Response to Reviewer #1

A) General Comments

In the manuscript "Uncertainties in the spatial distribution of snow sublimation in the semi-arid Andes of Chile" Réveillet et al. present results of their study aiming to simulate melt and sublimation rates over the instrumented watershed of La Laguna. They present the relative importance of sublimation versus snow melt using a distributed snowpack model for two meteorologically contrasting years. They detected a large difference in modelled sublimation rates forcing the model with data of AutomaticWeather Stations (AWS) and with Weather Research and Forecasting (WRF) model data. This difference is caused by (a) the different meteorological input, particularly in precipitation and temperature, and (b) by the modelled snow cover persistence. The objective of the study of Réveillet et al. is to assess the uncertainties in melt and sublimation arising from modelling snow evolution using AWS and/or WRF-model generated meteorological datasets. Since the seasonal snow cover and glacier melt as processes of the cryosphere have locally a high contribution to available fresh water in this region. The study of Réveillet et al. contributes to gain knowledge of snow depth distribution and snow cover processes in the semi-arid Andes of Chile, and thus the manuscript is in the scope of TC. In general, this study shows again the importance of a critical interpretation of model results with respect to model input data. The introduction is complete, the applied methods are appropriate and comprehensible, and the results are compared to referenced work. However, the manuscript at its present stage summarizes results of interesting work packages and analysis, but lacks in the overarching aim with a clear problem statement, the research questions and the respective conclusions. This is also obvious in the high number of subsections presenting methods and results which not necessarily contribute to the conclusions. My suggestion is to restructure the manuscript with a clear focus on formulated research questions and to revise the title reconsidering the term "uncertainty".

Authors'answer:
We thank the reviewer for this constructive and thorough review of the manuscript.
As requested, and in agreement with comments made by the reviewer #2, the manuscript has been restructured and now focuses on the differences in simulated sublimation depending on the forcing used. More information is provided in the detailed response to Specific comment #1.

B) Specific Comments

(1) *As addressed in the general comments, the manuscript shows an interesting work but without presenting an overarching aim and respective research questions. Forcing the model with different data from AWS and WRF does not result only in differences of sublimation rates, but also differences in e.g. snow covered area, snow persistence and snow melt. So I would suggest that not the uncertainties in the spatial distribution of snow sublimation are shown. Rather the variation of snow related parameters and processes forcing the applied model with different input is presented. Since the weaknesses of the WRF model output are known (cold bias, precipitation overestimation) and the AWS data might be the more appropriate model input, the study shows the error of forcing the model with WRF data for snow parameters (i.e. the overestimation of the snow cover duration by 2 month). The impacts of these errors are particularly obvious in the sublimation rates and ratios, which again are a function of snow coverage, elevation, temperature, etc. If the (model?!) uncertainty in sublimation should be addressed in more detail, I would suggest to show at least one additional figure presenting the calculated and simulated sublimation rates at AWS locations. In my opinion, the manuscript at its* *present stage presents "Differences in simulated sublimation in a high mountain catchment of the semi-arid Andes of Chile using AWS data and WRF meteorological forcing". Possible research question may address the main differences (errors?) in sublimation simulated using the WRF forcing, the impact of SCA and SCD under/overestimation, and the effect of different meteorological conditions of the two contrasting years on sublimation ratios. This can lead to conclusions about advantages and disadvantages of using the different forcing data. Most of the results are already presented, but the paper should be restructured accordingly to answer the formulated research questions and further drawing the conclusions.*

Authors'answer: To address the comments of both reviewers, the paper has been restructured (including changing the title) to focus more on the differences in terms of snow depth, snow cover and sublimation as a result of the chosen forcing. This modification includes a change in result section, where a better comparison between the two forcings is provided (i.e. section 4.2 renamed to "Snow depth and snow cover comparison" for consistency).
The results sections of the original manuscript have also been revised and organized in:
4.3 Ablation and energy balance fluxes
4.3.1 Mean annual elevation gradients
This includes changes to Figure 10 and the addition of a new figure (Fig. 9) that show the energy fluxes contribution with respect to elevation (as suggested by reviewer #2)
4.3.2 Monthly evolutions
In this section, Figures 9 and 8 are presented and commented Figures 9 and 8.
The discussion section has also been re-organized with a stronger focus on (i) differences in sublimation as a function of the chosen forcing (ii) differences in sublimation between the two years and (iii) the impact of snow depth on the sublimation ratio and (iii) the limits of the study.
This re-organisation was chosen to focus the conclusions on advantages and disadvantages of using the different forcing data. For that purpose, differences in terms of meteorological data and the consequences on SD, SC and sublimation are studied, as suggested in comment #1.

***(2)** Two years with contrasting meteorological conditions have been chosen for this study. This has the advantage of testing the simulation results, but also seems to be restricted to AWS data availability. To get an overview of the overall climate in this region and to classify the two selected years in a climatological context, please present a short climate overview of the last 30 years from a nearby station, or at least some short statistics for the AWS with the longest data history (La Laguna?)*
Authors'answer: To address comment #2, a figure showing the monthly mean air temperature and precipitation over the 1976-2016 period recorded at la Laguna has been added to the supplementary information. The 2014 and 2015 measurements have been included in this figure.

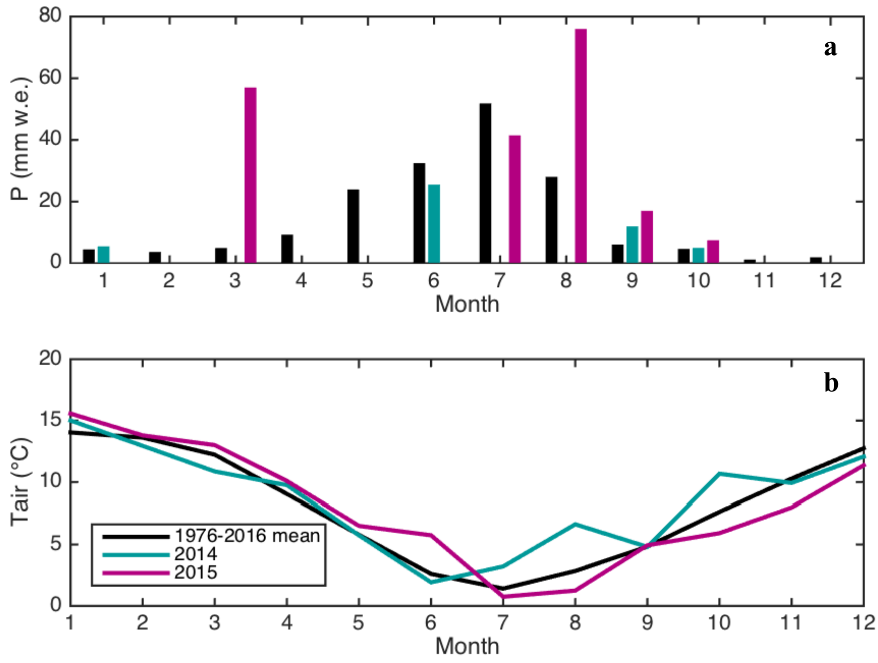


Figure S1: Monthly precipitation (a) and air temperature (b) recorded at La Laguna station. The monthly mean (black) is computed over the 1976-2016 period.

(3) *The downscaling of the WRF data still appears opaque to me. Is the relatively large T difference (Page 13 L22) before or after the adjustment? If before, what is the temperature offset after the adjustment? Please also present some standard deviation of the hourly/daily/monthly T values using the mean monthly gradients. What is about thermo-dynamics considering relative humidity and saturation for calculating lapse-rates. Please give some more detailed information in section 3.2.1. and the results.*

Authors'answer: We agree that the section 4.1.2 dealing with the comparison between the forcing was confusing. As the paper has been re-structured and now focuses in more details on the impact of the forcing choice on the simulation, the forcing data comparison is important. Modifications have been made in this section accordingly.

1- We agree that having the comparison before running the *Micromet* subroutine is interesting. Nevertheless, the direct comparison remains complicated in this study, mainly due to the spatial offset (and especially the vertical difference) between the AWS location and the closest WRF grid point. This is why we chose to present in the paper the comparison at the catchment scale from the *MicroMet* outputs to overcome this issue. As this information remains important, it is now mentioned in the manuscript and the vertical offset is available in the Table S1 in the supplementary material. In addition, a Table showing validation metrics (R2, RMSE and Absolute mean error) between the AWS measurements and the outputs from the closest WRF grid-point after running *MicroMet* is provided in the supplementary material.

"Details and statistics information about the comparison at each AWS locations are available in Table S1 (in the supplementary material). Note that here the comparison between the AWS measurements and the closest WRF grid point is not presented due to the significant vertical offset between the two points (Table S1 in the supplementary material)."

2- We don't really understand your request. Could you please clarify this point? Are you talking about the standard deviation for each station for each moth between the AWS measurements and the *Micromet* outputs forced by the AWS-forcing? Or a cross-validation study?

In addition, measurements have been used to compute the laspe rates, but as results were close to the default values, it has been chosen to keep the default parameterization to run the model. These information are given in section 3.2.1 :
"Spatial interpolation using the Barnes scheme was used to distribute the nine AWS measurements of T, RH, LWi, SWi and pressure over the model domain. As relative humidity is a non-linear function of elevation, the relatively linear dewpoint temperature is used for the elevation adjustment. For more details refer to Liston and Elder (2006). In this study the *MicroMet* subroutine has been run with the default setting for the Southern Hemisphere, for air temperature and dewpoint temperature monthly lapse rates (Liston and Elder, 2006b). Monthly lapse rates computed from the available measurements are dependent on the year considered. As the mean is close to the default settings, it has been chosen to conserve these values."
3- Section 3.2.1 has been clarified as follow:
"The 3km WRF outputs (i.e. the 240 points (Figure 1) decribed in section 2.2.1) were used as inputs for *MicroMet* which considers that each WRF cell corresponds to a virtual weather station located in the center of the WRF cell, following Mernild et al. (2017) and Baba et al. (2018a). In other words, this means that MicroMet has been forced by 240 virtual stations containing the WRF outputs meteorological dara. As an vertical offset exists between the WRF grid point elevation and the DEM, *MicroMet* adjusts this offset at the corresponding coordinate and downscales the data to a 100 m grid."
The result part was also modified as mention above.

C) Detailed Comments

P1 L23: *Please present the longitude in addition to the latitude.*
Authors'answer: This information has been added: 70°W

P1 L23: *Here an throughout the text: Above sea level can be abbreviated by "a.s.l."*
Authors'answer: Done

P1 L23: *Are the two years contrasting in hydrology or meteorology (or both).*
Authors'answer: This is a difficult question given that long-term gauges are located downstream of a dam (La Laguna). It's likely both, but in this study we are more focused on precipitation amounts. We have specified this in the manuscript:
"…La Laguna (3150–5630 m a.s.l., 30°S 70°W), during two hydrologically contrasting years (i.e. dry *vs.* wet)."
In addition, in the introduction and section 2 a reference to the figure S1 has been added.

P1 L27: *Replace "increased by 100%" with "doubled"*
Authors'answer: Done

P2 L3: *Replace "cryosphere" with "glaciers(?) and the seasonal snow cover"*
Authors'answer: Done

P2 L5: *"winter months". Please consider to present these months in the introduction (June, July, August?!)*
Authors'answer: It has been defined as follows: **"**that are largely limited to winter months (i.e. June, July and August)"

P2 L5: *"intermittent": This can also mean at regular intervals, but I think you mean "erratic"?*
Authors'answer: Yes, "intermittent" has been changed to "erratic"

P2 L24: *Delete "evolution"*
Authors'answer: Done

P3 L6: *Revise to one relatively wet and one d*
Authors'answer: The sentence was modified accordingly.

P3 L15: *Remove "over time". Instead you can present a date to which the snow cover duration persist (which month/season?)*
Authors'answer: "over time" has been changed to "at the end of the winter season (i.e. in August, September)", to address this comment.

P3 L18: *Add the longitude.*
Authors'answer: The longitude has been specified as in the abstract.

P3 L20: *"best instrumented": Please explain in more detail. In contrast to which other catchments? Or just write "well-equipped" or "mounted"*
Authors'answer: To address this comment, we have specified as follows: "…is the most instrumented within the region"

P3 L21: *Remove the "~" (also throughout the manuscript)*
Authors'answer: "~" has been removed throughout the manuscript.

P3 L23: *Remove "clean"*
Authors'answer: Done

P3 L25: *Please use 10x m3 instead of Mm3*
Authors'answer: Done, in addition the value was wrong. Therefore, "200 Mm^3" has been change by "38.10^6 m^3".

P3 L26: *Revise "rate" to "mean annual precipitation"*
Authors'answer: Done

P3 L31: *Is "area" the "study site"?*
Authors'answer: Yes, this has been specified.

P3/ffP4: *This sentence is hard to understand. Are these trajectories "storm paths". Please give some more detail. Also the sentence can be condensed to "The seasonal variability and frequency of precipitation events is also affected by precipitation trajectories..."*
Authors'answer: The sentence has been re-written: "Seasonal precipitation variability and frequency are also complicated by individual storm trajectories (e.g. Sinclair and MacDonell, 2016) which can cause large differences in relative precipitation distribution across the catchment, a phenomenon also described in central Chile (Burger et al., 2019)."
And the following reference has been added:
Burger, F., Ayala, A., Farias, D., Shaw, T. E., MacDonell, S., Brock, B., McPhee, J. and Pellicciotti, F.: Interannual variability in glacier contribution to runoff from a high elevation Andean catchment:

understanding the role of debris cover in glacier hydrology. *Hydrological Processes*, 33(2), 214-229. https://doi.org/10.1002/hyp.13354, 2019

P5 L7: *Remove "Finally"*
Authors'answer: Done

P5 L5: Replace "for a specific campaign" by "next to the glacier"
Authors'answer: According to your comment, "for a specific campaign" has been replaced by "in the debris-covered part of the glacier"

P8 L12: *Shift "the" to the front of La Laguna*
Authors'answer: Done

P8 L13: *Shift the reference to Figure one to the sentence before "the La Laguna catchment (Figure 1)"*
Authors'answer: Done

P9 L9ff: *Please consider to remove the subsections and to highlight the sub-model description by paragraphs and the sub-model names by italic font.*
Authors'answer: Done

P10 L8: *Please unify "T" or "Tair"*
Authors'answer: "T" has been chosen and is now used over the entire manuscript.

P10 L10: *Replace "please" by "we"*
Authors'answer: Done

P10 L28: *Add "snow albedo" to "minimum"*
Authors'answer: Done

P12 L3: *Add "sublimation" in front of "rate"*
Authors'answer: Done

P12 L19: *Since the abbreviations have been introduced, use SWi here. Please check this throughout the text.*
Authors'answer: "SWi" is now used in the manuscript (and in the Figures) after being defined, as well as "LWi".

P12 L19: *You present absolute values here, but how much is this in % of mean SWi?*
Authors'answer: This information have been added for SWi and LWi. The paragraph has been re-written as follows:
"According to the AWS measurements, Jan-Jul 2015 was warmer than Jan-Jul 2014. Conversely, observations indicate lower temperatures for Aug-Dec 2015 than for Aug-Dec 2014 (daily mean difference of -2.6°C). Relative humidity was higher for 2015 compared to 2014 (daily mean difference of 11%) whereas SWi was lower (mean difference of -18 W m^{-2}, i.e. 6% of the mean SWi), with larger differences in Jul-Dec (daily mean difference of -32 W m^{-2}, i.e. 12% of the daily mean SWi), and LWi was higher (daily mean difference of 20 W m^{-2}, i.e. 7% of the daily mean LWi). This decrease SWi and increase in LWi can be explained by a larger number of clouds in 2015."

***P12 L20:** Why is it in agreement? Why are weather conditions with more clouds necessarily colder? Whats about clear sky conditions at night causing very low temperatures?*
Authors'answer: We agree that the relationship between SW and air temperature is more complex. To avoid confusion and considering that this information is not central to the paper, the sentence has been deleted.

***P13 L1:** Is this comparison performed before or after the Barne-downscaling? Please clarify here.*
Authors'answer: Yes, it was performed before the Barne-downscaling. Nevertheless this section is confusing. In agreement with your specific comment 3 and remarks made by the second reviewer, this information is now in the supplementary information as a Table."

***P13 L25:** Correct "annual"*
Authors'answer: Done

***P14 L8:** Revise this sentence to: "Simulated snow depths using. . . agreement with measured snow depth values.*
Authors'answer: The sentence has been changed according to your comment. It now reads: "Simulated snow depths using the AWS-forcings (Figures 5 a-f) are in good agreement with measured snow depth values (mean k=0.14 and mean *RMSE*=0.15 m)."

***P15 L1:** "forcings indicates": Remove one "s"*
Authors'answer: Done.

P19 L9: Please give more detail ion the time period and spatial extent of the averaged values here
Authors'answer: This sentence has been restructured and the issue in question is no longer relevant here. However, in order to address this comment and remarks made by reviewer #2, more details have been added in the methods section as follow: "Note that sublimation and energy balance are only computed over snow surfaces. This means that annual and monthly means are only computed at grid-cells with snow."

***P21 L7:** Delete "when the snow. . .."*
Authors'answer: Done

***P25 L5:** Revise to: Precipitation is known to be over-estimated using the WRF model*
Authors'answer: Done

***P25 L6:** Correct "exist"*
Authors'answer: Done

***P25 L10:** Please revise this sentence. Suggestion: Precipitation measurements using rain gauges can be biased towards an underestimation because of an undercatch particularly of snowfall due to wind influence.*
Authors'answer: *Done*

***P26 L26:** Here the sublimation rate (absolute values) should be compared.*
Authors'answer: We agree with your comment and also think that having these rates will also be very useful for the discussion. Therefore, this information has been added to the results section as

follows:
"The mean daily rate is 0.6 mm w.e. d^{-1} and 3.6 w.e. d^{-1} for 2014 and 2015, respectively, when the model is forced with the AWS-forcing. Values are larger and reach 3.1 mm w.e. d^{-1} and 4.1 mm w.e. d^{-1} for 2014 and 2015 when simulations are performed with the WRF-forcing."

The discussion has been entirely re-organized and all the sections in 5.2 have been re-written. Sublimation rates are now discussed in this section.

P27 L3: *There will be no sublimation without a snow cover. Thus, this sentence is redundant. Perhaps you want to say that the snow cover duration SCD has a significant influence on sublimation/melt ratio.*
Authors'answer: This sentence has been removed due to the restructuration and to avoid confusion.

P28 L17: *It is rather the mass and energy balance of the snow cover, which includes sublimation.*
Authors'answer: This sentence has been modified accordingly.

P29 L19: *Precipitation data is not an uncertainty, but the uncertainty of measured/modelled precipitation is.*
Authors'answer: The sentence has been re-written to address this comment: "First, the main forcing uncertainty is from precipitation due to measurement errors and lack of spatial representation as precipitation data was only available for two stations."

Figure 1:
- Please include the reservoir and the glacier in the legend. Please adjust the elevation in the legend to the colour transitions.
Authors'answer: Done

Figure 3:
- Please unify the units. I would suggest Wm-2 and ms-1
- Please present in addition the snow depth, since this is an important parameter of this study
- Caption: Since only two years are presented, no "climatic" conditions are shown.
Please revise to "meteorological conditions at the. . ."
- Please uniform the radiation abbreviations throughout the figures/manuscript to avoid confusion between incoming (index i) outgoing etc.
- Remove the "s" from "precipitations"
Authors'answer: Figure 3 and the caption have been revised to address this comment.

Figure 4:
- Caption: Replace 'studied' with "La Laguna"
- Please describe in the caption which output is subtracted from the other for interpretation of the sign on the differences?
Authors'answer: The caption has been changed. The Figure has been modified according to the reviewer #2 comment and the variables are now plotted instead of the differences.

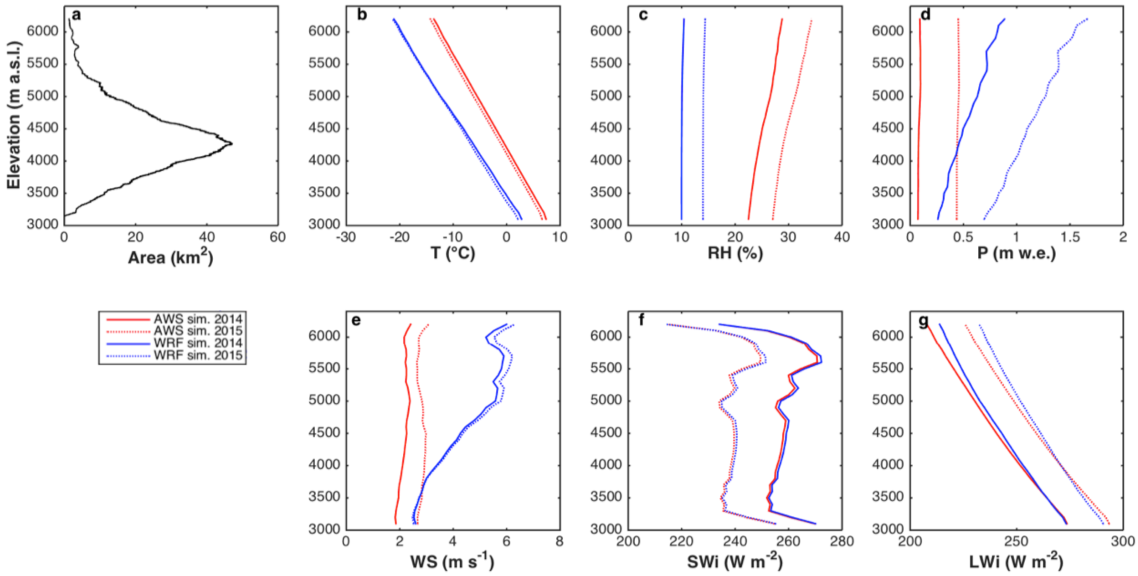


Figure 4: (a) Area-elevation distribution of the La Laguna catchment. (b to g) MicroMet outputs at the catchment scale forced by the AWS (red) and the WRF (blue) for 2014 (lines) and 2015 (dashed lines).

Figure 5
- I would suggest to bring the graphs of AWS/WRF-forced SD and observations in one figure for each station, and thus reduce the number of subfigures to 6.

Authors'answer: We initially did this, but it was difficult to distinguish AWS-forced SD and WRF-forced SD and almost impossible to compare it to the observation. So we decided to split it into different graphs.

Figure 6
- Please bring the decimal order (10ˆ8) to the label of the y-axes. I suggest to use km2 like in the RMSE

Authors'answer: Done, km2 is now used.

Figure 7
- Modelled "energy" fluxes are shown

Authors'answer: Done

Response to Reviewer #2

A) General Comments

This paper presents an assessment of sublimation and melt rates from the snowpack in a semi-arid region of Chile. A distributed physically-based snow model is used to simulate snowpack evolution and quantify losses from sublimation and melt. The model is forced with two datasets that are spatialized on a 100m grid – one created from in-situ meteorological observations, the other from meteorological model output. The simulations are validated against in-situ snow depth measurements as well as snow cover observed using the MODIS platform. The results highlight the complex interactions between meteorological forcing and surface energy and mass balances, along with the effects of spatio-temporal averaging when calculating catchment-wide metrics in areas with predominately ephemeral snow cover. The rationale is well developed, the methods are fit-for-purpose and generally well explained, and many interesting and relevant results are presented.

1) However, there are too many lines of inquiry that compete for the readers attention and the figures presented do not always clearly present the main conclusions reached. In places, the results seem to contradict each other, and it not always clear in what direction different factors affect the sublimation ratio. For example, increased precipitation is attributed to increased melt based on Figure 12, but to increased sublimation based on the WRF simulations). This all contributes to make the paper quite hard to follow and reduces the confidence in the conclusions reached. The aims and hypothesis need to be clarified and perhaps re-assessed given the results available to ensure a coherent story can be told from the results. I would suggest the authors have a few options to refine and narrow the aim of the paper:

- If the aim is to understand the spatio-temporal variability of sublimation and melt, then only the simulations with AWS forcing should be presented as they appear to show the best validation, and the inclusion of the WRF result only confuse the reader. The results relating to season and effect of SCD and elevation can be highlighted.
- If the aim is to compare the effect of using the different forcing datasets (which is a valid aim given that methods to extrapolate beyond areas with in-situ measurements are needed), then the paper should be framed in this way and some of the later results should either be amended to include WRF results or removed (i.e. fig 11 & 12).
- If the aim is to establish the uncertainty in modelling actual sublimation and melt rates, then a more systematic approach requiring further simulations would be needed.

Of course, the authors may have other ways they wish to reframe, these are just some suggestions.

Additionally, some important aspects of the simulation deserve more attention:

2) Validation needs to include comparison of wind speed and incoming radiative fluxes, as well as modelled surface temperature and albedo where possible.

3) Greater discussion of wind speed and surface temperature as a key control on sublimation in the main body of the paper – e.g. the sensitivity of sublimation ratio to 10% change in wind speed noted in S4-15.

4) Clearer description of how average results are calculated, especially the sublimation ratio vs ablation rates, considering the changing temporal and spatial scales associated with the ephemeral snow cover, and their effect on the results. The authors may wish to consider reporting surface energy balance terms as sums in MJ rather than rates (m yr-1 or W m-2) as these can be ambiguous when the you do not average over the full period (e.g. only over snow covered surfaces).

5) Elevational gradients of SEB components need to be shown as it currently very hard to sort out different mechanisms for change in sublimation ratio (e.g. change in meteorology, snow covered area, elevational gradient). Ideally these would come before the catchment-average results to set the context for the observed inter-annual and/or inter-model differences.

With a more focussed aim and the clarification of these points, I have no doubt that this paper will make a good contribution to the literature.

Authors'answer:
Thank you for your positive comments and interest in the paper. We have carefully answered each point presented in the general comments as well as the specific/technical points. Changes made in response to reviewer comments in the manuscript are in green.

1) Authors'answer: To address the comments of both reviewers, the paper has been restructured (including changing the title) to focus more on the differences in terms of snow depth, snow cover and sublimation as a result of the chosen forcing. This modification includes a change in result section, where a better comparison between the two forcings is provided (i.e. section 4.2 has been renamed to "Snow depth and snow cover comparison" for consistency).
The results sections of the original manuscript have also been revised and organized as follows:
4.3 Ablation and energy balance fluxes
4.3.1 Mean annual elevation gradients
This includes changes to Figure 10 and the addition of a new figure (Fig. 9) that show the energy fluxes contribution as a function of elevation (as suggested by reviewer #2)
4.3.2 Monthly evolutions
In this section, Figures 9 and 8 are presented and commented Figures 9 and 8.
The discussion section has also been re-organized with a stronger focus on (i) differences in sublimation as a function of the chosen forcing (ii) differences in sublimation between the two years and (iii) the impact of snow depth on the sublimation ratio and (iii) the limits of the study.
This reorganization was chosen to focus the conclusions on advantages and disadvantages of using different forcing data. For that purpose, differences in terms of meteorological data and the consequences on SD, SC and sublimation are analyzed, as suggested in your comment.

2) The comparison of wind speed and radiative fluxes has been added in section 4.1.2 and Figure 4 (in agreement with the specific comments P13 L1, L21 and L22). For more details please refer to these comments.
Regarding the albedo validation, measurement data have been used to calibrate the model. Information about the available measurements is given by Figure 2. In addition, this point has been clarified according to your comment P10 L30)
Regarding the surface temperature, we have chosen not to add a new graph. For more details please refer to comments P14 L6.

3) Due to the new reorganization of the paper, and a focus on the impact of different forcings on sublimation, we worry that this point will be a little bit disconnected from the main scientific question. Nevertheless since this point is important and interesting, we created a new section in the discussion, named 'Limits of the study', and the results are included in the supplementary material.

4) The calculation is done considering only days with snow on the ground. In order to address your comment and a comment made by the other reviewer, this information is now provided in the methods section: "Note that sublimation and energy balance are only computed over snow surfaces. This means that annual and monthly means are computed at grid-cells with snow only."

In addition, we tried reporting surface energy balance terms as sums in MJ (see Figures below). However, we think that in this case the number of days changes the MJ sum and the graph therefore illustrates the number of days more clearly than the energy flux differences. For instance, for the elevation plot when fluxes at a given elevation are compared, larger values are found at higher elevations and this is related to the number of days rather than changes in the energy flux. Regarding the monthly average, larger values using the unit MJ are found for the months when snow was on the ground for all days.

The alternative would be to compute the MJ over a similar time period, but given the data availability for this catchment, this would reduce the results to a very short time period. Therefore, even though the average cannot be calculated over the entire time period, rather only when there is snow covering the surface, we think that using W m^{-2} allows for a more accurate interpretation of the results.

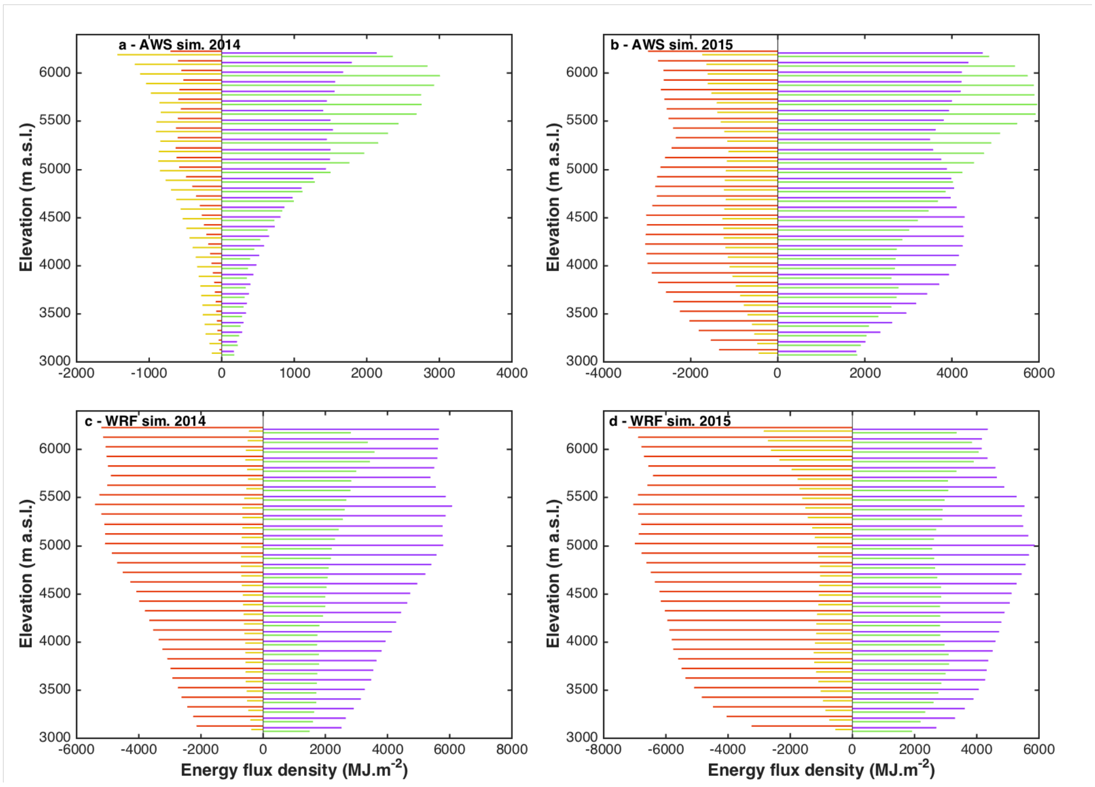


Figure: Annual sum of main modeled energy fluxes (computed over snow surfaces only) for each 200 m elevation band using AWS (a,b) and WRF (c,d) forcing for 2014 (a,c) and 2015 (b,d). SW (green) is net shortwave radiation, LW (yellow) is net longwave radiation, QE (red) is the latent heat flux and QH (purple) is the sensible heat flux.

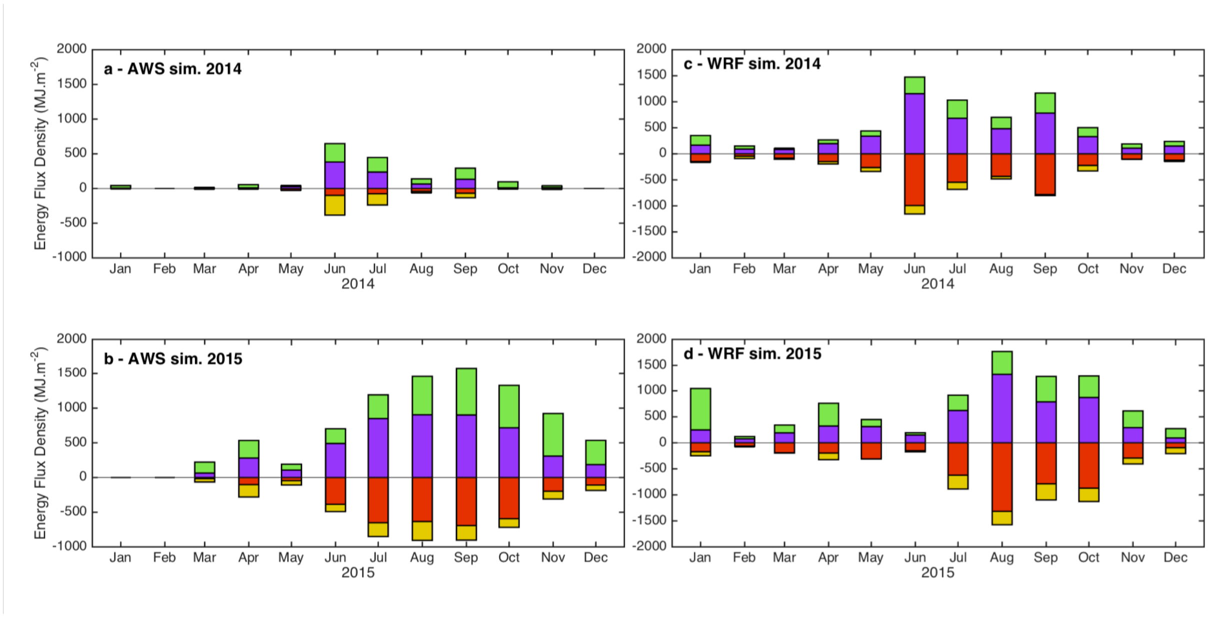


Figure: Monthly sum of the main modeled energy fluxes for the entire catchment, over snow surfaces only. SW (green) is net shortwave radiation, LW (yellow) is net longwave radiation, QE (red) is the latent heat flux and QH (purple) is the sensible heat flux

5) A Figure showing the energy fluxes against elevation has been added to the revised manuscript (Figure 9), before the catchment averages are discussed as suggested.

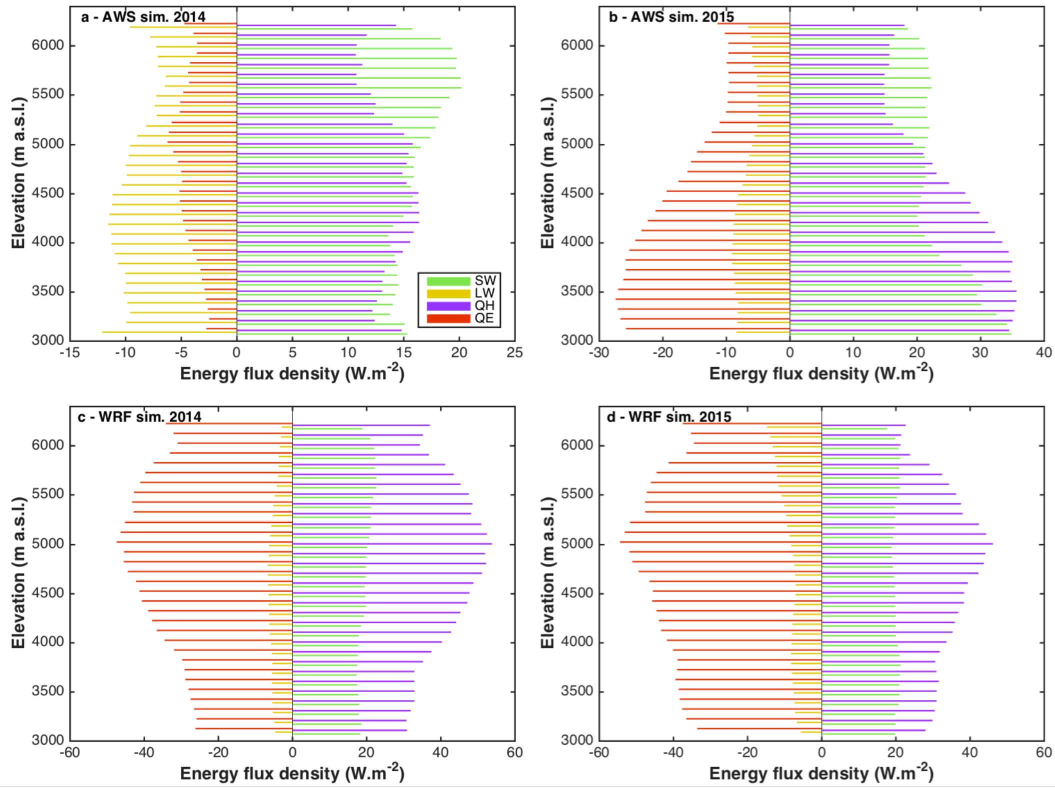


Figure 9: Annual mean of main modeled energy fluxes (computed over snow surfaces only) for each 200 m elevation band using AWS (a,b) and WRF (c,d) forcing for 2014 (a,c) and 2015 (b,d). SW is net shortwave radiation, LW is net longwave radiation, QE is the latent heat flux and QH is the sensible heat flux.

B) Specific Comments

P3-L21 *The maximum elevation of the catchment is listed as 5630 m, but figures 4,7,10 and 11 show elevation bins > 6000m. Please clarify.*
Authors'answer: Thank you for this observation, indeed, the maximum and the minimum elevation of the DEM presented in Figure 1 are respectively 6211 and 3143 m a.s.l.. This has been corrected in the revised manuscript.

P7-L1 *The figure caption describes these as hourly average values, but from the look of things (especially the SW) these appear to be daily averages. Please check and revise text.*
Authors'answer: Thank you for this observation; the caption is incorrect as daily data are plotted here. This has been corrected.

P8-L13 *Please indicate what height were the WRF output were output and if any scaling was used to transform their heights in Micromet.*
Authors'answer: The WRF outputs are 2 m above the surface. This information is an input into the *MicroMet* model, and the meteorological outputs are therefore at 2m. This information has been added in the manuscript as follows:
"The model outputs are at 2m above the surface and are available at 22 km resolution over Chile"

P10-L30 *Please indicate what sites and periods were used to choose the snow albedo values.*
Authors'answer: Albedo measurement availability is mentioned in Figure 2. All the measurements have been used to calibrate the model. This is point is now clarified clarified in the new manuscript:
"The minimum and maximum snow albedo (corresponding to old and fresh snow, respectively) are respectively fixed to 0.6 and 0.9 in agreements with all the measurements performed at the AWSs (Figure 2)."

P11-L26 *Please provide a fuller description of the kappa statistic as it is not a commonly used metric.*
Authors'answer: A more complete definition of kappa statistic has been added as follow:
"The performance was evaluated using a Kappa statistic coefficient (Cohen, 1960) denoted *k,* to measure the agreement between the simulation and the observation, considering the percentage of time with and without snow. The calculation of k is here performed according to the following formula:

$$k = \frac{\Pr(a) - \Pr(e)}{1 - \Pr(e)} \quad (1)$$

where *Pr(a)* represents the actual observed agreement (i.e. snow or no snow for both simulation and observation); and *Pr(e)* represents the hypothetical probability of chance agreement. Complete agreement is defined when k=1."

P12-L5 *The definition of the sublimation ratio is not clear – is it the ratio of ablation totals, or sublimation vs melt rates (which depend on whether the surface is snow covered or not). This ambiguity becomes apparent later (see note 23-1). Please clarify in the text, perhaps with an equation.*
Authors'answer: This is now better defined in the method section:
"The sublimation ratio is defined as a percentage, and equal to the sublimation divided by the total ablation (i.e. sublimation and melt rates). Note that sublimation and energy balance are only computed over snow surfaces. This means that annual and monthly means are only computed at grid-cells with snow."
P13-L1 *The comparison of WRF simulations with AWS measurements needs to be shown if they are to*

be discussed. A table showing validation metrics (mean bias, mean absolute error etc) for different variables at each site used would be useful.

Authors'answer: We agree with this comment. Nevertheless, the direct comparison between the AWS measurements and the WRF outputs remains complicated in this study, mainly due to the spatial offset (and especially the vertical difference) between the AWS location and the closest WRF grid point. Therefore we chose to present the comparison at the catchment scale from the *MicroMet* outputs to overcome this issue. As this information remains important, it is now mentioned in the manuscript and the vertical offset is available in the Table S1 in the supplementary material.

In addition, a Table showing validation metrics (R2, RMSE and Absolute mean error) between the AWS measurements and the outputs from the closest WRF grid-point after running *MicroMet* is provided in the supplementary material.

"Details and statistics information about the comparison at each AWS locations are available in Table S1 (in the supplementary material). Note that here the comparison between the AWS measurements and the closest WRF grid point is not presented due to the significant vertical offset between the two points (Table S1 in the supplementary material)."

P13-L21 *Please include comparison of WS, SWin, LWin in this section and Figure 4. These inputs are critical to the simulation of sublimation through the latent heat flux, surface temperature, and albedo.*

Authors'answer: The figure has been modified (see below) and new panels (Figure 4 e,f,g) have been added to the manuscript:

"The SWi and LWi remain very similar. The wind speed outputs differ (Figure 4e), especially above 4500 m a.s.l. where differences reach a maximum of 4 m s^{-1}. The comparison between the AWS measurements and the closest WRF grid point output yield similar results. However this comparison should be viewed with caution given that there is a spatial offset between the AWS location and the closest WRF grid (Table S1 in the supplementary material)."

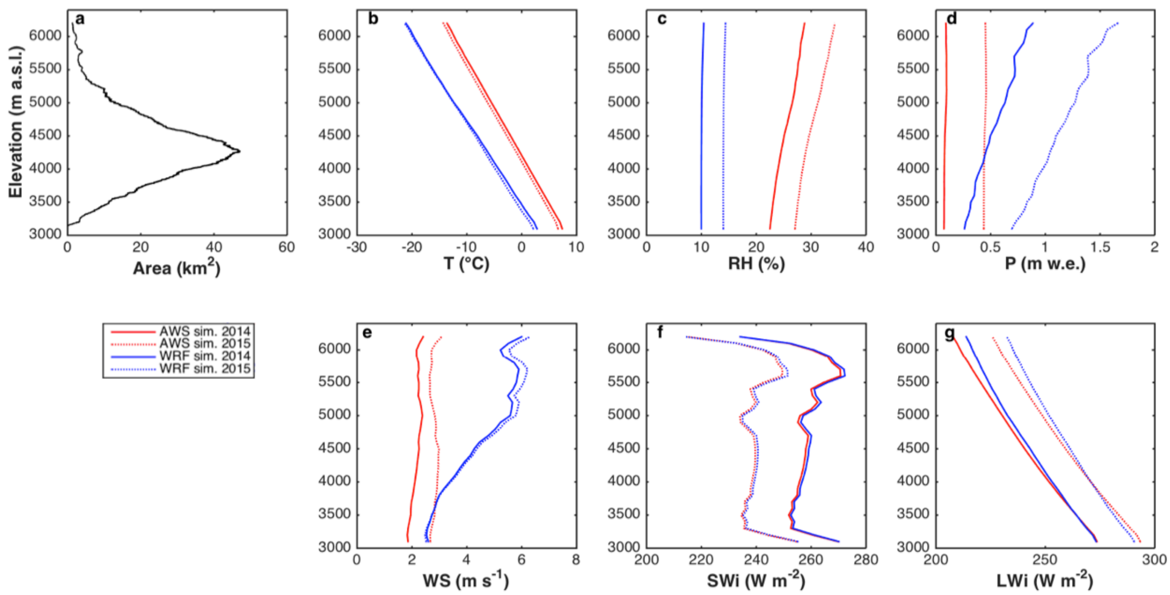
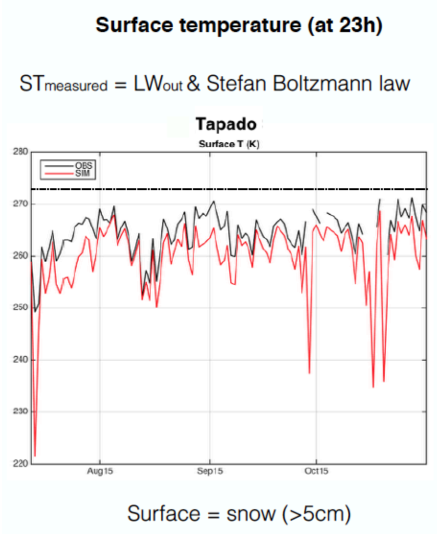


Figure 4: (a) Area-elevation distribution of the La Laguna catchment. (b to g) MicroMet outputs at the catchment scale forced by the AWS (red) and the WRF (blue) for 2014 (lines) and 2015 (dashed lines).

P13-L22 *Figure 4 would be more insightful if the actual mean values for T, RH etc were plotted for each forcing, rather than just the differences. E.g. Is the difference in precip because AWS precip decreases with height or WRF precip increases with height?*

Authors'answer: Figure 4 now represents the actual mean values (see figure above).

P14-L6 *Model validation. Were any LWout or Ts measurements available for validation? A comparison of modelled vs measured surface temperature would strengthen the validation of turbulent flux and subsurface scheme choices, which is a key area of uncertainty (as shown later by the sensitivity to z0).*
Authors'answer: We completely agree with this remark. There are LWO measurements available at the Tapado AWS for the July to December 2015 period. The comparison of these measurements (when snow height > 0.05 m) to the MicroMet output shows that the model generally follows a similar pattern to the measured surface temperature, however consistently underestimates surface temperature (see below Figure). Measured and modeled surface temperatures are consistently below zero, which gives confidence in the use of the parameterization. We have chosen not to include this new Figure in the revised version as it would likely complicate the flow of the paper.



P16-L1 *In the caption, please indicate that periods of the validation data are missing. The green colour is hard to distinguish from the black, thus it appears the AWS simulation performed poorly at the three Tapado sites in late 2015 when there is a data gap. Consider using a different colour for the observed snow depth.*
Authors'answer: The color of the measurement has been changed to red. The areas shaded in green indicate the period with validation data so we are not sure that adding this information in the legend is necessary.

P18-L6 *Please state what threshold was used to designate a snow-covered grid point in the model (e.g. 0.005 m w.e.). This can have a large bearing on the snow cover duration results, especially for small snowfalls such as those produced by WRF.*
Authors'answer: The threshold used to designate a snow-covered grid point is fixed at 3mm w.e.. This information has been added in the method part as new section:
"The snow cover area (SCA) and the snow cover duration (SCD) over the entire catchment were compared to the MODIS product. A threshold of 0.003 m w.e. was used to convert the simulated SWE into snow presence or absence for each grid cell (within the same range as Gascoin et al., 2015). Since the MODIS SCA product corresponds to the maximum visible extent over a period of 8 days, we also computed the maximum SCA over the same 8 day period from the simulated SCA for comparison."

P18-L6 *Please explain how data were averaged spatial and temporally (e.g. the average snow cover* *duration calculated for each individual grid point in the elevation band? Or the average of the grid cells that correspond with the modis pixels in each elevation band).*

Authors'answer: This has been clarified as follow:

"The simulated snow cover duration (SCD) was also compared to the observed duration (from MODIS) by elevation band. For all each 200 m elevation band, the total number of snow-covered days for each grid cell was computed and then averaged for each band."

P18-L7 *"Better performances were obtained for the AWS-forcings" while this is strictly correct, I don't think this comment is balanced. In 2015 the simulations are comparable and the improvement with the AWS forcing is minor.*

Authors'answer: We agree with this comment and the results are described for each year, allowing the reader to make this distinction: "For 2014, better performances were obtained for the AWS-forcing than for the WRF-forcing (Figure 7). For 2015, while better performances were also obtained for the AWS-forcing, the improvement using this forcing was minor."

P19-L9 *Because elevation seems to have a greater effect on the sublimation rate, it would be useful to present these results (figure 10) before presenting the SEB and sublimation ratio results that are calculated over the whole catchment for snow-covered points only (Fig 8, 9). This would give better context for the somewhat complex interactions between SCA, SCD and meteorology. It would also be very useful to show the SEB results averaged in elevation bins after figure 10 to show reasons why the WRF simulations have higher sublimation.*

Authors'answer: To address this comment, and in response to the general comment above, Figure 10 is now Figure 8 in the revised manuscript and comes before the SEB and sublimation ratio results computed for the entire catchment. In addition, the figure showing the energy contribution of each flux against elevation has been added:

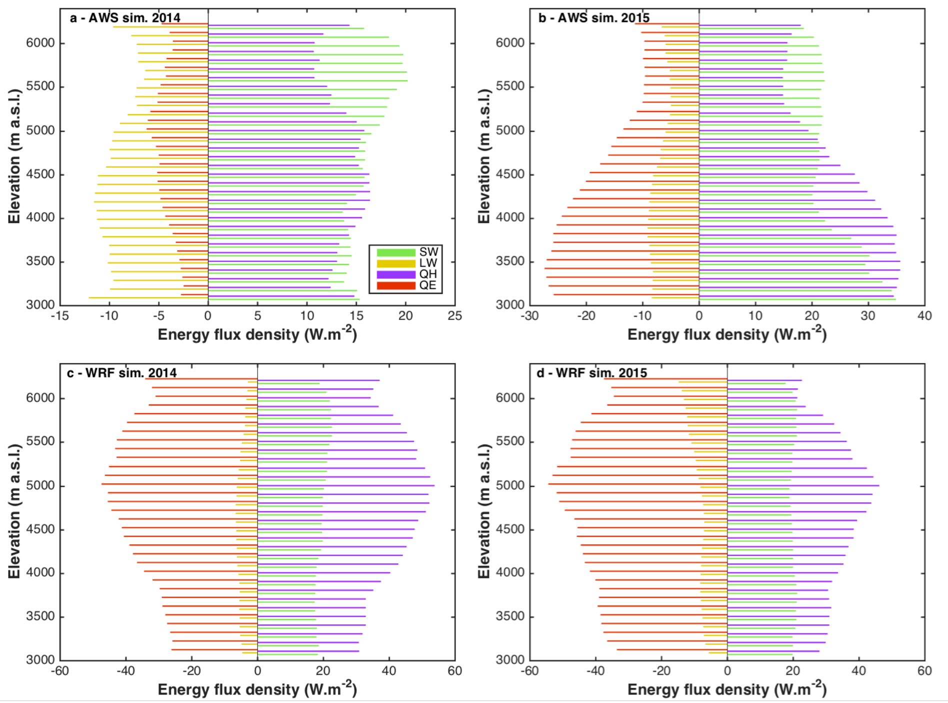


Figure 9: Annual mean of main modeled energy fluxes (computed over snow surfaces only) for each 200 m elevation band using AWS (a,b) and WRF (c,d) forcing for 2014 (a,c) and 2015 (b,d). SW is net shortwave radiation, LW is net longwave radiation, QE is the latent heat flux and QH is the sensible heat flux.

P19-L11 *Do the annual means include periods with no snow as 0 values? Please clarify how the annual means are calculated?*
Authors'answer: The means are calculated only for period with snow. This information has been added in the methods section as follows:
"Note that sublimation and energy balance are only computed over snow surfaces. This means that annual and monthly means are only computed at grid-cells with snow."

P19-L12 *"For the mean AWS-simulation net SW is 24 and 23" do you mean the WRF-simulation here?*
Authors'answer: Yes we mean WRF-simulation. This has been corrected.

P19-L14 *Do you mean -6 and -7 Wm-2? These figures represent fairly small losses compared to mid-latitude sites (e.g. -25 to -20 Wm-2 in Giesen et al, 2009), which is presumably due to the cold surface temperature of the snow surfaces.*
Giesen RH, Andreassen LM, Van den Broeke MR and Oerlemans J (2009) Comparison of the meteorology and surface energy balance at Storbreen and Midtdalsbreen, two glaciers in southern Norway. Cryosphere, 3(1), 57–74, doi: 10.5194/tc-3-57-2009
Authors'answer: Yes, we mean "-6 and -7 W m^{-2}" and this has been corrected. The reference to the study made by Giesen et al., has been added to address the comment above. The text now reads:
"The contribution of net LW on the other hand is low for all simulations (annual mean of -7/-6 W.m^{-2} for AWS/WRF-simulations respectively). Note that these losses are small in comparison to mid-latitude sites (e.g. -25 to -20 W m^{-2} according to the study by Giesen et al, (2009)), because of the very dry conditions of the atmosphere and to the cold surface temperature of the snow surfaces."

P22-L1 *Are these figures monthly average amounts for only snow-covered grid cells or something else? Please explain the averaging procedure in the methods section.*
Authors'answer: Yes the mean calculation only consider snow-covered grid cells. A sentence has been added in the methods section to clarify this: "Note that sublimation and energy balance are only computed over snow surfaces. This means that annual and monthly means are only computed at grid-cells with snow."

P23-L1 *Figure10 – the sublimation ratio and ablation rates do not seem to match up – the ratio at high elevations is ~100% which implies there is little melt, but for both AWS and WRF forcing there is still a significant melt rate, and for AWS in 2015, melt rate=sublimation rate. Is this an artefact of the averaging of melt rate over snow only? Also, why do melt rates increase with height? Perhaps you are better to present the ablation totals rather than the ablation rates? Either way, the top and bottom panels should be consistent.*
Authors'answer: Thank you for your comment, you were right; the ratios were computed incorrectly. This has been fixed and the figure has been changed accordingly:

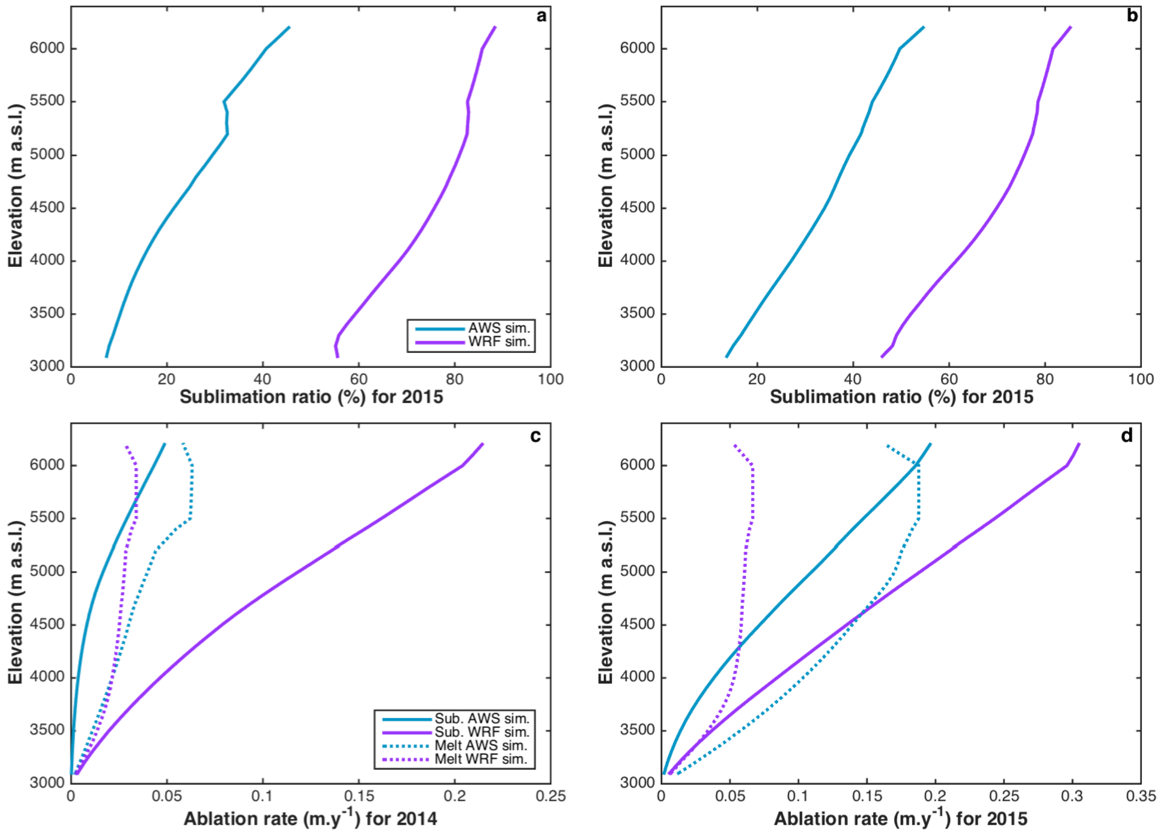


Figure 8: Simulated annual sublimation ratio (a,b) against elevation band using AWS (blue) and WRF (purple) forcing for 2014 (a,c) and 2015 (b,d). Simulated annual ablation ratio (sublimation and melt) against the elevation using AWS and WRF-forcing for 2014 (c) and 2015 (d).

P26-L30 *It is not clear what you mean by evaposublimation? Do you mean the evaporation of liquid from a melting surface or a combination of this process + sublimation from a frozen surface? If you are including evaporation from a melting surface, then doesn't the increased rate occur because the melting lowers the latent heat required to transform the water to vapour? Please be more explicit about the process occurring.*

Authors'answer: To avoid confusion this word has been removed. The sentence now reads: "This may be explained by warmer conditions which induce a warmer snow pack, increasing the saturated vapor pressure at the snow surface, providing energy to increase the sublimation rates (Herrero and Polo, 2016)"

Figure S2 *If this precipitation sensitivity analysis is retained, Figure S2 needs to be included in the results section as it is discussed directly.*

Authors'answer: As the paper has been restructured we decided to keep this figure in the supplementary material.

Impact of forcing on sublimation simulations for a high mountain catchment in the semi-arid Andes

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Abstract. In the semi-arid Andes of Chile, farmers and industry in the cordillera lowlands depend on water from snowmelt, as annual rainfall is insufficient to meet their needs. Despite the importance of snow cover for water resources in this region, understanding of snow depth distribution and snow mass balance is limited. Whilst the effect of wind on snow cover pattern distribution has been assessed, the relative importance of melt versus sublimation has only been studied at the point-scale over one catchment. Analyzing relative ablation rates and evaluating uncertainties are critical for understanding snow depth sensitivity to variations in climate and simulating the evolution of the snow pack over a larger area and over time. Using a distributed snowpack model (SnowModel), this study aims to simulate melt and sublimation rates over the instrumented watershed of La Laguna (3150–5630 m a.s.l., 30°S 70°W), during two hydrologically contrasting years (i.e. dry *vs.* wet). The model is calibrated and forced with meteorological data from nine Automatic Weather Stations (AWS) located in the watershed, and atmospheric simulation outputs from the Weather Research and Forecasting (WRF) model. Results of simulations indicate first a large uncertainty in sublimation ratios depending on the forcing. The melt/sublimation ratios doubled if forced with WRF compared to AWS data due to the cold bias and precipitation over-estimation observed in WRF output in this region. Second, the simulations indicate similar sublimation ratios for both years, but ratios vary with elevation with a relative decrease in melt at higher elevations. Finally results indicate that snow persistence during the spring period decreases the sublimation ratio due to higher melt rates.

1. INTRODUCTION

In the semi-arid Andes, glaciers and seasonal snow cover are the dominant water sources, as rainfall is episodic and insufficient to meet user demand. The region is characterized by very low precipitation amounts that are largely limited to winter months (i.e. June, July and August), and are erratic. Large interannual variability is observed, as the area is strongly affected by El Nino South Oscillations (ENSO) (e.g. Falvey and Garreaud, 2007; Garreaud, 2009; Montecinos et al., 2000). In broad terms, during El Niño periods the semi-arid Andes are characterized by warm air temperatures and higher precipitation totals, whereas La Niña periods are on average colder with less precipitation (e.g. Ducan *et al.,* 2008). Whilst snowmelt comprises the bulk of available water (Favier et al., 2009), due to low humidity, high solar radiation and strong winds, sublimation is a significant ablation process, especially at high elevations (Ginot et al., 2001; Gascoin et al., 2013; MacDonell et al., 2013). Consequently, quantifying snow mass balance processes are crucial for predicting current water supply rates, and for informing future projections.

Despite the importance of snow cover for water resources in this region, there is currently a limited understanding of snow depth distribution and mass balance, largely due to the difficulty of accurately measuring and modeling both accumulation and ablation processes in this area (Gascoin et al., 2011). Temperature index models have been shown to be inadequate to evaluate mass balance processes in the semi-arid Andes, due to the importance of the latent energy flux (Ayala et al., 2017). However, an energy balance model requires a larger input dataset that is often not available in Andean catchments due to the logistical difficulty of Automatic Weather Station (AWS) installation and maintenance. Therefore, the evaluation of alternative methods for acquiring distributed meteorological information is required. Options include the use of interpolation/extrapolation strategies (e.g. *MicroMet,* Liston and Elder, 2006b), reanalysis (NCEP, Kalnay et al., 1996) or atmospheric model outputs (e.g. Weather Research and Forecasting (WRF) model, Skamarock and Klemp, 2008). For the semi-arid Andes, both *MicroMet* extrapolation based on AWS data (Gascoin et al., 2013) and atmospheric models (e.g. Favier et al., 2009; Mernild et al., 2017) have been used to force snow models. However, none of these studies have quantified the uncertainties related to forcing data.

The relative importance of melt and sublimation to total ablation has been studied at both the point-scale (MacDonell *et al.,* 2013) and catchment scale (Gascoin *et al.,* 2013) in one catchment in the semi-arid Andes. MacDonell *et al.* (2013) estimated that the sublimation fraction was 90% at high altitude (>5000m a.s.l.) in an extreme environment with predominantly sub-freezing temperatures and strong local wind speeds. Using a distributed snowpack model Gascoin *et al.* (2013) found that the total contribution of sublimation (static-surface and blowing snow sublimation) to total ablation in the Pascua-Lama area (29.3° S, 70.1°W; 2600 - 5630 m a.s.l.) was 71%. However, this value was obtained for one snow season, and the precipitation was estimated from snow depth measurements as precipitation gauge data were unreliable. The sensitivity of sublimation to meteorological forcing and in particular to precipitation uncertainties was not evaluated.

The objective of this study is to assess the uncertainties related to modeling snow evolution in the semi-arid Andes using AWS and WRF-model generated meteorological datasets during two contrasting years. From this analysis, the snow mass balance for one relatively wet and one dry year will be compared, and an evaluation of the impacts of model choices on sublimation and melt rates in dry mountain areas will be discussed.

To address this aim, the model SnowModel described in Liston *et al.* (2006) will be applied to the La Laguna catchment in the semi-arid Chilean Andes during 2014 and 2015. These two years were selected because in this region, 2015 was considered to be a strong *El Nino* event, associated with warm and wet conditions, whereas 2014 was drier and colder and considered a neutral year (Ceazamet; http://origin.cpc.ncep.noaa.gov, Figure S1 in the supplementary information). We hypothesize a significant sublimation ratio for winter 2014, due to drier and cooler conditions which should inhibit melt. Regarding 2015, higher precipitation totals could lead to *(i)* increased snow depths and snow persistence at the end of the winter season (i.e. in August, September), favoring melt and therefore decreasing the sublimation ratio or *(ii)* increased sublimation in the spring can increase the saturation vapor pressure at the snow surface, providing more energy for sublimation (Herrero and Polo, 2016). This uncertainty regarding the impact of snow cover duration on sublimation highlights the need for further research.

2. STUDY SITE AND DATA

2.1 Study site

La Laguna watershed is located in the semi-arid Andes of Chile in the Elqui Valley (30°S, 70°W), 200km East of La Serena, close to the border with Argentina (Figure 1a). As it is easily accessible this catchment is the most instrumented within the region with an unusually high density of AWS, especially during 2014 and 2015.

The catchment covers an area of 513 km^2 and elevations range from 3150 to 6200 m a.s.l. (Figure 1b). At these elevations, only minimal vegetation in the form of shrubs is observed, so we do not consider vegetation in this study. The study area includes rock glaciers and glaciers. Tapado Glacier is the largest of these with an area of 2.2 km^2 (Figure 1b). This catchment was selected since it is an important water resource in the Elqui valley. Indeed it feeds water to the La Laguna reservoir (38.10^6 m^3 capacity), which is part of the strategic irrigation system in the Elqui Valley. Nevertheless the precipitation amount is very low. The mean annual precipitation measured at la Laguna station is 200 mm a^{-1} and precipitation events are episodic with less than 10 events per year. In this region, most of these events (90%) occur during the winter period (Figure S1, Rabatel et al., 2011), as snow fall. This seasonal difference is mainly due to differences in the position and intensity of a high-pressure cell in the eastern Pacific Ocean. During the summertime the high-pressure cell limits advection, while during the winter it moves further North, allowing the moisture-laden depressions to reach the study site (Garreaud et al., 2011). Seasonal precipitation variability and frequency are also complicated by individual storm trajectories (e.g. Sinclair and MacDonell, 2016) which can cause large differences in relative precipitation distribution across the catchment, a phenomenon also described in central Chile (Burger et al., 2019).

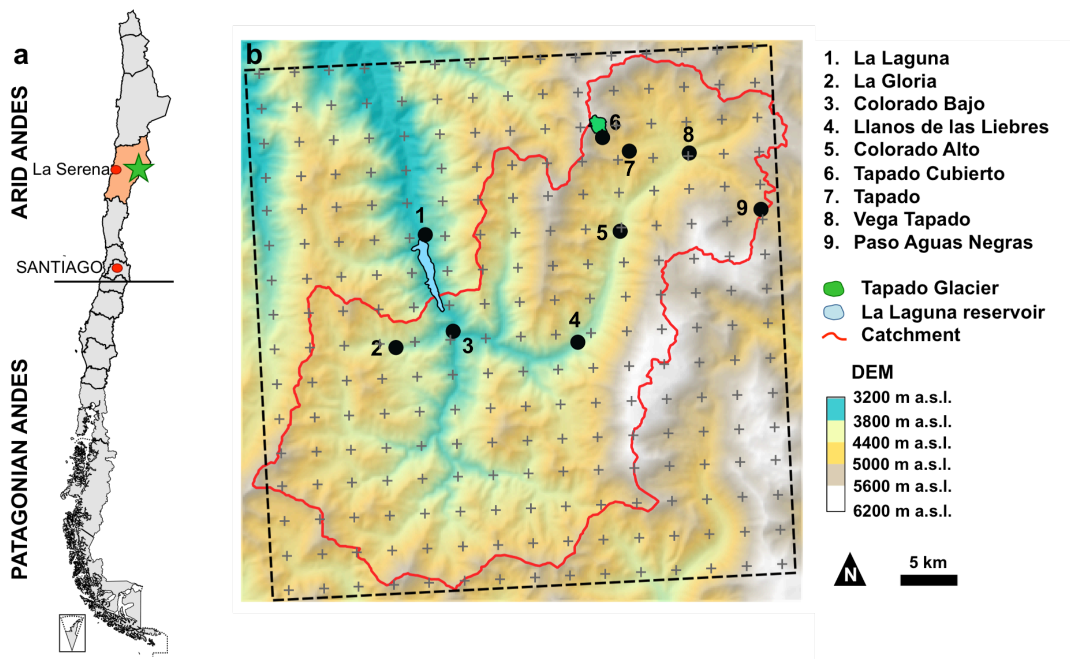

Figure 1: a) Map of Chile with Coquimbo Region colored orange and the catchment location identified with a star. b) DEM (SRTM, 100m) of La Laguna catchment. Red line corresponds to the catchment delineation, black dashed line to the WRF domain containing the virtual WRF stations (grey crosses). Blue area is La Laguna reservoir and greed area is the Tapado Glacier. AWS stations are the 9 black points.

2.2. Data

2.2.1 Digital elevation model

The digital elevation model (DEM) used in this study was derived from the CGIAR hole-filled 3 arc-second SRTM DEM resampled to 100 m resolution by the cubic method. The 100 m resolution was chosen to facilitate alignment of the model grid with the 500 m resolution MODIS products (see below).

2.2.1 Meteorological data

a/ Automatic weather station measurements

Meteorological data from nine Automatic Weather Stations (AWS) are available in the catchment (Figure 1b) over the study period 2014-2015. La Laguna, Tapado and Paso del Agua Negra AWSs are permanent stations maintained by CEAZA (www.ceazamet.cl) with hourly measurements. In addition, five HOBO® weather stations (Colorado Bajo, La Gloria, Llano de Las Liebres, Colorado Alto and Vega Tapado) were installed in March 2014 and set to record meteorological data every 30 minutes. The Tapado Cubierto station was installed in 2013 on the debris-covered part of the glacier and provides measurements at hourly intervals. More details regarding available measurements and the time periods for which these are available are provided in Figure 2. Tapado records are reported in Figure 3 as an example of the weather conditions in this catchment.

Due to the complexity of precipitation measurement (e.g. MacDonald and Pomeroy, 2007), datasets were post-processed. First, filters were applied to eliminate outliers (i.e. negative values and values larger than 30 mm h^{-1}). Second, satellite images (MODIS Aqua and MODIS Tierra) were used to remove recorded precipitation events on sunny days, which were probably due to wind transport. These precipitation events were only removed if five cloud-free images were available (i.e. the two for the day: one the afternoon before and one the next morning). In total, three precipitation events lower than 2 mm w.e. were removed with this method.

At Tapado, measurements are recorded at two Geonor weighing precipitation gauges, of which one is shielded (Alter Shield) and one is unshielded. After being filtered, the cumulative difference at the two gauges was 9.1 mm for 2014 (i.e. 10%; 97.1 mm for unshielded gauge 1 and 106.2 mm for shielded gauge 2) and 5.4 mm for 2015 (i.e. 1% ; 457.5 mm for gauge 1 and 462.9 mm for gauge 2) with a maximum hourly difference of 1.1 mm, however the relative bias between the sensors is neither constant nor unidirectional. As the difference between the two sensors was relatively small, the mean of the two datasets was used as the reference precipitation value, and a maximum uncertainty of 10% was estimated.

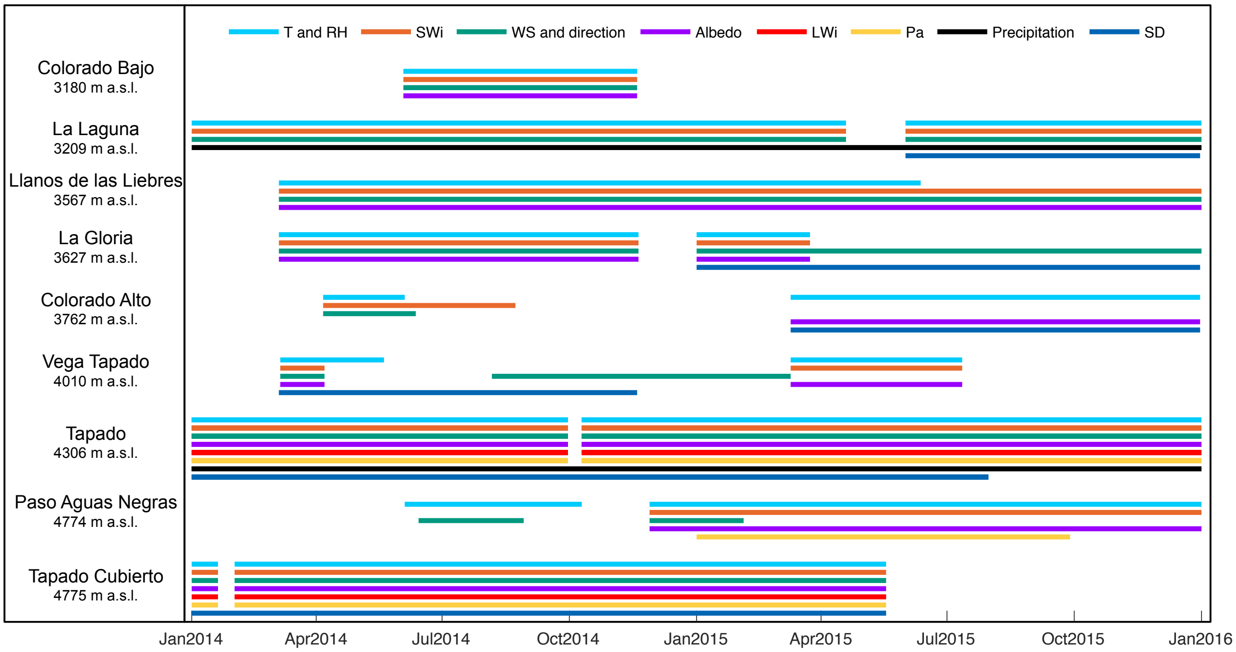

Figure 2: Date of available measurements from the nine AWSs used to calibrate and validate the model. T is the air temperature, RH the relative humidity, SWi and LWi the incoming short and long wave radiation respectively, WS the wind speed and Pa the atmospheric pressure and SD the snow depth.

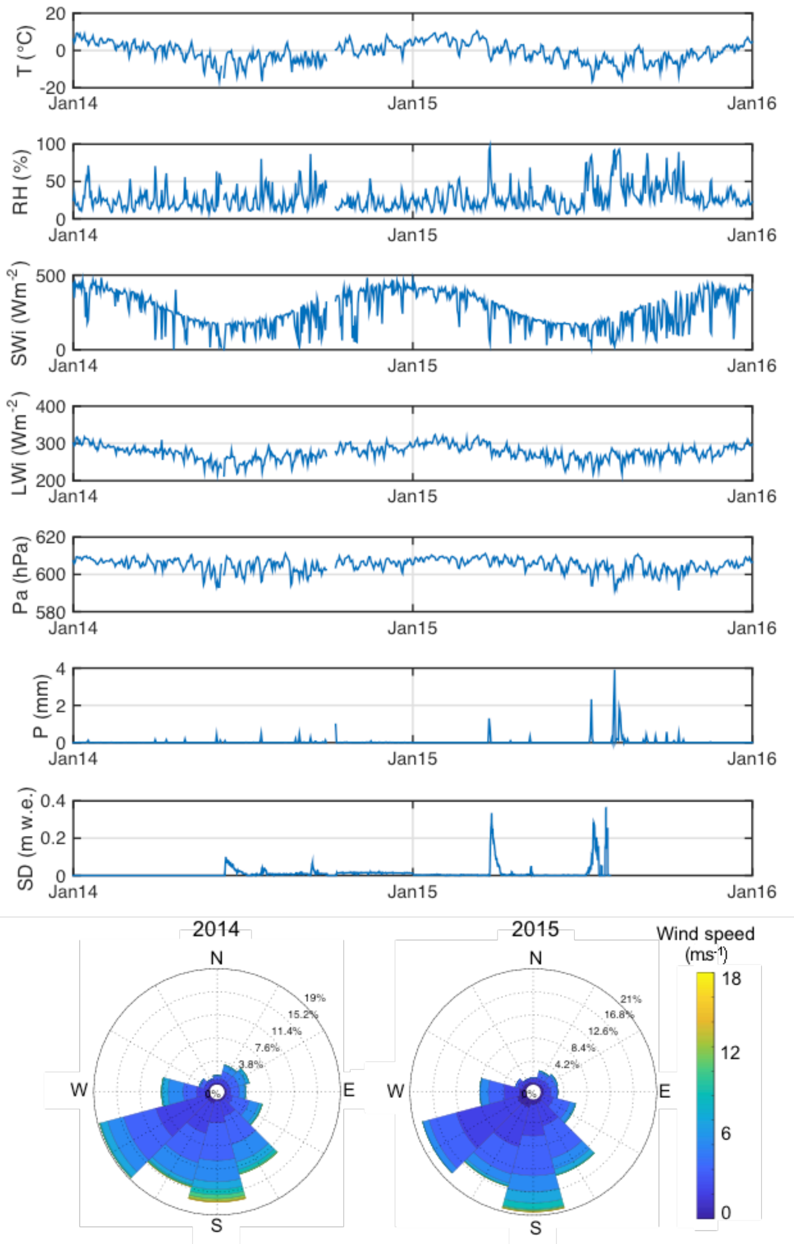

Figure 3: Example of meteorological conditions of the study area. Daily air temperature (T), relative humidity (RH), incoming shortwave (SWi) and longwave (LWi) radiation, air pressure (Pa), precipitation (P), snow depth (SD) and wind speed and direction (wind roses) measured at the Tapado AWS from 1 January 2014 to the 31 December 2015. Note that SD measurements are available until the 1st of August 2015.

b/ WRF model outputs

The Weather Research and Forecasting (WRF) model was used to force SnowModel. WRF is usually used to predict weather for atmospheric research and operational weather forecasting. Using reanalysis-data as boundary conditions, this model is able to provide hourly meteorological data such as air temperature, relative humidity, incoming radiation, wind speed and direction, atmospheric pressure and precipitation. In this study WRF was forced by 6 hourly data from the National Center for Environmental Prediction (NCEP) reanalysis data, at 1° grid resolution (Kalnay et al., 1996), as well as daily surface temperature of the ocean at 0.083° of resolution. WRF model has been run using the model version 3.7.1 (Skamarock and Klemp, 2008), with default parameterizations (this choice is discussed in Section 5.1). The model has been run over a time period covering the entire study period (from April 2013 to April 2016). The model outputs are at 2 m above the surface and are available at 22 km resolution over Chile, 7 km resolution at the regional scale, and 3 km resolution over the La Laguna catchment (Figure 1). The hourly 3 km outputs (T, RH, WS and direction, P, SW, LW, Pa) over the catchment represent the virtual stations that have been used in this study.

2.2.3 Local snow depth data

In 2014, three AWSs provided snow depth measurements at an hourly time step (Vega Tapado, Tapado and Tapado Cubierto; Figure 2). Over the 2015 winter, snow depth measurements were available at five stations (La Gloria, Colorado Alto, Tapado, La Laguna and Tapado Cubierto). The snow depths were measured with ultrasonic sensors and require post-treatment because they are particularly prone to measurement errors and typically produce a noisy signal (Lehning et al., 2002). Therefore, the control procedure described in Lehning et al., (2002) was applied to clean the signal, and in particular to eliminate spikes, check for outliers and physical limits.

2.2.4 MODIS snow products

MOD10A2 (Terra) and MYD10A2 (Aqua) snow products version 5 were downloaded from the National Snow and Ice Data Center (Hall et al., 2006; Hall and Riggs, 2007) for the period 1 January 2014 – 1 January 2016. The binary snow products were projected on a 500 m resolution grid in the same coordinate system as the DEM. Missing values, mainly due to cloud obstruction, were interpolated using the algorithm of Gascoin et al. (2015).

3. METHOD

3.1 SnowModel description

The physically-based model SnowModel (Liston and Elder, 2006b) was used to simulate the snow depth evolution over the entire catchment. SnowModel has already shown acceptable performance in the challenging context of semi-arid mountains, including the Andes (Gascoin *et al.* 2013, Mernild *et al.* 2017) and the High Atlas (Baba et al., 2018a, 2018b). It is a spatially distributed snowpack evolution modeling system composed of four submodels briefly described below.

Micromet is a physically-based meteorological distribution model developed specifically to produce high-resolution, spatially-distributed atmospheric forcing data. This model requires precipitation, wind speed and direction, temperature and humidity as input data, generally measured at weather stations. For the incoming solar and longwave radiation, and surface pressure, *MicroMet* can either compute these fields from other meteorological variables, or create them from observations through a data assimilation procedure (Liston and Elder, 2006a). *MicroMet* includes a preprocessor component that first analyzes meteorological data to identify and correct potential deficiencies (e.g. values out of the ranges given in the subroutine). It then fills in any missing data segments with realistic values. The atmospheric fields are distributed using a combination of lapse rates and spatial interpolation using the Barnes objective analysis scheme (Barnes, 1964).

EnBal performs standard surface energy balance calculations (Liston, 1995; Liston et al., 1999). This component simulates surface temperatures and energy fluxes in response to observed/modeled near-surface atmospheric conditions provided by *MicroMet*. Surface latent and sensible heat flux and snowmelt calculations are made using a surface energy balance model.

SnowPack is a single or multi-layer (max. six layers), snowpack evolution and runoff/retention model that describes snowpack changes in response to precipitation and melt fluxes defined by *MicroMet* and *EnBal* (Liston and Hall, 1995; Liston and Elder, 2006b).

SnowTrans-3D (Liston and Sturm, 1998; Liston et al., 2007) is a three-dimensional model that simulates snow depth evolution (deposition and erosion) resulting from windblown snow based on a mass-balance equation that describes the temporal variation of snow depth at each grid cell within the simulation domain.

3.2 Model set up

3.2.1 Spatialized meteorological forcing

Spatial interpolation using the Barnes scheme was used to distribute the nine AWS measurements of T, RH, LWi, SWi and pressure over the model domain. As relative humidity is a non-linear function of elevation, the relatively linear dewpoint temperature is used for the elevation adjustment. For more details refer to Liston and Elder (2006). In this study the *MicroMet* subroutine has been run with the default setting for the Southern Hemisphere, for air temperature and dewpoint temperature monthly lapse rates (Liston and Elder, 2006b). Monthly lapse rates computed from the available measurements are dependent on the year considered. As the mean is close to the default settings, it has been chosen to conserve these values. Radiation values for LWi and SWi are specified using the default parameterization (Liston and Elder 2006a). The model has been run on the SRTM DEM and as a result, hourly meteorological data over a 100m-grid resolution are available for entire study period. Precipitation was interpolated similarly but without considering a lapse rate, as the comparison between the available measurements did not reveal consistent elevation gradients. Wind data and direction were first interpolated using linear lapse rates and then each gridded value was corrected considering topographic slope and curvature relationships (Liston and Elder, 2006b).

The 3km WRF outputs (section 2.2.1) were used as inputs for *MicroMet* which considers that each WRF cell corresponds to a virtual weather station located in the center of the WRF cell, following Mernild et al. (2017) and Baba et al. (2018a). *MicroMet* adjusts the elevation bias to the DEM at the corresponding coordinate and downscales the data to a 100 m grid.

3.2.2 Albedo calibration

The snow albedo evolution is computed as a function of the snow density and air temperature (more details in Liston and Hall, 1995; Liston and Elder 2006b). Minimum and maximum values have been adjusted based on measurements. The minimum snow albedo (*i.e.* the soil) is fixed at 0.2 and is quite homogeneous in this basin, as there is almost no vegetation. The minimum and maximum snow albedo (corresponding to old and fresh snow, respectively) are respectively fixed to 0.6 and 0.9 in agreements with all the measurements performed at the AWSs (Figure 2).

3.2.3 Turbulent fluxes calibration

As the model is using a bulk approach to simulate the turbulent fluxes, the turbulent latent and sensible heat fluxes (respectively *LE* and *H)* are parameterized using an effective surface roughness length z_0 (Liston, 1995;

Liston et al., 1999). Note that this roughness length z_0 is considered as an effective value used in the model to represent the aerodynamic (z_m), temperature (z_t) and humidity (z_q) roughness values. As no measurements from the study period are available to calibrate/validate this value, it was initially fixed at 1 mm (Gromke et al., 2011; MacDonell et al., 2013), and a subsequent sensitivity test was undertaken.

3.2.4 Wind transport parameterization

The model considers the wind transport (saltation, turbulent suspension) after snow deposition, sublimation of blowing and drifting snow and erosion and deposition after snowfall, depending on the topography (Liston and Sturm, 1998). The topographic influence on wind transport has been set, following Gascoin et al. (2013). The curvature allows considering the typical redistribution length scale. Based on the DEM, it was estimated to be 500 m, *i.e.* approximately one-half the wavelength of the topographic features within the domain (Liston et al., 2007). The model considers different weights for slope and curvature and values. We have chosen 0.58 and 0.42, respectively, following Gascoin et al. (2013).

3.3 Simulations

Two types of simulations have been performed over the entire catchment for the period 1 January 2014 – 1 January 2016 on a 100-m resolution DEM. The first simulation was forced with input from the nine automatic weather station measurements (referred to as AWS-forcing), whereas the second simulation was forced with the WRF data (referred to as WRF-forcing).

After indicating the differences observed for these two forcing sets, the model is primarily validated at local points. Results for the two simulations were first compared to local snow depth measurements at each AWS (described in Section 2.2.1). The performance was evaluated using a Kappa statistic coefficient (Cohen, 1960) denoted *k,* to measure the agreement between the simulation and the observation, considering the percentage of time with and without snow. The calculation of k is here performed according to the following formula:

$$k = \frac{\Pr(a) - \Pr(e)}{1 - \Pr(e)} \qquad (1)$$

where: *Pr(a)* represents the actual observed agreement (i.e. snow or no snow for both simulation and observation); and *Pr(e)* represents the hypothetical probability of chance agreement. Complete agreement is defined when *k*=1. The Root Mean Square Error (*RMSE*) was also calculated.

Second, the model performance was evaluated over the entire catchment, by comparing the simulated snow cover extent and duration to that observed by the satellite images (described in Section 2.2.2). The model performance was evaluated by computing the Nash-Sutcliffe efficiency coefficient (*NSE*, Nash and Sutcliffe, 1970) between simulations and observations, and the *RMSE*.

After validating the model, the sublimation ratio and sublimation rate were computed over the catchment for the two years. The sublimation rate corresponds to the mass sublimated per unit of time. The sublimation ratio is defined as a percentage, and equal to the sublimation divided by the total ablation (i.e. sublimation and melt rates). Note that sublimation and energy balance are only computed over snow surfaces. This means that annual and monthly means are only computed at grid-cells with snow.

3.4 Comparison with MODIS

The snow cover area (SCA) and the snow cover duration (SCD) over the entire catchment were compared to the MODIS product. A threshold of 0.003 m w.e. was used to convert the simulated SWE into snow presence or absence for each grid cell (within the same range as Gascoin et al., 2015). Since the MODIS SCA product corresponds to the maximum visible extent over a period of 8 days, we also computed the maximum SCA over the same 8 day period from the simulated SCA for comparison.

4. RESULTS

4.1 Meteorological forcing comparison

4.1.1 2014 *vs* 2015

According to the AWS measurements, Jan-Jul 2015 was warmer than Jan-Jul 2014. Conversely, observations indicate lower temperatures for Aug-Dec 2015 than for Aug-Dec 2014 (daily mean difference of -2.6°C). Relative humidity was higher for 2015 compared to 2014 (daily mean difference of 11%) whereas SWi was lower (mean difference of -18 W m^{-2}, i.e. 6% of the mean SWi), with larger differences in Jul-Dec (daily mean difference of -32 W m^{-2}, i.e. 12% of the daily mean SWi), and LWi was higher (daily mean difference of 20 W m^{-2}, i.e. 7% of the daily mean LWi). This decrease SWi and increase in LWi can be explained by a larger number of clouds in 2015.

4.1.2 *MicroMet* output comparison: AWS *vs* WRF

Figure 4 shows *Micromet* outputs forced by WRF and AWS. Colder air temperatures are observed for the WRF-forcing (4.5 to 7.5°C depending on the year and the elevation), as well as lower RH (between 13 and 24%), and higher precipitation (annual cumulative difference larger than 1 m w.e.). The SWi and LWi remain very similar. The wind speed outputs differ (Figure 4e), especially above 4500 m a.s.l. where differences reach a maximum of

4 m s^{-1}. Details and statistics information about the comparison at each AWS locations are available in Table S1 (in the supplementary material). Note that here the comparison between the AWS measurements and the closest WRF grid point is not presented due to the significant vertical offset between the two points (Table S1 in the supplementary material). Despite these differences between AWS and WRF, both forcings were used as inputs in order to quantify the impact of the forcing choice on the sublimation estimation in this study.

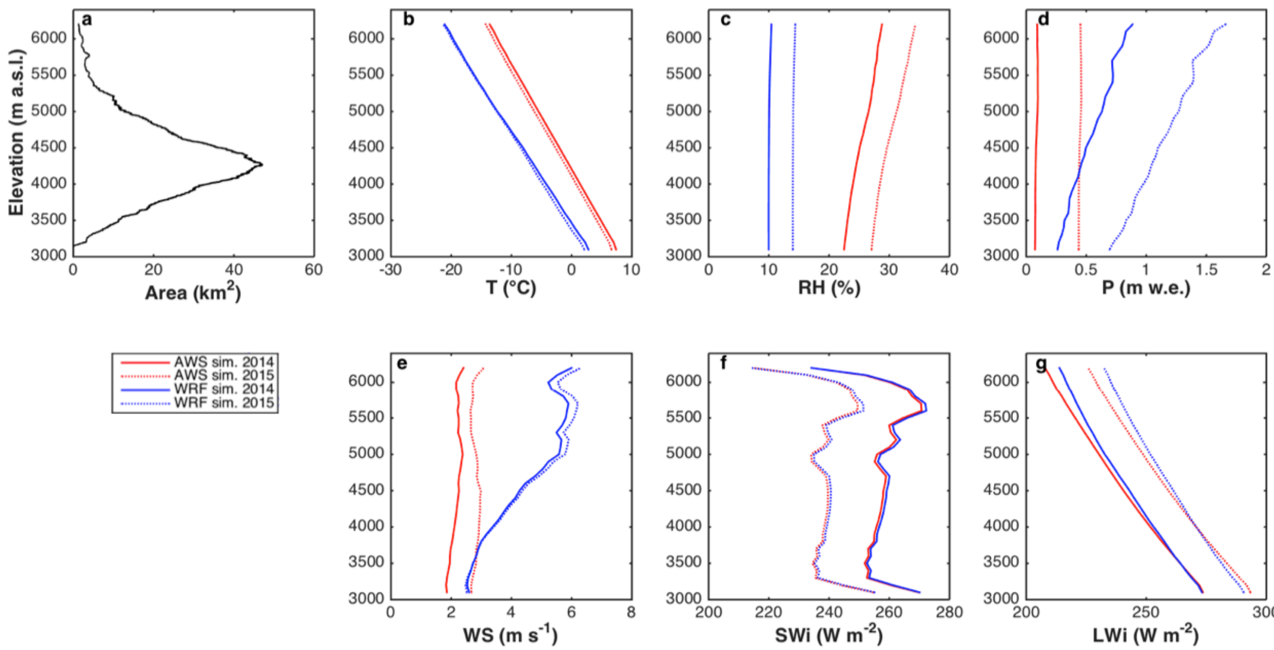

Figure 4: (a) Area-elevation distribution of the La Laguna catchment. (b to g) MicroMet outputs at the catchment scale forced by the AWS (red) and the WRF (blue) for 2014 (lines) and 2015 (dashed lines).

4.2 Snow depth and snow cover comparison

4.2.1 Comparison with local snow depth measurements

Simulated snow depths using the AWS-forcing (Figures 5 a-f) are in good agreement with measured snow depth values (mean *k*=0.14 and mean *RMSE*=0.15 m). While comparisons have been performed at distinct stations for 2014 and 2015, we can observe better performances (i.e. higher *k* and lower *RMSE*) for 2015 (Figures 5 d-f) than for 2014 (Figures 5 a-c). For 2014 the highest *k* and lower *RMSEs* are observed at Tapado AWS, as precipitation measurements were available at this site, but performances are much lower at the two other sites where precipitation was interpolated. In 2015, the simulated snow depth is generally overestimated, probably due to an over-estimation of the precipitation for the large event on June 21st 2015 (Figure 3). Nevertheless, the start/end date of the snow season are in good agreement with observations (maximum difference of 3 days observed at La Gloria site). Note that this comparison probably over-estimates the accuracy as snow depths are compared at the exact location of meteorological forcing. Larger uncertainties are expected at the interpolated locations.

Simulations performed with the WRF-forcing indicate lower performances in simulating snow depth evolution at the AWS (Figure 5 g-m; mean k=0.12, and mean $RMSE$=0.20 m). The results indicate an over-estimation of the simulated snow depth compared to the observations. In addition, for 2014, the timing of the start/end of the snow season does not fit well with observations (and explain the low k values). In 2015, the first day of snow is generally in good agreement with observations (maximum difference of 5 days observed at La Laguna).

While AWS-forcing yields a better performance overall, in both cases, better correspondence is obtained for 2015. This could possibly be explained by the dry conditions in 2014 which would have resulted in precipitation having a higher spatial variability. The low snow amounts in 2014 created localized snow patches, which are complex to represent in models.

These results underline the complexity of modeling the spatial variability of SD, even when snow transport is implemented. Results show an overall similarity of the simulated SD between some stations (e.g. Vega Tapado, Colorado Alto and La Gloria), while measurements indicate that SD are much more variable in reality. Note that the windy conditions on the local depression at Vega Tapado is very local (i.e. few meters) and make complicated the simulation at this site where the measured SD is larger than the surrounded area and not representative of the 100 m grid cell.

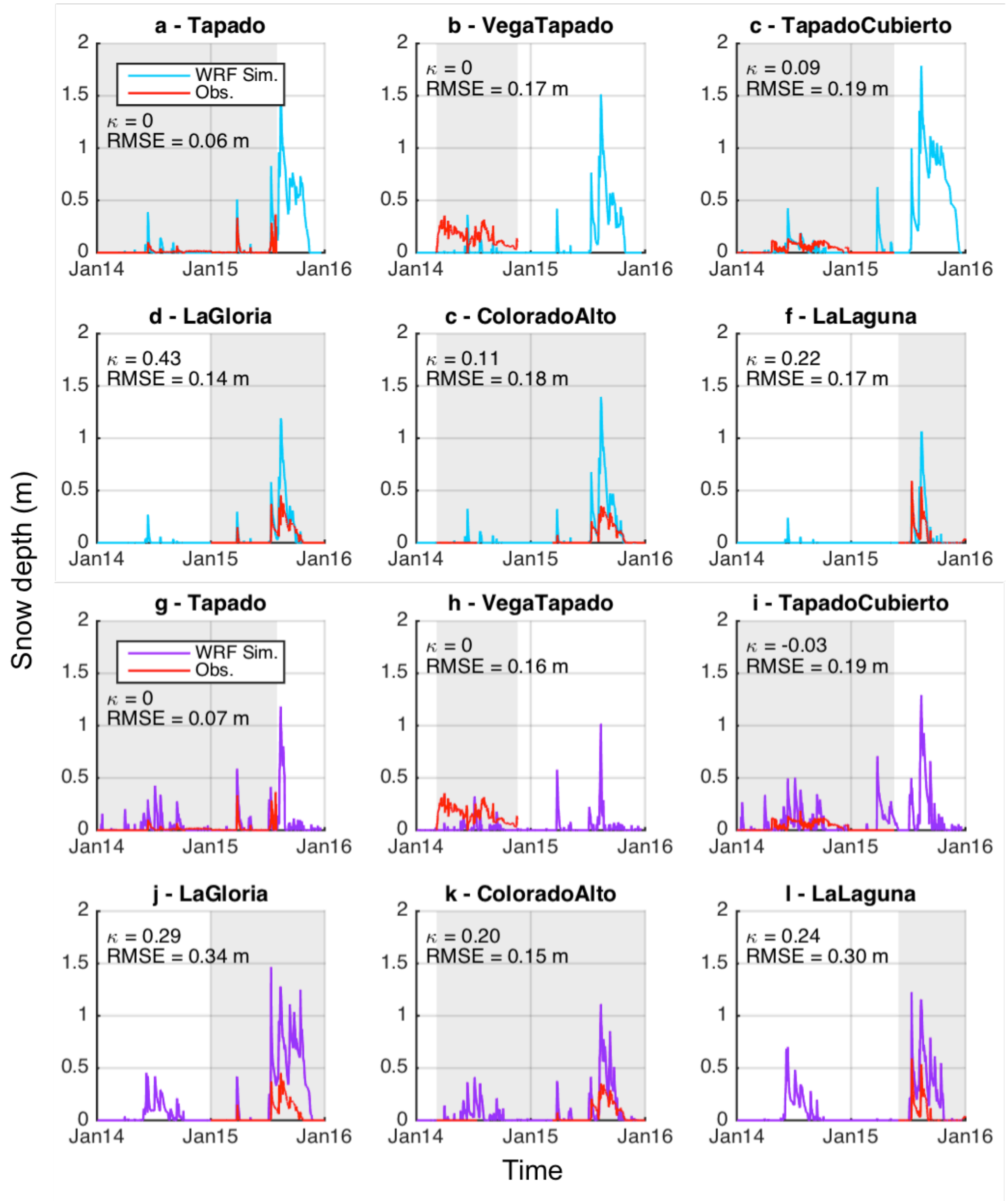

Figure 5: Simulated (cyan/purple) vs. observed (green) snow depth at 6 automatic weather stations. Blue lines (a-f) represent simulations performed using AWS meteorological forcing. Purple lines (g-m) correspond to simulations performed using WRF meteorological forcing. Green shaded areas indicate the period of available measurements.

4.2.2 Snow cover comparison with satellite images

a/ Snow cover area

The simulated snow cover area (SCA), forced by the AWS-forcing is in good agreement with observations from MODIS products (Figure 6a) with, in particular, a good simulation of the timing of precipitation events. Best fits are observed for the winter and spring 2015 (*i.e.* from July to December), with higher calculated correlations (NSE_{SCA}=0.94, $RMSE_{SCA}$=41.6 km^2 (i.e. 8.3%)). Regarding the ablation, in June 2014 and April - May 2015, the simulated SCA decreases faster that the observed SCA, which can be due to an over-estimation of melt or/and sublimation or an underestimation of accumulation.

When using the WRF-forcing, the agreement between SCA and MODIS is lower than with the AWS forcing (Figure 6b). The timing of snowfall events is not always in good agreement with the observations due to missing events (e.g. March 2015), a timing bias of a few days (e.g. March 2014) and/or additional events (during both 2014 and 2015 winter season). The simulated SCA evolution over winter and spring of 2015 shows strong variation over the entire catchment, which is not observed in the MODIS record. Here again, for both forcing datasets, better performances are observed for 2015 (NSE_{AWS} = 0.79, $RMSE_{AWS}$ = 93.2 km^2 (i.e. 19% of the total area); NSE_{WRF} = 0.61, $RMSE_{WRF}$ = 125 km^2 (25%)) than for 2014 (NSE_{AWS}=0.41, $RMSE_{AWS}$=117 km^2 (23%) ; NSE_{WRF} = 0.23, $RMSE_{WRF}$ = 133 km^2 (27%)).

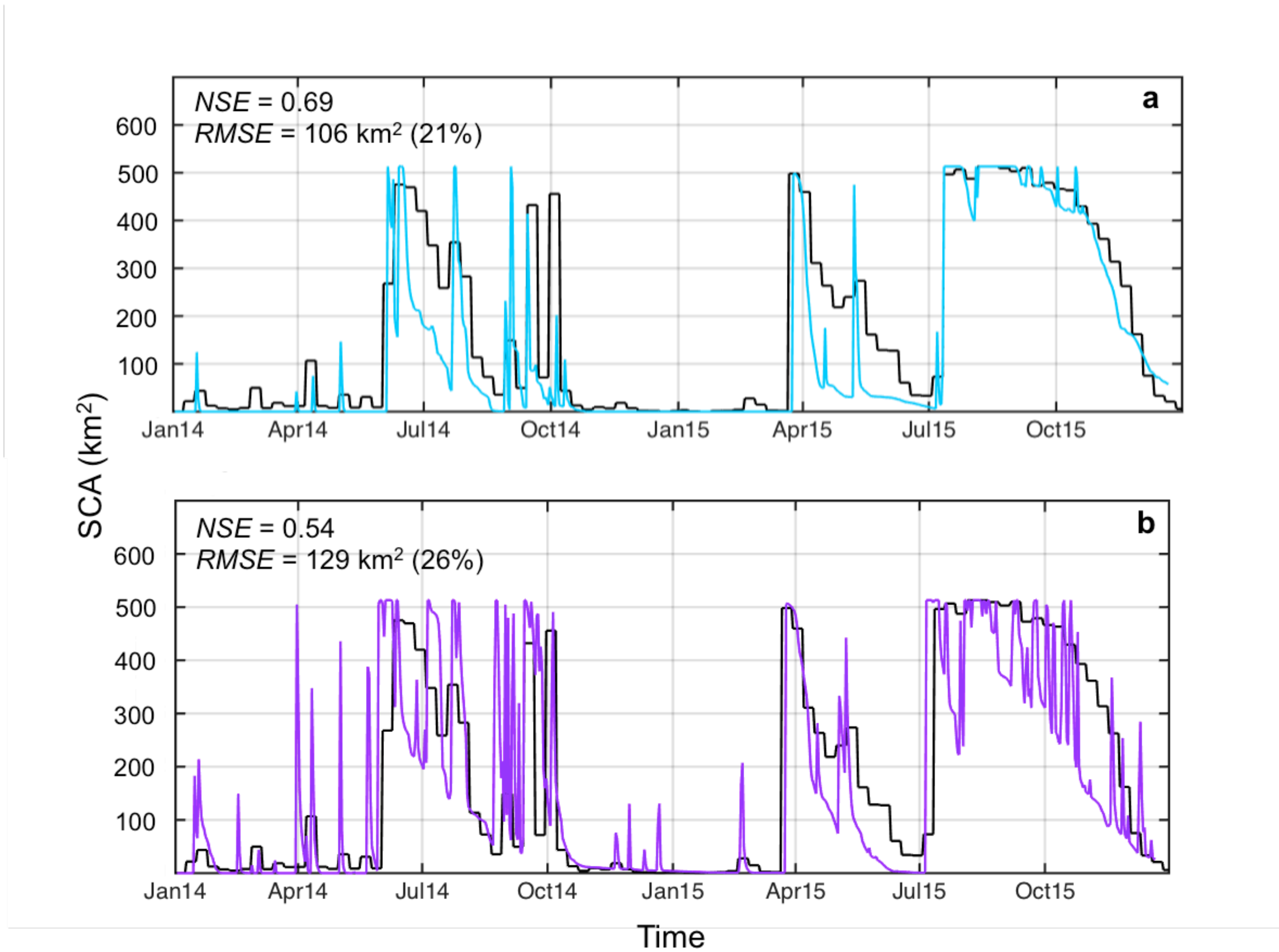

Figure 6: Snow cover area evolutions over the 2014-2015 period, from MODIS images (black lines), and simulations using (a) AWS-forcing (blue line) and (b) WRF-forcing (purple line).

b/ Snow cover duration over the catchment

The simulated snow cover duration (SCD) was also compared to the observed duration (from MODIS) by elevation band. For all each 200 m elevation band, the total number of snow-covered days for each grid cell was computed and then averaged for each band. For 2014, better performances were obtained for the AWS-forcing than for the WRF-forcing (Figure 7). For 2015, while better performances were also obtained for the AWS-forcing, the improvement using this forcing was minor.

Results based on AWS-forcing are in good agreement with observations at low elevations (i.e. below 4600 m a.s.l.; Figure 7), but show an over-estimation of the SCD at high elevation (absolute mean difference of 30 and 27 days for 2014 and 2015 respectively).

When using WRF forcing, SCD is over-estimated for the entire catchment in 2014 (absolute mean difference of 67 days). In 2015, simulations indicate an over-estimation of the SCD at low elevations (i.e. below 4500 m a.s.l.), and a small under-estimation at higher elevations (absolute mean error of 34 days for 2015).

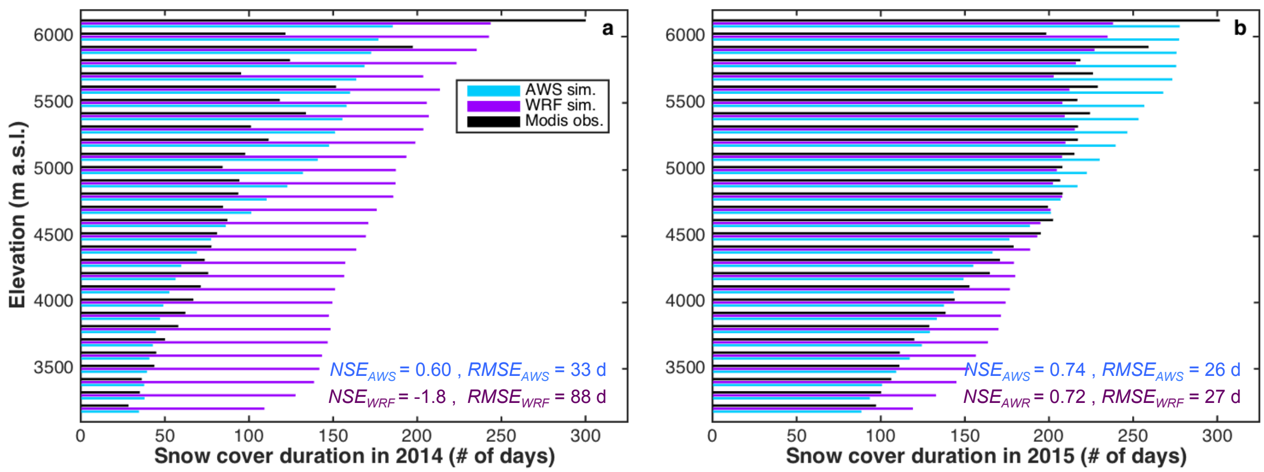

Figure 7: Snow cover duration per each 200m elevation band, from MODIS images (black), AWS-forcing (blue) and WRF-forcing (purple) for (a) 2014 and (b) 2015.

4.3 Ablation and energy balance fluxes

The forcing strongly impacts the simulated sublimation ratio. The annual means computed over the entire catchment (only considering snow grid-cells) for the AWS-forcing were 42/49% for 2014/2015, respectively, whereas 86/80% was obtained for WRF-forcing. The mean daily rate is 0.6 mm w.e. d^{-1} and 3.6 w.e. d^{-1} for 2014 and 2015, respectively, when the model is forced with the AWS-forcing. Values are larger and reach 3.1 mm w.e. d^{-1} and 4.1 mm w.e. d^{-1} for 2014 and 2015 when simulations are performed with the WRF-forcing.

4.3.1 Mean annual elevation gradients

a/ Ablation

The annual sublimation ratio is variable in space and increases with elevation for both years and both forcings (Figure 8 a,b). Comparison between the two forcings shows larger discrepancies below 5300 m a.s.l. (50% of differences for 2014 and 30% for 2015). Note that larger differences were observed for 2014 related to larger differences in snow cover and snow duration between forcings.

Melt predominates at all elevations when using the AWS-forcing (Figure 8 c,d), except above 6000 m a.s.l. in 2015. Melt and sublimation rates increase with elevation until 5300 m a.s.l.. Above this elevation the melt rate first stagnates and subsequently decreases. This increase in sublimation rate and decrease in melt at high elevations explains the increase in sublimation ratio with elevation observed in Figure 8 a,b.

For the WRF-forcing, sublimation rates are larger than the melt rates at all elevations. Melt is relatively constant above 3800 m a.s.l. whereas the sublimation ratio increases, explaining the larger values of the sublimation ratio at high elevations.

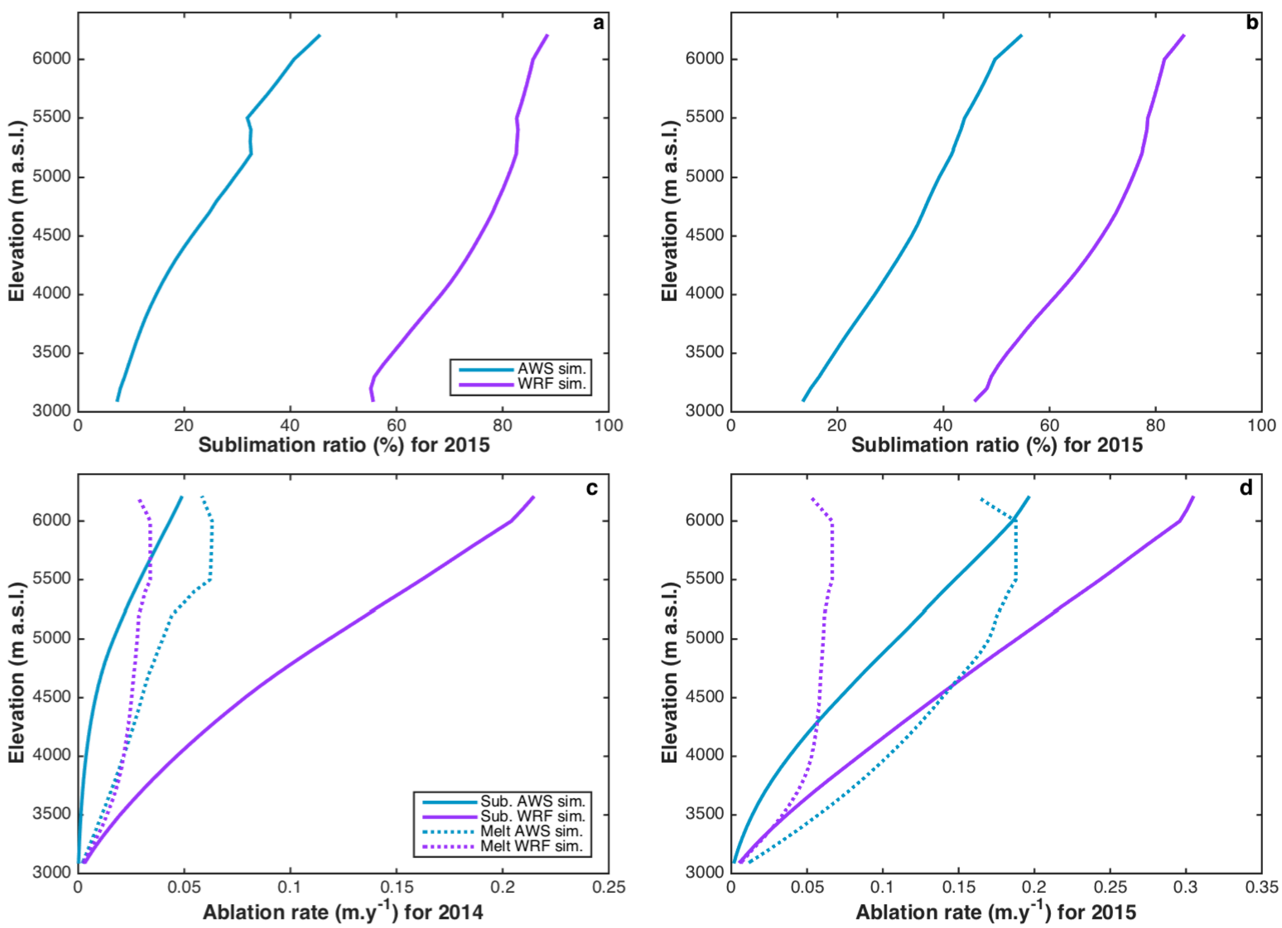

Figure 8: Simulated annual sublimation ratio (a,b) against elevation band using AWS (blue) and WRF (purple) forcing for 2014 (a,c) and 2015 (b,d). Simulated annual ablation ratio (sublimation and melt) against the elevation using AWS and WRF-forcing for 2014 (c) and 2015 (d).

b/ Energy fluxes.

Figure 9 shows the distribution of energy fluxes with elevation to aid the interpretation of the relationship between elevation and sublimation for both forcings. Both LW and SW show little variability between elevations bands for the AWS forcing. LW also does not change strongly between years. The SW and turbulent fluxes, however, show a strong variability between 2014/2015. In 2015 the turbulent fluxes (mainly QE) are higher, especially at lower elevations, resulting in higher sublimation ratios (Figure 8 a,b., section 4.3.1a). The WRF simulations, on the other hand, don't show this interannual difference in energy fluxes. Comparison of the AWS and WRF simulations, however, show higher turbulent fluxes for WRF-forcing, which in agreement with higher sublimation rate and ratio mentioned above.

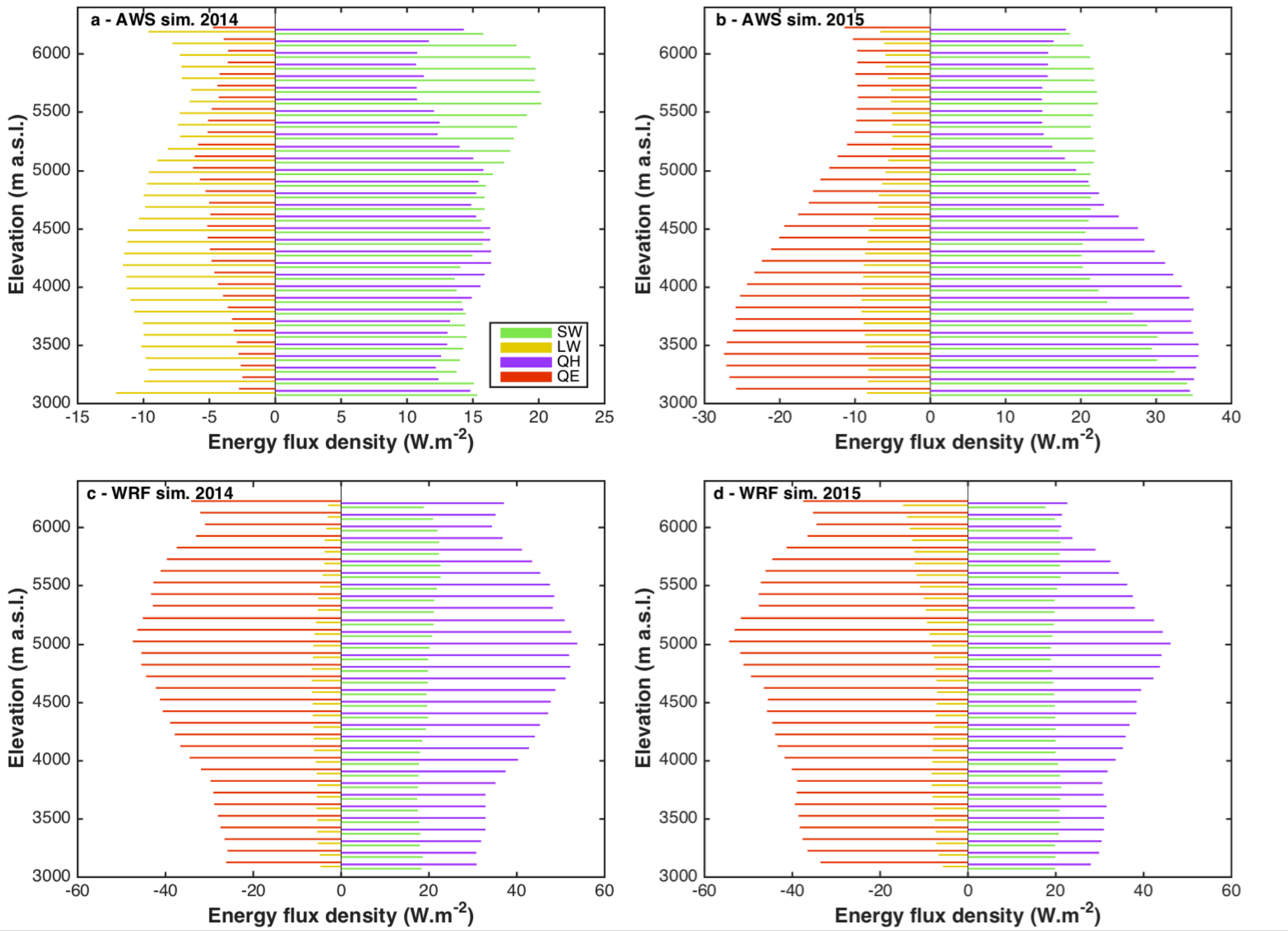

Figure 9: Annual mean of main modeled energy fluxes (computed over snow surfaces only) for each 200 m elevation band using AWS (a,b) and WRF (c,d) forcing for 2014 (a,c) and 2015 (b,d). SW is net shortwave radiation, LW is net longwave radiation, QE is the latent heat flux and QH is the sensible heat flux.

4.3.2 Monthly evolution

Analysis of the monthly sublimation ratios and rate show a strong seasonal variability in sublimation (Figure 10). Independently of the forcing chosen, larger sublimation rates are found in June and September for 2014, and in August, September and October for 2015, corresponding to the warm parts of the snow season.

Figure 11 indicates that turbulent fluxes (*QE* and *QH*) have the greatest impact on sublimation in all cases, except for the 2014 AWS-simulation. Net SW is also an important factor, and relatively similar for all the simulations. For the annual mean net SW is 18/22 W.m^{-2} for 2014/2015 for the AWS forcing and 24/23 W.m^{-2} for the WRF forcing, respectively. The contribution of net LW on the other hand is low for all simulations (annual mean of -7/-6 W.m^{-2} for AWS/WRF-simulations respectively). Note that these losses are small in comparison to mid-latitude sites (e.g. -25 to -20 W m^{-2} according to the study by Giesen et al, (2009)), because of the very dry conditions of the atmosphere and to the cold surface temperature of the snow surfaces.

Important differences are observed depending on the forcing used. For example, in 2014 the turbulent fluxes are dominant for the WRF forcing but not for the AWS forcing (Figure 8 a,c). This can be explained by the larger snow cover simulated by WRF-forcing with snow cover in the entire catchment while the AWS-forcing only results in snow at higher elevations. Since the fluxes are computed over snow surfaces only , WRF increases the contribution of warmer, low elevation areas. In both cases, the annual mean Bowen Ratio (*Br* = *Qh/Qe*) is larger than one (*Br* = 2.3/1.2 when using the AWS/WRF-forcing respectively), indicating that a greater proportion of the available energy at the surface is passed to the atmosphere as sensible heat than as latent heat.

While lower differences are observed for 2015 (Figures 8 b,d), the *Br* strongly depends on the forcing used: 1.9 and 0.9 for AWS and WRF-forcing, respectively. This means that contribution of sensible heat vs .latent heat is larger for the AWS forcing than for the WRF forcing.

Despite the difference between forcing, in both cases, larger *Br* are found for 2014 than 2015.

Nevertheless, part of the differences between years and forcings seem to be related to the snow depth differences, an aspect further discussed in Section 5.

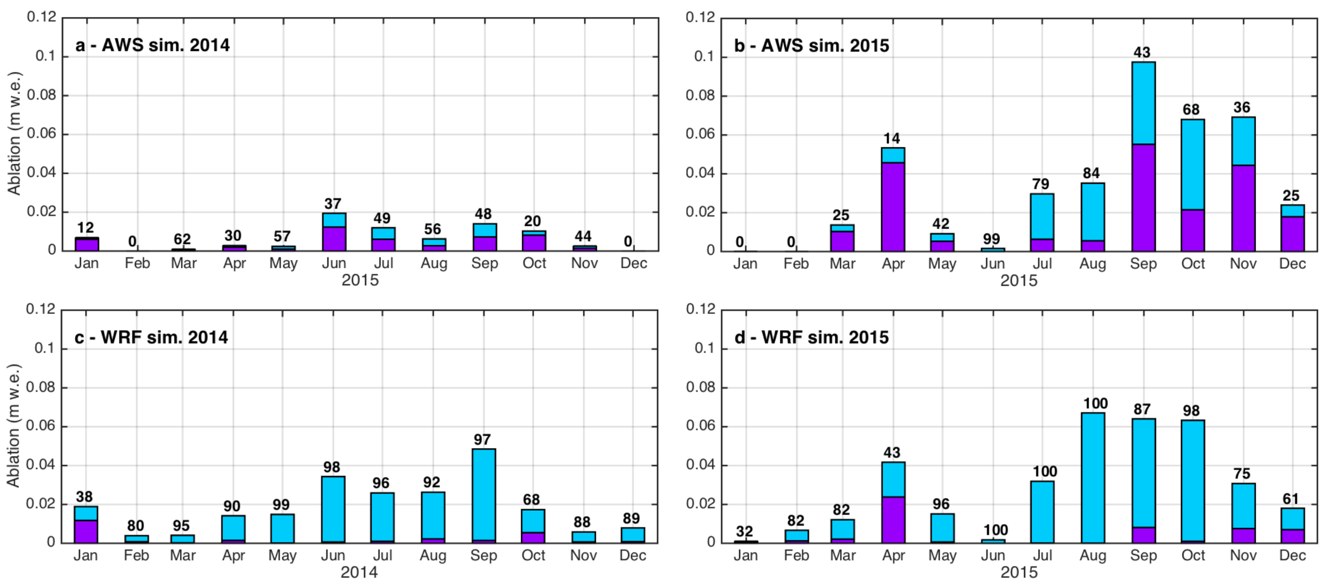

Figure 10: Cumulated simulated melt (purple) and sublimation (blue) per month using AWS-forcing (a,b) and WRF-forcing (c,d). Black numbers indicate the monthly sublimation ratio in %.

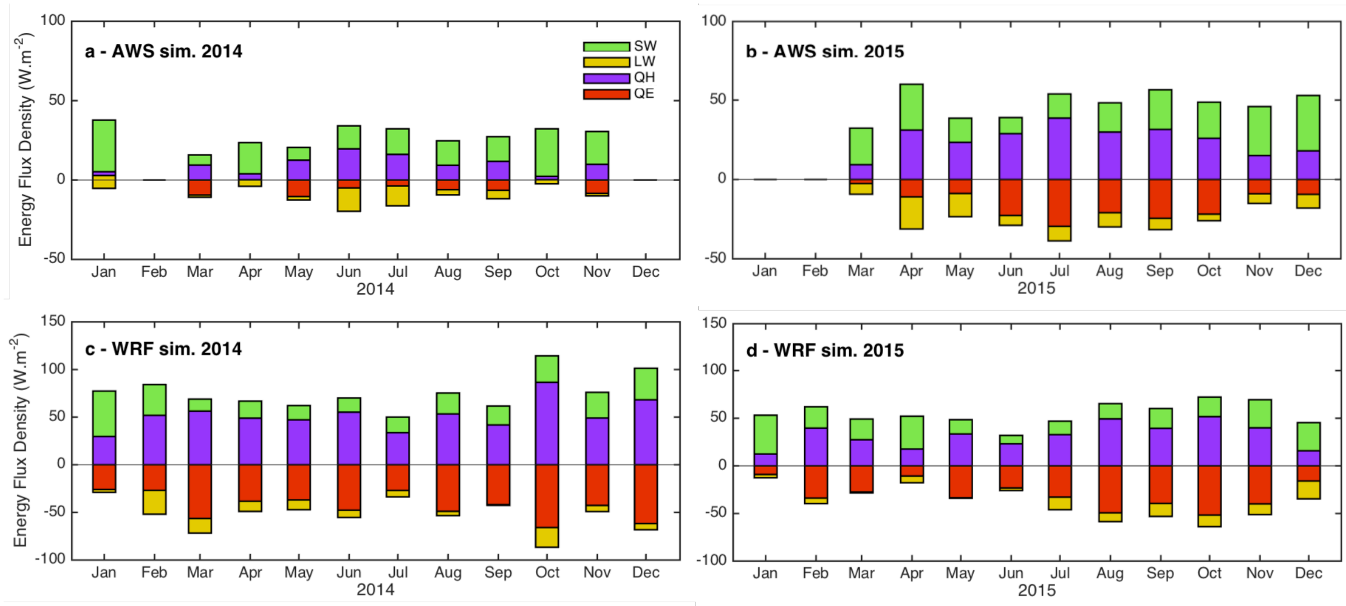

Figure 11: Monthly average of the main modeled energy fluxes for the entire catchment, over snow surfaces only. SW is net shortwave radiation, LW is net longwave radiation, QE is the latent heat flux and QH is the sensible heat flux.

5. DISCUSSION

5.1 AWS *vs.* WRF forcing.

Results presented in this study highlight the importance of forcing when modeling snow depth, snow cover and sublimation. Differences in model outputs are largely due to differences in temperature and precipitation inputs.

5.1.1 Air temperature and precipitation

The cold bias in air temperature from WRF simulations, using the combination NCEP-WRF, is often observed and well documented (e.g. Ruiz et al., 2010). It can be explained by the model parameterization complexity such as: *(i)* the initial or lateral conditions especially for the land surface surface temperature (Cheng and Steenburgh, 2005) or soil thermal conductivity (Massey et al., 2014), *(ii)* the parameterization of the planetary boundary layer scheme (Reeves et al., 2011), or *(iii)* the radiation parameterization scheme as it has been observed for other models (e.g. Müller and Scherer, 2005). However, the exact source of this bias remains difficult to identify (e.g. Reeve *et al.,* 2005). In this study, the default parameterization has been used, but works are in progress regarding the evaluation of the most appropriate calibration over this area, using direct observations.

Otherwise, precipitation is known to be over-estimated using the WRF model, particularly in the Andes (e.g. Mourre et al., 2016). One possible explanation is that biases can exist in the reanalysis data, in particular at high elevations, where observations are often scarce. Precipitation over-estimation might also be related to the parameterization used for the model which may not be the most appropriate for the Andes; further work is needed to determine the most appropriate ones. Outputs may also be inaccurate due to the relatively low-resolution DEM used (100 m).

Precipitation measurements using rain gauges can be biased towards an underestimation due to an undercatch, especially for snowfall because of the influence of wind (e.g. MacDonald and Pomeroy, 2007; Wolff et al., 2015). This gauge undercatch uncertainty (see Section 5.4.1) could increase the difference between the precipitation simulated by WRF and that measured at the AWSs. In addition, questions arise regarding the representativity of point measurements compared to the grid cell considered in the model.

The spatio-temporal variability observed in the difference between AWS and WRF precipitation data, highlight that it would be inappropriate to use a constant correction factor to adjust WRF data with measurements. More studies comparing WRF output to AWS among other data sets are required to determine a realistic correction method.

5.1.2 Consequences of the forcing used

Lower temperature and relative humidity values from WRF outputs compared to AWS measurements can explain, in part, the larger simulated sublimation ratio found with this forcing (Figures 8 a,b and 10). The relatively high amounts of precipitation simulated by the WRF outputs, and resulting snow cover overestimation, may also play a role. Differences in the sublimation ratio when using the AWS and WRF-forcing are quite similar for the two years (mean annual difference of 42% and 36% for 2014 and 2015 respectively), although the difference between the melt rate and sublimation rate depends on the year (Figures 8 c,d).

Larger differences in sublimation rates between the two forcing datasets are observed in 2014, especially at high elevation. In 2014 there are lower RH and P biases (Figure 4c,d), but larger air T differences, especially at high elevations (Figure 4b). On the other hand biases in wind speed, incoming LW and SWi and air pressure are low for both years (results not shown).

The larger RH bias in 2015 indicates an over-estimation of the dryness for this year (compared to 2014), and would lead to larger differences in sublimation rate for 2015 than for 2014, which is the opposite of the results observed. Likewise, the larger over-estimation of precipitation amount observed in 2015 (Figure 4d) does not explain the larger difference in sublimation, as a deeper snow depth should result in more persistent snow cover during the warm period and hence a lower sublimation ratio related to larger melt rate. Therefore, although the relationship between temperature and sublimation rate is complex and not necessarily direct, in this case, the colder temperature is the most probable explanation for at least part of the larger difference in sublimation rate observed at high elevation.

The SCD also have a significant influence on sublimation. For 2014, the differences in SCD between the two forcings were 100 days below 4500m, and close to 50 days above this elevation (Figure 7a). Snow that persists over a longer period results in an increased melt rate and can influence the sublimation rate and ratio (especially in 2015, Figure 10). This is the only explanation for the larger melt rate observed with AWS-forcing compared to WRF-forcing at low elevations, given the cold bias in WRF-forcing (Figures 8c and 4b). Since a larger SCD can be related to larger precipitation amount, precipitation uncertainties likely play a significant role and the sublimation estimation.

5.2 Comparison between dry and wet conditions

5.2.1 Comparison between 2014 and 2015

Differences in sublimation ratio and rates between 2014 and 2015 are related to both meteorological conditions related to energy fluxes, and snow cover duration. First, the similar annual mean sublimation ratio found for both years is likely due to a compensation between the dry 2014 year (low precipitation) associated with cold conditions in spring and summer, *vs.* the wet 2015 year with longer snow duration and warmer spring and summer (according to meteorological measurements made in the region). Both sublimation and melt rates were larger overall during the wet 2015 year compared to the dry 2014 year. Thus the higher melting rates in 2015 compensated the enhanced sublimation rates and resulted in sublimation ratios comparable with 2014. The larger sublimation rates observed in 2015 are related to higher RH and wind speed, but also higher precipitation, snow accumulation and snow duration in 2015 compared to 2014. Results show particularly large sublimation rates over the long melt period in 2015. This may be explained by the warmer conditions which induce a warmer snow pack, increasing the saturated vapor pressure at the snow surface and providing energy to increase the sublimation rates (Herrero and Polo, 2016). According to these results, the snow duration seems to modulate the annual average ablation ratio, such that a longer-lasting snow cover extending further into the warm spring climate is subjected to both enhanced sublimation and melt in response to an increase in incoming energy fluxes. Nevertheless, it remains difficult to disentangle the respective effects of meteorological conditions and snow duration on sublimation. To better evaluate these effects, the influence of the meteorological forcing related to energy fluxes and the snow cover duration must be evaluated separately. For that purpose, we performed simulation experiments in which a common precipitation input was used for both years. In the first experiment the 2014 precipitation inputs ('dry input' with shorter snow cover duration) were applied to both years, then the 2015 precipitation was applied to both years ('wet input' with longer snow cover duration). All other meteorological forcings were left unchanged.

5.2.2 Impact of the precipitation amount

Forcing the 2014 year with the 'wet precipitation input' reduces the mean annual sublimation ratio by 12% (Figure 12 a,d), while forcing the 2015 year with the 'dry precipitation input' increases the mean annual sublimation ratio by 3% (Figure 12 b,d). In summary, a decreased annual mean sublimation ratio is observed when the precipitation is increased (which likely increases the SD and SCD), and other factors are held constant. However the amplitude of the response differs between the two years. This is mainly due to differences in the ablation rates (Figure 12). For 2014, increasing the precipitation amount leads to a sublimation rate increase of 0.8 mm w.e. d^{-1} while for 2015, decreasing the precipitation amount decreases the rate by 2.8 mm w.e. d^{-1}. Despite these annual differences, the maximum monthly sublimation rates are still observed for the same months, independent of the precipitation forcing used, with the exception of June and August (Figure 12). In June, snow covered the entire catchment in 2014 but not in 2015 (Figure 6), related to a strong snow event in June 2014 and no precipitation in June 2015. The opposite was observed for August. Changing the precipitation forcing strongly impacts the SCA and therefore the snow amount available for ablation and sublimation.

Comparisons made for months with a maximum SCA (i.e. when the entire catchment is covered by snow and it persists over the entire month), allow the influence of SCD to be independently analyzed since the SCA remains constant. In July, a month where maximum SCA was observed in both years, sublimation differences of 27 mm w.e. m^{-1} and 57 mm w.e. m^{-1} were found between dry vs wet precipitation inputs for 2014 and 2015, respectively. In 2015 the SD was thicker than in 2014 for both dry and wet inputs, thus the results indicate an increased sublimation rate with thicker SD. The thicker SD also implies larger melt rates, such that the sublimation ratio decreases when increasing the precipitation in 2014 but increases with increased precipitation in 2015, highlighting the complexity of the influence of SD on the sublimation ratio.

Otherwise, differences in mean sublimation rates are much higher when changing the precipitation amount for the 2015 meteorological forcing than for the 2014 meteorological forcing 2014 (i.e. 0.8 mm w.e. d^{-1} for 2014 vs. 2.8 mm w.e. d^{-1} for 2015 as mentioned above). Sublimation rates are also higher in 2015 compared to 2014, especially at the end of the snow season (i.e. from September to November; Figures 12 a,d). This holds true when considering wet conditions (Figures 12 b,c). This highlights the significant influence of meteorological conditions on sublimation. As mentioned in section 5.2.1, 2015 experienced higher wind speeds and RH and colder air temperatures. The contribution of turbulent fluxes is higher in 2015 than 2014 (Figures S3 a,d in the supplementary information), suggesting that wind speed has a greater influence on sublimation than RH.

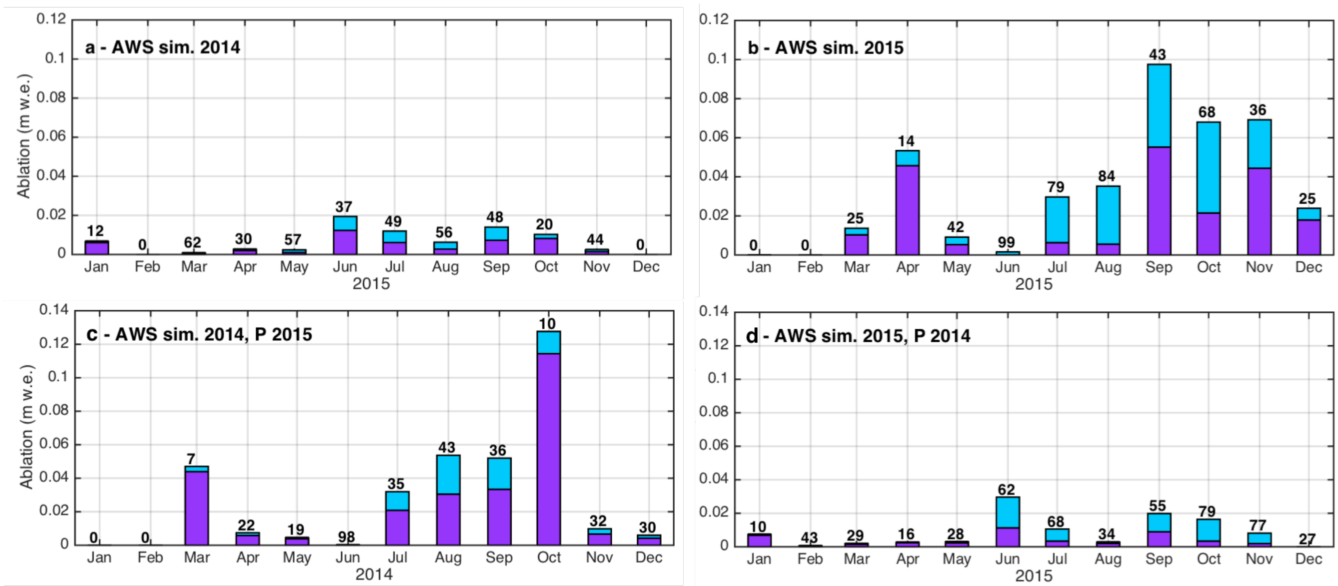

Figure 12: Monthly simulated melt (purple) and sublimation (blue) using AWS-forcing (a,b) and AWS-forcing with (c) 2015 precipitation ('wet forcing') and (d) 2014 precipitation ('dry forcing'). Back numbers indicate the monthly sublimation ratio in %.

5.3 Limits of the study

The main objective of this study was to investigate the impact of forcing data on modeled mass and energy balance, with a specific focus on snow depth, snow cover and sublimation rates. Nevertheless, we recognize that uncertainties also exist depending on model calibration choices. To discuss this point, four different parameters were tested to evaluate the uncertainties related to the calibration of modeled parameters: roughness value, precipitation amounts (due to measurement uncertainties), topographic curvature length and slope versus curvature length (Figure S4; Supplementary Information E). The results showed that the sublimation ratio was most sensitive to roughness values, and that differences due to the other three variables were an order of magnitude lower (For more details, please refer to the Supplementary Information). The strong sensitivity to the roughness value and the absence of measurements to validate the turbulent fluxes calibration limits precise sublimation quantification for this area.

6. CONCLUSION

In this study, the snow energy and mass balance have been simulated over La Laguna catchment located in the semi-arid Andes of Chile. Using the snow pack model SnowModel, simulations were performed over two contrasting years (2014 considered as a dry year and 2015 considered as a wet year), using two distinct forcings (nine AWS located in the catchment and 3km resolution WRF model outputs).

Results indicate strong differences in simulated snow depth depending on the forcing chosen, mainly due to a cold bias in air temperature in WRF as well as an over-estimation of precipitation. As a result, performances in simulating the snow cover using the AWS-forcing are more realistic, both at the local scale (comparison with AWS snow depth measurements), and over the entire catchment (comparison with SCA and SCD from MODIS images). In addition, independently of the forcing choice, the simulation of snow cover is better for 2015 compared to 2014, mainly due a larger sensitivity to the precipitation uncertainties during dry conditions. This highlights the complexity in properly modeling the snow cover evolution for years with low precipitation years.

There are also large differences in modeled sublimation ratio depending on the forcing chosen. When using WRF-forcing the sublimation ratio is approximately twice that modeled with the AWS-forcing. This is partially due to the differences in temperature and relative humidity between the two forcings, but mostly due to precipitation differences. For example, when holding all model inputs constant except for precipitation, there are significant differences in the modeled sublimation, especially for 2014 which was a dry year. Otherwise, the annual mean of the sublimation ratio over a catchment is similar during the two years and but it increases with elevation. This partly explains the larger sublimation values reported in previous studies performed at high elevations in the semi-arid Andes of Chile (e.g. Gascoin et al., 2013; Ginot et al., 2001; MacDonell et al., 2013).

Sublimation simulated in this study is associated with several sources of uncertainty. First, the main forcing uncertainty is from precipitation due to measurement errors and lack of spatial representation as precipitation data was only available for two stations. This study highlights that this uncertainty has a strong impact on sublimation and further work is suggested to *(i)* improve measurements uncertainties, *(ii)* increase the number of sensors over the catchment, and *(iii)* incorporate AWS measurements into the WRF model and use data assimilation to improve model outputs. CEAZA is currently working on point *(iii)* to provide improved WRF outputs for the semi-arid Andes of Chile.

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SUPPLEMENTARY MATERIAL

A – Climatology at La Laguna

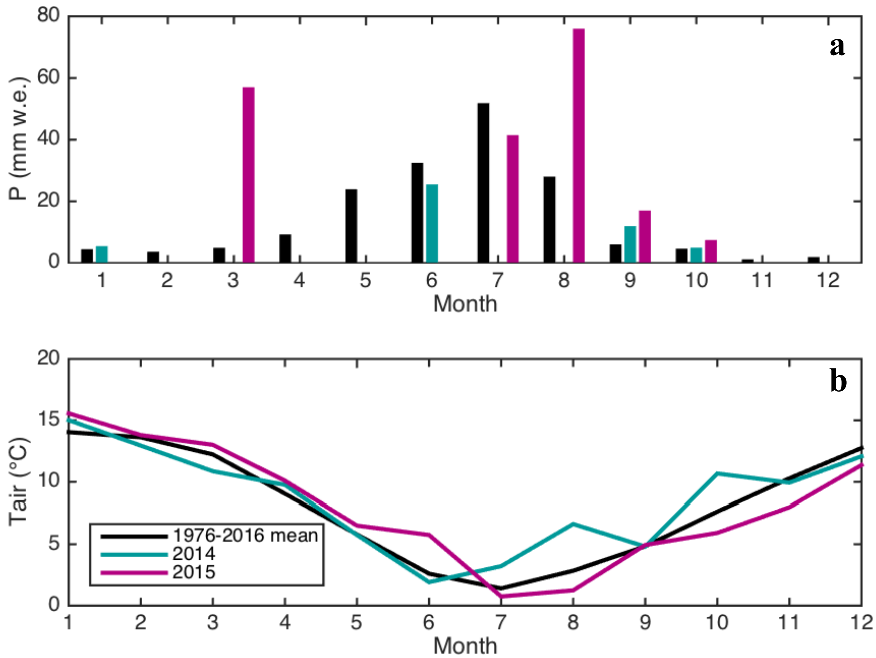

Figure S1: (a) Monthly precipitation and (b) air temperature recorded at La Laguna station. The monthly mean (black) is computed over the 1976-2016 period.

B – Comparison AWS vs. WRF grid point

Table S1: Statistics (R2, RMSE and AME (Absolute Mean Error)) between micromet outputs forced by the AWS measurements and the WRF outputs.

	Vertical offset with the WRF grid point	T (°C)			RH			SWi			LWi			WS (m s^{-1})			P (mm d^{-1})		
		R^2	RMSE	AME	R^2	RMSE	AME	R^2	RMSE	AME	R^2	RMSE	AME	R^2	RMSE	AME	R^2	RMSE	AME
Colorado Bajo	278m	0.94	5.02	5.32	0.04	15.7	15.7	1	1.29	0.65	0.96	5.53	4.10	0.01	1.61	1.29	0.35	2.96	3.42
La Laguna	144m	0.91	5.01	4.60	0.04	19.4	14.8	1	1.65	0.72	0.94	6.66	5.00	0.15	1.71	1.15	0.51	5.72	3.52
Llanos de las Liebres	305m	0.91	6.39	6.06	0.04	20.6	15.8	1	1.34	0.51	0.98	5.57	4.48	0.37	2.08	1.46	0.51	7.17	4.31
La Gloria	56m	0.89	5.33	4.81	0.08	19.7	15.2	0.99	2.95	1.09	0.93	6.61	5.12	0.17	1.34	1.01	0.58	5.05	3.05
Colorado Alto	196m	0.89	6.61	6.27	0.04	21.6	16.6	1	1.54	0.53	0.99	4.46	3.69	0.52	2.31	1.70	0.51	8.35	4.16
Vega Tapado	-145m	0.88	7.01	6.73	0.03	22.8	17.6	0.99	3.43	1.40	0.99	4.24	3.67	0.53	4.28	3.48	0.53	8.95	4.73
Tapado	462m	0.88	6.83	6.54	0..01	22.9	17.8	0.99	2.98	1.33	0.99	1.48	1.11	0.52	3.45	2.78	0.51	9.48	4.92
Paso Aguas Negras	-121m	0.83	7.29	6.99	0.00	24.6	19.0	1	1.96	0.75	0.98	2.96	2.39	0.54	5.19	4.27	0.56	7.89	4.25

C- Spatial variability of the annual SCD.

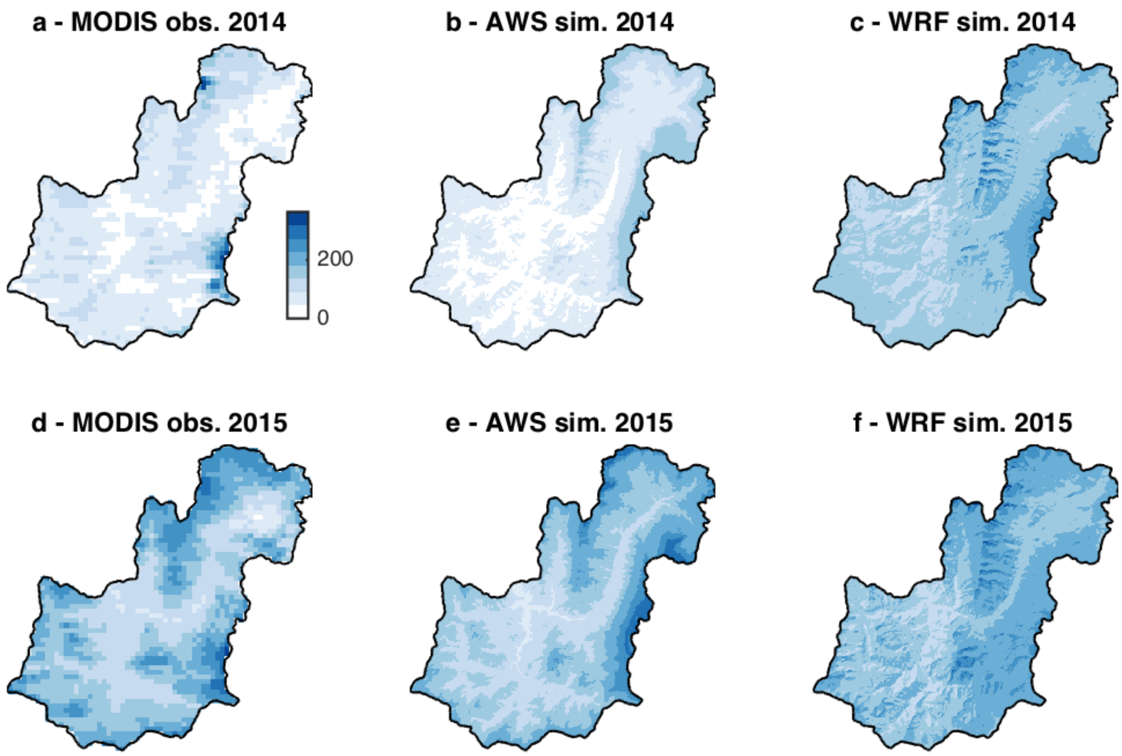

Figure S2: Snow cover duration from MODIS images for (a) 2014 and (d) 2015. Simulated snow cover duration using AWS-forcing for (b) 2014 and (e) 2015. Simulated snow cover duration using WRF-forcing (c) 2014 and (f) 2015.

D- Influence of the precipitation amount on the energy fluxes contribution

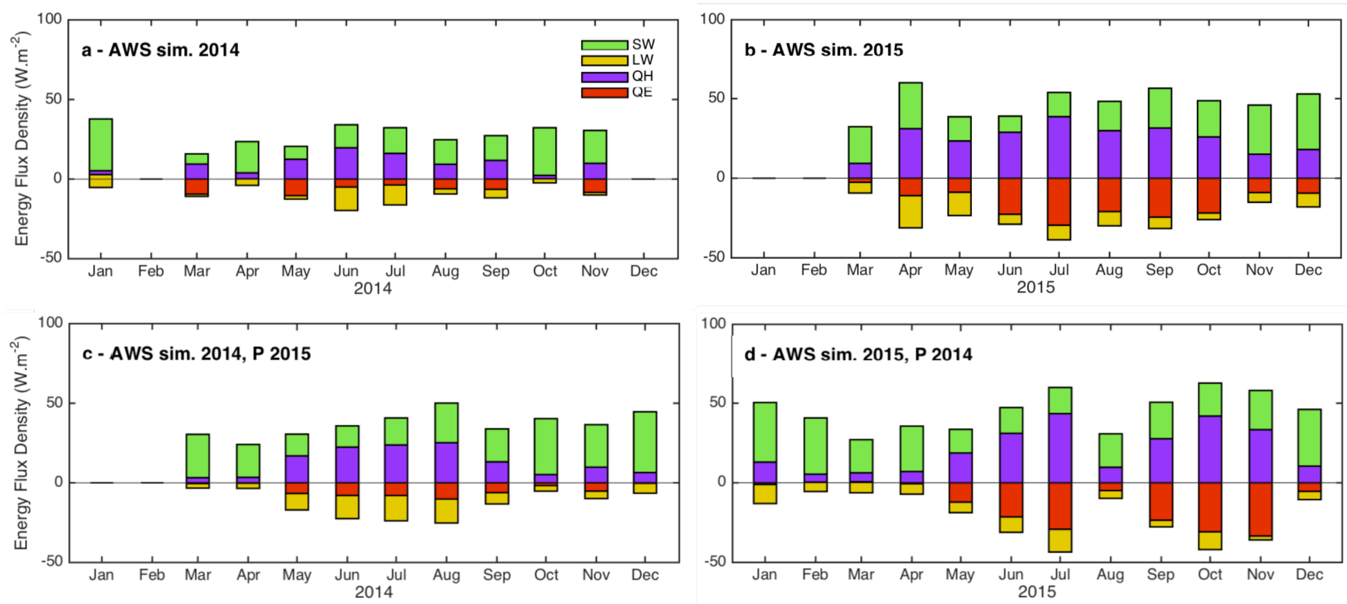

Figure S3: Monthly average (for the entire catchment, over snow surfaces only) of the main modeled heat fluxes for (a) 2014 and (b) 2015 AWS-forcings, (c) a simulation using the 2015 precipitation and the 2014 AWS-forcings, and (d) a simulation using the 2014 precipitation and 2015 AWS-forcings. SW is net shortwave radiation, LW is net longwave radiation, QE is the latent heat flux and QH is the sensible heat flux.

Figure S2: Monthly simulated melt (purple) and sublimation (blue) using AWS-forcing (a,b) and AWS-forcing with (c) 2014 precipitation and (d) 2015 precipitation. Forcing. Back numbers indicate the monthly sublimation ratio in %.

E. Model uncertainties

The main forcing uncertainties were estimated to be the precipitation (related to P measurements and the P spatialization as there are only 2 recording stations); and the wind speed spatialization (Gascoin *et al.,* 2013). Regarding the other variables T, RH, SW, and LW, a similar study performed in a nearby catchment indicated a very good performance of MicroMet to spatialize these variables, with high correlations and low biases (for more details please refer to Gascoin *et al.,* 2013).

The principal calibration uncertainties are the topographic length scale used for the wind distribution and *z0* due to the absence of measurements to properly calibrate the model. Note that the albedo measurements have been used to calibrate the model, that is why this calibration is not considered as a main calibration uncertainty in this study. Indeed, if we compare the model output albedo with the measurements, the mean *R* is 0.74 with mean *RMSE* of 0.22 and errors are considered related to the simple approach of the albedo computation of the model.

Table S2: Mean annual melt and sublimation ratio of each simulation. Bold values indicate when results are different than the reference study (i.e. results present in section 4 with the AWS-forcings) indicated in the first line.

	2014		2015	
	Melt (m.w.e.)	Sub. (m w.e.) (Sub. Ratio)	Melt (m.w.e.)	Sub. (m w.e.) (Sub. Ratio)
Reference sim.	0.047	0.030 (42%)	0.21	0.19 (48%)
Precipitation +10%	**0.048**	**0.029 (41%)**	**0.23**	0.19 **(47%)**
Curvature 100m	0.047	0.030 (42%)	0.21	0.19 (48%)
Curvature 1000m	0.047	0.030 (42%)	0.21	0.19 (48%)
Slope 0.25 - Curv. 0.75	0.047	0.030 (42%)	0.21	0.19 (48%)
Slope 0.75 - Curv. 0.25	0.047	0.030 (42%)	0.21	0.19 (48%)
Z0 = 10 mm	**0.033**	**0.049 (66%)**	**0.12**	**0.29 (72%)**

E1. Precipitation uncertainties

a) Precipitation measurements

As mentioned in section 5.1.2 snowfall measurements in windy conditions can suffer from an undercatch bias, and corrections are generally performed using empirical relationship (e.g. MacDonald and Pomeroy, 2007; Wolff *et al.,* 2015). The strong wind gusts in this region, and especially at high elevations (Figure 3) increase measurement uncertainties. Nevertheless, in this study it was chosen not to apply any correction. First, given the lack of continuous SWE measurements, it is not straightforward to establish an empirical correction. Also, precipitation data from two rain gauges (one shielded and the second one unshielded) located in Tapado have been averaged, to reduce the random error. Note that the data from the two rain gauges is surprisingly similar (see section 2.2.1), while we would expect a larger amount of precipitation catched by the shielded Geonor sensor, in this area of strong wind speed. This suggest that either the under catch is not si important or that the shield is not that efficient.

b) Spatialization

The main uncertainty for the precipitation data is due to the data spatialization at catchment scale. As only two stations have been used to force the model, the uncertainty is expect to be significant due to the orographic complexity of the catchment, but cannot be evaluated based on the current available measurements.

The interpolation of precipitation in MicroMet subroutine has been done without the use of an altitudinal gradient (called precipitation adjustment factor, Liston and Elder, 2006a) as no consistent altitudinal gradients were found in the observations (results not shown). Each event is very specific (e.g. Sinclair and MacDonell, 2016) and as a result, the altitudinal lapse rate can be either positive or negative. In addition, due to low precipitation rate and the few number of events, mainly in 2014, most of the time precipitations are recorded at one station but not at the other, or there is a delay between the events recorded at both stations, which are 14 km from one another. Different altitudinal gradients (monthly *vs* event scale) were tried but the best comparisons between simulated and observed snow depths were found without considering any gradient. Considering an altitudinal lapse rate systematically leads to an over-estimation, especially at high elevations, where the snow persists until the next season.

In addition, the model simulates the wind transport only after deposition and does not consider the preferential deposition. Again, the available measurements make it difficult to estimate this uncertainty.

c) Sensitivity test

A sensitivity test was performed by increasing the precipitation by 10%. Results indicate that the mean annual sublimation ratio over the catchment is very similar to that of the initial simulation (Figure 2). Indeed, it decreases by 1% for 2014 and for 2015. Regarding the spatial variability (Figure 11) the difference varies between +1 and -3 %, and larger differences are observed for 2014 between 5000 and 5500 m a.s.l. and around 4600 m a.s.l. for 2015. This maximum difference can be related to changes in spatial distribution of snow when some events occur only at high elevations.

d) Impact on model performances

The precipitation uncertainties explain also the better performances of the model for 2015 than 2014. Indeed, the model is sensitive to patchy snow, mainly observed at low elevation. As mentioned in section 4.2.1, modeling the spatial variability of the SD is complex and results show an overall similarity of the simulated SD between some stations. When dealing with low amount of snow, patches over the catchment are more present an increase the error.

E2. Wind uncertainties

a) Wind data spatialization uncertainty

As mentioned by Gascoin *et al.,* (2013), the wind speed simulated by MicroMet model tend to be under-estimated especially at low elevation. With the exception of Paso del Agua Negra, similar results are found in this study, with largest bias found at low elevations. Indeed, the results of the cross validation test indicate an *RMSE* of at

4.1 m.s^{-1} at La Laguna and a larger bias (RMSE = 7.8 m.s^{-1} at Paso del Agua Negra. Differences are related to the MicroMet interpolation and can be explained by different reasons. First, The main shortcoming of the wind interpolation module is the lack of thermal winds (e.g. katabatic winds). In addition MicroMet does not take any topography into account that determines the dynamic wind direction, implying bias in the wind interpolation. Nevertheless, the absence of general trends of the under-estimation (both low and high values are under-estimated and the bias strongly depend on the location and the wind speed) makes difficult to establish a relationship to correct the bias and also to evaluate the uncertainty at catchment scale.

Therefore, the number of stations used is important as increasing the number will decrease the uncertainty. The wind uncertainty has an impact on the sublimation ratio. Indeed, for instance, increasing the wind speed by 10% can induces sublimation ratio changes of 40% at high elevation (i.e. where there is no melt). The wind speed is, in fact, known to directly affect the turbulent fluxes (e.g. Litt et al., 2017)

In addition, the wind speed also impacts the snow density, which directly affects the thermal conductivity of the upper snow layers (Yen, 1981). As a consequence it impacts the surface temperatures thus the turbulent fluxes.

b) Topographic influence on wind transport

In the model, the curvature length and the influence of the slope *vs.* curvature can be calibrated to consider the topographic influence of the wind transport. While the curvature length can be approximately constrained from the DEM, the relative influence of slope and curvature is more difficult to quantify a priori. As such, sensitivity tests have been performed to evaluate the impact of these parameters on the simulation.

First, the curvature length value has been varied from 100m to 1000m, and does not impact the annual mean sublimation ratio at the catchment scale (Figure 2). Nevertheless the spatial variability of the differences depends on the elevation (Figure 11). Considering a larger curvature length leads to larger sublimation ratio at low elevation (in the valley) and lower one at high elevation. When choosing a larger curvature value, the simulated snow depth is larger in the valley as the snow transport is from a larger area, and increasing the snow depth decreases the sublimation ratio. Indeed, in that case the snow persists longer in spring, and warmer temperature allow increasing the melt rate.

The annual mean of the sublimation ratio at the catchment scale is not sensitive to the influence of the slope *vs.* curvature either (Figure 2) when values are ranging between 0.25 and 0.75. Nevertheless, varying this influence changes the spatial distribution of snow depth. Larger snow depths (between 18 and 26%) are observed on the ridges when the influence of the slope is larger than the curvature (results not shown). As a consequence, the sublimation ratio decreases by about 10 to 20% in areas with thicker snow, and can also be explained by a the persistence of the snow cover during the spring, increasing the melt rate. On the contrary the sublimation ratio is larger on steep slopes, when the influence of the slope is set to be larger than the curvature, as this calibration allows for more snow redistribution, decreasing the mean snow depth.

The change in snow distribution is more important when changing the influence of slope vs. curvature from 0.25 to 0.75 than when changing the curvature length from 100 to 1000 m. The calibration of these parameters remains important when the sublimation is evaluated in the valley for instance but according to our results, it does not affect the sublimation ratio when evaluated at the catchment scale

E3. Roughness value

Increasing the roughness value by a factor 10 increases the annual mean of the sublimation ratio by 24% for 2014 and by 20% for 2015 (Table S1). Larger changes are observed around 4600 m a.s.l. for 2014 and 2015 where the difference can reach 30% (Figure 11) .

This sensitivity test highlights the strong sensitivity and the importance of choosing an accurate value to properly quantify sublimation over the catchment. Further studies are therefore recommended to calibrate this value using turbulent flux measurements such as with an Eddy Covariance System (e.g. Litt *et al.,* 2017). Nevertheless even with measurements, significant uncertainty remains due to the strong spatio-temporal variability of the snow surface roughness. While the roughness value is used as a calibrated parameter and is not an absolute physical value, it depends on the surface roughness. The roughness is expected to increase with elevation, as penitentes are commonly observed on the lower Tapado glacier (e.g. Lhermitte et al., 2014; Nicholson et al., 2016) and surrounding areas. There is therefore a strong spatial variability of the roughness value, as penitentes are not observed over the entire catchment, but mainly in the upper part. In addition, penitentes grow in size over the season (Lliboutry, 1954) leading to a strong temporal variability of the roughness.

Due to the strong sensitivity to z_0 and the potential for significant spatio-temporal variability of the snow surface roughness, to reduce uncertainties, a spatio-temporal evolution of z_0 could be envisaged. At this stage, without more measurement it is a complicated task. Further studies based on two EC measurements over the season could help to evaluate the variability.

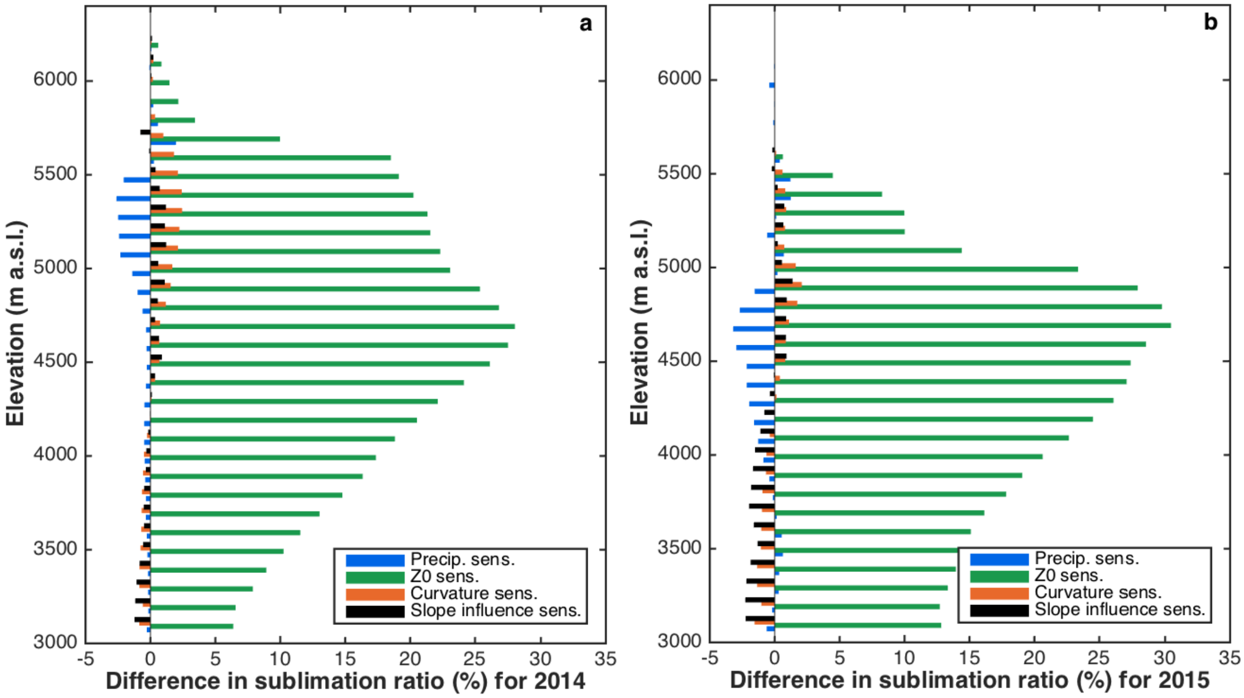

Figure S4: Differences in sublimation ratio per elevation range for (a) 2014 and (b) 2015, between: reference simulation and the simulation performed with a precipitation increase at the two AWS by 10% (blue); reference simulation (z_0=1mm) and with an increase of z_0 to 10mm (green); 100 and 1000m curvature length simulations (orange) and slope vs. curvature weight of 0.25 – 0.75 and 0.75 – 0.25 (black).