Puelo River (Table 2). The Maule and Puelo River reconstructions shared the period 1818-1822 as one of the most extreme 5-year droughts. In all three reconstructions the 1680s were one of the five driest decades of the last 400 years. During this common period reconstructed, the Maule and Puelo Rivers registered two and the Biobío River only one of the driest decades in the 20th century. For the three reconstructions, the most severe dry decade did not occur during the second part of the 20th century (Table 2).

Observing the temporal changes in the frequency of the severe and extreme droughts, defined as events below the 10th and 20th percentile for all three reconstructions, we found an increase toward the present especially in annual and two consecutive years of drought events in all reconstructions (Fig. 4). The mean return interval for annual droughts below the 10th percentile in the Maule, Biobío, and Puelo Rivers for the last four hundred years fluctuated around 10-20 years, but for the second part of the 20th century became a 3-5 year recurrence, suggesting an increase in the frequency of severe droughts in the region (Fig. 4). The annual droughts were also highly frequent during the beginning of the 17th century in the Maule and Biobío rivers (Fig. 4A, C). However, in the case of the two-consecutive years, this pattern was less clear (Fig. 4B, D). The Puelo River showed a different pattern, where especially in the annual drought and the 10th percentile of the two-consecutive-year drought, and the recurrence of extreme events has increased to the present during the last four hundred years (Fig. 4E, F).

Streamflow reconstructions and large-scale modes of climate variability.

A differential response pattern of streamflow reconstructions to large-scale climate forcing during the instrumental period (1943-1999) was found. The ENSO pattern is characterized by atmospheric changes associated to sea surface temperature variation in the tropical Pacific, while the SAM represents atmospheric pressure variability between mid and high latitudes of the Southern Hemisphere. As expected, the Maule reconstruction exhibited significant correlations with the ENSO (Niño3.4), indicating a relationship with tropical Pacific activity (Fig. 5A). However, the Biobío and Puelo streamflow reconstructions were strongly correlated with the SAM variability in the instrumental period (Fig. 5B, C). The correlations between El Niño 3.4 variability in the same months, and the Maule, Biobío and Puelo reconstructions in the instrumental period, were $r = 0.44$ ($p < 0.1$), $r = 0.10$ ($p < 0.1$) and $r = 0.06$ ($p < 0.1$). The best relationships in the three reconstructions for the instrumental period are shown in Figure 5. Even though the relationships between ENSO with Biobío and Puelo rivers were weaker than the Maule rivers, most of the extreme events in all the three reconstructions occur during El Niño (e.g., 1940, 1951, 1968-1969, and 1997-1998) and La Niña (e.g., 1924, 1950-1951, 1955-1956, 1967-1968, and 1998-1999) years (Birk et al. 2010; NOAA: http://ggweather.com/enso/oni.htm).

Spectral analysis was used to identify potential common cycles of variability through the frequency domain between the streamflow reconstructions and large-scale climate forcings (ENSO, SAM). MTM analysis of the reconstructions showed common cycles in the 2-6 year band. Also, an 83-year long-term cycle was identified ($p<0.001$) in the Biobío and Puelo Rivers (Appendix 6), explaining around 16-18% of the variance. We found a high correlation between the principal oscillatory modes of the three streamflow reconstructions and the SAM and ENSO forcing, especially at the band of 2-6 years (Fig. 6A, B, C). At the low frequency, cycles of around 17 and 30 years were found in Maule and Biobío rivers respectively (Appendix 6), but only the Maule River reconstruction showed similarities with the PDO reconstruction in a cycle of around 22 years (Fig. 6D). The longer cycles founded in the Biobío and Puelo reconstructions, around 83-years, were well correlated with a cycle of similarly long SAM reconstructions (Fig. 6E, F). In the SAM reconstruction, this cycle explains only the 3 – 4 % of the variance (Fig. 6F). A wavelet analysis shows that an increase in the high frequency of 2-8 years of variability was observed in the 20th century in the Maule watershed, while only the Maule and Biobío reconstructions showed a slight increase in decadal and interdecadal variability in the same period (Appendix 7).

In order to understand the magnitude of the reduction in water availability in recent decades in South-Central Chile, we compared the driest ten-year period of the Maule, Biobío, and Puelo reconstructions with the most recent period in each reconstruction (Maule: 1991-2000; Biobío: 1994-2003; Puelo: 1990-1999). For the Maule reconstruction, the periods 1991-2000 and 1625-1634 had 14% and 26% less water than the 400-year mean. For the Biobío reconstruction, these differences were 27% and 59% for the 1994-2003 and 1672-1681 periods, respectively. In the case of the Puelo River, these differences were 38% and 57% for the 1990-1999 and 1907-1916 periods, respectively.

Discussion

Spatio-temporal streamflow variability and large-scale forcing influences in the Temperate-Mediterranean transition.

The Biobío River reconstruction is the longest proxy streamflow record in Chile (Southern Pacific domain SPD; 1500-2003 years). Instrumental variance explained by the regression model (R^2 adj. = 0.45, Appendix 6) is similar compared with the previous reconstructions of Maule and Puelo Rivers (R^2 adj. = 0.42), which cover 410 and 400 years, respectively. The three reconstructions are based on different combinations of *Araucaria araucana*, *Pilgerodendron uviferum*, and *Austrocedrus chilensis* tree-ring chronologies, species that have proven useful in representing hydroclimatic variability in Chile and Argentina (Holmes et al. 1979; Lara et al. 2008; LeQuesne et al. 2006; 2009; Christie et al. 2011; Urrutia et al. 2011; Mundo et al. 2012).

Rubio-Álvarez & McPhee (2010) examined hydrological records of 44 rivers in southern Chile, between 34°S and 45°S for the 1952–2003 period, showing that the dominant effects of ENSO and SAM over river discharges exist to the north and south of 37.5°S, respectively. The reconstruction of the Biobío River corroborates this result, differentiating itself more from the Maule than the Puelo River despite its closer geographic proximity to the former (Fig. 1). Lara et al. (2008) also note in the analysis for the Puelo River a broad geographic correspondence between rivers located in 37°S - 43°S. However, the Biobío River reconstruction presented here has similar characteristics with both Maule and Puelo Rivers in terms of both extreme high and low annual flow and multiannual events (Table 2), and these rivers also share similar frequencies of single and consecutive years below and above average (Fig. 3, 4).

A strong relationship between reconstructed streamflow and ENSO and SAM climatic forcings proved to be a strong result. The activity of these forcings results in precipitation and temperature anomalies that vary geographically across Chile (Garreaud et al. 2009). The SAM is considered to be the principal precipitation control on the southern pacific domain (40°S - 55°S, Lara et al. 2008; Aravena & Luckman 2010), while ENSO activity strongly influences the climate of central Chile and northern Patagonia (Montecinos & Aceituno 2003). High frequency cycles (< 6 years) are common in all three reconstructions, but increase in frequency of these cycles occurs clearly only in the Maule reconstruction during the 20th century (Wavelet; Appendix 6). This increase in the variability and the cycles between 2-6 years has been noted in recent ENSO reconstructions (Fowler et al. 2012). The ENSO variability was especially related to the Maule River flow during the instrumental period (Fig. 5A) and also during the reconstructed period, using a comparison with the ENSO reconstruction by Li et al. (2013) as an indicator of the activity of this climate forcing in long-term variability (Fig. 6B). ENSO cycles around 6 years derived from the Li et al. (2013) reconstruction were well correlated with the Maule River. These cycles explained around the 8% and 13% of the variance of the Maule River and the ENSO reconstructions, respectively (Fig. 6B). The inter-decadal influence of the Pacific Decadal Oscillation (PDO) over the three rivers reconstructions was significant only for the Maule River, using the PDO reconstruction of Biondi et al. (2001; Figure 6D). By contrast, the Biobío and Puelo Rivers were strongly related to the interannual variability of SAM during the instrumental period (Fig. 5B, C). Also, both reconstructions were related with the interannual variability of ENSO ($p < 0.1$; Lara et al. 2008; Muñoz 2012). In both cases, the Biobío and Puelo rivers presented cycles between 4-6 years, which explained around 7% of the variance, but in these cases this cycles were related with the same cyclical frequency band of the SAM (AAO), which explains only 4% of the variance of the reconstruction published by Zhang et al. (2010; Fig. 6C). No inter-decadal cycles were found for these rivers in correlation with climate forcing (Appendix 6; Fig. 6). A reconstruction of Palmer's Drought Severity Index (PDSI) developed for the late spring-early summer season in the temperate-Mediterranean transition (36°S - 38°S) also showed a relationship with the SAM and ENSO activity to a lesser degree, corroborating that the convergence or transitional zone is sensitive to the activity of both climatic forcings (Christie et al. 2011). Recent studies have identified climatic signals from high latitudes in instrumental records of precipitation in La Serena (29º 54'S) and Ovalle (30º 36'S) cities, both located in northern Chile, which suggests that the influence of SAM could be quite extensive in the Mediterranean climate zone (Vuille & Milana 2007).

In the context of our results, cycles found in the reconstruction of ENSO from Li et al. (2013) and SAM reconstructions from Zhang et al. (2010) and Villalba et al. (2012) were also found in all three streamflow reconstructions, corroborating the large-scale influence of ENSO and SAM in the hydroclimatic

Southern Pacific Domain (SPD). Short-term cycles between 2-6 years for the Maule, Biobío and Puelo were related with SAM and ENSO variability (Fig. 5). These cycles explained between 4% and 5% of the variance of the reconstructed record, while common cycles of 83 years in rivers south to 37.5°S (Biobío and Puelo) explained over 16%, of the reconstructed records and were related to the SAM activity in the same frequency (Fig. 6E, F). For the SAM reconstructions these cycles only represent around 5% of the variance of the time series (Fig. 6E, F). Given the small part of the variance explained by this cycle in the SAM reconstructions, the 83-year cycle could be better explained by orbital forcing such as the Gleissberg solar cycle, described around 50-140 years (Ma 2009), affecting both the hydrological regimes of these rivers and also the atmospheric pressure in high and mid latitude (SAM) in the southern hemisphere. The recent streamflow reduction showed by the instrumental data after 1950 in the south-central Chile could be a part of the low-frequency 83-year cycle identified in the SAM reconstructions developed by Zhang et al. (2010), Villalba et al. (2012) and also Lara et al. (2008), and is shared by the Biobío and Puelo rivers (Fig. 6E, F). These cycles, around 80-year long on average, were previously related to solar forcing (or Gleissberg cycle) using a temperature reconstruction inferred from *Fitzroya cupressoides* tree-rings (Villalba et al. 1996). More recently, the negative trend in precipitation and streamflow in recent decades in northern Patagonia has been related to a persistently positive phase of the SAM (Villalba et al. 2012). The regularity of this cycle in the Biobío and Puelo streamflow reconstructions (Fig. 6E) could be utilized in the next decades as a good approach for modeling changes in the climate system in these important basins in Chile

Toggweiler (2009) has described a southern displacement of the Pacific Westerlies, which are described over the last 50 years as the principal cause of increased precipitation in southern Patagonia (high latitudes, 55°S) and the decrease in precipitation at mid-latitudes (38°S - 43°S). Movement, intensity and stability of pressure belts at mid and high latitudes over South America have become a principal area of study in recent decades, especially because of connections with extreme climate events and long-term regime shifts (Montecinos & Aceituno 2003; Lara et al. 2008; Garreaud et al. 2009). Our study helps to clarify the predominant interannual variability influence of ENSO over the Mediterranean climate zone and the interannual and long-term variability influence of SAM, especially in the temperate climate zone. The reconstructions of the Maule, Biobío and Puelo rivers showed a relationship with climate forcings ENSO and SAM. From these results, a decreasing SAM influence to the north of 37.5°S and an increase of the ENSO influence over the streamflow variability can be deduced. Studies of fire ecology (Holz et al. 2012; Holz & Veblen 2012) and climatology using instrumental records and gridded data have confirmed these patterns (Garreaud et al. 2009).

Changes in the frequency of extreme drought events of the Temperate-Mediterranean climate transition

An increase in the recurrence of one and two consecutive years of drought to the present was observed in all three streamflow reconstructions. This trend was especially prominent during the first part of the 17th and the second part of the 20th century for both the Maule and Biobío rivers. A similar increase was seen in the Puelo River, which showed an increment of these events through the complete reconstructed record, starting in 1599 (Fig. 4). Extreme events (10th percentile) of low flows in the three reconstructions occurred every 5 years on average at the end of the 20th century, but these events were variable throughout the records with return intervals greater than 10 years throughout most part of the reconstructed records in previous centuries (Fig. 4). This pattern was also seen in two consecutive years of droughts in the Maule and Biobío Rivers, but the recurrence of the severe low-flow periods changed from >40-years in most of the reconstructions to close to a 10-year recurrence of dry consecutive years in the second part of the 20th century (Fig. 4). In the case of the Puelo River, the recurrence of the most severe 2-year consecutive low flows were 30-40 years across the complete reconstruction, but in the second part of the 20th century these events occurred close to 20 years on average (Fig. 4).

The most intense single-year drought event of the last 400 years occurred in 1681 according to the Biobío and Puelo River reconstructions, whereas 1998 was the most intense single event in the instrumental record. Both years have been associated with the El Niño activity in South America (Quinn & Neal 1992, 1995; Li et al. 2013) and the majority of the extreme annual events in the three streamflow reconstructions are modulated by ENSO activity. The driest year in the 400-year-long Maule reconstruction occurred in 1924 (strong La Niña year, Diaz & Markgraf 2000, Birk et al 2010), while 1968 (weak La Niña year, NOAA: http://ggweather.com/enso/oni.htm) was the driest in the instrumental record. These two years represent the lowest precipitation levels on record in Santiago (Rutllant & Fuenzalida 1991) and the lowest streamflow recorded in the rivers of Central Chile. In the case of the Maule River streamflow reconstruction, four of the lowest five years were reported within the 20th century (1924, 1968, 1908, 1998), and these same years were also ranked among the ten driest years of the last 800 years in a precipitation reconstruction of Central Chile (LeQuesne et al. 2006). In the Mediterranean climate, the El Niño years are characterized by wet winters and springs in central Chile followed by dry summers in the temperate climate of North-Patagonia (Garreaud et al. 2009), which can explain the relationship between high flows in the three rivers associated with El Niño activity. On the other hand, La Niña years are associated with dry conditions in Chile (Garreaud et al. 2009) producing low flows in most cases for the three rivers. There are some clear coincidences between rivers and extreme flows (Table 2), in instances of moderate explained variance (42% - 45% of the explained variance), as the three reconstructions compared in this study, the strength of the reconstructions occur more in the low-frequency trends than individual years (Appendix 5). This is especially the case when using a composite flow record, which can integrate the regional climatic signal but also could reduce the ability to recognize high-frequency variability.

At the ten-year period scale, the most extreme period (both high and low flows) in the instrumental period (Maule: 1937-2000; Biobío: 1943-2003; Puelo 1943-2000) was not the top one or most severe of the streamflow reconstructions (Table 2). Even with this, the 20th century included extreme high flows, especially in the Biobío River, which had three of the five highest flow of ten-years of the entire period reconstructed (1600-2003; Table 2). The two wettest ten-year periods in the Biobío reconstruction were during the first half of the 20th century (1936-1945, 1946-1955). The periods 1932-1941 and 1944-1953 were within the five wettest ten-year period of the Puelo River reconstruction. Corroborating evidence for the relative wetness of the earlier 20th century is also shown at a regional scale by the Neuquén reconstruction, fed by snowmelt on the eastern side of the Andes, where 1927-1951 was the second wettest 25-year period in the last 654 years (Mundo et al. 2012). Since the 1850s Valdivia precipitation showed a reduction from a high at the end of 19th century and progressively lower precipitation in the second part of the 20th century (González-Reyes & Muñoz 2013), corroborating the extreme nature of the hydrological variability during this century. This was also shown by Masiokas et al. (2008) presenting streamflow data from Argentinean rivers at the same latitude as this study, and by Villalba et al. (2012) discussing a regional pattern of precipitation in relation to the SAM and storm tracks in the Pacific domain of South America.

Conclusion

The streamflow reconstructions discussed in this study exhibit periods of drier conditions much lengthier than those observed by recent instrumental data, this information is valuable in improving our understanding of the natural range of streamflow variability in three of Chile's most important rivers. This study links the long-term variability of streamflow to large-scale climate forcings such as ENSO and SAM along a commercially and ecologically important latitudinal gradient of Chile. In addition, this study lends a new perspective on hydro-climatic extremes observed over the last century in the Mediterranean-Temperate transition of western South America. This information is critical for developing climate change adaptation policy, planning and management action in the agricultural, energy and industrial sectors.

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Figures

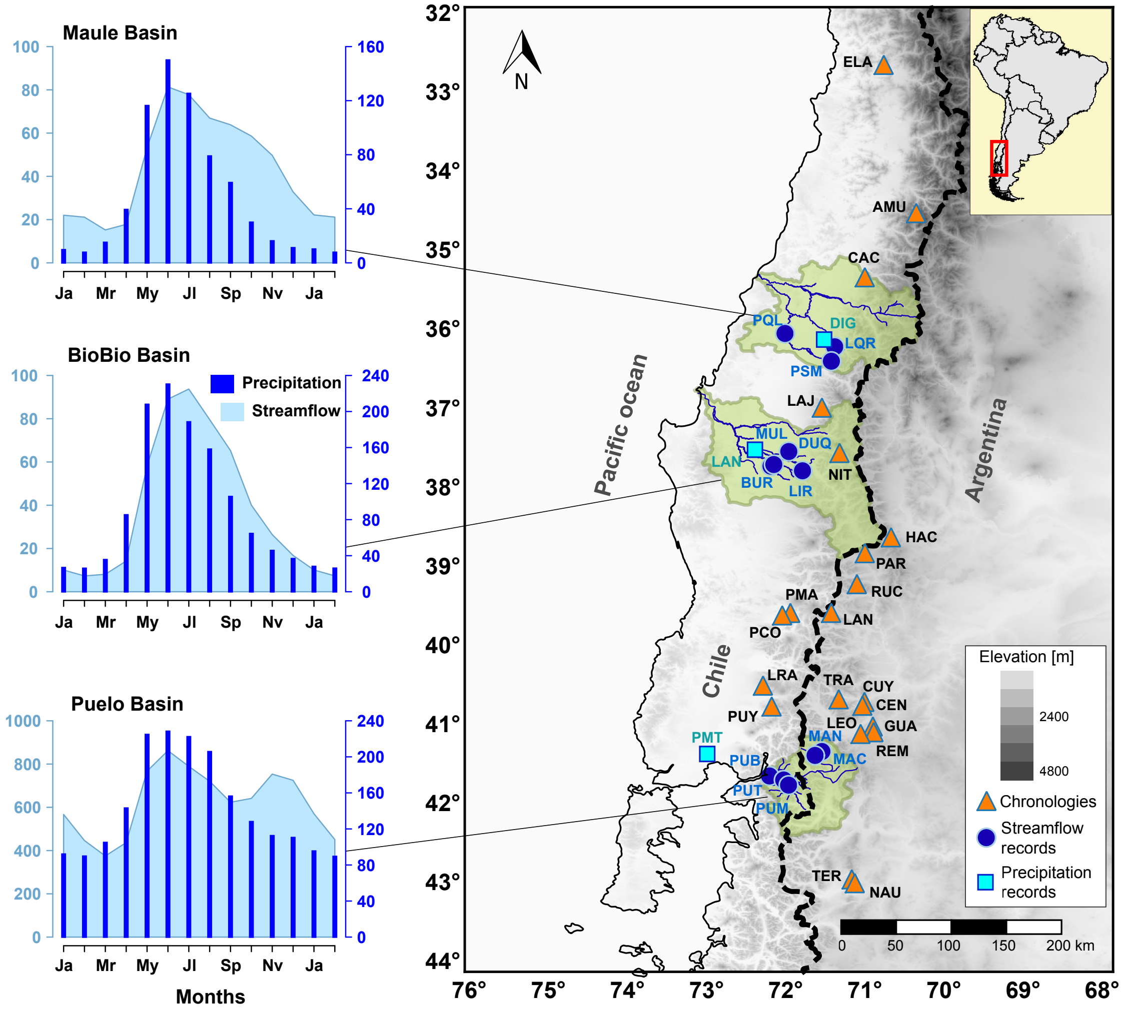

Fig. 1 The Maule, Biobío, and Puelo watersheds in south-central Chile are mapped between the Mediterranean to temperate climate zone. The segmented line indicates the international border between Chile and Argentina, which generally follows the continental divide formed by the Andes Mountains (the Puelo headwaters are in Argentina). Watershed surface areas are outlined in solid green lines while blue lines indicate the main river channels. The location of tree-ring chronologies and gauge stations used to reconstruct streamflow are mapped in orange triangles and blue dots, respectively. Precipitation records are shown in light blue squares. At the left, mean monthly streamflow (in m^3 s^{-1} units from January to next March months) is plotted with solid lines for the Maule, Biobío, and Puelo Rivers at Longaví (LON), Bureo (BUR) and Carrera Basilio (PUB) gauge stations, respectively, and mean monthly precipitation (in mm units) obtained from weather stations nearby is plotted with blue bars. Precipitation records of Digua (DIG; 36° 15´S, 71° 33´W), Los Angeles (LAN; 37° 30’S, 72° 24’W) and Puerto Montt (PMT; 41° 28´S, 72° 56´W) covering the period 1943-2000 were used to represent the rainfall regime for the Maule, Biobío, and Puelo basins, respectively.

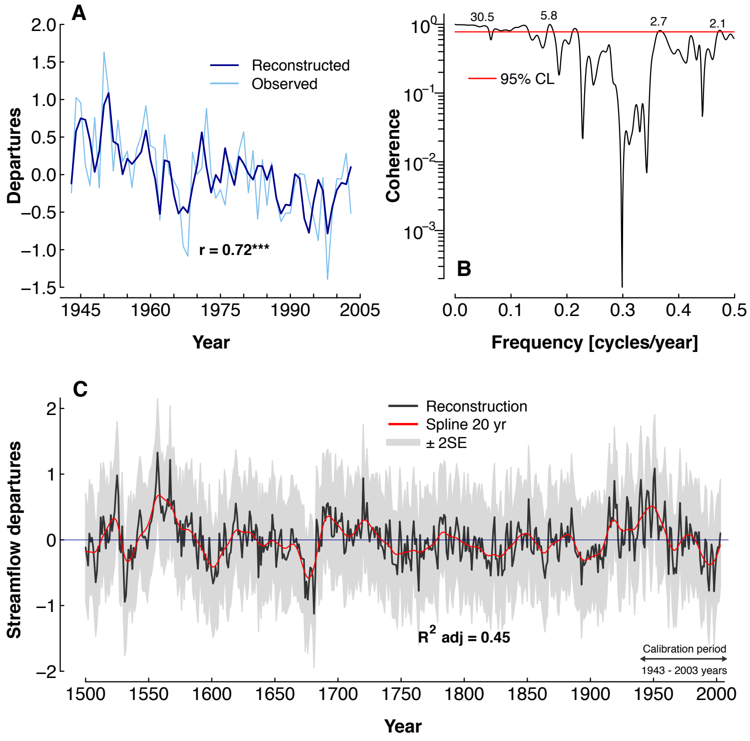

Fig. 2 (A) Observed and reconstructed mean annual streamflow departures are plotted for the Biobío River during the calibration period (April-March; 1943-2003). The correlation between observed and reconstructed series is significant at $P < 0.001$, (B) Spectral coherence calculated between the observed and reconstructed records using the Multi-Taper Method (MTM), significant cycle lengths are indicated above the plot (95% confidence), and (C) April-March streamflow of the Biobío River, 1500-2003. The light gray shading presents a ± 2 standard error band. The reconstruction is fitted with a 20-year cubic smoothing spline (red) in order to emphasize low-frequency variability in the reconstruction. The statistics of the reconstruction are: $R^2 = 0.48$; R^2adj = 0.45; F = 10.26, p = 0.0001; SE = 0.41; RE = 0.40; RMSE = 0.43; DW = 2.28; VIF = 1.39, where SE = Standard Error; RE = Reduction Error; P_f= probability value of the F statistic; The Variance Inflation Factor was calculated as the average VIF value of the five predictors in the regression model.

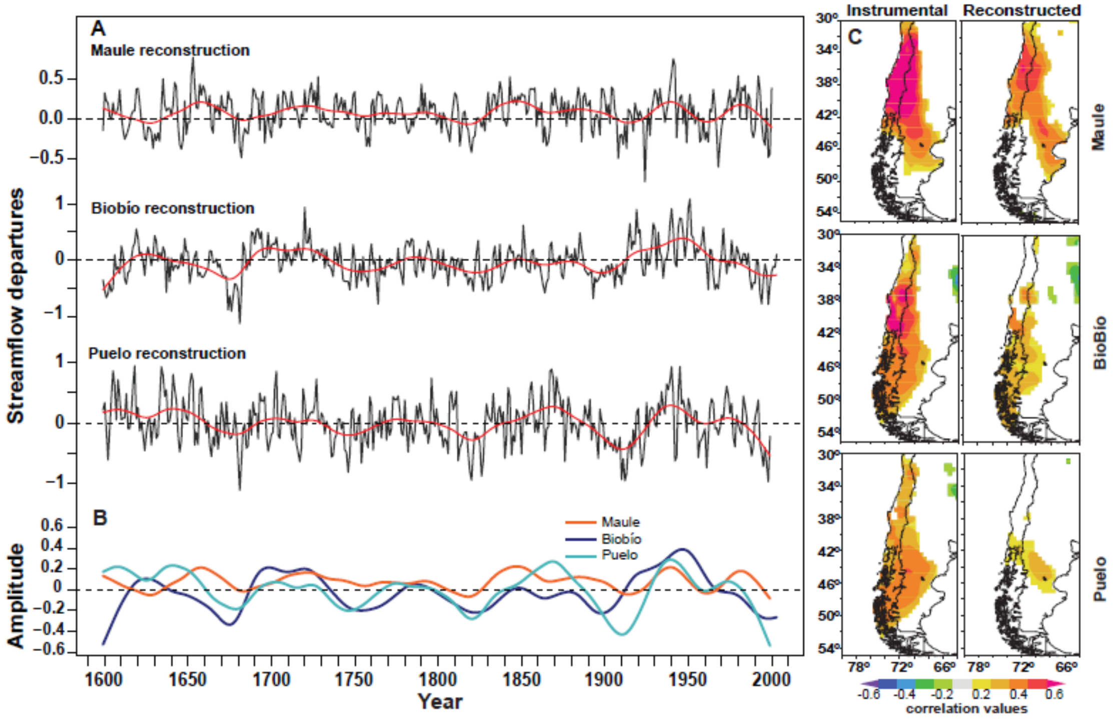

Fig. 3 (A) Streamflow departures of Maule, Biobío, and Puelo river reconstructions covering the 1599 - 1999 period. The annual flows are shown in black and fitted with a 25-year cubic spline shown by red lines, (B) A 25-year spline fitted to each reconstruction to show the low frequency patterns, and (C) correlation between the CRU TS 0.5° x 0.5° gridded with the instrumental precipitation datasets (left) and reconstructed (right) streamflow over the 1943-1999 period. The precipitation stations used are showed in Figure 1.

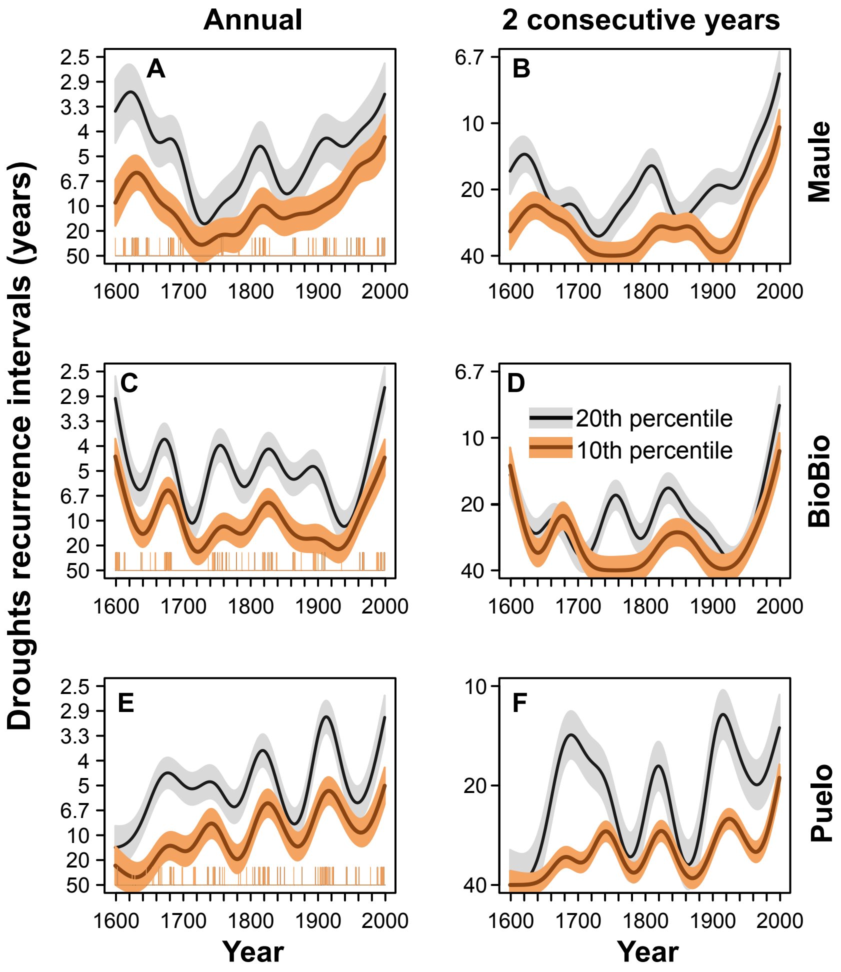

Fig. 4 A – F) Recurrence rate (years) of severe and extreme dry events calculated for the three river reconstructions in south-central Chile using one and two consecutive years and based on 20th and 10th percentile thresholds (see Methods). The confidence bands at 95% have been obtained from 1,000 bootstrap simulations. Individual years above the 20th percentile are shown at the base of panels A, C, and E.

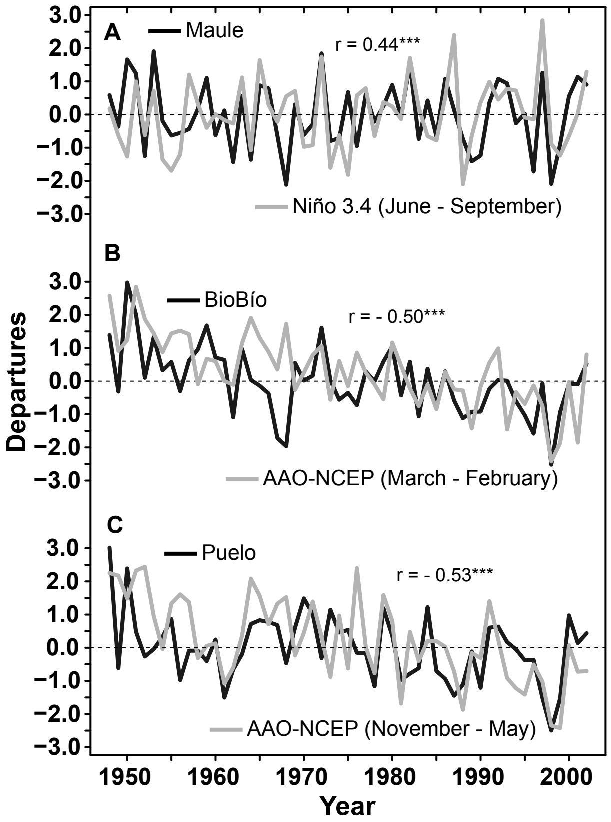

Fig. 5 The three streamflow reconstructions are plotted along with large-scale synoptic indices, SST – Niño 3.4 and the Antarctic Oscillation index (AAO). The best fit seasonal data for each reconstruction is shown. The time series of AAO has been inverted to facilitate a visual comparison with the streamflow records. Correlations are significant P < 0.05 *, P < 0.01 **, P < 0.001 ***.

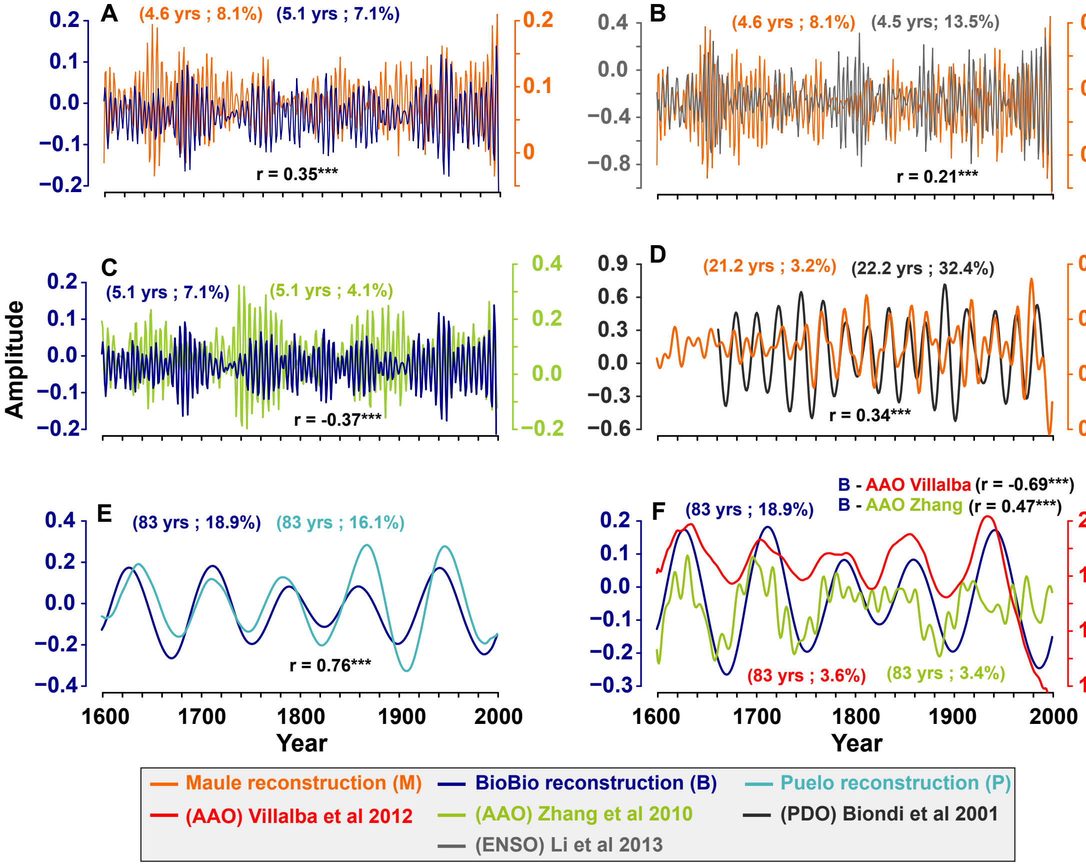

Fig. 6 The main oscillatory modes of the three streamflow reconstructions (Maule, Biobío, and Puelo Rivers) and the best fit for each reconstruction and climate forcing reconstructions (ENSO, PDO and AAO) from different authors are plotted. Values were extracted using Singular Spectral Analysis (SSA). All correlations are significant at 99% of confidence. In all cases, the explained variance of the respective oscillatory mode is expressed as percentage. A) The main inter-annual (4 - 6 years) oscillatory modes from the Maule, Biobío and Puelo reconstruction. B) The inter-annual oscillatory modes of Maule streamflow reconstruction and the ENSO reconstruction from Li *et al.,* 2013. C) The inter-annual (4 - 6 years) oscillatory modes of Biobío streamflow reconstruction and the AAO reconstruction from Zhang *et al.,* 2010 and Villalba *et al.,* 2012. D) The PDO oscillatory mode of 22 years from Biondi *et al.,* 2001 and the inter-decadal oscillatory mode (21 years) of Maule streamflow reconstruction. E) The long-term (83 years) oscillatory modes of Biobío and Puelo reconstructions. F) The 83-year oscillatory mode of Biobío streamflow reconstruction and Zhang *et al.,* 2010 and Villalba *et al.,* 2012 AAO reconstruction. The AAO reconstructions have been inverted. Correlations are significant P < 0.05 *, P < 0.01 **, P < 0.001 ***.

Tables

Table 1. Location of the Maule, Biobío, and Puelo basins and latitudinal precipitation gradient. The precipitation station for the Maule, Biobío, and Puelo Rivers in the coastal precipitation stations are Nirvilo (Maule), Concepción, and Puerto Montt, respectively. The Andean stations were Armerillo, Pangue, and Llanada, respectively, and Puelo Lake in Argentina represents conditions east of the Andes.

Basin	Latitudinal range	Precipitation (mm) Coast-Andes-East	Area (ha^{-1})
Maule River	35°00'S - 36°30´S	830 - 2300	2,107,247
Biobío River	36°45´S - 39°00'S	1170 – 3700	2,435,359
Puelo River	41°00'S - 42°20´S	1,840 - 2,432 - 700	900,249

Table 2. Ranking of the five most extreme annual, 5-year, and 10-year periods reconstructed for the Maule River (1599-2000), the Biobío River (1599-2003), and the Puelo River (1599-1999). The most severe values in the observed instrumental data are also shown for the Maule (1937-2000), Biobío (1943-2003), and Puelo Rivers (1943-2000). Ranked coincidences of extreme events shared by two or more reconstructions are listed in bold.

Period (years)	Rank.	Pluvials			Droughts		
		Maule	Biobío	Puelo	Maule	Biobío	Puelo
1	1	1653	1951	1618	1924	**1681**	**1681**
	2	1941	1720	1945	1968	1676	**1998**
	3	1942	1950	1634	1908	1674	1912
	4	1590	**1940**	**1940**	1682	**1998**	1820
	5	**1940**	1919	1868	**1998**	1764	1910
	Observed	1953	1950	1948	1968	**1998**	**1998**
5	1	1938-1942	**1944-1948**	1867-1871	**1818-1822**	1674-1678	1910-1914
	2	1590-1594	1917-1921	**1937-1941**	1908-1912	1601-1605	1994-1998
	3	1652-1656	1950-1954	1633-1637	1628-1632	1680-1684	**1818-1822**
	4	1980-1984	1720-1724	1605-1609	1682-1686	1997-2001	1679-1683
	5	1656-1660	**1937-1941**	**1944-1948**	1966-1970	1991-1995	1743-1747
	Observed	**1950-1954**	**1950-1954**	1944-1948	**1995-1999**	**1995-1999**	1996-2000
10	1	1650-1659	1936-1945	1866-1875	1625-1634	1672-1681	1907-1916
	2	1975-1984	1946-1955	1633-1642	1815-1824	1599-1608	1818-1827
	3	1935-1944	1915-1924	1932-1941	1905-1914	1992-2001	1989-1998
	4	1720-1729	1687-1696	1604-1613	1960-1969	1889-1898	1677-1686
	5	1850-1859	1778-1787	1944-1953	1680-1689	1826-1835	1737-1746
	Observed	**1944-1953**	**1944-1953**	**1944-1953**	1970-1979	1978-1987	1980-1989