Review for Hydrology and Earth System Sciences

Title: Assessing glacier contribution to river runoff in the Andes of central Chile: Analysis of in situ weather station data, runoff measurements and melt modelling at Universidad glacier (34° 40'S, 70°20' W)

Authors: Bravo, Loriaux, Rivera, Brock

PAPER SUMMARY AND RECOMMENDATION

Bravo et al. estimate the runoff contribution of Universidad Glacier (~34°, central Chile) during the austral summer 2009-10. The authors use a set of meteorological, glaciological and hydrological measurements to run a point-scale energy balance model and to calibrate a degree-hour model, which is later used to calculate melt at the distributed scale. The authors found that glacier melt rates are extremely high (>10 m w.e.) at the glacier terminus and that the runoff contribution of the glacier represents a 10-13% of the summer runoff of the upper Tinguiririca River catchment (560 m asl). This contribution reaches 34% during late summer (March). They also conclude that a temperature-index model provides good estimations due to the availability of on-glacier data and the observed large melt rates.

The manuscript is within the scope of HESS, it is in general well-written and most of the methodology is clearly explained (with some exceptions). The discussion section needs to be strengthened and the conclusions are somehow vague. I think this paper provides interesting data and results to the glaciological and hydrological communities and, in my opinion, it will be acceptable for publication after solving/clarifying some issues (see major comments) and a careful revision of the text (see minor comments).

MAJOR COMMENTS

1. Specify if the glacier contribution to runoff is coming from the snow or the bare ice.

As the authors use MODIS images to decide the type of surface of each grid cell, it would be easy to calculate the runoff contribution from the snow and the bare ice separately (as in (Huss, 2011; Ragettli and Pellicciotti, 2012; Ayala *et al.*, 2016)). Melt rates of bare ice are important to estimate (maybe in future studies) the reduction of ice volume.

2. Validation of the degree-hour method in Figure 6

The authors justify the use of a temperature-index model based on the good agreement with the EB model results and the ablation measurements (Figure 6), but, why the time period in the x-axis of Figure 6 finishes on December 12? I think that the authors have the necessary data to run the EB and the degree-hour models after that date. I know that the sonic range stops on December 12, but it would be interesting to see the comparison with the EB model. Maybe I missed something, please clarify.

3. Comparison to other studies (section 4.3)

In order to stablish a meaningful comparison with other studies, previous results from other catchments should be always provided with: i) the percentage of glacierized area, ii) the elevation of the catchment outlet, iii) the analyzed time period and iv) if they refer to ice melt or glacier (i.e. including snow and ice) melt. Otherwise it is difficult to extract clear conclusions. For example, in lines 11/10-13, the authors mention that Brock et al. (2009) estimated 3960 to 4950 mm w.e. on Pichillancahue Glacier. The authors state that the ablation measured on Universidad Glacier doubles

that of Pichillancahue Glacier, but the time periods covered by these studies are very different in extension (Pichillancahue from January to March, Universidad from October to March).

4. *DHF for snow*

I think there might be an underestimation of the DHFs for snow (lines 4/11-15). If total ablation at S1 is 519 mm w.e. (Table 2) and the average positive air temperature is 3.5°C, is the DHF of 0.12 mm w.e. h-1 °C-1 coming from the use of all time steps (52 days*24 hours) in equation (1)? Shouldn't you use only the time steps with positive air temperatures? What is the percentage of time steps with negative temperatures before the 21st of November? Please briefly explain the mentioned procedure of Braithwaite et al. (1998).

5. *Text corrections*
- The introduction would benefit from a couple of recent articles by (Mernild *et al.*, 2015, 2016).
- Section 2.5 (temperature-index models) should be written more clearly.
- Please improve the content and structure of the conclusions section. I suggest enumerating the main outcomes of the study.
- Please perform a careful proofreading of the entire article.

MINOR COMMENTS

- Please correct systematically throughout the paper the use of capital letters for glaciers and rivers. Universidad glacier -> Universidad Glacier, Tinguiririca river -> Tinguiririca River.
- Check the use of present and past tenses. You frequently change from one tense to another, especially in the methods section.

1/11: "during late summer and autumn"

1/12: "To address these shortcomings", why in plural? You only describe the fact that few studies are available.

1/15: "to compare"

1/28: "water is a crucial resource"

1/28-29: Could you add more references apart from Masiokas et al. 2006 to sustain this sentence? The study of Masiokas et al. 2006 is about snowpack variations and not water uses.

1/30-31: Please reword: "In this region, winter precipitation is driven by the interactions…., and summer runoff (or summer water supply) by the storage and release from glaciers and the seasonal snow cover".

1/32: Maybe replace "water supply" by "runoff generation".

1/35: I think you need to replace "altitude" by "elevation" if you refer to terrain. How do you calculate the 4000 m asl? Is it the average of the peaks? Do you have a reference?

2/2: "warm temperatures"

Consider to change "trigger" by "produce" or "cause"

2/3: "rivers in the Andean basins of central Chile are mainly driven by the melting of the seasonal snowpack."

Please specify that you refer to the highest river sections. The annual regime is driven by winter precipitation in the lower sections.

2/3-4: The expression "is related to the existence" sounds awkward.

2/6-7: "For example, Peña and Nazarala (1987) estimated that the contribution of glacier melt to the Maipo River basin in summer 1981/82 was maximum in February and represented 34% of total discharge".

Please provide the elevation of the outlet and the percentage of the glacierized area of the catchment analyzed by Peña and Nazarala (2012). Also if by "glacier melt" they include the seasonal snow over the glacier.

2/10-12: Please provide one or two sentences with the main conclusions of Pellicciotti et al. (2008). Otherwise this reference is not very meaningful.

2/12-14: Please provide the elevation of the outlet and the percentage of the glacierized area of the catchment analyzed by Ragettli and Pellicciotti (2012). Also if by "glacier melt" they include the seasonal snow over the glacier.

2/14-16: Please check this sentence. "Results are available only for one basin" sounds strange.

2/17: "or on the impact of…"

2/18-19: can you be more specific? What do you mean by "melt patterns"? Temporal, spatial?

2/20: deficiencies -> knowledge gaps, issues

2/33: the words "which convergent" are not clear.

From where did you obtained the ELA? References?

2/33-34: Below this -> Below this elevation, below the ELA

3/10: "After the analysis of energy fluxes at the location of the lower AWS, a temperature-index model was calibrated and applied at the glacier scale. Resulting melt amounts were used to estimate total glacier discharge, which is compared with downstream discharge records."

3/21: Please choose another title. Snow density is not an ablation measurement.

3/22: re-measured -> read

3/26: melt -> of surface ablation. The ablation stake also includes sublimation.

3/27: "(Table 1). The sensor recorded surface …".

3/31-32; Please provide more details about the regression between Modis and Landsat products. At least the basic principles.

3/35: elevational distribution of snow cover -> snow line

4/1: What is the acquisition date of the DEM? Is it similar to that of the study period?

4/3: "Images were used…" , Modis images?

4/3-4: Remove "For modelling purposes".

4/8: remove the second "applied".

4/10-11: ", which we refer to as the degree-day factor, …".

4/11-12: stake 1 melt measurements -> stake 1 ablation measurements.

4/11-13: This sentence is not clear. Please reword, perhaps you should split it in two.

4/12: "negative temperatures are set to 0°C" This sounds very strange. Say instead that you set to zero all melt occurring at time steps when the air temperature is below the temperature threshold.

4/13: Please place the value 3.5°C in another part of the sentence.

4/13 "With these values" What values?

4/13: "Following the procedure of Braithwaite et al. (1998)" What procedure? Please briefly explain it. Do you divide the total ablation by the total number of hours or only by those with positive air temperatures?

4/14: Why would you multiply by 24? I would think that melt only occurs during daytime (maybe 14 or 16 hours per day).

4/16: Please add at the beginning of the sentence a short explanation of why you cannot use the same procedure as for snow: "As we do not have ablation stake measurements in the period when the ice surface is exposed, we use a range of published….".

4/21: Can you use only one symbol? Either Df or DHF.

5/3: Since these are negative values, maybe write "with a minima in magnitude".

5/6: It should be "entrainment of warm air from the upper atmospheric layers". Please see the articles from van den Broeke (1997a, 1997b) in Pasterze Glacier for a more theoretical perspective. Insolated bare rock surfaces can also locally increase near-surface air temperature, but I don't think that "entrainment" is the right term.

5/6-7: Could you please check if wind directions reveal up-winds from the proglacial valley? Petersen and Pellicciotti (2012) observed this feature in Juncal Norte Glacier.

5/12: "was determined following Oerlemens (2010)". Remove also the parenthesis.

5/17: Why do you need the reference of Oerlemans and Klok to neglect the heat from the rain? Or is the reference wrongly placed?

5/19: "The sensible heat fluxes were calculated…"

5/22-23: Do you assume the same value of z0 for snow and ice?

6/3-5: I guess this is ok, but you are assuming the surface temperature as 0°C for the sensible heat fluxes, so, to be consistent, everything should be evaporation.

6/13: You missed the evaporation rate.

6/26: Do not mention what you did not do, delete "There were no direct measurements…"

6/28: Add a space before "Water level…"

7/30: replace "almost always" and "more frequently" by a percentage of time.

8/3-6: Can you say something about the ELA with this procedure? If we use the elevation of the snowline at the end of the ablation season as an indicator of the ELA that year, we would get a number much higher than the value of 2900 m asl (mentioned in line 2/33).

8/14: Please use the same number of significant digits for the DHFs (in lines 4/18 you use only two).

8/18-19: Please see main comment number 2.

8/32-33: Move to methods.

9/3: October -> November

9/15: "purposes".

9/19-20: Do you have data before November 24? Why don't you start the comparison on October 1?

9/23: "…contributions from glaciers…"

9/23: Please mention these lakes in the catchment description.

9/29-31: Please explain this sentence better:

"At the beginning of the common period": What period do you mean exactly?

"in the basin": what basin? The largest one?

Why is the high daily variability associated with the control of air temperature over snowmelt?

10/3: "is suitable"

10/4: "high melt regime" is not a very precise term. Do you mean something like "large retreat during last years"? Please precise.

10/5: Please see main comment 2.

10/8: "locally-calibrated", "on-glacier"

10/9-12: Please connect this sentence better with the rest of the discussion. Why are you discussing off-glacier temperature data here?

10/13: in converting -> to convert

10/23-24: This sentence is a bit obvious. A temperature-index model is always very sensitive to air temperature variations. Please remove or explain better this idea.

10/25-27: Check the grammar of this sentence. It is very difficult to read.

10/29-30: I am not sure if you are expressing your results correctly. Please be more precise. Based on Table 4, I would say that the average contribution is between 10% and 13% over the entire period. Individual daily values range between 3 and 34%.

10/36: high levels -> high-elevation sites

10/37: Remove "which generate more water per surface unit than the non-glaciated area".

11/1-6: This is not really a discussion of your results.

11/2: What is the elevational retreat of Universidad Glacier?

11/3-6: The idea of "peak water" is interesting. Other authors have suggested that this peak will not happen in the Andes or it already happened (Ragettli *et al.*, 2016). If you keep this paragraph, consider to extend this discussion adding more literature: (Rubio-Álvarez and McPhee, 2010) and (Cortés *et al.*, 2011) also examined streamflow trends of Chilean rivers.

11/14-15: This is not clear: "is located at a particular climatic zone which maximizes summer melting" What does it mean "to maximize summer melting"?

11/16: Check the grammar.

11/23: "estimated"

11/24: "debris-free" and "debris-covered"

11/25 "snow rich years, such as 2013-2014".

11/28: "In this study, we have investigated"

11/29: "using a distributed degree-hour melt model"

11/34: ". The ablation…"

12/7: "MacDonell et al."

12/8-9: "off-glacier air temperature measurements to the glacier boundary-layers" This sentence is not clear and you did not analyze the regional scale. For a comparison to a regional scale maybe you can use results from (Mernild *et al.*, 2015, 2016).

12/15: I am not sure if the groundwater flow is depleted in summer.

12/18: What is your source for those numbers?

12/20: "Carrasco, 2005"

12/23: "In the long term"

12/17-23: These are not conclusions from your study. They sound more like a discussion. Please move or restructure.

12/29: "thank".

12/35: add volume and page numbers

TABLES

Table 4: Are those max and min values daily values?

FIGURES

Figure 1: Please move A to the left and refer to the letters (A, B and C) in the caption (instead of upper left, etc).

Figure 2: Add letters to the panels and refer to wind speed and relative humidity in the caption.

Figure 4: Can you split this plot in several hours? similar to figure 7 in (Petersen and Pellicciotti, 2011). It would be interesting to observe the diurnal cycle of wind directions and when is the katabatic flow disrupted.

Figure 5: Can you add other reference elevations? For example, the ELA or the altitude of the AWS2.

Figure 6: Why do you cut this plot in December? Please see main comment 2.

Figure 7: "latent and sensible heat fluxes".

Is there a reason why the incoming shortwave radiation changes so sharply around January 23?

Figure 8: Another panel showing the differences between these two panels would be very informative.

How do you calculate ablation for October and November 2009 if you do not have the air temperature lapse rates for that month?

Figure 9: Why don't you show results for S1?

Why don't you show results with an uncertainty range as in Figure 6?

Figure 10: If you discarded it, don't show the HydroChile data after the earthquake.

Add the correlation coefficient you calculated in lines 9/11.

Figure 12: "and the HydroChile station"

REFERENCES

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