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*Supplement of*

# Bias adjustment and downscaling of snow cover fraction projections from regional climate models using remote sensing for the European Alps

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**Figures**

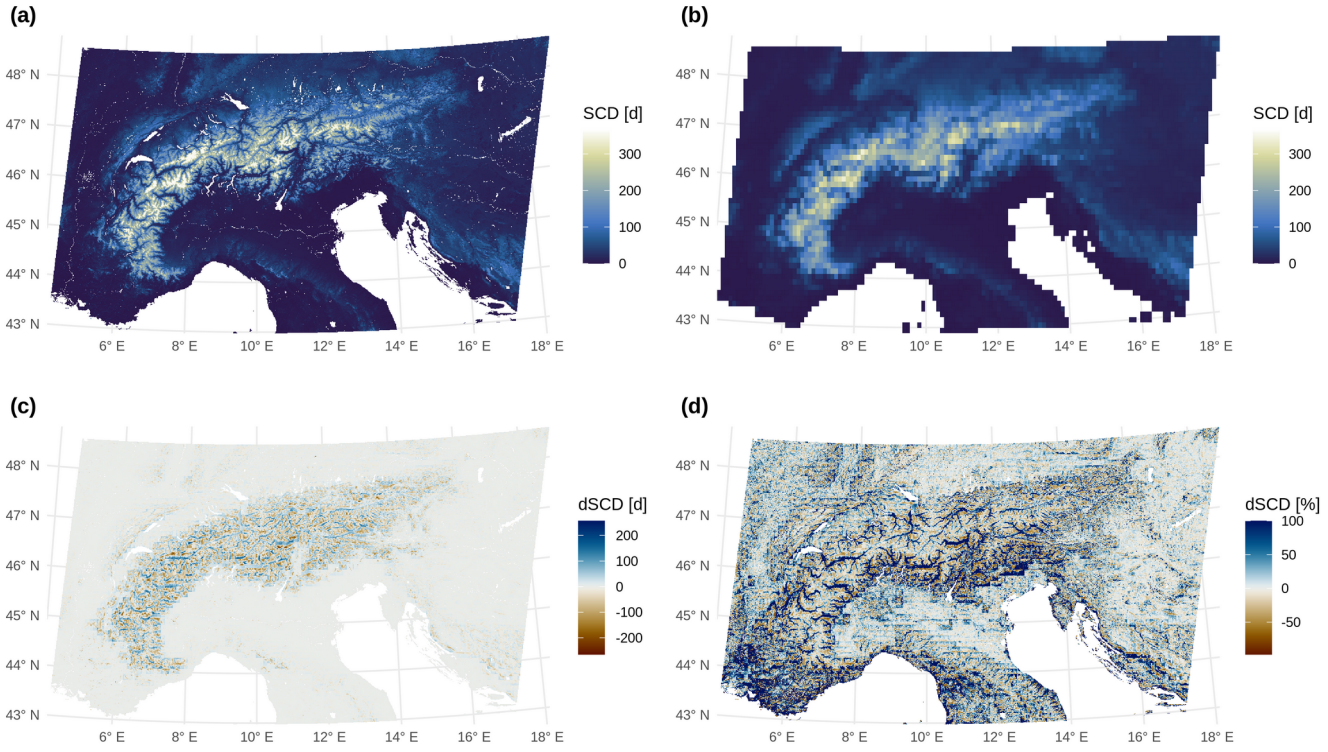


**Figure S1. Average annual snow cover duration (SCD) 2001-2020 at high and low resolution, and their differences. (a) SCD at 250 m .(b) SCD at 0.11°, aggregated from the map in (a). (c) Absolute differences in snow cover duration (dSCD) between (b) and (a). (d) Same as (c), but relative differences.**

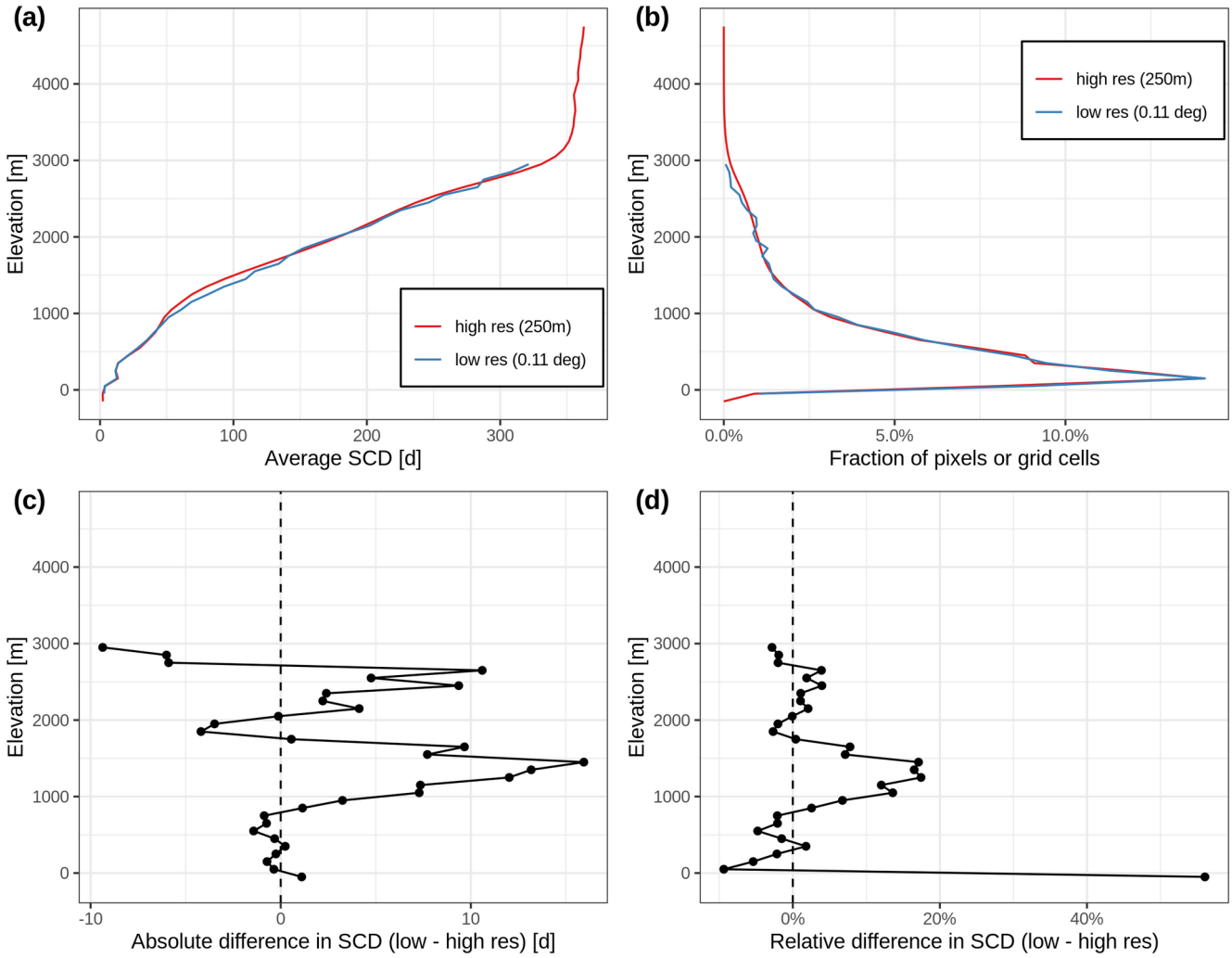


**Figure S2. Impact of aggregating annual snow cover duration (SCD) maps from 250 m to 0.11° on SCD averaged by elevation. (a) SCD averaged by elevation (in 100 m bins) from high (250 m) and low resolution (0.11°) maps; low resolution map is aggregated from the 250 m map. (b) Relative distribution of the elevation of pixels (250 m) and grid cells (0.11 °); grid cells aggregated from the same elevation map at 250 m. (c) Absolute differences in SCD by elevation (averaged over 100 m bins) between low and high resolution SCD maps. (d) Same as (c), but relative differences.**

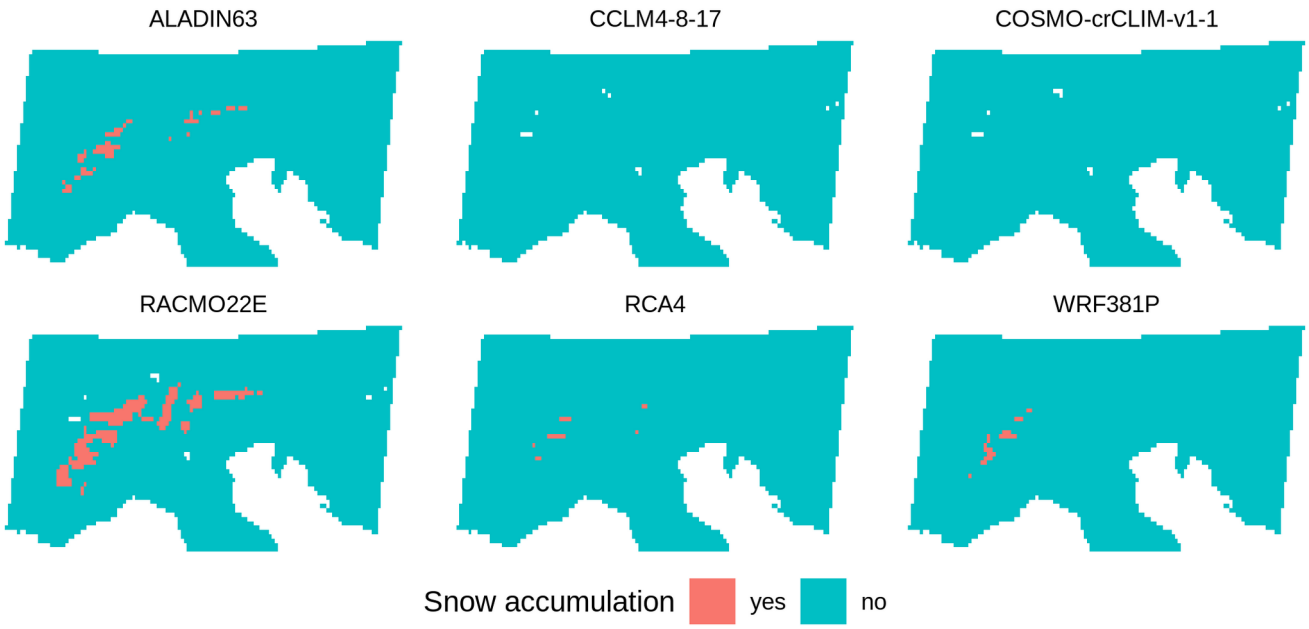


**Figure S3. Grid cells excluded due to unrealistic snow accumulation.**

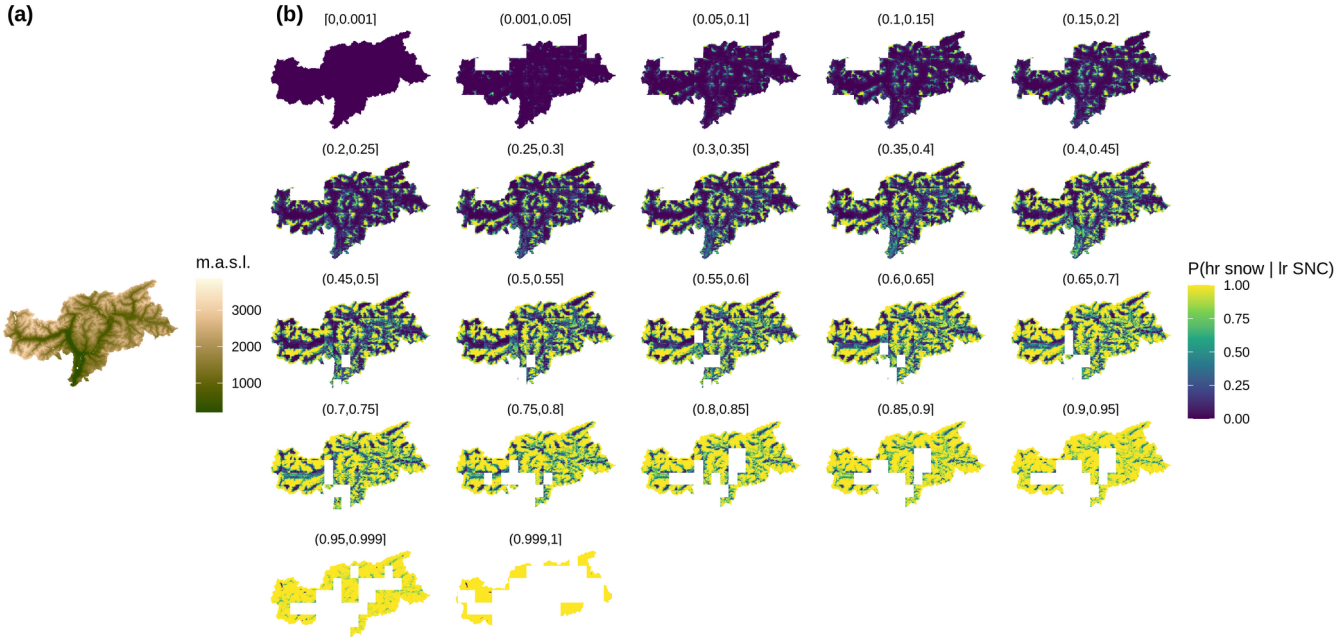


**Figure S4. Elevation (a) and example conditional probability (b) for the South Tyrol province in northern Italy. (b) shows the probability that a high-resolution (hr) pixel is snow covered depending on the snow cover fraction (SNC) of the encompassing low-resolution (lr) grid cell. The title of each panel denotes the SNC bin. Empty/missing areas imply that less or equal than 30 observations were available for this SNC bin.**

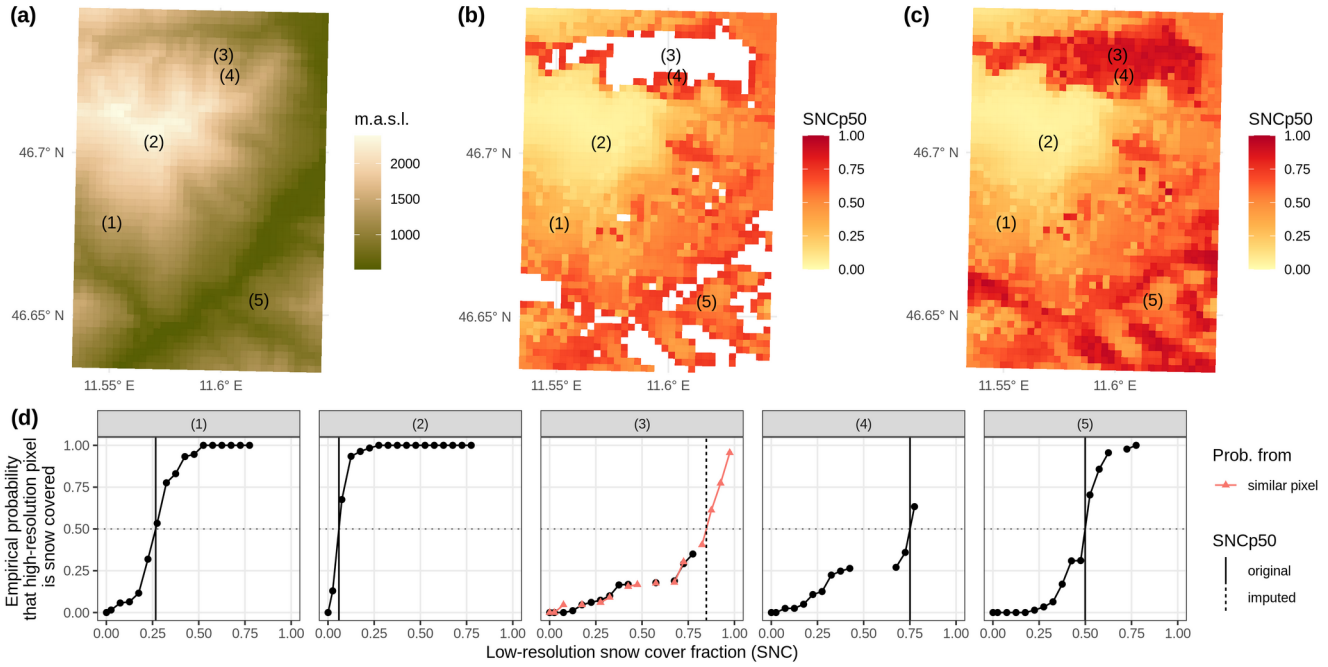


**Figure S5. Downscaling method exemplified at one low-resolution grid cell. (a) Elevation of high-resolution pixels within example low-resolution grid cell. (b) Low-resolution snow cover fraction threshold at which the probability that the high-resolution pixel is snow covered exceeds 0.5 (SNCp50). (c) Same as (b) but after imputation based on similarity of probability curves (as well as similarity of low-resolution sub-grid topography). (d) Empirically estimated probability curves that high-resolution pixels are snow covered depending on the low-resolution snow cover fraction. Labels (1) to (5) denote five example high-resolution pixels in panels (a-d).**

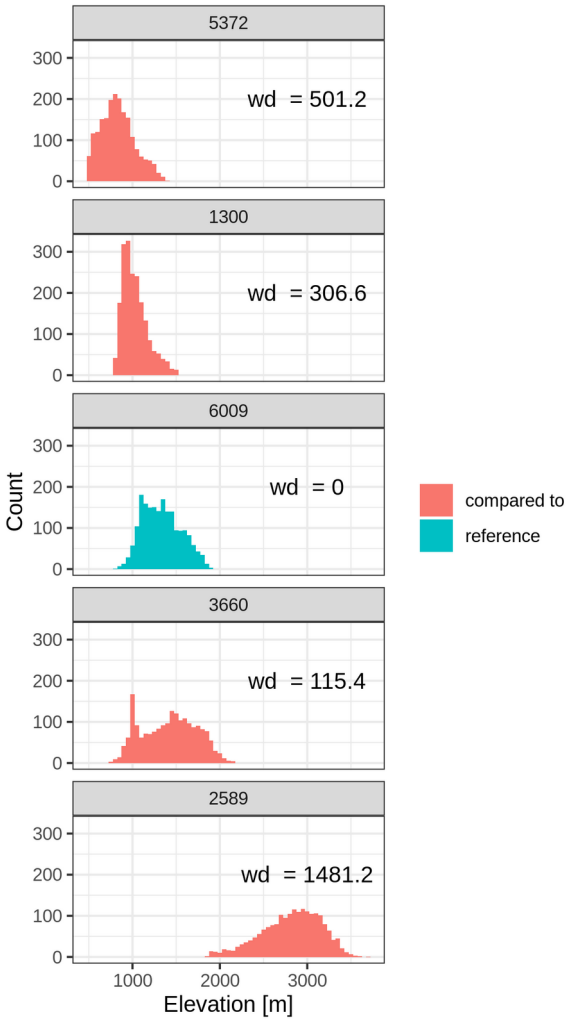


**Figure S6. Example elevation distributions and Wasserstein distances (wd). The five panels correspond to five low-resolution grid cells. Each panel shows the distribution of the elevation of all high-resolution pixels within the respective grid cell. The Wasserstein distances (wd) to the reference grid cell (6009, third panel) are given as text in each panel.**

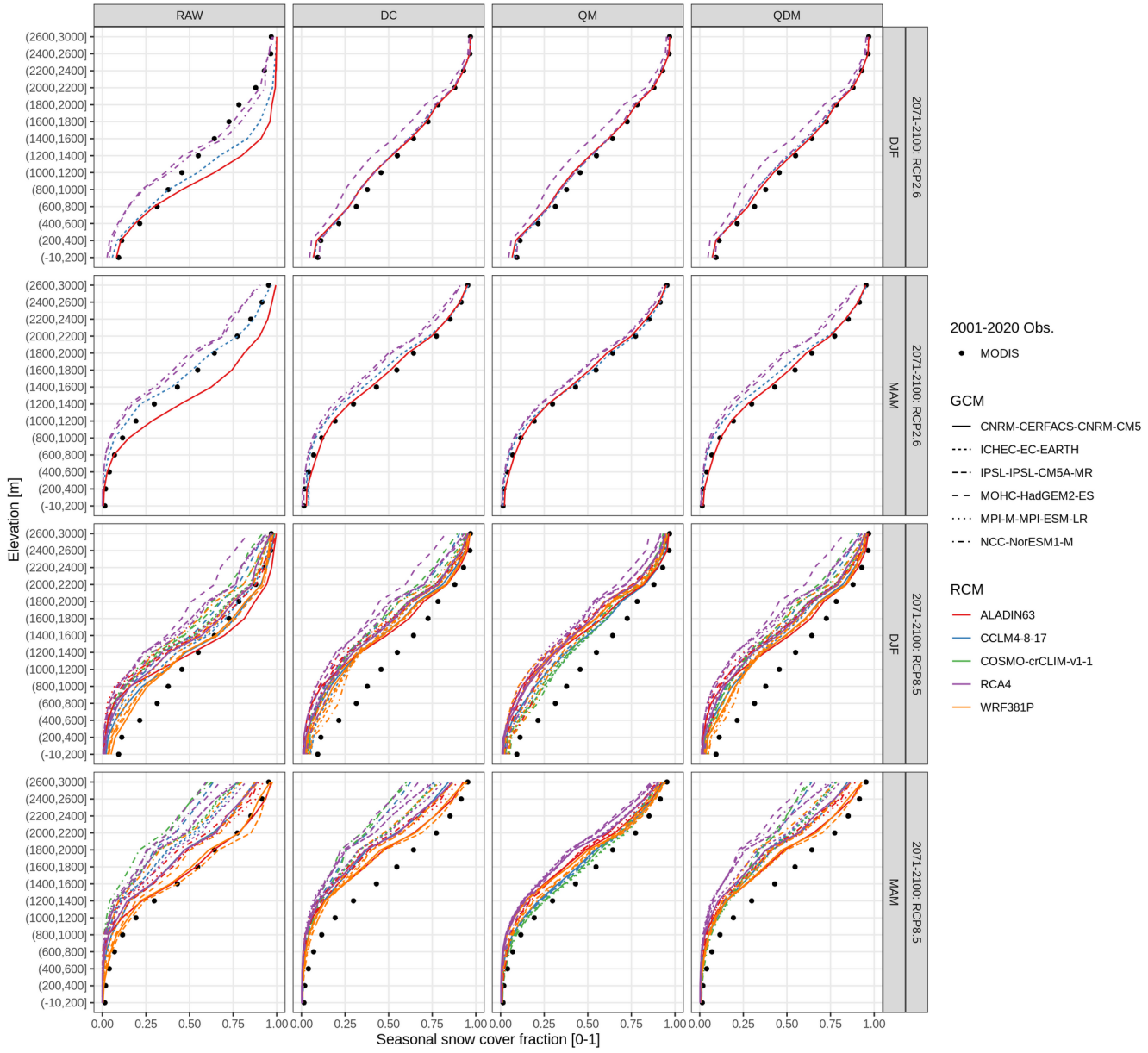


**Figure S7. Observed and projected seasonal snow cover fraction by elevation. Black points denote observations from remote sensing for the period 2001-2020 (the same in all panels), and colored lines the regional climate model (RCM) simulations with associated general circulation model (GCM) for the future period 2071-2100. Rows denote emission scenario (RCP, representative concentration pathway) and season (DJF: December to February, MAM: March to May). Column RAW is for original RCM output, DC is the delta change approach, QM is quantile mapping, and QDM quantile delta mapping.**

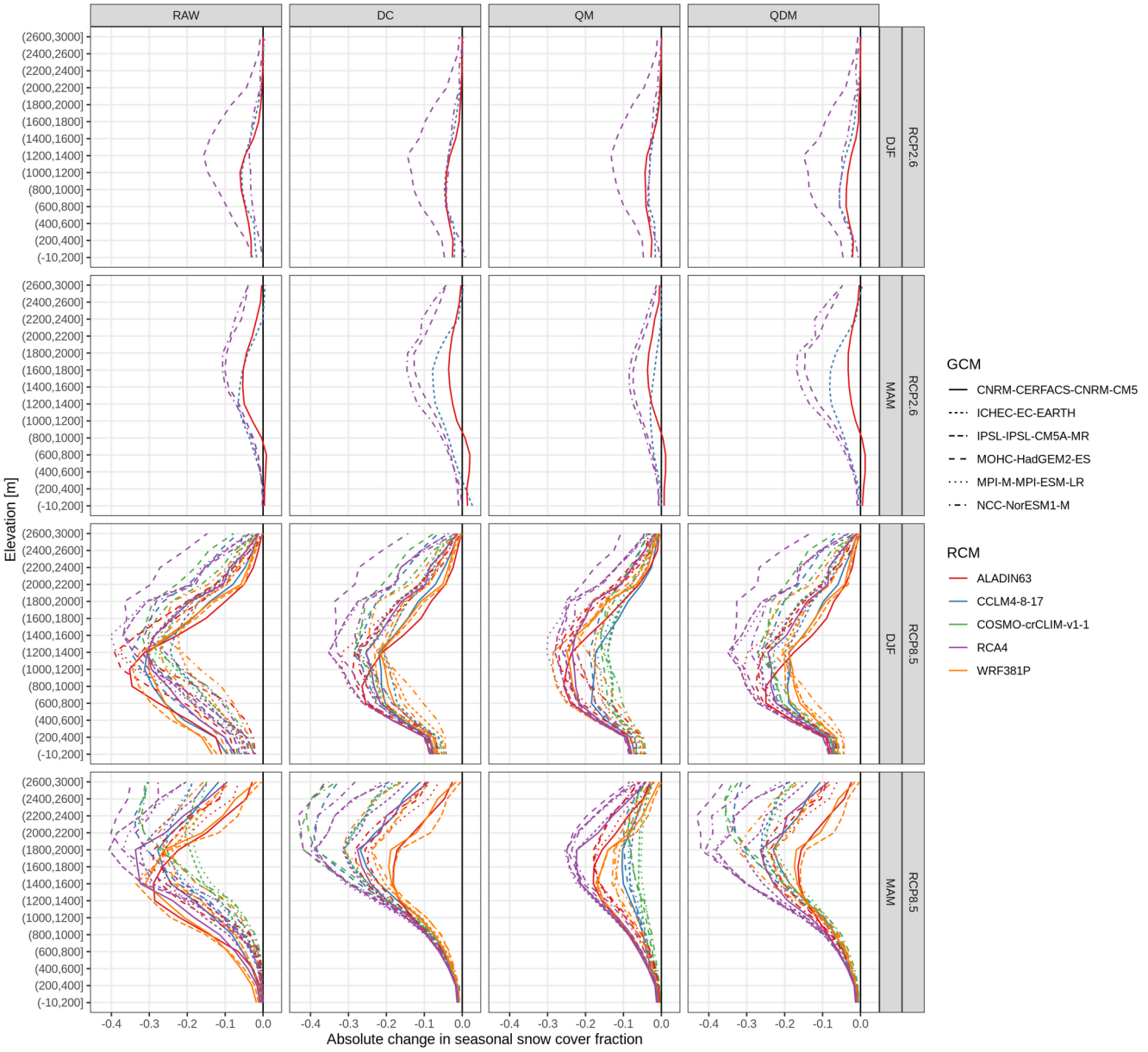


**Figure S8. Absolute changes in future seasonal snow cover fraction relative to the past. Same information as in Figure S7 as differences between future and past model output.**

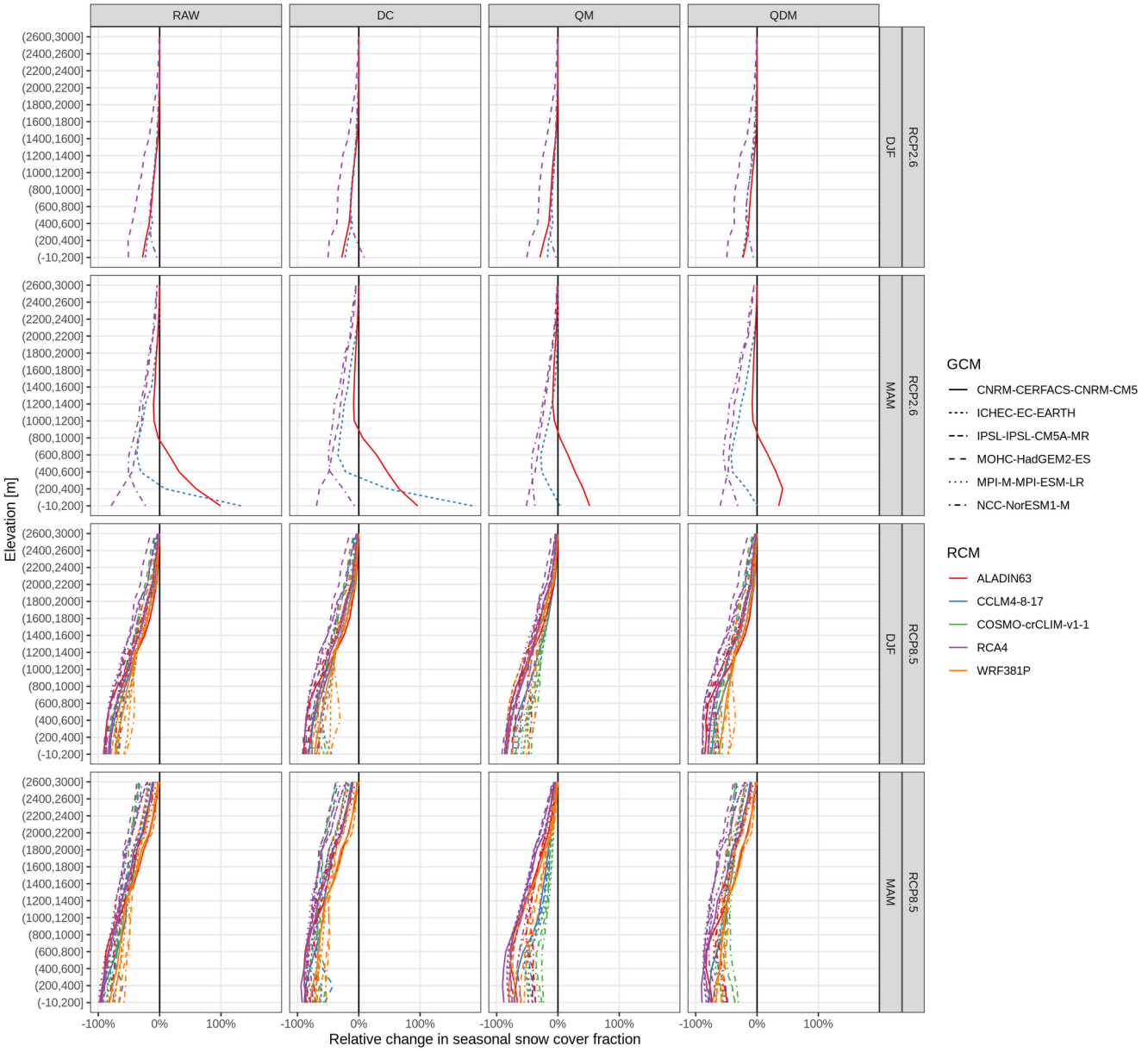


**Figure S9. Relative changes in future seasonal snow cover fraction. Same information as in Figure S7 and S8, but as difference between future and past model output, relative to the past.**

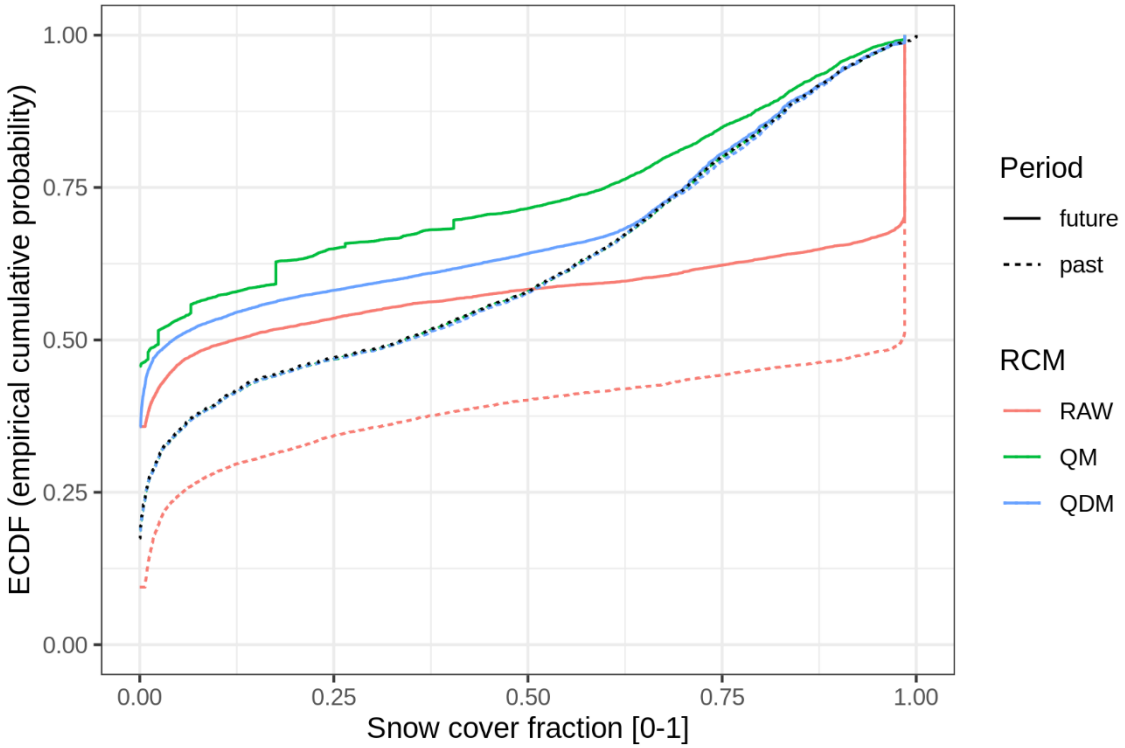


**Figure S10. Empirical cumulative probability distribution (ECDF) of daily snow cover fraction for a single grid cell of the SMHI-RCA4 regional climate model (RCM) by period and bias adjustment algorithm. Dotted black line shows the ECDF of MODIS observations for the past (2001-2020), while the coloured dashed lines are the RCM data for the same period, original (RAW) and bias adjusted using QM (quantile mapping) and QDM (quantile delta mapping). Dashed lines of QM and QDM coincide with observations (by definition), and thus might be not visible. Coloured solid lines are RCM for the future (2071-2100) under a strong warming scenario (RCP8.5).**

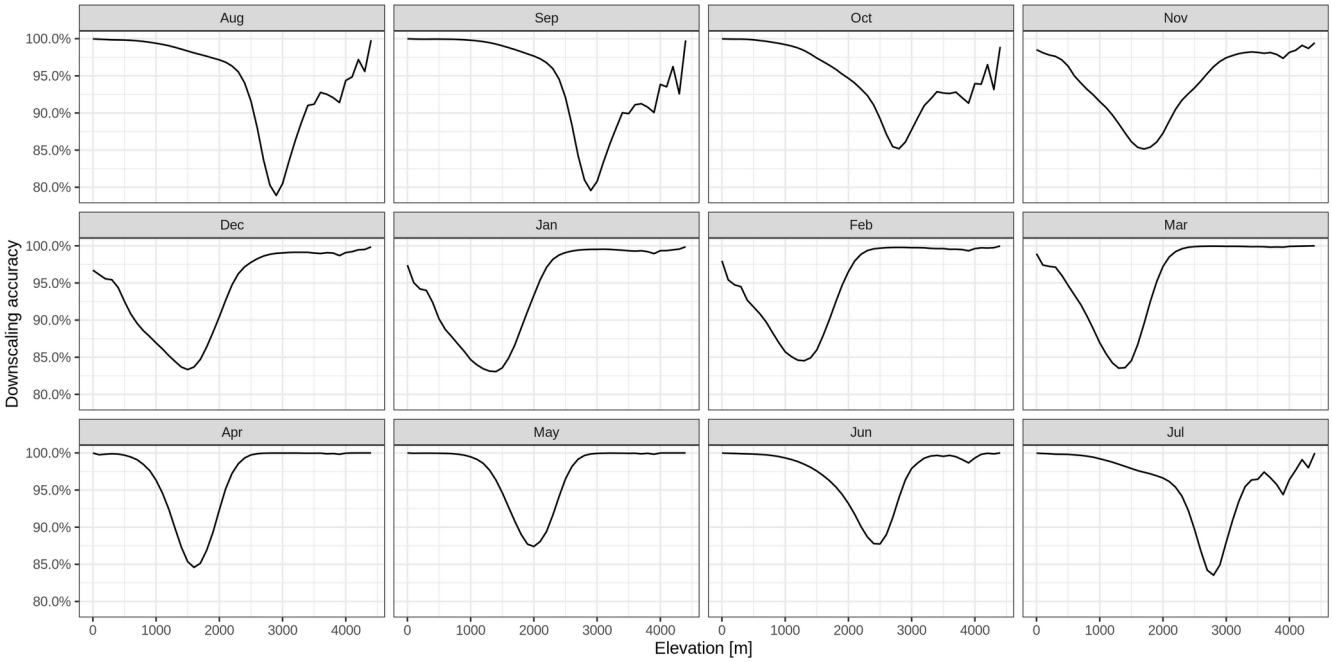


**Figure S11. Overall accuracy of downscaling procedure from internal validation, where the downscaling has been applied to upscaled observed MODIS data, and then compared to the original daily maps used in the upscaling. Accuracy is defined as fraction of correctly downscaled pixels over all pixels. Lines show aggregated values for elevation bins of 100 m (x-axis), and by month (sub-panels).**

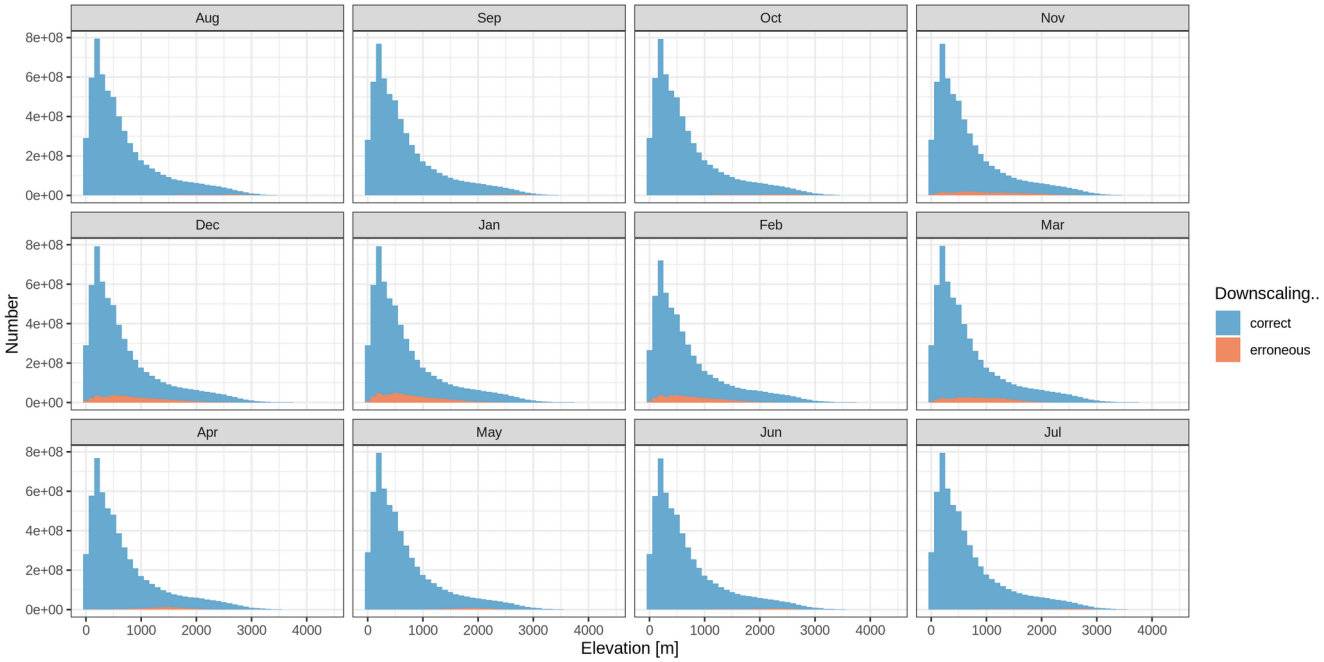


**Figure S12. Validation of downscaling accuracy in absolute terms. The downscaling has been applied to upscaled observed MODIS data, and then compared to the original daily maps used in the upscaling. The histogram shows the absolute number of correctly and erroneously downscaled pixels (snow and land) for elevation bins of 100 m (x-axis), and by month (sub-panels). The total number of evaluated pixels is approximately 71 billions.**

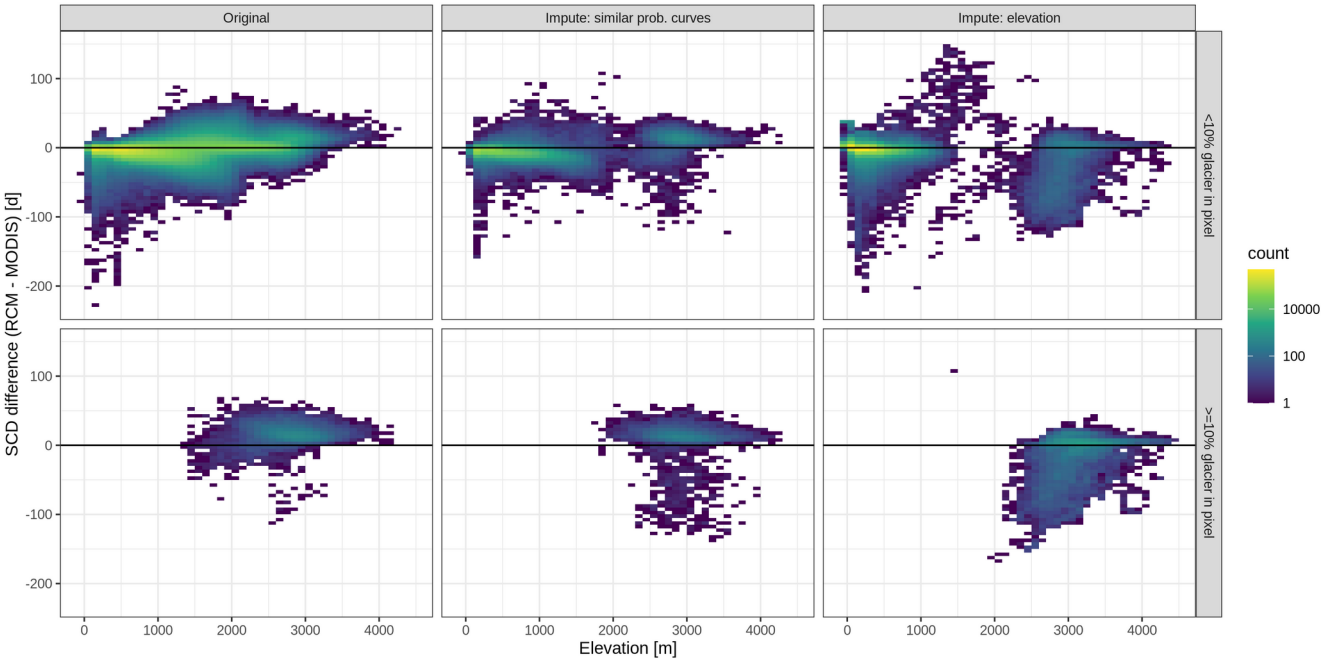


**Figure S13. Downscaling errors in snow cover duration climatology. Difference in 2001-2020 annual snow cover duration (SCD) between a downscaled bias adjusted RCM and high-resolution observations from MODIS. The RCM shown here is CLMcom-CCLM4-8-17 driven by CNRM-CERFACS-CNRM-CM5 and bias adjusted with quantile delta mapping. But since all past bias adjusted RCMs have, by definition, the same snow cover fraction distribution as low-resolution MODIS observations, the choice is arbitrary. The different columns denote where the SNC threshold for downscaling originates from: empirical probability curves (left), imputed from pixels with similar probability curves (middle), and imputed from pixels with similar elevation (right); see methods in main manuscript for more details. The rows divide by pixels having less or more than 10% glacierized area (based on RGI v6.0).**

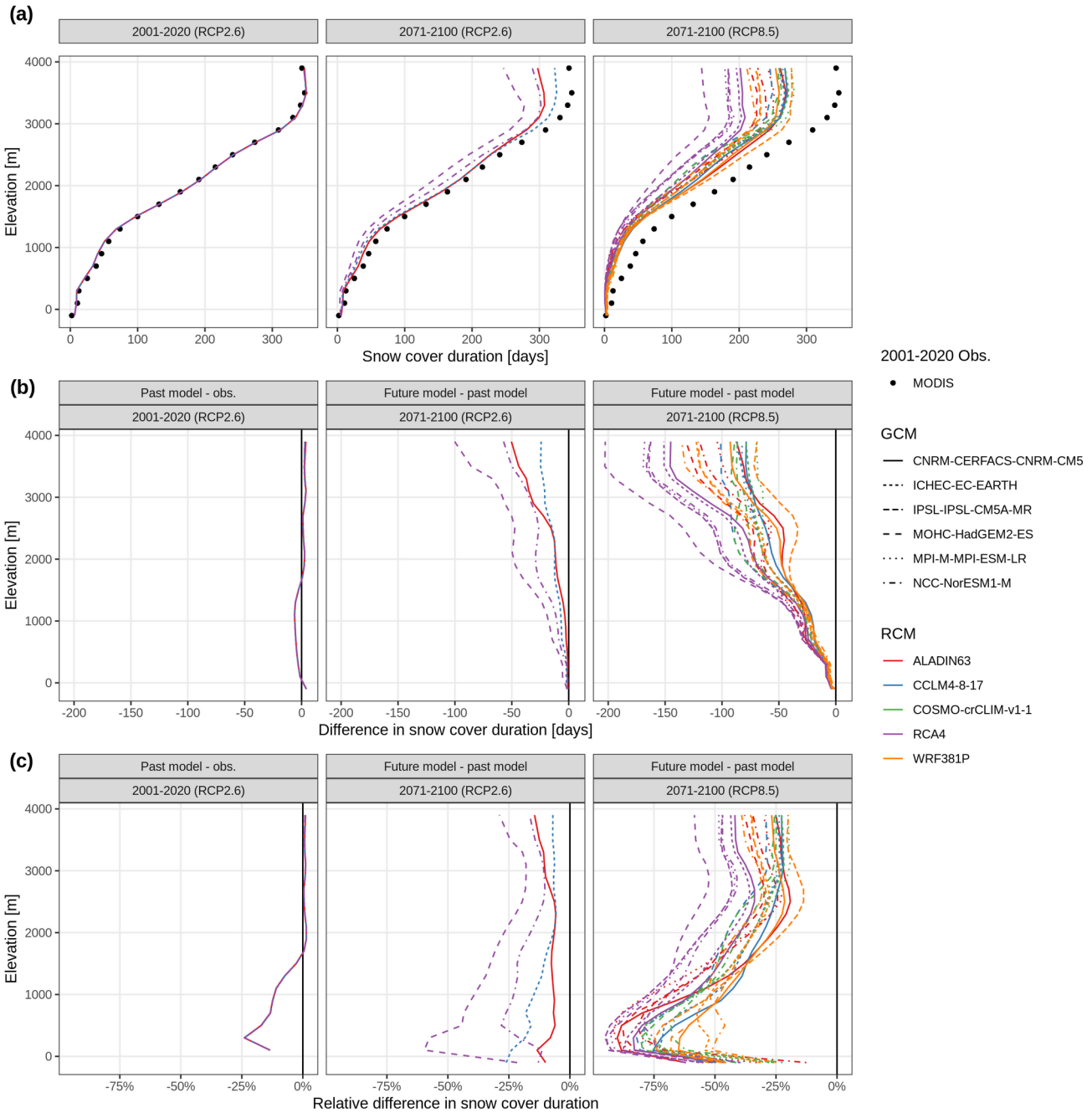


**Figure S14. Observed and downscaled modelled annual snow cover duration (SCD) by elevation. (a) Black points denote observations from remote sensing for the period 2001-2020 (the same in all panels), and colored lines the downscaled regional climate model (RCM) simulations with associated general circulation model (GCM). Downscaling was applied to QDM (quantile delta mapping) bias adjusted snow cover fraction. RCP is representative concentration pathway. (b) Differences between past model and remote sensing observations (left, "downscaling error") and between future and past model output (middle and right, absolute changes). (c) Same as (b) but as relative differences.**

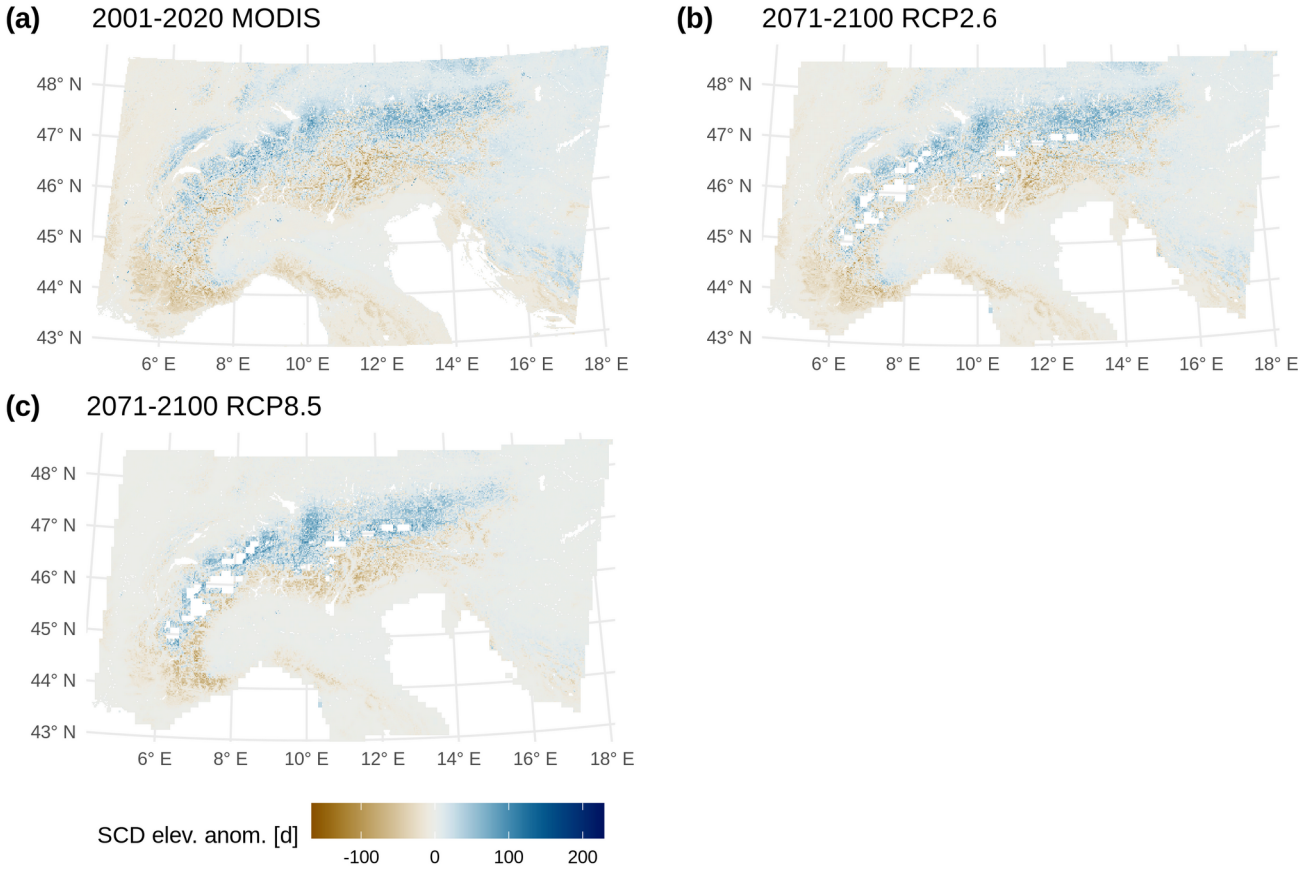


**Figure S15. Annual snow cover duration (SCD) anomalies by 100 m elevation bins for past remote sensing observations (a) and climate models under low (b) and high (c) emission scenarios (RCP, representative concentration pathway). (b) and (c) are from model means based on ensembles of 4 and 23 models, respectively. Empty areas denote pixels removed because of snow accumulation issues (see methods), glaciers, or water bodies.**

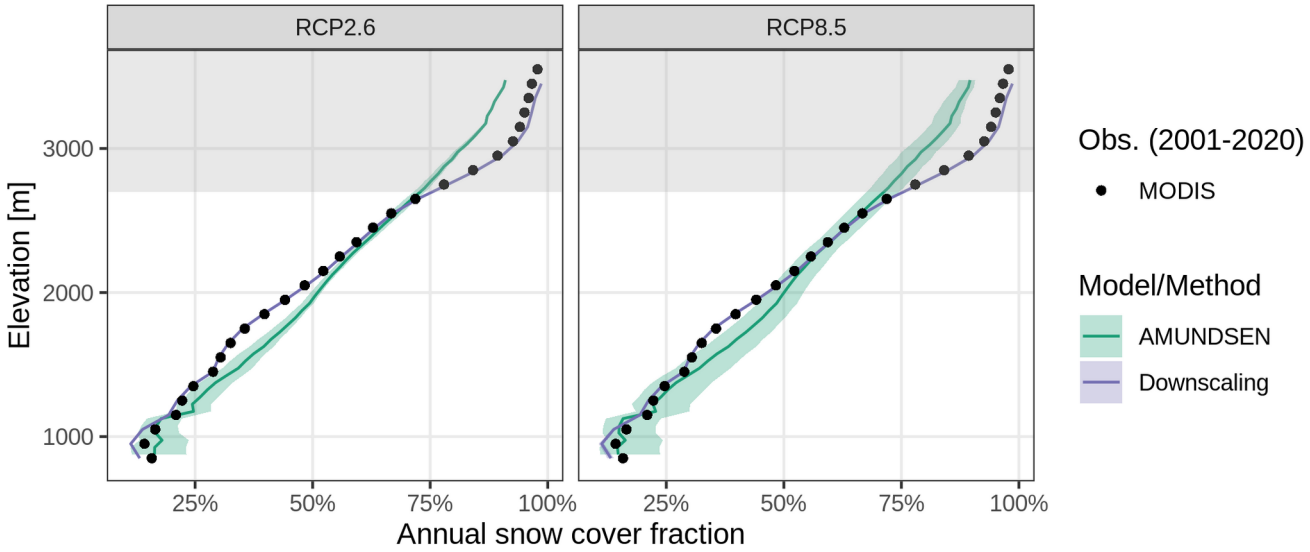


**Figure S16. Past annual snow cover fraction (SNC) for the Ötztal Alps region by elevation band (see Figure 1 for location and extent of the catchment). Black points denote observed SNC from 20 years of MODIS remote sensing. Colored lines and transparent regions denote model means and model spread from running a snow and hydroclimatological model (AMUNDSEN), forced by downscaled meteorology from regional climate models (RCMs), and from bias adjusted downscaled SNC from RCMs. Shaded grey area (above 2700 m) indicates elevations, where >20 % of the pixels entering the average per elevation band were removed from MODIS and Downscaling but remained included in AMUNDSEN: these consist of glacierized pixels or pixels subject to snow accumulation in RCMs, while AMUNDSEN resolved the whole domain.**

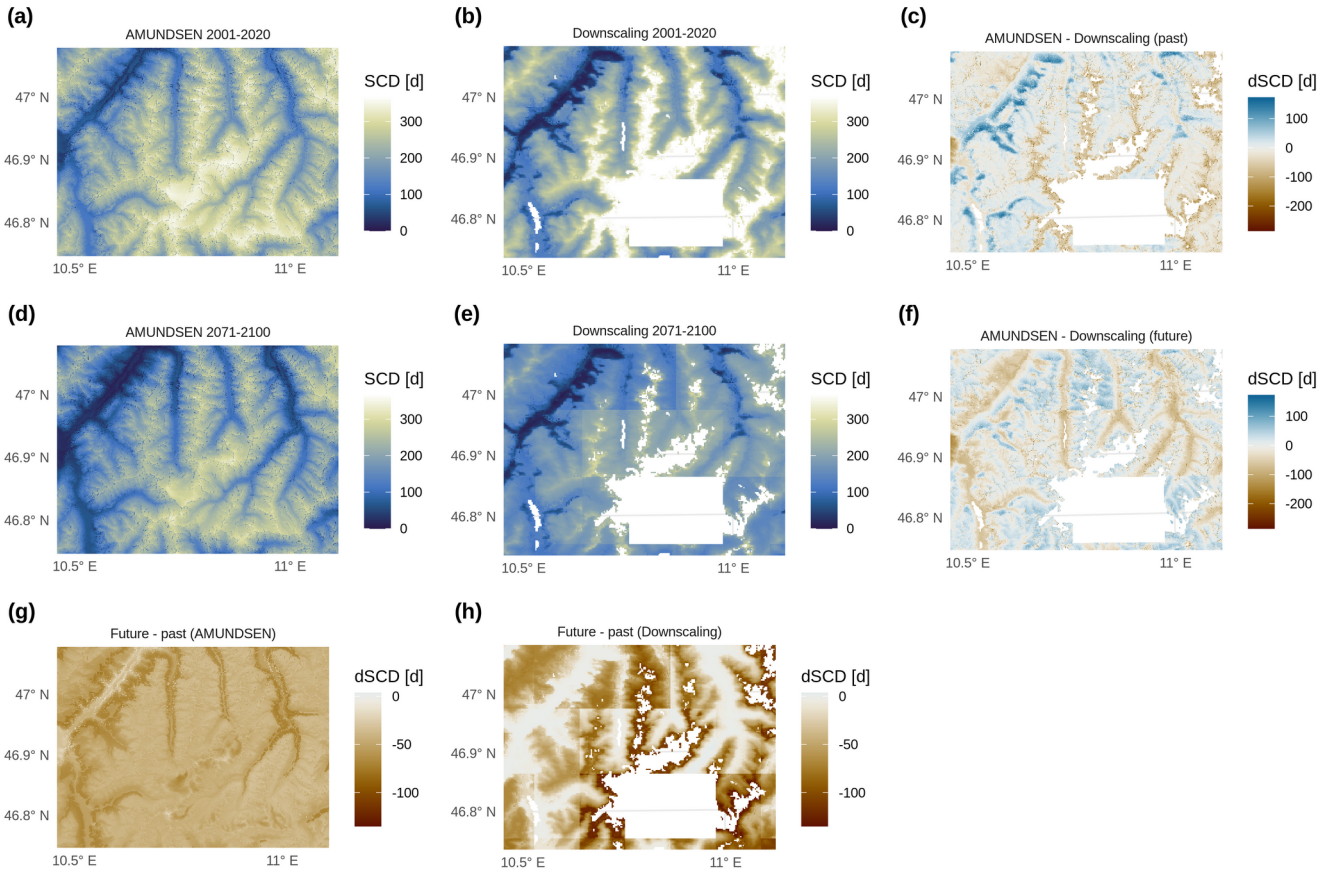


**Figure S17. Comparison of past and future estimates of annual snow cover duration (SCD) from AMUNDSEN (snow and hydroclimatological model) and downscaling. Maps show model ensemble means under RCP8.5 for the past (a,d) and future (b,e). AMUNDSEN has been forced by downscaled meteorology from RCMs, while Downscaling relies on statistical post-processing of RCM snow cover fraction. (c,d) show differences between AMUNDSEN and Downscaling per period, while (g,h) show differences between future and past per model/method (AMUNDSEN, Downscaling). Empty areas in downscaling, and differences to downscaling, denote pixels removed because of snow accumulation issues (see methods), glaciers, or water bodies.**

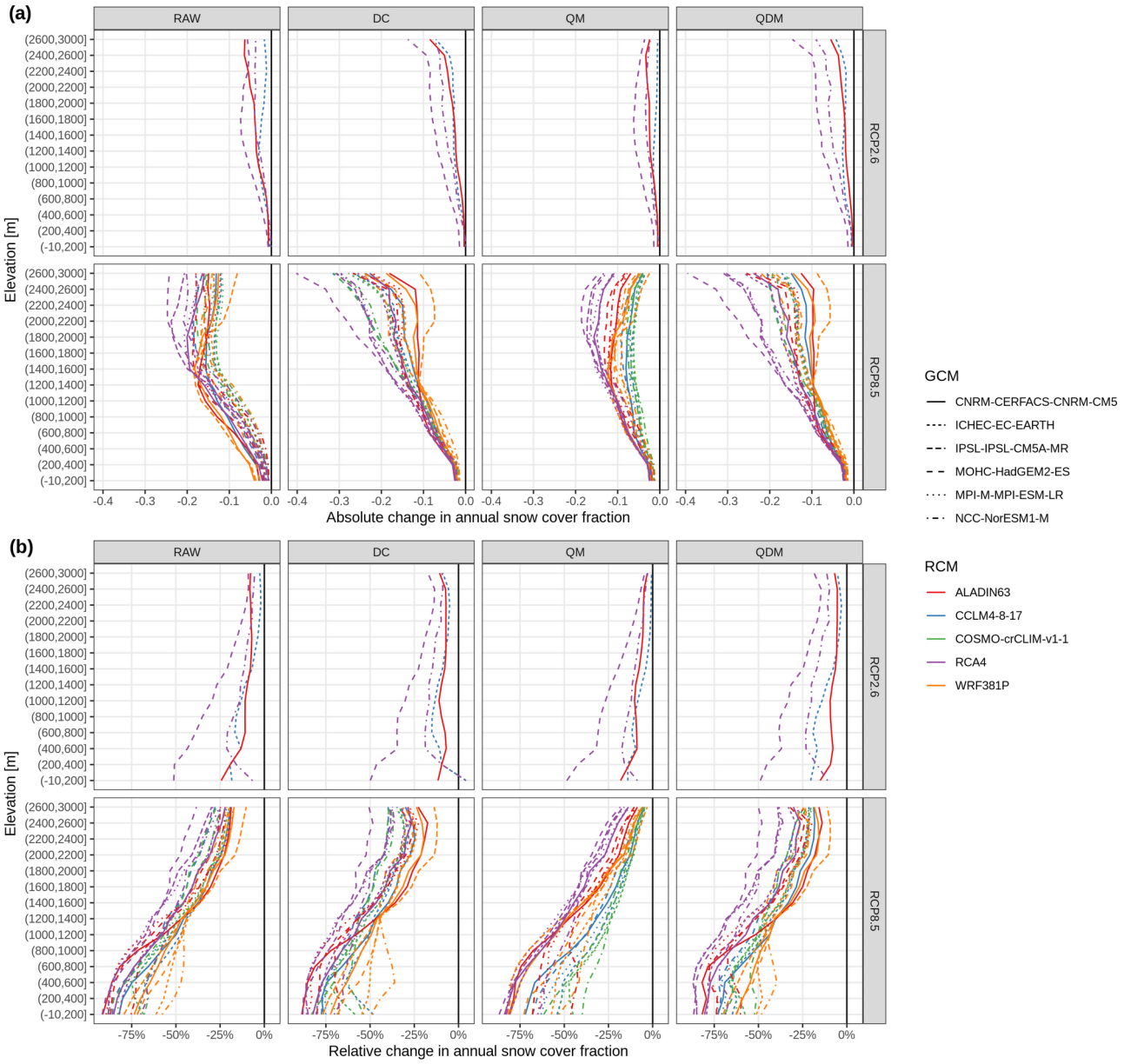


**Figure S18. Projected changes in annual snow cover fraction by elevation. The changes are for the future period 2071-2100 relative to 2001-2020. Colored lines denote the regional climate model (RCM) simulations with associated general circulation model (GCM). Rows denote emission scenario (RCP, representative concentration pathway). Column RAW is for original RCM output, DC is the delta change approach, QM is quantile mapping, and QDM quantile delta mapping. Panel (a) shows absolute changes in snow cover fraction, and (b) the relative changes.**

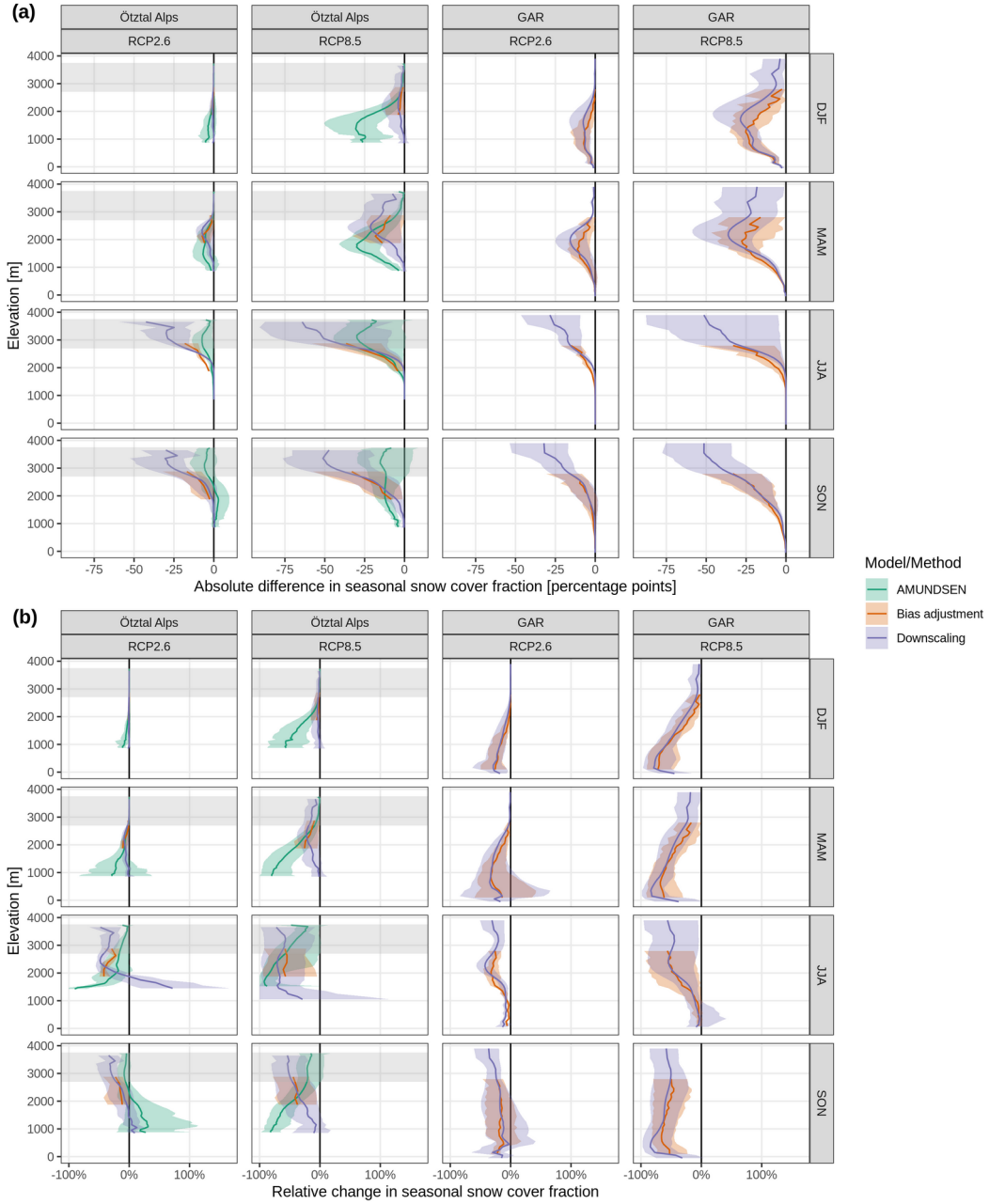


**Figure S19. Same as Figure 6 in the main manuscript but divided also by season (rows). [Original figure legend: Change in future ~~annual~~ seasonal snow cover fraction (SNC) for the Ötztal Alps region and the whole study area (GAR, Greater Alpine Region) by elevation band. Colored lines and transparent regions denote model means and model spread from running a snow and hydroclimatological model (AMUNDSEN), forced by downscaled meteorology from regional climate models (RCMs), from bias adjusted SNC from RCMs, and from downscaled SNC from RCMs. Shaded grey area in the Ötztal Alps panels (above 2700 m) indicates elevations, where >20 % of the pixels entering the average per elevation band were removed from MODIS and Downscaling but remained included in AMUNDSEN: these consist of glacierized pixels or pixels subject to snow accumulation in RCMs, while AMUNDSEN resolved the whole domain. (a) shows absolute changes and (b) relative changes.]**

**Tables**

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**Table S1. Overview of models used in the study. RCM denotes regional climate model (with modelling institute), GCM the driving general circulation model and RCP* the representative concentration pathway.**

| RCM | GCM | RCP2.6 | RCP8.5 |
|---|---|---|---|
| CLMcom-CCLM4-8-17 | CNRM-CERFACS-CNRM-CM5 | | X |
| CLMcom-CCLM4-8-17 | ICHEC-EC-EARTH | X | X |
| CLMcom-CCLM4-8-17 | MOHC-HadGEM2-ES | | X |
| CLMcom-CCLM4-8-17 | MPI-M-MPI-ESM-LR | | X |
| CLMcom-ETH-COSMO-crCLIM-v1-1 | ICHEC-EC-EARTH | | X |
| CLMcom-ETH-COSMO-crCLIM-v1-1 | MOHC-HadGEM2-ES | | X |
| CLMcom-ETH-COSMO-crCLIM-v1-1 | MPI-M-MPI-ESM-LR | | X |
| CLMcom-ETH-COSMO-crCLIM-v1-1 | NCC-NorESM1-M | | X |
| CNRM-ALADIN63 | CNRM-CERFACS-CNRM-CM5 | X | X |
| CNRM-ALADIN63 | MOHC-HadGEM2-ES | | X |
| CNRM-ALADIN63 | MPI-M-MPI-ESM-LR | | X |
| CNRM-ALADIN63 | NCC-NorESM1-M | | X |
| IPSL-WRF381P | CNRM-CERFACS-CNRM-CM5 | | X |
| IPSL-WRF381P | ICHEC-EC-EARTH | | X |
| IPSL-WRF381P | IPSL-IPSL-CM5A-MR | | X |
| IPSL-WRF381P | MOHC-HadGEM2-ES | | X |
| IPSL-WRF381P | NCC-NorESM1-M | | X |
| KNMI-RACMO22E | CNRM-CERFACS-CNRM-CM5 | X | X |
| KNMI-RACMO22E | ICHEC-EC-EARTH | | X |
| KNMI-RACMO22E | IPSL-IPSL-CM5A-MR | | X |
| KNMI-RACMO22E | MOHC-HadGEM2-ES | X | X |
| KNMI-RACMO22E | MPI-M-MPI-ESM-LR | X | X |
| KNMI-RACMO22E | NCC-NorESM1-M | X | X |
| SMHI-RCA4 | CNRM-CERFACS-CNRM-CM5 | | X |
| SMHI-RCA4 | ICHEC-EC-EARTH | | X |
| SMHI-RCA4 | IPSL-IPSL-CM5A-MR | | X |
| SMHI-RCA4 | MOHC-HadGEM2-ES | X | X |
| SMHI-RCA4 | MPI-M-MPI-ESM-LR | | X |
| SMHI-RCA4 | NCC-NorESM1-M | X | X |

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**Table S2. Number of total land grid cells in the study region and number of grid cells excluded due to unrealistic snow accumulation.**

| RCM | Total [#] | Kept [#] | Removed [#] | Removed, fraction |
|---|---|---|---|---|
| CLMcom-CCLM4-8-17 | 5,047 | 5,047 | 0 | 0.0% |
| CLMcom-ETH-COSMO-crCLIM-v1-1 | 5,045 | 5,045 | 0 | 0.0% |
| CNRM-ALADIN63 | 5,061 | 4,990 | 71 | 1.4% |
| IPSL-WRF381P | 5,061 | 5,032 | 29 | 0.6% |
| KNMI-RACMO22E | 5,046 | 4,813 | 233 | 4.6% |
| SMHI-RCA4 | 5,061 | 5,045 | 16 | 0.3% |

**Table S3. Projected absolute changes in percentage points of winter (December to February) snow cover fraction from regional climate models. RCP2.6 and 8.5 denote low and high emission scenarios. Column RAW is for original RCM output, DC is the delta change approach, QM is quantile mapping, and QDM quantile delta mapping. Each cell denotes the model mean with model spread (min, max) in parentheses. RCP2.6 is based on an ensemble of 4 models (GCM-RCM combinations), and RCP8.5 on an ensemble of 23 models. See also Figure S8.**

| Scenario | Elevation [m] | RAW | DC | QM | QDM |
|---|---|---|---|---|---|
| RCP2.6 | (2600,3000] | -0.0 (-0.8, 0.6) | -0.1 (-0.7, 0.5) | -0.2 (-1.0, 0.1) | -0.1 (-0.7, 0.2) |
| | (2400,2600] | -0.3 (-1.2, 0.1) | -0.4 (-1.2, 0.1) | -0.4 (-1.4, -0.0) | -0.5 (-1.2, 0.0) |
| | (2200,2400] | -0.9 (-2.7, -0.0) | -0.9 (-2.8, 0.0) | -1.0 (-2.9, -0.1) | -1.1 (-2.9, -0.0) |
| | (2000,2200] | -1.5 (-4.4, -0.3) | -1.4 (-4.1, -0.2) | -1.6 (-4.6, -0.4) | -1.4 (-3.9, -0.2) |
| | (1800,2000] | -3.1 (-8.4, -0.6) | -2.7 (-7.4, -0.5) | -2.8 (-7.6, -0.6) | -2.7 (-7.0, -0.5) |
| | (1600,1800] | -4.4 (-11.5, -1.2) | -3.8 (-9.8, -0.8) | -3.7 (-9.9, -1.3) | -3.5 (-9.3, -0.5) |
| | (1400,1600] | -5.8 (-14.0, -2.6) | -4.7 (-11.4, -1.7) | -4.8 (-11.8, -2.2) | -4.5 (-10.9, -1.2) |
| | (1200,1400] | -7.2 (-15.7, -3.7) | -6.3 (-14.4, -3.2) | -5.7 (-13.2, -2.8) | -6.6 (-15.0, -2.5) |
| | (1000,1200] | -7.4 (-14.5, -3.3) | -6.4 (-13.4, -3.7) | -5.8 (-12.6, -3.0) | -6.7 (-13.8, -3.3) |
| | (800,1000] | -6.6 (-12.0, -3.2) | -6.5 (-12.8, -4.2) | -5.6 (-11.5, -3.3) | -7.1 (-13.5, -3.7) |
| | (600,800] | -5.4 (-9.6, -2.8) | -5.9 (-10.9, -4.0) | -5.2 (-9.9, -3.2) | -6.6 (-11.8, -3.8) |
| | (400,600] | -3.9 (-7.3, -2.0) | -4.1 (-7.7, -2.3) | -3.7 (-7.1, -1.8) | -4.5 (-7.9, -2.9) |
| | (200,400] | -2.6 (-4.4, -0.8) | -2.6 (-5.4, -0.5) | -2.6 (-5.1, -1.3) | -2.7 (-5.2, -1.4) |
| | (-10,200] | -2.0 (-3.1, -0.2) | -2.1 (-4.7, 0.8) | -2.3 (-4.7, -0.3) | -2.4 (-4.6, -0.6) |
| RCP8.5 | (2600,3000] | -2.8 (-14.7, 0.1) | -2.8 (-14.3, -0.1) | -2.4 (-10.7, -0.1) | -2.5 (-13.3, -0.2) |
| | (2400,2600] | -6.4 (-20.6, -1.3) | -6.6 (-21.1, -1.3) | -4.3 (-12.5, -1.0) | -6.3 (-20.7, -1.4) |
| | (2200,2400] | -9.8 (-27.1, -2.6) | -9.8 (-27.3, -2.4) | -6.9 (-17.5, -2.6) | -9.3 (-26.7, -2.2) |
| | (2000,2200] | -13.3 (-29.6, -5.0) | -12.3 (-28.3, -4.2) | -10.2 (-20.9, -5.2) | -11.3 (-27.2, -3.2) |
| | (1800,2000] | -21.1 (-36.5, -10.0) | -18.4 (-33.6, -8.2) | -15.8 (-25.3, -8.8) | -16.8 (-32.6, -7.0) |
| | (1600,1800] | -25.1 (-36.0, -15.1) | -21.1 (-33.2, -10.9) | -18.0 (-26.6, -11.3) | -19.3 (-32.6, -8.9) |
| | (1400,1600] | -29.0 (-40.2, -22.4) | -23.7 (-33.4, -15.5) | -20.7 (-29.9, -13.1) | -21.8 (-33.0, -12.7) |
| | (1200,1400] | -30.4 (-39.2, -21.3) | -26.4 (-35.3, -20.6) | -21.7 (-30.2, -14.1) | -25.1 (-35.0, -17.5) |
| | (1000,1200] | -27.8 (-37.4, -16.6) | -24.6 (-32.0, -18.0) | -20.7 (-28.6, -13.2) | -23.8 (-31.8, -17.9) |
| | (800,1000] | -22.5 (-34.6, -11.1) | -23.1 (-30.0, -13.8) | -19.6 (-27.6, -11.3) | -23.0 (-30.3, -15.0) |
| | (600,800] | -17.6 (-29.5, -7.8) | -20.9 (-26.2, -10.3) | -18.1 (-24.9, -10.3) | -21.0 (-27.2, -11.7) |
| | (400,600] | -13.0 (-24.2, -4.7) | -15.2 (-18.6, -6.5) | -13.6 (-17.8, -8.0) | -15.0 (-19.0, -7.5) |
| | (200,400] | -7.8 (-16.2, -2.6) | -8.2 (-10.1, -4.5) | -7.6 (-9.8, -4.7) | -7.8 (-9.9, -4.4) |
| | (-10,200] | -6.1 (-13.4, -2.1) | -6.9 (-8.6, -4.1) | -6.6 (-8.5, -4.0) | -6.7 (-8.4, -4.3) |

**Table S4. Same as Table S3, but for spring (March to May).**

| Scenario | Elevation [m] | RAW | DC | QM | QDM |
|---|---|---|---|---|---|
| RCP2.6 | (2600,3000] | -1.9 (-4.0, 0.5) | -2.1 (-4.3, 0.4) | -0.7 (-1.3, -0.0) | -2.3 (-4.8, 0.5) |
| | (2400,2600] | -2.7 (-5.7, 0.3) | -3.7 (-7.8, -0.4) | -1.3 (-2.8, 0.1) | -4.2 (-8.6, -0.6) |
| | (2200,2400] | -3.7 (-7.4, -0.1) | -5.3 (-10.6, -1.0) | -2.3 (-4.1, -0.0) | -6.0 (-12.1, -1.2) |
| | (2000,2200] | -5.4 (-8.7, -2.0) | -6.9 (-11.0, -2.7) | -3.3 (-5.6, -0.5) | -7.3 (-11.9, -2.6) |
| | (1800,2000] | -7.2 (-10.6, -4.0) | -9.2 (-14.4, -3.3) | -4.6 (-7.5, -1.2) | -10.2 (-16.6, -3.2) |
| | (1600,1800] | -7.9 (-10.7, -5.3) | -9.7 (-14.6, -3.6) | -5.3 (-8.5, -1.8) | -10.7 (-16.9, -3.3) |
| | (1400,1600] | -7.6 (-10.0, -5.4) | -8.9 (-13.5, -3.2) | -5.4 (-8.4, -2.4) | -10.0 (-15.7, -3.0) |
| | (1200,1400] | -6.3 (-7.2, -5.0) | -7.6 (-11.8, -2.5) | -4.9 (-7.5, -2.5) | -8.7 (-13.5, -2.4) |
| | (1000,1200] | -4.5 (-5.4, -2.8) | -5.2 (-8.1, -1.4) | -3.6 (-5.5, -1.1) | -6.0 (-9.1, -1.3) |
| | (800,1000] | -2.4 (-3.6, -0.4) | -3.2 (-5.4, 0.8) | -2.4 (-4.1, 0.4) | -3.8 (-6.1, 0.4) |
| | (600,800] | -1.1 (-2.1, 0.9) | -1.7 (-3.5, 2.0) | -1.5 (-2.9, 1.1) | -2.2 (-3.8, 1.2) |
| | (400,600] | -0.4 (-0.8, 0.7) | -0.7 (-1.9, 1.9) | -0.8 (-1.7, 1.1) | -1.1 (-2.0, 1.2) |
| | (200,400] | 0.0 (-0.3, 0.4) | 0.1 (-1.2, 1.2) | -0.3 (-0.8, 0.8) | -0.3 (-1.0, 0.8) |
| | (-10,200] | 0.1 (-0.2, 0.4) | 0.7 (-1.0, 2.7) | -0.1 (-0.7, 0.7) | -0.2 (-0.9, 0.5) |
| RCP8.5 | (2600,3000] | -15.8 (-34.9, -0.4) | -16.2 (-36.1, -0.4) | -3.8 (-8.3, 0.0) | -15.9 (-35.9, -0.3) |
| | (2400,2600] | -18.7 (-35.6, -4.4) | -21.0 (-40.0, -4.0) | -7.1 (-14.4, -2.0) | -19.9 (-39.3, -3.4) |
| | (2200,2400] | -22.5 (-38.5, -6.6) | -24.8 (-43.3, -5.5) | -10.0 (-19.7, -3.5) | -23.3 (-43.2, -4.7) |
| | (2000,2200] | -25.8 (-40.1, -11.7) | -27.5 (-42.9, -8.4) | -12.4 (-23.2, -5.1) | -25.1 (-42.2, -7.0) |
| | (1800,2000] | -27.9 (-40.6, -18.0) | -30.4 (-41.9, -16.6) | -14.7 (-25.5, -5.3) | -27.4 (-42.1, -14.5) |
| | (1600,1800] | -26.3 (-37.1, -16.4) | -28.0 (-36.4, -17.9) | -14.8 (-24.4, -5.4) | -25.0 (-36.0, -15.8) |
| | (1400,1600] | -24.1 (-33.5, -13.7) | -24.4 (-30.9, -18.1) | -14.1 (-22.4, -5.0) | -21.8 (-30.5, -15.8) |
| | (1200,1400] | -17.0 (-29.3, -8.0) | -19.0 (-23.4, -14.6) | -11.4 (-17.6, -4.2) | -17.0 (-23.4, -12.6) |
| | (1000,1200] | -12.0 (-24.4, -4.7) | -12.8 (-15.5, -9.4) | -8.5 (-12.9, -3.5) | -11.6 (-15.6, -8.6) |
| | (800,1000] | -6.7 (-15.2, -2.1) | -8.2 (-9.8, -5.5) | -5.9 (-8.7, -2.5) | -7.4 (-9.9, -5.0) |
| | (600,800] | -3.6 (-9.3, -0.8) | -5.1 (-6.1, -3.4) | -4.0 (-5.9, -1.8) | -4.7 (-6.1, -3.0) |
| | (400,600] | -1.8 (-5.8, -0.3) | -3.0 (-3.6, -2.0) | -2.4 (-3.5, -1.1) | -2.7 (-3.5, -1.6) |
| | (200,400] | -0.8 (-2.9, -0.2) | -1.4 (-1.8, -0.8) | -1.1 (-1.7, -0.5) | -1.2 (-1.7, -0.6) |
| | (-10,200] | -0.4 (-1.8, -0.1) | -1.1 (-1.3, -0.8) | -0.8 (-1.3, -0.3) | -0.9 (-1.3, -0.4) |

**Table S5. Same as Table S3, but instead of absolute changes in winter snow cover fraction, here the relative changes are shown.**

| Scenario | Elevation [m] | RAW | DC | QM | QDM |
|---|---|---|---|---|---|
| RCP2.6 | (2600,3000] | -0.0% (-0.8, 0.6) | -0.1% (-0.8, 0.5) | -0.2% (-1.1, 0.1) | -0.1% (-0.7, 0.2) |
| | (2400,2600] | -0.4% (-1.2, 0.1) | -0.4% (-1.2, 0.1) | -0.5% (-1.4, -0.0) | -0.5% (-1.3, 0.0) |
| | (2200,2400] | -1.0% (-2.9, -0.0) | -1.0% (-3.0, 0.0) | -1.1% (-3.1, -0.2) | -1.2% (-3.1, -0.0) |
| | (2000,2200] | -1.5% (-4.6, -0.3) | -1.6% (-4.7, -0.3) | -1.8% (-5.2, -0.4) | -1.6% (-4.5, -0.2) |
| | (1800,2000] | -3.4% (-9.2, -0.6) | -3.5% (-9.4, -0.7) | -3.6% (-9.7, -0.8) | -3.4% (-8.9, -0.6) |
| | (1600,1800] | -5.1% (-13.3, -1.2) | -5.2% (-13.5, -1.1) | -5.2% (-13.6, -1.7) | -4.9% (-12.9, -0.7) |
| | (1400,1600] | -7.2% (-17.6, -2.7) | -7.3% (-17.7, -2.7) | -7.5% (-18.4, -3.3) | -7.1% (-16.9, -1.9) |
| | (1200,1400] | -11.1% (-25.4, -5.7) | -11.4% (-26.3, -5.9) | -10.4% (-24.1, -5.2) | -12.0% (-27.3, -4.5) |
| | (1000,1200] | -13.7% (-28.8, -7.9) | -14.0% (-29.3, -8.0) | -12.7% (-27.6, -6.7) | -14.7% (-30.3, -7.2) |
| | (800,1000] | -17.6% (-34.7, -11.2) | -17.2% (-33.8, -11.0) | -14.9% (-30.4, -8.8) | -18.8% (-35.8, -9.9) |
| | (600,800] | -20.8% (-39.3, -13.8) | -18.7% (-34.5, -12.9) | -16.5% (-31.5, -10.3) | -21.2% (-37.5, -12.0) |
| | (400,600] | -22.7% (-44.9, -11.8) | -18.9% (-35.8, -10.7) | -17.3% (-32.9, -8.2) | -21.1% (-37.1, -13.7) |
| | (200,400] | -27.1% (-51.5, -13.4) | -23.1% (-48.3, -4.3) | -23.7% (-45.5, -11.5) | -23.9% (-47.1, -12.3) |
| | (-10,200] | -26.6% (-50.7, -4.6) | -22.8% (-49.9, 9.0) | -25.0% (-50.6, -3.0) | -25.6% (-49.4, -6.1) |
| RCP8.5 | (2600,3000] | -2.9% (-14.9, 0.1) | -2.9% (-14.7, -0.1) | -2.5% (-11.1, -0.1) | -2.6% (-13.8, -0.2) |
| | (2400,2600] | -6.5% (-21.4, -1.3) | -6.8% (-21.8, -1.4) | -4.4% (-13.1, -1.1) | -6.6% (-21.6, -1.4) |
| | (2200,2400] | -10.1% (-28.6, -2.6) | -10.5% (-29.3, -2.6) | -7.4% (-18.9, -2.8) | -10.0% (-28.8, -2.3) |
| | (2000,2200] | -13.8% (-31.5, -5.0) | -14.0% (-32.2, -4.8) | -11.6% (-23.9, -5.9) | -12.9% (-30.9, -3.7) |
| | (1800,2000] | -22.8% (-41.7, -10.2) | -23.5% (-42.9, -10.4) | -20.3% (-32.3, -11.2) | -21.5% (-41.7, -9.0) |
| | (1600,1800] | -28.4% (-44.2, -15.6) | -29.0% (-45.8, -15.0) | -24.8% (-36.7, -15.5) | -26.5% (-45.0, -12.3) |
| | (1400,1600] | -35.5% (-50.0, -24.4) | -36.9% (-52.0, -24.2) | -32.2% (-46.5, -20.4) | -33.9% (-51.3, -19.8) |
| | (1200,1400] | -46.3% (-60.9, -36.5) | -48.1% (-64.2, -37.5) | -39.5% (-55.0, -25.7) | -45.7% (-63.7, -31.9) |
| | (1000,1200] | -52.1% (-66.4, -40.8) | -53.9% (-70.2, -39.4) | -45.4% (-62.8, -28.9) | -52.1% (-69.7, -39.3) |
| | (800,1000] | -60.5% (-76.8, -42.2) | -61.2% (-79.4, -36.5) | -51.8% (-73.1, -29.8) | -60.8% (-80.2, -39.8) |
| | (600,800] | -67.1% (-82.9, -41.3) | -66.4% (-83.5, -32.7) | -57.5% (-79.5, -32.7) | -67.0% (-86.5, -37.4) |
| | (400,600] | -72.7% (-85.9, -42.0) | -70.7% (-86.6, -30.5) | -63.3% (-83.1, -37.5) | -69.9% (-88.9, -34.9) |
| | (200,400] | -75.9% (-89.7, -47.3) | -73.2% (-90.3, -40.4) | -68.1% (-87.9, -42.1) | -70.0% (-89.1, -39.6) |
| | (-10,200] | -78.3% (-91.6, -55.9) | -73.5% (-91.6, -44.2) | -70.7% (-91.3, -43.4) | -72.0% (-89.8, -45.9) |

**Table S6. Same as Table S5, but for spring.**

| Scenario | Elevation [m] | RAW | DC | QM | QDM |
|---|---|---|---|---|---|
| RCP2.6 | (2600,3000] | -2.0% (-4.2, 0.6) | -2.2% (-4.5, 0.4) | -0.8% (-1.4, -0.0) | -2.4% (-5.1, 0.5) |
| | (2400,2600] | -3.1% (-6.5, 0.3) | -4.1% (-8.5, -0.5) | -1.5% (-3.0, 0.1) | -4.6% (-9.5, -0.6) |
| | (2200,2400] | -4.6% (-9.3, -0.1) | -6.2% (-12.5, -1.2) | -2.7% (-4.9, -0.0) | -7.1% (-14.2, -1.4) |
| | (2000,2200] | -6.8% (-11.2, -2.5) | -8.9% (-14.2, -3.4) | -4.3% (-7.2, -0.7) | -9.5% (-15.4, -3.3) |
| | (1800,2000] | -11.0% (-17.6, -5.1) | -14.3% (-22.4, -5.1) | -7.1% (-11.6, -1.9) | -15.9% (-25.8, -5.0) |
| | (1600,1800] | -14.0% (-20.9, -6.6) | -17.7% (-26.7, -6.6) | -9.8% (-15.5, -3.2) | -19.5% (-30.8, -6.0) |
| | (1400,1600] | -17.0% (-25.0, -7.9) | -20.6% (-31.3, -7.6) | -12.6% (-19.6, -5.5) | -23.3% (-36.4, -7.0) |
| | (1200,1400] | -23.1% (-31.8, -10.0) | -25.4% (-39.6, -8.5) | -16.3% (-25.0, -8.5) | -29.0% (-45.2, -7.9) |
| | (1000,1200] | -25.2% (-35.0, -9.1) | -27.1% (-41.9, -7.4) | -18.7% (-28.6, -5.7) | -30.8% (-47.4, -6.7) |
| | (800,1000] | -28.3% (-41.9, -2.4) | -27.2% (-46.2, 6.5) | -20.8% (-35.0, 3.4) | -32.4% (-52.3, 3.1) |
| | (600,800] | -28.0% (-50.3, 15.4) | -24.6% (-49.7, 29.1) | -21.7% (-42.2, 16.3) | -31.3% (-55.1, 17.7) |
| | (400,600] | -23.7% (-51.0, 31.9) | -17.6% (-48.6, 46.4) | -19.6% (-43.1, 28.1) | -26.9% (-51.3, 31.0) |
| | (200,400] | -8.5% (-62.4, 59.6) | 5.8% (-64.1, 65.7) | -14.2% (-45.8, 41.3) | -17.4% (-54.4, 41.8) |
| | (-10,200] | 32.5% (-78.9, 132.7) | 51.3% (-69.0, 185.3) | -8.5% (-51.5, 51.7) | -13.9% (-59.9, 35.3) |
| RCP8.5 | (2600,3000] | -16.5% (-37.0, -0.5) | -17.0% (-37.9, -0.4) | -4.0% (-8.8, 0.0) | -16.7% (-37.9, -0.3) |
| | (2400,2600] | -20.8% (-40.4, -4.5) | -23.0% (-43.7, -4.4) | -7.7% (-15.8, -2.2) | -21.8% (-43.1, -3.7) |
| | (2200,2400] | -26.4% (-47.0, -6.8) | -29.1% (-50.8, -6.4) | -11.8% (-23.2, -4.1) | -27.3% (-50.9, -5.5) |
| | (2000,2200] | -32.1% (-51.5, -12.1) | -35.5% (-55.4, -10.8) | -16.1% (-30.1, -6.6) | -32.4% (-54.5, -9.1) |
| | (1800,2000] | -41.9% (-59.5, -25.9) | -47.4% (-65.2, -25.9) | -22.9% (-39.7, -8.2) | -42.6% (-65.5, -22.6) |
| | (1600,1800] | -45.7% (-60.3, -33.1) | -51.2% (-66.5, -32.8) | -27.1% (-44.7, -9.9) | -45.8% (-65.9, -28.9) |
| | (1400,1600] | -51.6% (-65.4, -41.7) | -56.8% (-71.9, -42.1) | -32.8% (-52.1, -11.7) | -50.7% (-70.9, -36.8) |
| | (1200,1400] | -59.6% (-72.6, -45.7) | -63.6% (-78.5, -48.9) | -38.3% (-59.0, -14.1) | -57.2% (-78.6, -42.2) |
| | (1000,1200] | -63.1% (-75.9, -47.3) | -66.4% (-80.5, -48.6) | -44.2% (-66.7, -18.3) | -59.9% (-81.2, -44.4) |
| | (800,1000] | -68.8% (-80.9, -48.3) | -70.6% (-84.4, -47.5) | -51.1% (-75.2, -21.4) | -64.0% (-85.3, -43.2) |
| | (600,800] | -74.0% (-88.1, -50.9) | -73.6% (-87.4, -48.9) | -57.8% (-85.1, -26.0) | -67.3% (-87.7, -43.6) |
| | (400,600] | -78.1% (-92.3, -55.2) | -74.9% (-89.4, -51.3) | -59.6% (-88.5, -26.4) | -67.2% (-88.0, -39.4) |
| | (200,400] | -81.9% (-97.1, -55.6) | -74.4% (-94.3, -41.9) | -58.1% (-90.3, -24.9) | -63.8% (-90.7, -33.5) |
| | (-10,200] | -85.8% (-99.1, -58.1) | -74.3% (-92.4, -53.0) | -56.2% (-88.2, -23.3) | -61.6% (-89.8, -30.3) |

**Table S7. Observed and downscaled modelled annual snow cover duration (days) based on high-resolution satellite imagery (MODIS) and an ensemble of regional climate models. RCP2.6 and 8.5 denote low and high emission scenarios and cells denote the model mean with model spread (min, max) in parentheses. RCP2.6 is based on an ensemble of 4 models (GCM-RCM combinations), and RCP8.5 on an ensemble of 23 models. See also Figure S11.**

| | 2001-2020 | | | 2071-2100 | |
|---|---|---|---|---|---|
| Elevation [m] | MODIS | RCP2.6 | RCP8.5 | RCP2.6 | RCP8.5 |
| (3600,4200] | 344 | 347 (347, 348) | 347 (346, 348) | 289 (247, 323) | 232 (144, 278) |
| (3400,3600] | 348 | 350 (350, 351) | 351 (350, 352) | 299 (265, 326) | 237 (148, 282) |
| (3200,3400] | 342 | 345 (345, 345) | 345 (344, 346) | 302 (278, 322) | 235 (150, 277) |
| (3000,3200] | 331 | 334 (334, 335) | 334 (334, 335) | 296 (274, 313) | 234 (155, 276) |
| (2800,3000] | 309 | 312 (312, 312) | 312 (312, 312) | 277 (256, 291) | 220 (148, 263) |
| (2600,2800] | 274 | 275 (275, 275) | 275 (275, 275) | 245 (225, 257) | 193 (130, 237) |
| (2400,2600] | 241 | 242 (242, 242) | 242 (242, 242) | 216 (195, 228) | 166 (108, 209) |
| (2200,2400] | 215 | 217 (217, 217) | 217 (217, 217) | 192 (169, 205) | 143 (91, 182) |
| (2000,2200] | 191 | 194 (194, 194) | 194 (194, 194) | 168 (144, 182) | 121 (75, 155) |
| (1800,2000] | 163 | 166 (166, 166) | 166 (166, 166) | 141 (119, 155) | 98 (60, 125) |
| (1600,1800] | 132 | 132 (132, 132) | 132 (132, 132) | 110 (92, 122) | 73 (45, 92) |
| (1400,1600] | 100 | 97 (97, 97) | 97 (97, 97) | 80 (66, 90) | 50 (32, 62) |
| (1200,1400] | 74 | 68 (68, 68) | 68 (68, 68) | 56 (45, 63) | 33 (21, 42) |
| (1000,1200] | 57 | 51 (51, 51) | 51 (51, 51) | 41 (32, 47) | 22 (13, 29) |
| (800,1000] | 46 | 41 (41, 41) | 41 (41, 41) | 32 (24, 38) | 15 (8, 21) |
| (600,800] | 38 | 33 (33, 33) | 33 (33, 33) | 25 (19, 31) | 10 (4, 17) |
| (400,600] | 25 | 21 (21, 21) | 21 (21, 21) | 16 (12, 20) | 5 (1, 11) |
| (200,400] | 13 | 10 (10, 10) | 10 (10, 10) | 7 (4, 9) | 2 (0, 5) |
| (0,200] | 10 | 9 (9, 9) | 9 (9, 9) | 7 (4, 8) | 2 (1, 4) |
| (-200,0] | 2 | 6 (6, 6) | 6 (6, 6) | 5 (5, 6) | 4 (2, 6) |

**Table S8. Projected changes in annual snow cover duration between 2071-2100 and 2001-2020 by elevation. Estimates are based on downscaled and bias adjusted output of an ensemble of regional climate models. RCP2.6 and 8.5 denote low and high emission scenarios and cells denote the model mean with model spread (min, max) in parentheses. RCP2.6 is based on an ensemble of 4 models (GCM-RCM combinations), and RCP8.5 on an ensemble of 23 models. See also Table S7 and Figure S11.**

| | Absolute changes [days] | | Relative changes | |
|---|---|---|---|---|
| Elevation [m] | RCP2.6 | RCP8.5 | RCP2.6 | RCP8.5 |
| (3600,4200] | -58 (-100, -24) | -115 (-203, -69) | -16.7% (-28.9, -7.0) | -33.2% (-58.4, -20.0) |
| (3400,3600] | -51 (-86, -25) | -114 (-203, -69) | -14.6% (-24.5, -7.1) | -32.5% (-57.9, -19.6) |
| (3200,3400] | -42 (-67, -23) | -110 (-194, -68) | -12.3% (-19.5, -6.5) | -31.9% (-56.3, -19.8) |
| (3000,3200] | -38 (-60, -21) | -100 (-179, -59) | -11.4% (-18.0, -6.3) | -30.0% (-53.5, -17.5) |
| (2800,3000] | -35 (-56, -21) | -92 (-163, -49) | -11.3% (-18.0, -6.7) | -29.5% (-52.4, -15.6) |
| (2600,2800] | -30 (-50, -18) | -82 (-145, -38) | -10.8% (-18.2, -6.6) | -29.9% (-52.9, -13.7) |
| (2400,2600] | -26 (-47, -14) | -76 (-134, -33) | -10.7% (-19.5, -6.0) | -31.4% (-55.3, -13.7) |
| (2200,2400] | -25 (-48, -12) | -74 (-127, -35) | -11.6% (-22.3, -5.7) | -34.0% (-58.3, -16.0) |
| (2000,2200] | -26 (-50, -12) | -72 (-119, -39) | -13.2% (-25.6, -6.1) | -37.4% (-61.3, -20.0) |
| (1800,2000] | -25 (-47, -11) | -68 (-106, -41) | -15.0% (-28.3, -6.7) | -41.0% (-63.9, -24.7) |
| (1600,1800] | -22 (-41, -10) | -59 (-87, -40) | -16.9% (-30.7, -7.4) | -44.7% (-65.7, -30.3) |
| (1400,1600] | -18 (-32, -7) | -47 (-65, -35) | -18.1% (-32.6, -7.6) | -48.1% (-66.9, -36.3) |
| (1200,1400] | -13 (-24, -5) | -36 (-47, -27) | -18.7% (-34.5, -7.2) | -52.1% (-69.2, -38.8) |
| (1000,1200] | -10 (-19, -3) | -29 (-38, -22) | -20.1% (-37.6, -6.8) | -57.5% (-74.7, -42.5) |
| (800,1000] | -9 (-17, -3) | -26 (-33, -19) | -21.6% (-40.7, -6.4) | -63.6% (-81.3, -47.6) |
| (600,800] | -8 (-14, -2) | -24 (-29, -16) | -23.6% (-43.5, -6.7) | -71.0% (-88.4, -49.0) |
| (400,600] | -5 (-9, -1) | -16 (-19, -10) | -23.6% (-44.3, -6.1) | -76.3% (-93.0, -45.9) |
| (200,400] | -3 (-6, -1) | -8 (-9, -5) | -26.2% (-57.6, -8.0) | -78.0% (-95.1, -49.1) |
| (0,200] | -2 (-5, -1) | -7 (-9, -5) | -27.1% (-59.6, -11.4) | -76.3% (-94.0, -51.2) |
| (-200,0] | -1 (-2, -1) | -3 (-4, -1) | -17.7% (-26.1, -10.0) | -42.5% (-61.9, -12.6) |