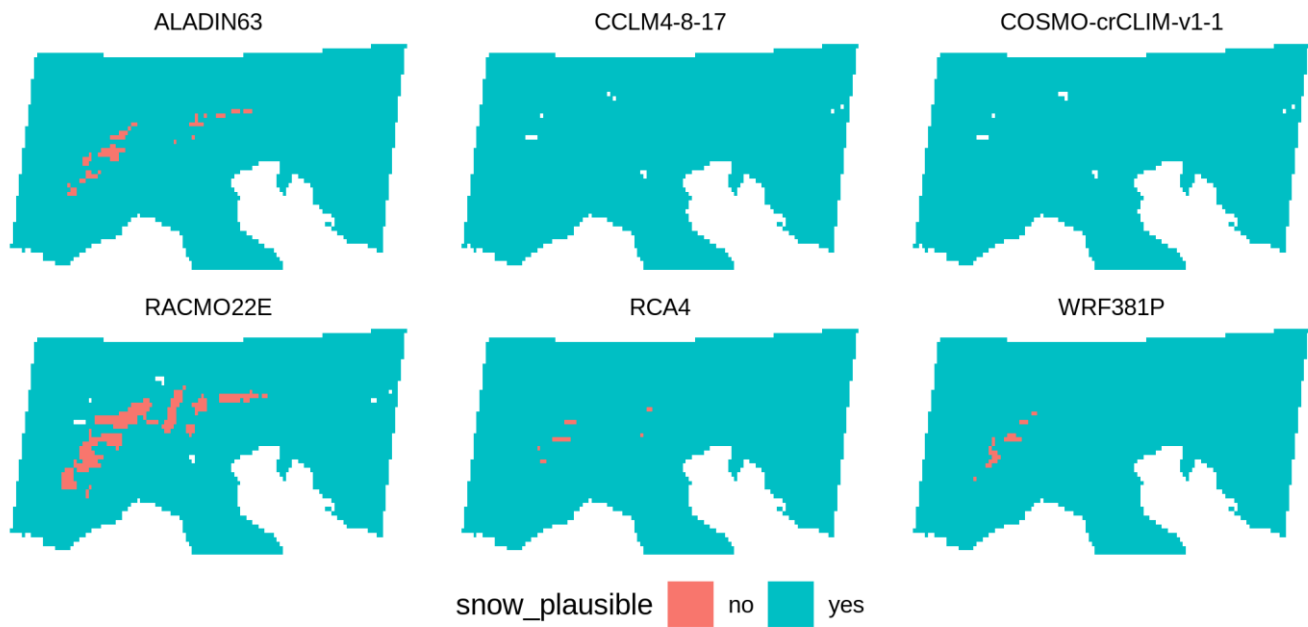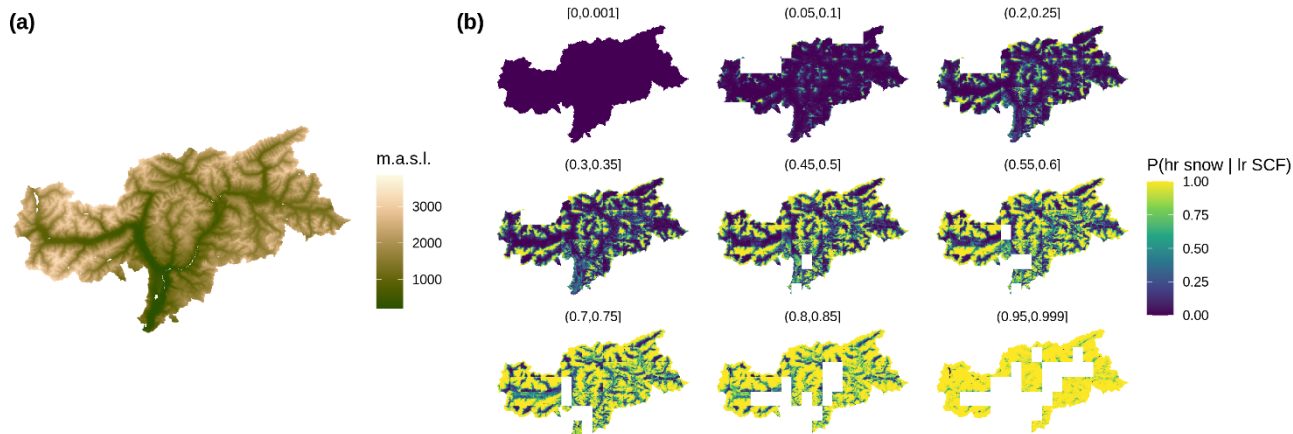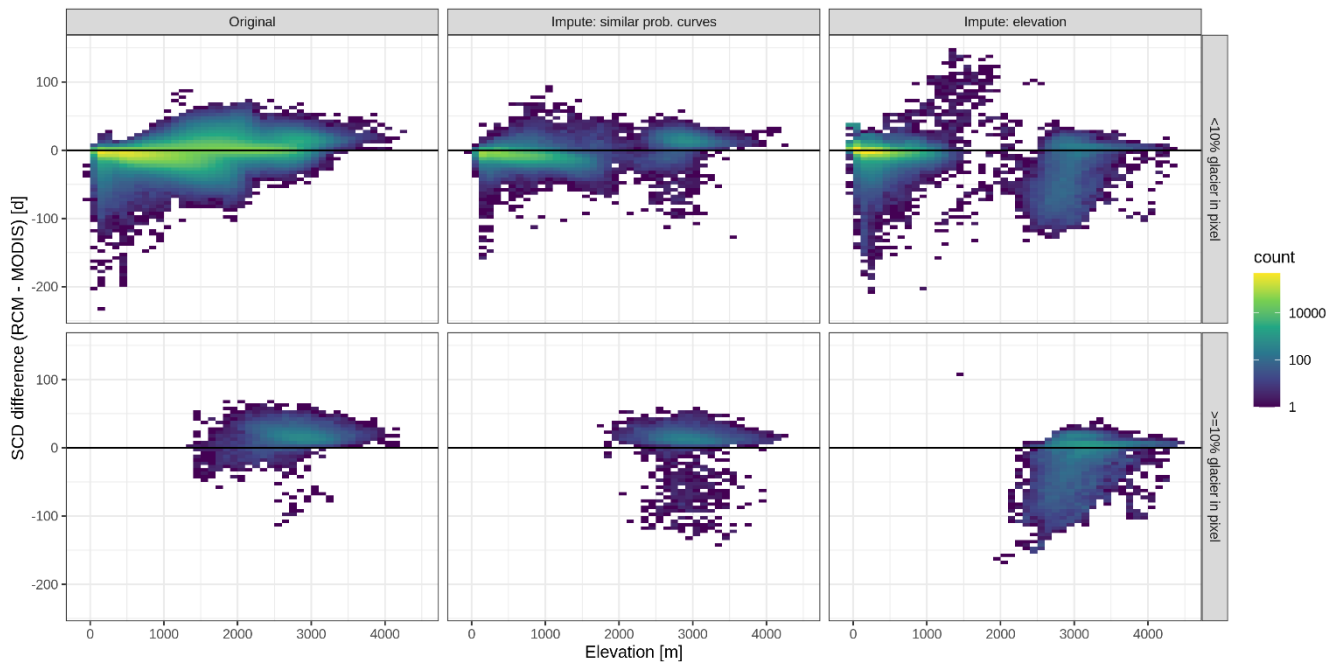**Figures**

**Figure S1. Grid cells excluded due to unrealistic snow accumulation.**

5

**Figure S2.** 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 (SCF) of the surrounding low-resolution (lr) pixel. The title of each panel denotes the SCF bin. Empty/missing areas imply that less or equal than 30 observations were available for this SCF bin.

**Figure S3. Downscaling errors.** Difference in 2000-2020 annual snow cover duration (SCD) between a downscaled bias corrected RCM and high-resolution observations from MODIS. The RCM shown here is CLMcom-CCLM4-8-17 driven by CNRM-CERFACS-CNRM-CM5 and bias corrected with quantile mapping. But since all past bias corrected 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).
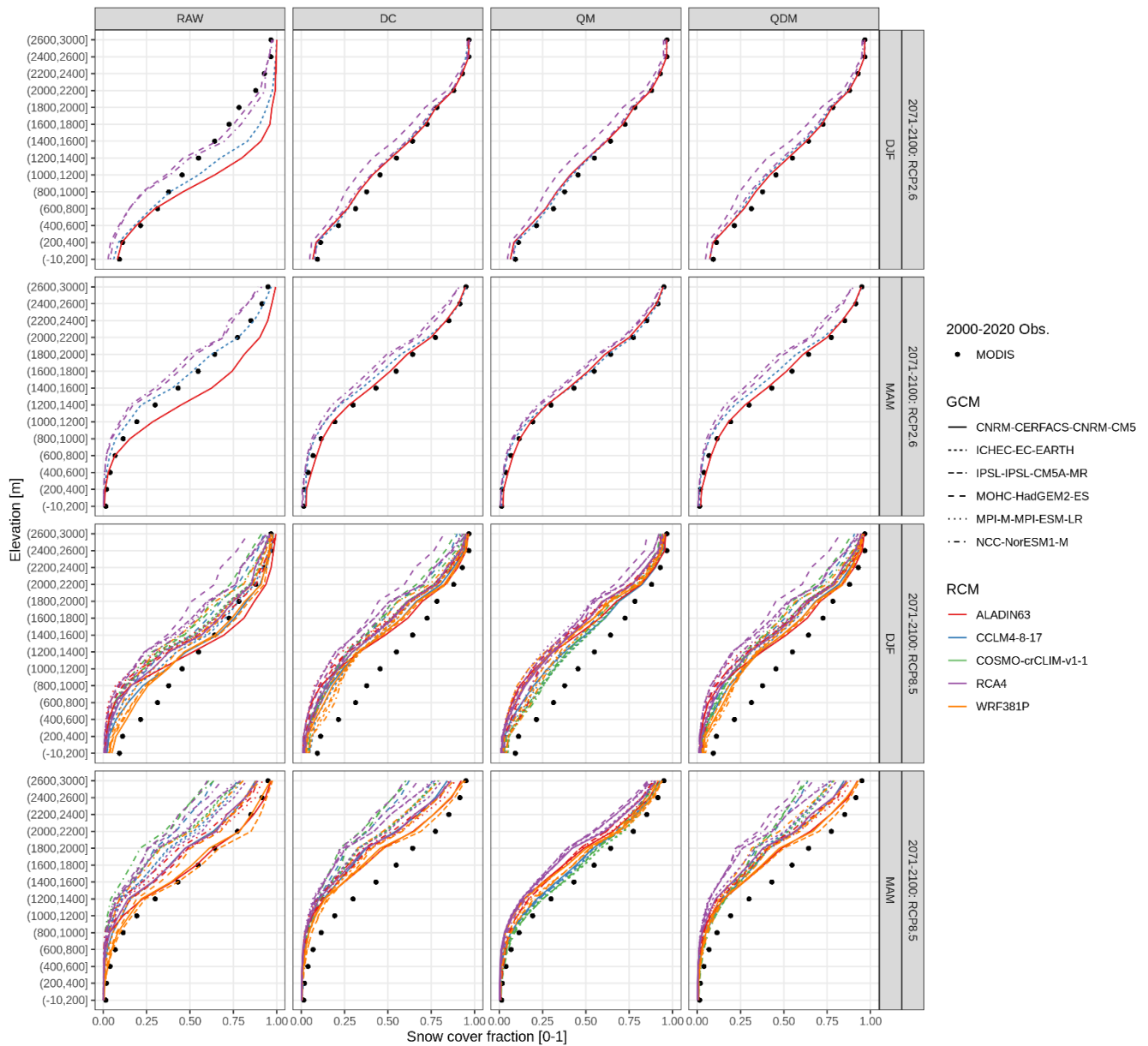
**Figure S4. Observed and projected snow cover fraction by elevation. Black points denote observations from remote sensing for the period 2000-2020 (the same in all panels), and colored lines the regional climate model (RCM) simulations with associated general circulation model (GCM) for the future period 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.**
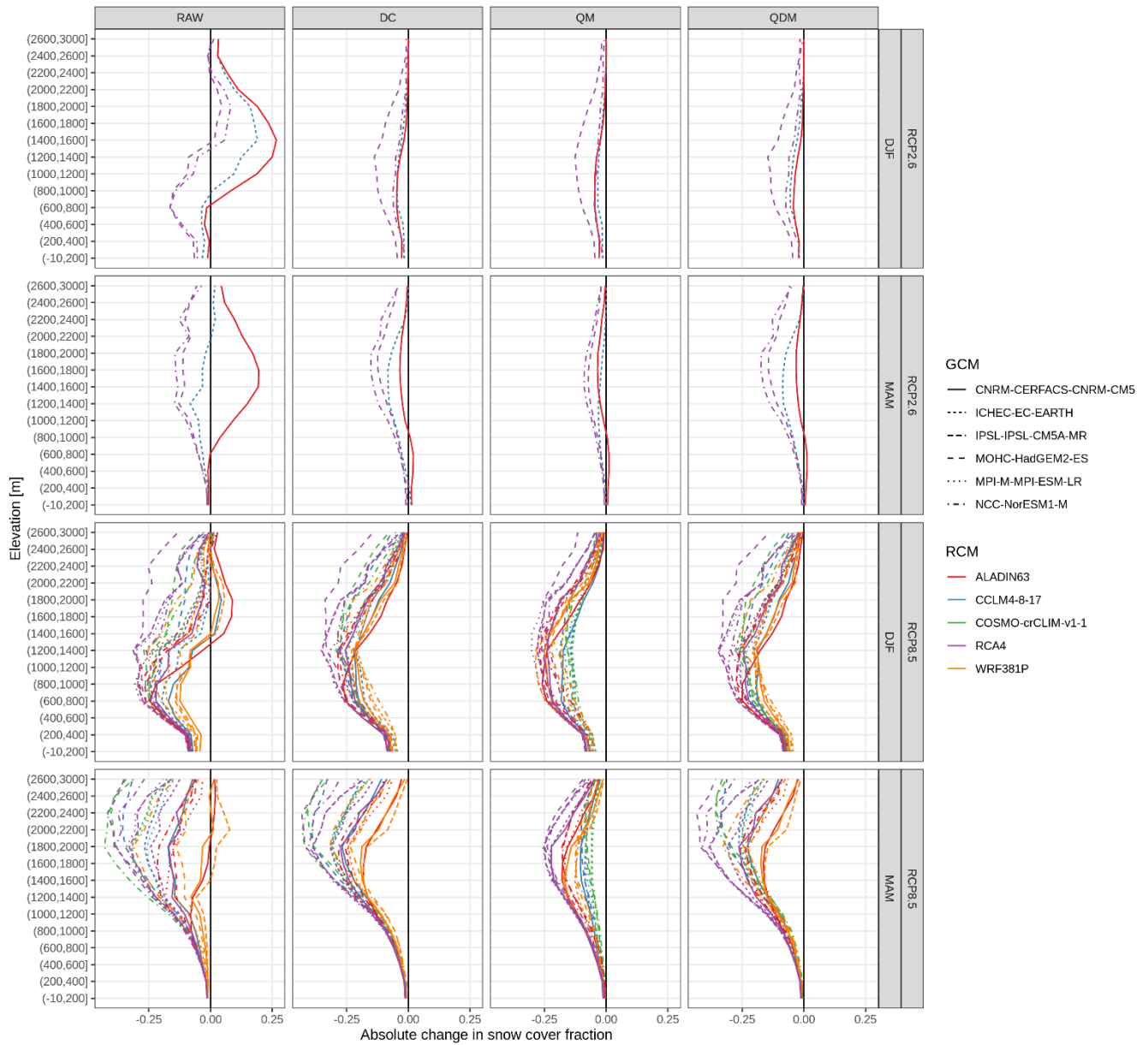
**Figure S5. Difference between future projections and past observations of snow cover fraction. Same information as in Figure S4 but relative to observations, thus highlighting the changes better.**
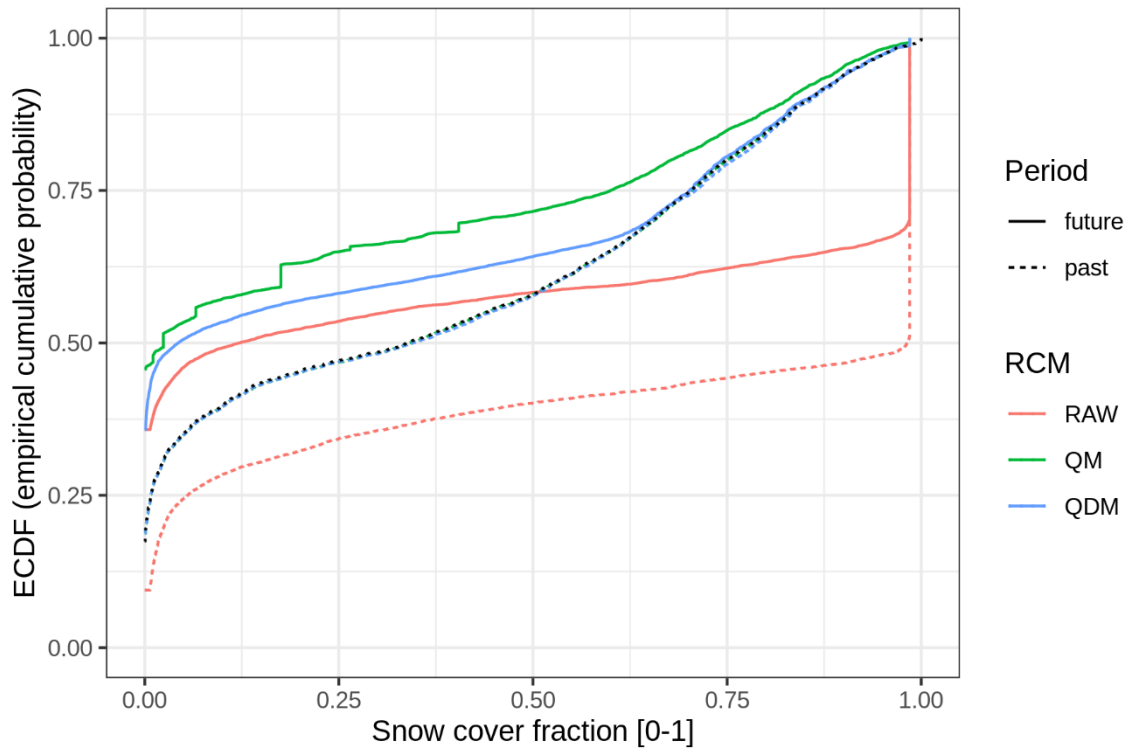
**Figure S6. Empirical cumulative probability distribution (ECDF) of snow cover fraction for a single pixel of the SMHI-RCA4 regional climate model (RCM) by period and bias correction algorithm. Dotted black line shows the ECDF of MODIS observations for the past (2000-2020), while the coloured dashed lines are the RCM data for the same period, original (RAW) and bias corrected 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).**

40
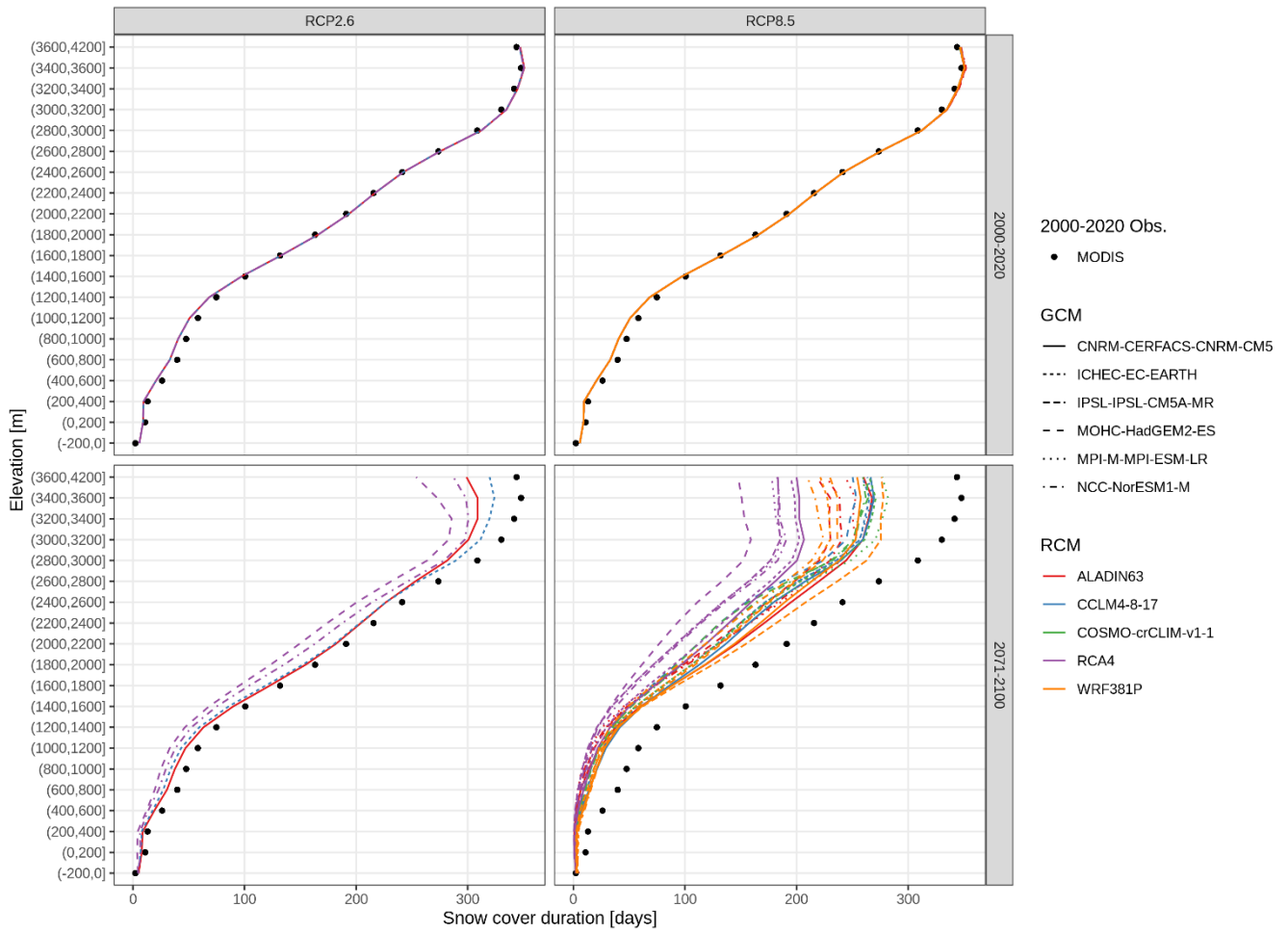
**Figure S7. Observed and projected snow cover duration (SCD) by elevation. Black points denote observations from remote sensing for the period 2000-2020 (the same in all panels), and colored lines the downscaled regional climate model (RCM) simulations with associated general circulation model (GCM) for the future period 2071-2100. Downscaling was applied to QDM (quantile delta mapping) bias corrected snow cover fraction. Columns denote emission scenarios (RCP, representative concentration pathway), and rows past and future period.**
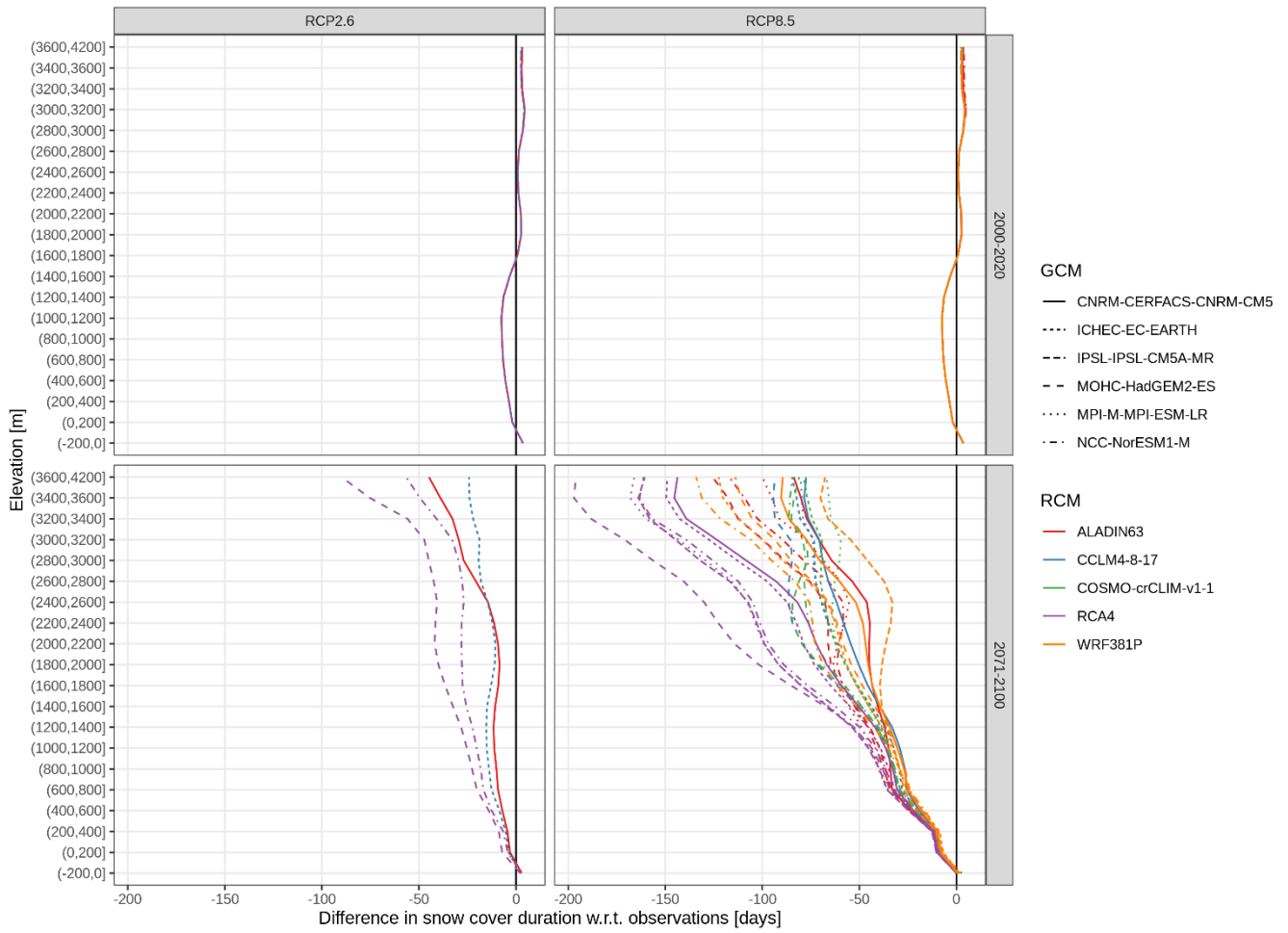
**Figure S8. Difference between future projections and past observations of snow cover duration. Same information as in Figure S7 but relative to observations.**

**(a)** 2000-2020 MODIS
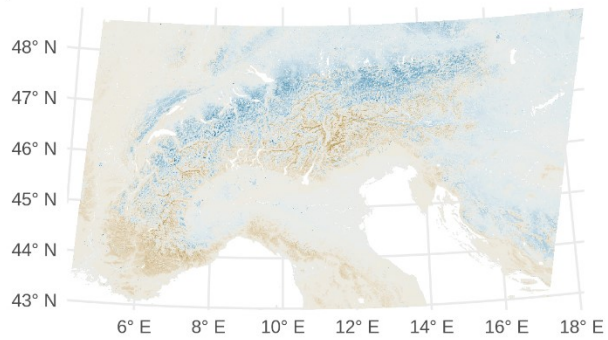
**(b)** 2071-2100 RCP2.6

**(c)** 2071-2100 RCP8.5

SCD elev. anom. [d]
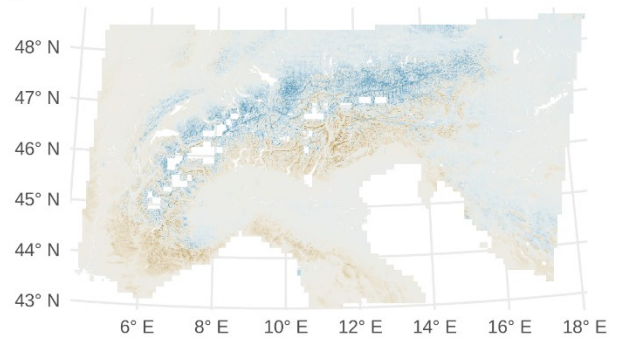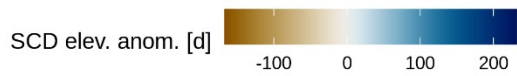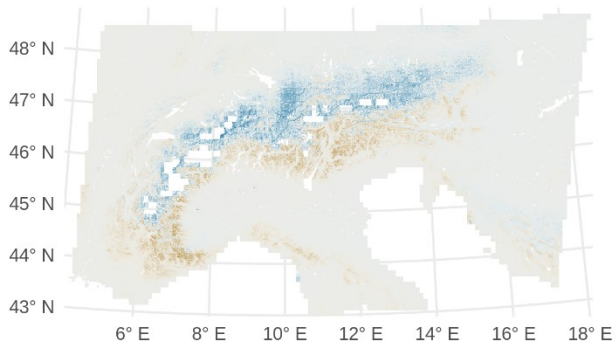
-100    0    100    200

**Figure S9. 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.**

60

65
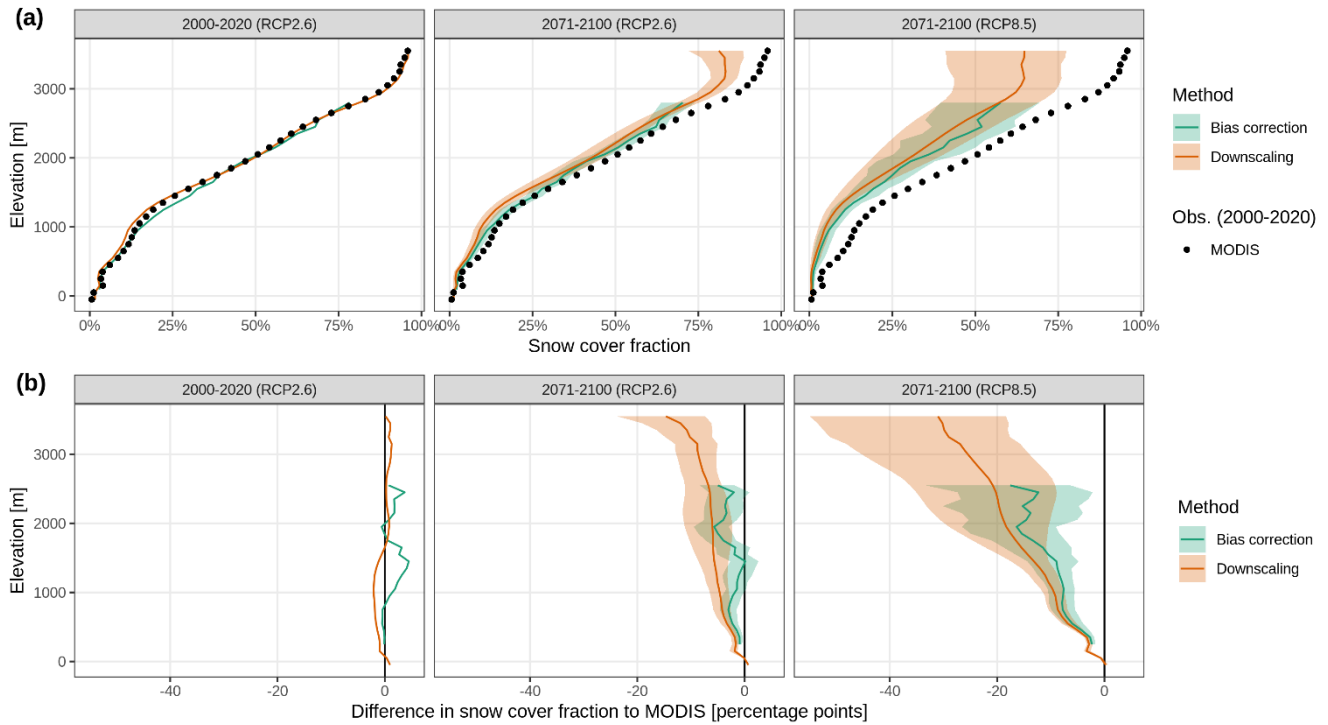
**Figure S10. Comparison of past and future estimates of snow cover fraction from bias correction and downscaling. Downscaled annual snow cover duration was converted to annual snow cover fraction for comparison. Solid line represents the model mean and the transparent region the model spread from 4 GCM-RCM pairs under RCP2.6 and 23 GCM-RCM pairs under RCP8.5. (a) shows absolute values of snow cover fraction from bias corrected and downscaled RCMs with observations based on MODIS remote sensing (points). (b) shows the same, but as differences to MODIS observations.**
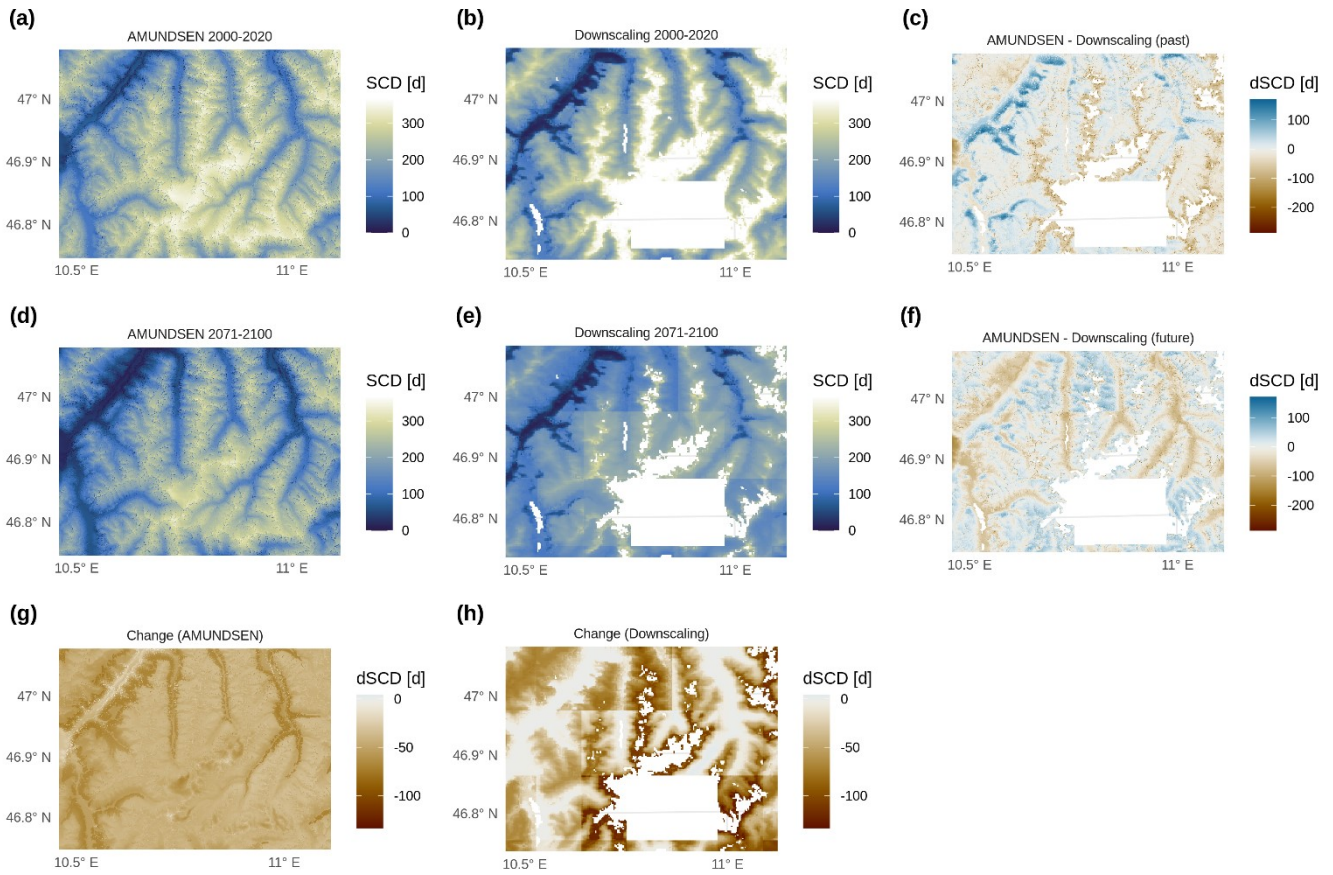
**Figure S11. Comparison of past and future estimates of snow cover duration (SCD) from AMUNDSEN (snow and hydroclimatological model) to downscaling. Maps show model ensemble means under RCP8.5 for the past (a,d) and future (b,e). AMUNDSEN has been forced by downscaled meteorology from RCMs, while Downscaling 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.**
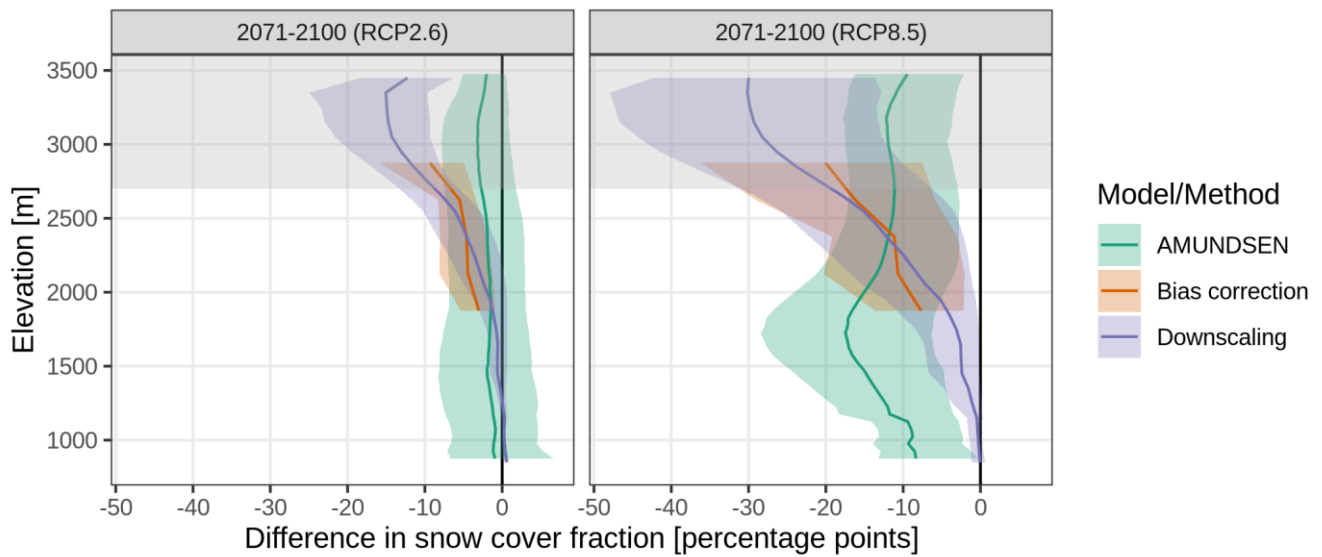
Figure S12. Difference between future and past snow cover fraction for the Ötztal Alps region in Austria by elevation and under two emission scenarios (RCP, representative concentration pathway). See also Fig. 6.

[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 corrected SNC from RCMs, and from 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.]

**Tables**

105

**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 |

110

**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% |

115

Table S3. Projected changes in percentage points of winter (December to February) snow cover fraction from regional climate models relative to observed snow cover fraction from remote sensing. 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 S5.

| Scenario | Elevation [m] | RAW | DC | QM | QDM |
|---|---|---|---|---|---|
| RCP2.6 | (2600,3000] | 2.0 (0.3, 3.3) | -0.1 (-0.8, 0.5) | -0.6 (-1.8, 0.0) | -0.5 (-1.5, 0.1) |
| | (2400,2600] | 0.9 (-1.1, 2.9) | -0.4 (-0.9, 0.1) | -0.8 (-2.0, -0.0) | -0.9 (-1.7, 0.0) |
| | (2200,2400] | 3.1 (-0.4, 6.7) | -0.9 (-2.6, 0.0) | -1.2 (-3.1, -0.1) | -1.3 (-3.1, -0.1) |
| | (2000,2200] | 7.3 (2.7, 11.3) | -1.4 (-3.8, -0.2) | -1.6 (-4.4, -0.4) | -1.5 (-3.9, -0.2) |
| | (1800,2000] | 11.9 (4.6, 19.0) | -2.7 (-6.9, -0.5) | -2.7 (-7.0, -0.6) | -2.7 (-6.7, -0.5) |
| | (1600,1800] | 12.7 (2.6, 23.5) | -3.7 (-9.2, -0.8) | -3.6 (-9.1, -1.3) | -3.6 (-9.0, -0.6) |
| | (1400,1600] | 13.2 (1.6, 26.7) | -4.7 (-10.7, -1.7) | -4.7 (-11.0, -2.2) | -4.6 (-10.5, -1.2) |
| | (1200,1400] | 5.9 (-8.9, 25.0) | -6.5 (-13.8, -3.3) | -5.8 (-12.6, -3.0) | -6.8 (-14.6, -2.5) |
| | (1000,1200] | 3.0 (-9.3, 18.8) | -6.7 (-12.8, -4.4) | -5.9 (-12.0, -3.3) | -7.0 (-13.5, -3.5) |
| | (800,1000] | -5.1 (-15.1, 8.3) | -6.9 (-12.3, -4.6) | -5.9 (-11.1, -3.3) | -7.5 (-13.3, -4.0) |
| | (600,800] | -9.5 (-16.4, -1.5) | -6.3 (-10.4, -4.2) | -5.6 (-9.6, -3.2) | -7.1 (-11.5, -4.3) |
| | (400,600] | -7.5 (-12.5, -2.4) | -4.4 (-7.3, -2.0) | -4.0 (-6.8, -1.6) | -4.9 (-7.8, -3.1) |
| | (200,400] | -3.9 (-7.0, -0.4) | -2.9 (-5.2, -1.8) | -2.8 (-4.9, -1.5) | -2.9 (-5.1, -2.0) |
| | (-10,200] | -4.1 (-6.6, -1.2) | -2.6 (-4.5, -1.5) | -2.6 (-4.6, -1.4) | -2.6 (-4.5, -1.9) |
| RCP8.5 | (2600,3000] | -1.0 (-13.2, 2.8) | -3.0 (-14.4, -0.2) | -2.9 (-11.5, -0.7) | -3.1 (-14.1, -0.3) |
| | (2400,2600] | -4.5 (-19.7, 1.5) | -6.2 (-20.1, -1.5) | -4.4 (-12.7, -1.2) | -6.4 (-20.4, -1.5) |
| | (2200,2400] | -5.5 (-25.3, 3.9) | -9.9 (-27.4, -2.7) | -7.2 (-17.9, -2.8) | -9.6 (-27.2, -2.4) |
| | (2000,2200] | -4.6 (-23.7, 5.9) | -12.5 (-28.4, -4.2) | -10.4 (-21.1, -5.4) | -11.6 (-27.4, -3.5) |
| | (1800,2000] | -6.3 (-27.3, 8.8) | -18.6 (-33.8, -8.5) | -16.1 (-25.5, -9.1) | -17.0 (-32.9, -7.3) |
| | (1600,1800] | -8.7 (-27.3, 8.5) | -21.2 (-33.4, -11.1) | -18.2 (-27.0, -11.5) | -19.4 (-32.7, -9.1) |
| | (1400,1600] | -11.0 (-27.4, 5.4) | -23.9 (-33.5, -15.7) | -20.8 (-30.1, -13.0) | -21.9 (-33.1, -12.8) |
| | (1200,1400] | -19.3 (-31.4, -3.2) | -26.6 (-35.3, -20.7) | -21.8 (-30.2, -13.9) | -25.2 (-35.0, -17.7) |
| | (1000,1200] | -19.7 (-28.6, -8.2) | -24.7 (-31.9, -18.6) | -20.7 (-28.4, -13.0) | -23.8 (-31.6, -18.0) |
| | (800,1000] | -22.9 (-30.7, -12.0) | -23.2 (-30.0, -15.3) | -19.6 (-27.4, -12.1) | -23.1 (-30.2, -16.4) |
| | (600,800] | -22.5 (-28.5, -12.3) | -21.0 (-26.3, -11.9) | -18.1 (-24.6, -11.2) | -21.1 (-27.1, -13.3) |
| | (400,600] | -16.4 (-19.9, -8.1) | -15.3 (-18.5, -7.9) | -13.7 (-17.9, -9.1) | -15.1 (-19.1, -8.8) |
| | (200,400] | -8.6 (-10.5, -3.8) | -8.3 (-10.0, -5.1) | -7.7 (-9.7, -5.4) | -7.9 (-9.9, -4.8) |
| | (-10,200] | -7.6 (-9.0, -4.3) | -7.0 (-8.5, -4.4) | -6.7 (-8.5, -4.3) | -6.8 (-8.4, -4.4) |

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

| Scenario | Elevation [m] | RAW | DC | QM | QDM |
|---|---|---|---|---|---|
| RCP2.6 | (2600,3000] | -0.8 (-5.5, 4.4) | -2.2 (-4.6, 0.2) | -1.0 (-2.0, 0.1) | -2.7 (-5.8, -0.0) |
| | (2400,2600] | -2.5 (-8.5, 5.7) | -3.5 (-7.5, -0.2) | -1.7 (-3.4, 0.0) | -4.4 (-8.8, -0.6) |
| | (2200,2400] | -2.9 (-12.7, 9.7) | -5.5 (-11.0, -1.3) | -2.5 (-4.6, -0.2) | -6.4 (-12.7, -1.5) |
| | (2000,2200] | -0.9 (-8.7, 12.9) | -7.1 (-11.4, -2.6) | -3.5 (-5.9, -0.6) | -7.6 (-12.4, -2.5) |
| | (1800,2000] | -2.6 (-14.4, 17.1) | -9.4 (-15.0, -3.2) | -4.7 (-7.9, -1.3) | -10.5 (-17.2, -3.1) |
| | (1600,1800] | -2.3 (-14.2, 19.6) | -9.8 (-15.3, -3.5) | -5.4 (-8.9, -2.0) | -10.8 (-17.4, -3.2) |
| | (1400,1600] | -1.9 (-13.2, 19.3) | -9.1 (-14.1, -3.1) | -5.5 (-8.9, -2.5) | -10.2 (-16.3, -2.9) |
| | (1200,1400] | -5.2 (-14.6, 14.9) | -7.7 (-12.2, -2.4) | -4.9 (-7.8, -2.4) | -8.9 (-13.9, -2.3) |
| | (1000,1200] | -3.5 (-9.8, 9.1) | -5.3 (-8.3, -1.3) | -3.7 (-5.8, -1.1) | -6.0 (-9.4, -1.2) |
| | (800,1000] | -3.6 (-7.3, 3.9) | -3.2 (-5.4, 0.7) | -2.5 (-4.2, 0.4) | -3.8 (-6.1, 0.4) |
| | (600,800] | -3.3 (-5.1, -0.2) | -1.7 (-3.5, 2.0) | -1.5 (-3.0, 1.2) | -2.2 (-3.8, 1.2) |
| | (400,600] | -2.4 (-3.2, -1.1) | -0.7 (-1.9, 1.9) | -0.8 (-1.7, 1.2) | -1.1 (-2.1, 1.3) |
| | (200,400] | -1.2 (-1.6, -0.7) | -0.1 (-1.2, 1.3) | -0.3 (-0.9, 0.8) | -0.4 (-1.0, 0.8) |
| | (-10,200] | -1.1 (-1.4, -0.7) | 0.3 (-1.0, 1.4) | -0.2 (-0.8, 0.7) | -0.2 (-0.9, 0.5) |
| RCP8.5 | (2600,3000] | -13.9 (-35.0, 2.6) | -15.8 (-35.5, -0.4) | -4.3 (-9.3, -0.9) | -15.8 (-35.9, -1.2) |
| | (2400,2600] | -17.6 (-39.1, 2.7) | -20.1 (-38.7, -3.0) | -7.3 (-14.9, -2.3) | -19.4 (-38.6, -3.3) |
| | (2200,2400] | -20.3 (-41.7, 5.4) | -24.7 (-43.2, -5.5) | -10.2 (-20.2, -3.9) | -23.4 (-43.5, -5.0) |
| | (2000,2200] | -21.0 (-41.9, 7.8) | -27.4 (-43.0, -8.3) | -12.5 (-23.5, -5.1) | -25.1 (-42.2, -7.0) |
| | (1800,2000] | -23.9 (-43.1, 2.5) | -30.4 (-42.0, -16.6) | -14.7 (-25.6, -5.5) | -27.4 (-42.1, -14.5) |
| | (1600,1800] | -22.2 (-38.6, 1.7) | -28.0 (-36.6, -18.0) | -14.8 (-24.5, -5.6) | -25.1 (-36.0, -15.8) |
| | (1400,1600] | -19.7 (-32.7, -0.0) | -24.5 (-30.9, -18.2) | -14.1 (-22.3, -5.4) | -21.9 (-30.5, -15.9) |
| | (1200,1400] | -18.0 (-25.6, -5.7) | -19.0 (-23.4, -14.2) | -11.4 (-17.4, -4.6) | -17.1 (-23.5, -13.2) |
| | (1000,1200] | -12.1 (-16.9, -2.7) | -12.8 (-15.5, -9.1) | -8.5 (-12.7, -3.5) | -11.5 (-15.6, -8.6) |
| | (800,1000] | -8.2 (-10.5, -1.9) | -8.1 (-9.6, -5.4) | -5.8 (-8.5, -2.5) | -7.3 (-9.8, -5.0) |
| | (600,800] | -5.4 (-6.6, -1.4) | -5.0 (-5.9, -3.3) | -3.9 (-5.8, -1.8) | -4.6 (-6.0, -3.0) |
| | (400,600] | -3.3 (-3.8, -1.2) | -2.9 (-3.5, -2.0) | -2.3 (-3.4, -1.0) | -2.6 (-3.4, -1.5) |
| | (200,400] | -1.6 (-1.8, -0.9) | -1.4 (-1.7, -0.7) | -1.1 (-1.6, -0.5) | -1.2 (-1.6, -0.6) |
| | (-10,200] | -1.3 (-1.4, -1.0) | -1.1 (-1.3, -0.7) | -0.8 (-1.3, -0.3) | -0.9 (-1.3, -0.4) |

125

18

**Table S5. Past observed and future projected snow cover duration (days) based on high-resolution satellite imagery (MODIS) and downscaled 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 S6.**

130

| Elevation [m] | MODIS 2000-2020 | RCP2.6 2071-2100 | RCP8.5 2071-2100 |
|---|---|---|---|
| (3600,4200] | 344 | 290 (254, 320) | 232 (148, 277) |
| (3400,3600] | 348 | 301 (273, 324) | 237 (151, 282) |
| (3200,3400] | 342 | 304 (286, 319) | 235 (153, 277) |
| (3000,3200] | 330 | 298 (283, 311) | 234 (159, 276) |
| (2800,3000] | 309 | 278 (264, 289) | 220 (152, 263) |
| (2600,2800] | 274 | 247 (231, 256) | 193 (133, 236) |
| (2400,2600] | 241 | 217 (201, 227) | 166 (111, 208) |
| (2200,2400] | 216 | 192 (174, 204) | 143 (93, 182) |
| (2000,2200] | 191 | 169 (149, 182) | 121 (77, 155) |
| (1800,2000] | 163 | 141 (123, 155) | 98 (61, 125) |
| (1600,1800] | 132 | 110 (95, 123) | 74 (47, 92) |
| (1400,1600] | 101 | 80 (68, 90) | 51 (33, 62) |
| (1200,1400] | 75 | 55 (47, 63) | 33 (21, 42) |
| (1000,1200] | 58 | 40 (33, 47) | 22 (13, 29) |
| (800,1000] | 48 | 32 (25, 38) | 15 (8, 21) |
| (600,800] | 40 | 25 (20, 30) | 9 (4, 16) |
| (400,600] | 26 | 16 (12, 19) | 5 (1, 10) |
| (200,400] | 13 | 7 (4, 9) | 2 (0, 5) |
| (0,200] | 11 | 6 (4, 8) | 2 (1, 4) |
| (-200,0] | 2 | 5 (4, 5) | 3 (2, 5) |