Author's Response

We really appreciate the critic review from the two referees and the comments of the editor. We introduce changes in all section, from the Title and especially the Discussion and the Conclusions. We rewrite the Discussion section adding more references and data to compare the results from our work. In the Conclusion section, we pointed the answers to the main aims indicated in the Introduction section and adding more information of the context of the socioeconomic activities in the basin. In the next pages we response point by point for both referees, indicating the changes made in the new manuscript.

Author's response to Anonymous Referee #1

We appreciate the constructive review of Anonymous Referee #1.We agree with the general comments and we introduced changes in the manuscript in order to address the reviewer's concerns. Also we clarified and corrected the manuscript considering specific comments. We think that these changes (and English and Technical corrections) benefited the manuscript, especially improving the discussion/conclusion section and providing a stronger context for the study. Here, we provide a brief point by point response to the general and specific comments (enumerated) of the Referee #1:

1) **The authors must contextualize their findings with more studies about glacial hydrology, discussing more thoroughly the current status of Universidad glacier (area decrease of the last decades?) and its possible future point of peak water considering current shrinkage rates as well as local and downstream impacts of changing river runoff (in the region).**

Author's response

We re-wrote the Discussion section considering this comment and have added some further context to the Introduction. It is difficult to relate the results obtained from one ablation season to a long term perspective, however, considering previous research and our results we have discussed the future runoff and the related impacts on water availability in the region. To address this point we added more literature discussion regarding future runoff trend in the region.

2) **It is not clear, if the results should be seen as a first short snapshot (only 5-6 months measurements) at the beginning of an anomalous period of drought (2010-2015) or if they can be brought into a wider context (ideally with longer in-situ data)**

Author's response

We have clarified this point (also made by two specific comments of this reviewer). We focused on one ablation season due to the availability of data (after March 2010 no more data/observations were obtained from the glacier). Hence, we prefer touse the results as representative of certain synoptic/weather conditions. The analyzed period coincided with the beginning of the "mega-drought" that affected central Chile in the last 7 years so we assume that the results are representative of a dry period.

3) **While relative glacier melt fraction to river runoff might be high particularly in dry periods and the upper Tinguiririca catchment, relative contribution is expected to decrease with**

increasing distance from headwaters, i. e. for the low-lying coastal cities and water users. The mention of (the insignificance of) groundwater flows, probably difficult to estimate without direct measurements / tracing methods, should be revised as many different hydrological models have not been capable to adequately represent groundwater flows. Some studies of the last years suggest that they represent an important driver (e. g. Baraer et al., 2014 for the outer tropical Andes of Peru).

Author's response

We agree with this comment, therefore we changed the text adding, discussing related literature as suggested.

4) **The manuscript contains multiple tables and figures, most of them helpful for further comprehension, others less substantial. In order to reduce total paper volume, I would skip e.g. Table 1 and Figure 4. However, all anomalies / data gaps in the plots should be briefly indicated and explained in the text or subtitles.**

Author's response

We remove Table 1 as the referee#1 suggested, however we kept Fig. 4 since Referee #2 recommended to improved and not skipped. This implies hourly wind rose to see if katabatic flow is interrupted during the evening. We explain data gap and anomalies in the data, as specified in Reviewer's specific comments.

Response to specific comments:

All the specific comments and technical correction were addressed in the revised manuscript.

1 / 10-11: is that true that glacier melt represents more than the half of total streamflow contribution in lowlands during dry years in Chile? I would rather expect a reduction of relative contribution with increasing distance from the glacier and headwaters converting glacier streamflow to an important but not the main contributor in the lowlands.

We agree that the manuscript was not clear on this point. Considering that the comparison of glacier melt with observed runoff in this research, as with many previous studies, was made with data from stations located in the upper part of the main valleys, it is difficult to make an assessment of glacier contribution to runoff in the central valley of Chile or on the coast. We clarify this point, in the Abstract and in the Discussion section 4.2.

2 / 38 – 3 / 1: what about glacier area and (estimated) volume changes and current retreat rates of Universidad glacier and/or in the region?

We didn't estimate the area/volume changes for Universidad glacier. We used available literature (Le Quesne et al., 2009; Wilson et al., 2016) regarding these changes in the last years. However we added more literature to contextualize the glacier reduction in the region.

3 / 7-8: you identify the year 2009/2010 as (just) the beginning of a longer dry season (2010-2015) but it is unclear why you did not incorporate a longer period of measurements into you study and **3 / 18-19: again, you do not explain why your study only covers six months of data measurements**

We clarify this point. See General comment 2).

3 / 33-34: how did you discriminate snow from ice with the NDSI? Thresholds and techniques should be mentioned 4 / 3: clarify which images were selected with a cloud cover threshold: Landsat 5 TM?

We have stated more clearly that only MODIS products were used for snowline elevation identification and snow/ice discrimination. The mention of Landsat relates to earlier work not done by us to improve retrieval of sub-pixel snow cover information, and possibly this has been a source of confusion. We have used the MOD10A1 product since provides a better differentiation of the ice surface of Universidad glacier (which is dirty due the presence of ogives, debris and impurities), from and the fresh snow areas. However, 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 with a fractional value of 100. Despite this we expect some uncertainties in the snowline altitude as Fig.5 shows for the end of the ablation where high variability exists.

4 / 14-15: the explanation of how to convert hourly to daily format is very basic and can be neglected

OK. Deleted

10 / 29-31: again, be careful that you distinguish upstream from downstream (lowland) glacier streamflow contribution, the latter possibly less significant; what about flow contribution in austral winter? Although you have only worked in the ablation period, it would be good that the reader gets a general idea of glacier streamflow contribution changes during a whole hydrological year.

We added more literature regarding streamflow contribution during a complete hydrological year.

11 / 3-6: the point of (future) peak water is not sufficiently investigated in many mountainous regions worldwide but an increasingly important research question, particularly for future water management, can you examine this question about the possible peak water of Central-Andean glaciers in Chile a bit more? More literature?

We added more literature discussing this point. (See General comment 1).

11 / 13-14: is it true that melt rates are generally reduced further north (until where?) of Universidad glacier? Sublimation process are strongest with a pronounced water vapor gradient which is true for the dry season of e. g. the outer tropics (Peru/Bolivia) but not for glaciers in the inner tropics.

We were referring to high altitude glaciers in the north of Chile and in the outer tropics from Peru and Bolivia. We clarified this point in the new version of the manuscript.

11 / 37 – 12 / 1: is Universidad glacier really such a particular glacier with highest melt rates in Chile? cite comparing literature

We compared our results with other studies in section 4.3. However, as referee 2 suggests we provided more data from previous studies to establish a meaningful comparison.

12 / 2-3: this affirmation is obsolete as it represents a typical mechanism of glacier energy budget and mass balance

OK. Deleted

12 / 15: does groundwater flow really become depleted? any studies (e. g. tracers: Rodriguez et al., 2014)? in other parts of the Andes (where reduced ablation also takes place during the winter season) groundwater has been identified to be a strong contributor and generally underestimated inmany studies

We reviewed this point and changed the sentence considering that groundwater could be a major contributor. (See also General Comment 3).

12 / 24: the last argument should be more developed. The region isimportant for multiple water users. As an example, just some kilometers downstream,the hydropower plants La Higuera / La Confluencia are situated and possibly strongly affected by annual/seasonal changes in river runoff

We added this information about the water used by hydropower as well as for agriculture activities in this particular basin.

16 / Table 1: this table does not contribute substantially to the study comprehension, therefore I would take it out

OK. Deleted

18 / Table 3: indicate period in the title "(2009-2010)"

Added

20 / Figure 1: upper left: the three gauges are not clearly identifiable; the map text "CECs HydroChile" confuses; also, the abbreviations "CECs" and "DGA" in the legend are not proper; text of the figure: add "(orange outline)" after "Universidad glacier"

OK. Changed and added accordingly.

21 / Figures 2-13: indicate altitude (m asl) for ALL station data

OK. Added

23 / Figure 4: in order to reduce paper volume, I would skip this graph as it does not substantially contribute for a further process comprehension

We have preferred to kept this Figure with some changes suggested by referee 2.

25/ Figure 6: eliminate "[dd-mmm-yyyy]" at x-axis legend; you also do not use this definition in Figure 7

OK. Deleted

26 / Figure 7: indicate gaps which are present between November 21-22

OK. We have added and explained each data gap

Figure 12: no runoff measurements from March on? explain this data gap

We explained that period of observations (AWS, PS) is until end of March. See General Comment 2).

Technical corrections

1 / 1-3: with 28 words, the title is too long and complicated. Amore concise title would be: "Glacier melt contribution to river runoff at Universidad glacier, central Andes of Chile"

We changed the title as suggested by "Assessing glacier melt contribution to river runoff at Universidad glacier, central Andes of Chile"

1 / 11: eliminate "the" before "glacier melt"

Done

1 / 13: insert "within the" before "central Andes of Chile" 1 / 19: replace "altitude part" by "ablationarea"

Done

1 / 28: insert "a" before "crucial resource"

Done

2 / 21: change order "Mediterraneanclimate type"

Done

2 / 26: use directly the previously introduced abbreviation "AWS"

Done

2 / 32:correct "altitudinal range"

Done

2 / 33: improve "which converge at an altitude"

Done

2 / 35-37:change order considering a clockwise aspect of glaciers (north to the west)

Done

3 / 2-3:“fastest period” does not exist, improve

Changed

3 / 9-10: three times the word “measurements”, Replace

Replaced: “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”

3 / 14-15: not a full phrase, a verb is missing!

We have added the verb

3 / 16: correct “net all-waveradiation”

Done

3 / 32: insert “spatial” before “resolution” (there are also other types of resolutions)

Done

3 / 33: better specify “Landsat 5 TM (30 m spatial resolution)”

Done

4 / 1-2: eliminatethe long parenthesis “(Advanced Spaceborne. . . Version 2)”

Eliminated

4 / 30-31: improve phrase:it is not “melt overestimation” which is dominated by melt from the ablation zone; insteadof “however” you could use “as it”

Done

5 / 5: “and the afternoon maximum” could bethe beginning of a new phrase and needs a verb

Changed

5 / 14: include “shortwave” before “radiation”

Done

5 / 21: insert “to be” before “a constant”

Done

5 / 22: add “a” before “function”

Done

8 / 2:eliminate “(100% relative humidity” – very basic

Done

8 / 4: correct “was covered”

Done

8 / 21-22:improve phrase, you could separate it into two phrases from “fluxes calculated by” or inserting a new verb

We rather prefer to keep this phrase adding “turbulent” after the first comma.

10 / 3: eliminate “a” before “suitable”

Done

10 / 4: use also the word“correlation” instead of only “agreement”

Done

10 / 8: improve, e. g. “an hourly calibratedlapse rate at the glacier”

Done

10 / 19: maintain the same terms, here “Universidad glacier”

Done

10 / 37: replace “that” by “than”

Done

11 / 14: add “cover” after “cloud”

Done

11 / 20: eliminate“the” before “each”

Done

11 / 24: add “the” before “central Andes”

Done

11 / 25: correct “dependson”; insert “as” before “2013”

Done

11 / 26: correct phrase “while in dry years”

Done

11 / 28: betterwrite “climatic conditions” instead of “meteorology”

Done

11 / 29: insert “model” after “melt”

Done

11 / 34: a final point is missing before “The ablation”

Added

11 / 37: improve phrase avoidingthe semicolon with e.g. “and are thus greater”

Changed

12 / 2: “latitudinal” instead of “latitude”

Changed

12 / 3: “persistent” instead of “persistence”

Changed

12 / 11: add “km” after “1.7”

Added

12 / 12: aspace is missing before “The total”

Added

12 / 13: improve phrase: “Universidad glacier onlyrepresents 36%”

Changed

12 / 14: add the year “2010” after “March”

Added

12 / 20: insert “the” before“zero-degree”

Added

Author's response to Anonymous Referee #2

We would like to thank anonymous Referee #2 for his/her constructive and useful comments that have significantly improved the manuscript. We agree that discussion and conclusion needed to be improved (as Referee#1 also suggests), so have changed the text accordingly.Here, we provide a brief point by point response to the general comments (enumerated) of the Referee #2:

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

Author's response

This is a good suggestion. As the referee indicates we can separate between melt from snow over the glacier and bare ice. We added this information in the manuscript and in the Figure.

2) **Validation of the degree-hour method in Figure 6**

Author's response

We have extended the comparison between EB and temperature-index model until the end of January 2010improving the validation of the degree-hour method. After that date, and as the referee noted in the minor comments for Fig.7, the radiation (shortwave and net) was reduced sharply. So we did not use data of February and March.

3) **Comparison to other studies (section 4.3)**

Author's response

We added the data that the referee suggested.

4) **DHF for snow**

Author's response

We used all time steps (24 h * 52 d) to estimate the DHF for snow, since the hours with negative temperatures were set to 0°C to calculate the mean temperature. With this procedure we obtained a DHF of 0.1188 mm we h^{-1} $°C^{-1}$.However, the percentage of hours with negative temperatures during the period were close to 25%. Using only the positive time steps, the mean temperature was4.6°Cwhich gives a DHF for snow of 0.1192 mm we h^{-1} $°C^{-1}$. The impact of these changes on the DHF value is therefore negligible. Anyway, we changed the explanation of this procedure in the text.

Response to minor comments

In general we agree with all suggested text corrections and minor comments. Here,we response directly every minor comment:

Please correct systematically throughout the paper the use of capital letters for glaciers and rivers. Universidad glacier -> Universidad Glacier, Tinguiririca river ->Tinguiririca River.

Done

Check the use of present and past tenses. You frequently change from one tense to another, especially in the methods section.

Checked

1/11: "during late summer and autumn"

Changed

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

We changed to singular

1/15: "to compare"

Changed

1/28: "water is a crucial resource"

Changed

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

We discussed and added more references regarding water uses (e.g. Meza et al., 2013).

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

Done

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

Done

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

We replaced "altitude" by "elevation" and added a reference indicating the mean altitude of the Andes in the region.

2/2: "warm temperatures"

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

Done, we changed "trigger" by "cause"

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

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

We explained "high" was related to Central Chile Andes basins

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

We changed by "is related to the presence"

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

Please provide the elevation of the outlet and the percentage of the glacierized area of the catchment analyzed by Peña and Nazarala (1987). Also if by "glacier melt" they include the seasonal snow over the glacier.

We provided the information of the outlet. On the other side it is not clear in the work of Peña and Nazarala (1987) if glacier melt include snow over the glacier. However the 34% contribution corresponds to February of a dry year. The same authors indicate that "snow remaining at the end of a dry year is negligible". This makes suppose that the indicated percentage is referred only to ice.

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

We added "…zone, showing that the ablation process is dominated by incoming shortwave radiation."

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

We added this information

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

We changed to "Despite these advances, results are limited to one basin and cannot necessarily be extrapolated"

2/17: "or on the impact of…"

Done

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

Both, we explained this in the text

2/20: deficiencies -> knowledge gaps, issues

Done

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

Re-written; "which converge at an altitude of ~2900 m asl"

From where did you obtained the ELA? References?

We re-estimated the ELA. See below Minor comment 8/3-6

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

Changed: "below this elevation"

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

Changed as suggested

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

Re-written: "Ablation measurements: stakes and sonic ranger"

3/22: re-measured -> read

Changed

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

Changed

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

Changed

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

We added more literature

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

Changed

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

Unfortunately ASTER GDEM did not give time acquisition. We added this point as one uncertainty in the melt estimation.

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

We changed by “MODIS product were used…”

4/3-4: Remove “For modelling purposes”.

Removed

4/8: remove the second “applied”.

Removed

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

Changed

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

Changed

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

Re-written; “We use stake 1 ablation measurements (Table 2) and the mean positive air temperature (3.5 °C) at the AWS1 to estimate a DHF for snow. Dividing the ablation value by the mean of positive air temperature (Braithwaite et al.,1998), we obtained a DHF for snow of 0.12 mm w.e. h^{-1} $°C^{-1}$.”

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

Deleted

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

Done

4/13 “With these values” What values?

Changed

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

For the total number. We have clarified this point. See general comment 4).

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

See general comment 4).

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

Added

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

We changed and use just one symbol: F_{dh}

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

Changed

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

We changed by "advected"

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

We check this. During the afternoon, data from AWS1 show up-winds. However katabatic winds still are the prevalent during all day. We showed this in a new Fig. 4

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

Changed

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

We used this reference as an example, since they neglected heat from rain in their calculations. We added e.g. in the reference to clarify.

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

Changed

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

No. We assumed to be 0.001 m for melting snow and 0.01 m for ice on mid latitude glaciers (Brock et al., 2006). We added in the manuscript.

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

That's right we clarified this point in the manuscript

6/13: You missed the evaporation rate.

Added.

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

Changed

6/28: Add a space before “Water level…”

Added

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

Replaced

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

Effectively the ELA was wrong (too low). We changed the value at 2/33 and explained the estimation procedure. Also we discussed the value obtained from the ASTER image (Fig1) and the values obtained using MOD10A1

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

Ok, we used two all along the text.

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

ok

8/32-33: Move to methods.

Done

9/3: October -> November

Changed

9/15: “purposes”.

Done

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

Yes we have AWS data before this date, however the pressure sensor only have data from this date and on

9/23: “…contributions from glaciers…”

Changed

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

Added

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

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

We added the explanation about the period. **“in the basin”: what basin? The largest one?**

We referred to the entire high Tinguiririca basin (added)

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

The interdaily variability of the air temperature is similar to the interdaily variability of the runoff in the DGA station. We added air temperature as reference in Fig. 13.

10/3: “is suitable”

Changed

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

We deleted “high melt regime” to avoid confusion

10/5: Please see main comment 2.

Ok

10/8: “locally-calibrated”, “on-glacier”

Changed

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

10/13: in converting -> to convert

Changed

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

Removed

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

Changed

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

Yes, we changed 10% by 3%

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

Changed

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

Removed

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

We used Carrasco et al. (2005) and LeQuesne et al. (2009) as general precedent relating frontal retreat and temperature trends in the glacier. We agree that it is not directly a discussion of our results, instead is a discussion of the implications of the context of glacier retreat and future melt.

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

Elevation retreat is close to 70 m between 1955 and 2007 (LeQuesne et al., 2009).

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

We added the suggested references to the discussion.

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

11/16: Check the grammar.

Ok

11/23: "estimated"

Changed

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

Changed

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

Changed

11/28: “In this study, we have investigated”

Changed

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

Changed

11/34: “. The ablation…”

Changed

12/7: “MacDonell et al.”

Changed

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

We clarified and addressed this point.

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

As referee 1 suggested we introduced changes in this topic, adding more literature discussion.

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

We added a reference for SST

12/20: “Carrasco, 2005”

Changed

12/23: “In the long term”

Changed

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

Moved to discussion

12/29: “thank”.

Changed

12/35: add volume and page numbers

Added

TABLES

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

Yes. We added this in the explanation

FIGURES

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

Changed

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

Added

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

Changed

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

Added

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

We changed the extension. See General comment 2).

Figure 7: "latent and sensible heat fluxes".

Changed

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

There is not a clear reason so we preferred discarding this data. See General comment 2).

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

We added a new panel with these differences. We also indicated how much corresponded to ice melt and how much corresponded to snow melt on the glacier.

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

We assumed the same lapse rate observed in the common period. We clarified this in the manuscript.

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

Result from S1 are showed in Fig. 6

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

We only plotted results from one DHF (0.38 mm w.e. h-1 °C-1). However we added both result to show the uncertainty range.

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

Done

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

Added

Figure 12: “and the HydroChile station”

Changed

~~Assessing glacier contribution to river runoff in the Andes of central Chile: Analysis of in situ weather station data, runoff measurements and melt modelling at Universidad glacier (34° 40' S, 70° 20' W)~~Assessing glacier melt contribution to river runoff at 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 ~~the main~~an important contributor to ~~lowland~~ flows ~~in~~ during late summer and autumn. However, few studies have quantified~~ the~~ glacier melt contribution to river runoff. To address ~~some of these shortcomings~~this shortcoming, we present an analysis of meteorological conditions and melt for Universidad glacier, a large valley glacier in the ~~Mediterranean climate~~ whitin central Andes of Chile at the head of the 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 runoff routing model, and to compare total modelled glacier melt to 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 ~~showing~~ and showed good agreement with melt estimates from an ablation stake and sonic ranger, and with a physically-based energy balance model. Universidad glacier is characterized by extremely high melt rates over the ablation season which may exceed 10 m water equivalent on the lower ~~altitude part~~ablation area~~ of the glacier~~, representing a contribution between 10% and 13% of the total runoff observed in the upper Tinguiririca basin during the November 2009 to March 2010 period. This contribution rises to a maximum of 34% in late summer demonstrating the importance of glacier runoff to river flow, particularly in dry summers such as 2009-2010. The temperature-index approach benefits from the availability of on-glacier meteorological data 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, ~~hydroelectric~~ 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 population and urban expansion in recent years is increasing the demographic pressure on water resources. In this region, winter precipitation~~ water supply~~ is driven by the interactions between the westerlies circulation and the Andean natural barrier, and summer runoff is strongly influenced by the~~water~~ storage and release from glaciers and snow covers (Garreaud, 2013). Accurate knowledge of the processes involved in the ~~water~~

~~supply~~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 ~~altitude~~ elevation of ~4000 m asl (Garreaud, 2013). The majority of annual precipitation occurs during the winter months, which is accumulated 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 ~~increased~~ warm temperatures and incoming solar energy ~~triggers~~ 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 ~~show a predominant snow regime~~ (Cortés et al., 2011). However, another key source of water in the summer dry season is related to the ~~existence~~ presence of glaciers along the Andes 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 (Masiokas et al., 2013, Gascoin et al., 2010, Ohlanders et al., 2013). ~~For example~~ Peña and Nazarala (1987) estimated that the contribution of ice~~glacier~~ melt to the high basin of the Maipo River ~~basin~~(5000 km^2, outlet at 850 m asl) in summer 1981/1982 ~~reached a~~was ~~maximum~~ highest in February and represented 34%~~, representing 34%~~ of ~~the~~ total discharge. ~~in the summer 1981/1982.~~

There ~~are~~ 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 ~~furthermore critic~~an important limitation on understanding of current future glcier contribution to river flows, considering the current status 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 glaciers in the region, is Juncal Norte glacier, where Pelliciotti et al. (2008) investigated the point scale energy balance and melt regime using an automatic weather station (AWS) located in 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 ~~water~~ from Juncal Norte glacier contributed 14% of the basin (241 km^2, 14% ~~is~~ glacierized, outlet at ~2250 m asl) runoff for the entire hydrological year 2005/2006, with a maximum of 47% over the late ablation season (February to April). Despite these advances, results are ~~only available for~~limited to one basin and cannot necessarily be extrapolated, particularly along climatic gradients to the north and south. Other glacier energy balance studies in 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 ~~the~~ 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 over a full ablation season.

To address some of these ~~deficiencies~~issues, we present an analysis of meteorological conditions and melt for Universidad glacier, a large valley glacier in central Chile, located in a climatic transition zone with a Mediterranean ~~type~~ 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 ablation and their patterns and trends across 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 ~~automatic weather stations (AWS)~~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 Tinguirirca river.

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 ~~U~~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~~e~~ 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~~nt~~ at an altitude of ~2900 m asl~~, where the Equilibrium Line Altitude (ELA) is located~~. 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 ~~using~~ the end of summer snowline ~~concept is~~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, ~~Palomo glacier flowing to the north-east~~ and other small glaciers flowing to the west. ~~Other characteristic~~Another feature of the basin is the presence of small lakes mainly associated ~~to~~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 ~~1969, and 1985 and~~ 2015. ~~The fastest period was between 1967 and 1987~~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 Experimental setting

The study focuses on the ablation season (October 1 to March 31) of the 2009/2010 hydrological year ~~(October 1 to March 31)~~, 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).

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

2.2 Automatic weather stations (AWS)

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

2.3 Ablation measurements: stakes and~~,~~ sonic ranger~~ and snow density measurements~~

Three stakes installed in the ablation zone of the glacier between September 30 and October 3 2009 were ~~re-measured~~read on November 21 while the surface was still snow covered at each stake (Fig. 1, Table ~~2~~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 ~~2~~1) and water equivalent (w.e.) ~~melt ~~surface ablation for each stake.

A Campbell Scientific SR-50 sonic ranging sensor was installed next to AWS1~~ (Table 1)~~. The sensor~~ which~~ 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~~).

2.4 Snowline elevation estimation using MODIS snow product

We 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~~This~~ was developed using regression with Landsat ~~Thematic Mapper~~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 ~~elevational distribution of snow cover~~snow line throughout the monitored period, we obtained the hypsometric curve of Tinguiririca basin from an ASTER GDEM V2 ~~(Advanced Spaceborne Thermal Emission and Reflection Radiometer – Global Digital Elevation Model Version 2)~~ (Tachikawaet al., 2011) and then calculated the snowline altitude for the austral summer of 2009-2010 in the upper Tinguiririca basin. ~~Images ~~The MODIS snow cover product ~~were ~~was used only if the cloud fraction for each satellite image was less than 30%. ~~For modelling purposes, t~~The snowline altitude 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 ~~are ~~is used as an input for modelling to define snow or ice surface areas on the glacier. We have used the MOD10A1 product since it provides a ~~better~~realiable differentiation of the ice surface of Universidad glacier, which is dirty due the presence of ogives, debris and impurities, from the fresh snow areas. 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 ~~with~~only when the ~~a~~ fractional value ~~of~~was 100. Despite this we expect some uncertainties in the snowline altitude

2.5 Degree-hour model (DHM)

We applied a standard degree-day model (DDM) (e.g. Hock, 2003, 2005)~~, applied ~~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 refer to as the degree~~-~~day factor (F_{DD}~~DDF~~), or degree-hour factor (~~DHF~~F_{DH}) when applied at an hourly interval (De Michele et al., 2013). We use stake 1 ~~melt ~~ablation measurements (Table ~~2~~1) ~~together with~~and ~~-~~the mean positive air temperature (4.6 °C) ~~(negative temperatures are set to 0°C)~~ at~~ the~~ AWS1 ~~for the same period (3.5 °C) ~~to estimate a F_{DH}~~DHF~~ for snow. The

~~P~~percentage of hours with positive temperatures was close to 75%, therefore we used only time steps with positive values. ~~With these values and following~~ Dividing the ablation value by the mean of positive air temperature~~the procedure of~~ (Braithwaite et al.~~, (~~1998), we obtained a F_{DH}~~DHF~~ for snow of 0.12 mm w.e. °C^{-1} h^{-1} ~~°C^{-1}~~. ~~If the DHF is multiplied by 24 to convert to DDF we obtained 2.9 mm w.e. d^{-1} °C^{-1}.~~ The F_{DH}~~DHF~~ is multiplied by the positive hourly temperature at hourly interval and results are summed for every day. As we did~~o~~ not have ablation stake measurements in the period when the ice surface is exposed, ~~For ice~~ we used a range of published F_{DD}~~DDFs~~ (Hock, 2003) to obtain a range of uncertainty in calculated melt. In this case we used values between 7 and 9 mm w.e. °C^{-1} d^{-1} ~~°C^{-1}~~, commonly used for glacier ice. The hourly F_{DH}~~DHF~~ for ice was calculated by dividing the ice F_{DH}~~DDFs~~ by 24 to give F_{DH}~~DHF~~s for ice of 0.29 and 0.38 mm w.e. °C^{-1} h^{-1} ~~°C^{-1}~~, respectively.

Therefore melt, *a* (mm w.e. h^{-1}), is estimated by the following relationship:

$$a(t,z) = \cancel{D}F_{DH\cancel{f}}T_h^+(t,z), \tag{1}$$

~~D_f is the DHF for ice or snow.~~

The published F_{DD}~~DDF~~ values for ice were calibrated for daily average temperature and therefore could lead to a melt overestimation when applied as F_{DH}~~DHF~~s 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 DDF of 9 mm w.e. °C^{-1} d^{-1} and F_{DH}~~DHF~~ of 0.~~375~~ 38 mm °C^{-1} ~~d~~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 continuous positive 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., representing an increase in melt of 15% over the ~~degree-day model~~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 ~~much~~ small impact~~er influence~~ on total glacier ~~melt~~runoff, ~~however~~as it, which is dominated by melt from the ablation zone. Furthermore, there will be no melt estimation bias on snow as the F_{DH}~~DHF~~ for snow was calibrated using measurements from 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).

2.6 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). Following the recommendation of Petersen and Pellicciotti (2011), we estimated a daily LR cycle considering that melt occurs mostly during the day. The mean hourly temperature gradient over an average day oscillates between -0.004 °C m^{-1} to -0.~~0066~~ 007 °C m^{-1}. During the night (24:00 to 08:00 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 and -0.004°C m^{-1} at 19:00, separated by a maximum of -0.~~0066~~ 007 °C m^{-1} at 16:00. 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 potentially due to the erosion of the katabatic boundary layer on the lower glacier tongue and ~~entrainment of~~ warm air advected from bare rock surfaces at the glacier sides and proglacial area (van de Broeke, 1997; Ayala et al., 2015).

Using the hourly LR, we distributed 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 March 27, 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.

2.7 Energy balance model (EBM)

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

Energy available for ablation, ψ (W m^{-2}) was determined following~~by~~ ~~(~~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 precipitation totals 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 directly measured by the net radiometer sensor of the AWS1~~ (Table 1)~~. The ~~turbulent fluxes~~sensible heat fluxes were calculated using the bulk approach (Cuffey and Paterson, 2010):

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

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):

$$C^* = \frac{k_0^2}{ln^2\ (\frac{z}{z_o})}, \qquad (4)$$

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:

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

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):

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

The latent heat flux H_l is:

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

e is 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 surface, $L_{v/s}$ 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):

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

And *e* is found by rearranging the following equation:

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

Melt rate (M) is calculated following (Hock, 2005):

$$M = \frac{\psi}{L_m \rho_w}, \tag{10}$$

L_m is the latent heat of fusion and $\rho_w$is the water density (1000 kg m^{-3}). Sublimation rate (S) is calculated (Cuffey and Paterson, 2010):

$$S = \frac{H_l}{L_s \rho_w}, \tag{11}$$

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):

$$\text{for } Ri_b \text{ positive (stable): } (\Phi_m\Phi_h)^{-1} = (\Phi_m\Phi_v)^{-1} = (1-5Ri_b)^2, \tag{12}$$

$$\text{for } Ri_b \text{ negative (unstable): } (\Phi_m\Phi_h)^{-1} = (\Phi_m\Phi_v)^{-1} = (1-16Ri_b)^{0.75}.$$

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

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

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

2.8 Proglacial discharge estimation

~~There were no direct measurements of the discharge during the study period in the proglacial zone.~~ The estimation of the river ~~velocity and of the total volume of~~ 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 November 24, 2009, until April 14, 2010. The proglacial stream receives the waters draining from an 86 km^2 catchment, partially covered by the 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 ~~the~~ environmental parameters such as stream slope, bed roughness and river section shape and area, for uniform open channel flow. It defines the discharge Q [m³ s^{-1}] as follows:

$$Q = VA, \tag{14}$$

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

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

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

~~Geometrical parameters~~The geometry of the channel cross section were 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 to estimate the slope of the terrain 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 correspond 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, ~~which is~~ 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 Tinguiririca river at 560 m asl, 50 km downstream the Universidad 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 glacier is by far the largest single ice body.

2.9 Discharge routing

Estimated 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:

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

Where $M(t)$ is the rate of water inflow to the reservoir, which is considered to be equivalent to the total glacier melt. k 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).

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. At AWS1 temperature is ~~almost always~~generally above 0°C during December-March even during the night, while temperature at AWS2 shows more frequent negative values during the night (Fig. ~~3~~2).

Wind speed shows some inter-daily variability but the hourly values are predominantly between 2 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. The ~~D~~daily cycle of wind direction reveals that predominant katabatic wind is slightly ~~interrupted~~weakened during ~~evening~~afternoon hours (between 14:00 to 18:00, local time, Fig. 4). Relative humidity shows a large diurnal variability. Saturation ~~(100% relative humidity)~~ is reached 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 altitude range is slightly higher than the altitude of the ELA estimated with the ASTER image from the end of March of 2010 (Fig. 1). In the first half of the ablation season high 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~~ and Table 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 November 7, 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 November 21, after which the EBM and sonic ranger estimates fall within the DHM range for F_{DH}~~DHFs~~ between 0.29~~2~~ and 0.~~375~~ 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.

3.3 Energy balance

Figure 7 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, Table ~~3~~2). Incoming shortwave radiation was the main source of melt energy (Table 2~~3~~). Energy available for melt is higher in December and January and tends to diminish during February to March, in close association with the annual cycle of incoming shortwave radiation.

3.4 Distributed degree hour model (DDHM)

Figure 8 shows the accumulated melt for each pixel of Universidad glacier estimated by the DDHM during the period October 1 2009 to March 31 2010 using ice F_{DH}~~DHF~~s of 0.29~~2~~ and 0.~~375~~ 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). ~~Calculated melt values were not adjusted for reduction under debris cover on a medial moraine in the ablation zone.~~ All parts of the glacier experienced at least some melting, with melting values around 1 m w.e. in the upper accumulation area. Bare ice surfaces ~~Main contributor from glacier surface correspond to ice with~~accounted for ~~the~~ ~85% of the total melt.

3.5 Discharge

During the study period we estimated an average stream flow of 12 m^3 s^{-1} with a range from 4 m^3 s^{-1} and 43 m^3 s^{-1} (Fig. 10). Discharge values increased gradually between the end of ~~October~~ 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 the end of October (Fig. 10).

The hourly mean hydrographs have strong diurnal amplitude cycles (Fig.11) during the high discharge months 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, from a minimum at 10:00 AM which, considering the large size of the glacier, indicates an efficiently channelized drainage system flow.

Water discharge estimated ~~by~~ at the HydroChile station showed high correlation with 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 27th February when there was a large earthquake in central Chile. The sudden jump in HydroChile values around this date (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 reject 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 HydroChile station, at 500 m and 1700 m from the glacier snout, respectively, between November 24, 2009 and March 31, 2010 (Figs. 1 and 12). At 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% and 66% of the runoff estimated from the pressure sensor, depending on the ice F_{DH}~~DHF~~ value used (Fig. 12). The remaining 34% to 50% of proglacial runoff 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.

Mean total melt from Universidad glacier represents between 10% and 13% (depending on ice F_{DH}~~DHF~~ used) of the total runoff of the entire upper Tinguiririca basin (1478 km^2) over the November 2009 to March 2010 period (Fig. 13, DGA station, Table ~~4~~3). This percentage is much more than the area of the Universidad glacier (~2%) with respect to the total basin area of the upper Tinguiririca. The percentage of glacier contribution is variable during the season (Table ~~4~~3). At the beginning of the common period of pressure sensor and AWS1 measurements (end of November ~~until end of March~~) runoff is dominated by the snow melt in the entire high Tinguirirca basin, reflected in the high daily variability in runoff in the DGA station until January, due the control of air temperature iover snow melt (Fig. 13). In these months, the glacier melt contribution ranged between 3% and 10%. After the peak in the runoff at the end of January, the contribution of Universidad glacier to total basin runoff ~~reached~~ increased to 14-19% 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 was 0 mm. In February and March the DDHM calculated melt and the DGA station runoff 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 ~~a~~ suitable for estimating glacier melt contribution to river runoff from glaciers in Chile ~~experiencing a high melt regime~~. This interpretation is based on the close ~~agreement~~ correlation between ablation estimates from the DHM and melt estimates from an energy balance model~~EBM,~~, 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, the availability of on-glacier meteorological data; second, a locally calibrated degree-hour factor for snow; and third, an hourly-calibrated lapse rate at the glacier ~~a locally calibrated on glacier hourly temperature lapse rate~~ for spatial extrapolation of air temperature inputs to the distributed melt model. 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 and variability in the strength and thickness of the katabatic boundary layer 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).

The key sources of model uncertainty are: (a) snow density, which is required to ~~in converting stake~~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 ~~at the start of the~~ 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; (c) 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; ~~and~~ (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.

~~Our observation that the DHM has high sensitivity to air temperature variations is in agreement with previous work, e.g. Pellicciotti et al. (2008).~~ During periods of low positive temperature and high insolation, the DHM underestimated melt, and *vice versa* during periods of high temperature. This implies spatial and temporal errors, i.e. overestimation of melt during warm weather and on the lower glacier,~~;~~ and melt underestimation during cold weather and on the upper glacier,~~ which~~ will tend to compensate over time and in summation of total glacier melt, but will lead to short term errors.

4.2 Glacier contribution to basin runoff ~~and representativeness of results~~

The finding that Universidad glacier, while accounting for just 2% of the total basin area, contributed between ~~10~~3% and 34% of total runoff from the entire upper Tinguirirca basin over the December to March period, demonstrates the importance of glaciers for ~~lowland~~ river flows in central Chile during the summer months. The ~~total~~ overall glacier melt contribution to the 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. Hence, glacier runoff becomes critical to maintaining flows in the 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 ~~levels~~ elevation sites is small. Research by Gascoin et al. (2011) and Pourrier et al. (2014) ~~in the~~on glaciers of the arid Andes ~~also~~ has revealed the hydrological importance of glaciers to the north of Tinguiririca basin.~~, which generate more water per surface unit that the non-glaciated area.~~

The recent and ongoing retreat for Universidad glacier 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 impacts on river runoff are expected over the next decades. In the 1950-2007 period positive trend in runoff for upper Tinguiririca basin was observed (0.3 m^3 s^{-1} y^{-1}, not significant) (Casassa et al., 2009). Considering ~~Carrasco et al. (2005) estimated~~ that ~~an~~ the estimated upward migration (200 m) of the zero degree isotherm between 1975-2001 in central Chile ~~of 200 m in central Chile between 1975-2001~~, ~~from radiosonde records~~(Carrasco et al., 2005)~~. This increase~~ far exceeds the elevational retreat (~60-70 m) of the Universidad glacier snout (~~Le Quesne et al., 2009~~Wilson et al., 2016) over a ~~similar~~ longer period (1967-2015) the~~. Hence,~~ contributing melt area, and hence total glacier melt of Universidad glacier has increased in the last ~30 years. This increase in glacier melt might explain the the positive trends 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 of mass of annual flow for the upper Tinguirica shows a negative trend in the period 1961-2007 (Cortez et al., 2011), indicating the bulk of the annual flow is shifting towards earlier in the year. This implies that snowmelt tends to occurs earlier and hence glacier ice is also exposed earlier in the year, increasing the hydrological importance of glaciers. ~~in the short to medium term, the contributing melt area of large glaciers such as Universidad is increasing more rapidly than the ice-covered area is being depleted, indicating there will be increased glacier runoff contribution to lowland flows over the next decades, continuing the observed positive trend (0.3 m^3 s^{-1} y) in runoff for upper Tinguiririca basin in the period 1950-2007 (Casassa et al., 2009).~~

From our analyses is uncertain wheter Tinguiririca runoff has already reached the “peak water” expected for glacierized basins as a consequence of deglaciation (Casassa et al., 2009). The observed positive recent trend in the runoff of the Tinguiririca (Masiokas et al., 2006 and Casassa et al., 2009) suggests that peak water is yet to occurs. In contrast recent modelling work has shown that peak water has already passed for the Juncal basin further to the north and that future runoff for this basin is likely to sharply decrease (Ragettli et al., 2016). Estimation 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.

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 high altitude glaciers of northern Chile and in the dry season of the outer tropics of Perú 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, lower incident shortwave radiation due to increasing latitude and cloud cover reduces available energy for melt (Brock et al., 2007). Hence, Universidad glacier may be located in a climatic zone which maximizes relative summer melting. Local factor such as the large accumulation area and extension of the glacier tongue to relatively low elevation also contributes to the high melt detected in the lower zone of the glacier (Fig. 8).

~~The m~~Modelled ablation season melt at Universidad glacier is high in comparison ~~to other glaciers in Chile. The range of cumulative melt during the ablation season estimated at~~ to Juncal Norte glacier (33°S) ~~to the north~~ where maximum accumulated melt is in the order of 5000-6000 mm w.e., depending on the model applied ~~model~~ (Pellicciotti et al., 2014). These values are near half of the estimated values obtained at the lower tongue of Universidad glacier (Figs. 8 and 9). However, melt rate distribution shows great variations depending on altitude. The melt rate at the equilibrium line of Universidad 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 ~~in the order of~~of 4950 and 3960 ~~3960 to 4950~~ mm w.e~~. close to the equilibrium line altitude of Pichillancahue glacier in Villarrica volcano (39°S)~~ between January and March of 2004 and 2005~~. These values are near half of the estimated values obtained at the lower tongue of Universidad glacier (Figs. 8 and 9).~~ respectively. However, it is worth noting that ablation below this elevation is greatly reduced on Pichillancahue glacier by an extensive cover of thick insulating tephra.~~It is likely that further to the north, melt rates are reduced as more ablation occurs through sublimation, whereas, to the south, increasing cloud reduces available energy for melt. Hence, Universidad glacier is located at a particular climatic zone which maximizes summer melting.~~

Recently Ayala et al. (2016) estimated that ice melt contribution at the 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 30% of summer water runoff while in dry years such as 2014-2015 the summer contribution was 50%. This latter value is similar to the ice melt contribution recorded at the outlet of Universidad 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. As Ayala et al. (2016) suggest, melt comparison with other glaciers must made with caution, considering that 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 in the Tinguiririca is of similar magnitude to previous results for the central Andes, e.g. Ragettli and Pellicciotti (2012) estimate that 14% of the total runoff of the Juncal River Basin (241 km^2, outlet at ~2250 m asl) comes from Juncal Norte glacier (9.9 km^2) in the hydrological year 2005/2006 with a maximum of 47% during the late ablation season. For the Maipo basin, Peña and Nazarala (1987) estimate 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 during the end of ~~the~~ each hydrological year. An important issue of the results showed by Peña and Nazarala (1987) is that there is an interannual variability in the discharge from glaciers, for example the percentage of the glacier contribution to total runoff in the Maipo in February of 1983 was just 5%, but in February of 1982 it was 34%. It has been suggested that another source of runoff during dry years at the end of the ablation season is groundwater flow (Baraer et al., 2014; Rodriguez et al., 2016) however it is difficult to estimate this contribution at Universidad glacier without direct measurements.

~~Recently Ayala et al. (2016) estimate that ice melt contribution from glaciers Bello, Yeso (debris free glaciers) and Piramide (debris cover glacier) in central Andes (~33.53°S), depend of the meteorological conditions of each year. Snow rich years such 2013-2014 contributed 15% of annual water runoff (30% during summer) and dry years such as 2014-2015 the annual contribution is 35% (50% during summer).~~

5 Conclusions

In ~~T~~this study, we have ~~has~~ investigated the ~~meteorology~~climatic conditions, ablation and melt water contribution to downstream river flow of Universidad glacier, located in central Chile during the 2009-2010 summer ablation season, using a distributed degree-hour melt model, driven by data from two on-glacier weather stations. The main outcomes of this work are:

- Good agreement was found between melt estimated from ~~the~~ degree-hour ~~model melt~~ and ~~melt estimated from an~~ 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.

- The ablation regime is dominated by incoming shortwave radiation, with highest melt rates occurring during December to February, and is also ~~characterised~~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~~e~~ location, combined with predominantly positive air temperature. Melt totals were much lower in the accumulation area due to lower temperatures and persistent~~ce~~ snow cover above about ~3800 m.

~~- The successful application of a simple temperature-index melt model to estimate total seasonal melt at Universidad glacier is partly a consequence of the predominant high melt regime of this glacier which favours the application of the degree-hour model. In this sense, estimation of runoff 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. At the regional scale, estimates of glacier contribution to downstream runoff also depend on extrapolation of off-glacier air temperature measurements to the glacier boundary layers, as on-glacier temperature data are rarely available.~~

- ~~In~~ 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 river, we estimate that Universidad glacier, contributed between 10% and 13% of the total runoff observed in the upper Tinguiririca basin for the period November 2009 to March 2010. The total contribution of all glaciers to runoff in the upper Tinguiririca basin will be greater considering that Universidad glacier ~~is~~ 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 ~~and groundwater flow~~ 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 glacier is partly a consequence of the predominant high melt regime of this glacier which favours the application of the degree-hour model. In this sense, estimation of runoff 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.

~~The winter of 2009 was in a normal year according to the sea surface temperature (SST) anomalies in the Niño 3.4 region, and although the analysed ablation season had positive anomalies of SST (between 0.7 °C and 1.3 °C) suggesting El Niño conditions, there was no precipitation in the study area. This suggests that the 2009-2010 season is representative of relatively dry years in central Chile.~~ Climatic warming, leading to a rapid rise in the zero-degree isotherm (Carrasco et al. ~~2015~~2005) and upward expansion of glacier melt contributing area into the accumulation zone, means Universidad 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~~er~~ term, glacier shrinkage will lead to a depletion of glacier melt and in downstream flow in the Tinguiririca, particularly in late summer, with severe implications for human activities in the ~~lower~~ 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 hydropower generation on the Tinguiririca river has been recognized (Pelto, 2010), with plants already working at La Higuera and La Confluencia, which can be affected by interannual variability and medium to long term trends. Finally, more studies are necessary to establish the inter-annual variability of glaciers contribution for entire basins in order to help manage future water availability, considering climate change and the increasing demand for water in the region.

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~~Table 1: Meteorological sensor specifications~~

~~Sensor~~	~~Model~~	~~Manufacturer~~	~~Accuracy~~	~~Range~~
~~Anemometer~~	~~5103~~	~~Young~~	~~±0.3 m/s~~ ~~±3°~~	~~0-100 m/s~~
~~Temperature* and relative humidity~~	~~HMP45C-L11~~	~~Vaisala~~	~~±0.3°C (0°C),~~ ~~±3% (90% to 100% at 20°C)~~	~~-39.2° to +60°C~~ ~~0.8% to 100%~~
~~Atmopsheric pressure~~	~~CS106~~	~~Vaisala~~	~~±0.6 - 1 (-20°C -45°C)~~	~~500 mb to 1100 mb~~
~~Pyranometer**~~	~~CMP3-L34~~	~~Kipp and Zonen~~	~~±5%~~	~~0.3 to 2.8 µm~~
~~Net Radiometer**~~	~~NR-LITE-L48~~	~~Kipp and Zonen~~	~~±5%~~	~~0.2 to 100 µm~~
~~Sonic ranging**~~	~~SR50A-L34~~	~~Campbell Scientific~~	~~0.25 mm~~	~~0.5 to 10 m~~

~~* Probe housed in a naturally-ventilated radiation shield~~ - -

~~** AWS1only~~ - - - -

Table ~~2~~1: Stake ablation measurements

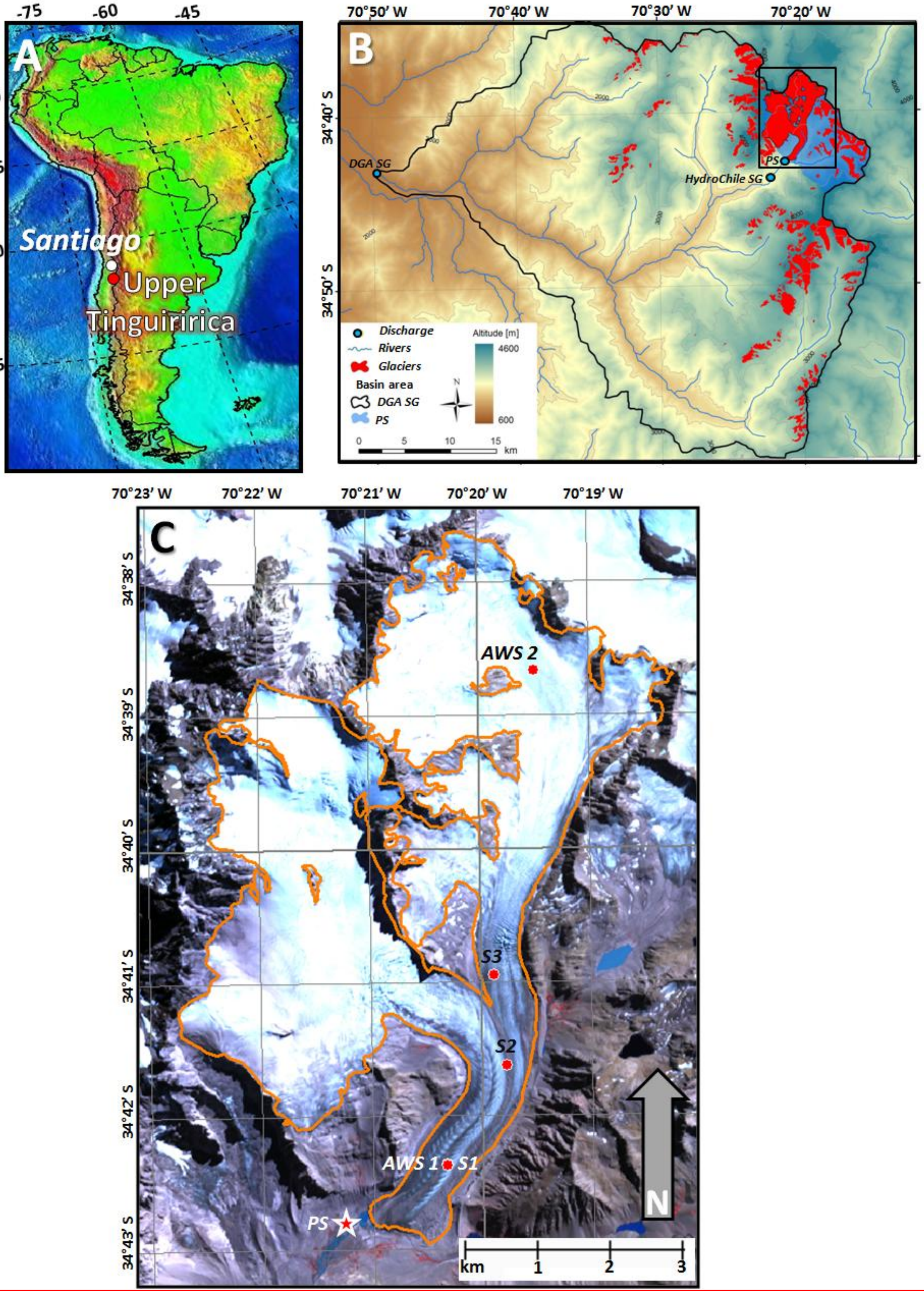
Stake N°	Altitude (m asl)	Installation date	Measurement date	Difference (m)	Mean snow density (kg m^{-3})	Water equivalent (mm)
1	2646	30-09-2009	21-11-2009	-1.23	422	519
2	2828	02-10-2009	21-11-2009	-0.81	441	357
3	2939	03-10-2009	21-11-2009	-0.33	413	136

Table ~~3~~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
~~February~~	~~222~~	~~101~~	~~-9~~	~~24~~	~~115~~
~~March~~	~~173~~	~~46~~	~~-10~~	~~20~~	~~57~~

Table ~~4~~3: Monthly discharge from Universidad glacier as percentage of the total discharge in the Tinguiririca river, measured at the DGA station. Ranges in the percentages are for F_{DH}~~DHF~~ ice values of 0.29~~2~~ and 0.~~375~~ 38 mm w.e. °C^{-1} h^{-1}. Maximum and minimum are daily values.

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%


A
-75
-60
-45
0
-15
-30
-45
Santiago
Upper
Tinguiririca
B
70°50' W
70°40' W
70°30' W
70°20' W
34°40' S
34°50' S
DGA SG
PS
HydroChile SG
Discharge
Rivers
Glaciers
Basin area
DGA SG
PS
Altitude [m]
4600
600
N
0
5
10
15
km
C
70°23' W
70°22' W
70°21' W
70°20' W
70°19' W
34°38' S
34°39' S
34°40' S
34°41' S
34°42' S
34°43' S
AWS 2
S3
S2
AWS 1
S1
PS
N
km
1
2
3

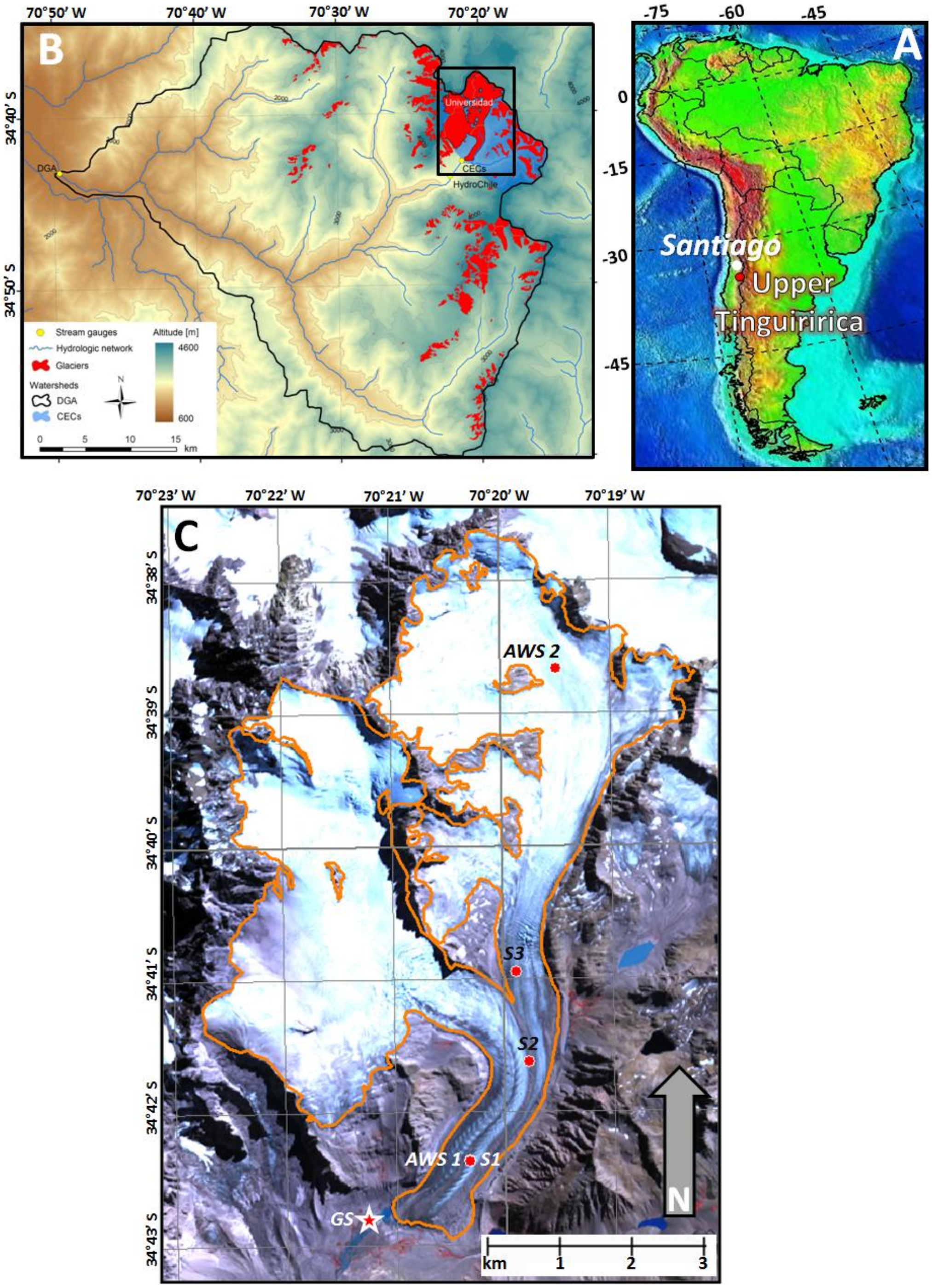
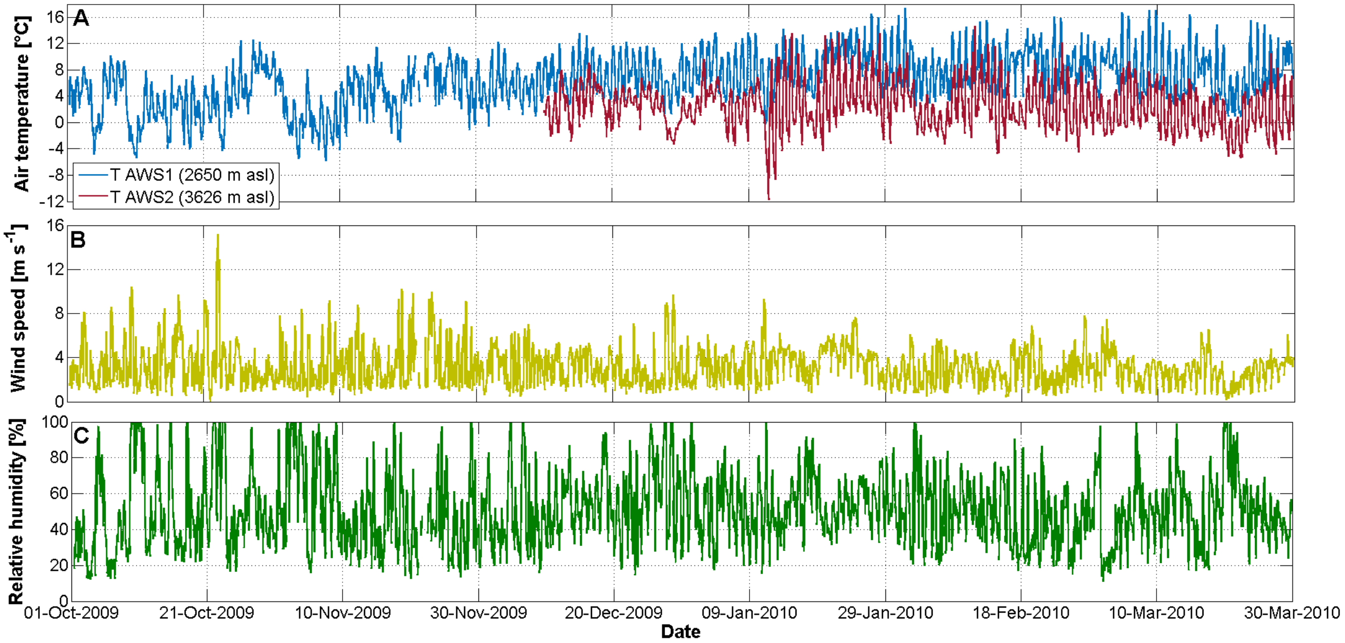


Figure 1: Location of the Universidad glacier in central Chile. Panel A shows the regional location, ~~The upper left P~~panel B shows the entire upper Tinguiririca basin and panel C~~, the lower panel~~ shows Universidad glacier (orange outline), automatic weather stations (AWS) and ablation stakes (S) installed. ~~GS~~ PS indicates the location of the ~~water level~~ pressure sensor, SG indicates the location for stream gauge of DGA and HydroChile.~~.~~ The background is an ASTER image from 27 March 2010, UTM 19S.



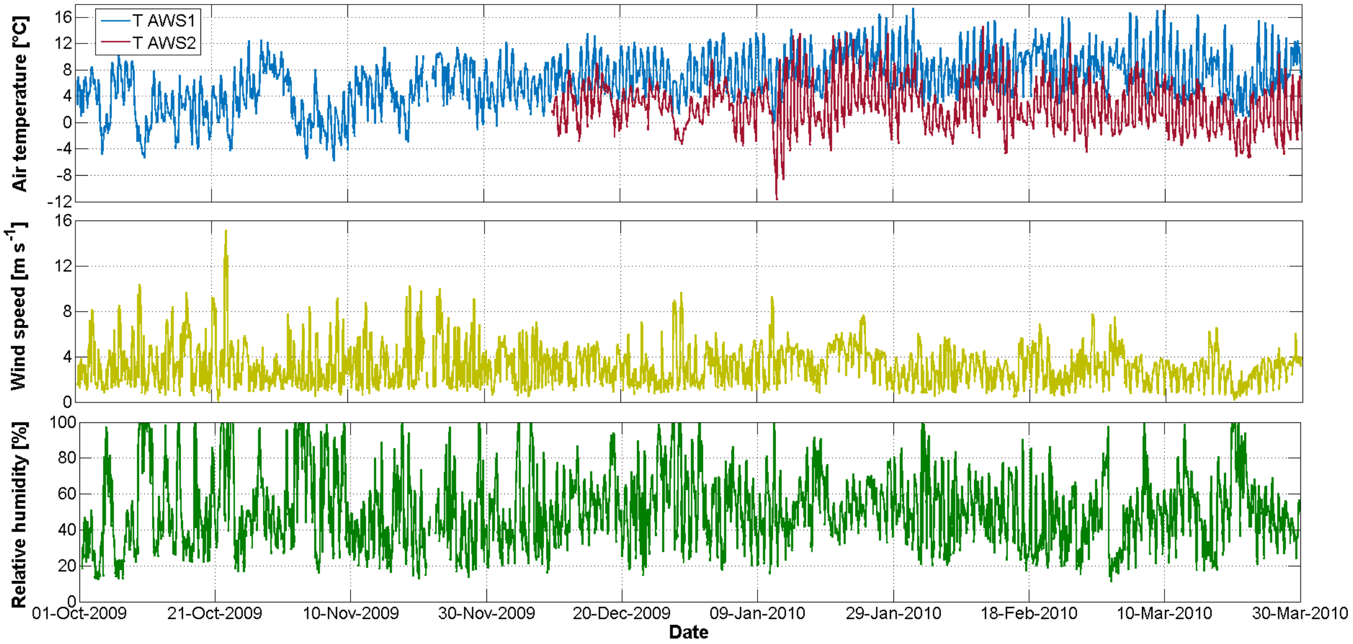


Figure 2: Time series of hourly meteorological variables observed. A) Air temperature at AWS1~~,~~ and AWS2, B) Wind speed at AWS1 and C) Relative humidity at AWS1. ~~air temperature in the upper panel.~~

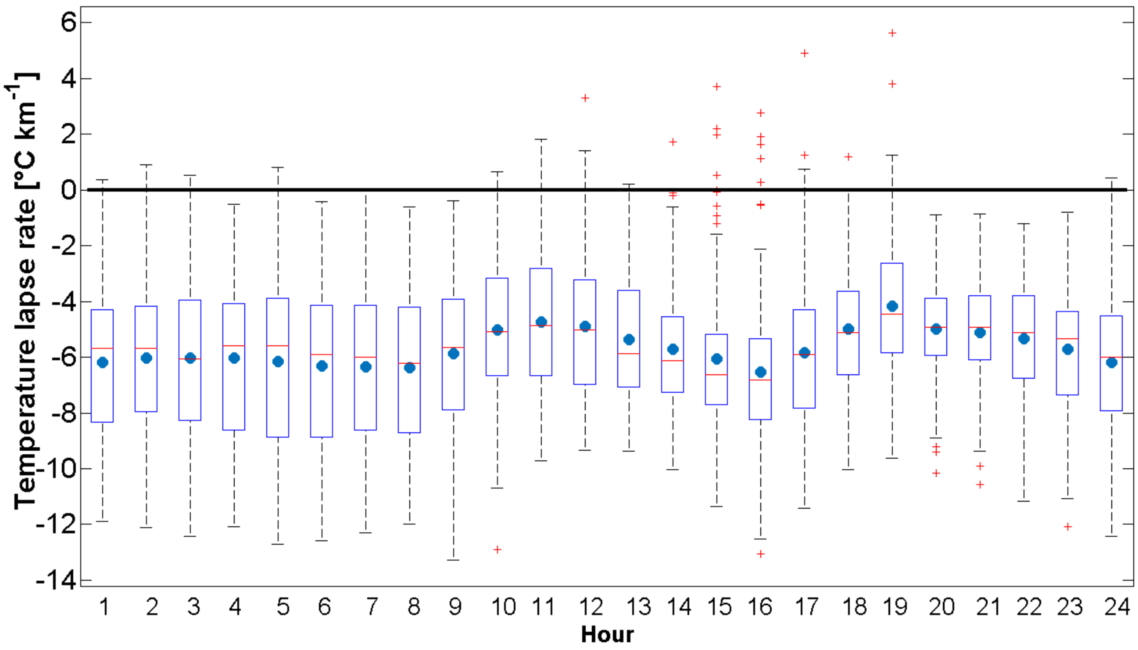


Figure 3: Boxplot showing the statistical distribution of hourly lapse rate calculated between AWS1 and AWS2 in the common period. Upper and lower box limit are the 75% and 25% quartiles, the red horizontal line is the median, the fill circle is the mean, crosses are outlying values.

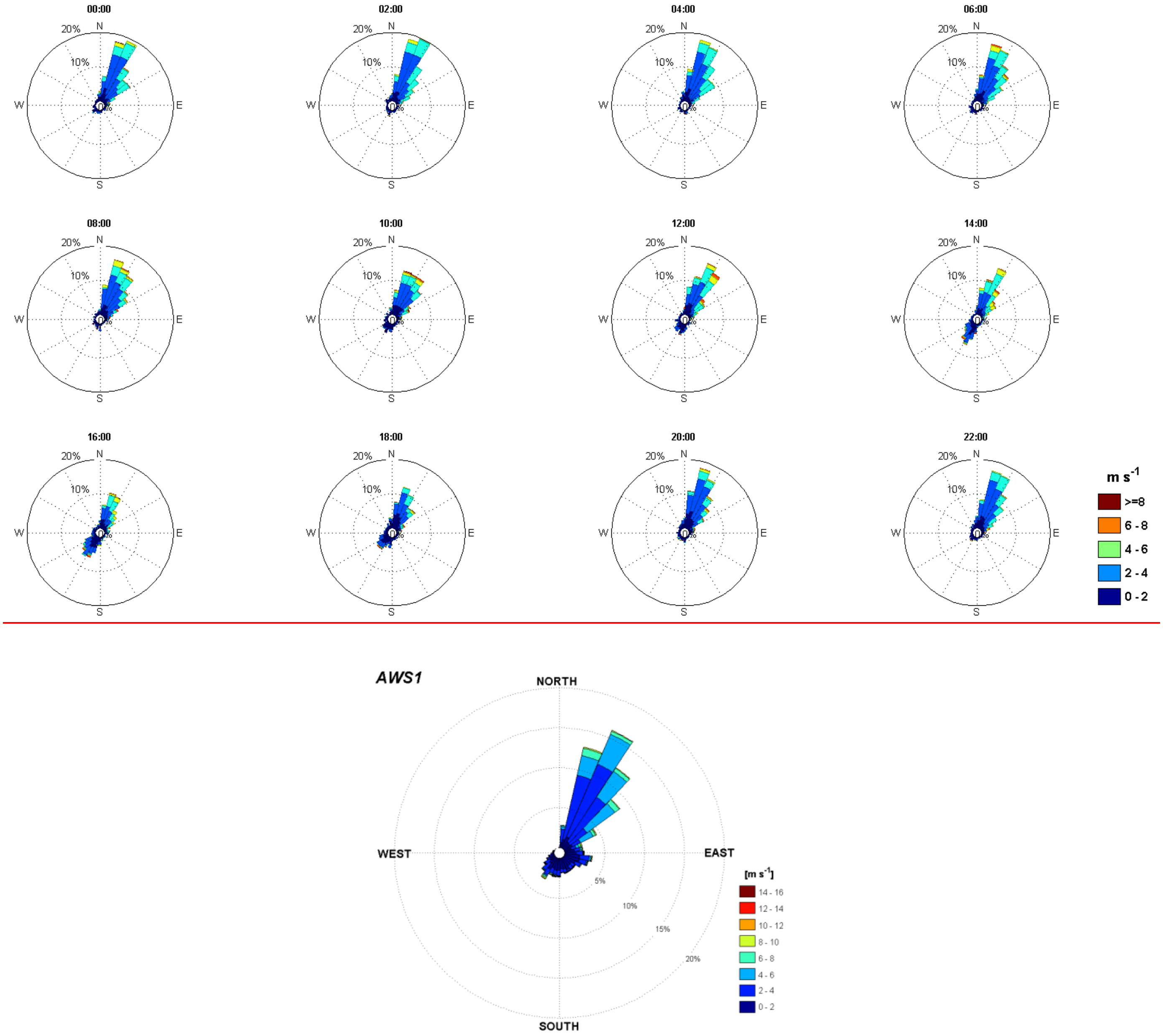
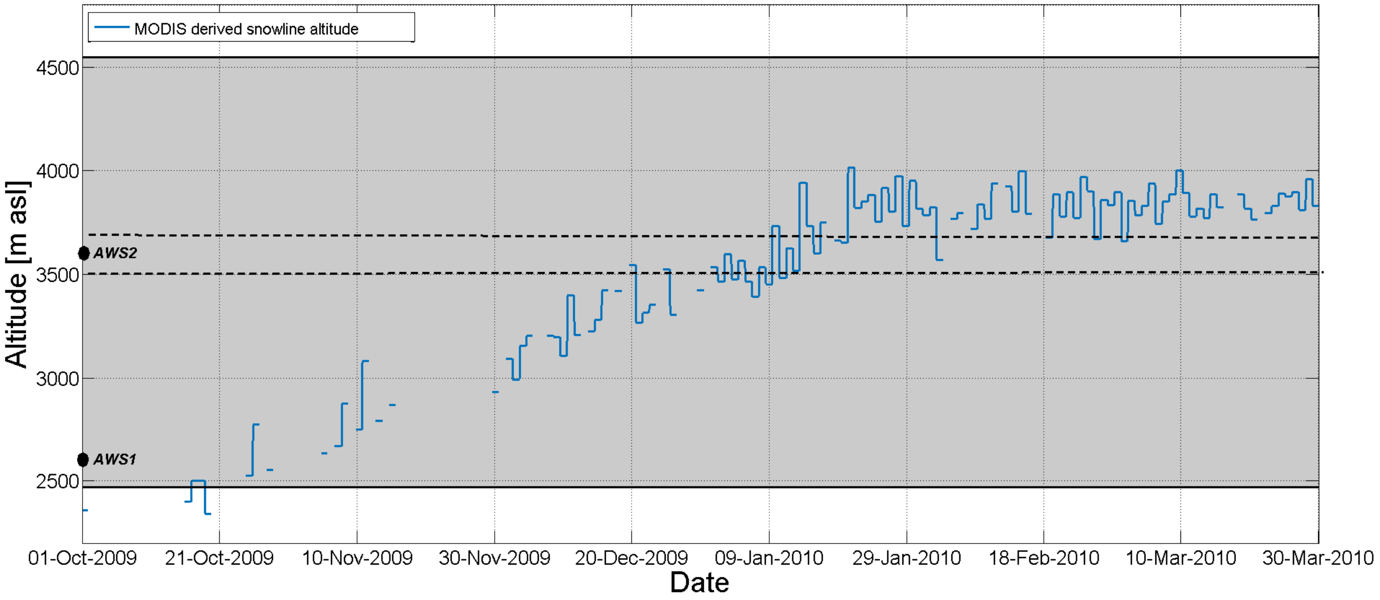


Figure 4: Hourly ~~W~~wind roses showing the predominant wind direction and the wind speed at AWS1 (local time).



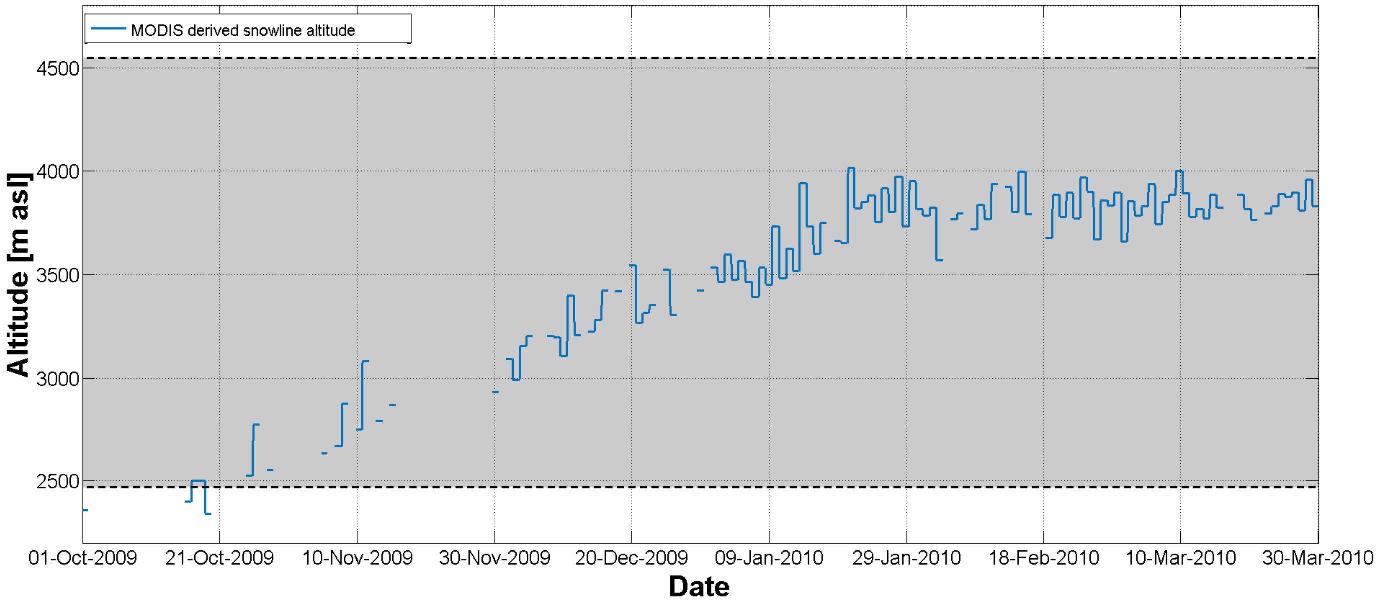


Figure 5: Snow line elevation estimated using the MODIS snow product. The grey area corresponds to the altitude range of Universidad glacier,~~.~~ dashed line shows the Equilibrium Line Altitude range estimated using an ASTER image and black points show the AWS elevations.

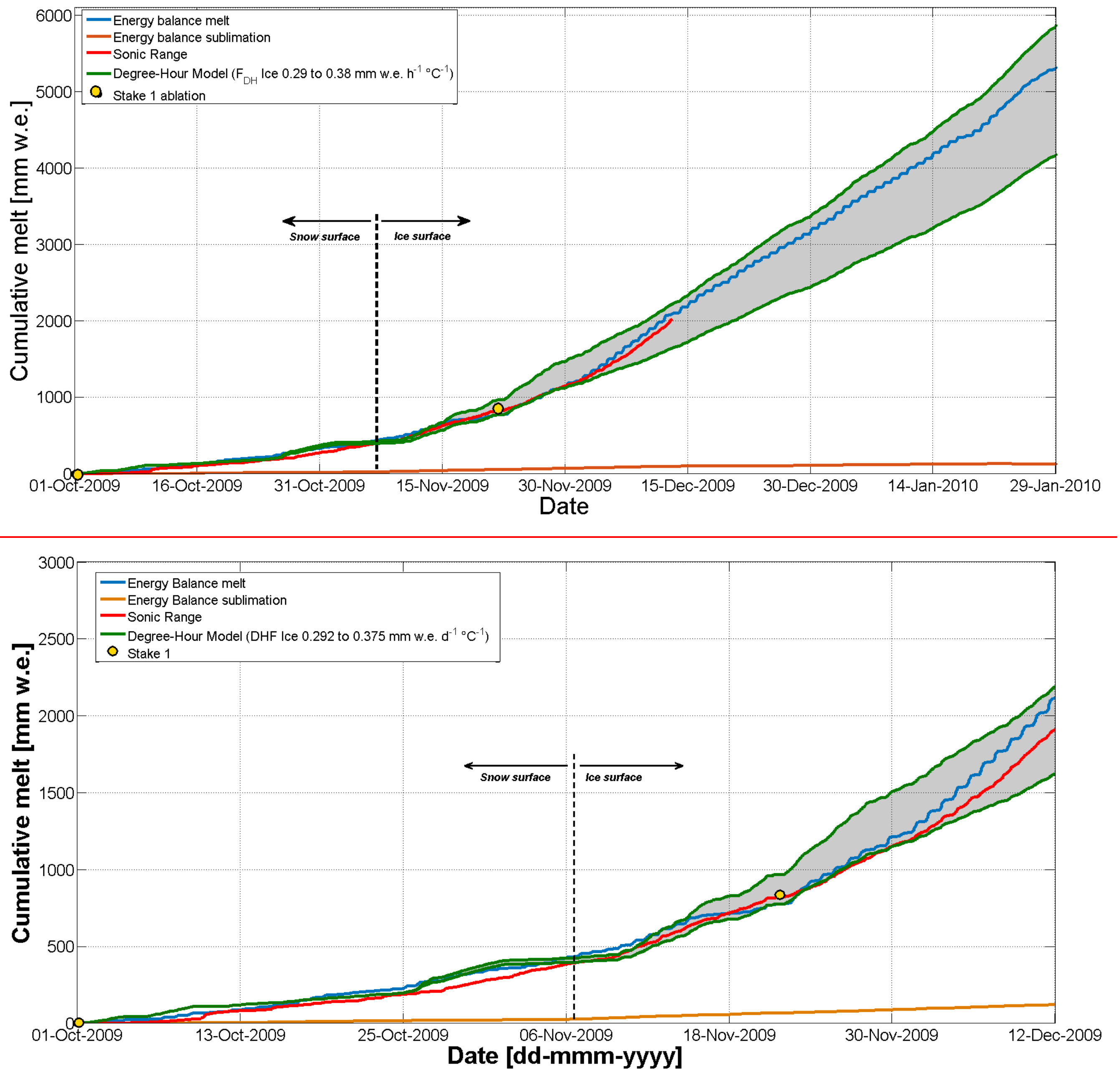


Figure 6: Comparison of cumulative melt estimated by the point scale degree-hour model (grey area), point scale energy balance model, sonic ranger and stake 1 located near the AWS1 (2650 m asl).

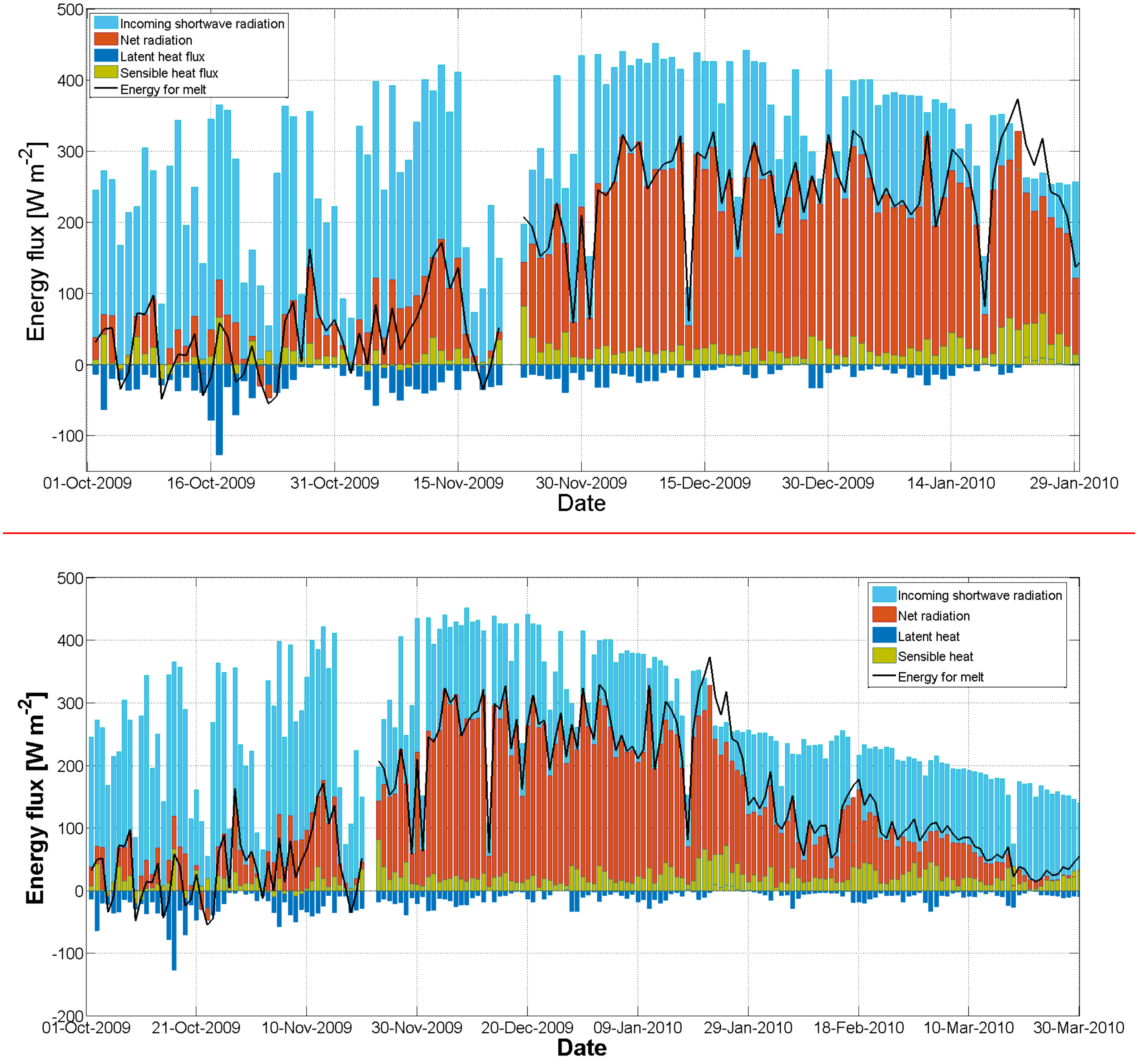


Figure 7: Daily mean net radiation, incoming shortwave radiation, latent and sensible heat fluxes and the calculated energy available for melt at AWS1 (2650 m asl). On November 21 and 22 there is no data due to maintenance of the AWS1.

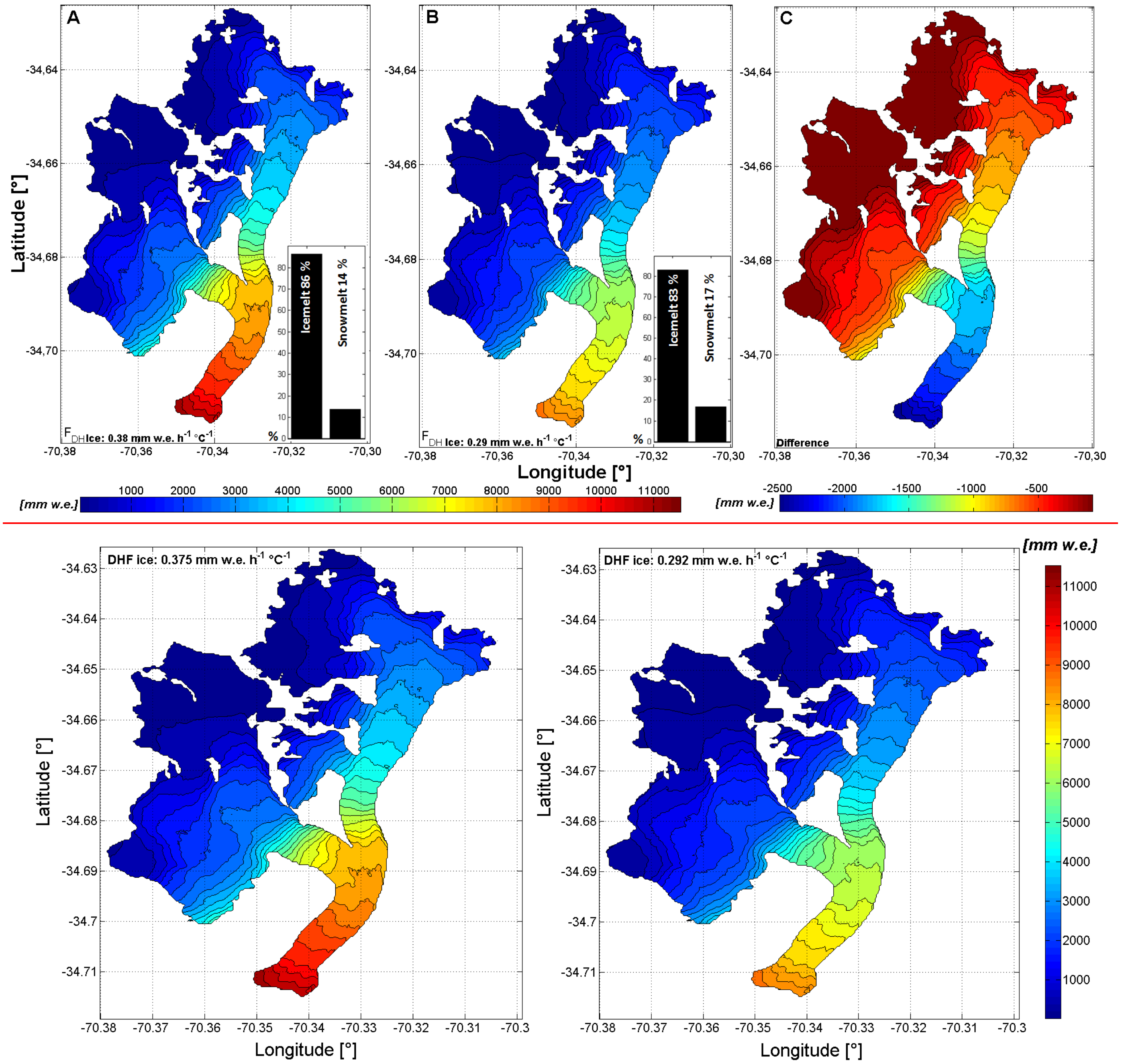
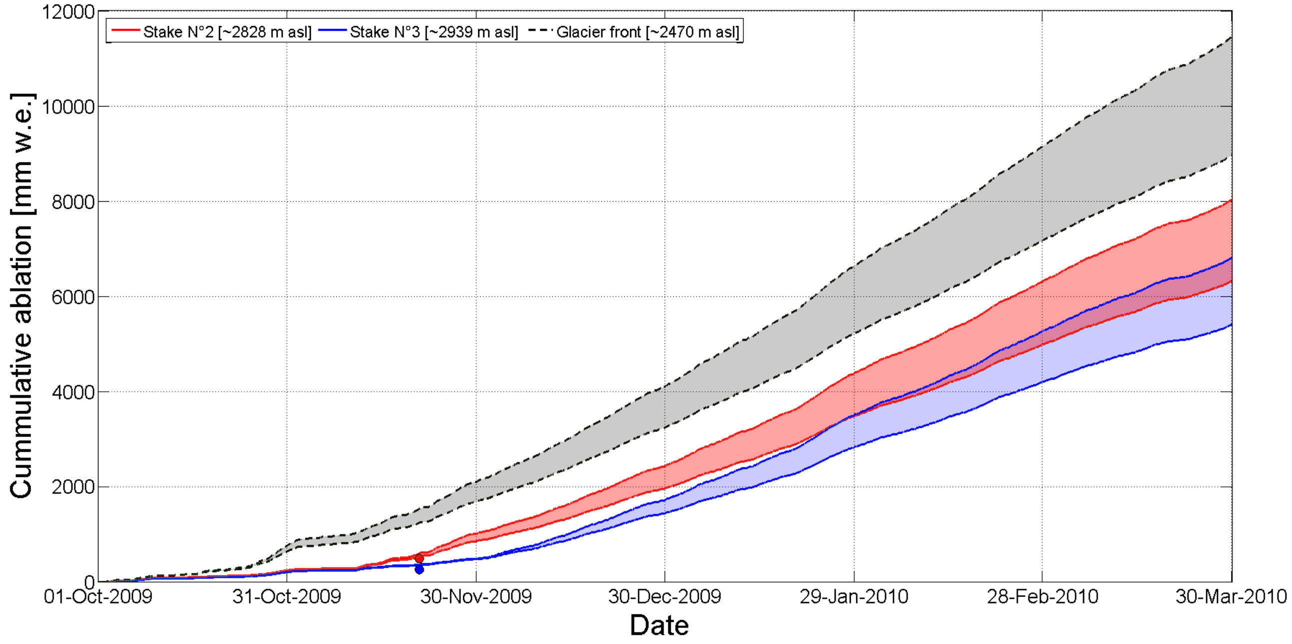


Figure 8: Spatial distribution of cumulative glacier melt for Universidad glacier using two different F_{DH}~~DHF~~ values for ice. A) F_{DH} 0.38 mm w.e. h^{-1} °C^{-1}, B) F_{DH} 0.29 mm w.e. h^{-1} °C^{-1} and C) Difference. Totals for October -2009 to March 2010 period.



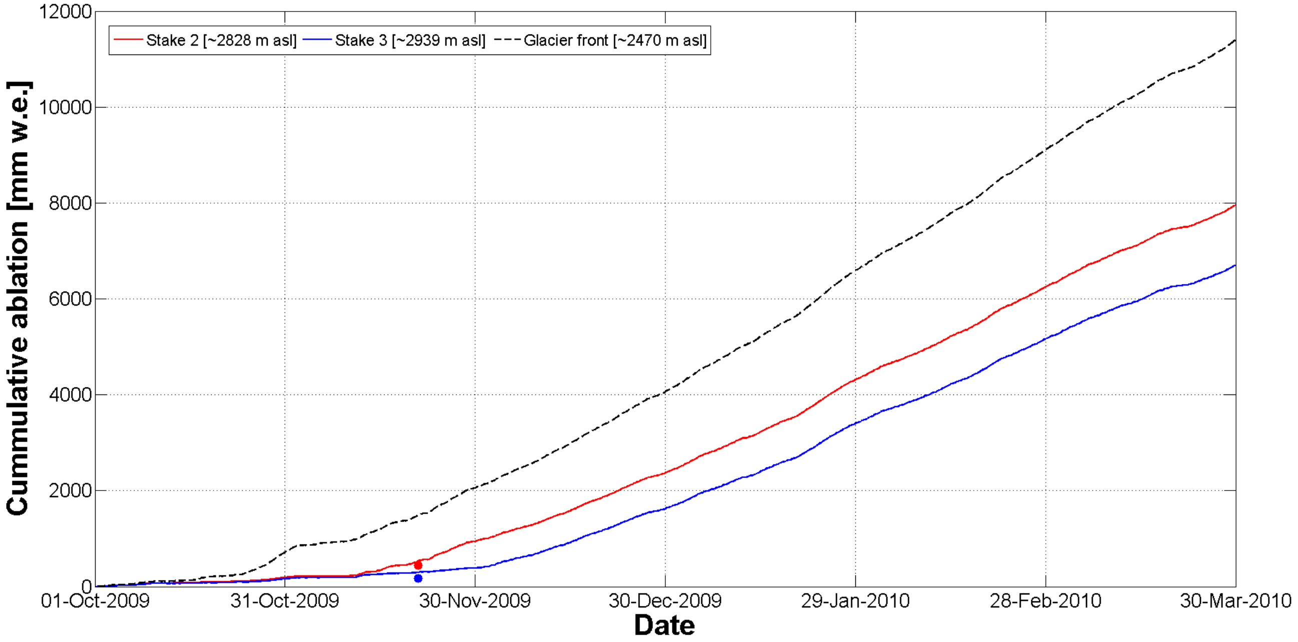


Figure 9: Total cumulative melt of Universidad glacier using the degree~~-day~~-hour model. ~~with a DHF for ice of 0.375 mm h^{-1} °C^{-1}.~~ The red and blue lines and areas represent the cumulative melt at the locations of stakes 2 and 3, respectively. Points indicate the stake measurements. The area in grey enclosed by dashed black lines represents the lowest altitude of the glacier.

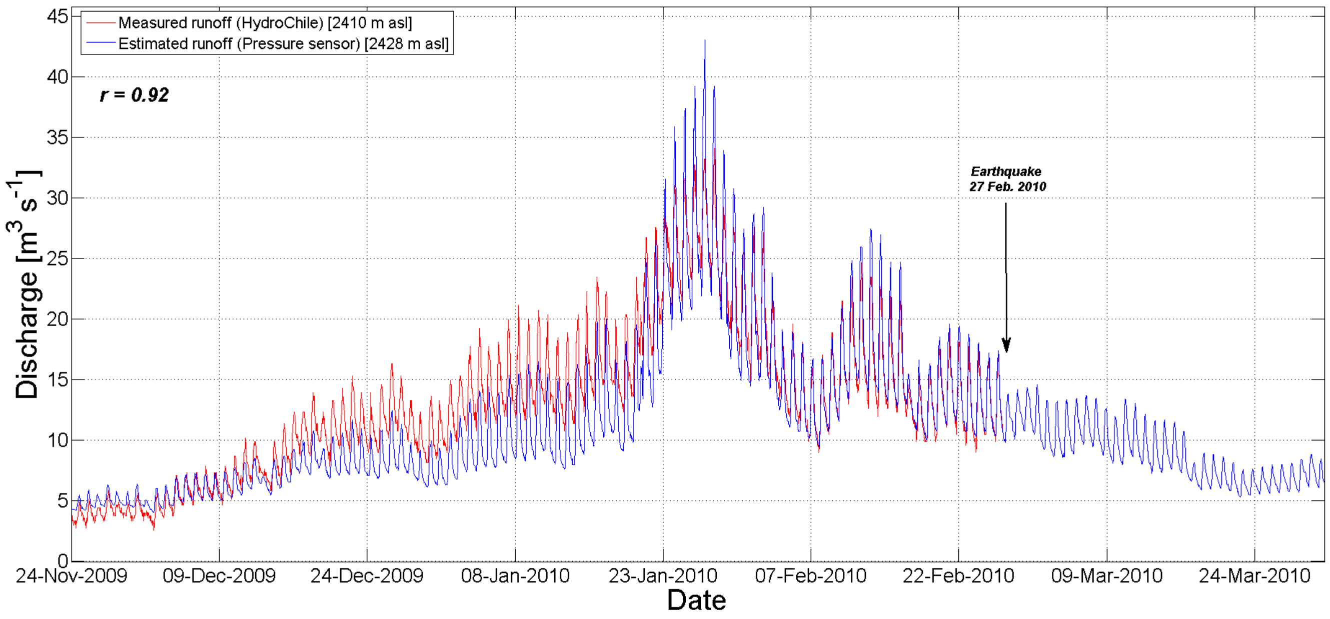


Figure 10: Time series of hourly runoff in the proglacial stream from the water level pressure sensor and HydroChile gauging station.

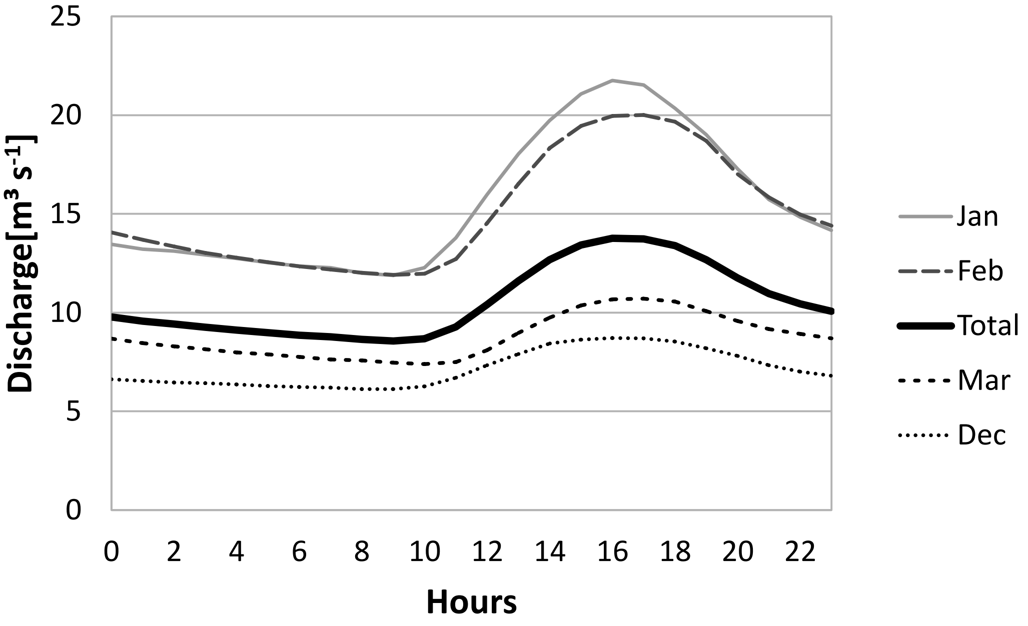


Figure 11: Hourly mean discharge during the total monitored period (black solid line) and for each month estimated from pressure sensor at 2438 m asl.

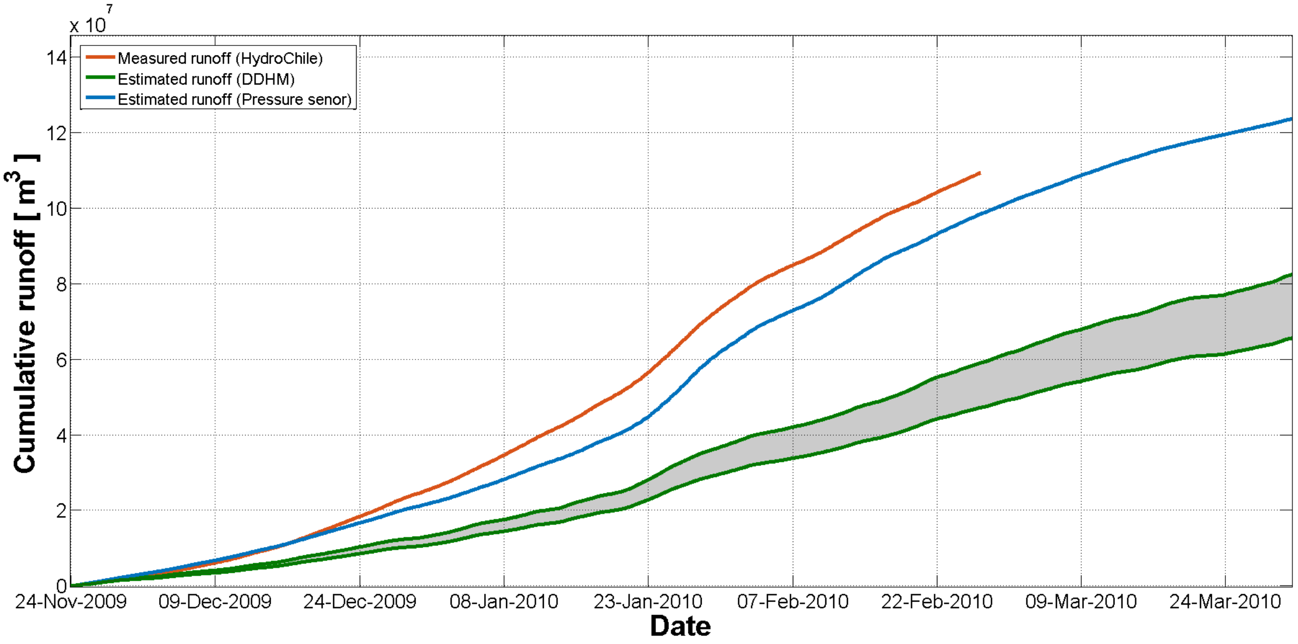


Figure 12: Comparison of cumulative runoff calculated with distributed degree-~~day~~ hour model (grey area), and river runoff measurements from water level sensor data and the HydroChile station.

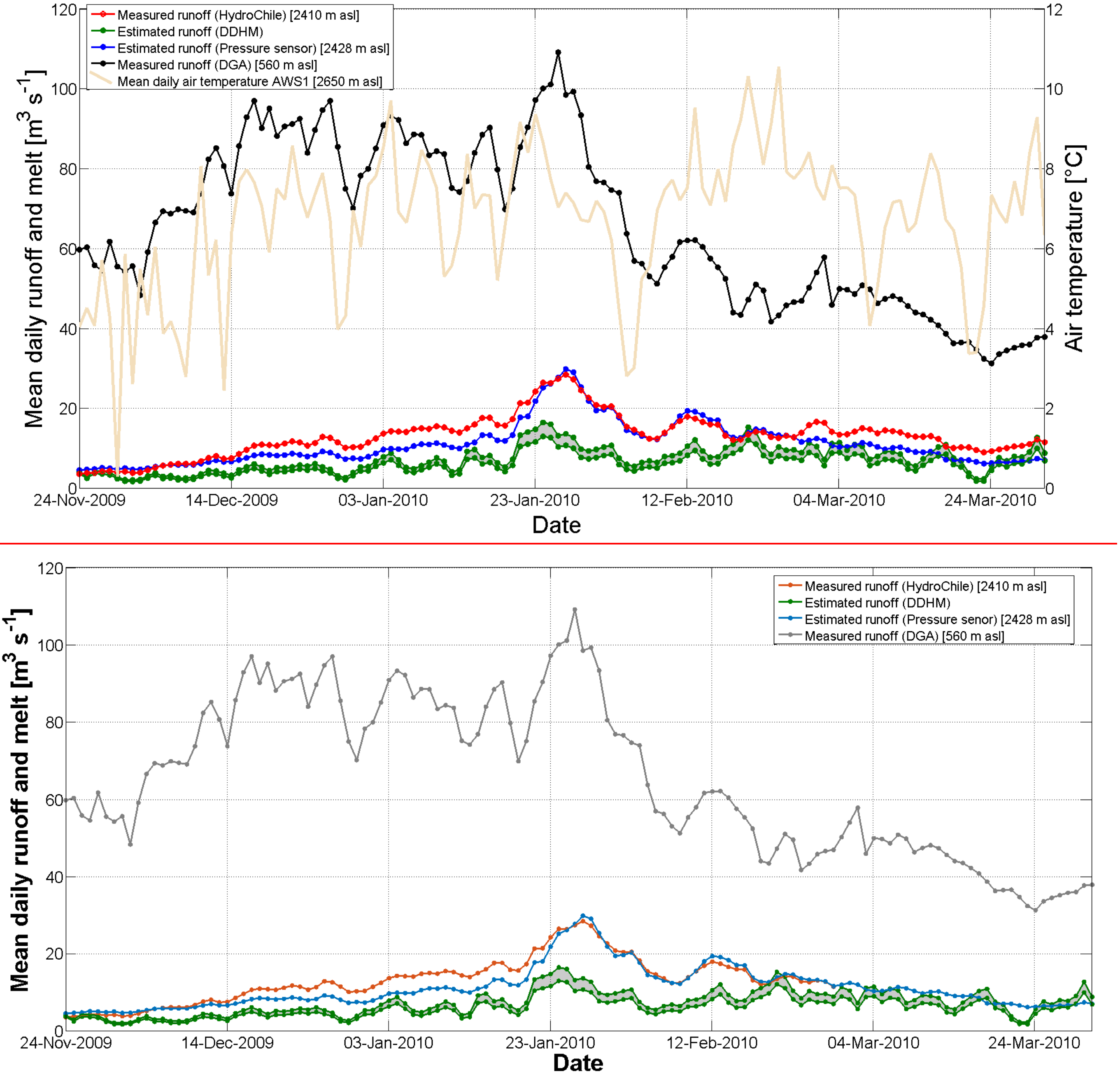


Figure 13: Daily mean runoff from distributed degree-hour model, and river runoff measurements from water level sensor, HydroChile station and DGA station. For reference mean daily air temperature at AWS1 is plotted in right y axis.