Future snowfall in the Alps: Projections based on the EURO-CORDEX regional climate models

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- Response to Referees –

General

We thank the three referees for their careful revision of the manuscript and for their constructive comments. Please find below our replies to all major comments and our suggestions on how to address these issues in a revised manuscript. We hope that we satisfactorily addressed all referee comments and that the proposed changes are considered as being appropriate. In case that not, we'd be looking forward to discuss individual remaining issues in more detail.

As several referee comments addressed the RCM evaluation and the evaluation of the 2 km snowfall reference itself, we'd like to put in front the following two statements on the scope of the paper:

(1) Our work is primarily concerned with the analysis of future snowfall projections. However, a basic notion on the quality of raw RCM snowfall and, hence, the general ability of RCMs to represent our variable of interest is required for such an exercise in our opinion. In the manuscript this is accomplished by comparing RCM raw snowfall against site-scale measurements obtained from new snow sums (Figure 3). Such a comparison is subject to considerable uncertainties, mostly originating from the scale gap between RCM grid cells and site-scale observations and from representativity issues of observed snow cover. Due to a missing high-quality observational reference at the scale of the RCM resolution (in our opinion also the HISTALP dataset has its shortcomings; see below) we refrain from evaluating RCM snowfall in more detail and, at least when interpreting raw snowfall change signals, implicitly assume stationary model biases. As a consequence, the projection aspect of the current work is much larger than the evaluation aspect, and we tried to better clarify this issue by modifying the text in Chapters 1 and 3.1. Furthermore, we adjusted the title of the manuscript accordingly and removed the term "Evaluation".

(2) Relating to the previous issue but especially to the validation of the snowfall reference against which the RCM-derived snowfall is adjusted: As it was already mentioned in the introduction of the original manuscript, we do not claim to present an ultimate solution for bias-adjusting RCM-based snowfall but employ a spatially and temporally aggregated adjustment procedure that does nevertheless separately account for temperature and precipitation biases. Aspects of the snowfall climate that are not corrected for, such as details of the spatial snowfall pattern, are described in Sections 2.6 and 3.3. The simplifications also include the fact that we basically accept a non-perfect observation-based reference. A well-validated and appropriate reference does not exist in our opinion (see also above). The very core of our work is the analysis of projected future snowfall changes and the comparison of three different ways to produce such estimates: (1) Raw RCM snowfall, (2) RCM snowfall as separated from simulated temperature and precipitation, and (3) RCM snowfall as separated from simulated temperature and precipitation and additionally bias-adjusted. The latter version is the basic dataset for the climate scenario analysis as it can be constructed for all participating RCMs (raw snowfall is not available for all of them) and as it is, in principle, able to account for temperature-dependent and hence non-stationary snowfall biases. However, Chapter 5.3 shows that relative change estimates largely agree among all three datasets and are robust. From that point of view, the influence of remaining inaccuracies in the bias-adjusted snowfall projections due to inaccuracies of the reference is presumably small. In the revised version we now try to better clarify these issues by modifying Chapters 1, 2.5, 2.6 and 5.3.

Response to Referee #1

Comment *L. 65-66: replace "the GCM provides the lateral boundary conditions to the RCM" with "the GCM provides the lateral and sea surface boundary conditions to the RCM".*

Response and changes to manuscript Modified accordingly.

Comment *L. 88-89: the fact that "a gridded observational snowfall product that could serve as reference for RCM evaluation does not exist" is not a good reason for not using raw outputs, it can actually be evaluated as in Fig. 13 of this paper:*

Response and changes to manuscript You are perfectly right, thanks very much for pointing this out. The reason is indeed the non-availability of raw snowfall output in several experiments. We removed the second part of this sentence.

Comment *L. 133-135: the RCMs also have an effective resolution that is larger than their grid resolution, see e.g. Skamarock et al. (Mon. Wea. Rev. 2004), Lefèvre et al. (Mar. Pol. Bull. 2010).*

Response and changes to manuscript Thanks for pointing this out. We now use the term “nominal resolution of the available climate model data”, but would like to refrain from further discussing the even coarser effective resolution of climate models as we believe that this would distract the reader at this point.

Comment *L. 151: the authors should make clear that what they refer to as “control” is based on the CMIP5 historical simulations (not the one based on reanalyses).*

Response and changes to manuscript The fact that GCM-driven experiments are employed has already been mentioned several times in the respective paragraph. We slightly revised this paragraph now to make this point even clearer.

Comment *Section 2.2: it is worth mentioning that daily-averages from EURO-CORDEX are used (or specify what other time sampling/averaging is used).*

Response and changes to manuscript This point is mentioned now.

Comment *Fig. 1: which topography is shown?*

Response and changes to manuscript Thanks for this comment, this information was indeed missing so far. The topography shown is the GTOPO30 digital elevation model of the U.S. Geological Survey. The figure caption was adjusted accordingly. As GTOPO30 is also the basis for computing the topographical standard deviation σ_h for each RCM grid cell in the course of calibrating the Richards method we furthermore provide this information now in Section 2.5 of the manuscript and also added one sentence to the acknowledgments.

Comment *L.246-249: it is not clear to me why the explanation cannot be reversed: coarse cells with grid temperature lower than T* should overestimate snowfall at some locations covered by the cell, don’t they? If it’s not zero on average, is it because elevation distribution is generally skewed within the coarse cell?*

Response and changes to manuscript A skewed subgrid topography distribution might be one reason, but the main factor is probably the fact that precipitation-elevation gradients over many parts of the analysis domain are positive, i.e. higher total precipitation sums at higher (=colder) elevations. Snowfall separation on the high-resolution grid would therefore lead to higher spatially-averaged mean snowfall sums compared to the coarse-resolution version, hence a systematic non-zero difference of the two versions. We modified the respective text section in order to better clarify this point.

Comment *L. 463: I think that “Rhone Valley” would be more appropriate than “Western France”.*

Response and changes to manuscript Thanks a lot, we modified this sentence accordingly.

Comment *L. 485: typo “change sin”.*

Response and changes to manuscript Corrected.

Comment *Fig. 11: indicate what the grey area represents.*

Response and changes to manuscript We’re sorry, this information was mentioned in the text but not in the figure caption so far. The grey area represents the overall temperature interval at which snowfall occurs (light grey) as well as the preferred temperature interval for heavy snowfall to occur (dark grey). This information has been added to the figure caption now.

Comment *Section 5.3: that relative changes in snowfall from raw model outputs are very similar to separated and bias-corrected fields is a very interesting finding and should definitely be reported in the Abstract.*

Response and changes to manuscript You are perfectly right, thanks for pointing this out. One sentence on this finding has now been added to the abstract.

Comment *L.656-658: It is indeed a pity that no evaluation is performed based on datasets from other alpine countries. It would also help validate the overall methodology since the methods tuning is undertaken over the Swiss Alps.*

Response and changes to manuscript Following a suggestion of Referee #2 an additional comparison of the constructed reference snowfall against the HISTALP dataset has been added to the manuscript. Please see our replies to Referee #2 and Figure S5 of the revised manuscript. Please also see our general replies above concerning the importance of an accurate reference in the context of our study.

Response to Referee #2

Comment *First of all, in absence of a daily observational gridded snowfall dataset for the Alpine region the authors derive a dataset using daily temperatures and precipitation. They separate the snow fraction from the total precipitation using a fixed temperature threshold T*=2 C. While this method works fine with hourly data, it is probably weak when using data at daily scale. As the rest of the paper builds on the hypothesis that this snowfall dataset represents the ground truth (i.e. the hypothesis is used for the calculation of Richardson snowfall fraction fs,Ri ; for the bias correction of RCM snowfall fields) authors should provide some evidence that their snowfall dataset closely represent the real snowfall distribution.*

Response and changes to manuscript We are thankful for this comment. It relates to a detail of the manuscript where (1) we might have been misunderstood when laying out the scope and the objectives of the work, but where also (2) a proper comparison to other datasets was obviously missing. Please see our comments in the introduction of these replies concerning the scope and objectives of the work. In the revised manuscript we now try to make the point clear that our climate scenario assessment is, in the end, based on three different snowfall datasets that differ with respect to if and how the climate model data were postprocessed. Chapter 5.3 of the manuscript inter-compares the three approaches and concludes that at least for relative change signals the results are robust and do only slightly depend on the postprocessing strategy that is applied. The observation-based snowfall reference grid is used in two of these approaches, but not in the assessment based on raw RCM snowfall. The fact that all three estimates basically agree with each other in terms of relative change signals (which are the core of the paper) downweights the importance of the reference dataset for snowfall separation and bias-adjustment, and we can accept an only approximate reproduction of the (unknown) real snowfall climate. Concerning the evaluation of the reference snowfall grid the new manuscript version now includes a comparison to station-based fresh snow sums as well as a comparison to the HISTALP product. These additional analyses are part of the new sub-Chapter 3.2 “Evaluation of the reference snowfall”. Please see the replies below for further details. We hope these changes to the manuscript are considered appropriate.

Comment *In the Results (section 3.1) it comes really unexpected that the authors validate the RCM raw snowfall outputs by using 29 fresh-snow daily time series from MeteoSwiss stations. This dataset was not presented before and should be described in the “Observational datasets” section. Moreover this datasets is by definition “the” ground-truth, and I wonder why it comes out only at this point. It should be used for a detailed validation of the 2 km gridded snowfall product that you derive from temperature and precipitation fields. How the 2km gridded product compares to the fresh snow observations? Does it represent properly the snowfall climatology (mean, extremes) in correspondence of the stations? Does it represent the altitudinal gradient of mean/extreme snowfalls intensities? This information on the quality of the gridded reference dataset should be provided as it is necessary to set the basis for the whole methodology.*

and

Comment *Finally the RCM bias correction methods is calibrated on the area of Switzerland only and then applied to the whole Alpine region. This is justified by the authors with the lack of information on snowfall beyond the borders of Switzerland. Indeed previous efforts were made to derive a gridded snowfall dataset for the Alpine Region: HISTALP dataset provides monthly snowfall over the full Alpine domain, since 1800, at about 10 km spatial resolution, i.e. resolution comparable to the RCM gridsize (12 km). I believe this manuscript should include the HISTALP dataset in the analysis, in order to provide a comprehensive view on the reference datasets. In particular I would suggest to discuss i) how HISTALP compares with the stations and the 2km gridded dataset in the Swiss Alps; ii) if it is a good quality reference for validating the RCM snowfall outputs at monthly (or longer) time scales over the Swiss domain.*

Response and changes to manuscript Thank you very much for these detailed suggestions on improving the manuscript. We agree that a quality assessment of our 2 km snowfall reference has been missing so far. At the same time, however, a comparison against the station-based fresh snow sums is subject to considerable uncertainties as well (see our comments in the beginning of these replies and the new text section in Chapter 3.1). Furthermore, the bias-adjusted RCM snowfall (adjusted against the aggregated 2 km reference) is only one out of three estimates used for the snowfall projections. The three estimates yield rather similar results in terms of relative snowfall changes, which downweights the relevance of the specific reference used.

Altogether, we still agree that some quality assessment of the reference is helpful. For this purpose we introduced a new sub-Chapter 3.2 “Evaluation of reference snowfall”. This sub-Chapter includes a modification to the existing Figure 3 (additional comparison of the reference against the new snow observations at stations in terms of the mean snowfall climate) and a new supplementary Figure S5 (comparison against the monthly HISTALP dataset). Regarding the suggested evaluation of individual grid cells of the 2km gridded snowfall reference against the fresh snow sums at stations we refrain from including this analysis at a prominent place in the paper as little can be learned due to the remaining scale gap (2 km grid cells vs. site scale) and the problem of non-representativity of snow depth measurements in topographically structured terrain (see new text in Chapter 3.1). For your information, we however present this analysis in Figure R1 below. Despite the inherent uncertainties of the intercomparison, the 2 km snowfall reference and the site observations agree fairly well with each other in terms of climatological mean snowfall. This basic information is now also provided in the manuscript (Chapter 3.2) though without showing the figure.

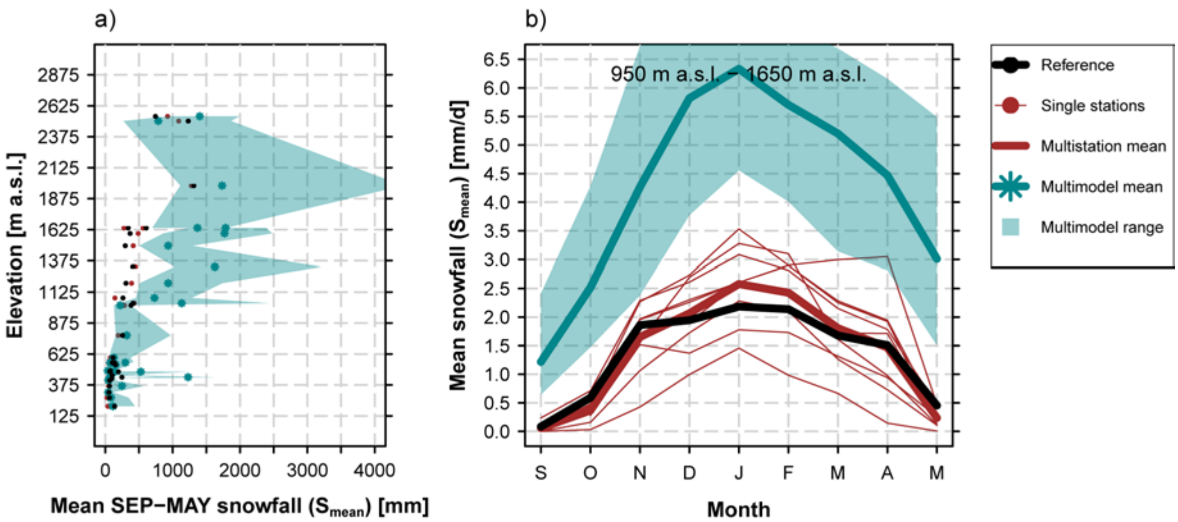

Figure R1: As Figure 3 of the revised manuscript but for the simulated data (green) and for the 2 km snowfall reference (black) only those grid cells that directly cover the 29 MeteoSwiss stations are considered.

Concerning the evaluation against HISTALP, a comparison of the 2 km reference as well as of the reference on the RCM grid (after applying the Richards equation) yields an approximate agreement. However, due to the method used to construct the HISTALP solid precipitation grid (application of monthly snowfall fraction factors to a spatially interpolated total precipitation grid) and the comparatively coarse station network considered for the total precipitation grid (192 stations) we believe that also the HISTALP reference is subject to considerable uncertainties and only a qualitative comparison is valid. The strength of HISTALP clearly lies in the long period covered, but not necessarily in spatial detail at high (daily) temporal resolution.

Following your suggestion, we now also introduce the station-based fresh snow sum dataset in Chapter 2.1.

Comment *P 7 L254: "We apply this regression to relate the surface temperature T to the snow fraction fs by accounting for the topographic subgrid variability. At each coarse gridpoint k, the Richards method-based snowfall fraction fs,RI for a given day is hence computed as follows ... First, we estimate the two parameters C and D of Equation 4 for each single coarse grid point k by minimizing the least-square distance to the fs values derived by the Subgrid method via the reference snowfall SSG (local fit)."*

The method used to separate snowfall with the temperature threshold T=2 C is effective with hourly data but it is crude when using daily data as it returns snowfall fraction fs=1 or fs=0 in a given day. This can be far from the reality, expecially at middle elevations (throughout the snow season) but also at high elevations in spring and autumn. The fs,RI depends on the C and D, and the latter are estimated assuming that fs is a good estimator of the solid precipitation fraction. But as said above fs is characterized by unknown uncertainty. You should prove that fs closely reproduce the real snowfall fraction, before applying your method for deriving fs,RI and your snowfall reference dataset. Minimum requirement is to provide a quantification of this error, using fresh snow manual observations in the 29 manual stations.*

Response and changes to manuscript Please see our replies above and at the beginning of the replies section. The 2 km reference snowfall grid is now approximately evaluated. However, your concerns are certainly right. Any binary method based on near-surface air temperature can only be an approximation of true snowfall. further presumably more accurate methods are listed by Steinacker (2013). But note that binary methods on daily scales are frequently used in the literature to separate snowfall from total precipitation, for instance in the hydrological and glaciological modelling community. A further example cited in the manuscript is the work of Zubler et al. (2014) who applied the same binary separation at a temperature threshold of 2°C.

Comment *P9 L317-321: "the initial snow fractionation temperature T*=2 C of the Richards separation method (see Sec 2.5) is shifted to the value T*a for which the spatially and temporally averaged simulated snowfall amounts for elevations below 2750 m a.s.l. match the respective observation-based reference."*

With this temperature correction you basically report the RCM snowfall to your reference. So, also in this case, before applying this procedure you need an evaluation of the error on your snowfall reference. Moreover, can you give details on how you calculate spatial and temporal averages, i.e. which domain/ time range?

Response and changes to manuscript Concerning the evaluation of the snowfall reference please see our replies above. Regarding the domain and time range, this information was actually provided two sentences afterwards (Swiss domain and September to May). In the revised manuscript we moved this information to the sentence you are referring to.

Comment P9 L327: *"Note that, as the underlying high-resolution data sets are available over Switzerland only, the calibration of the bias correction methodology is correspondingly restricted, but the correction is then applied to the whole Alpine domain." HISTALP dataset provides gridded snowfall monthly fields for the Alpine region at about 10 km spatial resolution (Chimani et al 2011), it should be included in the analysis and discussed in comparison to your reference/manual observations in Switzerland: Chimani, B., Böhm R., Matulla C., Ganekind M.: Development of a longterm dataset of solid/liquid precipitation Adv.Sci.Res,6,39-43, 2011http://www.adv-scires. net/6/39/2011/asr-6-39-2011.html*

Response and changes to manuscript Please see our replies above. HISTALP is now used to approximately validate both the 2 km and the 0.11° snowfall reference. The paper of Chimani et al. is cited now. Thanks for pointing us to this dataset (of which we have not been aware)!

Comment *P10 L338-341: "EURO-CORDEX simulations ... are compared against observations derived from measured fresh snow sums from 29 Meteo Swiss stations with data available for at least 80% of the evaluation period. For this purpose a mean snow density of 100 kg/m3 for the conversion from measured snow height to water equivalent is assumed."*

As said before, I am surprised to see at this point of the paper that you have 29 fresh snowfall time series covering the 1970-2005 period. They should be presented before (section 3.1) & exploited much more than you do. These manned observations are the ground truth and they should be used to validate the snowfall gridded dataset that you derive from temperature and precipitation over Switzerland. Please provide a quality control of the snowfall gridded dataset prior to use it

Response and changes to manuscript Please see our replies above. The comparison against fresh snow sums can only be of approximate nature and is subject to large uncertainties. See the additional text in Chapter 3.1. We'd refrain from considering these data as the "ground truth". These data are now introduced in Chapter 2.1 along with gridded observational data. They are also employed to approximately validate the 2 km and 0.11° snowfall reference grid.

Comment *P10 L345-347: "The positive bias at high elevations might arise from the fact that the very few observations were made at a specific location while simulated grid point values of the corresponding elevation interval might be located in different areas of Switzerland." Here you consider all Switzerland and you really mix very different areas far away one from another. Please discuss the case when only the gridpoints containing stations are considered, i.e. showing the spread of the models around the observed time series (i.e. in plots for the three - low, middle and high - elevation ranges?*

Response and changes to manuscript Please see our replies above and Figure R1. In our opinion such a comparison is subject to large uncertainties, mainly due to the mismatch of spatial representativeness between an individual grid cell and an individual site. By design, such an evaluation can only be of approximate nature. See also the additional text in Chapter 3.1 on the limitations of such a comparison. In our opinion, averaging over elevation intervals and showing the respective spread (which covers or does not cover the site-scale observations) is clearly the safer option.

Comment *P14 L487: "In between is a transition zone with rather strong changes with elevation". Can you explain why?*

Response and changes to manuscript This transition approximately corresponds to the mean elevation of the SEP-MAY zero-degree line in today's climate. We added this information to the manuscript plus two additional references. Elevations close to this line seem to be especially sensitive, which is in line with previous works addressing future snow cover changes.

Comment *P14 L494-6: Could it also be residual biases along the snowfall line?*

Response and changes to manuscript We do not think so, as further analyses (see above; comparison of the three approaches) indicate a robust relative climate change signal also at low elevations, no matter if raw (and hence biased), separated or separated + bias-adjusted snowfall is analyzed.

Comment *P16 L587-8: Given more precipitation at high elevation & temperatures more favorable to heavy snowfalls, why does the snowfall frequency decrease?*

Response and changes to manuscript This is explained in the brackets at the end of this sentence: The light grey range (which is now explicitly mentioned in the caption of Figure 11) represents the temperature interval below 2°C, i.e. approximately the interval where snowfall occurs at all (neglecting subgrid-scale effects and assuming a binary threshold). Due to the general shift of the temperature distribution to the right (to higher temperatures) the fraction underneath the red curve (scenario period) that falls into this interval is much smaller than the one underneath the blue curve (control climate). This is equivalent to a decrease of the total snowfall frequency, despite potential precipitation increases and higher mean snowfall intensities.

Further technical corrections

Response and changes to manuscript Thank you very much for these additional comments and ideas. All suggested further technical corrections were implemented with the exception of: (1) P3 L79 "low" to "lower" (which is not meaningful in our opinion), (2) suggested changes to Figure 6 (an important point here is the differing spatial distribution of mean snowfall, this would not be apparent in figures of anomaly wrt. the reference), (3) P8 L280 (the respective text section refers to the Richards method, here the spread is indeed +/- 0.1 at maximum) and (4) Figure 11 (this figure is schematic only, low and high elevations are not defined in detail).

Response to Referee #3

Comment *Half-way the introduction (lines 75-80) the authors write " Within the last few years …" followed by "Most of these analyses are based on GCM output or older generations of RCM ensembles at comparatively low spatial resolution : : :". This may indeed be the case for most of the* *studies cited in the sentence before, but not for all of them, and the authors should specify explicitly which of them is the exception, and how that study. compares with their work. E.g. Piazza et al. use, amongst other models, a number of RCMs operated at 12 km resolution, the study by de Vries et al. (2014) is based on a 8-member ensemble of EC-EARTH-RACMO simulations at 12km resolution (historical and rcp8.5) configured on a smaller domain, but in principle quite comparable to the simulations used in this paper.*

Response and changes to manuscript You are perfectly right, thanks for pointing this out. We added further information on the existing RCM-based studies in this section. Furthermore, reference to the mentioned works had already been given in the conclusions of the original manuscript.

Comment *Instead of using "bias correction" I would strongly recommend to use the phrase "bias adjustment" as was also the adopted terminology by the EURO-CORDEX community. The word "correction" suggests there is a well-established methodology including a ground truth observed state which we all agree on. This is obviously not the case. It is therefore much better to use the word "adjustment" which automatically triggers the questions "how" and "to what" or "in which context" as it should be.*

Response and changes to manuscript We are aware of the current discussion on this issue and basically agree with the referee's suggestion. There are pros and cons to it, however. The term "bias correction" is currently used and better understood by a wider community and is also better reflected by the available literature. But exactly due to the points mentioned we agree that "bias adjustment" is the more suitable term. We therefore changed "bias correction" ("bias-corrected") to "bias adjustment" ("bias-adjusted") throughout the entire manuscript. This also involves modifications to the legend of Figure 13. Accordingly, we also changed "RCM_{sep+bc}" ("$RCM_{sep+nbc}$") to "RCM_{sep+ba}" ("$RCM_{sep+nba}$"). In Chapter 2.6 we include the following sentence outlining the reasons behind the choice of the term: "Note that we deliberately employ the term bias adjustment as opposed to bias correction to make clear that only certain aspects of the snowfall climate are adjusted and that the resulting dataset might be subject to remaining inaccuracies."

Comment *In section 2.2 it is mentioned that all GCM-driven EUR-11 simulations for which control, RCP4.5 and RCP8.5 runs are currently available have been included in the study. This can obviously not be a correct state of affairs. Currently means "at the moment" and since the number of simulations published in the ESGF-archive is still growing, there will be a moment that the statement is no longer true. In fact, already in October 2016 there were 16 simulations that met the criteria set by the authors. In addition to the their selection there were results published from HadGEM2-RACMO and MPI-ESM (r2i1p1)-REMO. In April 2016, none of the two MPI-ESM-REMO simulations were available, but the HadGEM2-RACMO simulation was, albeit based on version v1 which was replaced by version v2 in August 2016. So, a) you need to specify currently, and b), either include the simulations that were in the archive but not in your selection, or convincingly explain why some simulations were not selected.*

Response and changes to manuscript You are completely right, thanks for pointing this out. We're now providing the date on which the ESGF database was accessed for the purpose of this paper. And we also provide the reasons for not including two of the available experiments. HadGEM2-RACMO was disregarded due to serious snow accumulation issues over the Alps with obvious feedbacks on temperature (which is used in the snowfall separation process). MPIM-REMO realization 2 was disregarded as our purpose was to assess model uncertainty by employing an ensemble analysis and not internal climate variability (realization 1 is contained in our ensemble, see also footnote of Table 1 in the original manuscript).

Comment *Following the previous point, it is important mentioning that three different realizations of ICHEC-EC-EARTH are used to force four different RCMs: r12i1p1 is used to force CCLM and RCA, r3i1p1 is used for HIRHAM, and r1i1p1 for RACMO. Different realizations of a GCM can show distinct behavior owing to long-term large-scale natural variability implying that differences between the EC-EARTH forced RCM simulations are not only due to differences in the RCMs. This would only hold for the CCLM end RCA simulations forced with r12i1p1. Please, mention this aspect when introducing the 14 GCM-RCM chains.*

Response and changes to manuscript Thanks a lot, this fact is now mentioned in the Caption of Table 1. It is, however, of minor importance for the present study, as for instance the influence of the driving GCM is not analyzed in detail but only mentioned at one point in the manuscript.

Comment *In section 2.5 the methodology to separate snowfall from total precipitation is discussed (Richards method). In the final paragraph a parametric formulation fs,Ri is introduced (Eqs 4-7) to express the snowfall fraction in terms of coarse-grid temperature Tk, the topographic standard deviation h of the designated grid cell, and a number of constants (E,F,G,H) which are determined through an empirical fitting procedure. The function fs,Ri is meant to be used to separate snowfall in the RCMs as well (line 282-283). Since the subgrid-scale orographic variance parameter of the model orography is not known (at least this parameter is not in the ESGF-archive) I presume the authors have used h from the observational dataset. Somehow the observational h and model height should match. This is not guaranteed a priori. The authors already mention that orography fields from different RCMs can be quite different from each other, and from the observations (line 157-159). The authors should explain how they deal with such mismatches.*

Response and changes to manuscript The origin of the "observed" high resolution topography (GTOPO30) is now properly referenced. This information was indeed missing so far. Concerning a potential mismatch between mean grid cell topography of the RCM and mean grid cell topography as obtained from GTOPO30 we do not believe that this leads to any problem. The parameterizations in the Richard method rely on topographic variance at a subgrid level only, not on mean topography. We assume that this variance is properly represented by GTOPO30. In any case, the relation is later on fitted again (see Figure S1). Whether the models internally work with a similar topographic variance or not is not relevant here in our opinion. Nevertheless we now explicitly mention this apparent and potential mismatch of mean orographies in Section 2.5.

Comment *In section 2.6 the bias adjustment approach is discussed. I was surprised to see that after the detailed treatment of snowfall separation, the adjustment of temperature has been dealt with so crudely. While according to Fig S4 the temperature bias considerably depends on elevation the authors have chosen the shifted fractionation temperature to be independent of elevation. According to Fig 4 the adjusted fractionation temperature and the temperature bias (one point per GCM-RCM realization) show considerable scatter around a linear relation, but it is not at all clear and also not explained what causes this scatter. It might be due to bias depending to elevation, but also to month of the year and/or region. Or is there something else? The authors should discuss their treatment of shifting the fractionation temperature in more detail, it is particularly relevant because the snow fractionation temperature appears to be a crucial, and probably also a sensitive, parameter in the analysis.*

Response and changes to manuscript Thanks very much for pointing out this issue. We agree that our bias correction is approximate only. For instance, it only targets spatially and temporally averaged mean snowfall but not the spatial pattern (see Figure 6). These limitations are actually mentioned. More sophisticated methods can be thought of, but bear the danger of overparameterisation and often require a more accurate observational reference. The bias adjustment of snowfall in the frame of the present paper is only one of three postprocessing methods (in addition to raw = no postprocessing and separation only but no bias adjustment). See also our replies in the very beginning of this document. In the end, we find that relative change signals of snowfall indices closely agree no matter what the postprocessing is. Concerning the adjustment of the fractionation temperature: the bulk adjustment for the entire domain is mainly based on our target (domain mean snowfall). Adjusting separately for individual elevation intervals might be a better account of elevation-dependent temperature biases but would probably over-interpret the uncertain snowfall reference in terms of its elevation dependency. This is mentioned now in the revised version of the manuscript (Section 2.6). Regarding the relation between mean temperature bias and adjusted fractionation temperature: There are several potential reasons for deviations from a linear relation. In addition to the ones mentioned in your comments, also differences in daily temperature variability or in the bivariate temperature-precipitation distribution can be thought of. In the revised manuscript we now mention potential reasons in more detail.

Comment *Line 565-566: The sentence "Previous studies : : : with this theory (e.g. Allen and Ingram, 2002; Ban et al. 2015)" is completely out of context. I strongly suggest to omit this sentence and the corresponding references. The focus of the Ban et al. paper is on summertime convectively driven sub-daily (hourly) precipitation extremes and its relation with temperature. This is miles away from the Sq99 and S1d snowfall parameters used in this paper to indicate heavy (but not extreme) snowfall at the daily scale outside the summer season.*

Response and changes to manuscript It is certainly true that we neither deal with sub-daily extremes nor with the very tail of the daily snowfall distribution. However, we still believe that this information is relevant and not out of context as is presents general evidence for applicability of the C-C-relation concerning precipitation extremes. We'd therefore like to refrain from removing this sentence, but tried to better clarify the fact that different variables are addressed in the cited works.

Further minor comments

Response and changes to manuscript Thank you very much for these additional comments and ideas! All suggested further minor corrections were implemented with the exception of comment 28 (Sorry, this one is not clear to us) and comment 29 (If left up to us, we'd prefer to stick to the current color scheme which is intuitive in our opinion and still allows to grasp the important characteristics of the spatial distribution).

Further changes to the manuscript

Chapter 2.1 "Observational data" For reasons of completeness we additionally included the information that the temperature and precipitation grids employed are slightly shifted with respect to their reference time interval (midnight UTC - midnight UTC for temperature, 06 UTC - 06 UTC for precipitation).

Chapter 2.2 "Climate model data" In the last paragraph we erroneously spoke of *six* RCMs considered. We corrected this to *seven* RCMs.

Chapter 3.1 To better account for uncertainties in this simplified evaluation we now additionally cite the work of Grünewald and Lehning (2015) that highlights the danger of non-representativity of single-site snow depth observations in Alpine terrain.

Figure 3 In the left panel two of the 29 stations employed (WFJ and MVE) were plotted at a wrong elevation in the original version. For both stations the correct elevation differs by about 100 m from the previously used elevation. The figure has been corrected accordingly, in addition to the modifications to this figure mentioned above. The conclusions of the analysis do not change.

Overall manuscript Several minor spelling and wording mistakes as well as an inconsistent use of past and present tense were corrected.

Future s~~S~~nowfall in the Alps: ~~Evaluation and~~ ~~p~~Projections based on the EURO-CORDEX regional climate models

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Abstract. Twenty-first century snowfall changes over the European Alps are assessed based on high-resolution regional climate model (RCM) data made available through the EURO-CORDEX initiative. Fourteen different combinations of global and regional climate models with a target resolution of 12 km, and two different emission scenarios are considered. As raw snowfall amounts are not provided by all RCMs, a~~A~~ newly developed method to separate snowfall from total precipitation based on near-surface temperature conditions and accounting for subgrid-scale topographic variability is employed. The evaluation of the simulated snowfall amounts against an observation-based reference indicates the ability of RCMs to capture the main characteristics of the snowfall seasonal cycle and its elevation dependency, but also reveals considerable positive biases especially at high elevations. These biases can partly be removed by the application of a dedicated RCM bias ~~correction~~ adjustment that separately considers temperature and precipitation biases.

Snowfall projections reveal a robust signal of decreasing snowfall amounts over most parts of the Alps for both emission scenarios. Domain and multi-model -mean decreases of mean September-May snowfall by the end of the century amount to -25% and -45% for RCP4.5 and RCP8.5, respectively. Snowfall in low-lying areas in the Alpine forelands could be reduced by more than -80%. These decreases are driven by the projected warming and are strongly connected to an important decrease of snowfall frequency and snowfall fraction and are also apparent for heavy snowfall events. In contrast, high-elevation regions could experience slight snowfall increases in mid-winter for both emission scenarios despite the general decrease of the snowfall fraction. These increases in mean and heavy snowfall can be explained by a general increase of winter precipitation and by the fact that, with increasing temperatures, climatologically cold areas are shifted into a temperature interval which favours higher snowfall intensities. In general, percentage changes of snowfall indices are robust with respect to the RCM postprocessing strategy employed: Similar results are obtained for raw, separated and separated + bias-adjusted snowfall amounts. Absolute changes, however, can differ among these three methods.

1 Introduction

Snow is an important resource for the Alpine regions, be it for tourism, hydropower generation, or water management (Abegg et al., 2007). According to the Swiss Federal Office of Energy (SFOE) hydropower generation accounts for approximately 55% of the Swiss electricity production (SFOE, 2014). Consideration of changes in snow climatology needs to address aspects of both snow cover and snow~~-~~fall. In the recent past, an important decrease of the mean snow cover depth and duration in the Alps was observed (e.g, Laternser and Schneebeli, 2003; Marty, 2008; Scherrer et al., 2004). ~~Future p~~Projections of future snow cover changes based on ~~using~~ climate model simulations ~~of the anthropogenic greenhouse effect~~ indicate a further substantial reduction (Schmucki et al., 2015a; Steger et al., 2013), strongly linked to the expected rise of temperatures (e.g., CH2011, 2011; Gobiet et al., 2014). On regional and local scales rising temperatures exert a direct influence on snow cover in two ways: First, total snowfall sums are expected to decrease by a ~~decreasing~~ lower probability for precipitation to fall as snow implying ~~and~~ a decreasing snowfall fraction (ratio between solid and total precipitation). Second, snow on the ground is subject to faster and accelerated melt. These warming-induced trends might be modulated by changes in atmospheric circulation ~~statistics~~patterns.

Although the snowfall fraction is expected to decrease ~~at lower elevations~~ during the 21st century (e.g., Räisänen, 2016)~~,~~ extraordinary snowfall events can still leave a trail of destruction. A recent example was the winter 2013/2014 with record-breaking heavy snowfall events along the southern rim of the European Alps (e.g., Techel et al., 2015). The catastrophic effects of heavy snowfall range from avalanches and floods to road or rail damage. In extreme cases these events can even result in the weight-driven collapse of buildings or loss of human life (Marty and Blanchet, 2011). Also mean snowfall conditions, such as the mean number of snowfall days in a given period, can be of high relevance for road management (e.g. Zubler et al., 2015) or airport operation. Projections of future changes in ~~the~~ snowfall~~ climate~~, including mean and extreme conditions, are therefore highly relevant for long-term planning and adaptation purposes in order to assess and prevent related socio-economic impacts and costs.

21st century climate projections typically rely on climate models. For large-scale projections, global climate models (GCMs) with a rather coarse spatial resolution of 100 km or more are used. ~~For assessing~~ To assess regional to local scale impacts, where typically a much higher spatial resolution ~~of the projections~~ is required, a GCM can be dynamically downscaled by nesting a regional climate model (RCM) over the specific domain of interest (Giorgi, 1990). In such a setup, the GCM provides the lateral and sea surface boundary conditions to the RCM. One advantage of climate models is the ability to estimate climate change in a physically based manner under different greenhouse gas (GHG) emission scenarios. With the Intergovernmental Panel on Climate Change's (IPCC) release of the Fifth Assessment Report (AR5; IPCC, 2013) the so-called representative concentration pathway (RCP) scenarios have been introduced (Moss et al., 2010) which specify GHG concentrations and corresponding emission pathways for several radiative forcing targets. To estimate inherent projection uncertainties, ensemble approaches employing different climate models, different greenhouse gas scenarios, and/or different initial conditions are being used (e.g., Deser et al., 2012; Hawkins and Sutton, 2009; Rummukainen, 2010).

Within the last few years several studies targeting the future global and European snowfall evolution based on climate model ensembles were carried out (e.g., de Vries et al., 2013; de Vries et al., 2014; Krasting et al., 2013; O'Gorman, 2014; Piazza et al., 2014; Räisänen, 2016; Soncini and Bocchiola, 2011). Most of these analyses are based on GCM output or older generations of RCM ensembles at comparatively low spatial resolution, which are not able to properly resolve snowfall events over regions with complex topography. New generations of high resolution RCMs are a first step toward an improvement on this issue. This is in particular true for the most recent high-resolution regional climate change scenarios produced by the global CORDEX initiative (Giorgi et al., 2009) and its European branch EURO-CORDEX (Jacob et al., 2014). The present work aims to exploit this recently established RCM archive with respect to future snowfall conditions over the area of the European Alps. It thereby complements the existing works of Piazza et al. (2014) and de Vries et al. (2014) who among others also exploit comparatively high-resolved RCM experiments (partly originating from EURO-CORDEX as well) but with a reduced ensemble size and/or not specifically targeting the entire Alpine region.

In general and on decadal to centennial time scales, two main drivers of future snowfall changes over the European Alps with competing effects on snowfall amounts are apparent from the available literature: (1) Mean winter precipitation is expected to increase over most parts of the European Alps and in most EURO-CORDEX experiments (e.g., Rajczak et al., in prep.; Smiatek et al., 2016) which in principle could lead to higher snowfall amounts. (2) Temperatures are projected to considerably rise throughout the annual cycle (e.g., Gobiet et al., 2014; Smiatek et al., 2016; Steger et al., 2013) with the general effect of a decreasing snowfall frequency and fraction, thus potentially leading to a reduction in overall snowfall amounts. Separating the above two competing factors is one of the targets of the current study. A potential complication is that changes in daily precipitation frequency (here events with precipitation > 1 mm/day) and precipitation intensity (average amount on wet days) can change in a counteracting manner (e.g., Fischer et al., 2015; Rajczak et al., 2013), and that relative changes are not uniform across the event category (e.g. Ban et al., 2015; Fischer and Knutti, 2016).

We here try to shed more light on these issues by addressing the ~~By covering both model evaluation and high-resolution future snowfall projections we are addressing the~~ following main objectives:

Snowfall separation on an ~~(coarse resolution)~~ RCM grid. Raw snowfall outputs are not available for all members of the EURO-CORDEX RCM ensemble ~~and, furthermore, a gridded observational snowfall product that could serve as reference for RCM evaluation does not exist~~. Therefore, an adequate snowfall separation technique, i.e., the derivation of snowfall amounts based on readily available daily near-surface air temperature and precipitation data, is required. Furthermore, ~~as the observational and simulated grids of the two latter variables are typically not available at the same horizontal resolution,~~ we seek for a snowfall separation method that accounts for the topographic subgrid-scale variability of snowfall on the ~~the coarser (~~RCM~~)~~ grid.

Snowfall bias ~~correction~~adjustment. Even the latest generation of RCMs is known to suffer from systematic model biases (e.g., Kotlarski et al., 2014). In GCM-driven setups as employed within the present work these might partly be inherited from the driving GCM. To remove such systematic model biases in temperature and precipitation, a simple bias ~~correction~~ adjustment method~~ology~~ is ~~will be~~ developed and employed in the present work. To assess its performance and applicability, different snowfall indices in the bias-~~corrected~~ adjusted and not bias-~~corrected~~ adjusted output are ~~will be~~ compared against observation-based~~al~~ estimates.

Snowfall projections for the late 21st century. Climate change signals for various snowfall indices over the Alpine domain and for specific elevation intervals, derived by a comparison of 30-year control and scenario periods, are ~~will be~~ analysed under the assumption of the RCP8.5 emission scenario. In addition, we aim to identify and quantify the main drivers of future snowfall changes and, in order to assess emission scenario uncertainties, compare RCP8.5-based results with experiments assuming the more moderate RCP4.5 emission scenario. Snowfall projections are generally based on three different datasets: (1) raw RCM snowfall where available, (2) RCM snowfall separated from simulated temperature and precipitation, and (3) RCM snowfall separated from simulated temperature and precipitation and additionally bias-adjusted. While all three estimates are compared for the basic snowfall indices in order to assess the robustness of the projections, more detailed analyses are based on dataset (3) only.

In addition and as preparatory analysis, we carry out a basic evaluation of RCM-simulated snowfall amounts. This evaluation, however, is subject to considerable uncertainties as a high-quality observation-based reference at the required spatial scale is not available, and the very focus of the present work is laid on the snowfall projection aspect.

~~On centennial time scales, two main drivers of future snowfall changes over the European Alps with competing effects on snowfall amounts are apparent: (1) Mean winter precipitation is expected to increase over most parts of the European Alps and in most EURO-CORDEX experiments (e.g., Rajczak et al., in prep.; Smiatek et al., 2016) which in principle could lead to higher snowfall amounts. (2) Temperatures are projected to considerably rise throughout the annual cycle (e.g., Gobiet et al., 2014; Smiatek et al., 2016; Steger et al., 2013) with the general effect of a decreasing snowfall frequency and fraction, thus potentially leading to a reduction in overall snowfall amounts changes. Separating the above two competing factors is one of the targets of the current study. A potential complication is that changes in daily precipitation frequency (here events > 1 mm/day) and precipitation intensity (average amount on wet days) can change in a counteracting manner (e.g., Fischer et al., 2015; Rajczak et al., 2013), and that relative changes are not uniform across the event category (e.g. Ban et al., 2015; Fischer and Knutti, 2016).~~

The article is structured as follows: Section 2 describes the data used and methods employed. In Sections 3 and 4 results of the bias ~~correction~~ adjustment approach and snowfall projections for the late 21st century are shown, respectively. The latter are further discussed in Section 5 while overall conclusions and a brief outlook are provided in Section 6. Additional supporting figures are provided in the supplementary material (prefix ‘S’ in Figure numbers).

2 Data and methods

2.1 Observational data

To estimate observation-based snowfall, two gridded data sets, one for precipitation and one for temperature, derived from station observations and covering the area of Switzerland are used. Both data sets are available on a daily basis with a horizontal resolution of 2 km for the entire evaluation period 1971-2005 (see Sec. 2.3).

The gridded precipitation data set (RhiresD) represents a daily analysis based on a high-resolution rain-gauge network (MeteoSwiss, 2013a) consisting of more than 400 stations ~~which has~~ that have a balanced distribution in the horizontal but under-represent~~s~~ high altitudes (Frei and Schär, 1998; Isotta et al., 2014; Konzelmann et al., 2007). Albeit the data set's resolution of 2 km, the effective grid resolution as represented by the mean inter-station distance is about 15 - 20 km and thus comparable to the nominal resolution of the available climate model data (see Sec. 2.2). The dataset has not been corrected for the systematic measurement bias of rain gauges (e.g., Neff, 1977; Sevruk, 1985; Yang et al., 1999).

The gridded near-surface air temperature (from now on simply referred to as *temperature*) data set (TabsD) utilises a set of approx. 90 homogeneous long-term station series (MeteoSwiss, 2013b). Despite the high quality of the underlying station series, errors might be introduced by unresolved scales, an uneven spatial distribution and interpolation uncertainty (Frei, 2014). The unresolved effects of land cover or local topography, for instance, probably lead to an underestimation of spatial variability. ~~Another problem arises in inner Alpine valleys, where the presence of cold air pools is systematically overestimated.~~Also note that, while RhiresD provides daily precipitation sums aggregated from 6 UTC to 6 UTC of the following day, TabsD is a true daily temperature average from midnight UTC to midnight UTC. Due to a high temporal autocorrelation of daily mean temperature this slight inconsistency in the reference interval of the daily temperature and precipitation grids is expected to not systematically influence our analysis.

In addition to the gridded temperature and precipitation datasets and in order to validate simulated raw snowfall amounts station-based observations of fresh snow sums (snow depth) at daily resolution from 29 stations in Switzerland with data available for at least 80% of the evaluation period 1971-2005 are employed.

2.2 Climate model data

In terms of climate model data we exploit a recent ensemble of regional climate projections made available by EURO-CORDEX (www.euro-cordex.net), the European branch of the World Climate Research Programme's CORDEX initiative (www.cordex.org; Giorgi et al., 2009). RCM simulations for the European domain were run at a resolution of approximately 50 km (EUR-44) and 12~~.5~~ km (EUR-11) with both re-analysis boundary forcing (Kotlarski et al., 2014; Vautard et al., 2013) and GCM-forcing (Jacob et al., 2014). We here disregard the reanalysis-driven experiments and employ the ~~The latter include~~ GCM-driven simulations only. These include historical control simulations and future projections based on RCP greenhouse gas and aerosol emission scenarios. Within the present work we employ daily averaged model output of all except two [1]GCM-driven EUR-11 simulations for which control, RCP4.5 and RCP8.5 runs ~~are currently~~ were available in December 2016. This yields a total set of 14 GCM-RCM model chains, combining five driving GCMs with seven different RCMs (Tab. 1). We exclusively focus on the higher resolved EUR-11 simulations and disregard the coarser EUR-44 ensemble due to the apparent added value of the EUR-11 ensemble with respect to regional-scale climate features in the complex topographic setting of the European Alps (e.g., Giorgi et al., 2016; Torma et al., 2015).

It is important to note that each of the seven~~six~~ RCMs considered uses an individual grid cell topography field. Model topographies for a given grid cell might therefore considerably differ from each other, and also from the observation-based orography. Hence, it is not meaningful to compare snowfall values at individual grid cells since the latter might be situated at different elevations. Therefore, most analyses of the present work were carried out as a function of elevation, i.e., by averaging climatic features over distinct elevation intervals.

2.3 Analysis domain and periods

The arc-shaped European Alps - with a West-East extent of roughly 1200 km , a total of area 190'000 km^2 and a peak elevation of 4810 m a.s.l. (Mont Blanc) - are the highest and most prominent mountain range which is entirely situated in Europe. In the present work, two different analysis domains are used. The evaluation of the bias ~~correction~~ adjustment approach depends on the observational data sets RhiresD and TabsD (see Sec. 2.1). As these cover Switzerland only, the evaluation part of the study (Sec. 3) is constrained to the Swiss domain (Fig. 1, bold line). For the analysis of projected changes of different snowfall indices (Sec. 4 and 5) a larger domain covering the entire Alpine crest with its forelands is considered (Fig. 1, coloured region).

Our analysis is based on three different time intervals. The evaluation period (EVAL) 1971-2005 is~~was~~ used for the calibration and validation of the bias ~~correction~~ adjustment approach. Future changes of snowfall indices are ~~were~~ computed by comparing a present~~-~~day control period (1981-2010, CTRL) to a future scenario period at the end of the 21st century (2070-2099, SCEN). For all periods (EVAL, CTRL and SCEN), the summer months June, July and August (JJA) are excluded from any statistical analysis. In addition to seasonal mean snowfall conditions, i.e., averages over the nine-month period from September to May, we also analyse the seasonal cycle of individual snowfall indices at monthly resolution.

2.4 Analysed snowfall indices and change signals

A set of six different snowfall indices is considered (Tab. 2). Mean snowfall (S_{mean}) refers to the (spatio-) temporally-averaged snowfall amount in mm SWE (note that from this point on we will use the term "mm" as a synonym for "mm SWE" as unit of several snowfall indices). The two indices heavy snowfall (S_{q99}) and maximum 1-day snowfall (S_{1d}) allow the assessment of projected changes in heavy

[1] The HadGEM2-RACMO experiments were excluded due to serious snow accumulation issues over the European Alps. Furthermore, only realization 1 of MPI-M-REMO was included in order to avoid mixing GCM-RCM sampling with pure internal climate variability sampling.

snowfall events and amounts. S_{1d} is derived by averaging maximum 1-day snowfall amounts over all individual months/seasons of a given time period (i.e., by averaging 30 maximum values in the case of the CTRL and SCEN period), while S_{q99} is calculated from the grid point-based 99th all-day snowfall percentile of the daily probability density function (PDF) for the entire time period considered. We use all-day percentiles as the use of wet-day percentiles leads to conditional statements that are often misleading (see the analysis in Schär et al. 2016). Note that the underlying number of days differs for seasonal (September-May) and monthly analyses. Snowfall frequency (S_{freq}) and mean snowfall intensity (S_{int}) are based on a wet-day threshold of 1 mm/day and provide additional information about the distribution and magnitude of snowfall events, while the snowfall fraction (S_{frac}) describes the ratio of solid precipitation to total precipitation. As climate models tend to suffer from too high occurrence of drizzle and as small precipitation amounts are difficult to measure, daily precipitation values smaller or equal to 0.1 mm were ~~initially~~ set to zero in both the observations and the simulations prior to the remaining analyses.

Projections are assessed by calculating two different types of changes between the CTRL and the SCEN period. The absolute change signal (∆) of a particular snowfall index X (see Tab.2)

$$\Delta X = X_{SCEN} - X_{CTRL} \quad (1)$$

and the relative change signal (δ) which describes the change of the snowfall index as a percentage of its CTRL period value

$$\delta X = \left(\frac{X_{SCEN}}{X_{CTRL}} - 1\right) \cdot 100 \quad (2)$$

To prevent erroneous data interpretation due to possibly~~e~~ large relative changes of small CTRL values, certain grid boxes were masked out before calculating and averaging the signal of change. This filtering was done by setting threshold values for individual indices and statistics (see Table 2).

2.5 Separating snowfall from total precipitation

Due to (a) the lack of a gridded observational snowfall data set and (b) the fact that not all RCM simulations available through EURO-CORDEX provide raw snowfall as an output variable, a method to separate solid from total precipitation depending on near-surface temperature conditions is developed. ~~This method also allows for a more physically-based bias correction of simulated snowfall amounts (see Sec. 2.6). Due to the temperature dependency of snowfall occurrence, snowfall biases of a given climate model cannot be expected to remain constant under current and future (i.e., warmer) climate conditions. For instance, a climate model with a given temperature bias might pass the snow-rain temperature threshold earlier or later than reality during the general warming process. Hence, traditional bias correction approaches based only on a comparison of observed and simulated snowfall amounts in the historical climate would possibly fail due to a non-stationary bias structure.~~

The simplest approach to separate snowfall from total precipitation is to fractionate the two phases binary by applying a constant snow fractionation temperature (e.g., de Vries et al., 2014; Schmucki et al., 2015a; Zubler et al., 2014). More sophisticated methods estimate the snow fraction f_s dependence on air temperature with linear or logistic relations (e.g., Kienzle, 2008; McAfee et al., 2014). In our case, the different horizontal resolutions of the observational (high resolution of 2 km) and simulated (coarser resolution of 12 km) data sets further complicate a proper comparison of the respective snowfall amounts. Thus, we explicitly analysed the snowfall amount dependency on the grid resolution and exploited possibilities for including subgrid-scale variability in snowfall separation~~ based on coarse grid information~~. This approach is important as especially in Alpine terrain a strong subgrid-scale variability of near-surface temperatures due to orographic variability has to be expected, with corresponding effects on the subgrid-scale snowfall fraction.

For this preparatory analysis, which is entirely based on observational data, a reference snowfall is derived. It is based on the approximation of snowfall by application of a fixed temperature threshold to daily total precipitation amounts on the high resolution observational grid (2 km) and will be termed *Subgrid method* thereafter: First, the daily snowfall *S′* at each grid point of the observational data set at high resolution (2 km) is derived by applying a snow fractionation temperature T^*=2°C. The whole daily precipitation amount *P′* is accounted for as snow *S′* (i.e., f_s=100%) for days with daily mean temperature $T' \leq T^*$. For days with $T' > T^*$, *S′* is set to zero and *P′* is attributed as rain (i.e., f_s=0%). This threshold approach with a fractionation temperature of 2°C corresponds to the one applied in previous works and results appear to be in good agreement with station-based snowfall measurements (e.g., Zubler et al., 2014). The coarse grid (12 km) reference snowfall S_{SG} is determined by averaging the sum of separated daily high resolution *S′* over all *n* high-resolution grid points *i* located within a specific coarse grid point *k*. I.e., at each coarse grid point *k*

$$\boldsymbol{S_{SG}} = \frac{1}{n} \cdot \sum_{i=1}^{n} \boldsymbol{P'_i} \, [\boldsymbol{T'_i} \leq \boldsymbol{T^*}] = \frac{1}{n} \sum_{i=1}^{n} \boldsymbol{S'_i} \qquad (3)$$

For comparison, the same binary fractionation method with a temperature threshold of T^*=2°C is directly applied on the coarse 12 km grid (*Binary method*). For this purpose, total precipitation *P′* and daily mean temperature *T′* of the high-resolution data are conservatively remapped to the coarse grid leading to *P* and *T*, respectively. Compared to the *Subgrid method*, the *Binary method* neglects any subgrid-scale variability of the snowfall fraction. As a result, the *Binary method* underestimates S_{mean} and overestimates S_{q99} for most~~all~~ elevation intervals (Fig. 2). The underestimation of S_{mean} can be explained by the fact that even for a coarse grid temperature above T^* individual high-elevation subgrid cells (at which $T' \leq T^*$) can receive substantial snowfall amounts~~, a process that is not accounted for by the *Binary method*~~. As positive precipitation-elevation gradients can be assumed for most parts of the domain (larger total precipitation at high elevations; see e.g. Kotlarski et al., 2012 and Kotlarski et al., 2015 for an Alpine-scale assessment) the neglect of subgrid-scale snowfall variation in the *Binary method* hence leads a systematic underestimation of mean snowfall compared to the *Subgrid method*. Furthermore, following O'Gorman (2014), heavy snowfall events are expected to occur in a narrow temperature range below the rain-snow transition. As the *Binary method* in these temperature ranges always leads to a snowfall fraction of 100%, too large S_{q99} values would result.

To take into account these subgrid-scale effects, a more sophisticated approach – referred to as the *Richards method* – is developed here. This method is based upon a generalised logistic regression (Richards, 1959). Here, we apply this regression to relate the surface temperature *T* to the snow fraction f_s by accounting for the topographic subgrid-scale variability. At each coarse grid-point k, the *Richards method*-based snowfall fraction $f_{s,RI}$ for a given day is hence computed as follows:

$$f_{s,RI}(T_k) = \frac{1}{\left[1 + C_k \cdot e^{D_k \cdot (T_k - T^*)}\right]^{\frac{1}{C_k}}} \quad (4)$$

with C as the point of inflexion (denoting the point with largest slope), and D the growth rate ~~D~~ (reflecting the mean slope). T_k is the daily mean temperature of the corresponding coarse grid box k and T^*=2°C the snow fractionation temperature. First, we estimate the two parameters C and D of Equation 4 for each single coarse grid point k by minimizing the least-square distance to the f_s values derived by the *Subgrid method* via the reference snowfall S_{SG} (local fit). Second, C and D are expressed as a function of the topographic standard deviation σ_h of the corresponding coarse resolution grid point only (Fig. S1; global fit). This makes it possible to define empirical functions for both C and D that can be used for all grid points k in the Alpine domain and that depend on σ_h only.

$$\sigma_{h,k} = \sqrt{\frac{\sum_i^n (h_i - \overline{h_k})^2}{n-1}} \quad (5)$$

$$C_k = \frac{1}{(E - \sigma_{h,k} \cdot F)} \quad (6)$$

$$D_k = G \cdot \sigma_{h,k}{}^{-H} \quad (7)$$

Through a minimisation of the least square differences the constant parameters in Equations 6 and 7 are calibrated over the domain of Switzerland and using daily data from the period September to May 1971-2005 leading to values of E=1.148336, F=0.000966 m^{-1}, G=143.84113 °C^{-1} and H=0.8769335. Note that σ_h is sensitive to the resolution of the two grids to be compared (cf. Eq. 5). It is a measure for the uniformity of the underlying topography and has been computed based on the high-resolution GTOPO30 digital elevation model (https://lta.cr.usgs.gov/GTOPO30) aggregated to a regular grid of 1.25 arc seconds (about 2 km) which reflects the spatial resolution of the observed temperature and precipitation grids (cf. Section 2.1). Small values of σ_h indicate a low subgrid-scale topographic variability, such as in the Swiss low-lands, while high values result from non-uniform elevation distributions, such as in areas of inner Alpine valleys. σ_h as derived from GTOPO30 might be different from the subgrid-scale topographic variance employed by the climate models themselves, which is however not relevant here as only grid cell-averaged model output is analysed and as we considere σ_h as a proper estimate of subgrid-scale variability.

Figure S1 (panel c) provides an example of the relation between daily mean temperature and daily snow fraction f_s for grid cells with topographical standard deviations of 50 m and 500 m, respectively. The snowfall amount S_{RI} for a particular day and a particular coarse grid box is finally obtained by multiplying the corresponding $f_{s,RI}$ and P values. A comparison with the *Subgrid method* yields very similar results. For both indices S_{mean} and $S_{q99,}$ mean ratios across all elevation intervals are close to 1 (Fig. 2). At single grid points, maximum deviations are not larger than 1±0.1. Note that for this comparison calibration and validation period are identical (EVAL period). Based on this analysis, it has been decided to separate snowfall according to the *Richards method* throughout this work in both the observations and in the RCMs. The observation-based snowfall estimate obtained by applying the *Richards method* to the observational temperature and precipitation grids after spatial aggregation to the 0.11° RCM resolution will serve as reference for the RCM bias ~~correction~~ adjustment and will be termed *reference* hereafter. One needs to bear in mind that the parameters *C* and *D* of the Richards method were fitted for the Swiss domain only and were later on applied to the entire Alpine domain (cf. Fig. 1).

2.6 Bias ~~correction~~ adjustment approach

Previous work has revealed partly substantial temperature and precipitation biases of the EURO-CORDEX RCMs over the Alps (e.g. Kotlarski et al., 2014; Smiatek et al., 2016), and one has to expect that the separated snowfall amounts are biased too. This would especially hamper the interpretation of absolute climate change signals of the considered snow indices. We therefore explore possibilities to bias-adjust~~correct~~ the simulated snowfall amounts and to directly integrate this bias ~~correction~~ adjustment into the snowfall separation framework of Section 2.5. Note that we deliberately employ the term *bias adjustment* as opposed to *bias correction* to make clear that only certain aspects of the snowfall climate are adjusted and that the resulting dataset might be subject to remaining inaccuracies.

~~We compare results with and without employment of the bias correction procedure outlined below.~~ A simple two-step approach that separately accounts for precipitation and temperature biases and their respective influence on snowfall is chosen. The separate consideration of temperature and precipitation biases allows for a more physically-based bias adjustment of snowfall amounts: Due to the temperature dependency of snowfall occurrence, snowfall biases of a given climate model cannot be expected to remain constant under current and future (i.e., warmer) climate conditions. For instance, a climate model with a given temperature bias might pass the snow-rain temperature threshold earlier or later than reality during the general warming process. Hence, traditional bias adjustment approaches based only on a comparison of observed and simulated snowfall amounts in the historical climate would possibly fail due to a non-stationary bias structure. The bias ~~correction~~ adjustment is calibrated in the EVAL period for each individual GCM-RCM chain and over the region of Switzerland, and is then applied to both the CTRL and SCEN period of each chain and for the entire Alpine domain. To be consistent in terms of horizontal grid spacing, the observational data sets RhiresD and TabsD (see Sec. 2.1) are conservatively regridded to the RCM resolution beforehand.

In a first step, total simulated precipitation was adjusted by introducing an elevation-dependent ~~correction~~ adjustment factor which ~~corrects for~~adjusts precipitation biases regardless of temperature. For this purpose, mean precipitation ratios (RCM simulation divided by observational analysis) for 250 m elevation intervals were calculated (Fig. S2). An almost linear relationship of these ratios with elevation was found. Thus, a linear regression between the intervals from 250 m a.s.l. to 2750 m a.s.l. was used for each model chain separately to estimate a robust ~~correction~~ adjustment factor. As the number of both RCM grid points and measurement stations at very high elevations (>2750 m a.s.l.) is small (see Sec. 2.1) and biases are subject to a considerable sampling uncertainty, these elevations were not considered in the regression. Overall the fits are surprisingly precise except for the altitude bins above 2000 m (Fig. S2). The precipitation adjustment factors (P_{AF}) for a given elevation were then obtained as the inverse of the fitted precipitation ratios. Multiplying simulated precipitation P with P_{AF} for the respective model chain and elevation results in the ~~corrected~~ adjusted precipitation:

$$P_{corradj} = P \cdot P_{AF} \tag{8}$$

For a given GCM-RCM chain and for each elevation interval, the spatially and temporally averaged corrected total precipitation ~~P_{corr}~~ P_{adj} approximately corresponds to the observation-based estimate in the EVAL period.

In thea second step of the bias adjustment~~correction~~ procedure, temperature biases are accounted for. For this purpose the initial snow fractionation temperature T*=2°C of the Richards separation method (see Sec 2.5) is shifted to the value T^*_a for which the spatially (Swiss domain) and temporally (September to May) averaged simulated snowfall amounts for elevations below 2750 m a.s.l. match the respective observation-based reference (see above). Compared to the adjustment of total precipitation, T^*_a is chosen independent of elevation~~,~~ but separately for each GCM-RCM chain, in order to avoid overparameterization and to not over-interpret the elevation dependency of mean snowfall in the snowfall reference grid. After this second step of the bias adjustment~~correction~~, the spatially ~~(Swiss domain)~~ and temporally ~~(September to May)~~ averaged simulated snowfall amounts below 2750 m a.s.l. ~~by definition~~ match the reference by definition. Hence, the employed simple bias adjustment ~~correction~~ procedure ~~corrects~~ adjusts domain-mean snowfall biases averaged over the entire season from September to May. It does, however, not correct for biases in the spatial snowfall pattern, in the seasonal cycle, or in the temporal distribution of daily values. Note that, as the underlying high-resolution data sets are available over Switzerland only, the calibration of the bias ~~correction~~ adjustment methodology is correspondingly restricted, but the ~~correction~~ adjustment is then applied to the whole Alpine domain. This approach is justified as elevation-dependent mean winter precipitation and temperature biases of the RCMs employed – assessed by comparison against the coarser-resolved EOBS reference dataset (Haylock et al., 2008) - are very similar for~~over~~ Switzerland and for ~~over~~ the entire Alpine analysis domain (Figs. S3 and S4).

3 Evaluation

3.1 RCM raw snowfall

We first carry out an illustrative comparison of RCM raw snowfall amounts (for those simulations only that directly provide snowfall flux) against station observations of snowfall~~,~~ in order to determine whether the simulated RCM snowfall climate contains valid information despite systematic biases. To this end, simulated raw snowfall amounts of nine EURO-CORDEX simulations (see Tab. 1) averaged over 250 m-elevation intervals and over ~~in~~ the range 950 – 1650 m a.s.l. are compared against observations ~~derived from~~of measured fresh snow sums from 29 MeteoSwiss stations (see Section 2.1).~~with data available for at least 80% of the EVAL period~~. For this purpose a mean snow density of 100 kg/m^3 for the conversion from measured snow ~~height~~ depth to water equivalent is assumed. Note that this simple validation is subject to considerable uncertainties as it does not explicitly correct for the scale and elevation gap between grid-cell based RCM output and single-site observations. Especially in complex terrain and for exposed sites, point measurements of snow depth might be non-representative for larger-scale conditions (e.g., Grünewald and Lehning, 2015). Also, the conversion from snow depth to snow water equivalent is of approximate nature only, and fresh snow sums might furthermore misrepresent true snowfall in case that snow melt or snow drift occurs between two snow depth readings.

At low elevations simulated mean September-May raw snowfall sums match the observations well while differences are larger aloft (Fig. 3a). The positive bias at high elevations might arise from the fact that (the very few) observations were made at ~~a~~ specific locations while simulated grid point values of the corresponding elevation interval might be located in different areas of Switzerland. It might also be explained by positive RCM precipitation and negative RCM temperature biases at high elevations of the Alps (e.g., Kotlarski et al., 2015). At lower elevations, the station network is geographically more balanced and the observations are probably more representative of the respective elevation interval. Despite a clear positive snowfall bias in mid-winter, the RCMs are generally able to reproduce the mean seasonal cycle of snowfall for elevations between 950 m a.s.l. - 1650 m a.s.l. (Fig. 3b). The fact that the major patterns of both the snowfall-elevation relationship and the mean seasonal snowfall cycle are ~~basically~~ well represented indicates the general and physically consistent applicability of RCM output to assess future changes in mean and heavy Alpine snowfall. However, substantial biases in snowfall amounts are apparent and a bias ~~correction~~ adjustment of simulated snowfall seems to be required prior to the analysis of climate change signals of individual snowfall indices.

3.2 Evaluation of the reference snowfall

The snowfall separation employing the *Richards method* (Section 2.5) and, as a consequence, also the bias adjustment (Section 2.6) make use of the 2 km reference snowfall grid derived by employing the *Subgrid method* on the observed temperature and precipitation grids. Hence, the final results of this study could to some extent be influenced by inaccuracies and uncertainties of the reference snowfall grid itself. In order to assess the quality of the latter and in absence of a further observation-based reference we here present an approximate evaluation.

First, the reference snowfall grid is evaluated against fresh snow sums at the 29 Swiss stations that were also used for evaluating RCM raw snowfall. Note the limitations of such a comparison as outlined in Chapter 3.1. The comparison of black and red markers and lines in Figure 3 indicates a good agreement of mean snowfall at individual elevation intervals (left panel) as well for the mean annual cycle of snowfall at medium elevations (right panel). The reference snowfall grid is obviously a good approximation of site-scale fresh snow sums. Note that similarly to the RCM raw snowfall evaluation, all 2 km reference snowfall grid cells in the respective elevation interval are considered. The good agreement, however, still holds if only those 2 km grid cells covering the 29 site locations are considered (not shown here).

Second, both the 2 km reference snowfall grid and the 0.11° reference snowfall grid obtained by employing the Richards method to aggregated temperature and precipitation values (see Section 2.5) are compared against the gridded HISTALP dataset of solid precipitation (Chimani et al., 2011). The latter is provided at a monthly resolution on a 5' grid covering the Greater Alpine Region. It is based on monthly snowfall fraction estimates that are used to scale a gridded dataset of total precipitation. The comparison of the three datasets for the region of Switzerland (for which the 2 km reference snowfall is available) in the EVAL period 1971-2005 yields an approximate agreement of both the magnitude of mean winter snowfall and its spatial pattern. The three data sets differ with respect to their spatial resolution but all show a clear dependency of snowfall on topography and mean September-May snowfall sums above 1000 mm over most parts of the Alpine ridge. Climatologically warm and dry valleys, on the other hand, are represented by minor snowfall amounts of less than 400 m only.

As mentioned before these evaluations of the reference snowfall grid are subject to uncertainties and, furthermore, they only cover mean snowfall amounts. However, they provide basic confidence in the applicability of the reference snowfall grid for the purposes of snowfall separation and bias adjustment in the frame of the present study.

3.3~~2~~ Calibration of bias ~~correction~~ adjustment

The analysis of total precipitation ratios (RCM simulations with respect to observations) for the EVAL period, which are computed to carry out the first step of the bias ~~correction~~ adjustment procedure, reveals substantial elevation dependencies. All simulations tend to overestimate total precipitation at high elevations (Fig. S2~~1~~). This fact might ultimately be connected to an overestimation of surface snow amount in several EURO-CORDEX RCMs as reported by Terzago et al. (2017). As the precipitation ratio between simulations and observations depends approximately linearly ~~depends~~ on elevation, the calculation of P_{AF} via a linear regression of the ratios against elevation (see Sec. 2.6) seems reasonable. By taking the inverse of this linear relation, P_{AF} for every model and elevation can be derived. For the CCLM and RACMO simulations, these correction factors do not vary much with height, while P_{AF} for MPI-ESM - REMO and EC-EARTH - HIRHAM is much larger than 1 in low lying areas, indicating a substantial underestimation of observed precipitation sums (Fig. 4a). However, for most elevations and simulations, P_{AF} is generally smaller than 1, i.e., total precipitation is overestimated by the models. Similar model biases in the winter and spring seasons have already been reported in previous works (e.g., Rajczak et al., in prep.; Smiatek et al., 2016). Especially at high elevations, these apparent positive precipitation biases could be related to observational undercatch, i.e., an underestimation of true precipitation sums by the observational analysis. Frei et al. (2003) estimated seasonal Alpine precipitation undercatch for three elevation intervals. Results show that measurement biases are largest in winter and increase with altitude. However, a potential undercatch (with a maximum of around 40% at high elevations in winter; Frei et al., 2003) can only partly explain the partly substantial overestimation of precipitation found in the present work.

After applying P_{AF} to the daily precipitation fields, a snowfall fractionation at the initial T^* of 2 °C (see Eq. (4)) would lead to a snowfall excess in all 14 simulations as models typically experience a cold winter temperature bias. To match the observation-based and spatio-temporally averaged reference snowfall below 2750 m a.s.l., T^* for all models needs to be decreased during the second step of the bias ~~correction~~ adjustment (Fig 4b). The adjusted T^*_a values indicate a clear positive relation with the mean temperature bias in the EVAL period. This feature is expected since the stronger a particular model's cold bias the stronger the required adjustment of the snow fractionation temperature *T** towards lower values in order to avoid a positive snowfall bias. Various reasons for the scatter around a simple linear relation in Figure 4b can be thought of. These include remaining spatial inaccuracies of the corrected precipitation grid, elevation-dependent temperature biases and misrepresented temperature-precipitation relationships at daily scale. Note that precipitation and temperature biases heavily depend on the GCM-RCM chain and seem to be rather independent from each other. While EC-EARTH – RACMO, for instance, shows one of the best performances in terms of total precipitation, its temperature bias ~~of~~ close to -5 °C is the largest deviation in our set of simulations. Concerning the partly substantial temperature biases of the EURO-CORDEX models shown in Figure 4 b, their magnitude largely agrees with Kotlarski et al. (2014; in reanalysis-driven simulations) and Smiatek et al. (2016).

3.4~~3~~ Evaluation of snowfall indices

We next assess the performance of the bias ~~correction~~ adjustment procedure by comparing snowfall indices derived from separated and bias-~~corrected~~ adjusted RCM snowfall amounts against the observation-based reference. The period for which this comparison is carried out is EVAL, i.e., it is identical to the calibration period of the bias ~~correction~~adjustment. We hence do not intend a classical cross validation exercise with separate calibration and validation periods, but try to answer the following two questions: (a) Which aspects of the Alpine snowfall climate are ~~corrected for~~adjusted, and (b) for which aspects do biases remain even after application of the bias ~~correction~~ adjustment procedure.

Figure 5 shows the evaluation results of the six snowfall indices based on the separated and not bias-~~corrected~~ adjusted simulated snowfall ($RCM_{sep+nbac}$), and the separated and bias-~~corrected~~ adjusted simulated snowfall ($RCM_{sep+bac}$). In the first case the snowfall separation of raw precipitation is performed with T*=2°C, while in the second case precipitation is ~~corrected~~ adjusted and the separation is performed with a bias-adjusted temperature T^*_a. The first column represents the mean September to May statistics, while columns 2-4 depict the seasonal cycle at monthly resolution for three distinct elevation intervals.

The analysis of S_{mean} confirms that $RCM_{sep+bac}$ is able to reproduce the observation-based reference in the domain mean as well as in most individual elevation intervals. The domain-mean agreement is a direct consequence of the design of the bias ~~correction~~ adjustment procedure (see above). $RCM_{sep+nbac}$, on the other hand, consistently overestimates S_{mean} by up to a factor of 2.5 as a consequence of positive precipitation and negative temperature biases (cf. Fig. 4). Also the seasonal cycle of S_{mean} for $RCM_{sep+bac}$ yields a satisfying performance across all three elevation intervals, while $RCM_{sep+nbac}$ tends to produce too much snowfall over all months and reveals an increasing model spread with elevation.

For the full domain and elevations around 1000 m, the observation-based reference indicates a mean S_{freq} of 20% between September and May. Up to 1000 m a.s.l. $RCM_{sep+bac}$ reflects the increase of this index with elevation adequately. However, towards higher elevations the approximately constant S_{freq} of 30% in the reference is not captured by the simulation-derived snowfall. Notably during wintertime, both $RCM_{sep+bac}$ and $RCM_{sep+nbac}$ produce too many snowfall days, i.e., overestimate snowfall frequency. This feature is related to the fact that climate models typically tend to overestimate the wet day frequency over the Alps especially in wintertime (Rajczak et al., 2013) and that the bias correction adjustment procedure employed does not explicitly correct for potential biases in precipitation frequency. Due to the link between mean snowfall on one side and snowfall frequency and mean intensity on the other side, opposite results are obtained for the mean snowfall intensity S_{int}. $RCM_{sep+bac}$ largely underestimates mean intensities during snowfall days while $RCM_{sep+nbac}$ typically better reflects the reference. Nevertheless, deviations during winter months at mid-elevations are not negligible. Mean September-May S_{frac} in the reference exponentially increases with elevation. This behaviour is reproduced by both $RCM_{sep+bac}$ and $RCM_{sep+nbac}$. Notwithstanding, $RCM_{sep+bac}$ results are more accurate compared to $RCM_{sep+nbac}$, which turns out to be biased towards too large snowfall fractions.

For the two heavy snowfall indices S_{q99} and S_{1d}, $RCM_{sep+nbac}$ appears to typically match the reference better than $RCM_{sep+bac}$. Especially at high elevations, $RCM_{sep+bac}$ produces too low snowfall amounts. This again highlights illustrates the fact that the bias adjustment correction procedure is designed to correct adjust for biases in mean snowfall, but does not necessarily improve further aspects of the simulated snowfall climate.

The spatial patterns of S_{mean} for the 14 $RCM_{sep+bac}$ simulations from September to May are presented in Figure 6. The observational-based reference (lower right panel) reveals a snowfall distribution with highest values along the Alpine main ridge, whereas the Swiss plateau, Southern Ticino and main valleys such as the Rhône and Rhine valley experience less snowfall. Almost all bias-corrected adjusted models are able to represent the overall picture with snow-poor lowlands and snow-rich Alpine regions. Nevertheless substantial differences to the observations concerning the spatial snowfall pattern can arise. EC-EARTH - HIRHAM, for example, is subject to a "pixelated" structure. This could be the result of frequent grid-cell storms connected to parameterisations struggling with complex topographies. Such inaccuracies in the spatial pattern are not corrected for by our simple bias correction adjustment approach whichthat only targets domain-mean snowfall amounts at elevations below 2750 m a.s.l. and that does not considerably modify the simulated spatial snowfall patterns.. Note that these patterns are obviously strongly determined by the RCM itself and only slightly depend on the driving GCM (see, for instance, the good agreement among the CCLM and the RCA simulations).

In summary, after applying the bias adjustment correction to the simulations most snowfall indices are fairly well represented at elevations below 1000 m a.s.l.. With increasing altitude and smaller sample sizes in terms of number of grid cells, reference and $RCM_{sep+bac}$ diverge. This might be caused by the remaining simulated overestimation of S_{freq} and an underestimation of S_{int}. While the bias adjustment correction approach leads to a reduction of S_{int} due to the total precipitation adjustment, S_{freq} is only slightly modified by this correction and by the adjustment of T^*. Nevertheless, these two parameters strongly influence other snowfall indices. The counteracting effects of overestimated S_{freq} and underestimated S_{int} result in appropriate amounts of S_{mean} whereas discrepancies for S_{q99} and S_{1d} are mainly driven by the underestimation of S_{int}.

4 Snowfall projections for the late 21st century

For the study of climate change signals, the analysis domain is extended to the entire Alps (see Sec. 2.3). Due to the identified difficulties of bias-~~- correcting ~~adjusting certain snowfall indices (see Sec 3.4~~3~~), emphasis is laid upon relative signals of change (see Eq. 2). This type of change can be expected to be less dependent on the remaining inaccuracies after the ~~correction~~adjustment. If not stated otherwise, all results in this Section are based on the RCM_{sep+ba}~~c~~ data, i.e., on separated and bias-~~corrected ~~adjusted RCM snowfall, and on the RCP8.5 emission scenario.

Projections for seasonal S_{mean} show a considerable decrease over the entire Alpine domain (Fig. 7). Most RCMs project largest percentage losses of more than 80% across the Alpine forelands and especially in its topographic depressions such as the Po and Rhone v~~V~~alleys~~ or Western France~~. Over the Alpine ridge, reductions are smaller but still mostly negative. Elevated regions between Southeastern Switzerland, Northern Italy and Austria seem to be least affected by the overall snowfall reduction. Some of the simulations (e.g., CNRM-RCA, MPI-ESM-RCA or MPI-ESM-REMO) project only minor changes in these regions. Experiments employing the same RCM but different driving GCMs (e.g. the four simulations of RCA), but also experiments employing the same GCM but different RCMs (e.g. the four simulations driven by EC-EARTH, though different realizations) can significantly disagree in regional-scale change patterns and especially in the general magnitude of change. This highlights a strong influence of both the driving GCMs and the RCMs themselves on snowfall changes, representing effects of large-scale circulation and meso-scale response, respectively.

A more detailed analysis is provided in Fig. 8 ~~that ~~which addresses the vertical and seasonal distribution of snowfall changes. It reveals that relative (seasonal mean) changes of S_{mean} appear to be strongly dependent on elevation (Fig.8, top left panel). The multi-model mean change ranges from -80% at low elevations to -10% above 3000 m a.s.l.. Largest differences between neighbouring elevation intervals are obtained from 750 m a.s.l. to 1500 m a.s.l.. Over the entire Alps, the results show a reduction of S_{mean} by -35% to -55% with a multi-model mean of -45%. The multi-model spread appears to be rather independent of elevation and is comparably small, confirming that, overall, the spatial distributions of the change patterns are similar across all model chains (cf. Fig. 7). All simulations point to decreases over the entire nine-month period September to May for the two elevation intervals <1000 m a.s.l. and 1000 to 2000 m a.s.l.. Above 2000 m a.s.l., individual simulations show an increase of S_{mean} by up to 20% in mid-winter which ~~forces the ~~leads to a slightly positive change in multi-model mean ~~change to be slightly positive ~~in January and February.

Decreases of S_{freq} are very similar to changes in mean snowfall. Mean September-May changes are largest below 1000 m a.s.l., while differences among elevation intervals become smaller ~~in the upper part~~at higher elevations. In-between is a transition zone with rather strong changes with elevation, which approximately corresponds to the mean elevation of the September-May zero-degree line in today's climate (e.g., Ceppi et al., 2012; MeteoSchweiz, 2016). Individual simulations with large reductions in S_{mean}, such as the RCA experiments, also project strongest declines in S_{freq}. In contrast, the mean snowfall intensity S_{int} is subject to smallest percentage variations in our set of snowfall indices. Strong percentage changes for some models in September are due to the small sample size (only few grid points considered) and the low snowfall amounts in this month. Apart from mid elevations with decreases of roughly -10%, mean intensities from September to May are projected to remain almost unchanged by the end of the century. For both seasonal and monthly changes, model agreement is best for high elevations while the multi-model spread is largest for lowlands. Large model spread at low elevations might be caused by the small number of grid points used for averaging over the respective elevation interval, especially in autumn and spring.

Similar results are obtained for the heavy snowfall indices S_{q99} and S_{1d}. While percentage decreases at lowermost elevations are even larger than for S_{mean}, losses at high elevations are less pronounced, resulting in similar domain-mean change signals for heavy and mean snowfall. Substantial differences between monthly δS_{q99} and δS_{1d} appear at elevations below 1000 m a.s.l.. Here, percentage losses of S_{q99} are typically slightly more pronounced. Above 2000 m a.s.l. both indices appear to remain almost constant between January and March with change signals close to zero. The multi-model mean changes even hint to slight increases of both indices. Concerning changes in the snowfall fraction, i.e., in the relative contribution of snowfall to total precipitation, our results indicate that current seasonal and domain mean S_{frac} might drop by about -50% (Fig. 8, lowermost row). Below 1000 m a.s.l., the strength of the signal is almost independent of the month, and multi-~~tli~~model average changes of the snow fraction of about -80% are obtained. At higher elevations changes during mid-winter are less pronounced compared to autumn and spring but still negative.

5 Discussion

5.1 Effect of temperature, snowfall frequency and intensity on snowfall changes

The results in Section 4 indicate substantial changes of snowfall indices over the Alps in regional climate projections. With complementary analyses presented in Figures 9 and 10 we shed more light on the responsible mechanisms, especially concerning projected changes in mean and heavy snowfall. For this purpose Figures 9a-b,e-f show the relationship of both mean and heavy snowfall amounts in the CTRL period and their respective percentage changes with the climatological CTRL temperature of the respective (climatological) month, elevation interval and GCM-RCM chain. For absolute amounts (S_{mean}, S_{q99}; Fig. 9a,e) a clear negative relation is found, i.e., the higher the CTRL temperature the lower the snowfall amounts. For S_{mean} the relation levels off at mean temperatures higher than about 6°C with mean snowfall amounts close to zero. For temperatures below about -6°C a considerable spread in snowfall amounts is obtained, i.e., mean temperature does not seem to be the controlling factor here. Relative changes of both quantities (Fig. 9b,f), however, are strongly controlled by the CTRL period's temperature level with losses close to 100% for warm climatic settings and partly increasing snowfall amounts for colder climates. This dependency of relative snowfall changes on CTRL temperature is in line with previous works addressing future snowfall changes on both hemispheric and regional scales (de Vries et al., 2014; Krasting et al., 2013; Räisänen, 2016). The spread of changes within a given CTRL temperature bin can presumably be explained by the respective warming magnitudes that differ between elevations, months and GCM-RCM chains. About half of this spread can be attributed to the month and the elevation alone (compare the spread of the black markers to the one of the red markers which indicate multi-model averages).

For most months and elevation intervals, percentage reductions in S_{mean} and S_{q99} reveal an almost linear relationship with δS_{freq} (Fig. 9c, g). The decrease of S_{freq} with future warming can be explained by a shift of the temperature probability distribution towards higher temperatures, leading to fewer days below the freezing level (Fig. 10, top row). Across the three elevation intervals <1000 m a.s.l., 1000-2000 m a.s.l. and > 2000 m a.s.l., relative changes in the number of days with temperatures below the freezing level ($T \leq 0°C$) are in the order of -65%, -40% and -20%, respectively (not shown). This approximately corresponds to the simulated decrease of S_{freq} (cf. Fig 8), which in turn, is of a similar magnitude as found in previous works addressing future snowfall changes in the Alps (Schmucki et al., 2015b; Zubler et al., 2014). Due to the general shift of the temperature distribution and the "loss" of very cold days (Fig. 10, top row) future snowfall furthermore occurs in a narrower temperature range (Fig. 10, second row).

Contrasting this general pattern of frequency-driven decreases of both mean and heavy snowfall, no changes or even slight increases of S_{mean}, S_{q99} and S_{1d} at high elevations are expected in mid-winter (see Fig. 8). This can to some part be explained by the general increase of total winter precipitation (Rajczak et al., in prep; Smiatek et al., 2016) that obviously offsets the warming effect in high-elevation regions where a substantial fraction of the future temperature PDF is still located below the rain-snow transition (Fig. 10, top row). This process has also been identified in previous works to be, at last partly, responsible for future snowfall increases (de Vries et al., 2014; Krasting et al., 2013; Räisänen, 2016). Furthermore, the magnitude of the increases of both mean and heavy snowfall is obviously driven by positive changes of S_{int}, while S_{freq} remains constant (Fig. 9c,g). An almost linear relationship between positive changes of S_{int} and positive changes of S_{mean} and S_{q99} is obtained (Fig. 9d,h; upper right quadrants. Nevertheless, the high-elevation mid-winter growth in S_{mean} is smaller than the identified increases of mean winter total precipitation. This can be explained by the persistent decrease of S_{frac} during the cold season (see Fig. 8, lowermost row).

For elevation intervals with simulated monthly temperatures between -6°C and 0°C in the CTRL period, S_{mean} appears to decrease stronger than S_{q99} (cf. Fig. 9b,f). O'Gorman (2014) found a very similar behaviour when analysing mean and extreme snowfall projections over the Northern Hemisphere within a set of GCMs. This finding is related to the fact that future snowfall decreases are mainly governed by a decrease of snowfall frequency while snowfall increases in high-elevated regions in mid-winter seem to be caused by increases of snowfall intensity. It can obviously be explained by the insensitivity of the temperature interval at which extreme snowfall occurs to climate warming and by the shape of the temperature – snowfall intensity distribution itself (Fig. 10, third row). The likely reason behind positive changes of S_{int} at high-elevated and cold regions is the higher water holding capacity of the atmosphere in a warmer climate. According to the Clausius-Clapeyron relation, saturation vapour pressure increases by about 7% per degree warming (Held and Soden, 2006). Previous studies have shown that simulated changes of heavy and extreme precipitation (though not necessarily targeting the daily temporal scale and moderate extremes as in our case) are consistent with this theory (e.g., Allen and Ingram, 2002; Ban et al., 2015). In terms of snowfall, we find the Clausius-Clapeyron relation to be applicable for negative temperatures up to approximately -5°C as well (Fig. 10, third row, dashed lines). Inconsistencies for temperatures between -5°C and 0°C are due to a snow fraction *sf* < 100% for corresponding precipitation events.

For further clarification, Figure 11 schematically illustrates the governing processes behind the changes of mean and heavy snowfall that differ between climatologically warm (decreasing snowfall) and climatologically cold climates (increasing snowfall). As shown in Figure 10 (third row), the mean S_{int} distribution is rather independent on future warming and similar temperatures are associated with similar mean snowfall intensities. In particular, heaviest snowfall is expected to occur slightly below the freezing level in both the CTRL and the SCEN period (Fig. 11a). How often do such conditions prevail in the two periods? In a warm current climate, i.e., at low elevations or in the transition seasons, heavy snowfall only rarely occurs as the temperature interval for highest snowfall intensity is already situated in the left tail of the CTRL period's temperature distribution (Fig. 11b). With future warming, i.e., with a shift of the temperature distribution to the right, the probability for days to occur in the heavy snowfall temperature interval (dark grey shading) decreases stronger than the probability of days to occur in the overall snowfall regime (light gre~~a~~y shading). This results in (1) a general decrease of snowfall frequency, (2) a general decrease of mean snowfall intensity and (3) a general and similar decrease of both mean and heavy snowfall amounts. In contrast, at cold and high-elevated sites CTRL period temperatures are often too low to trigger heavy snowfall since a substantial fraction of the temperature PDF is located to the left of the heavy snowfall temperature interval (Fig. 11 c). The shifted distribution in a warmer SCEN climate, however, peaks within the temperature interval that favours heavy snowfall. This leads to a probability increase for days to occur in the heavy snowfall temperature range despite the general reduction in S_{freq} (lower overall probability of days to occur in the entire snowfall regime, light gre~~a~~y). As a consequence, mean S_{int} tends to increase and the reduction of heavy snowfall amounts is less pronounced (or even of opposing sign) than the reduction in mean snowfall. For individual (climatologically cold) regions and seasons, the increase of mean S_{int} might even compensate the S_{freq} decrease, resulting in an increase of both mean and heavy snowfall amounts. Note that in a strict sense these explanations only hold in the case that the probability of snowfall to occur at a given temperature does not change considerably between the CTRL and the SCEN period. This behaviour is approximately ~~given~~ found (Fig. 10, bottom row), which presumably indicates only minor contributions of large scale circulation changes and associated humidity changes on both the temperature - snowfall frequency and the temperature - snowfall intensity relation.

5.2 Emission scenario uncertainty

The projections presented in the previous sections are based on the RCP8.5 emission scenario, but will depend on the specific ~~emission~~ scenario considered. To assess this type of uncertainty we here compare the $RCM_{sep+ba\sout{c}}$ simulations for the previously shown RCP8.5 emission scenario against those assuming the more moderate RCP4.5 scenario. As a general picture, the weaker RCP4.5 scenario is associated with less pronounced changes of snowfall indices (Fig. 12). Differences in mean seasonal δS_{mean} between the two emission scenarios are most pronounced below 1000 m a.s.l. where percentage changes for RCP4.5 are about one third smaller than for RCP8.5. At higher elevations, multi-model mean changes better agree and the multi-model ranges for the two emission scenarios start overlapping, i.e., individual RCP4.5 experiments can be located in the RCP8.5 multi-model range and vice versa. Over the entire Alpine domain, about -25% of current snowfall is expected to be lost under the moderate RCP4.5 emission scenario while a reduction of approximately -45% is projected for RCP8.5. For seasonal cycles, the difference of δS_{mean} between RCP4.5 and RCP8.5 is similar for most months and slightly decreases with altitude. Above 2000 m a.s.l., the simulated increase of S_{mean} appears to be independent of the chosen RCP in January and February, while negative changes before and after mid-winter are more pronounced for RCP8.5. Alpine domain mean δS_{q99} almost doubles under the assumption of stronger GHG emissions. This is mainly due to differences at low elevations whereas above 2000 m a.s.l. δS_{q99} does not seem to be strongly affected by the choice of the emission scenario. Differences in monthly mean changes are in close analogy to δS_{mean}. Higher emissions lead to a further negative shift in δS_{q99}. Up to mid-elevations differences are rather independent of the season. However, at highest elevations and from January to March, differences between RCP4.5 and RCP8.5 are very small.

Despite the close agreement of mid-winter snowfall increases at high elevations between the two emission scenarios, obvious differences in the spatial extent of the region of mean seasonal snowfall increases can be found (cf Figs. S6~~5~~ and 7 for δS_{mean}, and Figs. S7~~6~~ and S8~~7~~ for δS_{q99}). In most simulations, the number of grid cells along the main Alpine ridge that show either little change or even increases of seasonal mean S_{mean} or S_{q99} is larger for RCP4.5 than for RCP8.5 with its larger warming magnitude.

5.3 Intercomparison of projections with separated and raw snowfall

The snowfall projections presented above are based on the RCM_{sep+ba} data set, i.e. on separated and bias-adjusted snowfall amounts. To assess the robustness of these estimates we here compare the obtained change signals against the respective signals based on ~~An intercomparison of relative change signals for RCM_{sep+bc} (separated and bias-corrected),~~ $RCM_{sep+nba}$~~c~~ (separated and not bias-~~corrected~~adjusted) and simulated raw snowfall output (RCM_{raw}). ~~based on~~ This comparison is restricted to the nine RCMs providing raw snowfall as output variable (see Tab. 1).

The three different change estimates agree well with each other In terms of relative snowfall change signals ~~reveals no substantial differences~~ (Fig. 13, top row). ~~In the three data sets, m~~Multi-model mean relative changes are very similar for all analysed snowfall indices and elevation intervals. In many cases, separated and not bias-adjusted snowfall ($RCM_{sep+nba}$) is subject to slightly smaller percentage decreases. ~~Furthermore, m~~Multi-model mean differences between RCM_{sep+ba}~~c~~ , $RCM_{sep+nba}$~~c~~ and RCM_{raw} simulations are smaller than the corresponding multi-model spread of RCM_{sep+ba}~~c~~ simulations and emission scenario uncertainties (cf. Figs. 12, 13 and S10~~8~~).

This agreement in terms of relative change signals ~~finding~~ is in contrast to absolute change characteristics (Fig. 13, bottom row). Results based on the three data sets agree in the sign of change, but not in their magnitude, especially at high elevations >2000 m a.s.l.. As the relative changes are almost identical, the absolute changes strongly depend upon the treatment of biases in the control climate.

~~-~~In summary, these findings indicate that (a) the snowfall separation method developed in the present work yields rather good proxies for relative changes of snowfall indices in raw RCM output (which is not available for all ~~for many~~ GCM-RCM chains ~~not available~~), and that (b) the additional bias -adjustment ~~correction~~ of separated snowfall amounts only has a weak influence on relative change signals of snowfall indices, but can have substantial effects on absolute changes.

6 Conclusions and outlook

The present work makes use of state-of-the-art EURO-CORDEX RCM simulations to assess changes of snowfall indices over the European Alps by the end of the 21st century. For this purpose, snowfall is separated from total precipitation using near-surface air temperature in both the RCMs and in the an observation-based estimate~~s~~ on a daily basis. The analysis yields a number of robust signals, consistent across a range of climate model chains and across emission scenarios. Relating to the main objectives we find the following:

Snowfall separation on an RCM grid. Binary snow fractionation with a fixed temperature threshold on coarse-resolution grids (with 11 km resolution) leads to an underestimation of mean snowfall and an overestimation of heavy snowfall. To overcome these deficiencies, the Richards snow fractionation method is implemented. This approach expresses that the coarse-grid snow fraction depends not only on daily mean temperature, but also on topographical subgrid-scale variations. Accounting for the latter results in better estimates for mean and heavy snowfall. However, due to limited observational coverage the parameters of this method are fitted for Switzerland only and are then applied to the entire Alpine domain. Whether this spatial transfer is robust could further be investigated by using observational data sets covering the full domain of interest but is out of the scope of this study.

Snowfall bias ~~correction~~adjustment. Simulations of the current EURO-CORDEX ensemble are subject to considerable biases in precipitation and temperature, which translate into biased snowfall amounts. In the EVAL period, simulated precipitation is largely overestimated, with increasing biases toward higher altitudes. On the other hand, simulated near surface temperatures are generally too low with largest deviations over mountainous regions. These findings were already reported in previous studies for both the current EURO-CORDEX data set but also for previous RCM ensembles (e.g. Frei et al., 2003; Kotlarski et al., 2012; Kotlarski et al., 2015; Rajczak et al., 2013; Smiatek et al., 2016). By implementing a simple bias adjustment~~correction~~ approach, we are able to partly reduce these biases and the associated model spread, which should enable more robust change estimates. The ~~corrected~~ adjusted model results reproduce the seasonal cycles of mean snowfall fairly well. However, substantial biases remain in terms of heavy snowfall, snowfall intensities (which in general are overestimated), snowfall frequencies, and spatial snowfall distributions. Further improvements might be feasible by using more sophisticated bias adjustment ~~correction~~ methods, such as quantile mapping (e.g., Rajczak et al., 2016), local intensity scaling of precipitation (e.g., Schmidli et al., 2006), or weather generators (e.g. Keller at al., 2016). Advantages of the approach employed here are its simplicity, its direct linkage to the snowfall separation method and, as a consequence, its potential ability to account for non-stationary snowfall biases. Furthermore, a comparison to simulated raw snowfall for a subset of nine simulations revealed that relative change signals are almost independent of the chosen post-processing strategy.

Snowfall projections for the late 21st century. Snowfall climate change signals are assessed by deriving the changes in snowfall indices between the CTRL period 1981 - 2010 and the SCEN period 2070 - 2099. Our results show that by the end of the 21st century, snowfall over the Alps will be considerably reduced. Between September and May mean snowfall is expected to decrease by approximately -45% (multi-model mean) under an RCP8.5 emission scenario. For the more moderate RCP4.5 scenario, multi-model mean projections show a decline of -25%. These results are in good agreement with previous works (e.g. de Vries et al., 2014; Piazza et al., 2014, Räisänen, 2016). Low-lying areas experience the largest percentage changes of more than -80%, while the highest Alpine regions are only weakly affected. Variations of heavy snowfall, defined by the 99% all-day snowfall percentile, show ~~at low-lying elevations~~ an even more pronounced signal at low-lying elevations. With increasing elevation, percentage changes of heavy snowfall are generally smaller than for mean snowfall. O'Gorman (2014) found a very similar behaviour by analysing projected changes in mean and extreme snowfall over the entire Northern Hemisphere. He pointed out that heavy and extreme snowfall occurs near an optimal temperature (near or below freezing, but not too cold), which seems to be independent of climate warming. We here confirm this ~~conclusion~~finding. At mid and high elevations ~~the optimal temperature for~~ heavy snowfall in a warmer climate will still occur in ~~a warmer climate~~ the optimal temperature range~~and~~, hence, heavy snowfall amounts will decrease less strongly compared to mean snowfall, and may even increase in some areas.~~.~~

At first approximation, the magnitude of future warming strongly influences the reduction of mean and heavy snowfall by modifying the snowfall frequency. Snowfall increases may however occur at high (and thus cold) elevations, and these are not caused by frequency changes. Here, snowfall increases due to (a) a general increase of total winter precipitation combined with only minor changes in snowfall frequency, and (b) more intense snowfall. This effect has a pronounced altitudinal distribution and may be particularly strong under conditions (depending upon location and season) where the current climate is well below freezing. Such conditions may experience a shift towards a ~~more snowfall-friendly~~ temperature range more favourable to snowfall (near or below freezing, but not too cold) with corresponding increases of mean snowfall, despite a general decrease of the snowfall fraction.

The identified future changes of snowfall over the Alps can lead to a variety of impacts in different sectors. With decreasing snowfall frequencies and the general increase of the snowline (e.g., Beniston, 2003; Gobiet et al., 2014; Hantel et al., 2012), both associated with temperature changes, ski lift operators are looking into an uncertain future. A shorter snowfall season will likely put them under greater financial pressure. Climate change effects might be manageable only for ski areas reaching up to high elevations (e.g. Elsasser and Bürki, 2002). Even so these resorts might start later into the ski season, the snow conditions into early spring could change less dramatically due to projected high-elevation snowfall increases in mid-winter. A positive aspect of the projected decrease in snowfall frequency might be a reduced expenditures for airport and road safety (e.g., Zubler et al., 2015).

At lower altitudes, an intensification of winter precipitation, combined with smaller snowfall fractions (Serquet et al., 2013), increases the flood potential (Beniston, 2012). Snow can act as a buffer by releasing melt water constantly over a longer period of time. With climate warming, this storage capacity is lost, and heavy precipitation immediately drains into streams and rivers which might not be able to take up the vast amount of water fast enough. Less snowmelt will also have impacts on hydropower generation and water management (e.g., Weingartner et al., 2013). So far, many Alpine regions are able to bypass dry periods by tapping melt water from mountainous regions. With reduced snow-packs due to less snowfall, water shortage might become a serious problem in some areas.

Regarding specific socio-economic impacts caused by extreme snowfall events, conclusions based on the results presented in this study are difficult to draw. It might be possible that the 99% all-day snowfall percentile we used for defining heavy snowfalls, is not appropriate to speculate about future evolutions of (very) rare events (Schär et al., 2016). To do so, one might consider applying a generalized extreme value (GEV) analysis which is more suitable for answering questions related to rare extreme events.

7 Data Availability

The EURO-CORDEX RCM data analysed in the present work are publicly available - parts of them for non-commercial use only - via the Earth System Grid Federation archive (ESGF; e.g., https://esgf-data.dkrz.de). The observational datasets RHiresD and TabsD as well as the snow depth data for Switzerland are available for research and educational purposes from kundendienst@meteoschweiz.ch. The analysis code is available from the corresponding author on request.

8 Competing Interests

The authors declare that they have no conflict of interest.

9 Acknowledgements

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Figures

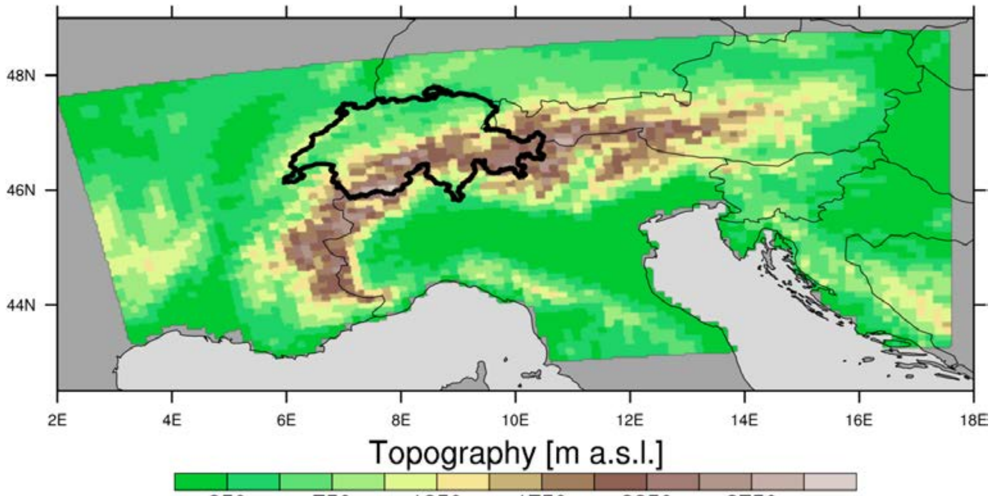


Figure 1 GTOPO30 t~~T~~opography (*https://lta.cr.usgs.gov/GTOPO30*) aggregated to the ~~at~~ EUR-11 (0.11°) RCM grid. ~~resolution of~~ The coloured area shows the Alpine domain used for the assessment of snowfall projections. The bold black outline marks the Swiss sub-domain used for the assessment of the bias adjustment~~correction~~ approach.

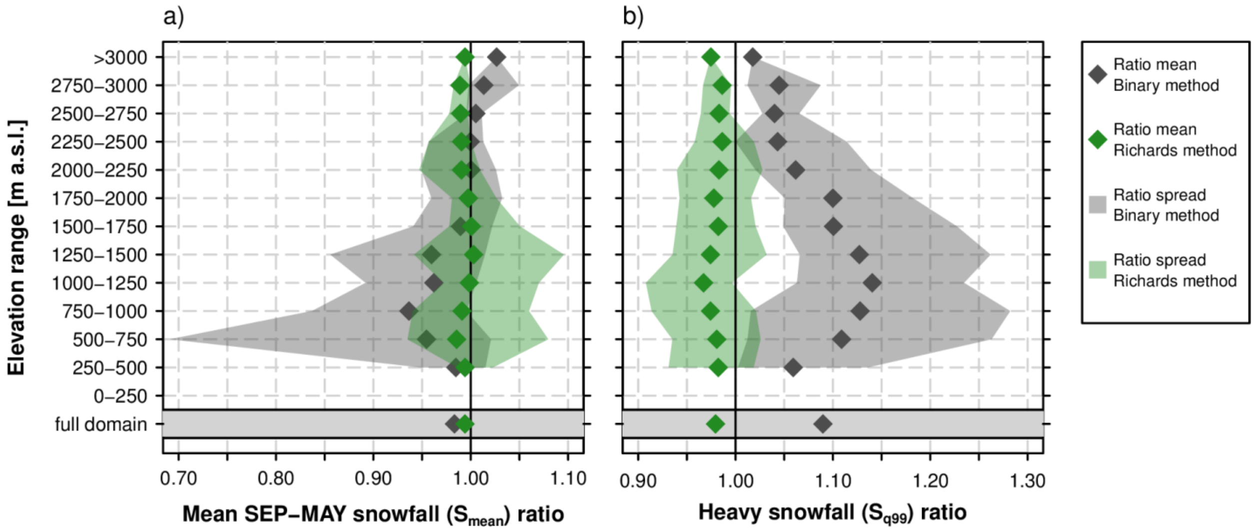
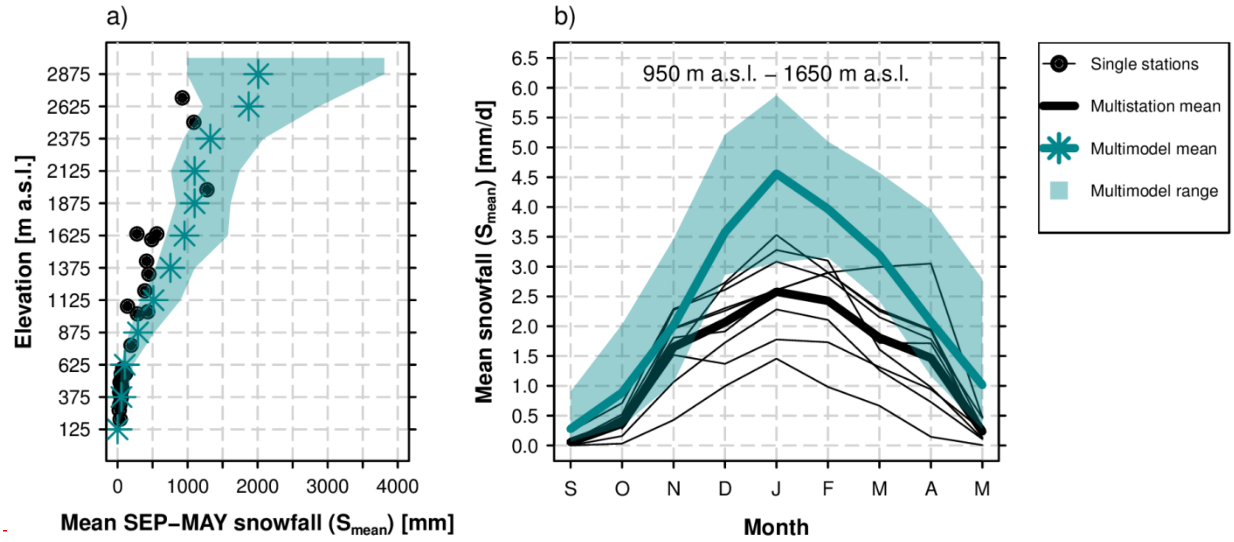


Figure 2 Snowfall ratios for the Binary and Richards snow fractionation method (ratio between the snowfall of the respective method and the ~~full subgrid snow representation~~*Subgrid* method). The ratios are valid at the coa~~u~~rse-resolution grid (12 km). a) Ratios for mean snowfall, S_{mean}. b) Ratios for heavy snowfall, S_{q99}. Ratio means were derived after averaging the corresponding snowfall index for 250 m elevation intervals in Switzerland while the ratio spread represents the minimum and maximum grid point-based ratios in the corresponding elevation interval. This analysis is entirely based on the observational data sets TabsD and RhiresD.



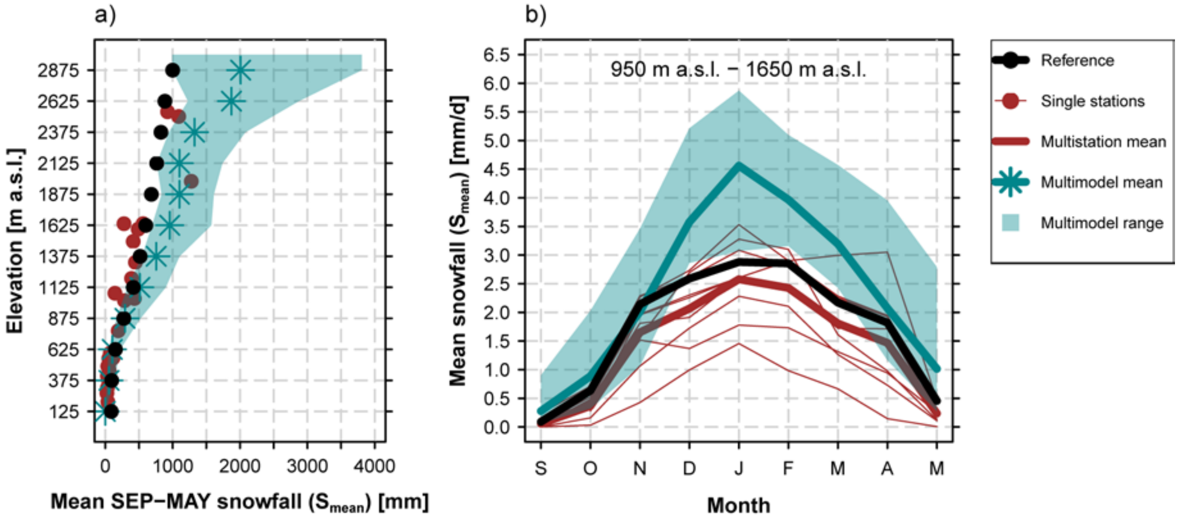


Figure 3 Comparison of measured fresh snow sums of 29 MeteoSwiss stations (red) against vs. simulated RCM raw snowfall in Switzerland (green) and against the 2 km reference snowfall grid obtained by employing the *Subgrid method* (black) in the EVAL period 1971-2005. a) Mean September – May snowfall vs. elevation. Both tThe simulation data (green) and the reference data (black) are based on the spatio-temporal mean of 250 m elevation ranges and plotted at the mean elevation of the corresponding interval. b) Seasonal September-May snowfall cycle for the elevation interval 950 m a.s.l. to 1650 m a.s.l.. Simulated multi-model means and spreads are based on a subset of 9 EURO-CORDEX simulations providing raw snowfall as output variable (see Tab. 1).

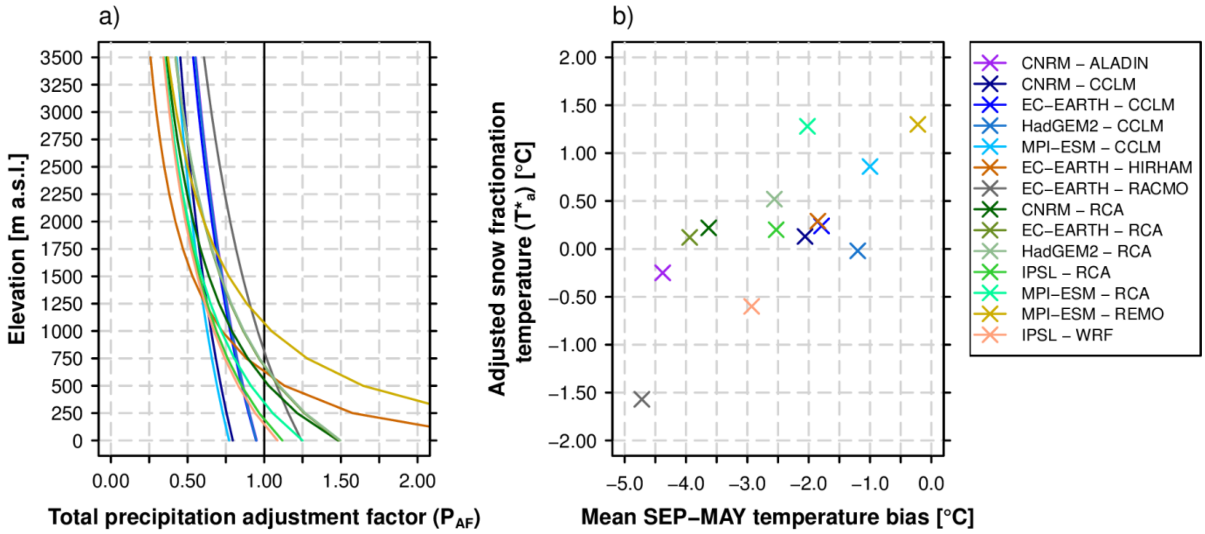


Figure 4 ~~Bias correction and adjustment factors~~Overview on bias adjustment. a) Elevation-dependent total precipitation adjustment factors, P_{AF}, for the 14 GCM-RCM chains (see Eq. 10). b) Scatterplot of mean September to May temperature biases (RCM simulation minus observational analysis) vs. adjusted snow fractionation temperatures, T^*_a.

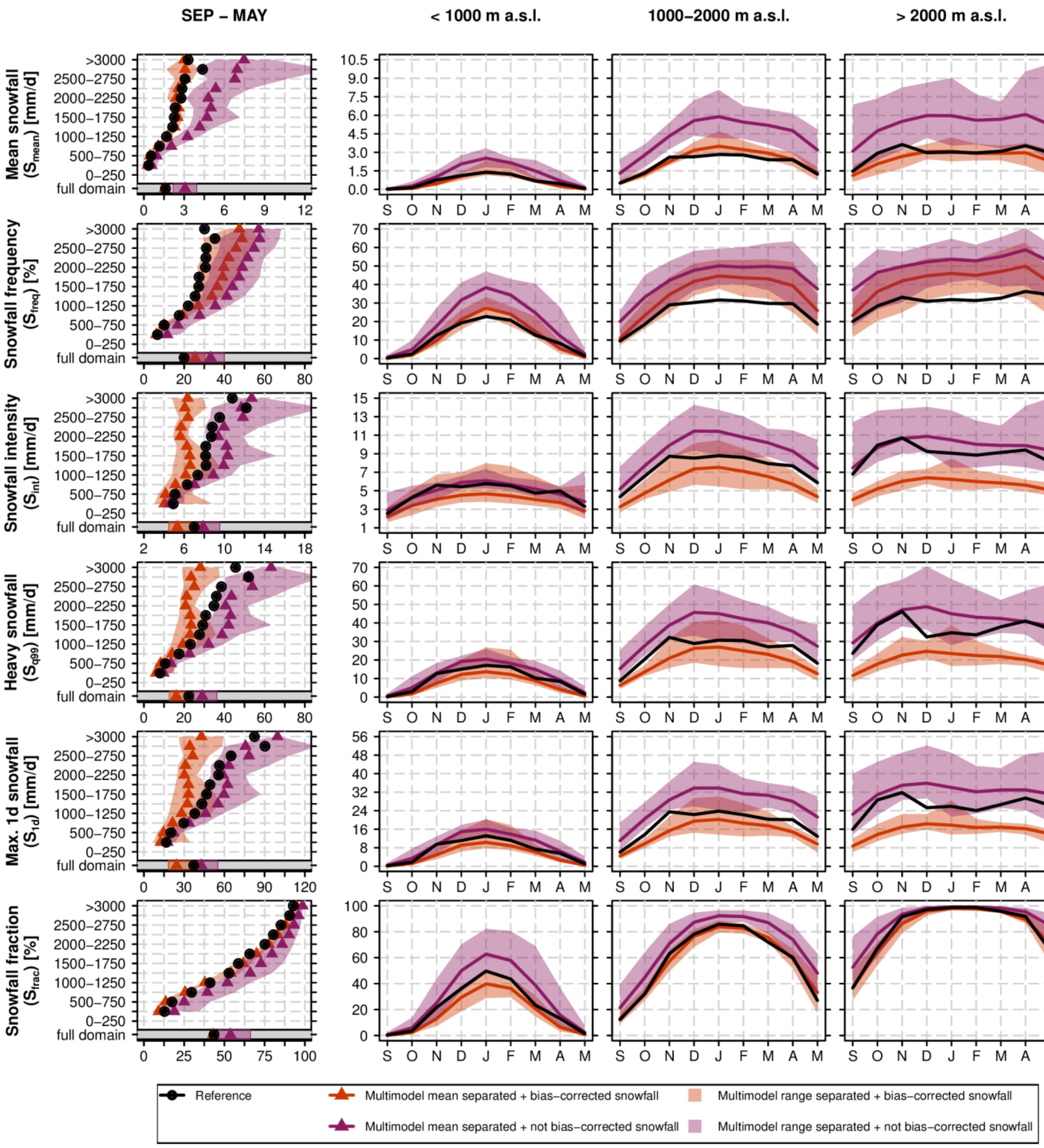


Figure 5 Evaluation of snowfall indices in the EVAL period 1971-2005 for the 14 snowfall separated + bias- corrected adjusted ($RCM_{sep+bae}$) and 14 snowfall separated + not bias- corrected adjusted ($RCM_{sep+nbae}$) RCM simulations vs. observation-based reference. The first column shows the mean September-May snowfall index statistics vs. elevation while the monthly snowfall indices (spatially averaged over the elevation intervals <1000 m.a.s.l., 1000 m a.s.l.-2000 m a.s.l. and >2000 m a.s.l.) are displayed in columns 2-4.

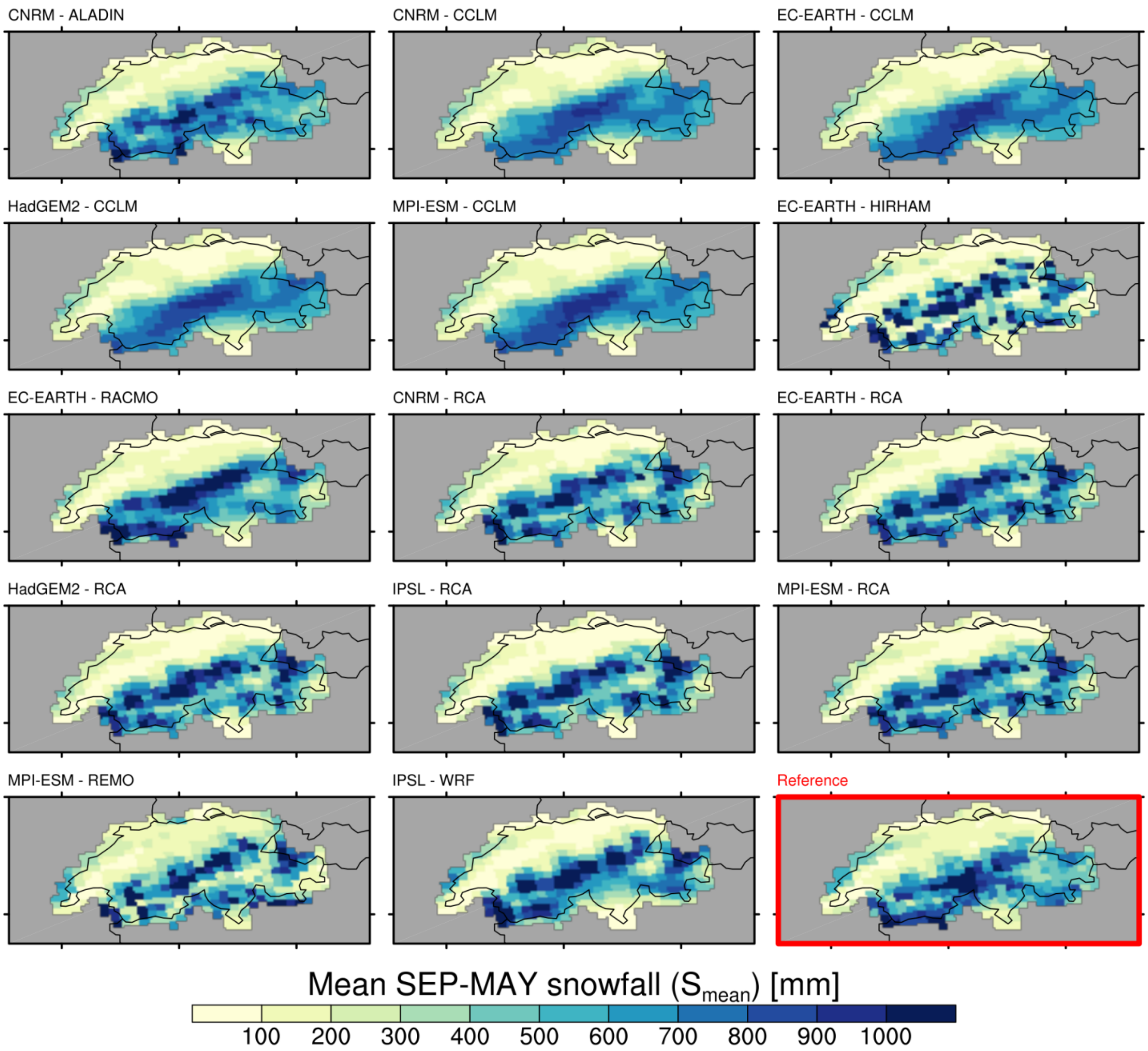


Figure 6 Spatial distribution of mean September-May snowfall, S_{mean}, in the EVAL period 1971-2005 and for the 14 snowfall separated + bias- corrected adjusted RCM simulations ($RCM_{sep+bac}$). In the lower right panel, the map of the observation-based reference is shown.

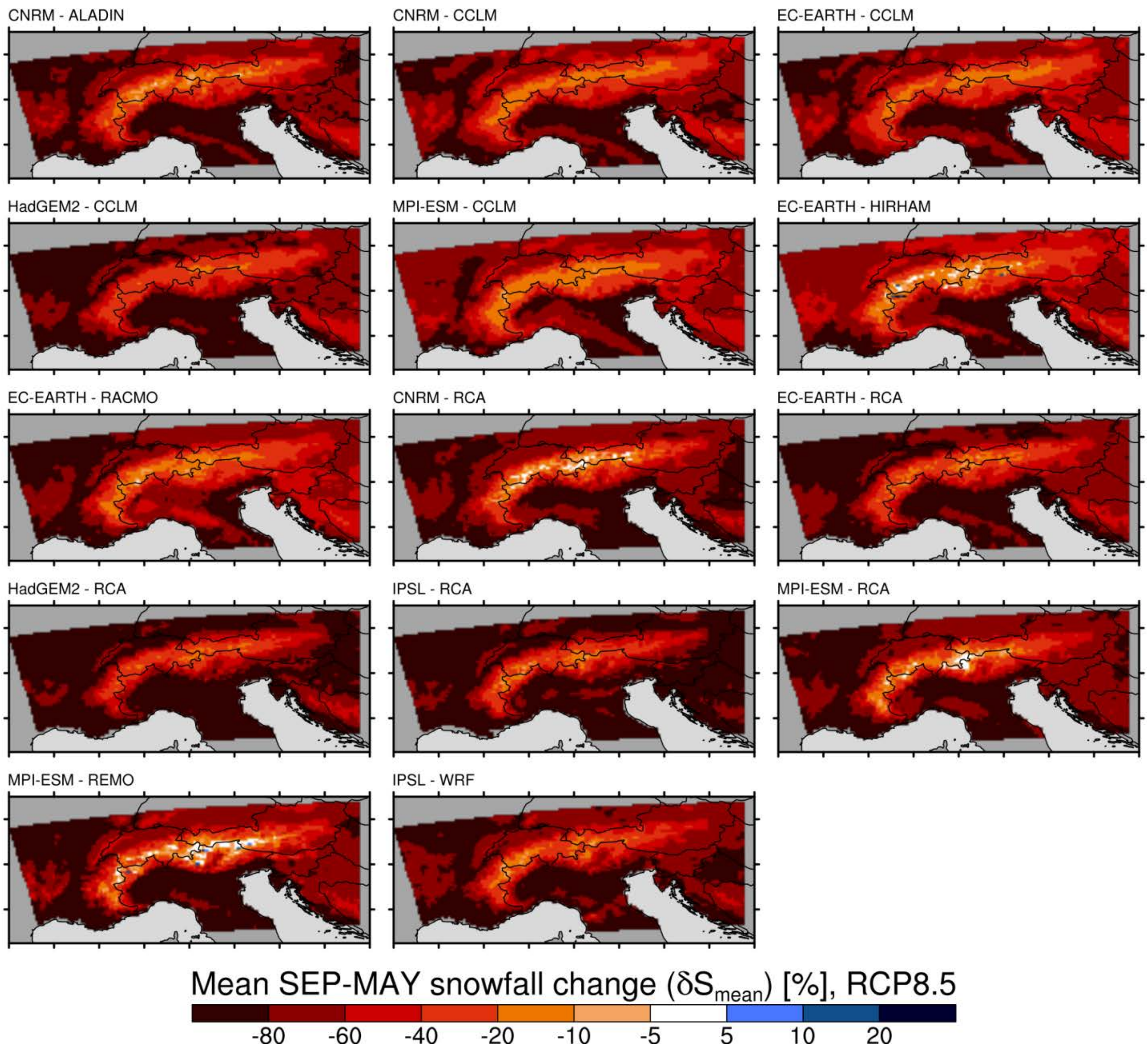


Figure 7 Spatial distribution of relative changes (SCEN period 2070-2099 with respect to CTRL period 1981-2010) in mean September-May snowfall, δS_{mean}, for RCP8.5 and for the 14 snowfall separated + bias- corrected adjusted RCM simulations ($RCM_{sep+bac}$). For RCP4.5, see Fig. S65.

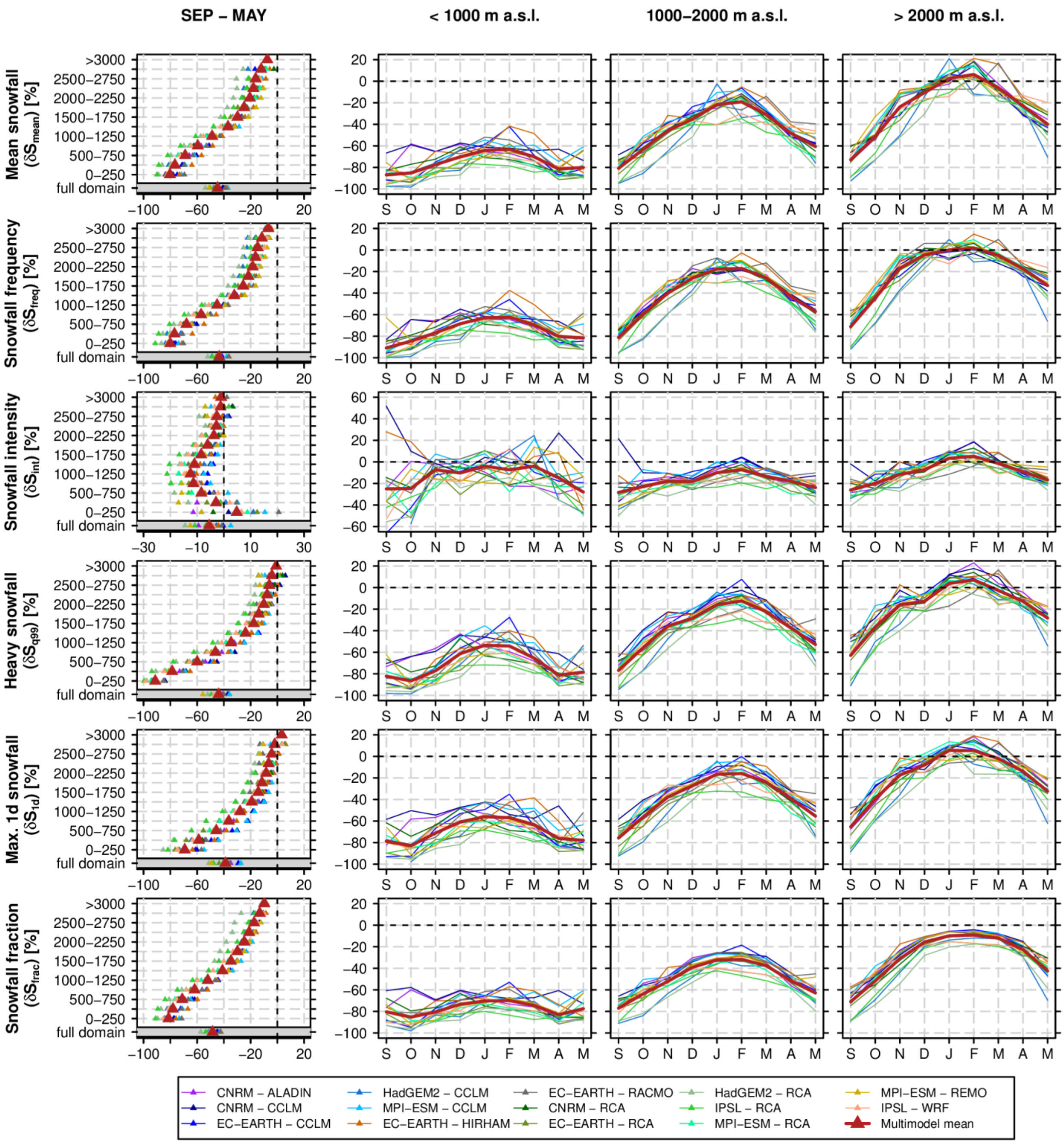


Figure 8 Relative changes (SCEN period 2070-2099 with respect to CTRL period 1981-2010) of snowfall indices based on the 14 snowfall separated + bias- corrected adjusted RCM simulations ($RCM_{sep+bac}$) for RCP8.5. The first column shows the mean September-May snowfall index statistics vs. elevation while monthly snowfall index changes (spatially averaged over the elevation intervals <1000 m.a.s.l., 1000 m a.s.l.-2000 m a.s.l. and >2000 m a.s.l.) are displayed in columns 2-4.

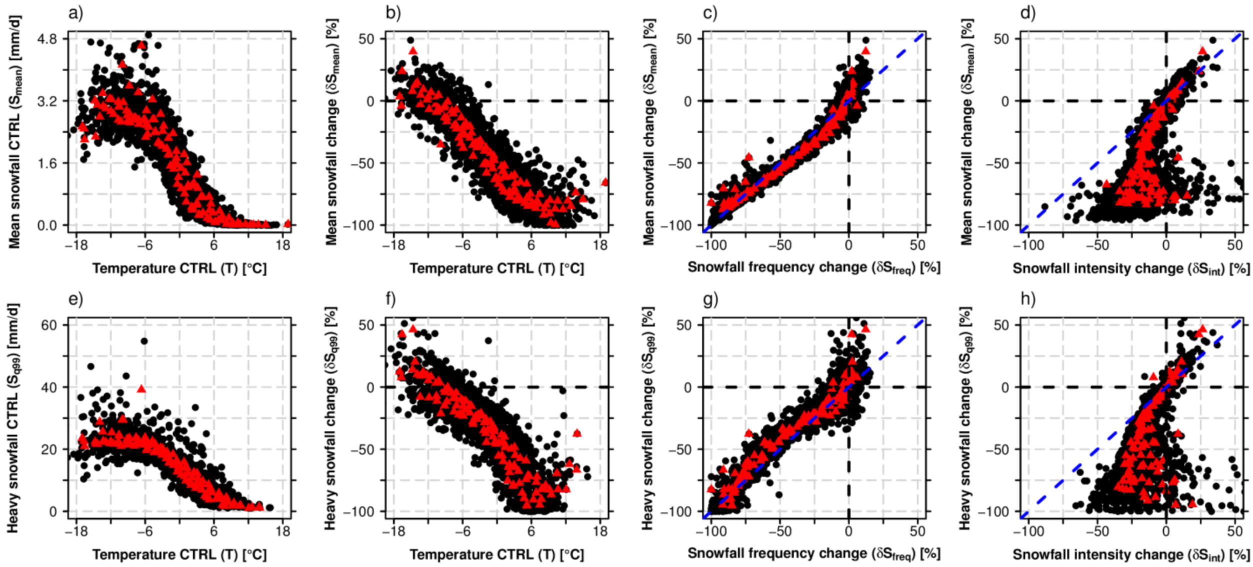


Figure 9 Intercomparison of various snowfall indices and relationship with monthly mean temperature in CTRL. For each panel, the monthly mean statistics for each 250 m elevation interval and for each of the 14 individual GCM-RCM chains were derived (black circles). Red triangles denote the multi-model mean for a specific month and elevation interval. The monthly statistics were calculated by considering all grid points of the specific elevation intervals which are available for both variables in the corresponding scatterplot only (area consistency). The data were taken from the 14 snowfall separated + bias- ~~corrected~~ adjusted (RCM$_{sep+ba\sout{c}}$) RCM simulations. Relative changes are based on the RCP8.5 driven simulations (SCEN 2070-2099 wrt. CTRL 1981-2010).

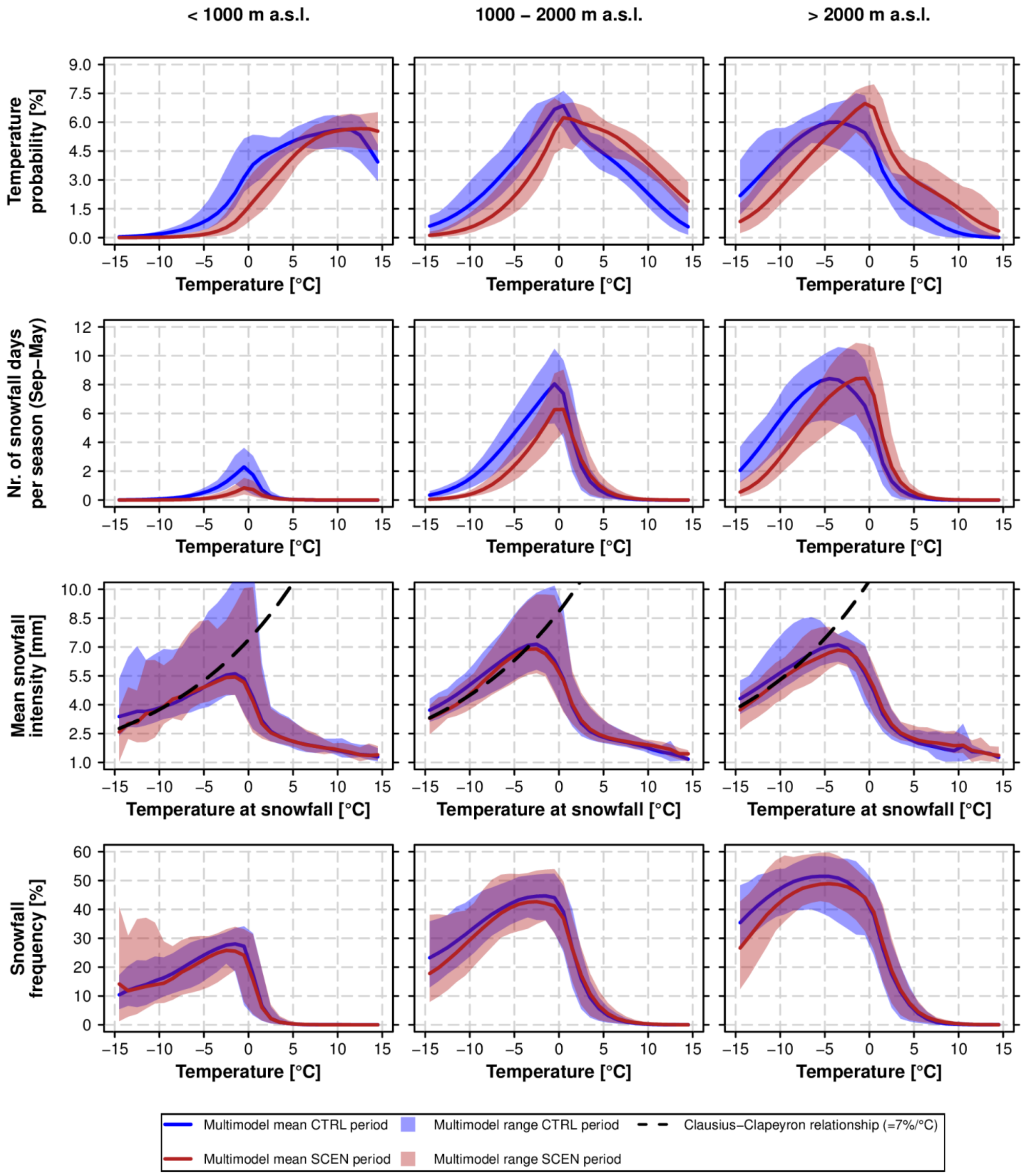


Figure 10 Comparison of temperature probability, snowfall probability and mean snowfall intensity for the CTRL period 1981-2010 and SCEN period 2070-2099 for RCP8.5. The analysis is based on data from the 14 snowfall separated + bias- corrected adjusted RCM simulations ($RCM_{sep+bae}$). The top row depicts the PDF of the daily temperature distribution, while the second row shows the mean number of snowfall days between September and May, i.e., days with S > 1 mm/d (see Tab. 2), in a particular temperature interval. The third row represents the mean snowfall intensity, S_{int}, for a given snowfall temperature intervall. In addition the Clausius-Clapeyron relationship, centred at the -10°C mean S_{int} for SCEN, is displayed by the black dashed line. PDFs and mean S_{int} were calculated by creating daily mean temperature bins of width 1 °C.

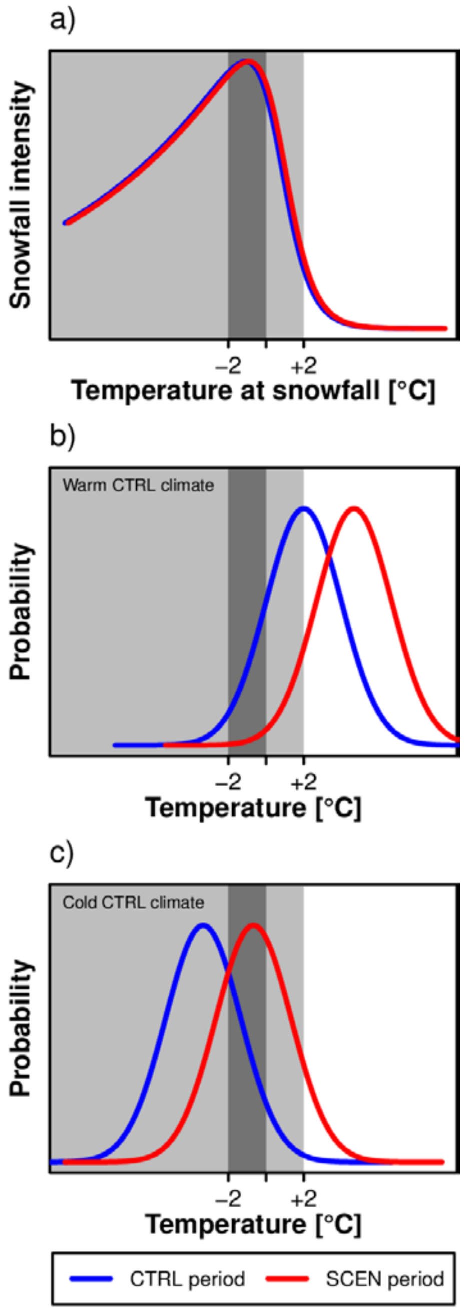


Figure 11 Schematic illustration of the control of changes in snowfall intensity on changes in mean and extreme snowfall. a) Relation between temperature and mean snowfall intensity. b) Daily temperature PDF for a warm control climate (low elevations or transition seasons, i.e., beginning or end of winter). c) Daily temperature PDF for a cold control climate (high elevations or mid-winter). The blue line denotes the historical CTRL period, the red line the future SCEN period. The light grey shaded area represents the overall temperature interval at which snowfall occurs, the dark grey shading shows the preferred temperature interval for heavy snowfall to occur.

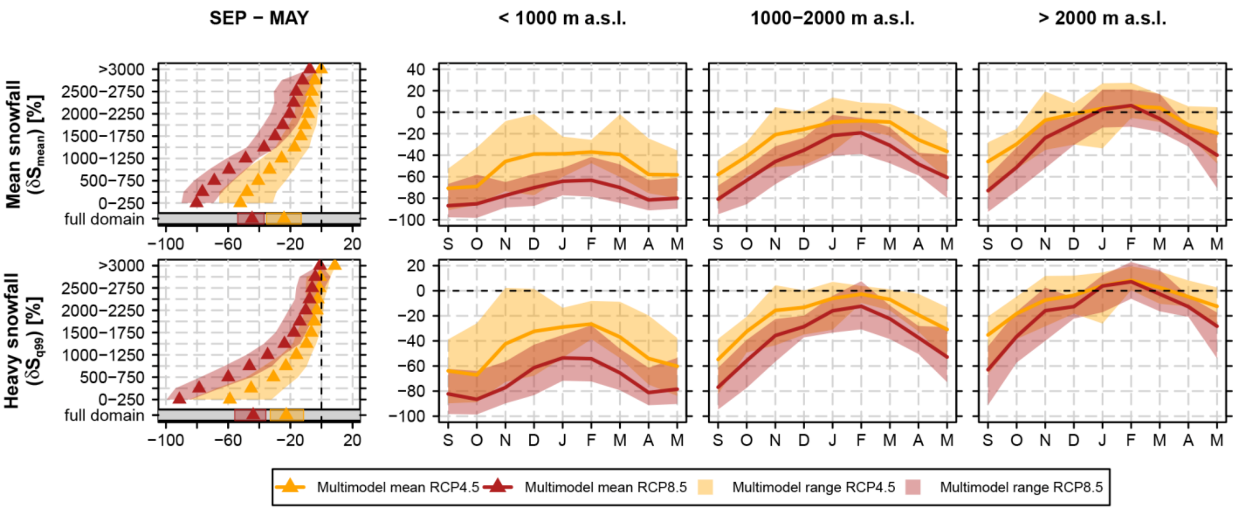
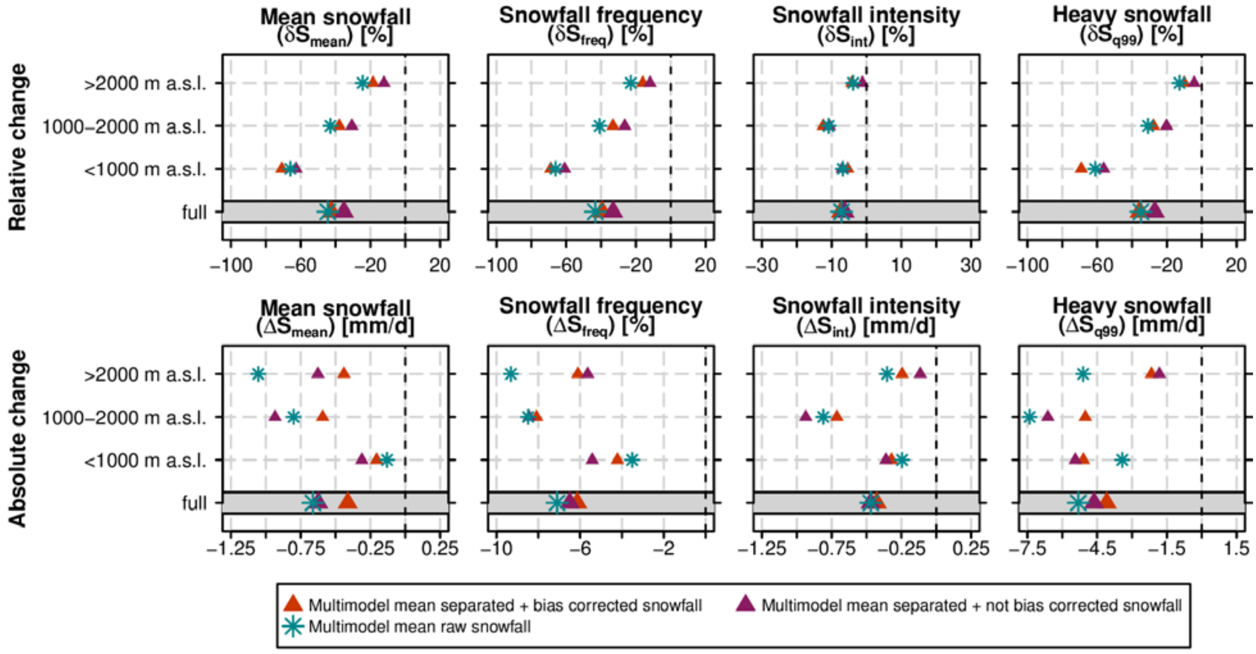


Figure 12 Similar as Figure 8 but showing projected changes of mean snowfall, δS_{mean}, and heavy snowfall, δS_{q99}, for the emission scenarios RCP4.5 and 8.5. See Fig. S98 for the emission scenario uncertainty of the remaining four snowfall indices.



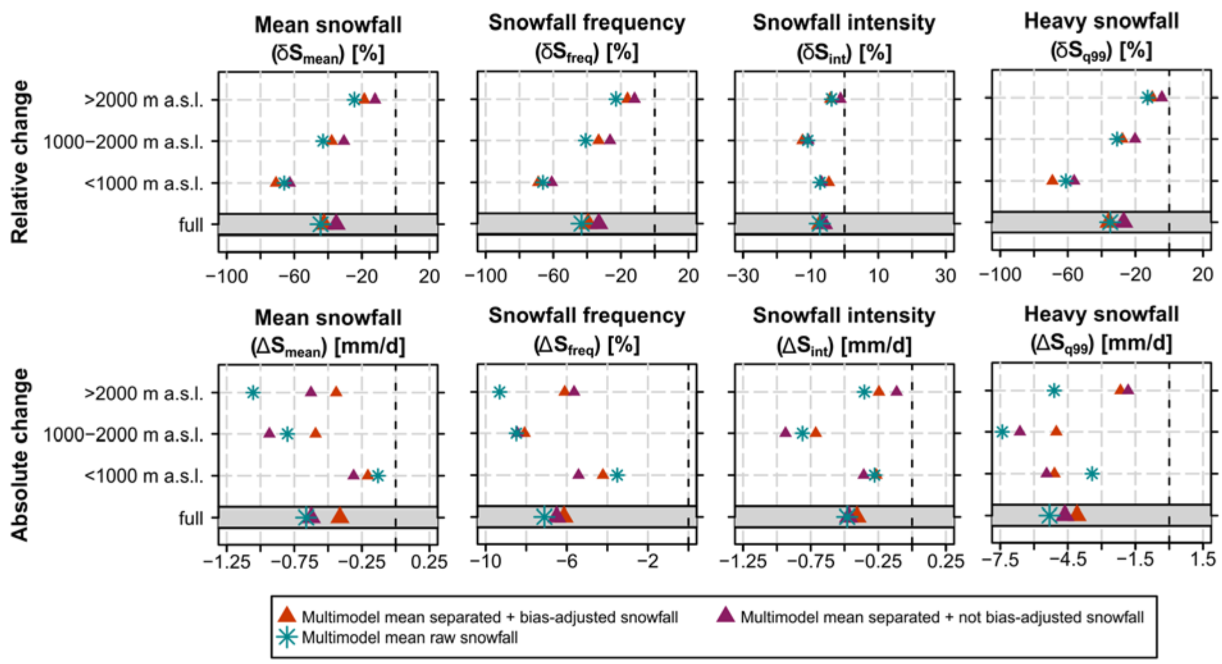


Figure 13 Relative and absolute changes (SCEN period 2070-2099 with respect to CTRL period 1981-2010) of mean September-May snowfall indices based on a subset of 9 snowfall separated + bias~~- corrected~~ adjusted (RCM$_{sep+bac}$), 9 snowfall separated + not bias~~- corrected~~ adjusted (RCM$_{sep+nbac}$) and 9 raw snowfall RCM simulations (RCM$_{raw}$) for RCP8.5. Only RCM simulations providing raw snowfall as output variable (see Tab. 1) were used in this analysis.

Tables

Table 1 Overview on the 14 EURO-CORDEX simulations available for this study. The whole model set consists of seven RCMs driven by five different GCMs. All experiments were realized on a grid, covering the European domain, with a horizontal resolution of approximately 12.5 km (EUR-11) and were run for control RCP4.5 and RCP8.5 scenarios within the considered time periods of interest. A subset of 9 simulations provides raw snowfall, i.e., snowfall flux in kg/m^2s, as output variable. For full institutional names the reader is referred to the official EURO-CORDEX website www.euro-cordex.net. Note that the EC-EARTH-driven experiments partly employ different realizations of the GCM run, i.e., explicitly sample the influence of internal climate variability in addition to model uncertainty.

RCM	**GCM**	**Acronym**	**Institute ID**	**Raw snowfall output**
ALADIN53	CNRM-CERFACS-CNRM-CM5	CNRM - ALADIN	CNRM	no
CCLM4-8-17	CNRM-CERFACS-CNRM-CM5	CNRM - CCLM	CLMcom/BTU	no
CCLM4-8-17	ICHEC-EC-EARTH	EC-EARTH - CCLM	CLMcom/BTU	no
CCLM4-8-17	MOHC-HadGEM2-ES	HadGEM2 - CCLM	CLMcom/ETH	no
CCLM4-8-17	MPI-M-MPI-ESM-LR	MPI-ESM - CCLM	CLMcom/BTU	no
HIRHAM5	ICHEC-EC-EARTH	EC-EARTH - HIRHAM	DMI	yes
RACMO22E	ICHEC-EC-EARTH	EC-EARTH - RACMO	KNMI	yes
RCA4	CNRM-CERFACS-CNRM-CM5	CNRM - RCA	SMHI	yes
RCA4	ICHEC-EC-EARTH	EC-EARTH - RCA	SMHI	yes
RCA4	MOHC-HadGEM2-ES	HadGEM2 - RCA	SMHI	yes
RCA4	IPSL-IPSL-CM5A-MR	IPSL - RCA	SMHI	yes
RCA4	MPI-M-MPI-ESM-LR	MPI-ESM – RCA	SMHI	yes
REMO2009	MPI-M-MPI-ESM-LR	MPI-ESM – REMO*	MPI-CSC	yes
WRF331F	IPSL-IPSL-CM5A-MR	IPSL - WRF	IPSL-INERIS	yes

* r1i1p1 realisation

Table 2 Analysed snowfall indices. The last column indicates the threshold value in the CTRL period for considering a grid cell in the climate changes analysis (grid cells with smaller values are skipped for the respective analysis); first number: threshold for monthly analyses, second number: threshold for seasonal analysis.

Index name	**Acronym**	**Unit**	**Definition**	**Threshold for monthly / seasonal analysis**
Mean snowfall	S_{mean}	mm	(Spatio-)temporal mean snowfall in mm snow water equivalent (only “mm" thereafter).	1 mm / 10 mm
Heavy snowfall	S_{q99}	mm/d	Grid point-based 99% all day snowfall percentile.	1 mm / 1 mm
Max. 1 day snowfall	S_{1d}	mm/d	Mean of each season’s or month’s maximum 1 day snowfall.	1 mm / 1 mm
Snowfall frequency	S_{freq}	%	Percentage of days with snowfall S>1mm/d within a specific time period.	1 % / 1 %
Snowfall intensity	S_{int}	mm/d	Mean snowfall intensity at days with snowfall S>1mm/d within a specific time period.	S_{freq} threshold passed
Snowfall fraction	S_{frac}	%	Percentage of total snowfall, S_{tot}, on total precipitation, P_{tot}, within a specific time period.	1 % / 1 %