Author’s Response

We appreciate the insightful reviews from the two referees and for the time involved in the detailed revision of our manuscript. Also we appreciate the comments of the editor. We believe this input has greatly improved the quality of our paper. In general, we agree with all comments, and have introduced changes in all sections, and have revised the Discussion where we expanded the discussion of uncertainty as the referees suggested. Furthermore, we conducted a detailed revision of the grammar and typing, and we hope that the revised manuscript meets the criteria for publishing in HESS. In the next sections, we answered point by point the comments of the referees (in bold) and give our responses in normal text, and also marked-up manuscript version showing the changes made.

Author Response to Referee 1

Specific comments

1 / 18: does glacier contribution account for 10-13% for the whole period (November 2009 to March 2010) or even 3-34%? do you really differentiate between November to March and December to March? quite confusing! Table 3 does not include November - I guess you have not revised and adapted all sections, do so now!: 1 / 18; 10 / 03; 10 / 9-11; 11 / 06; 13 / 13

We clarified and simplified this point in all sections. We now use just monthly mean values and removed references to November in the text (1/17-20; 10/18-19; 12/2-3 of the new manuscript).

3 / 21: the ‘mega-drought’ conditions in Central Chile are still prevailing, right? considering that we are already in 2017 and you want to emphasize this present effect of drought you could extend “2015-2016” (and, if available, include some latest bibliography) – also in the other sections

We agree with this comment, and add that the drought extends to 2017 with reference to government agencies in Chile (3 / 21-22). Initially, we stated 2010-2015 as this was the period covered by the most up to date reference on the topic.

10 / 21-23: the good agreement you mention does not result from data availability itself, improve this Part

We changed by “This good agreement results from: first, on-glacier measurements of meteorological data at two locations, enabling the use of a local hourly-calibrated lapse rate to extrapolate air temperature inputs to the distributed melt model;” (10/29-31)

11 / 17-18: is the “positive trend” of 0.3 m³/s/y significant or not? if not, you cannot refer to a“positive trend”

We clarify this, stating that the trend is not significant (12/14-15)

11 / 31: start a new sentence "However, the possibility…" and sharpen your argumentation as a) I understood that drought conditions are still going on and b) this sentence calls for a consequence, e. g. "… in the future and therefore more research is needed in order to address these issues."

We changed this to: "Estimations of the future runoff trend and melt contribution from Universidad Glacier are beyond the scope of this work. However, the possibility of increased persistence and recurrence of droughts in central Chile (Boisier et al., 2016) would increase the hydrological importance of Universidad Glacier in the future and therefore more research is needed in order to address these issues." (12/27-30)

12 / 07-10: the periods are both three months, from January to March for 2004 and 2005 with corresponding melt values of 4950 mm w.e. (2004) and 3960 mm w.e. (2005)? a little bit confusing

We apologize for the confusion caused and changed this sentence to: "Brock et al. (2007) estimated cumulative melt of 4950 mm w.e. and 3960 mm w.e in the January to March periods of 2004 and 2005, respectively, at 2000 m asl on Pichillancahue Glacier on Villarrica Volcano further to the south (39°S)."

12 / 29-30: both studies you are mentioning in the context of the importance of groundwater flows were performed in climatically different regions, the outer tropics in Peru and central Chile. Baraer et al. 2014 refer particularly to the dry season (of each year) - please clarify

We added addition detail to specify the different regions of these 2 studies, and that Rodriguez et al. (2016) suggest that subsurface storages is the main contributor in winter and fall: "It has been suggested that another source of streamflow during the dry season is groundwater flow i.e. in the outer tropics in Peru, the groundwater contribution to outflow is greater than 24% in all of the analyzed valleys by Baraer et al. (2014). In central Chile, Rodriguez et al. (2016) estimated that contribution associate to subsurface storage in winter and fall is of 60% in Juncal Norte Basin" (13/27-30).

13 / 32: although it is very likely, please cite your statement "increasing demand for water in the region"

We changed by:"…considering climate change and the increasing demand for water in the region (Meza et al., 2012)."(14/26)

Technical corrections

1 / 19: better reduce "during November 2009 and March 2010."
Done.

2 / 02: Delete (Garreaud, 2013), already cited in line 3
Done.

2 / 38: correct "between November and January"
Done.

3 / 04: “depending on” the aspect
Done.

3 / 18-19: delete “(after March 2010 no more data/observations were obtained from the glacier)”, no additional information
Ok, we deleted this.

3 / 26-27: three times “installed”, avoid redundancies
New sentence: “Two AWS were installed on the surface of the glacier (Fig. 1). One on the ablation zone (AWS1, 34° 42’ S, 70° 20’ W, 2650 m asl) and the second one on the accumulation zone (AWS2, 34° 38´ S, 70°19’ W, 3626 m asl).”

4 / 17-18: “dirty” is a very colloquial and “impurities” a very broad term, better write “partially covered by debris and aerosols”
We changed by term suggested.

4 / 30: add “up” after “summed”
Added.

4 / 31-32: be consistent with the use of units “between 7 mm w.e. °C-1 d-1 and 9 mm w.e. °C-1 d-1” or just “from 7-9 mm w.e. °C-1 d-1”
We used the first one.

5 / 16: again “between … and …”
Corrected.

5 / 28: use past instead of present “We restricted”
Done.

5 / 29: be consistent with other date formats in your manuscript “29 January”
Ok.

7 / 14: better write “from a catchment with a total area of 86 km² which is partially covered by…”
Changed.

7 / 24: use singular “The geometry... was measured”
Done.

8 / 16: again “between … and …”
Corrected.

9 / 13-14: avoid redundancies “some melting, with values around…”
All parts of the glacier experienced melting with values around 1 m w.e. in the upper accumulation area.

9 / 22: use “16:00 h… 10:00 h” or “4:00 pm … 10:00 am”, be consistent with the same format used in 8 / 16-17 and other sections
Ok, we used the first format.

10 / 08: correct "Tinguiririca basin" and add "to" after "due"
Done.

11 / 14: divide "Tinguiririca basin"
Done.

11 / 19: again "between 1975 and 2001"
Corrected.

11 / 21-22: better write "positive discharge trends for several rivers in central Chile"
Done.

11 / 23: correct "Tinguiririca"
Done.

11 / 24: "indicating that"
Done.

11 / 24-25: be careful, a typical grammar issue in your manuscript "tends to occur"
Changed.

11 / 26: correct "it is uncertain" and write "whether" (avoidable with a normal grammar check!)
Done.

11 / 28: correct "is yet to occur"
Done.

11 / 30: use plural "Estimations of"
Ok.

11 / 37: use the English form for "Peru"
Ok.

11 / 39: eliminate "due to increasing latitude" and use plural "reduce"
Done.

12 / 01: use plural "Local factors"
Done.

13 / 10: add "asl" after "~3800 m"
Added.

13 / 28: eliminate first "forestry" and "irrigation", both are redundant
Done.

13 / 30: not clear "medium to long term trends" – you refer to future discharge trends, clarify

Changed by:” will be affected by interannual variability in water supply and future streamflow trends in the medium to long term.

13 / 31: more precise is “glacier contribution to river discharge”
Changed.

Author Response to Referee 2

General comments

1. Conclusions
Some conclusions are confusing and not all of them are properly supported by the obtained results. The authors might consider restructuring the conclusions based on to the proposed objectives. I copy here the conclusions:

a. “Good agreement was found between melt estimated from degree-hour and energy balance models, and ablation stake and sonic ranger records at the lower weather station site in the ablation zone, supporting the application of a simple temperature-index method of calculating total glacier melt at this location. The degree-hour model was distributed at the glacier wide scale accounting for hourly variations in the local temperature lapse rate, which tended to be shallower during the daytime, when most melt occurs.”

This conclusion is very confusing, as it mixes results (“Good agreement was found…”) and methods (“The degree-hour model was distributed…”). In my opinion, the most relevant conclusion in this paragraph is that a degree-hour model provides a good simulation of surface lowering at the glacier tongue. This is probably because surface temperature is constantly close to 0°C and negative latent heat fluxes are negligible.

We understand that this conclusion is confusing. Following the referee’s recommendations we changed the text to:

- “The distributed degree-hour model provides a robust simulation of surface melt, especially on the glacier tongue where good agreement was found between melt estimated from the point scale degree-hour model, energy balance model, ablation stake measurements and sonic ranger records. Almost continuously positive air temperatures in the ablation zone between November and March are well suited to the application of a simple temperature index method to calculate glacier melt, however, some melt overestimation was identified for the accumulation zones due to more frequent negative air temperatures at higher elevations.” (13/37-38; 14/1-4)

b. “The ablation regime is dominated by incoming shortwave radiation, with highest melt rates occurring during December to February, and is also characterized by high air temperature which is almost continuously positive on the lower ablation zone between November and March. These climatic conditions result in very high melt totals, which exceed 10 m w. e. melt on the lower tongue and are thus greater than melt values reported for other glaciers in central Chile. This is attributed to the relative insignificance of sublimation to total ablation, and the high insolation due to low cloud cover and

latitudinal location, combined with predominantly positive air temperature. Melt totals were much lower in the accumulation area due to lower temperatures and persistent snow cover above about ~3800 m."

As incoming longwave radiation was not measured, I'm not sure if the authors can state that incoming shortwave controls the ablation regime. Or what do they mean exactly? That melt correlates to shortwave radiation or that incoming shortwave is the main energy input? Please be more explicit. In fact, at the end of January, incoming shortwave clearly decreases, but the energy available for melt keeps constant (or even increases) (Figure 7). Furthermore, if the regime is dominated by shortwave radiation a good explanation must be provided for the successfully use of a temperature-index model. Would an enhanced-temperature index model (that includes shortwave radiation) improve simulations?

The comparison with other glaciers does not support the hypothesis that melt rates on Universidad Glacier are larger than those on other glaciers of the central region. Only one glacier in the central region is used for comparison (Juncal Norte Glacier), but the simulated period was different (I think that Pellicciotti et al. 2014 used data described in Ragettli and Pellicciotti 2012: only the period December 2008 to February 2009). Furthermore, only one season at each glacier is not enough to provide a meaningful comparison. The hypothesis of large melt rates at Universidad Glacier is interesting, but should be better justified. If this is the case, is Universidad Glacier retreating faster than other glaciers? Has this been observed? Is there any other evidence that supports this hypothesis? Surface sublimation on Juncal Norte is also negligible on the glacier tongue (Pellicciotti et al. 2008).
"Melt totals were much lower in the accumulation area…" This is obvious. Please delete or explain further.

We agree that to conclude that the ablation regime is dominated by incoming shortwave radiation is a large assumption considering that we don't have longwave radiation measurements and have deleted the statements to this effect. Also we deleted the assumption that Universidad Glacier has the highest melt values in central Chile, and replaced this with the more cautious statement:

"Hence, Universidad Glacier may be located in a climatic zone which enhances high rates of summer melting as Sagredo and Lowell (2012) suggest in their climate zone classification for Andean glaciers. Local factors such as the large accumulation area and extension of the glacier tongue to a relatively low elevation also contributes to the high melt detected in the lower zone of the glacier (Fig. 8)."(12/36-39)

In the paragraph comparing melt totals at Universidad Glacier with other glaciers in Chile (Juncal Norte and Picchillancahue), we have redone the melt calculations to compare the same months between each study, and made the interpretation more cautious to emphasise the difficulty in comparing different locations in different years:

" Although melt rates cannot be compared directly between different glaciers in different years, two other studies in Chile provide a context for the DDHM results for Universidad Glacier in the 2009-2010 season. Pellicciotti et al. (2014) estimated the total melt in the lower ablation zone of Juncal Norte Glacier (33°S) to be between 5000-6000 mm w.e. in the December 2008 to February 2009 period, which is slightly lower than the total melt of ~5000-6000 mm w.e.

for the equivalent months of 2009-2010 at the AWS1 location on Universidad Glacier. Brock et al. (2007) estimated cumulative melt of 4950 mm w.e. and 3960 mm w.e in the January to March periods of 2004 and 2005, respectively, at 2000 m asl on Pichillancahue Glacier on Villarrica Volcano further to the south (39°S). This location likely represents the maximum ablation on Pichillancahue Glacier due to a continuous thick mantle of insulating tephra covering the glacier below this elevation. The total melt for the equivalent months of 2010 at the AWS1 location (2650 m asl) on Universidad glacier was higher, between 4800-5700 mm w.e., however, comparison of melt at different elevations on these two glaciers should be interpreted with caution."(13/1-9).

Finally we shortened the related point in the conclusion to:

- "Meteorological conditions result in very high ablation season melt totals, which reach 10 m w. e. on the lower tongue. This finding is attributed to the high insolation due to a low percentage of cloud cover, combined with a predominantly positive air temperature."(14/5-7)

c. "During the late ablation season, in February and March 15 2010, when other runoff sources such as snowmelt become depleted, the daily contribution of Universidad glacier to total runoff in the Tinguiririca reached as high as 34%."

As the authors state that there is a 1 or 2 days of lag between the simulated runoff from Universidad Glacier and streamflow measured at the DGA station (lines 10/15), daily values should not be used to estimate the percentage of glacier contribution. Calculations should be made only at the monthly scale, i.e. the 3rd and 4th column of Table 3 should be deleted.

We agree and delete all result indicating daily values including the columns of Table 3 and now use only monthly values in the paper (1/17-20; 10/18-19; 12/2-3)

2. Discussion

a. "Forcing temperature-index models with off-glacier data is problematic due to the depression of near-surface air temperature within the glacier boundary layer (Shea and Moore, 2010) under positive ambient temperature conditions"
Actually, many researchers argue that on-glacier data is affected by the glacier surface temperature and that temperature-index models should be forced only with off-glacier temperature data, because it is a better indicator of ambient conditions. As the authors did not evaluate the degree-hour model using off-glacier data, they cannot state that on-glacier data works better than off-glacier on this glacier.

We apologise for being unclear on this point. The reviewer is correct that, at a point scale, temperature-index model melt estimation using off-glacier temperature data has been shown to result in better performance than using on-glacier data. However, our point is that the availability of temperature data at 2 locations of greatly differing altitude enables us to calculate the local on-glacier lapse rate, which is advantageous for a distributed, as opposed to point-scale, melt model. A few recent studies have shown high variability in on-glacier lapse rates and recommended the use of hourly variable lapse rates in distributed melt models, where possible. Another recent study has shown that off-glacier temperature data are a poor indicator of on-glacier lapse rate. This study is available only as a recently awarded PhD thesis and paper currently under review. However, we have included these references in the paper and will take the Editor's advice on whether these references are acceptable for inclusion in the paper.

We have revised the discussion in Section 4.1 to take account of these issues, first:

"This good agreement results from: first, on-glacier measurements of meteorological data at two locations, enabling the use of a local hourly-calibrated lapse rate to extrapolate air temperature inputs to the distributed melt model;" (10/29-31)

And second:

"Forcing distributed temperature-index melt models with off-glacier data can be problematic due to the difficulty in estimating the temperature distribution across the glacier (Shaw, 2017; Shaw et al., submitted). At a point scale, a locally-calibrated temperature-index model forced with off-glacier air temperature data can lead to improvement over use of on-glacier temperature data, due to damping of temperature within the glacier boundary layer (Guðmundsson et al., 2009). However, recent glacier studies have revealed high variability in the local air temperature lapse rate , due to variations in the strength and thickness of the katabatic boundary layer and changes associated with cloud cover and synoptic-scale wind field (Petersen and Pellicciotti, 2011; Petersen et al., 2013; Ayala et al., 2015), which are difficult to account for in off-glacier data. Hence, the availability of temperature measurements for 2 on-glacier locations at different elevations provided suitable data for driving the DDHM." (10/32-37; 11/13)

b. Others comments

The discussion of the uncertainties misses the uncertainty in degree-day factors, which is actually very large. Figure 12 shows that the uncertainty in cumulative runoff at the end of the season is about 7±1 m^3 x 10^7, i.e. about 15%. As the streamflow at the DGA station is very large, this uncertainty is translated as a small percentage of total streamflow (10-13%). Hock (2003) provides a table with a large range of values, how did the authors choose the range between 7 and 9 mm d-1? Did they do some previous tests or used another reference? Another important missing source of uncertainty is the calculation of the snow line from MODIS.

The authors should add a discussion about the shortcomings of using a temperature-index model in relation to a more physically-based model. This is one of the aims proposed by the authors (number 2) Do you think that the degree-hour model could be missing something important? Maybe shading effects? Radiation fluxes? Is the model appropriate to simulate long-term mass balance or should only be used to simulate ablation at the glacier tongue?

Please include in the discussion the influence of debris-covered areas on the glacier tongue. Are the large observed melt rates substantially reduced by the thermal insulation of debris? Maybe those values above 11 m are not realistic?

We clarify the estimation of the degree day/hour factor for ice in Section 2.6, including an explanation of an initial calibration using the sonic ranger data:

"We did not have ablation stake measurements in the period when the ice surface was exposed, so we instead calibrated the F_{DD} for ice based on melt estimated from the sonic ranger for the period after the 21 November, when field observations confirmed the site was snow free, to 10 December, the end of the sonic ranger record. The resulting F_{DD} value was close to 8 mm w.e. °\`C^{-1} d^{-1}, but to account for uncertainty due to the short period of ablation data on ice we applied a range of F_{DD} values between 7 mm w.e. °C^{-1} d^{-1} and 9 mm w.e. °C^{-1} d^{-1}, which corresponds to the mid-range of values for glacier ice reported in the review of Hock (2003). (4/32-37).

And added text in the discussion (4.1) to emphasise this key source of model uncertainty:

"The key sources of uncertainty in the results are: (a) The degree-hour factor of ice. A lack of stake measurements and only a short period of sonic ranger data on ice means there is some uncertainty in a representative ice F_{DH} value at Universidad Glacier. A range of F_{DH} values between 0.29 mm w.e. °C^{-1} h^{-1} and 0.38 mm w.e. °C^{-1} h^{-1} was applied to account for this uncertainty, but we note that published ice F_{DD} values show a much greater range (Hock, 2003). Figure 7 shows that the accumulated melt of the DHM using an F_{DH} of 0.29 mm w.e. °C^{-1} h^{-1} was similar to the melt estimated by the EBM, stake and sonic range measurements in November. However, at the end of the comparison period (end of January), melt estimated using an F_{DH} of 0.38 mm w.e. °C^{-1} h^{-1} more closely matches the energy balance melt estimation. This translates into an uncertainty of 11% in the cumulative runoff from the DDHM at the end of the ablation season (Fig. 11). As the streamflow at the DGA station is large, this ice melt uncertainty contributes only a small percentage of total streamflow (3%)."(11/8-16)

We have added some discussion about the uncertainty in the snow line altitude estimation using MODIS data and annotated Fig. 7 with the lag in the snow/ice transition date between MODIS and field observations at the location of AWS1.

"(b) The snow line altitude derived from the MOD10A1 product. Although glacier surface characteristics on the tongue allow differentiation between ice and snow, the resolution of the snow product is similar to the width of the glacier tongue. A lag of 10 to 12 days was found between the MOD10A1 product and field observations of the transition from snow to ice at the AWS1 site (Fig. 7). Furthermore, in the highest zone of the glacier, fewer debris and aerosols cover the ice surface, making it harder to distinguish between ice and snow, which could have led to errors in identifying surface type."(11/16-21)

We added more information about the general limitation of this kind of model and some specific issues as the referee suggests, related to debris-cover (section 4.1):

"Although we consider the model outputs to be robust, it is important to bear in mind that empirical temperature-index models do not attempt to simulate the real physical processes of glacier ablation, and the DDHM ignores other influences on rates and spatial patterns of ablation, such as topographic shading, blowing snow, debris-cover and subsurface fluxes. Hence, the DDHM may not be suitable for longer term mass balance studies where climatic and surface factors may undergo change."(11/4-7)

And:

“c) DDHM melt estimates were not adjusted for the effects of moraine and patchy distributed debris in the ablation zone (Fig. 1). The moraines are of substantial thickness on lower areas of the tongue and likely to reduce ablation below the highest values shown in Fig. 8 in the terminus zone. However, other areas of the ablation zone are affected by a thin and patchy layer of debris or aerosol, which is likely to increase ablation through local albedo reduction (Fyffe et al., 2014). Although, quantification of the effects of debris on melt is beyond the scope of this study it would be expected that impacts of thick morainic debris and thin patchy debris elsewhere will tend to compensate in overall melt estimations for the glacier.”(11/21-26)

MINOR COMMENTS

The Introduction could benefit from a better structure in which climate, hydrology and economic characteristics are separately described.

Please check the use of terms “runoff” and “streamflow”. I think that they are not the same: Runoff is the portion of precipitation or melt that does not infiltrate or evaporate. Streamflow is the runoff of surface water through a channel.

We checked the terms and made changes according referee suggestions, including the paper title.

2/22: Why is 40°S important?

We deleted this.

2/27: “To address some of these issues”, which ones? Please be more specific or delete.

Deleted.

2/29: what do you mean by “surface controls”?

We changed by “to identify the principal meteorological drivers of ablation and their patterns and trends during a full ablation season”

2/35: Section 1.1? This section numbering is odd. I wouldn’t use 1.1 if there is not a 1.2.

Ok, we moved this section to methods.

3/10: Did you observe penitentes on the glacier? These could be an indication of non-negligible sublimation.

We don’t observed penitents in the glacier. We added observations of Lliboutry (1958) to the Study Area section.

5/24-25: This should be included in the discussion. Maybe total ablation values larger than 11 m w.e. are not realistic.

We agree and added to discussion.

7/26: Please add the value that you calculated for the slope from Aster.

Added.

8/6-8: Please explain better the procedure to calculate k. What value do you obtain? Do you use the water level sensor to calibrate it?

We explain better this issue. We use the water level sensor to calibrate it.

8/13-17: What did you find at AWS2? Is this station more influenced by free atmospheric flow? Is there a predominant wind direction?

We added the wind direction of AWS2 in the description but not as a new Figure.

8/24: This section should be moved to 3.3, i.e. after presenting results from the EBM.

Ok, section moved.

9/6: "Incoming shortwave radiation …" but you did not measure the incoming longwave radiation.

We agree, please see response to General Comments.

12/7: Please be consistent in these comparisons. You are not comparing melt rates (which should be given in units of time), but total melt amounts. However, these total melt amounts are not really comparable because they were calculated for different time periods (Juncal Norte Glacier: December-February, Phichillancahue Glacier: January-March, Universidad Glacier: October to March). Is melt at Universidad Glacier really larger than at the other glaciers of the region? Please see main comment 1b.

We agree, but we maintain the comparison, but now for the same periods (months). Please see our response to the General Comments. This is due to give a context of our results using previous studies. However we agree that the conclusion of Universidad Glacier has the larger melt in the region does not find support in our results.

13/29-30: "The potential for hydropower…" This sounds like a study site description.

We changed this to "Hydropower generation on the Tinguiririca River at La Higuera and La Confluencia (Pelto, 2010), will be affected by interannual variability…".

13/31: "More studies…" What type of studies? or do you mean more long-term stations?

We changed this to: "Finally, more long-term high elevation stations in the Andes are necessary to establish the inter-annual variability of glacier contribution to river discharge in order to help manage future water availability, considering climate change and the increasing demand for water in the region (Meza et al., 2012)."

Figure 8: The description/discussion of this figure is very short.

We don't think it is necessary to add more text at this point as the key points are displayed visually by the figure. However, Fig. 8 does inform the later discussion at various points, e.g. in assessing the impact of debris areas on melt rates.

Figure 11: Consider deleting this figure or extending its description/discussion. The authors state that it shows an efficiently channelized drainage system, but it is not clear from the figure. Maybe you can add a comparison of calibrated k values with those from other glaciers?

We deleted this Figures as referee suggests.

TECHNICAL CORRECTIONS
Please correct systematically throughout the paper the use of capital letters for glaciers and rivers. Universidad glacier -> Universidad Glacier, Tinguiririca river -> Tinguiririca River. In the revision statement, the authors state that they have done that, but they did not (e.g. in the title).
Done

1/11: melt -> glacier ablation (you also analyze surface sublimation)
Done.

1/12: Here and throughout the article: Universidad glacier -> Universidad Glacier
Done.

1/12: Here and throughout the article: Tinguiririca river -> Tinguiririca River
Done.

1/14: ->distributed temperature-index and runoff routing model (delete melt)
Done.

1/14: Please check the grammar of this long sentence or split it in two. "meteorological measurements" are not used to "compare total model modelled glacier melt to river flow measurements". "meteorological measurements" are only used to drive the melt models.
Changed to:
"We used meteorological measurements from two automatic weather stations installed on the glacier to drive a distributed temperature-index and runoff routing model. Total modelled glacier melt is compared with river flow measurements at three sites located between 0.5 and 50 km downstream."

1/18: delete "a contribution"
Deleted.

1/19: total runoff -> streamflow at the outlet of Tinguiririca River Basin
Changed.

2/2: Please check with the native English speakers (I'm not) in the author's list the use of "which". I think that it is not used correctly in this sentence.
Checked.

2/13: Same as in 2/2.
Checked.

2/13: on -> for the

Done.

2/13: “current future”?
Changed by “future glacier contribution”.

2/17: “in the glacier ablation zone” -> “on …”
Done.

2/30: across -> during?
Done.

2/34: Tinguiririca
Done

2/38: November to January -> November and January
Done.

3/2: Consider to remove “lower”, or is there an “upper tongue”?
Removed.

3/18-19: Consider to remove the sentence in the parenthesis.
Removed.

3/26: -> “on the ablation zone”
Done.

3/27: -> “on the accumulation zone”
Done.

3/34: -> “on the ablation zone”
Done.

4/8: “We used the…” for what? Check the grammar.
Corrected.

4/9: using “a regression”?

Done.

4/12: What is the resolution of Aster GDEM?
30 m added.

4/14: altitude -> elevation
Changed.

4/16: We have used -> We used. Please be consistent with the verb tense.
Ok.

4/31: “calculated ice melt”

Done.

4/34: Consider to replace “a” by “M”.
Replaced as suggested

5/14: Fig 2 -> Fig 3?
Changed.

5/15: over an average day -> on an average day?
Changed.

5/18: Please consider the use of this wording: “While the LR minima are likely to be related to …., the afternoon maxima are potentially caused by the erosion …”.
Changed:
“While the LR minima are likely to be related to the strengthening of katabatic flow during the daytime (Petersen and Pellicciotti, 2011), the afternoon maximum is potentially caused by the erosion of the katabatic boundary layer on the lower glacier tongue, due to warm air advection from bare rock surfaces at the glacier sides and proglacial area (van de Broeke, 1997; Ayala et al., 2015).”

5/22: “we distribute air temperature”
Done.

5/28: “Check grammar: “We restrict use of data only up until this date”.
Changed.

5/29: occurs -> occurred.
Changed.

5/34: “and, as summer precipitation amounts are small, ”
Changed.

6: If I checked correctly, terms P and e_sat were not explained.
Added.

6/7: Is k the same as k_0?
Yes, changed.

6/9: Where -> where
Done.

6/9: “Finally,”
Changed.

6/11: Delete the “,”.
Done.

6/14: add “where”
Added.

6/24: The reference to Hock (2005) is not necessary for that equation.
Deleted

6/25: Mention that only positive Ψ values are used for that equation.
Added.

6/29: Add "where".
Added.

7/9: You already described z.
Ok, deleted.

8/2: Consider: "At each grid cell and time step, glacier melt obtained with the ….".
Changed as referee suggested.

8/10: Consider to reduce the section title. "Meteorological and snow conditions" should be enough.
Done.

8/11: Please consider something like: "During the period December-March, air temperature is almost constantly above 0°C at AWS1, but it shows more frequent negative nocturnal values at AWS2."
Changes as referee suggested.

8/13: "variability, but hourly values".
Changed.

8/22: Please check the term "high cloud cover", it might be misunderstood as high in elevation.
Changed by: "a high percentage of cloud cover (greater than 30%) affected snowline detection"

8/25: "compared to melt"
Changed.

8/31: Delete: "between 0.29…".
"…fall within the DHM range for F_{DH} values between 0.29 mm w.e. h^{-1} $°C^{-1}$ and 0.38 mm w.e. h^{-1} $°C^{-1}$.".

8/35: "in the range of the values estimated by…"
Changed.

9/19: -> "similar to those at the end of October".
Changed.

9/25-26: "At the hourly scale, water discharge estimated…"
Changed.

9/26: Consider: "the values derived from the water pressure sensor".
Changed as referee suggests.

9/35-36: "between 50% and 66%" (delete "the").
Deleted.

10/3: Delete "Mean total".
Deleted.

10/10: "After the peak in runoff" (delete "the").
Deleted

10/19: "from glaciers in the central region of Chile".
Changed.

11/11: "becomes depleted" -> "depletes".
Changed.

11/14: missing space after Tinguiririca.
Corrected.

11/18: Is this information relevant if the trend was not significant?
Probably not but we maintain as previous studies.

11/18-22: Check grammar or split.
Corrected.

11/24: "wheter" -> "whether". Furthermore, if you use "whether", then you need to provide two alternatives.
Deleted "whether".

11/29: "for e.g."?
Corrected.

11/35-36: Move this to the Introduction or to the Study area.
Corrected.

12/23: estimate -> estimated.
Changed.

12/34-36: Please split this sentence. It is too long and difficult to follow.
Changed to: "In this study, we have investigated the meteorological conditions, ablation and melt water contribution to downstream river flow of Universidad Glacier, located in central Chile during the 2009-2010 summer ablation season. We used a point scale energy balance and a distributed degree-hour melt model, driven by data from two on-glacier weather stations. The main outcomes of this work are:".

12/34: You didn't really investigate the "climatic conditions". This would require a long time series.
Agree, corrected.

13/7: “greater than melt values reported for other glaciers in central Chile”.
Deleted.

13/13: “will be” -> “should be”?
Corrected.

Figure 1:
19/2“Location of Universidad Glacier” (delete “the”).
19/2: delete “entire”.
19/4: “indicates the locations of stream gauge”?
Done.

Figure 2:
“Hourly time series of observed meteorological variables”.
Done.

Figure 3:
“of hourly lapse rates”.
“upper and lower box limits”
Done.

Figure 5:
Indicate the date of the ASTER image also in the caption
Added.

Figure 8:
c) difference of panels a and b.
Corrected.

Figure 10:
“and the HydroChile…”
Corrected.

Figure 11:
“estimated from the pressure sensor”.
Figure deleted.

Figure 13:
Delete “for reference”.
Deleted (new Figure 12).

Assessing glacier melt contribution to ~~river runoff~~streamflow –at ~~Universidad glacier~~Universidad Glacier, central Andes of Chile

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Abstract. Glacier melt is an important source of water for high Andean rivers in central Chile, especially in dry years when it can be an important contributor to flows during late summer and autumn. However, few studies have quantified glacier ~~melt~~ melt contribution to ~~river runoff~~streamflow. To address this shortcoming, we present an analysis of meteorological conditions and ~~melt~~ ablation for ~~Universidad glacier~~Universidad Glacier, a large valley glacier in the central Andes of Chile at the head of the ~~Tinguiririca river~~Tinguiririca River, for the 2009-2010 ablation season. We used meteorological measurements from two automatic weather stations installed on the glacier to drive a distributed temperature-~~index melt and~~index and runoff routing model.~~, and to compare~~ ~~total~~ Total modelled glacier melt is compared ~~to~~ with river flow measurements at three sites located between 0.5 and 50 km downstream. The temperature-index model was calibrated at the lower weather station site and showed good agreement with melt estimates from an ablation stake and sonic ranger, and with a physically-based energy balance model. ~~Universidad glacier~~Universidad Glacier is characterized by extremely high melt rates over the ablation season which may exceed 10 m water equivalent on the lower ablation area, representing ~~a contribution~~ between 10% and 13% of the mean monthly streamflow ~~total runoff~~ at the outlet of the ~~observed in the upper~~ Tinguiririca River ~~basin~~ Basin between~~during the~~ ~~November~~ December 2009 and ~~to~~ March 2010~~ period~~. ~~-~~This contribution rises to a monthly maximum of almost ~~34~~20% in ~~late summer~~March 2010 demonstrating the importance of glacier runoff to ~~river flow~~streamflow, particularly in dry summers such as 2009-2010. The temperature-index approach benefits from the availability of on-glacier meteorological data, enabling the calculation of the local hourly-variable lapse rate, ~~-~~and is suited to high melt regimes, but would not be easily applicable to glaciers further north in Chile where sublimation is more significant.

1 Introduction

The central region of Chile (30° - 37° S), in southern South America, is characterized by a high dependence on the water supply coming from the Andes. This region, incorporating the capital city, Santiago, has more than 10 million inhabitants representing 60% of the country's population. In addition to domestic supply, water is a crucial resource for agriculture irrigation, industries, mining, hydropower generation, tourism and transport (Aitken et al., 2016; Masiokas et al., 2006; Meza et al., 2013; Ayala et al., 2016, Valdés-Pineda et al., 2014).~~ Growing~~ P~~p~~opulation growth and urban expansion in recent years ~~is~~ are increasing the demographic pressure on water resources (Meza et al., 2012).

In this region, winter precipitation is driven by the interactions between the westerlies circulation and the Andean natural barrier, and summer runoff is strongly influenced by the storage and release from glaciers and snow covers (Garreaud, 2013). Accurate knowledge of the processes involved in the runoff generation from mountainous areas is vital to understand and predict the availability of water resources and contribution to sea level rise (Mernild et al., 2016) especially considering the ongoing and projected future decrease in glacier volume under climate warming scenarios (Pellicciotti et al., 2014, Ragettli et al., 2016).

In these latitudes, the Andes present several peaks over 6000 m above sea level (asl) and have a mean elevation of ~4000 m asl ~~(Garreaud, 2013)~~. The majority of annual precipitation occurs during the winter months, which~~ is~~ accumulat~~es~~ed as snow above the winter 0°C isotherm altitude, between 1500 and 3500 m asl (Garreaud, 2013). This seasonal snowpack provides an important water reservoir for the following summer months, when warm temperatures and high incoming solar energy cause the melting of snow. As a consequence, rivers in the high Andes basins of central Chile are mainly driven by the melting of the seasonal snowpack (Cortés et al., 2011). However, another key source of water in the summer dry season is ~~is related to~~ the presence of glaciers along the Andes ~~c~~Cordillera. Crucially, glacier melt is an important source of water for Andean rivers in dry summers when little or no precipitation occurs at the upper watersheds and the seasonal snowpack is exhausted (Gascoin et al., 2010, Masiokas et al., 2013, ~~Gascoin et al., 2010,~~ Ohlanders et al., 2013). For example, Peña and Nazarala (1987) estimated that the contribution of ice melt to the high basin of the Maipo River (5000 km^2, outlet at 850 m asl) in the ~~summer~~ 1981/1982 summer was highest in February and represented 34% of total~~-~~ streamflow~~discharge~~.

There have been only a few physically-based distributed glacio-hydrological modelling investigations in the Andes of Chile (Pellicciotti et al., 2014; Ayala et al., 2016), which is an important limitation ~~on~~ for the understanding of~~ current~~ future glacier contribution to river flows, considering the current ~~status~~trends of glacier shrinkage (e.g. Bown et al., 2008; Le Quesne et al., 2009; Malmros et al., 2016) and negative mass balance (Mernild et al., 2015) in the region. One of the most studied glacier~~s~~ in the region is Juncal Norte ~~glacier~~Glacier, where Pellicciotti et al. (2008) investigated the point scale energy balance and melt regime using an automatic weather station (AWS) located ~~in~~ on the glacier ablation zone, showing that the ablation process is dominated by incoming shortwave radiation. Using a physically-based distributed glacier-hydrological model, Ragettli and Pellicciotti (2012) estimated that melted glacier ice from Juncal Norte ~~glacier~~ Glacier contributed 14% of the basin (241 km^2, 14% glacierized, outlet at ~2250 m asl) ~~runoff~~ streamflow for the entire hydrological year 2005/2006, with a maximum of 47% over the late ablation season (February to April). Despite these advances, such results are limited to one basin and cannot necessarily be extrapolated, particularly along climatic gradients to the north and south. Other glacier energy balance studies in central Chile ~~north of 40°S~~ have focused on improving understanding of energy fluxes and ablation at the point scale (Corripio and Purves, 2004; MacDonnell et al., 2013) or on the impact of volcanic ash on energy balance and melt (Brock et al., 2007; Rivera et al., 2008). There is therefore a lack of knowledge of spatial and temporal melt patterns at the glacier-wide scale and ~~the progress~~ of glacier melt contribution to downstream ~~runoff~~ discharge over a full ablation season.

~~To address some of these issues, w~~We present an analysis of meteorological conditions and ~~melt~~ ablation for ~~Universidad glacier~~Universidad Glacier, a large valley glacier in central Chile, located in a climatic transition zone with a Mediterranean climate type, between the humid temperate south and arid north of the country. The main aims are: (1) to identify the principal meteorological drivers~~, and surface controls,~~ ~~on~~ of ablation and their patterns and trends ~~across~~ during a full ablation season; (2) to compare methods of ablation estimation using two models of differing complexity and input data requirements; and (3) to estimate the contribution of glacier melt to downstream river flows and its water resource implications. The aims are addressed using point energy balance and distributed temperature-index models forced with data from two AWS located on the glacier ablation and accumulation zones, and stream gauging records both proximal to the glacier snout and 50 km downstream at mid-altitude on the ~~Tinguiririca~~Tinguiririca R~~r~~iver.

1.1 Study area

Universidad glacier (34° 40’ S, 70°20’ W) is located in Central Chile, in the upper part of Tinguiririca basin (1436 km^2), 55 km east of San Fernando city and 120 km south-east of Santiago (see Fig. 1 for location). The upper Tinguiririca basin is defined as a snowmelt dominated river (Cortez et al., 2011) with runoff peak occurring between November to January (Valdés-Pineda et al., 2014). The area of the glacier is 29.2 km^2 with a length of 10.6 km and an altitudinal range of 2463 m asl to 4543 m asl (Le Quesne et al., 2009). The glacier has an accumulation zone divided in two basins which converge at an altitude of ~2900 m asl. Below this elevation, the glacier has a well-defined lower tongue. The Equilibrium Line Altitude (ELA) for the 2009-2010 hydrologic year, based on the position of the end of summer snowline was located in the range between 3500 and 3700 m asl depending the aspect of the glacier (Fig. 1). The general aspect is southerly, but the west accumulation zone has an easterly aspect. Universidad is a valley glacier that is part of a more extended glacier complex, which includes the Cipreses glacier flowing to the north, Palomo glacier flowing to the north-east, Cortaderal glacier flowing to the east, and other small glaciers flowing to the west. Another feature of the basin is the presence of small lakes mainly associated with glaciers (proglacial lakes) and debris-covered glaciers (supraglacial lakes).

Scientific investigations at Universidad glacier were initiated by Lliboutry (1958) who described some morphological characteristics of the glacier surface including ogives, blue bands, penitents and moraines. A frontal retreat of 1000 m for the period 1955-2007 was documented from aerial photographs, historical documents, tree ring chronologies and satellite images (Le Quesne et al., 2009). More recently Wilson et al. (2016) estimated Universidad glacier surface velocities between 1967 and 2015. This analysis reveals an increase in the surface velocities between 1967 and 1987, followed by a deceleration between 1987 and 2015. Also a cumulative retreat of 465 ± 44 m was found between 1967 and 2015.

2 Data and methods

2.1 Study area

Universidad Glacier (34° 40’ S, 70°20’ W) is located in Central Chile, in the upper part of the Tinguiririca Basin (1436 km^2), 55 km east of San Fernando city and 120 km south-east of Santiago (see Fig. 1 for location). The upper Tinguiririca Basin is defined as a snowmelt dominated river (Cortez et al., 2011) with runoff peak occurring between November and January (Valdés-Pineda et al., 2014). The area of the glacier is 29.2 km^2 with a length of 10.6 km and an altitudinal range of 2463 m asl to 4543 m asl (Le Quesne et al., 2009). The glacier has an accumulation zone divided into two basins which converge at an altitude of ~2900 m asl. Below this elevation, the glacier has a well-defined tongue. The equilibrium line altitude (ELA) for the 2009-2010 hydrological year, based on the position of the end of summer snowline was located in the range between 3500 and 3700 m asl depending on the aspect of the glacier (Fig. 1). The general aspect is southerly, but the west accumulation zone has an easterly aspect. Universidad Glacier is a valley glacier that is part of a more extensive glacier complex, which includes the Cipreses Glacier flowing to the north, Palomo Glacier flowing to the north-east, Cortaderal Glacier flowing to the east, and other small glaciers flowing to the west. Another feature of the basin is the presence of small lakes mainly associated with glaciers (proglacial lakes) and debris-covered glaciers (supraglacial lakes).

Scientific investigations at Universidad Glacier were initiated by Lliboutry (1958) who described some morphological characteristics of the glacier surface including ogives, blue bands, penitents and moraines, noting the absence of penitentes above 3800 m asl, in contrast to glaciers further north in -Chile. According to his observationsobservations, the lower part of the glacier had a sudden advance around 1943hedescribed“” [surge]. After this event, a spectacular recession from 1946-1950 was describedrecorded. In term of surface characteristics the most striking fact is the absence of penitentes above 3800 m. AmMore recently, a frontal retreat of 1000 m for the period 1955-2007 was documented from aerial photographs, historical documents, tree ring chronologies and satellite images (Le Quesne et al., 2009). Wilson et al. (2016) estimated Universidad Glacier surface velocities between 1967 and 2015 and identified an increase in surface velocities between 1967 and 1987, followed by a deceleration between 1987 and 2015. ~~Furthermore~~Furthermore, a cumulative frontal retreat of 465 ± 44 m was found between 1967 and 2015.

2.2~~1~~ Experimental setting

The study focuses on the ablation season (1 October to 31 March) of the 2009/2010 hydrological year, when the discharge, meteorological and glaciological conditions were monitored. We focused on one ablation season due to availability of data. ~~(after March 2010 no more data/observations were obtained from the glacier).~~ The 2009/2010 hydrological year is of significance as it marks the beginning of a period of extreme aridity (2010-2015) in central and southern Chile (Bosier et al., 2016) which extended into 2017 according to data from the Dirección General de Aguas de Chile (DGA) and Dirección Meteorológica de Chile.

Data collected include meteorological observations at two AWS, surface lowering monitoring from ablation stakes and a sonic ranger (Fig. 1), satellite-derived snow cover distribution and discharge measurements in the proglacial stream. ~~After~~Following the analysis of energy fluxes at the location of the lower AWS, a temperature-index model was calibrated and applied at the glacier scale. The ~~R~~resulting melt amounts were used to estimate total glacier discharge, which is compared with downstream discharge records.

~~2.~~2. ~~2~~3 Automatic weather stations (AWS)

Two AWS were installed on the surface of the glacier (Fig. 1). One ~~was installed in~~on the ablation zone (AWS1, 34° 42’ S, 70° 20’ W, 2650 m asl) and the second one ~~was installed in~~on the accumulation zone (AWS2, 34° 38´ S, 70°19’ W, 3626 m asl). AWS1 recorded a full set of energy balance variables including air temperature, humidity, wind speed and direction, net all-wave radiation, incoming shortwave radiation and atmospheric pressure, while AWS2 recorded the same variables but omitted~~ing~~ radiation measurements. Although AWS1 was installed at the beginning of 2009 we restricted the analysis to the ablation season defined as 1 October 2009 to 31 March 2010. AWS2 recorded data from 10 December 2009 to 31 March 2010. Both AWS recorded data averaged at a 15-minute interval; however, we use hourly mean values as model inputs.

2.4~~3~~ Ablation measurements: stakes and sonic ranger

Three stakes installed ~~in~~ on the ablation zone of the glacier between 30 September and 3 October 2009 were read on 21 November while the surface was still snow covered at each stake (Fig. 1, Table 1). Stake 1 was located close to AWS1 and was used to assess point melt estimations from the different models. Snow density was measured using the standard Mount Rose procedure (U.S. Department of Agriculture, 1959) on the days of installation and re-measurement of stakes. We calculated the mean snow density (Table 1) and water equivalent (w.e.) surface ablation for each stake.

A Campbell Scientific SR-50 sonic ranging sensor was installed next to AWS1. The sensor recorded surface lowering continuously every 15 minutes during a 73 day period. SR-50 data were filtered using a Hampel filter (Pearson, 2002) and then hourly means were calculated. Lowering measurements were converted to w.e. ablation values using snow density measured at stakes (Table 1).

2.54 Snowline elevation estimation using MODIS snow product

To derive snowline elevation, Wwe used the MODIS/Terra L3 global daily snow cover product (MOD10A1, Hall et al., 2002) with a spatial resolution of 500 m, which retrieves subpixel fractional snow cover area. MOD10A1 was developed using a regression with Landsat TM (30 m spatial resolution) Normalized Difference Snow Index (NDSI), offering a much more accurate approach for detecting snow covered area than previous satellite snow-cover products (Cortés et al., 2014). In order to map the snow line throughout the monitored period, we obtained the hypsometric curve of Tinguiririca basinTinguiririca Basin from an ASTER GDEM V2 with a resolution of 30 m (Tachikawa et al., 2011) and then calculated the snowline altitude for the austral summer of 2009-2010 in the upper Tinguiririca basinTinguiririca Basin. The MODIS snow cover product was used only if the cloud fraction for each satellite image was less than 30%. The snowline altitude elevation on days of high cloud cover was estimated using a linear interpolation between the last day before and the first day after the data gap. The time series of snowline altitude elevation is used as an model input for modelling to define snow or ice surface areas on the glacier. We have used the MOD10A1 product since it provides a reliable differentiation of the ice surface of Universidad glacierUniversidad Glacier, which is partially covered by debris and dirty due the presence of ogives, debris and impurities, from the fresh snow areas. Howeveraerosols. However, the MOD10A1 product gives the fractional snow cover for each pixel in the range 0 to 100, and to assure a correct snowline altitude we assumed the presence of snow in the pixel only when the fractional value was 100. Despite thisHowever we acknowledge expect some uncertaintyies in the snowline altitude.

2.65 Degree-hour model (DHM)

We applied a standard degree-day model (DDM) (e.g. Hock, 2003, 2005) at an hourly time step, in order to estimate glacier surface melt during the 2009/2010 ablation season. The model was forced with hourly temperature data from AWS1.

Melt is calculated by multiplying the hourly positive temperature, T_h^+ by a factor that relates temperature and melt, which we referred to as the degree-day factor (F_{DD}), or degree-hour factor (F_{DH}) when applied at an hourly interval (De Michele et al., 2013). We used the stake 1 ablation measurements (Table 1) and the mean positive air temperature (4.6 °C) –at AWS1 to estimate a F_{DH} for snow. The percentage of hours with positive temperatures was close to 75%, therefore we only used only time steps with positive values. Dividing the ablation value by the mean of positive air temperature (Braithwaite et al., 1998), we obtained a F_{DH} for snow of 0.12 mm w.e. –°C^{-1} h^{-1}. The F_{DH} is multiplied by the positive hourly temperature at an hourly interval and results are summed up for every day. As wWe did not have ablation stake measurements in the period when the ice surface is was exposed, so we instead calibrated the F_{DD} for ice based on melt estimated from the sonic ranger for the period after the 21 November, when field observations confirmed the site was snow free, to 10 December, the end of the sonic ranger record. The resulting gave a F_{DD} value was close to 8 mm w.e. °`C^{-1} d^{-1}, but to account for uncertainty due to the short period of ablation data on ice we used applied a range of published F_{DD} values between 7 mm w.e. °C^{-1} d^{-1} and - 9 mm w.e. °C^{-1} d^{-1}, which corresponds to the mid-range of values for glacier ice reported in the review of (Hock, (2003) and conducted tests to obtain a range of uncertainty in calculated ice melt. In this case we used values between 7 and 9 mm w.e. °C^{-1} d^{-1}, commonly used for glacier ice.. The hourly F_{DH} for ice was calculated by dividing the ice F_{DDH} by 24 to give F_{DH} values for ice of 0.29 mm w.e. °C^{-1} h^{-1} and and 0.38 mm w.e. °C^{-1} h^{-1}, respectively. Therefore mMelt, a M (mm w.e. h^{-1}), is estimated by the following relationship:

$$aM(t,z) = F_{DH} T_h^+(t,z), \quad (1)$$

The published F_{DD} values for ice were calibrated for daily average temperature and therefore could lead to a melt overestimation when applied as F_{DH}s values in the hourly model, since calculations are only made for hours with positive temperature. To test this potential bias, we compared melt calculations between a standard degree-day model and the DHM, using a F_{DD} of 9 mm w.e. °C^{-1}

d^{-1} and F_{DH} of 0.38 mm °C^{-1} h^{-1}, for the period of ice exposure at AWS1 and AWS2, representing the ablation and accumulation zones, respectively. At AWS1, the difference between daily and hourly model results is negligible (<2 mm w.e. out of a total of >8000 mm w.e.). This small difference reflects the ~~more or less~~almost continuously positive air temperature in the lower ablation zone during the study period (Fig. 2). At AWS2, the DHM overestimation is more significant at 290 mm w.e. out of a total of ~2000 mm w.e. of ice melt, representing an increase in melt of 15% over the DDM. This is due to more frequent negative temperatures in the accumulation zone during summer months. Melt overestimation in the accumulation zone will have a relatively small impact on total glacier runoff, which is dominated by melt from the ablation zone. Furthermore, there will be no melt estimation bias on snow as the F_{DH} for snow was calibrated using field measurements from ~~Universidad glacier~~Universidad Glacier. We therefore apply the DHM in our calculations as it has the advantage of enabling hourly variations in temperature lapse rate to be accounted for in the distributed melt calculations across the glacier (next section).

2.7~~6~~ Distributed degree-hour model (DDHM)

To distribute the DHM (distributed DHM, DDHM hereafter) we calculated the temperature lapse rate (LR) using both AWS in the common period (Fig. 2~~2~~). Following the recommendation of Petersen and Pellicciotti (2011), we estimated a daily LR cycle (Fig. 3) considering that melt occurs mostly during the day. The mean hourly LR ~~temperature gradient over~~ on an average day, oscillates between -0.004 °C m^{-1} ~~to~~ and -0.007 °C m^{-1}. During the night (24:00 h to 08:00 h local time) the mean temperature gradient was close to -0.006 °C m^{-1} and fairly constant. During the day the LR has two cycles with minima in magnitude close to -0.005 °C m^{-1} at 11:00 h and -0.004°C m^{-1} at 19:00 h, separated by a maximum of -0.007 °C m^{-1} at 16:00 h. While ~~T~~the LR minima are likely to be related to the strengthening of katabatic flow during the daytime (Petersen and Pellicciotti, 2011), ~~and~~ the afternoon maximum is potentially caused by ~~due to~~ the erosion of the katabatic boundary layer on the lower glacier tongue, ~~and~~ due to warm air advection~~ed~~ from bare rock surfaces at the glacier sides and proglacial area (van de Broeke, 1997; Ayala et al., 2015).

Using the hourly LR, we distribute~~d the~~ air temperatures over the entire glacier surface on a 30 m grid at an hourly time step, using the ASTER GDEM V2 and the glacier outline which was digitized from an ASTER image of 27 March, 2010. For October and November we assumed the same hourly lapse rate observed in the common period (December to March). Calculated melt values were not adjusted for reduction under debris cover on a medial moraine in the ablation zone.

2.8~~7~~ Energy balance model (EBM)

A point scale energy balance model (EBM hereafter) was applied using weather station data collected at the AWS1, between 1 October 2009 and 29 January~~,~~ 2010. We restrict use of data only up until this date because a sharp change in net radiation and incoming shortwave radiation ~~occur~~occurred~~s~~ after 29~~th~~ January;~~,~~ therefore data from late January onwards are of questionable accuracy.

~~-~~Energy available for ablation, ψ (W m^{-2}) was determined following Oerlemans (2010):

$$\psi = S_{in} + S_{ref} + L_{in} + L_{out} + H_s + H_l, \qquad (2)$$

Where S_{in} and S_{ref} are incoming and reflected solar shortwave radiation, L_{in} and L_{out} are incoming and outgoing longwave radiation and H_s and H_l are the turbulent fluxes of sensible and latent heat, respectively. In this study, the conductive heat flux is considered negligible due to the predominantly positive air temperatures (Fig. 2) and, as summer precipitation totals amount are small~~ in summer in the study region~~, the amount of sensible heat brought to the surface by rain or snow is neglected (e.g. Oerlemans and Klok, 2002). The balance of the radiative fluxes S_{in}, S_{ref}, L_{in} and L_{out} ~~were~~ was directly measured by the net radiometer sensor ~~of the~~at AWS1. The sensible heat fluxes were calculated using the bulk approach (Cuffey and Paterson, 2010):

$$H_s = \rho_a c_a C^* u[T - T_s] \ (\Phi_m \Phi_h)^{-1}, \quad (3)$$

u is wind speed in m s^{-1}, T is air temperature in K and T_s ice surface temperature which is assumed to be a constant of 273.15 K (0°C). $C^*$is a dimensionless transfer coefficient, which is a function of the surface aerodynamic roughness (z_o), assumed to be 0.001 m for melting snow and 0.01 m for ice on mid~~-~~latitude glaciers (Brock et al., 2006):

$$C^* = \frac{k^2 ~~k_0^2~~}{ln^2\left(\frac{z}{z_o}\right)}, \quad (4)$$

z is the height above the surface of the T and u measurements (2 m) and k is the von Kárman's constant (0.4). ρ_a is the density of air which depends on atmospheric pressure P (in Pa):

$$\rho_a = \rho_a^o \frac{P}{P_0}, \quad (5)$$

~~Where~~ where ρ_a^o (1.29 kg m^{-3}) is the density at standard pressure P_0 (101300 Pa). Finally, c_a is the specific heat of air at a constant pressure (J kg^{-1} K^{-1}) calculated as (Brock and Arnold, 2000):

$$c_a = 1004.67\left(1 + 0.84\left(0.622\left(\frac{e}{P}\right)\right)\right), \quad (6)$$

The latent heat flux H_l is:

$$H_l = \frac{0.622\, \rho_a\, L_{v/s} C^* u[e - e_s]}{P} (\Phi_m \Phi_h)^{-1}, \quad (7)$$

where e is air vapour pressure~~ above the surface~~, e_s is the vapour pressure at the glacier surface which is assumed to be 611 Pa (Brock & Arnold, 2000) the vapour pressure of a melting ice surface, and $L_{v/s}$ is the latent heat of vaporization or sublimation, depending on whether the surface temperature is at melting point (0°C) or below melting point (<0°C), respectively. Due to the absence of snow temperature measurements, the air temperature is assumed to determine the condition of evaporation or sublimation over the surface.

e is obtained from the observed relative humidity at AWS1 (f) and using the empirical formula of Clausius-Clapeyron (Bolton, 1980), which is only function of air temperature (T in °C):

$$e_{sat}(T) = 6.112 \exp\left(\frac{17.67\, T}{T + 243.5}\right), \quad (8)$$

where e_{sat} denotes the saturation vapour pressure in the air. Finally,~~And~~ e is found by rearranging the following equation:

$$f = 100\left(\frac{e}{e_{sat}}\right), \quad (9)$$

~~M~~The meelt rate (M) is calculated ~~following (Hock, 2005)~~using:

$$M = \frac{\psi}{L_m \rho_w}, \quad (10)$$

Only positive values of ψ are used in this equation. L_m is the latent heat of fusion and ρ_w is the water density (1000 kg m^{-3}). ~~S~~The sublimation rate (S) is calculated as (Cuffey and Paterson, 2010):

$$S = \frac{H_l}{L_s \rho_w}, \quad (11)$$

where L_s is the latent heat of sublimation.

Stability corrections were applied to turbulent fluxes using the bulk Richardson number (Ri_b), which is used to describe the stability of the surface layer (Oke, 1987):

for Ri_b positive (stable): $(\Phi_m \Phi_h)^{-1} = (\Phi_m \Phi_v)^{-1}$

$$= (1 - 5Ri_b)^2, \quad (12)$$

for Ri_b negative (unstable): $(\Phi_m \Phi_h)^{-1} \;\; = (\Phi_m \Phi_v)^{-1}$

$$= (1 - 16Ri_b)^{0.75}.$$

Ri_b is used to describe the stability of the surface layer:

$$Ri_b = \frac{g(T - T_s)(z - z_0)}{Tu^2}, \quad (13)$$

~~Where~~ where g is the acceleration due to gravity.~~, z is the height of the meteorological observation (2 m).~~

2.9~~8~~ Proglacial discharge estimation

The estimation of the river discharge was based on the determination of the cross section geometry and the monitoring of water level in the proglacial stream. Water level in the stream was monitored using a submersible pressure transducer (KPSI Series 500), installed 500 meters downstream of the glacier terminus (2428 m asl), which registered hourly water levels from 24 November ~~24~~ 2009, until 14 April 2010. The proglacial stream receives the waters draining from a catchment with a total area of 86 km^2 which is partially covered by ~~an 86 km^2 catchment, partially covered by~~ the ~~Universidad glacier~~Universidad Glacier (29.2 km^2) and some debris-covered ice bodies (4.4 km^2) (DGA, 2011).

In order to convert automatic water level measurements into discharge, we applied the widely used Manning's equation (Phillips and Tadayon, 2006; Fang et al., 2010; Gascoin et al., 2010; Finger et al., 2011) which combines environmental parameters such as stream slope, bed roughness and river section shape and area, for uniform open channel flow. It defines the discharge Q [m^3 s^{-1}] as follows:

$$Q = VA, \quad (14)$$

~~Where~~ where A is the area of the cross section and V is the average instantaneous velocity in the channel ~~which is~~ defined as:

$$V = \frac{1}{n} R^{\frac{2}{3}} \alpha^{\frac{1}{2}}, \quad (15)$$

~~Where~~ where R is the hydraulic radius, α is the slope of water surface, and n is the Manning coefficient of roughness.

The geometry of the channel cross section ~~were~~ was measured in the field at the location of the pressure transducer. The hydraulic radius is a measure of channel flow efficiency and is defined as the ratio of the cross sectional area to its wetted perimeter. We used the ASTER GDEM of 30 m resolution to estimate ~~the~~ a slope of 0.03° ~~the~~ for ~~terrain~~ water surface in the gauged section. The roughness coefficient was set as 0.05, according to the United States Geological Survey (USGS) value for cobble and boulder bedrocks (Phillips and Tadayon, 2006), which corresponded to our site. The area of the cross section A was estimated using water level observations from the pressure transducer and the width of the wet section, which in turn is estimated from an empirical relationship with water level.

We also make use of two other streamflow gauge measurements (see Fig. 1). The first is operated by a private company, Pacific HydroChile, located 1700 m from the glacier snout recording data every hour. The second one is operated by ~~the Dirección General~~

de Aguas (DGA), and is located on the Tinguiririca riverTinguiririca River at 560 m asl, 50 km downstream the Universidad glacierUniversidad Glacier. The contributing watershed to this lower gauge has an area of 1436 km^2 with a total ice cover of 81 km^2 (DGA, 2011), among which Universidad glacierUniversidad Glacier is by far the largest single ice body.

2.109 Discharge routing

Estimated glacier melt obtainedAt each grid cell and time step, glacier melt obtained- with the DDHM for each 30 m grid cell and each time step was transformed into discharge using a linear reservoir model (Baker et al., 1982; Hock and Noetzli, 1997). For hourly time intervals, the proglacial discharge Q is given by:

$$Q(t_2) = Q(t_1)e^{-1/kK} + M(t_2) - M(t_2)e^{-1/kK}, \quad (16)$$

Where where $M(t)$ is the rate of water inflow to the reservoir, which is considered to be equivalent to the total glacier melt. kK is the factor of proportionality in hours and is estimated from the time it takes for the water entering the top of the reservoir to flow out of the bottom (Baker et al., 1982). Using the record from the pressure transducer, the optimal value of K was identified as 14.

3 Results

3.1 Meteorological and snow conditions for the ablation period (October 2009 to March 2010)

Time series of meteorological variables are shown in Fig. 2. During the December-March period, air temperature is almost constantly above 0°C at AWS1, but negative nocturnal values are more frequent at AWS2. At AWS1 temperature is generally above 0°C during December-March even during the night, while temperature at AWS2 shows more frequent negative values during the night (Fig. 2).

Wind speed shows some inter-daily variability, but the hourly values are predominantly between 2 m s^{-1} and 8 m s^{-1}. Wind speed was generally lower in summer (December to March) than spring (October to November). The prevailing wind direction (~10° to ~45°) corresponds to the general ice flow direction (Fig. 4), indicating a strong and persistent katabatic wind. Wind direction in the accumulation zone (not shown) also shows a predominant katabatic flow aligned with the ice flow direction. The daily cycle of wind direction at AWS1 reveals that the prevailing predominant katabatic wind is slightly weakened during afternoon hours (between 14:00 h to 18:00 h, local time, Fig. 4), corresponding with a temporary strengthening of the daytime temperature lapse rate (Fig. 3). Relative humidity shows a large diurnal daily variability (Fig. 2). Saturation is reached on during several days in the period.

The snow line altitude derived from MODIS data is shown in Fig. 5. At the beginning of the ablation season, the entire glacier surface was covered by snow. The snowline altitude increased gradually until mid-January and thereafter stabilized between 3800 and 4000 m asl. There is some variability in the snow line positioning, probably due to varying proportions of cloud cover on different days. This snowline altitude range, derived from the MODIS MOD10A1 snow cover product (Section 2.5) is slightly higher than the altitude of the ELA estimated with the ASTER image from the end of March of 2010 (3500 to 3700 m asl, Fig. 1) possibly due to differences in spatial resolution in the two types of imagery. In the first half of the ablation season a high percentage of cloud cover (greater than 30%) affected snowline detection.

3.2 Point scale ablation comparison: observation and modelling

Sonic ranger measurements and stake observations (Fig. 1) were compared to the melt estimated with the EBM and DHM at the point scale for the location of AWS1 (Fig. 6). Sublimation represents a small percentage (2.8%) of the total ablation calculated

~~with the energy balance indicating the dominance of positive temperature and hence melt regime. Snow disappears at this location (~ 2650 m asl) near 7 November 2009.~~

~~Melt simulations from the DHM and EBM agreed well with the stake and sonic ranger ablation measurements. The DHM tended to lag behind the EBM and sonic ranger until 21 November, after which the EBM and sonic ranger estimates fall within the DHM range for F_{DH} between 0.29 and 0.38 mm w.e. h^{-1} °C^{-1}. The DHM estimated little or no melt during cold periods, e.g. the first 10 days of November, whereas the EBM indicates melt (as does the sonic ranger) caused by high insolation. During warm periods, e.g. 11-16 November, the DHM estimated higher melt rates than the sonic range sensor, indicating the high sensitivity of the DHM to temperature fluctuations. At the end of the comparison series, the EBM and sonic ranger total melt are in the range of the melt estimated by the DHM. Overall, despite uncertainties in snow density and melt model parameters, the good agreement between the different models and measurements, supports the use of the DDHM to estimate total glacier melt.~~

3.2~~3~~ Energy balance

Figure ~~7~~ 6 shows the daily mean of observed energy fluxes (net radiation and incoming shortwave radiation), turbulent fluxes calculated by the EBM (latent and sensible heat) and the resulting energy available for melt at AWS1, ~~also~~ calculated by the model. Daily mean melt energy closely matches daily mean net radiation through much of the ablation season due to compensation between generally positive H_s and mainly negative H_l, except during warm periods such as late January when H_l turns positive (Fig. ~~7~~6, Table 2). ~~Incoming shortwave radiation was the main source of melt energy (Table 2).~~ Energy available for melt is highest~~r~~ in December and January when both incoming shortwave radiation (Table 2) and air temperature (Fig. 2) are high.~~and tends to diminish during February to March, in close association with the annual cycle of incoming shortwave radiation.~~

3.3 Point scale ablation comparison: observation and modelling

Sonic ranger measurements and stake observations (Fig. 1) were compared to melt estimated with the EBM and DHM at the location of AWS1 (Fig. 7). Sublimation represents a small percentage (2.8%) of the total ablation calculated with the EBM reflecting the predominantly positive air temperatures and, hence, a melt regime. Snow disappears at this location (~ 2650 m asl) around 21-22 November 2009.

Melt simulations from the DHM and EBM agreed well with the stake and sonic ranger ablation measurements. The DHM tended to lag behind the EBM and sonic ranger until 21 November, after which the EBM and sonic ranger estimates fall within the DHM range for F_{DH} values between 0.29 mm w.e. h^{-1} °C^{-1} and 0.38 mm w.e. h^{-1} °C^{-1}. The DHM estimated little or no melt during cold periods, e.g. the first 10 days of November, whereas the EBM indicates melt (as does the sonic ranger) caused by high insolation. During warm periods, e.g. 11-16 November, the DHM estimated higher melt rates than the sonic ranger sensor, indicating the high sensitivity of the DHM to temperature fluctuations. At the end of the comparison series, the EBM and sonic ranger total melt are within the range of the values estimated by the DHM. Overall, despite uncertainties in snow density and melt model parameters, the good agreement between the different models and measurements, supports the use of the DDHM to estimate total glacier melt.

3.4 Distributed degree hour model (DDHM)

Figure 8 shows the accumulated melt for each pixel of ~~Universidad glacier~~Universidad Glacier estimated by the DDHM during the period 1 October 2009 to 31 March 2010 using ice F_{DH} values~~s~~ of 0.29 mm h^{-1} °C^{-1} and 0.38 mm h^{-1} °C^{-1}. As the degree-hour melt is only a function of temperature, the higher zones of the glacier presented the lowest melt and *vice versa*. The maximum values of ~11000 mm w.e. (for F_{DH} = 0.38 mm h^{-1} °C^{-1}) were located on the lower glacier tongue (Fig. 9). All parts of the glacier experienced ~~at least some~~ melting~~,~~ with ~~melting~~ totals ~~values~~ around 1 m w.e. in the upper accumulation area. Bare ice surfaces accounted for ~85% of the total melt. As is expected, differences in the cumulative melt calculated with the two ice F_{DH} values are higher in the tongue of the glacier (> 2000 mm w.e.) where ice is exposed for most of the ablation season.

3.5 Discharge

During the study period we estimated an average stream flow of 12 m³ s^{-1} with a range from 4 m³ s^{-1} and 43 m³ s^{-1} (Fig. 10). Discharge values increased gradually between the end of November and the end of December. The mid ablation season (January and February) experienced two major discharge peaks. Subsequently, values decreased from late February to the end of March to values similar to those at the end of October (Fig. 10).

The hourly mean hydrographs have strong daily~~diurnal~~ amplitude cycles ~~(Fig.11)~~ during the high discharge months (Fig.10) ~~-~~and exhibit a characteristic shape for a glaciated catchment, with a steep rise and gradual decline (Nolin et al., 2010; Willis, 2011). Discharge peaked typically at 16:00 ~~PM~~h, from a minimum at 10:00 ~~AM~~h ~~-~~which, considering the large size of the glacier, indicates an efficiently channelized drainage system flow.

At the hourly scale, ~~W~~water discharge estimated at the HydroChile station showed high correlation with the values derived from ~~estimations made from~~ the water ~~level/~~pressure sensor installed near the glacier front ~~at hourly scale~~ (r ~~-~~=0.92). Generally, the HydroChile station values exceeded water discharges estimated from the water pressure sensor before mid-January; thereafter the water pressure sensor derived values exceeded the HydroChile results, until 27 February when there was a large earthquake in central Chile. A ~~The~~ sudden jump in HydroChile values occurred around this date, most ~~(Fig. 10) is~~ likely due to this earthquake, whereas the pressure sensor derived values were adjusted for the change in water height. For comparison purposes we rejected data from the HydroChile station after the earthquake.

3.6 Comparison of glacier melt water with total proglacial river discharge

Total glacier melt calculated with the DDHM is compared with the discharge records estimated from the pressure sensor and the gauging records from the HydroChile station, at 500 m and 1700 m from the glacier snout, respectively, between 24 November, 2009 and 31 March 2010 (Figs. 1 and ~~12~~11). At an hourly time step, glacier melt and proglacial discharge estimations have correlations of 0.72 (pressure sensor station) and 0.75 (HydroChile station). Melt estimated from the glacier represents between ~~the 50~~42% and ~~66~~58% of the ~~runoff~~ streamflow estimated from the pressure sensor, depending on the ice F_{DH} value used (Fig. ~~12~~11). The remaining 42% to ~~34~~58% ~~to 50%~~ of proglacial ~~runoff~~ streamflow is attributed to contributions from glaciers and lakes in lateral valleys, ~~which also contribute to proglacial river discharge,~~ but are not accounted for in the DDHM calculations. Moreover, during the first half of the season, the proglacial river includes snow melt runoff from the non-glaciated area of the valley.

Monthly ~~Mean total~~ melt from ~~Universidad glacier~~Universidad Glacier represents between 10% and 13% (depending on ice F_{DH} used) of the total ~~runoff~~ streamflow of the entire upper ~~Tinguiririca basin~~Tinguiririca Basin (1478 km^2) ~~over the~~during the ~~November~~ December 2009 ~~to~~to March 2010 period (Fig. ~~13~~12, DGA station, Table 3). This percentage is much more than the area of the ~~Universidad glacier~~Universidad Glacier (~2%) as a portion of ~~with respect to~~ the total ~~basin~~ area of the upper ~~Tinguiririca~~Tinguiririca Basin. The percentage of glacier contribution is variable during the season (Table 3). At the beginning of the common period of pressure sensor and AWS1 measurements (end of November) ~~runoff~~ streamflow is dominated by the snow melt across ~~in~~ the entire upper ~~high Tinguiririca~~Tinguiririca ~~basin~~Basin. This is ~~,~~reflected in the high daily variability in ~~runoff~~ streamflow at ~~in~~ the DGA station until January, due to the control of air temperature over snow melt (Fig. ~~13~~12). ~~. In these months, the glacier melt contribution ranged between 3% and 10%.~~ After the ~~the~~ discharge peak ~~in the runoff~~ at the end of January, the contribution of ~~Universidad glacier~~Universidad Glacier to total ~~basin runoff~~ streamflow increased to 14-~~19~~19%~~ with peaks up to~34%~~.

The daily variability of all stream gauging series was similar between December and January. The DGA station measurements mainly show the additional influence of the air temperature variations on snow melt across the catchment, since the rainfall in the period of Fig. ~~13~~ 12 was 0 mm. In February and March, the DDHM calculated melt and the DGA station ~~runoff~~ streamflow display similar temporal variations with one to two days of lag~~ between each~~.

4 Discussion

4.1 Modelling approach and uncertainties

Our results suggest that a simple empirical melt model (DDHM) is suitable for estimating glacier melt contribution to ~~river runoff~~streamflow from glaciers in the central region of Chile. This interpretation is based on the close correlation between ~~ablation~~ melt estimates from the DHM and ~~melt~~ melt estimates from an energy balance model, ablation stake and sonic ranging sensor~~ data~~ at a point scale, and agreement between estimates of total glacier runoff and discharge estimations in the proglacial stream. This good agreement results from: first, on-glacier ~~the availability~~ measurements of ~~on-glacier~~ meteorological data at ~~>1~~two locations, enabling the use of a local hourly-calibrated lapse rate to extrapolate air temperature inputs to the distributed melt model;~~;~~ second, ~~a~~ locally calibrated degree-hour factors; ~~for snow; and third, an hourly-calibrated lapse rate at the glacier for spatial extrapolation of air temperature inputs to the distributed melt model~~and third, knowledge of the spatial distribution of snow and ice cover from satellite data. Forcing distributed temperature-index melt models with off-glacier data ~~is~~ can be problematic due to the difficulty in estimating the temperature distribution across the glacier (Shaw, 2017; Shaw et al., submitted). At a point scale, a locally-calibrated temperature-index model forced with off-glacier air temperature data can lead to improvement over use of on-glacier temperature data, due to damping of temperature within the glacier boundary layer (Guðmundsson et al., 2009). However, ~~the depression of near-surface air temperature within the glacier boundary layer (Shea and Moore, 2010) under positive ambient temperature conditions~~ recent glacier studies have revealed high ~~and~~ variability in the local air temperature lapse rate, due to variations in the strength and thickness of the katabatic boundary layer and changes associated with cloud cover and synoptic-scale wind field ~~which can lead to high hourly variability in local air temperature lapse rate~~ (Petersen and Pellicciotti, 2011; Petersen et al., 2013; Ayala et al., 2015), which are difficult to~~cannot be~~ accounted~~ed~~ for in off-glacier data. Hence, the availability of temperature measurements~~data~~ for 2 on-glacier locations at different elevations provided suitable data for driving the DDHM.

Although we consider the model outputs to be robust, it is important to bear in mind that empirical temperature-index models do not attempt to simulate the real physical processes of glacier ablation, and the DDHM ignores other influences on rates and spatial patterns of ablation, such as topographic shading, blowing snow, debris-cover and subsurface fluxes. Hence, the DDHM may not be suitable for longer term mass balance studies where climatic and surface factors may undergo change.

The key sources of ~~model~~ uncertainty in the results are: (a) The degree-hour factor of ice. A lack of stake measurements ~~on ice surfaces~~ and only a short period of sonic ranger data on ice means~~t~~ there is some uncertainty in a representative ice F_{DH} value at Universidad Glacier. ~~prevented local calibration of a F_{DH} for ice.~~ A~~The~~ range of F_{DH} values between 0.29 mm w.e. °C^{-1} h^{-1} and 0.38 mm w.e. °C^{-1} h^{-1} was applied to account for this uncertainty, but we note that published ice F_{DD} values ~~implies a potentially~~show a much greater range~~ of values~~ (Hock, 2003).~~used in this study were based on results from a range of earlier studies provided by Hock (2003).~~ Figure 7 shows that the accumulated melt of the DHM using an F_{DH} of 0.29 mm w.e. °C^{-1} h^{-1} was similar to the melt estimated by the EBM, stake and sonic range measurements in November. However, at the end of the comparison period (end of January), melt estimated using an F_{DH} of 0.38 mm w.e. °C^{-1} h^{-1} more closely match the energy balance melt estimation. This translates into an uncertainty of 11% in the cumulative runoff from the DDHM at the end of the ablation season (Fig. 11). As the streamflow at the DGA station is large, this ice melt uncertainty contributes only a small percentage of total streamflow (3%). (b) The snow line altitude derived from the MOD10A1 product. Although glacier surface characteristics on the tongue allow differentiation between ice and snow, the resolution of the snow product is similar to the width of the glacier tongue. A lag of 10 to 12 days was found between the MOD10A1 product and field observations of the transition from snow to ice at the AWS1 site (Fig. 7). Furthermore, in the highest zone of the glacier, fewer debris and aerosols cover the ice surface, making it harder to distinguish between ice and snow, which could have led to errors in identifying surface type. (c) DDHM melt estimates were not adjusted for the effects of moraine and patchy distributed debris in the ablation zone (Fig. 1). The moraines are of substantial thickness on lower areas of the tongue and likely to reduce ablation below the highest values shown in Fig. 8 in the terminus zone, as evidenced by their locally high elevation relative to debris-free ice areas. However, other areas of the ablation zone are affected by a thin and patchy layer of debris or aerosol, which is likely to increase ablation through local albedo reduction (Fyffe et al., 2014). Although, quantification of the effects of debris on melt is beyond the scope of this study it would be expected that impacts of thick morainic debris and thin patchy debris elsewhere will tend to compensate in overall melt estimations for the glacier.; (ad) Ssnow density, which is required to convert stake and ultrasonic sensor measurements of snow into w.e. melt for model validation and calculation of degree-hour factors, . Here snow density was -measured only two times in the early- ablation period.; (b) parameters in the energy balance model: albedo was not measured but was not needed here as net all-wave radiation was measured directly at AWS1; however, lack of albedo measurements prevented the application of an Enhanced temperature-index (ETI) model (Pellicciotti et al., 2008) at the glacier-wide scale; and, although the z_0 value cannot be evaluated due to lack of independent measurements, the small contribution of the turbulent fluxes to total melt means z_0 errors would account for only a small amount of total EBM error; (ce) Single, fixed z_0 values from published literature were applied to snow and ice. Although the representativeness of these z_0 values cannot be evaluated due to lack of independent measurements, the small contribution of the turbulent fluxes to total melt means z_0 errors would only have a small influence on EBM output. (f) Sublimation was ignored in the DDHM. However, Universidad Glacier has an ablation regime dominated by melt, more typical of temperate glaciers further south in Chile (Brock et al., 2007), therefore this omission is likely to have led to only a small overestimate of glacier runoff. (g) Groundwater flows and evaporative losses from glacier melt water are unknown but considered negligible. (h) The date of the ASTER GDEM is not known, which could have produced small errors in temperature distribution due to elevation changes in the glacier surface between the dates of GDEM acquisition and model analyses.

sublimation in the DDHM was ignored, but Universidad glacier has an ablation regime dominated by melt, more typical of temperate glaciers further south in Chile (Brock et al., 2007) therefore this is likely to have led to only a small overestimate of glacier runoff; (d) groundwater flows are not known and evaporative losses from glacier melt water were also unknown but considered negligible and (e) the date of ASTER GDEM is not know which could produce error in temperature distribution due to elevation changes in the glacier surface.

During periods of low positive temperature and high insolation, the DHM tends underestimated melt, and *vice versa* during periods of high temperature., due to the high temperature sensitivity of simple temperature-index models (Pellicciotti et al., 2005). This implies spatial and temporal errors will occur, i.e. overestimation of melt during warm weather and on the lower glacier, and melt underestimation during cold weather and on the upper glacier,. Such error will tend to compensate over time and in summation of total glacier melt, but will lead to short–term errorsinaccuracies.

4.2 Glacier contribution to basin ~~runoff~~streamflow

The finding that ~~Universidad glacier~~Universidad Glacier, while accounting for just 2% of the total basin area, contributed a monthly mean between ~~3~~10% and ~~34~~13% of total ~~runoff~~ streamflow from the entire upper ~~Tinguiririca basin~~Tinguiririca Basin over the December 2009 and~~to~~ March 2010 period, demonstrates the importance of glaciers for river flows in central Chile during the summer months. The overall glacier melt contribution to the ~~Tinguiririca river~~Tinguiririca River would be much larger considering that the total glacier area of the basin is 81 km^2, representing 5.5% of the total basin area. Crucially, the glacier contribution becomes more significant over the course of the summer as other sources, principally the seasonal snowpack, ~~become depleted~~deplete. Hence, glacier runoff becomes critical to maintaining flows in the ~~Tinguiririca river~~Tinguiririca River during years when summer drought extends into autumn, e.g. in the period 2010-2015 (Bosier et al., 2016), and in dry winters when snowpack accumulation at high-elevation sites is small. Research by Gascoin et al. (2011) and Pourrier et al. (2014) on glaciers of the arid Andes has revealed the hydrological importance of glaciers to the north of the ~~Tinguiriricabasin~~Tinguiririca Basin.

The recent and ongoing retreat ~~for~~ of ~~Universidad glacier~~Universidad Glacier is a direct consequence of ~~in response to~~ atmospheric warming (Le Quesne et al., 2009; Wilson et al., 2016) and the relevance of glacier melt contribution highlighted in this work, implies that serious negative impacts on river ~~runoff~~ discharge are expected over the next decades. In the 1950-2007 period, a ~~positive~~ trend in runoff for the upper ~~Tinguiririca basin~~Tinguiririca Basin was observed (0.3 $m^3 s^{-1} y^{-1}$, not significant) (Casassa et al., 2009). Considering that the estimated upward migration (200 m) of the zero degree isotherm between 1975 and ~~-~~2001 in central Chile~~,~~ (Carrasco et al., 2005) far exceeds the elevational retreat (~60-70 m) of the ~~Universidad glacier~~Universidad Glacier snout (Wilson et al., 2016) over a longer period (1967-2015), the contributing melt area~~, and hence total glacier melt~~ of ~~Universidad glacier~~Universidad Glacier has increased in the last ~30 years. Such ~~This~~ increases in glacier melt might explain the positive discharge trends for several rivers in central Chile ~~in rivers of central Chile~~ as suggested by Casassa et al. (2009). Another characteristic to consider is that the date marking the timing of the ~~center~~centre of mass of annual flow for the upper Tinguiririca River shows a negative trend in the period 1961-2007 (Cortez et al., 2011), indicating that the bulk of the annual flow is shifting towards earlier in the year. This implies that snowmelt ~~tends to~~ occurss earlier and hence glacier ice is also exposed earlier in the year, increasing the hydrological importance of glaciers.

From our analyses, it is uncertain ~~wheter~~if the Tinguiririca River's ~~runoff~~ discharge has already reached the "peak water" expected for glacierized basins as a consequence of deglaciation (Casassa et al., 2009). The observed recent positive ~~recent~~ trend in the ~~runoff~~ discharge of the Tinguiririca River (Masiokas et al., 2006 ~~and Casassa et al., 2009~~) suggests that peak water is yet to occur~~s~~. In contrast, recent modelling work has shown that peak water has already passed further north in the Juncal Norte Basin ~~for e.g. the Juncal basin further to the north~~ and that future runoff ~~for this basin~~ is likely to sharply decrease (Ragettli et al., 2016). Estimations of the future runoff trend and melt contribution from ~~Universidad glacier~~Universidad Glacier are beyond the scope of this work.~~,~~ H~~h~~owever, the possibility of increased persistence and recurrence of droughts in central Chile (Boisier et al., 2016) would increase the hydrological importance of ~~Universidad glacier~~Universidad Glacier in the future and therefore more research is needed in order to address these issues.~~.~~

4.3 Comparison to other studies in Chile

~~According to the classification of Sagredo and Lowell (2012), Universidad glacier is located in a climatic zone, characterized by positive mean air temperature in the ablation season, which favours the summer melting.~~ It has been shown that ~~in~~ on high altitude glaciers ~~of~~ in northern Chile and in the dry season of the outer tropics of ~~Perú~~Peru and Bolivia, melt rates are reduced as more ablation occurs through sublimation (Winkler et al., 2009; Sagredo and Lowell, 2012; MacDonell et al., 2013), whereas, to the south of ~37° S, lower incident shortwave radiation due to increasing latitude and increased cloud cover reduces available energy for melt (Brock et al., 2007). Hence, Universidad glacierUniversidad Glacier may be located in a climatic zone which maximizes enhances high rates ofrelative summer melting as Sagredo and Lowell (2012) suggest in their climate zone classification for Andean glaciers. Local factors such as the large accumulation area and extension of the glacier tongue to a relatively low elevation also contributes to the high melt detected in the lower zone of the glacier (Fig. 8).

Although melt rates cannot be compared directly between different glaciers in different years, two other studies in Chile provide a context for the DDHM results for Universidad Glacier in the 2009-2010 season. Pellicciotti et al. (2014) estimated the total melt in the lower ablation zone of Juncal Norte Glacier (33°S) to be between 5000-6000 mm w.e. in the December 2008 to February 2009 period, which is slightly lower than the total melt of ~75000-86000 mm w.e. for the equivalent months of 2009-2010 at the AWS1 location on Universidad Glacier. Brock et al. (2007) estimated cumulative melt of 4950 mm w.e. and 3960 mm w.e in the January to March periods of 2004 and 2005, respectively, at 2000 m asl on Pichillancahue Glacier on Villarrica Volcano further to the south (39°S). This location likely represents the maximum ablation on Pichillancahue Glacier due to a continuous thick mantle of insulating tephra covering the glacier below this elevation. The total melt for the equivalent months of 2010 at the AWS1 location (2650 m asl) on Universidad glacier was higher, between 504800-576000 mm w.e., however, comparison of melt at different elevations on these two glaciers should be interpreted with caution.

Modelled ablation season melt at Universidad glacierUniversidad Glacier is high in comparison to Juncal Norte glacier (33°S) where maximum accumulated melt is in the order of 5000-6000 mm w.e., depending on the model applied (Pellicciotti et al., 2014). These values are near around half of the estimated values on obtained at the lower tongue of Universidad glacierUniversidad Glacier (Figs. 8 and 9). However, melt rate distribution shows great variations depending on altitude. The total melt rate at the equilibrium line of Universidad glacierUniversidad Glacier (3500 - 3700 m asl; 2000 to 2500 mm w.e.) is less than the melt at the equilibrium line (~2000 m asl) of Pichillancahue glacier in Villarrica volcano further south (39°S), where Brock et al. (2007) estimated cumulative melt of 4950 mm w.e. and 3960 mm w.e between in the January andto March periods of 2004 and 2005, respectively. However, it should be is worth noteing that ablation below 2000 m asl this elevation is greatly reduced on Pichillancahue glacier Glacier by an extensive cover of thick insulating tephra, which is likely to reduce the local equilibrium line elevation..

Recently Ayala et al. (2016) found estimated that the glacier ice melt contribution at the river outlet of glaciers Bello, Yeso (debris-free glaciers) and Piramide (debris-covered glacier) in the central Andes (~33.53°S), depends on the meteorological conditions of each year. In snow rich years, such as 2013-2014, glaciers contributed an estimated 30% of summer water runoffstreamflow, while in dry years such as 2014-2015 the summer contribution was 50%. This latter value is similar to the glacier ice melt contribution recorded at the outlet of Universidad glacierUniversidad Glacier, which was in the range 42% to 58% of the total discharge estimated with the pressure sensor. Considering that almost no precipitation was recorded by weather stations close to the study site, the 2009-2010 ablation season is representative of relatively dry years in central Chile., which interestingly resulted in a similar percentage melt contribution with respect to the 2014-2015 season in Bello and Yeso glaciers. However, Aas Ayala et al. (2016) suggest, melt contribution comparison between different with other glaciers must made with caution, considering that glacier melt depends of altitudinal range, glacier characteristics, differences in atmospheric conditions for each year and even differences in methodology.

At a basin scale, glacier contribution to downstream runoff discharge in the Tinguiririca River is of similar magnitude to previous results for the central Andes., e.g.For example Ragettli and Pellicciotti (2012) estimated that 14% of the total runoff streamflow of the Juncal River Basin (241 km^2, outlet at ~2250 m asl) was contributed by comes from Juncal Norte glacier Glacier (9.9 km^2) in the 2005/2006 hydrological year reaching 2005/2006 with a maximum of 47% during the late ablation season. For the Maipo basinBasin, Peña and Nazarala (1987) estimated a mean contribution from glaciers (~7.2% of the total upper Maipo basin area) of 11.8% between hydrological years 1981/1982 and 1985/1986, with maximum values towards during the end of each hydrological year. An important issue raised in of the results of showed by Peña and Nazarala (1987) is the that there is high an interannual variability in the discharge from glaciers,. Ffor example, the percentage of the glacier contribution to total runoff streamflow in the Maipo River in February of 1983 was just 5%, but in February of 1982 it was 34%. It has been suggested that another source of runoff streamflow during the dry years season at the end of the ablation season is groundwater flow i.e. in the outer tropics in Peru, the groundwater contribution to outflow is greater than 24% in all of the analyzed valleys by Baraer et al. (2014). In central Chile, Rodriguez et al. (2016) estimated that contribution associate to subsurface storage in winter and fall is of 60% in Juncal Norte Basin. However it is difficult to estimate this contribution at Universidad Glacier without direct measurements. (Baraer et al., 2014; Rodriguez et al., 2016) however it is difficult to estimate this contribution at Universidad glacier without direct measurements.

5 Conclusions

In this study, we have investigated the climatic meteorological conditions, ablation and melt water contribution to downstream river flow of Universidad glacierUniversidad Glacier, located in central Chile during the 2009-2010 summer ablation season., usingWe used a point scale energy balance and a distributed degree-hour melt model, driven by data from two on-glacier weather stations. The main outcomes of this work are:

- The distributed degree-hour model provides a robust simulation of surface melt, especially on the glacier tongue where good Good agreement was found between melt estimated from the point scale degree-hour model and, energy balance models, and ablation stake measurements and sonic ranger records. at the lower weather station site in the ablation zone, supporting the application of a simple temperature-index method of calculating total glacier melt at this location. Almost continuously positive air temperatures in the ablation zone between November and March supportare well suited to the application of a simple temperature index method to calculate glacier melt, however, some melt overestimation was identified for the accumulation zones due to more frequent negative air temperatures at higher elevations. The degree-hour model was distributed at the glacier wide scale accounting for hourly variations in the local temperature lapse rate, which tended to be shallower during the daytime, when most melt occurs.

- WeatherTheMeteorological ablation regime is dominated by incoming shortwave radiation, with highest melt rates occurring during December to February, and is also characterized by high air temperature which is almost continuously positive on the lower ablation zone between November and March. These climatic conditions result in very high ablation season melt totals, which reach exceed 10 m w. e. melt on the lower tongue. and are thus greater than melt values reported for other glaciers in central Chile. This finding is attributed to the relative insignificance of sublimation to total ablation, and the high insolation due to a low percentage of cloud cover and latitudinal location, combined with a predominantly positive air temperature. Melt totals were much lower in the accumulation area due to lower temperatures and persistent snow cover above about ~3800 m.

- By comparing total glacier melt with discharge estimates 0.5 km from the glacier snout, and discharge measurements at gauges at 1.7 km and 50 km downstream on the Tinguiririca riverTinguiririca River, we estimate that the monthly mean contribution of Universidad glacierUniversidad Glacier is, contributed between 10% and 13% of the total runoff streamflow observed in the upper Tinguiririca basin Basin for the period November December 2009 to to March 2010. This estimated contribution reaches a maximum of 15% to 20% in March. The total contribution of all glaciers to runoff streamflow in the upper Tinguiririca basin

Basin will will be greaterconsiderably larger considering that Universidad glacierUniversidad Glacier only represents 36% of the total glacier area of the basin (~81 km^2). During the late ablation season, in February and March 2010, when other runoff sources such as snowmelt become depleted, the daily contribution of Universidad glacier to total runoff in the Tinguiririca reached as high as 34%.

The successful application of a simple temperature-index melt model to estimate total seasonal melt at Universidad glacierUniversidad Glacier is partly a consequence of the predominant high melt regime of this glacier, which favors the application of the degree-hour model. In this sense, estimation of runoff streamflow contributions from glaciers in northern Chile is more challenging as an increasing proportion of ablation energy is consumed by sublimation (MacDonell et al., 2013) which cannot be estimated from simple temperature- index methods.

Climatic warming, leading to a rapid rise in the zero-degree isotherm (Carrasco et al. 2005) and upward expansion of glacier melt contributing area into the accumulation zone, means Universidad glacierUniversidad Glacier will continue to make a crucial, and perhaps an increasing, contribution to downstream flows in the next few decades, particularly as smaller glaciers in the basin disappear. In the long term, glacier shrinkage will lead to a depletion of glacier melt and in downstream streamflow in the Tinguiririca River, particularly in late summer. This will have, with severe implications for human activities in the river valley such as mining, domestic consumption, industry, forestry, tourism, forestry and agriculture (Aitken et al., 2016) and irrigation and hydropower generation (Valdés-Pineda et al., 2014). The potential for hHydropower generation on the Tinguiririca riverTinguiririca River at La Higuera and La Confluencia has been recognized (Pelto, 2010), with plants already working at La Higuera and La Confluencia, which canwill be affected by interannual variability in water supply and future streamflow trends in the medium to long term trends. Finally, more studies long-term high elevation stations in the Andes are necessary to establish the inter-annual variability of glacier contribution to river glaciers contribution for entire basins indischarge in order to help manage future water availability, considering climate change and the increasing demand for water in the region (Meza et al., 2012).

Acknowledgments

This work was supported by CECs, which is funded by the Chilean Government through the Centers of Excellence Base Financing Program of Comisión Nacional de Investigación Científica y Tecnológica de Chile (CONICYT). Pablo Zenteno and Camilo Rada assisted with data collection. The Chilean Water CadastreDirección General de Aguas de Chile (DGA) also provided data and support to this paper. We would like to thank Christophe Kinnard for sharing his data. We would like to thank to two anonymous referees for their constructive and useful comments and recommendations.

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Table 1: Stake ablation measurements

Stake N°	Altitude (m asl)	Installation date	Measurement date	Difference (m)	Mean snow density (kg m^{-3})	Water equivalent (mm)
1	2646	30-09-2009	21-11-2009	-1.23	422	519
2	2828	02-10-2009	21-11-2009	-0.81	441	357
3	2939	03-10-2009	21-11-2009	-0.33	413	136

Table 2: Mean monthly energy fluxes at AWS1

	Incoming shortwave radiation [W m^{-2}]	Net radiation [W m^{-2}]	Latent heat [W m^{-2}]	Sensible heat [W m^{-2}]	Melt energy [W m^{-2}]
October 2009	238	43	-43	18	17
November 2009	279	99	-28	16	87
December 2009	373	249	-13	19	255
January 2010	322	225	-6	30	249

Table 3: Monthly discharge from ~~Universidad glacier~~Universidad Glacier as percentage of the total discharge in the ~~Tinguiririca river~~Tinguiririca River, measured at the DGA station. Ranges in the percentages are for F_{DH} ice values of 0.29 mm w.e. °C^{-1} h^{-1} and 0.38 mm w.e. °C^{-1} h^{-1}. ~~Maximum and minimum are daily values.~~

Months	Monthly Mean
Dec-09	4.3% - 5.2%
Jan-10	8.1% - 10.2%
Feb-10	14.1% - 17.9%
Mar-10	15.3% - 19.5%
Mean of the period	10.5% - 13.2%

Months	Monthly Mean	Monthly Max.	Monthly Min.
December 2009	4.3% - 5.2%	5.6% - 7.0%	3.0% - 3.7%
January 2010	8.1% - 10.2%	13.0% - 16.5%	4.5% - 5.6%
February 2010	14.1% - 17.9%	25.7% - 32.5%	7.5% - 9.5%
March 2010	15.3% - 19.5%	26.6% - 33.9%	5.4% - 7.0%
Mean of the period	10.5% – 13.2%	17.7% - 22.5%	5.1% - 6.5%

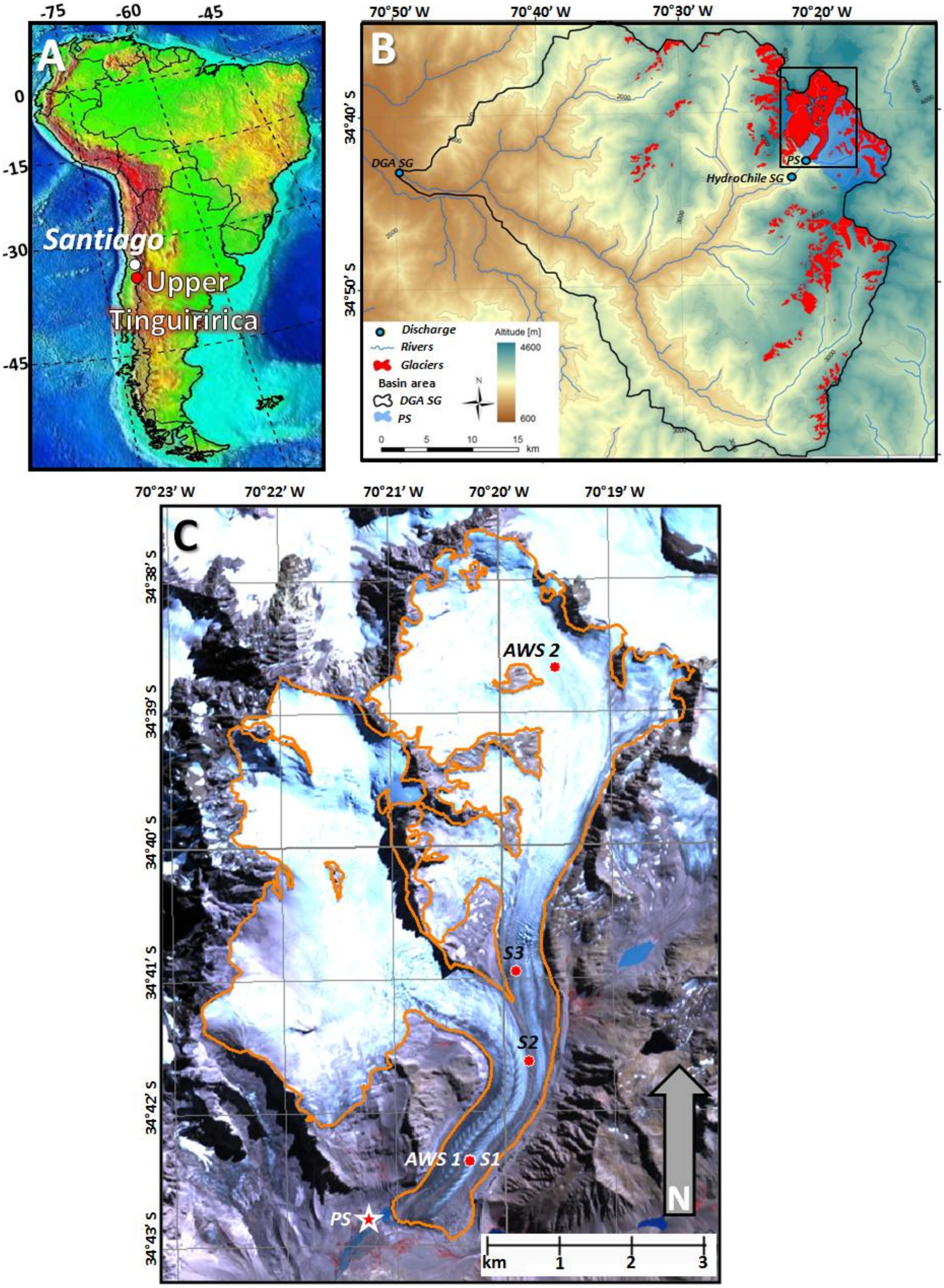


Figure 1: Location of ~~the Universidad glacier~~Universidad Glacier in central Chile. Panel A shows the regional location, ~~p~~Panel B shows the ~~entire~~ upper ~~Tinguiririca basin~~Tinguiririca Basin and panel C shows ~~Universidad glacier~~Universidad Glacier (orange outline), automatic weather stations (AWS) and ablation stakes (S) installed. PS indicates the location of the -pressure sensor, SG indicates the

locations of the ~~for stream gauge of~~ DGA and HydroChile stream gauge. The background is an ASTER image from 27 March 2010, UTM 19S.

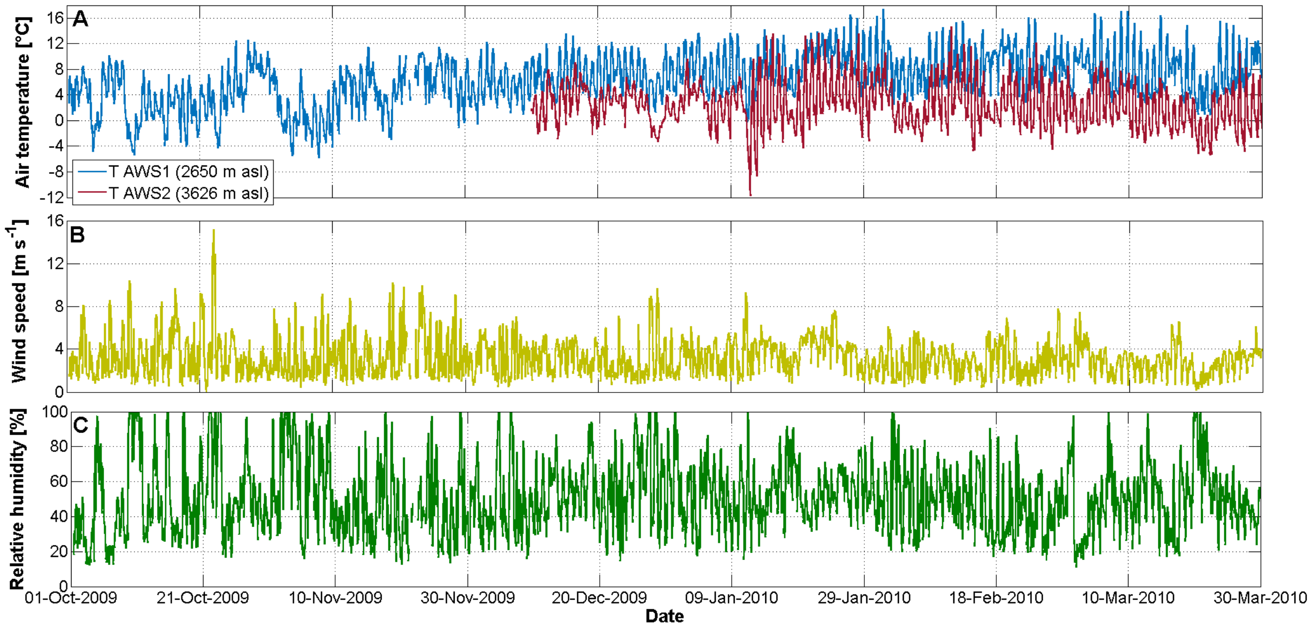


Figure 2: Hourly ~~T~~time series of ~~hourly~~ observed meteorological variables ~~observed~~. A) Air temperature at AWS1 and AWS2, B) Wind speed at AWS1 and C) Relative humidity at AWS1.

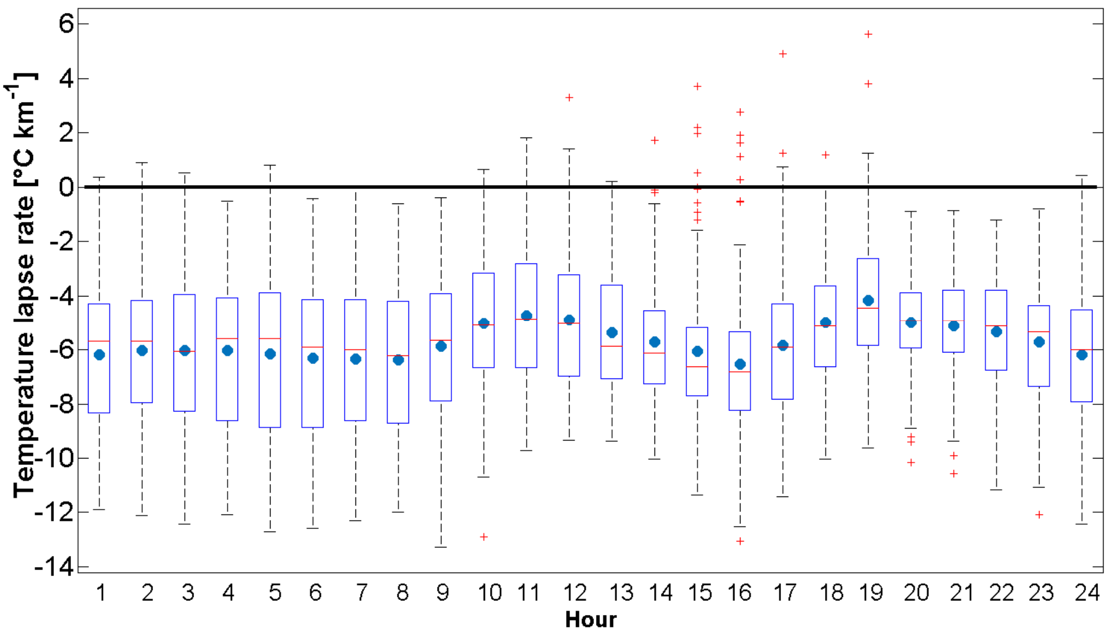


Figure 3: Boxplot showing the statistical distribution of hourly lapse rates calculated between AWS1 and AWS2 in the common period. Upper and lower box limits are the 75% and 25% quartiles, the red horizontal line is the median, the filled circle is the mean, and crosses are outlying values.

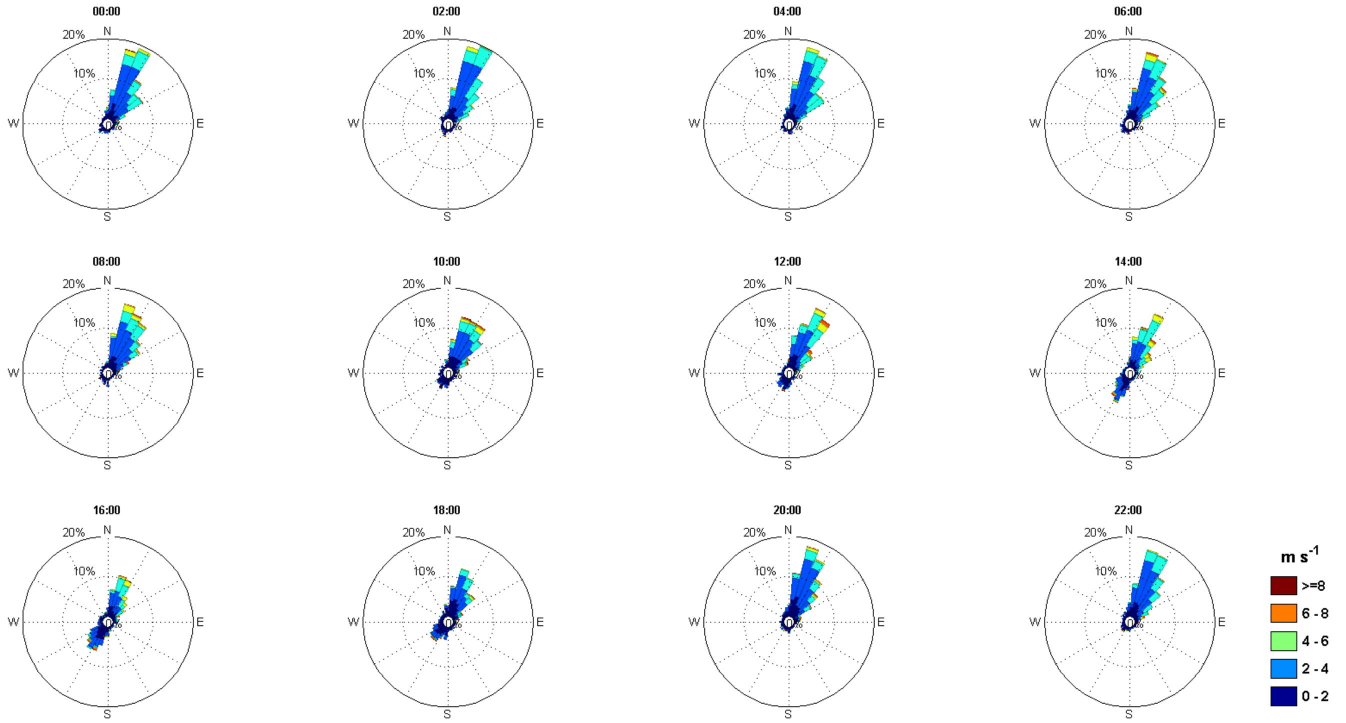


Figure 4: ~~Hourly w~~Wind roses showing the hourly ~~predominant~~ wind direction and the wind speed frequency at AWS1 (local time).

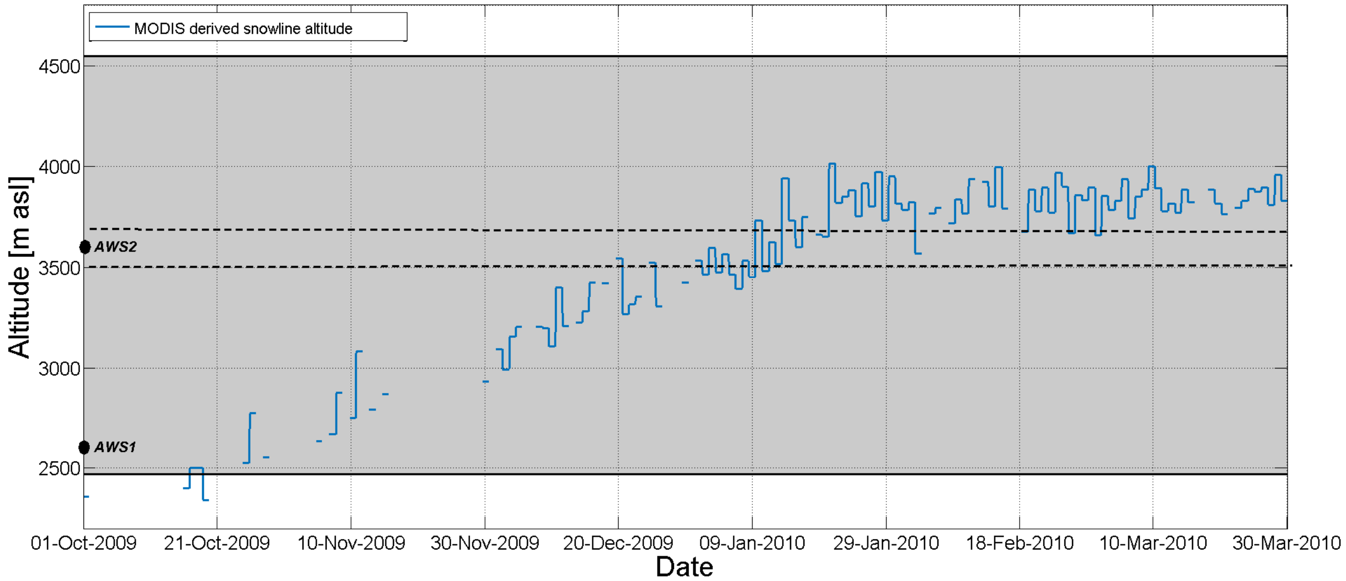
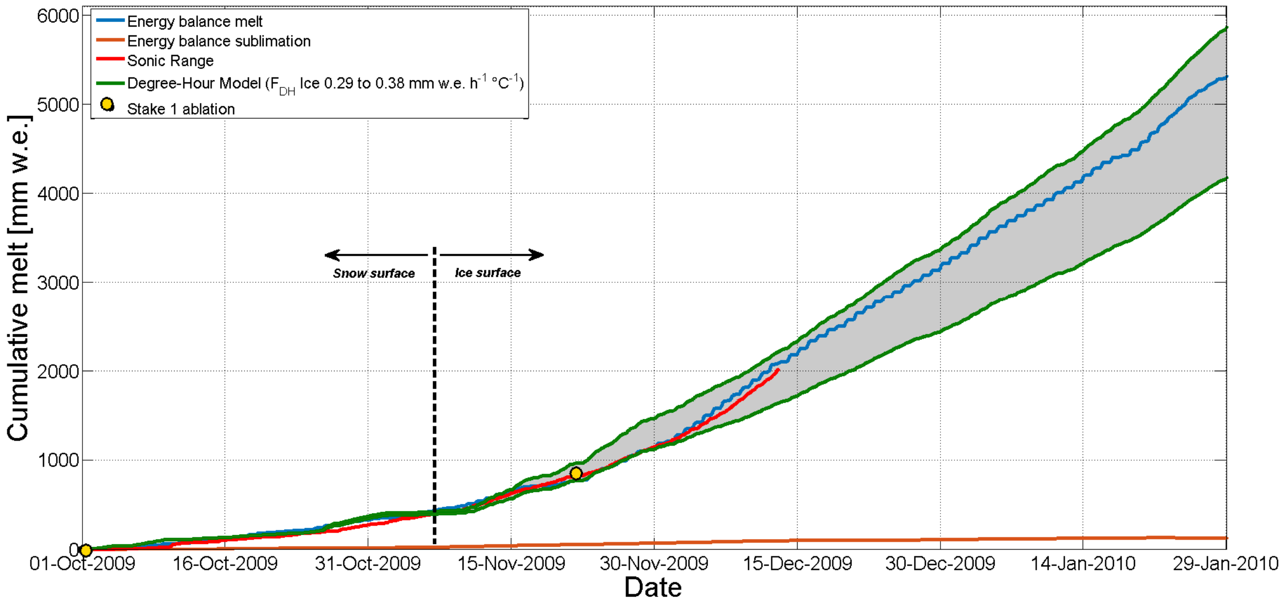


Figure 5: Snow line elevation estimated using the MODIS snow cover product. The grey area corresponds to the altitude range of ~~Universidad glacier~~Universidad Glacier, the dashed line shows the ~~Equilibrium~~ equilibrium ~~Line~~ line ~~Altitude~~ altitude range estimated using an ASTER image of 27 March 2010 and black points show the AWS elevations.



~~Figure 6: Comparison of cumulative melt estimated by the point scale degree-hour model (grey area), point scale energy balance model, sonic ranger and stake 1 located near the AWS1 (2650 m asl).~~

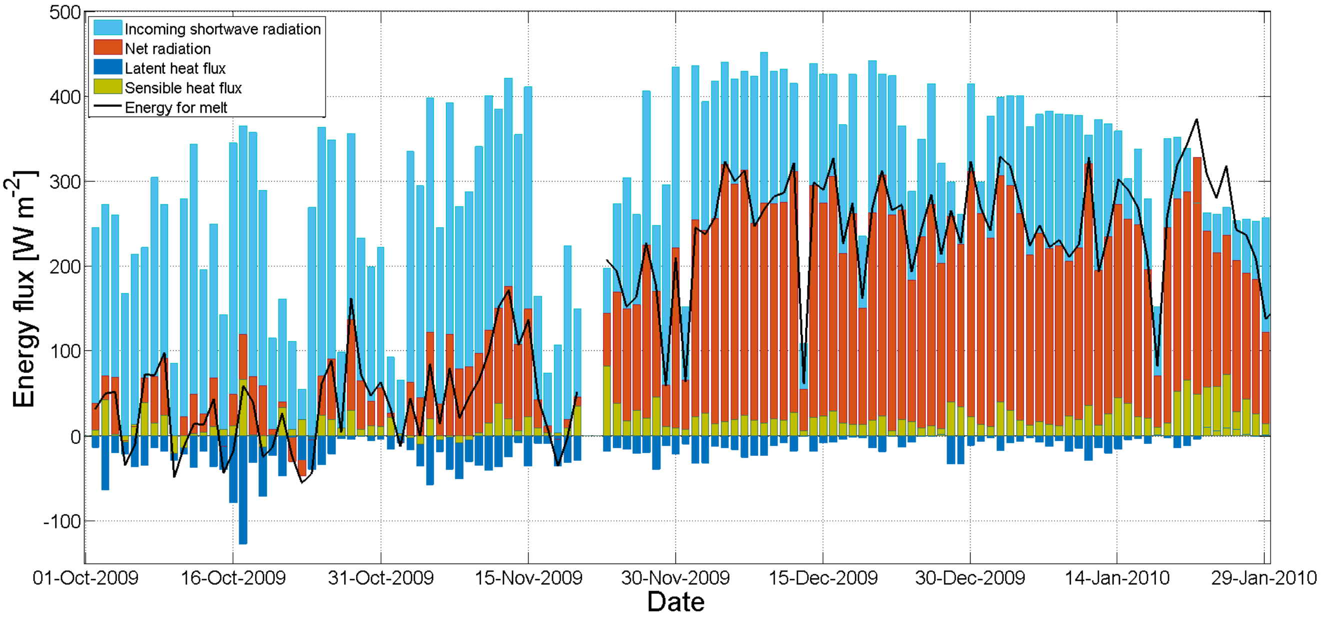
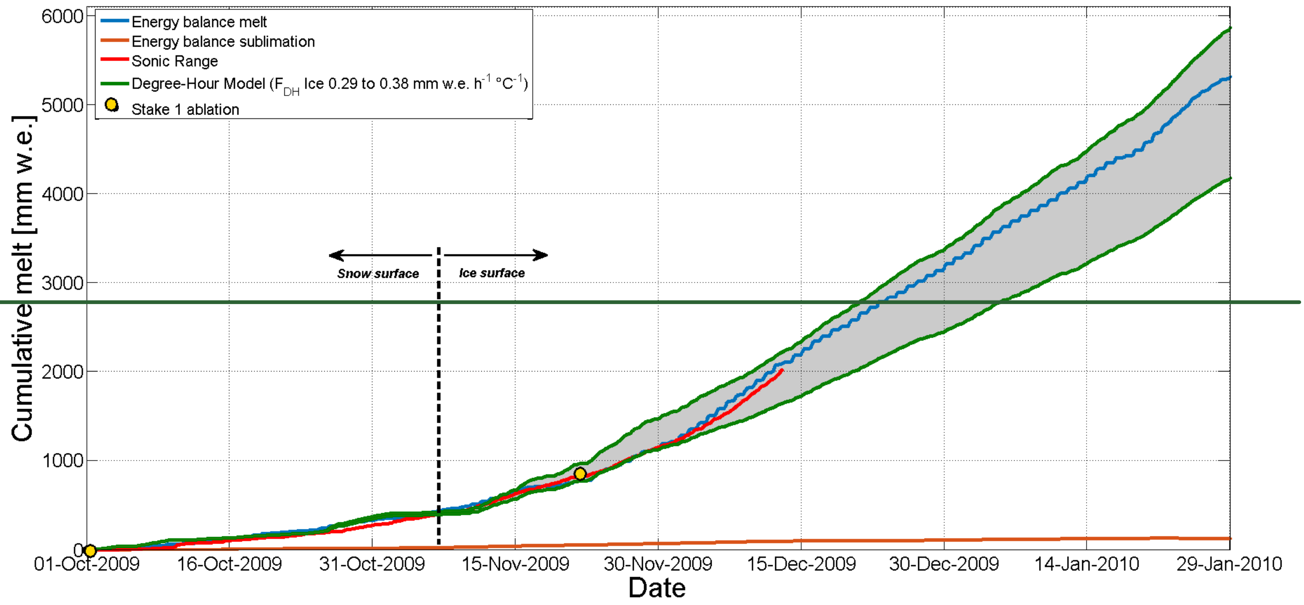


Figure ~~7~~6: Daily mean net radiation, incoming shortwave radiation, latent and sensible heat fluxes and the calculated energy available for melt at AWS1 (2650 m asl). On 21 and 22 November there are~~is~~ no data due to maintenance of ~~the~~ AWS1.



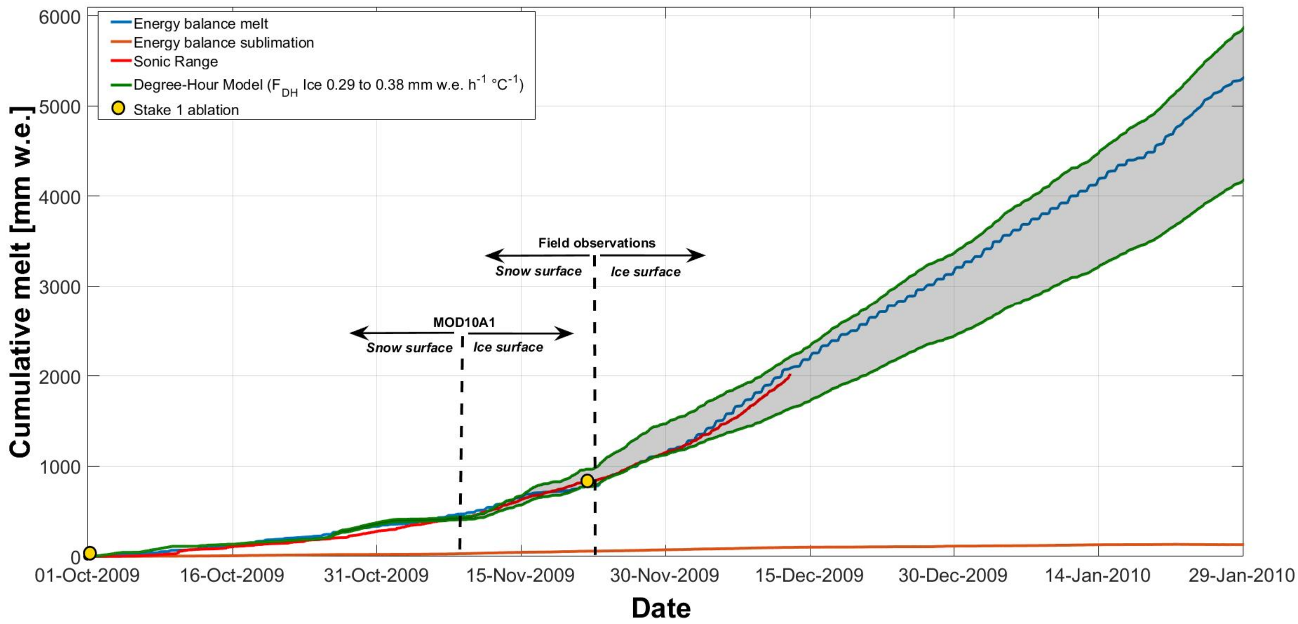


Figure 67: Comparison of cumulative melt estimated by the point scale degree-hour model (grey area between green lines), point scale energy balance model, sonic ranger and stake 1 located near the AWS1 (2650 m asl).

Figure 7: Daily mean net radiation, incoming shortwave radiation, latent and sensible heat fluxes and the calculated energy available for melt at AWS1 (2650 m asl). On 21 and 22 November there is no data due to maintenance of the AWS1.

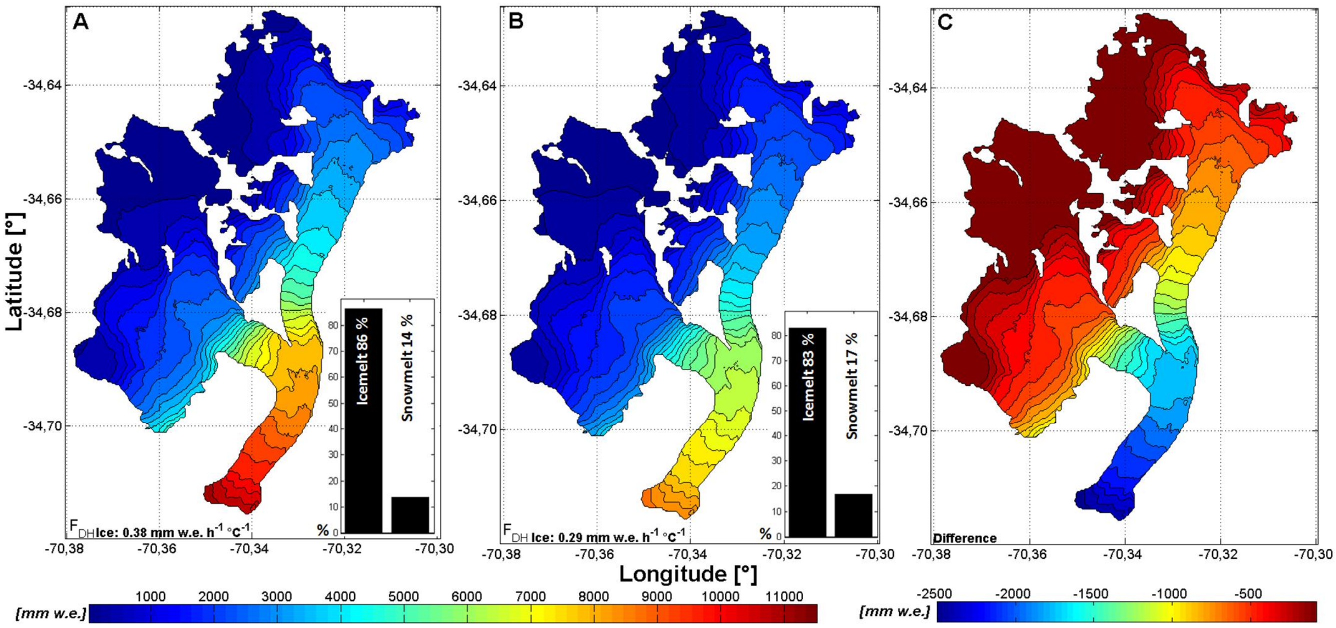


Figure 8: Spatial distribution of cumulative glacier melt for ~~Universidad glacier~~Universidad Glacier using two different F_{DH} values for ice. A) F_{DH} = 0.38 mm w.e. h^{-1} °C^{-1}, B) F_{DH} = 0.29 mm w.e. h^{-1} °C^{-1} and C) Difference of panels A and B. Totals are for the October 2009 to March 2010 period. In panels A) and B) the percentage of contributions of snow and ice surfaces to total melt are shown.

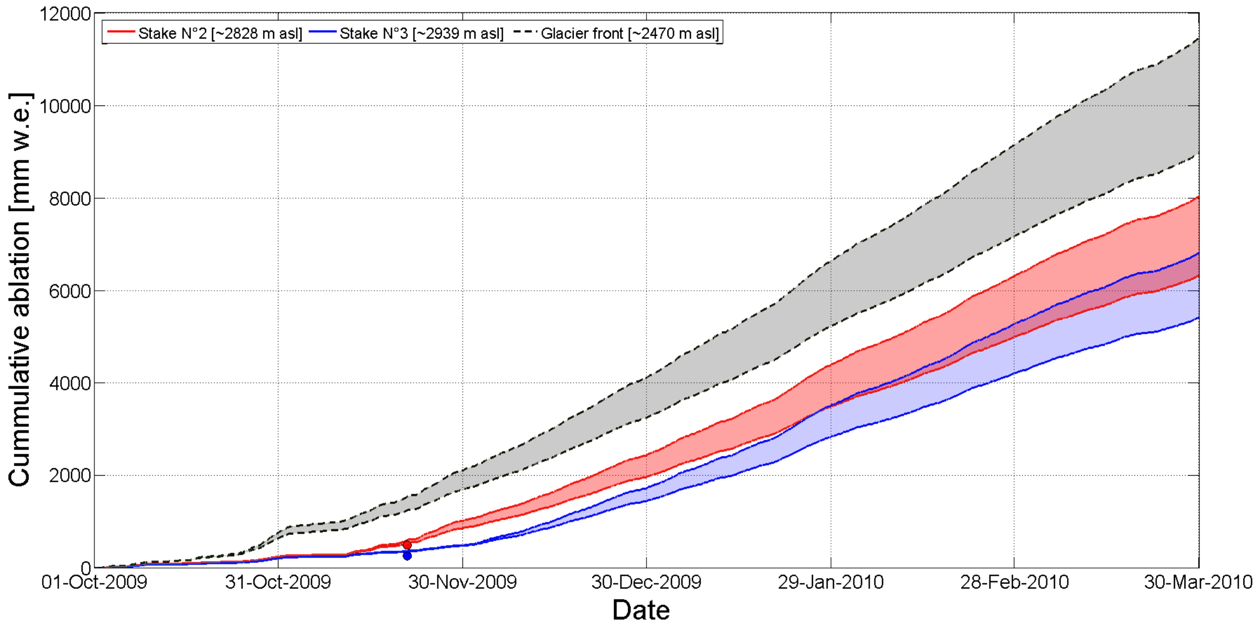
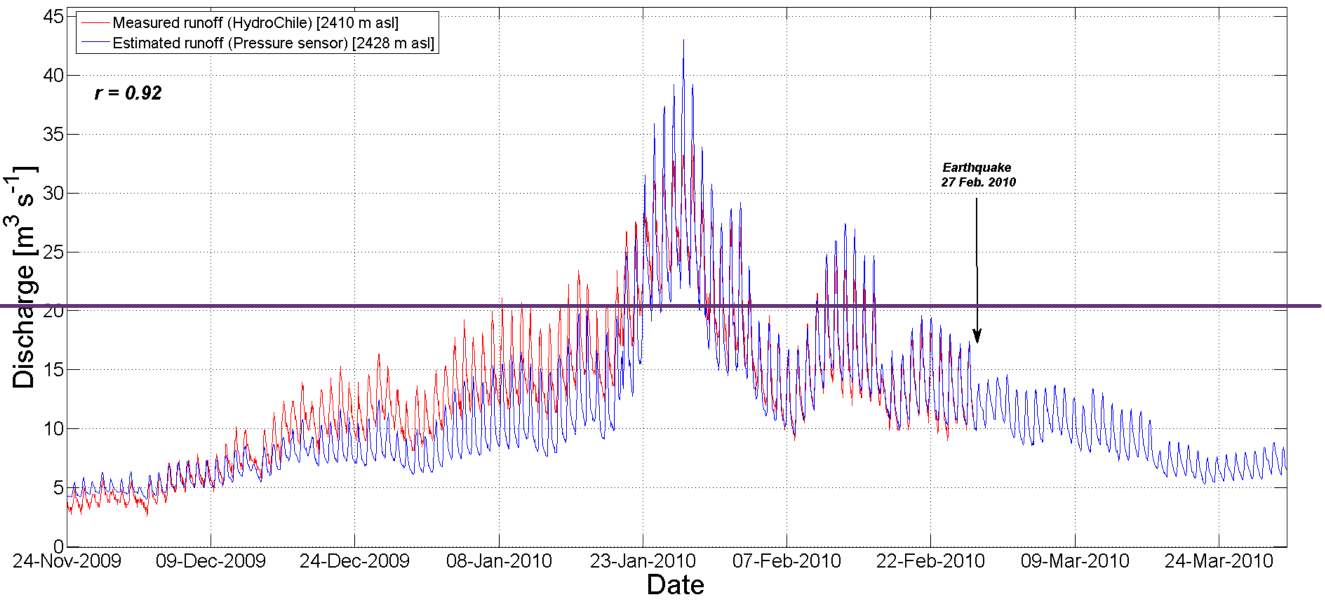


Figure 9: Total cumulative melt of ~~Universidad glacier~~Universidad Glacier using the degree-hour model. The red and blue lines and areas represent the cumulative melt at the locations of stakes 2 and 3, respectively. Points indicate the stake measurements. The area in grey enclosed by dashed black lines represents the lowest altitude of the glacier.



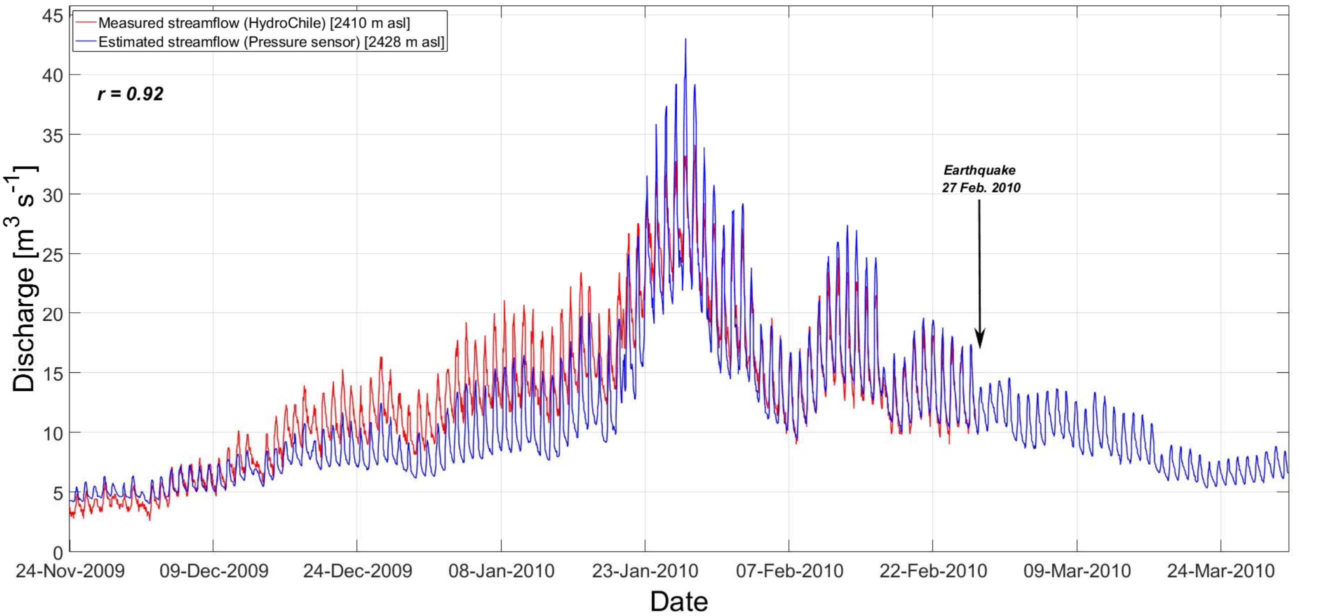


Figure 10: Time series of hourly ~~runoff~~ discharge in the proglacial stream from the water level pressure sensor and the HydroChile gauging station.

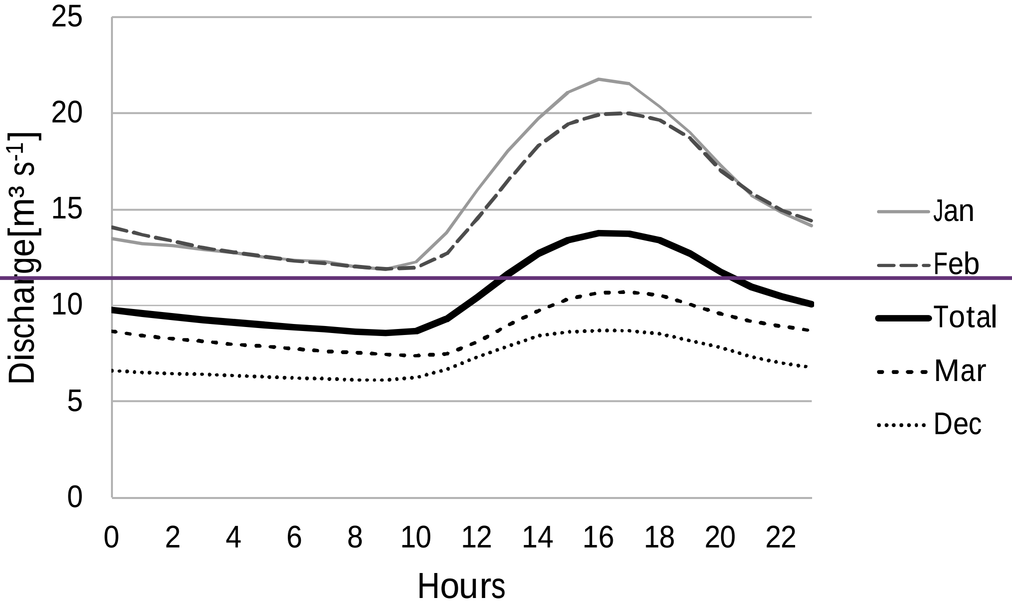


Figure 11: Hourly mean discharge during the total monitored period (black solid line) and for each month estimated from pressure sensor at 2438 m asl.

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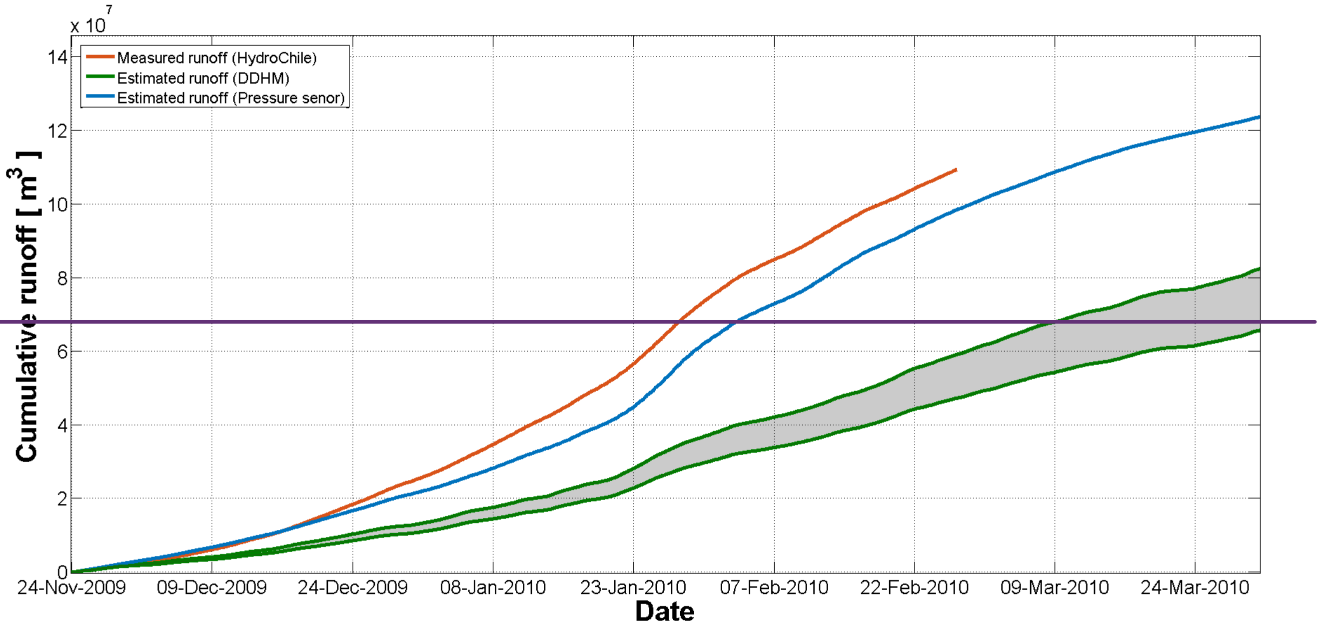


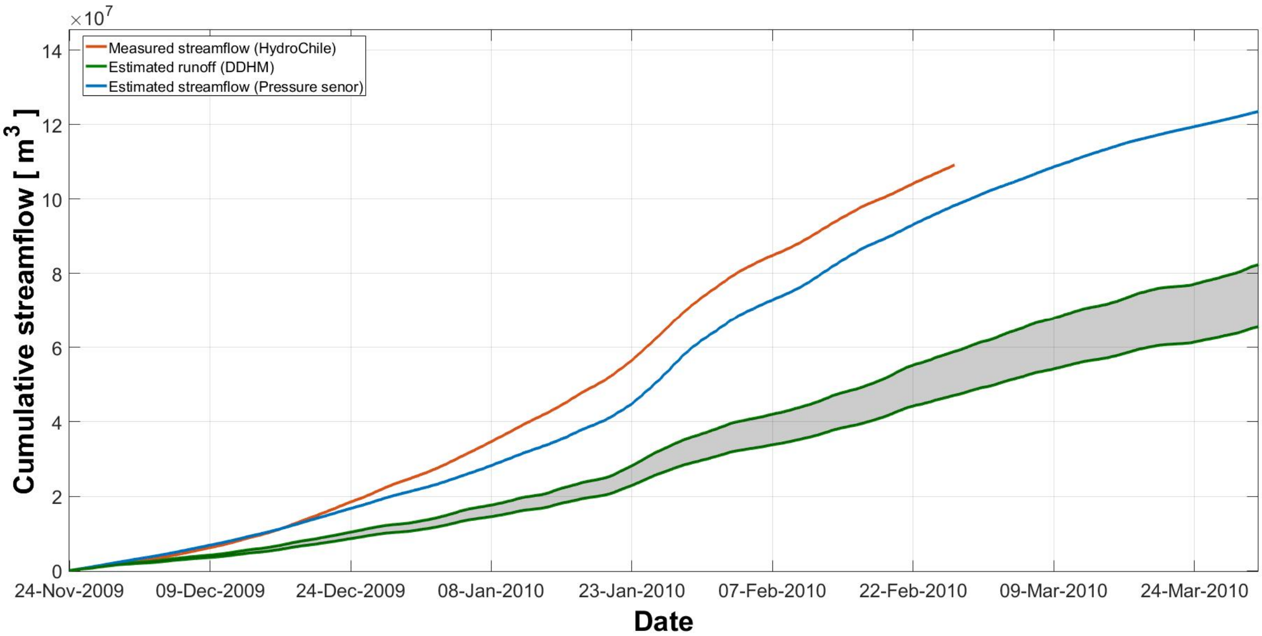
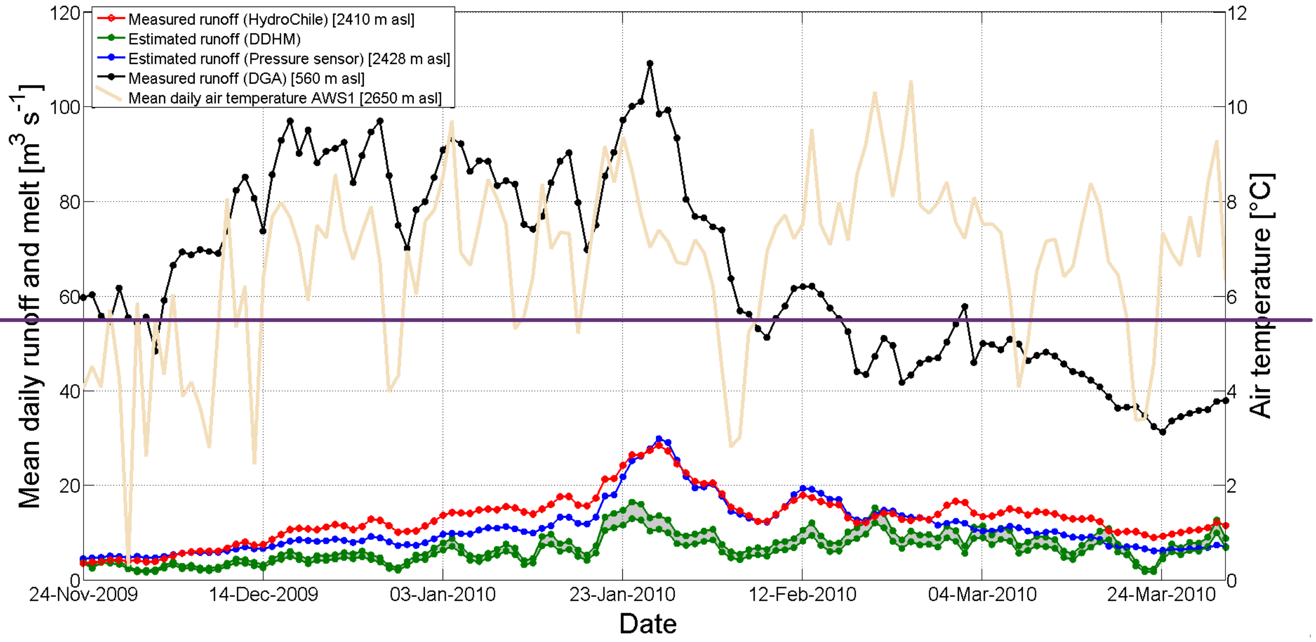


Figure ~~12~~11: Comparison of cumulative ~~runoff~~ melt calculated with distributed degree-hour model (grey area), and ~~river runoff~~ streamflow measurements from the water level sensor data and the HydroChile station.



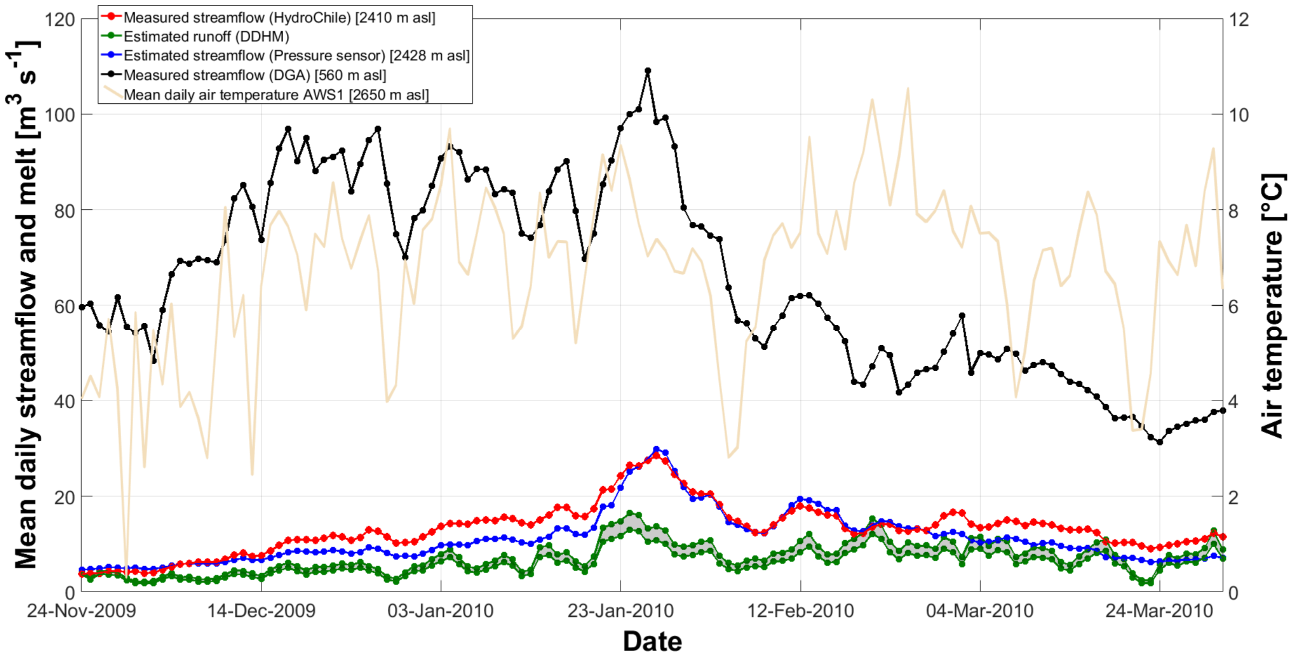


Figure 1<u>2</u>~~3~~: Daily mean ~~runoff~~ <u>melt</u> from<u> the</u> distributed degree-hour model, and ~~river runoff~~<u>discharge</u> measurements from <u>the</u> water level sensor, HydroChile station and DGA station. ~~For reference m~~<u>M</u>ean daily air temperature at AWS1 is plotted ~~in~~ <u>on the</u> right y axis.