

Summary and general comments

In this study, a statistical bias adjustment and downscaling method for snow cover fraction data is explored. Simulated snow cover fractions are obtained from the EURO-CORDEX regional climate model ensemble at a horizontal resolution of 0.11° – both for the present day climate and for the end of the 21st century (for RCP 2.6 and 8.5). The bias adjustment is performed with MODIS remote sensing data, which is spatially aggregated from a resolution of 250 m to a similar scale as the EURO-CORDEX data. For the bias adjustment, four different methods are initially applied – delta change, quantile mapping, quantile delta mapping (QDM) and multivariate QDM. Bias-adjusted snow cover fractions are then subsequently downscaled to the initial high resolution of 250 m. The entire procedure is, for a subdomain, compared to a rather conventional approach in which snow cover fraction is derived from a high-resolution snow model, which is forced by downscaled RCM output.

This study explores an interesting and novel approach – namely the application of bias adjustment for snow cover fraction. The authors evaluate the suitability of different bias adjustment methods for this challenging approach. The manuscript is predominantly well written – some sections, like the explanation of the downscaling method – are however difficult to follow and should be improved. At some places, a more extensive discussion of the results would be useful – for instance regarding projected relative changes in snow cover fractions – which are surprisingly largest at high elevations.

Major comments

Remapping of high-resolution MODIS and CORDEX data

I'm a bit confused about the performed remapping. You first aggregate MODIS data to a low resolution grid and then remap CORDEX data to this grid with a nearest neighbour method, right? This seems to be unnecessarily complicated. Wouldn't it be easier to remap MODIS data (for instance with a conservative method) directly to the default rotated latitude/longitude CORDEX grid?

Downscaling method

The downscaling method is very interesting but difficult to follow in some places:

- A general question (just out of curiosity): downscaling can also be performed directly within the bias adjustment method. However, it seems to be less appropriate if observational data is available on a much higher spatial resolution. Did you nonetheless consider this option?
- Line 229: Is the requirement for the function not rather “strictly increasing” to get a unique solution for SNCp50? Furthermore, I don't understand the subsequent part with the “longest non-strictly increasing subsequence”
- I found it particularly difficult to follow the “filling of missing SNCp50 values” section (lines 235 – 248). The comprehensibility might be improved with an additional sketch or figure. Moreover, I have some specific questions:
 - Could you explain why the Wasserstein distance is a suitable metric for this problem?
 - What do you mean by “no one-to-one correspondence”?
 - By nearest low-resolution pixels (line 240), you refer to the Wasserstein distance, not the horizontal distance, right?
 - Line 247: how do you determine these 100 pixels exactly from the theoretically $50 * 100$ available pixels?
 - How did you proceed with the very small fraction ($<0.001\%$) of pixels with still missing SNCp50 values?
- Line 249: Could the downscaling approach not simply be evaluated by reconstructing high-resolution MODIS snow cover from the spatially aggregated pixels?
- It seems that you assume a seasonally stationary downscaling relation, i.e. there is no temporal dependency. Is this assumption valid? Or could the relation look slightly different for e.g. late autumn and spring?

Projected changes in snow cover fraction for different elevations

I'm surprised that the elevation gradients in Figure S12 are so distinctively different. Could this also be caused by the different RCM ensembles used for AMUNDSEN and the statistical approach (i.e. do different RCMs for instance show different elevation gradients in warming)? It is generally a bit counter-intuitive that the largest relative reduction in snow cover fraction is projected for the highest elevations (see Figure S10b and S12).

Minor comments

Content-related (text)

Line 15: With which bias adjustment method were these number computed?

L17: “The comparison of the statistical” → This evaluation confirms the robustness of the downscaling method → I would therefore mention it before presenting results for the future climate.

L19: The term “bias correction” is a bit outdated. Better use the term “bias adjustment” (see e.g. <https://cordex.org/data-access/bias-adjusted-rcm-data/> and <https://hypeweb.smhi.se/what-is-bias-adjustment/>)

L19: “plausible” might be a bit vague. Maybe better “more suitable” or “applicable”.

L37: I find it difficult to follow this sentence. Maybe it’s better to write “because climate change violates the assumption of stationarity” (if you mean that).

L53: “...and even snow depth” → this part seems to be a bit contradictory to the previous sentence. Snow depth is reproduced relatively well but SWE not?

L54: “gridded estimates of SWE” → You refer to data derived from in-situ measurements (and not models), right? If so, I would explicitly state this. Furthermore, I guess you want to allude to the spatial representativeness of different data sets (in-situ vs. remote sensing) here. If so, you could discuss this in an additional sentence here...

L61: “The reference observations can be points or grids, are often limited in extent compared to RCMs, and feature, in case of grids, typically higher resolutions.”

L82: “The motivation is that...” → this sentence is rather long and difficult to read – could you rephrase it? I furthermore do not understand the end “...while future change estimates should be consistent.” Consistent with what?

L84: “While bias correction...” → I don’t understand this sentence entirely. What is the link between absolute values and bias adjustment?

L118: Did you apply a nearly or entirely cloud-free data set in the end?

L119: What does “nominal” and “effective” resolution mean in this context?

L127: “all variables” → which variables do you mean?

L139: I was wondering – would it also be possible to account for the snow accumulation issue within the bias adjustment method?

L160: What do you mean by “single GCM-RCM biases”?

L171: I would be careful that the reader is not confusing calendar with hydrological years. I guess you conduct all your evaluations for hydrological years – right? Then I would state the definition of a hydrological year somewhere and mention, that all years refer to hydrological years – unless otherwise stated.

L175: I would remove “, usually 1970 – 2000”

L189: “also to the maximum of 1.” → this is oddly phrased. I guess values above 0.999 are set to 1.0, right?

L188: The trace condition was applied to the about of the Q(D)M algorithm - right?

L195: “breaks the temporal consistency in the bias corrected SNC time series” → what do you mean by that?

L260: What do you mean by “preferred”? Are trends only preserved for ratio variables?

L388: What do you mean by “analogue based”?

Typos, phrasing and stylistic comments

General: Both the terms grid cell and pixel are used. To avoid ambiguity, it would be good to use them consistently: You could for instance use grid cell exclusively for climate models and pixel for remote sensing data.

L22: remove “only”

L28: “consequences in water supplies” sound odd. Maybe rather “on”?

L31: maybe better “snow cover causes a significant atmospheric feedback due to its high albedo”

L50: “such as for” sounds a bit odd. Maybe better: “for instance in”

L51: “but also from biases in RCM snow cover.” I would rephrase this to something like: “but also from biases caused by the relatively simple snow schemes of RCMs.”

L67: I would rearrange this sentence to: “Since QM has been show to modify trends in a few cases, quantile delta mapping (QDM) was developed, which represents a trend-preserving QM approach.”

L77: “We restrict the study to snow cover fraction, which is, in contrast to snow depth and SWE, globally available on a high spatial resolution. The presented method has therefore a global potential for application.”

L82: “meteorology” → “output”

L88: I would replace “representation” by “pattern”. “Representation” can be ambiguous in this context (one could understand that snow cover representation in RCMs is improved).

L91: “is as” → “is structure as”

L95: The study region (Fig. 1) encompasses the European Alps and spans from ~43 – 48.5° N and ~5 – 17° E, which roughly corresponds to the Greater Alpine Region (Auer et al., 2007).

L133: “although snow depth match very good” → “although snow depths are well reproduced”

L172: “merged to” → “merged with”

L270: “under- and overestimating” → “simulated”

L305: change “lower ensemble” to “smaller ensemble”

L325: change “a more of a fully snow free and fully snow-covered grid cell over time” to “more often fully snow free or snow-covered conditions over time”

L363: I would not write “became” if you compare two hypothetical projections

L383: Change to: “In contrast, the final imputation step of SNCp50 is based on a simple elevational dependence of snow cover, and could thus directly be estimated from a low-resolution RCM signal.”

L396/397: “in low/higher elevations” → “at low/higher elevations”

L407: “meteorology” → “output” or “meteorological output”

L470: What do you mean by “two months short snow cover duration”? A shortening by two months?

L474: “lower horizontal spacing” → “higher horizontal spacing”

Figures and Tables

Figure 3: Why is there no line in the upmost row in column “DC”? Furthermore, are results shown in this figure computed with bias adjustment and downscaling (or only the former)?

Figure 6: Interestingly, the line for “bias correction” is closer to “AMUNDSEN” than “downscaling” in the rightmost panel. Can you explain this?

Table 1: I’m only partially convinced about the point “+ Consistent climate change signal of surface meteorology with snow cover”. This is true for the raw RCM output, but no longer for the bias corrected product.

Figure S1: Replace “snow plausible” in caption with e.g. “snow accumulation”

Figure S2: “surrounding” is a bit misleading in the caption – maybe better “aggregated”

Figure S11: caption line 2: “and downscaling.”

Figure S12: I guess the part in the squared brackets belongs to the figure caption?

Table S5: I’m not sure if the reference “See also Figure S6” is correct/intended.