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Hydrology and Earth System Sciences Discussions

Interactive comment on "Stable water isotope variation in a Central Andean watershed dominated by glacier- and snowmelt" *by* N. Ohlanders et al.

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The authors would like to thank everyone for your very useful comments. We see this paper mostly as a qualitative study of a large isotope data set, which demonstrates how temporal patterns in snow- and glacier melt can be inferred from a daily-scale streamflow time series. Our finding that glacier contribution dominated streamflow during this dry year is also important, and in the revised manuscript we will improve the discussion on this conclusion, using some additional statistical analysis and improved figures, tables and text. The reply below addresses the comments that deserve additional discussion and/or modifications in the original text. Short editorial comments that we don't respond to here will be implemented as suggested.

Answer to Referee review #1

General Comments:

The crude estimate of 50-80% glacier contribution to Juncal River (JR) streamflow is a central result in this paper and we regret if the argumentation behind this finding is not clear. This number is based on glacier contributions in different periods as presented in Table 4. These contributions were estimated by qualitative interpretation of the streamflow δ2H-signal during each period:

In Section 3.5.3 it is stated that during the summer period, which represented more than half of cumulative discharge, the δ2H-signal unequivocally indicated that glacial meltwater dominated JR streamflow. δ2H in this period was far from the signal of mid- or high altitude snow. Instead it was sometimes observed within the upper range of the hatched field indicating glacier signal and sometimes more enriched (due to highly enriched warm rain, which was assumed to not to contribute with a significant streamflow volume).

Comparison with the key dates of Oct 15 and Dec 15, described in Section 3.5.2, for which contributions could be numerically estimated, supplies more valuable information to the analysis of snow/glacier-contribution to streamflow. Between these two dates, we observed a tendency of snowmelt arriving from higher altitudes with time (although even here glacier melt still had a strong influence). After Dec 15, this trend stopped, indicating that snowmelt ceased to be an important component of total flow. Instead of further influence from even higher-altitude-snow, which would cause δ2H to decrease further, the value increased, indicating glacier melt domination in JR streamflow. In the revised manuscript we will add a statistical analysis, calculating glacier contributions with a 95% confidence interval. See comments on review 2 from Jakob Yde. In general, we will amend the wording in the revised version of the manuscript in order to clarify

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this finding and to make a stronger case.

Specific comments:

1 Consideration of flowpaths and residence time does indeed give further depth to the analysis of hydrologic processes in this catchment. Unfortunately, this would require considerably more space in an article that is already quite long. This leads us to your question about further tracers. We do have a full major ion dataset. However, we prefer to present ion data and discuss flowpaths in further work. We will revise the discussion in this paper and mention the following observations: In general one would expect that glacier melt has a shorter residence time than snowmelt as the JG tributary transports much of glacier melt directly to the Juncal river streambed.

In Fig.7 it can be seen that JR samples collected in summer and (especially) autumn and winter are more depleted in δ18O relative to δ2H compared to those collected in spring. This may be an effect of longer a residence time within the catchment, because various studies have shown decreases in δ18O compared to δ2H that were caused by mineral weathering reactions. As glacier melt dominated streamflow at this late summer/ early autumn period we have to suppose that groundwater storage was important also for glacier melt. The fact that analysed spring samples at 2800 ma.s.l. were within the range of glacier melt and mid-to-high altitude snow suggested that evaporation during groundwater transport did not have a decisive effect on isotopic composition, at least in the upper reaches of the catchment.

2 We have analysed all samples for major ions. Our data set is useful for identification of flowpath and residence time (a scatter plot of TDS vs Q shows a typical annual hysteretic relationship). However for our main objective in this paper, which is to describe the seasonal and episodical changes in glacier- and snowmelt contributions, ion data provides little further valuable information. Both snow and glacier melt have very low concentrations of all measured ions. We are presently working on combining ion and isotope chemistry but this work leads us to other research questions related to

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differences in subcatchments in terms of geology and flowpaths, broadening the aims and perspectives of our first paper. We propose to comment on upcoming work within the conclusion section: for example, we are working on an article describing statistical evaluations of the full isotope/ion data set.

2 For consideration of isotopic differences in glacial meltwater, one would have to focus more on glacial flowpaths within the Juncal Norte glacier (including drilling work) as well as differences between this glacier and other glaciers within the studied basin. We think it is reasonable to assume that meltwater from different altitudes mixes relatively well during the period of glacier melt. Evolution of the glacier signal did not imply any tendency of enrichment or depletion.

In the introduction, we argue that different melt-stages at different altitudes are likely to cancel each other out, making altitude the most important variable determining snow isotope composition. As described on page 12240 from row 25 onwards, the altitude gradient was by far the most important observed trend in isotopic variability of snow. The upper part of Fig. 6 implies that the temporal isotopic variation of snow was relatively small, at least not greater than the spatial variation within each altitude/site; whereas the two late-melt-stage 2200 m a.s.l. samples were more enriched than other samples from that altitude, the difference between the two 2400 m a.s.l. samples, which were taken at the same date, was also large.

3 We will strive for economy in the revised version of the manuscript, in order to guarantee that no superfluous text is included in the manuscript.

4 A suggestion of an alternative title is “Glacier melt was the dominate source to streamflow in a Central Andean watershed during a year of low snow accumulation”. However, we prefer the present title which concentrates on presenting the nature of the data set rather than the objectives or results.

Technical corrections:

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P12330) (1) Yes, it should be snowmelt.

P12330) (2) The purpose of this sentence is to introduce the perspective of how we presently view the use of isotope tracers. Later on, we introduce our aims in the present work.

P12233) (1) Do you mean the second part/aim? Here we try to say that we want to explore how episodical changes in isotope composition along with meteorological andstreamflow data can be combined to discuss the hydrological processes that result in streamflow.

P12233) (2) We will ensure that a consistent abbreviation is used throughout the text, following an initial definition of all abbreviations.

P12236) (1) These are samples from the outflow of the tributaries draining two major sub-catchments. Such information might help interpret isotope variation in the main river (JR) as we know the altitude/glacial cover etc. of the sub-basins as explained in the Study Area section. We propose to clarify the legend of Fig. 1 by adding categories for the symbols i.e. “stream water samples”, “soil water samples”.

P12236) (2) These samples are called JS and their isotope composition is presented in Fig. 7. We propose to clarify by presenting them in Section 3.3 / Fig. 6 as they present another potential source to streamflow.

P12243) We suggest removing the sentence referring to “line 5”. Table 1 and Table 2) The study area section explains that XR samples are sampling points at the outlet of rivers/tributaries and that XB represents the sub-basins (as indicated in Fig. 1). We will propose a better site coding e.g. JUN for “JR” ,NAV for “JN”, NAV basin for “NB” etc.

Table 3) We agree that the table cannot be understood without a thorough understanding of Section 3.5.2. We will modify the Table in the revised version of the manuscript in order to make it more self-explanatory. d2H-values for each scenario will be included in the new table.

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Figure 6) We argue that it makes more sense to only show the JG results in the zoomed-in diagram because here their variation can be seen. Showing them in the lower diagram would make it difficult to see the rain and snow samples that have a δ2H-signal $\approx$ -150.

Figure 9) Presently, discharge is shown above with the same time signal, along with air temperature. This is a dense figure but it is still a compressed and effective way of showing most of the relevant findings of our study. We will make a second line graph beneath that shows the d2H time series along with discharge as well as the d18O time series, using colours.

Answer to Referee review #2 (Jakob Yde)

General comments:

We fully agree that more repeated sampling would be very useful, especially of snow at different altitudes. However, the periods of maximum accumulation and then snowmelt in this region are very short and the site and nearby roads are not always accessible in winter due to harsh weather conditions. We do hope to broaden the research line of spatial variation in isotopic composition of snow, doing more frequent field trips with a sharper focus on this specific research question.

12233,1) A more appropriate site code or full names will be used and the figure improved.

12233,24) Yes, this is true.

12234,9-10) Statement will be clarified. Most of precipitation (especially >2000 masl) is in solid form, because precipitation occurs almost exclusively during the cold period. It must be noted, though, the episodic occurrence of summer storms of unknown magnitude in the upper reaches of the mountain range.

12236, 8-13) Number of samples for each tributary is given on row 11-13. On row 11, the text "of glacier melt" will be deleted, as the statement of limited accessibility refers

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to sampling of all three tributaries of which only one (JG) represents glacier melt.

12236, 14-17) The fact that analysed spring samples (called JS) were within the range of glacier melt and mid-to-high altitude snow suggested that evaporation during groundwater storage did not have a decisive effect on isotopic composition. This is important for the estimation of contributions using the isotope data.

12237, 1) Samples were taken a few kilometres outside the catchment but we will try to include them in the figure.

12238, 21-23) Argumentation will be clarified.

12242, 6) This is a normal way of expressing a site name both as full text and abbreviation?

Section 3.4.3) A volume-weighted mean value for the April 3-4 period is 0.8 ‰ lower in d2H than the 17:00 value. This is therefore a comparatively low error that will not significantly affect our results.

STD 24 hours: 0.92 STD seasonal: 1.6

This information will be included in the revised manuscript.

12245, 19) Sunny day (so very representative for the melt period).

12248, 14) Each of the estimates of 50% and 80% glacier melt are based on extreme scenarios for 1) the altitude of the snow source 2) isotopic composition of snow at this altitude and 3) contributions during the winter period for which we could not calculate a mass balance. The minimum and maximum contributions that we used for different periods are presented in Table 4, with a minimum of 25% glacier contribution in winter which was justified by direct flow measurements. The exact minimum and maximum scenario results are 54% and 85%.

As an alternative, we have now calculated $p<0.05$ confidence intervals for all data points used in the mass balance, resulting in minimum and maximum glacier contribu-

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tions of 54 and 95% glacier contribution respectively. For snow, this confidence interval was calculated for the altitude/snow isotope composition regression line in Fig. 5b that uses all data points. The degree of uncertainty for chosen altitude of the snow source cannot be calculated. Using a higher altitude than 3000 m a.s.l. for Dec 15 which was selected here, results in higher glacier contribution estimations. This error calculation will be included in the revised manuscript.

12249, 18-21) We would prefer to clarify rather than delete this statement. Analysis for the Alps (Huss et al. 2008, Hydr Proc 22:3888-3902) predicts increasing glacier runoff for the next 40-50 years, after which volumes will diminish.

Answer to Referee review #3 (Daniele Penna)

12232, 12-18) The effect of "isotopic elution", i.e. fractionation during melt causing more enriched snowmelt leaving the pack through time, was probably dampened because as snowmelt progressed, different altitudes were in different stages of melt. As mentioned in the answer to reviewer 1 and in the conclusion Section of the paper (12249, 27), the temporal change in the isotopic signal of snowmelt that was due to higher altitudes having a more isotopically depleted snowpack, was far more important.

12333) We will improve the site coding and Figure 1b.

12337, 15-23) As described in the cited paper (which used the same lab, SIRFER at the Univ. of Utah) the technique is OA-ICOS. That paper presents repeated measurements of ultrapure water using the same equipment. Our accuracy is based on deviations from known concentrations in 10 samples. Isotope data will be presented with the appropriate number of digits according to error analysis, like you suggest.

12241, 26) We want to say here that samples all have a similar deviation from CMWL, not that they necessarily are close to this line. We then argue that because of the low variability in d2H/d18O ratio it is hard to use this ratio as a tracer. Due to the large

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range of latitudes in Chile, precipitation in the study area is indeed likely to be different from the average national water line. In Central Chile, most winter precipitation (which is nearly all snow above 2000 masl) is a result of westerly fronts. From the South part of the country up to well above Santiago, most precipitation therefore has a relatively similar composition, and will probably be rather different to that of Argentina (away from the Andes). The CMWL is therefore the best existing reference.

The CMWL demonstrated is calculated as an average of Santiago and locations further south from the IAEA database (equation from Spangenberg et al. Env Sci Techn 41:1870-1876 2007). A line from the Northern part of Chile is available (Aravena et al. Appl. Geochem. 1999, 14, 411-422) and this line plots at an equal distance from our measured samples, but in this case above our samples. It is therefore probable that our samples have a typical projection for the latitude of Central Chile. This will be commented on in the amended version of the paper.

12245, 19-12246, 5) Discharge variation within 24 hours has a similar amplitude throughout the year, although lowest in winter and highest at jan-apr. It is therefore probable that the latter period had a relatively high daily isotopic variability. See 12247.

12246, 15-16) We have the spring (JS) samples as our only reference. These show a d2H of around -135. This is more similar to the glacier signal than the winter "baseflow" signal, but JS is located at a relatively high altitude (ca. 2800 m) and was sampled at times when high altitude snow and glacier melt were the dominant input. Early and late winter snowfall was often accompanied by rain at the lowest part of the valley which probably caused enrichment of the stream signal. The lower-valley groundwater aquifer may also be affected by episodic melt of low-altitude snow and possibly by evaporation as during this period residence time of snow and glacier melt is probably long. The high uncertainty in source of streamflow for the winter period is of relatively small importance since it represents only 25% of cumulative runoff. However, we agree that representative samples of groundwater would be desirable for the analysis of the other periods . Unfortunately it is very hard to sample groundwater in this environment

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because most groundwater use is concentrated in the lower, central valley, and no wells exist in the mountain catchments.

12247) The calculations for these crucial “end-member” dates with especially high snow (oct 15) and glacier (dec 15) contributions are based on a simple tracer mass balance. As discussed above in the answers to reviewer 2, the deviation from the volume-weighted average is -0.8 for d2H on April 3-4. This is a very small error compared to the uncertainties related to the snow d2H signal. (see Fig. 5) This will be commented on in the revised manuscript.

12248, 16) As commented on in the answer to reviewer 2, a confidence interval calculation will be included in the revised manuscript. Our discussion of glacier melt contribution percentage in dry years is for the Aconcagua (and possibly Maipo) basin which comprise the water source for the economically important Metropolitana and Valparaiso regions of Chile. For other regions with a similar meteorological setting and glacial cover, we only suggest that the contribution of glacier melt in dry years should be revised as it is likely to be significant. Here, some of the recommended references will be introduced.

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