Supplement of

SWEDE v2: Emulating western US Dynamically Downscaled Snow Water Equivalent from Native CESM2 Large Ensemble

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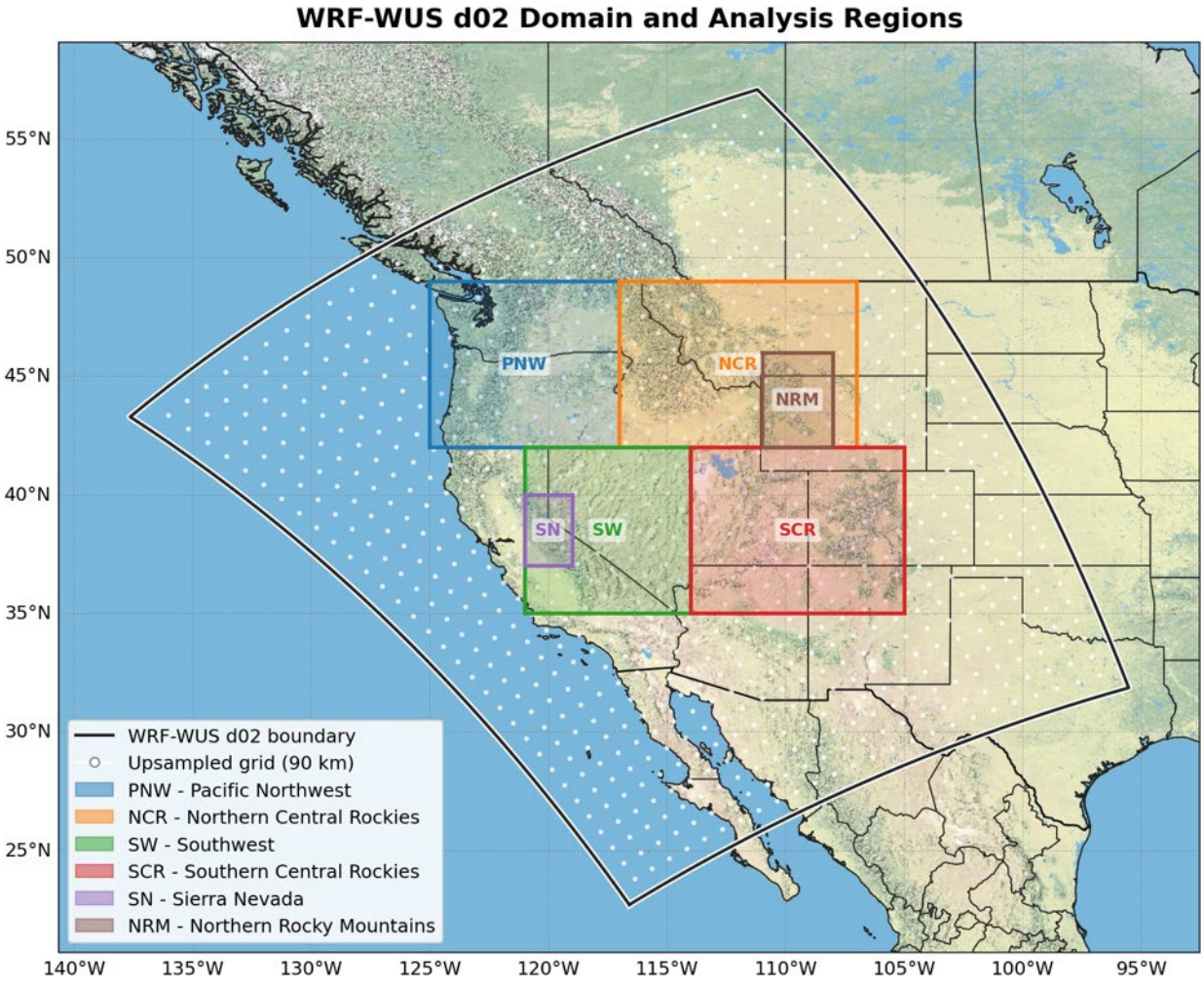


Figure S1. The WUS-D3 WRF simulation domain (d02, black outline) at 9 km resolution and the six evaluation subregions used in this study: Pacific Northwest (PNW), Northern Central Rockies (NCR), Southwest (SW), Southern Central Rockies (SCR), Sierra Nevada (SN), and Northern Rocky Mountains (NRM), following the regional definitions of Rahimi et al. (2022). White circles denote the coarsened input grid at approximately 90 km resolution, obtained via block averaging.

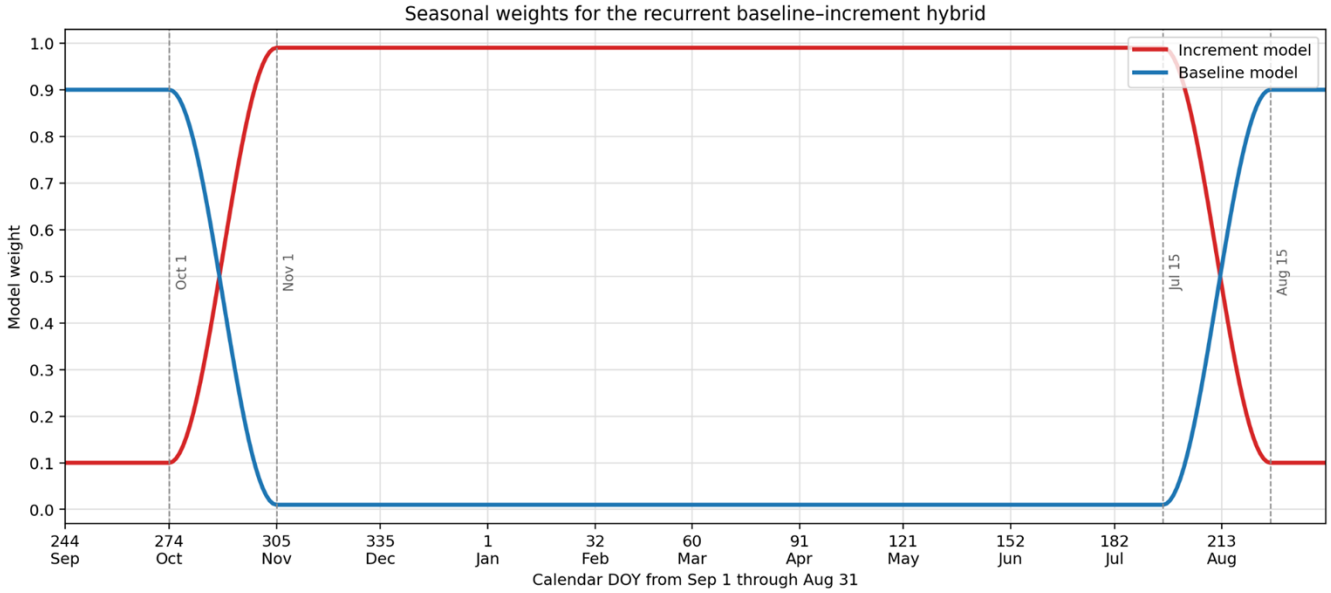


Figure S2. Seasonal weight w applied to the increment network in the SWEDE v2 hybrid, as a function of calendar day from 1 September to 31 August. The increment weight (red) is 0.99 from 1 November to 15 July, so that the recurrent network governs the field while snowpack persists. It decreases by a cosine ramp to 0.1 between 15 July and 15 August, holds 0.1 through 30 September, and returns by a cosine ramp to 0.99 between 1 October and 1 November. The baseline weight (blue) is (1 – w).

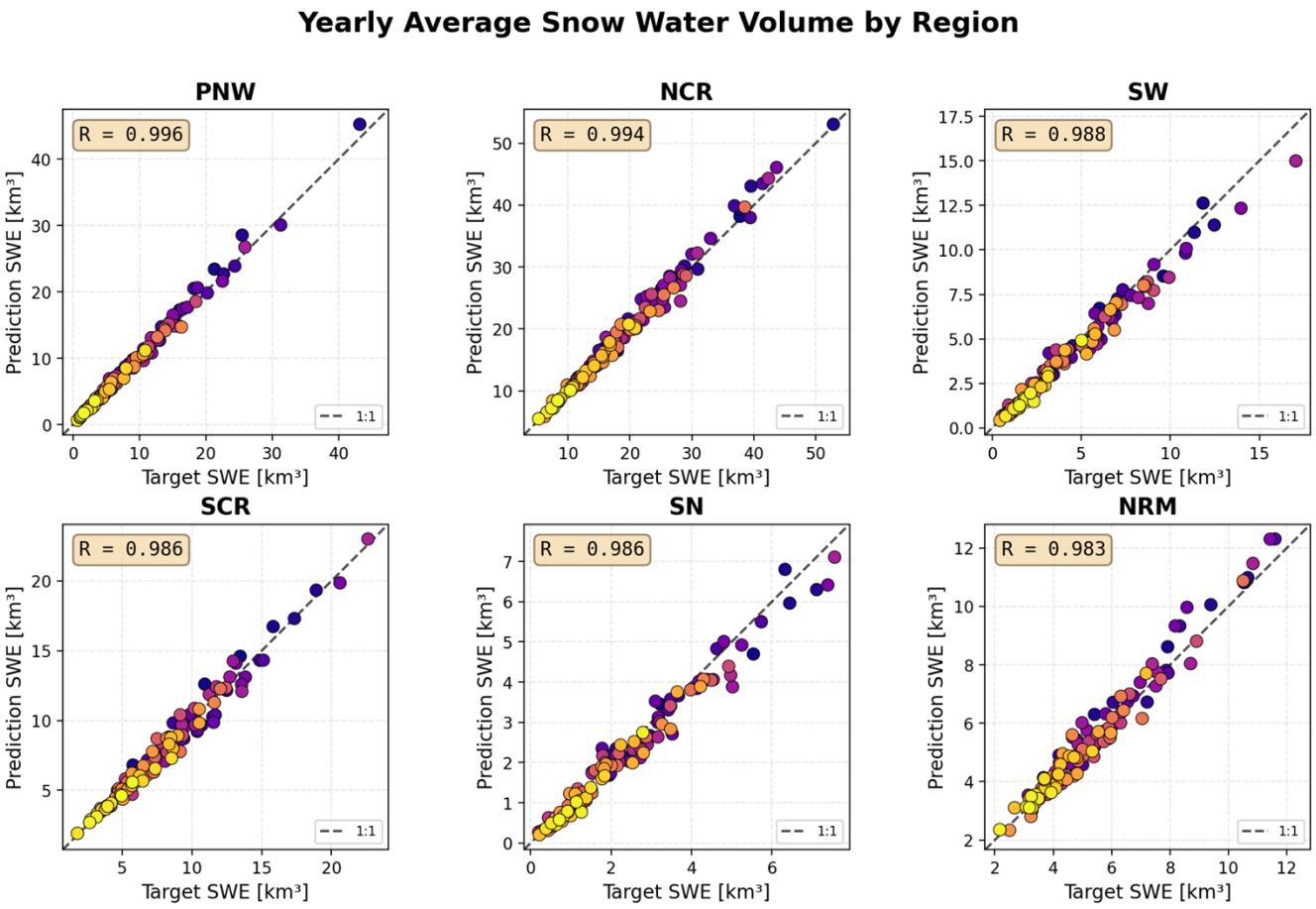
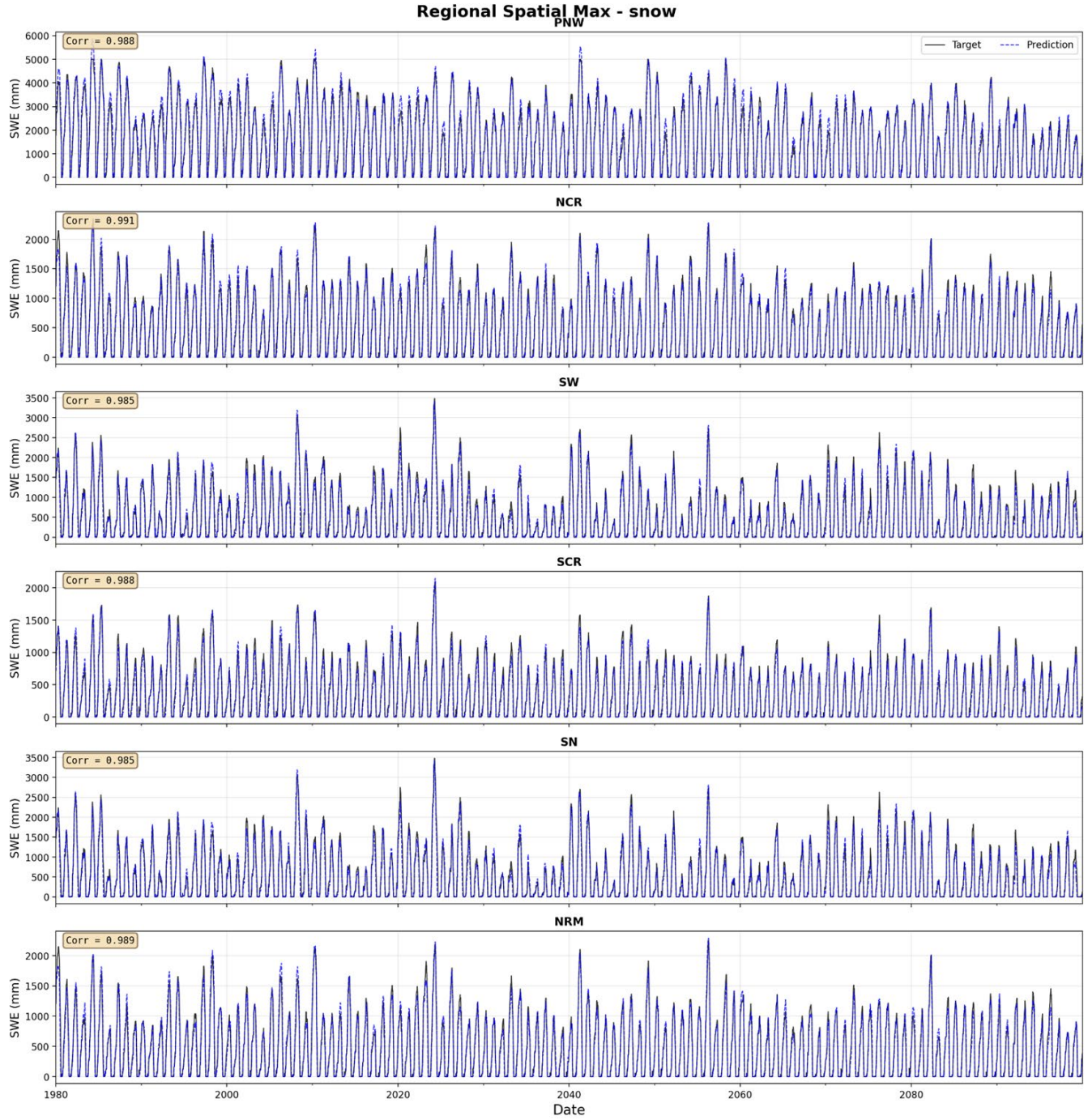


Figure S3. Water-year mean snow water volume from SWEDE v2 against the WRF target for each subregion on the test member, 1980 to 2099. Each marker is one water year, colored from dark purple (early in the record) to yellow (late). Both axes show snow water volume in km³, the sum of SWE multiplied by cell area over all terrestrial cells of the subregion. The dashed line is the 1:1 line.



35 Figure S4. Daily time series of the maximum SWE over all grid cells in each subregion for the test member, water years 1980 to 2099, from the WRF target (black) and SWEDE v2 (blue dashed).

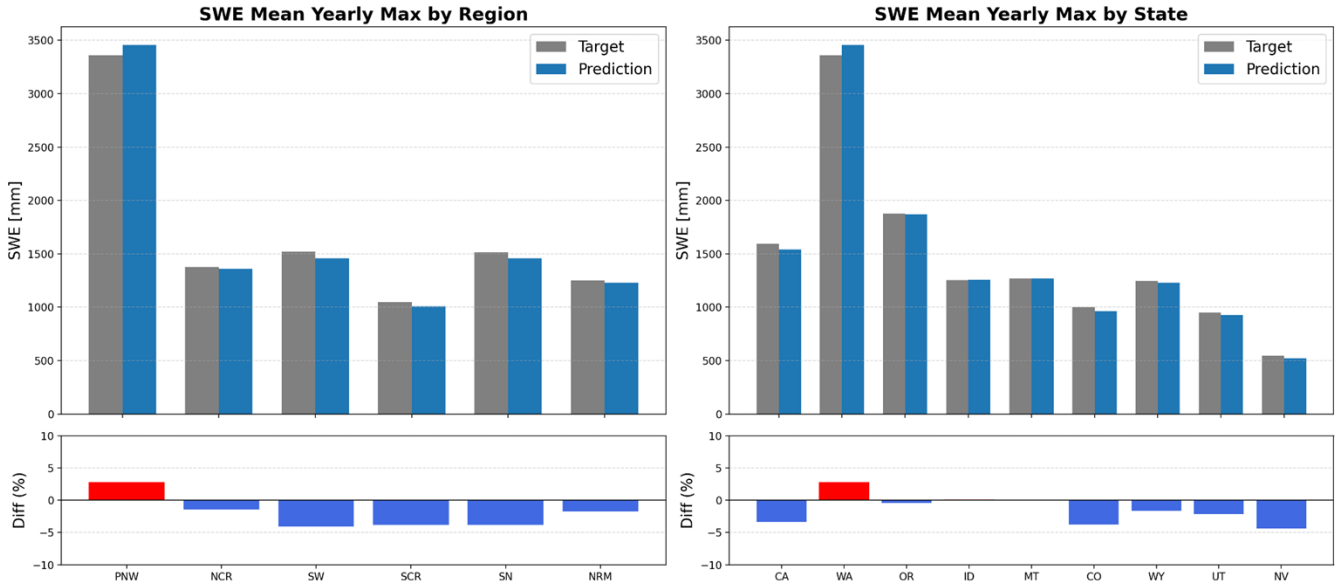


Figure S5. Mean annual maximum SWE for the test member, 1980 to 2099, from the WRF target (grey) and SWEDE v2 (blue), averaged over subregions (left) and over states (right). Lower panels show the relative difference of the emulator from the target.

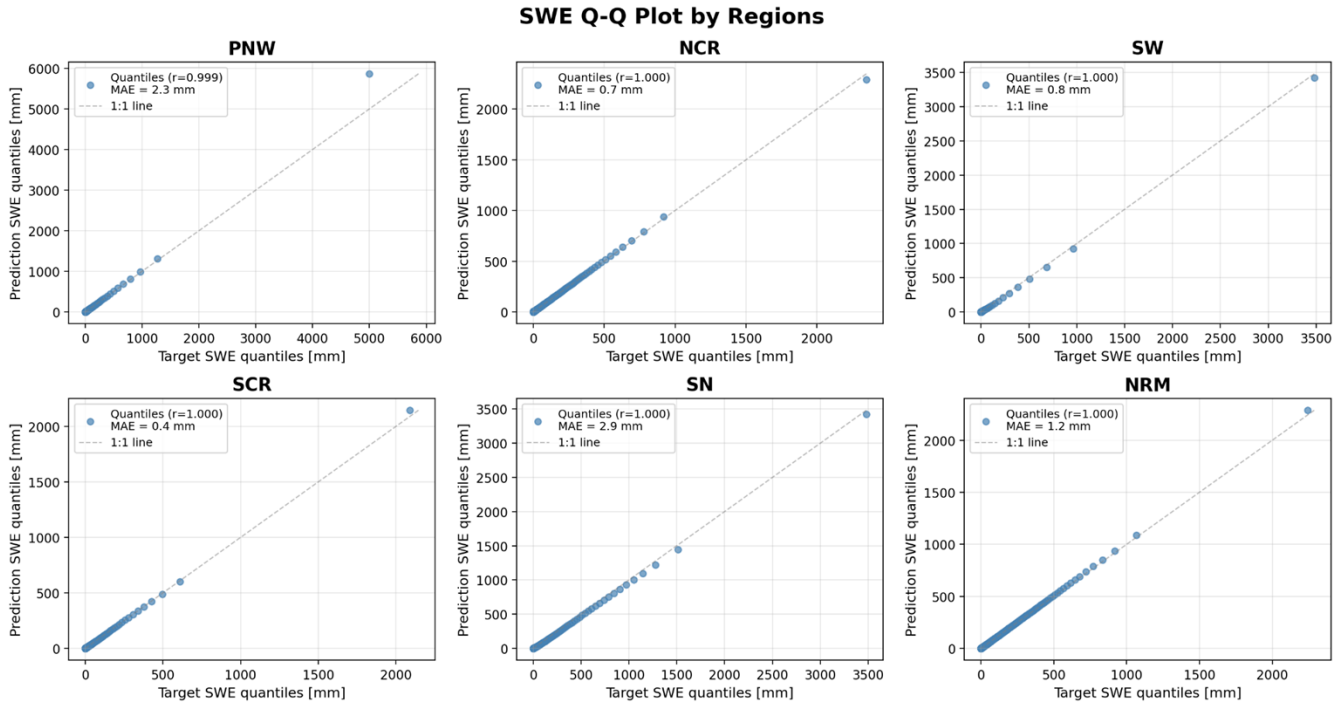


Figure S6. Quantiles of daily 9 km SWE from SWEDE v2 against the corresponding quantiles of the WRF target, pooled over all land cells and all days of 1980 to 2099 in each subregion, for the test member. The dashed line is the 1:1 line.

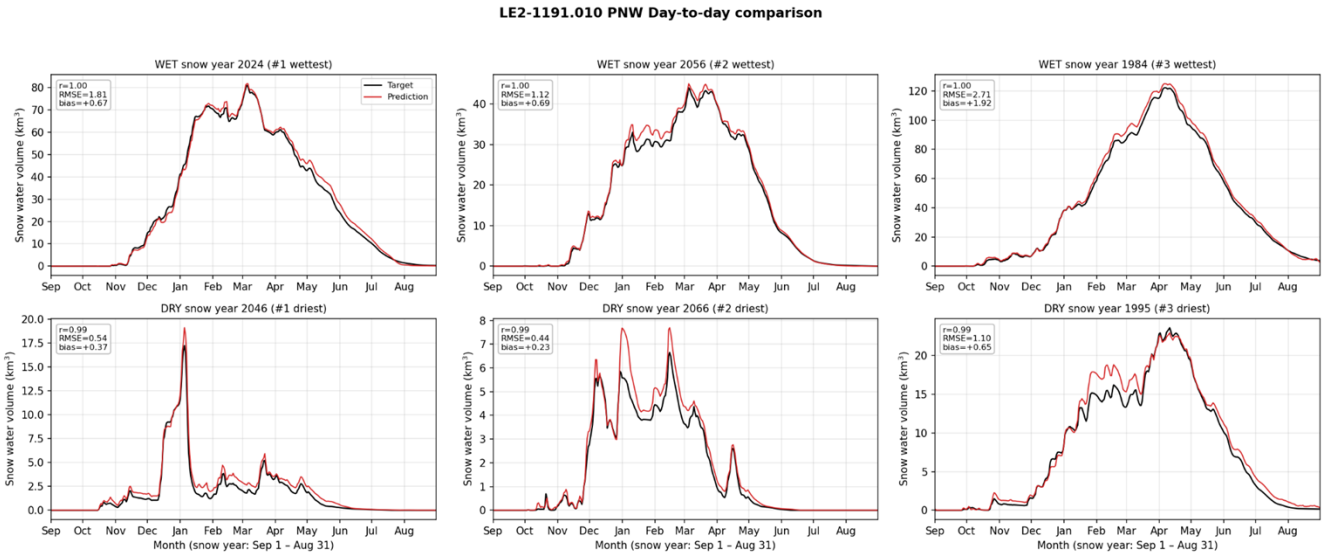


Figure S7. Daily snow water volume over the PNW subregion in the three wettest (top row) and three driest (bottom row) water years of the test member LE2-1191.010. Water years are ordered by the domain wide detrended peak volume anomaly, from left to right: 2024, 2056, and 1984 for the wet years and 2046, 2066, and 1995 for the dry years. Black is the WRF target and red is the SWEDE v2 free run. Snow water volume is the daily subregion sum of SWE in km³. The horizontal axis runs from 1 September to 31 August with a tick at the start of each month, and the vertical axis range is set separately for each panel. Daily correlation, root mean square error (km³), and mean bias (km³, prediction minus target) for each year are listed in the panel inset.

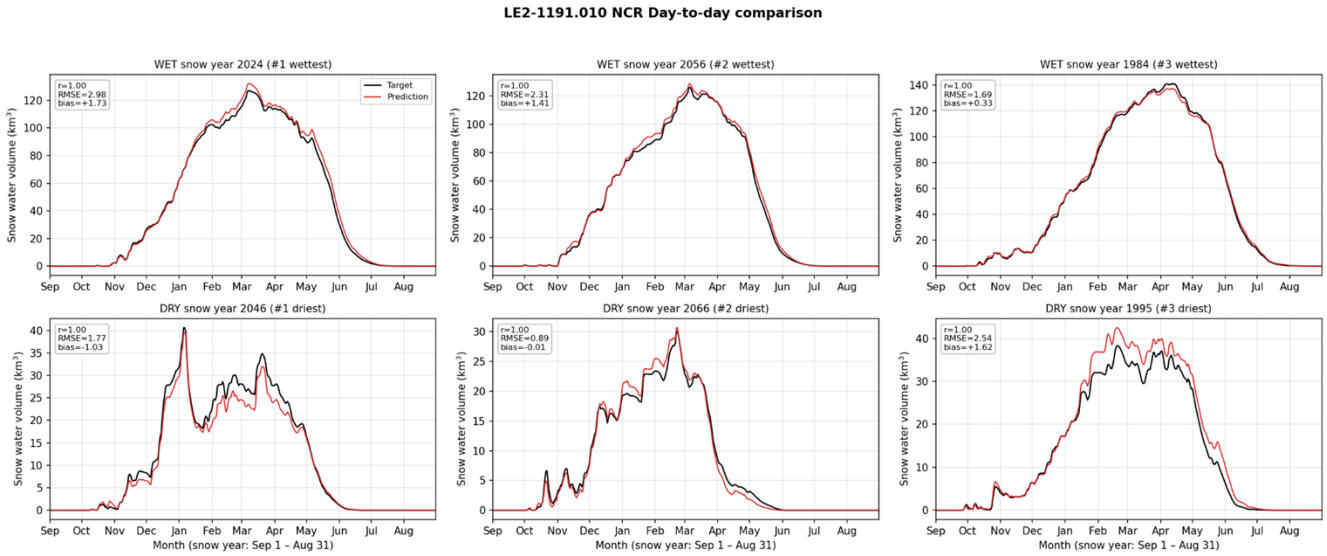


Figure S8. As Figure S7, daily snow water volume over the NCR subregion in the three wettest (top row) and three driest (bottom row) water years of the test member LE2-1191.010.

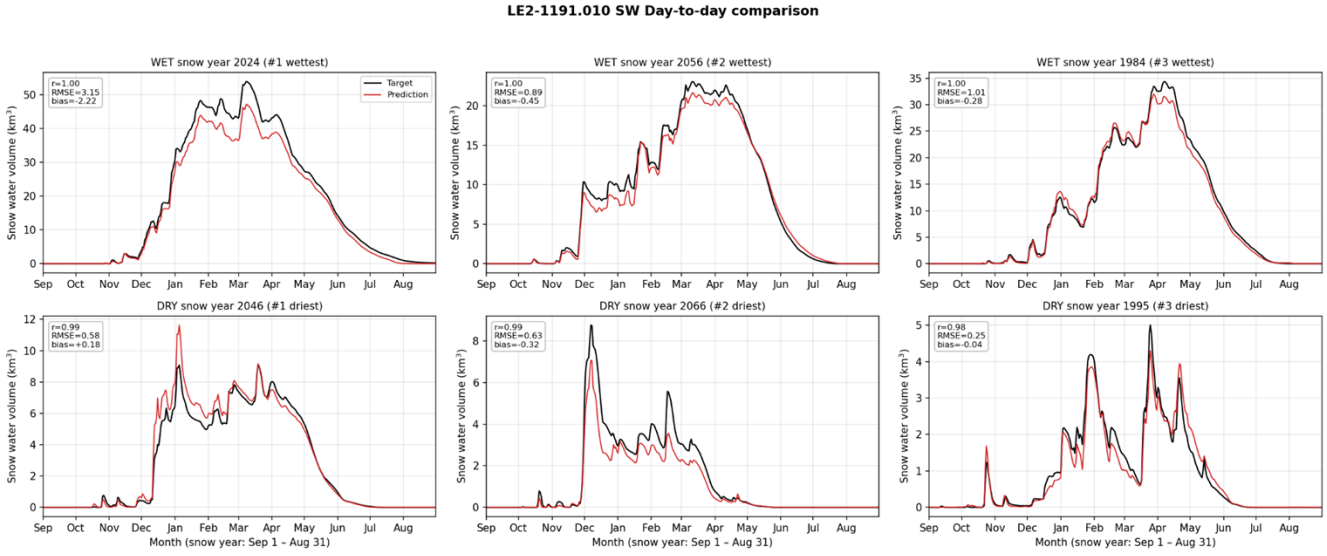


Figure S9. As Figure S7, daily snow water volume over the SW subregion in the three wettest (top row) and three driest (bottom row) water years of the test member LE2-1191.010.

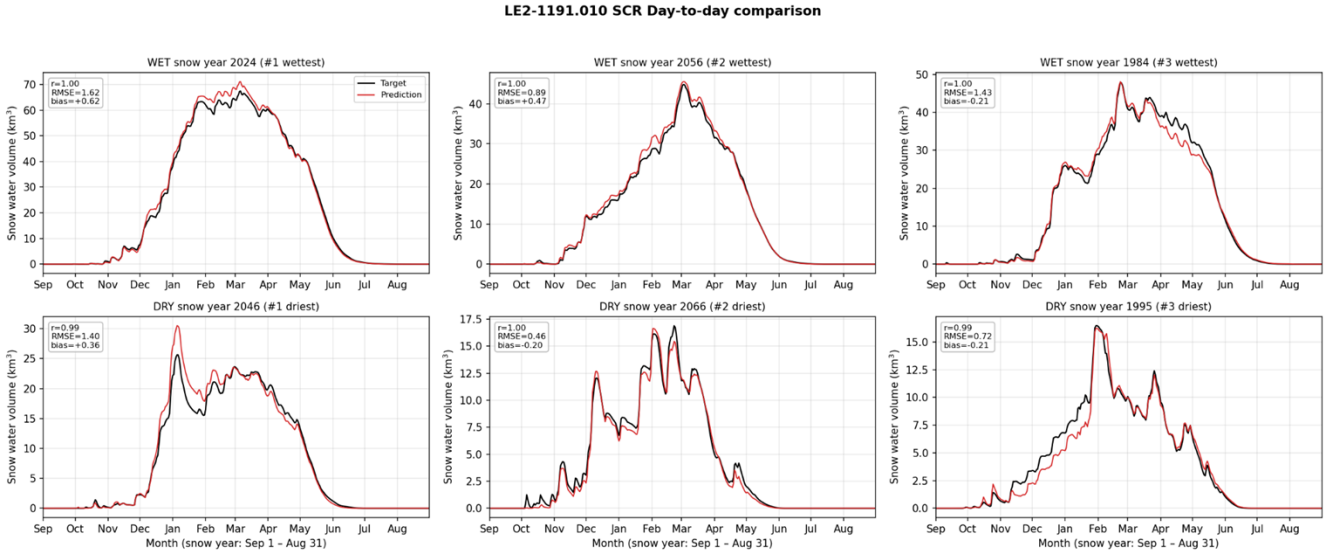


Figure S10. As Figure S7, daily snow water volume over the SCR subregion in the three wettest (top row) and three driest (bottom row) water years of the test member LE2-1191.010.

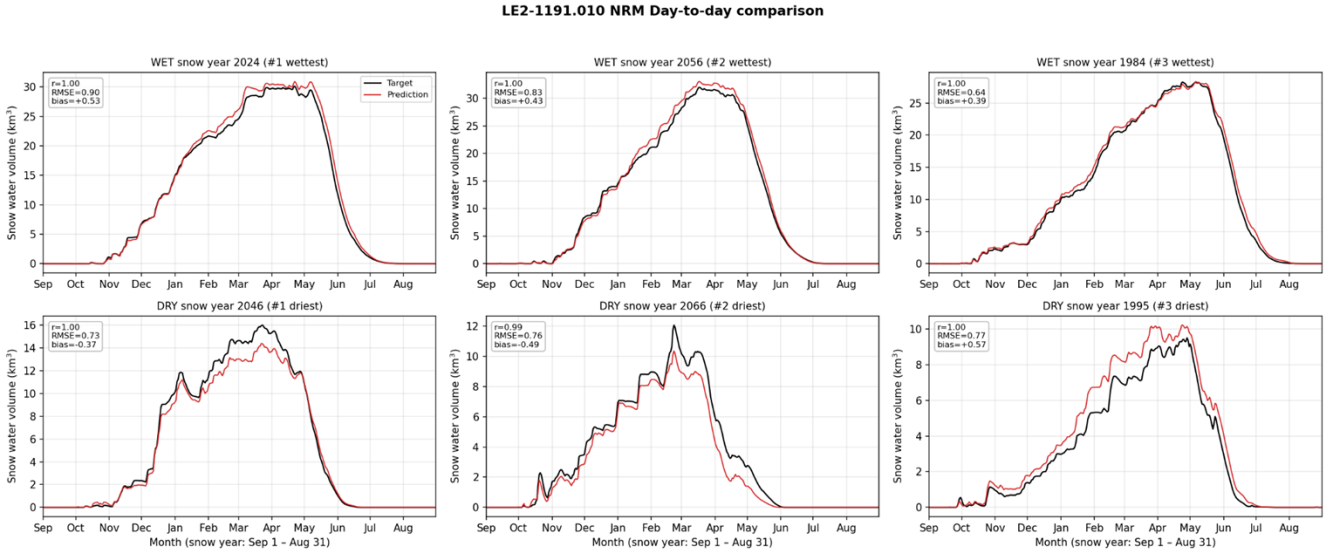


Figure S11. As Figure S7, daily snow water volume over the NRM subregion in the three wettest (top row) and three driest (bottom row) water years of the test member LE2-1191.010.

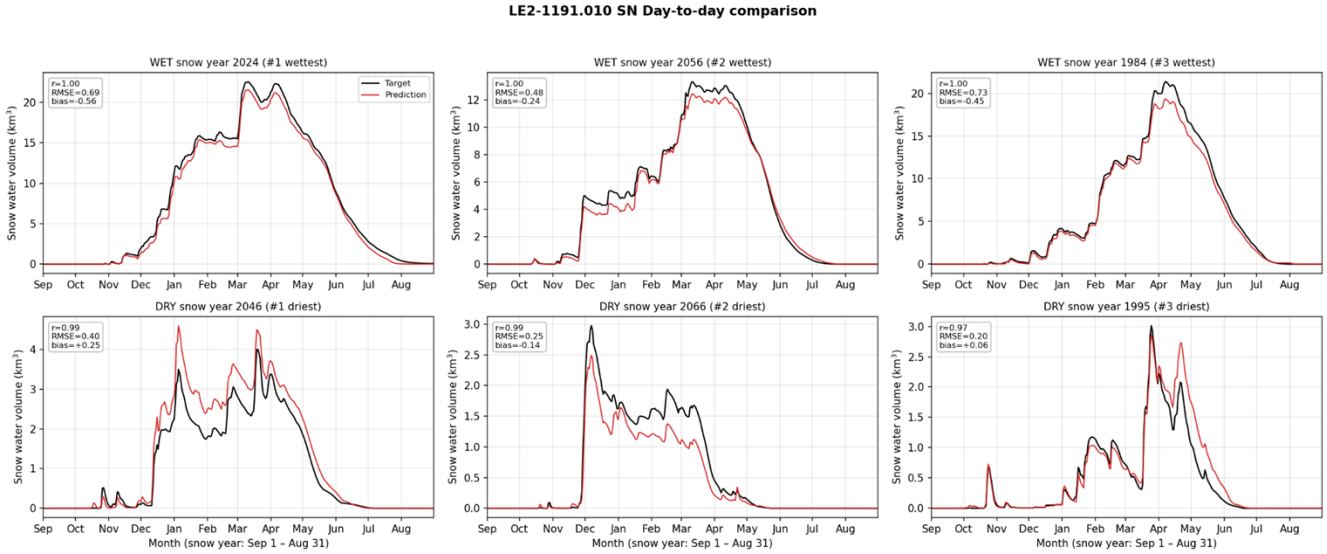


Figure S12. As Figure S7, daily snow water volume over the SN subregion in the three wettest (top row) and three driest (bottom row) water years of the test member LE2-1191.010.

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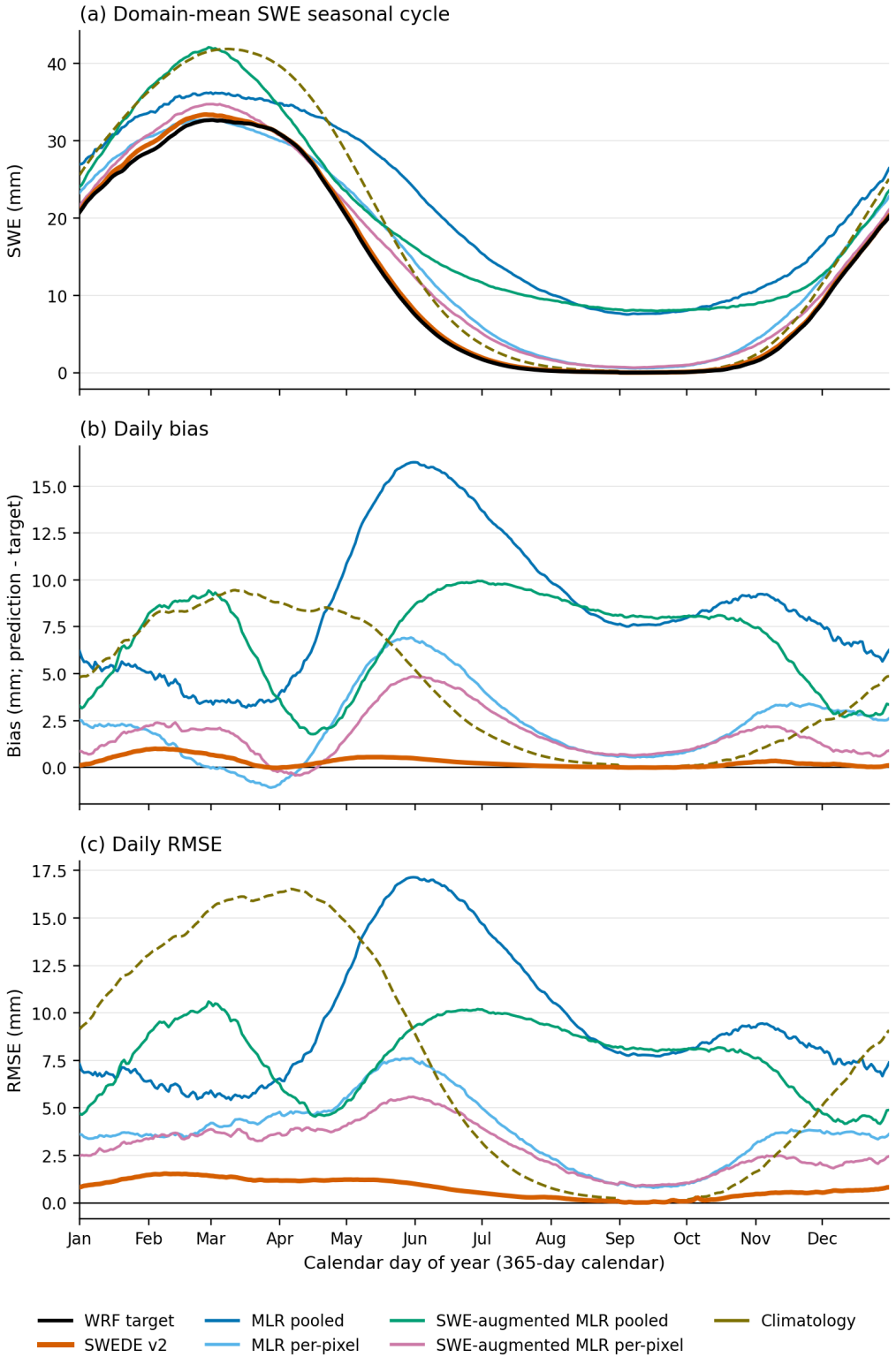
(a) Domain-mean SWE seasonal cycle
SWE (mm)
0
10
20
30
40
(b) Daily bias
Bias (mm; prediction - target)
0.0
2.5
5.0
7.5
10.0
12.5
15.0
(c) Daily RMSE
RMSE (mm)
0.0
2.5
5.0
7.5
10.0
12.5
15.0
17.5
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Calendar day of year (365-day calendar)
WRF target
SWEDE v2
MLR pooled
MLR per-pixel
SWE-augmented MLR pooled
SWE-augmented MLR per-pixel
Climatology

Figure S13. Comparison of seasonal SWE and errors for SWEDE v2 and the regression benchmarks. (a) Domain-mean SWE seasonal cycle for the test member averaged over 1980 to 2099, from the WRF target (black), the SWEDE v2 hybrid (orange), pooled and per-pixel multiple linear regression (MLR, dark and light blue), pooled and per-pixel SWE-augmented MLR with CESM2 snowpack as a predictor (green and pink), and the frozen training climatology (olive dashed). (b) Daily mean bias (prediction minus target) and (c) seasonal cycle of root mean square error of the domain-mean SWE, both as a function of calendar day.

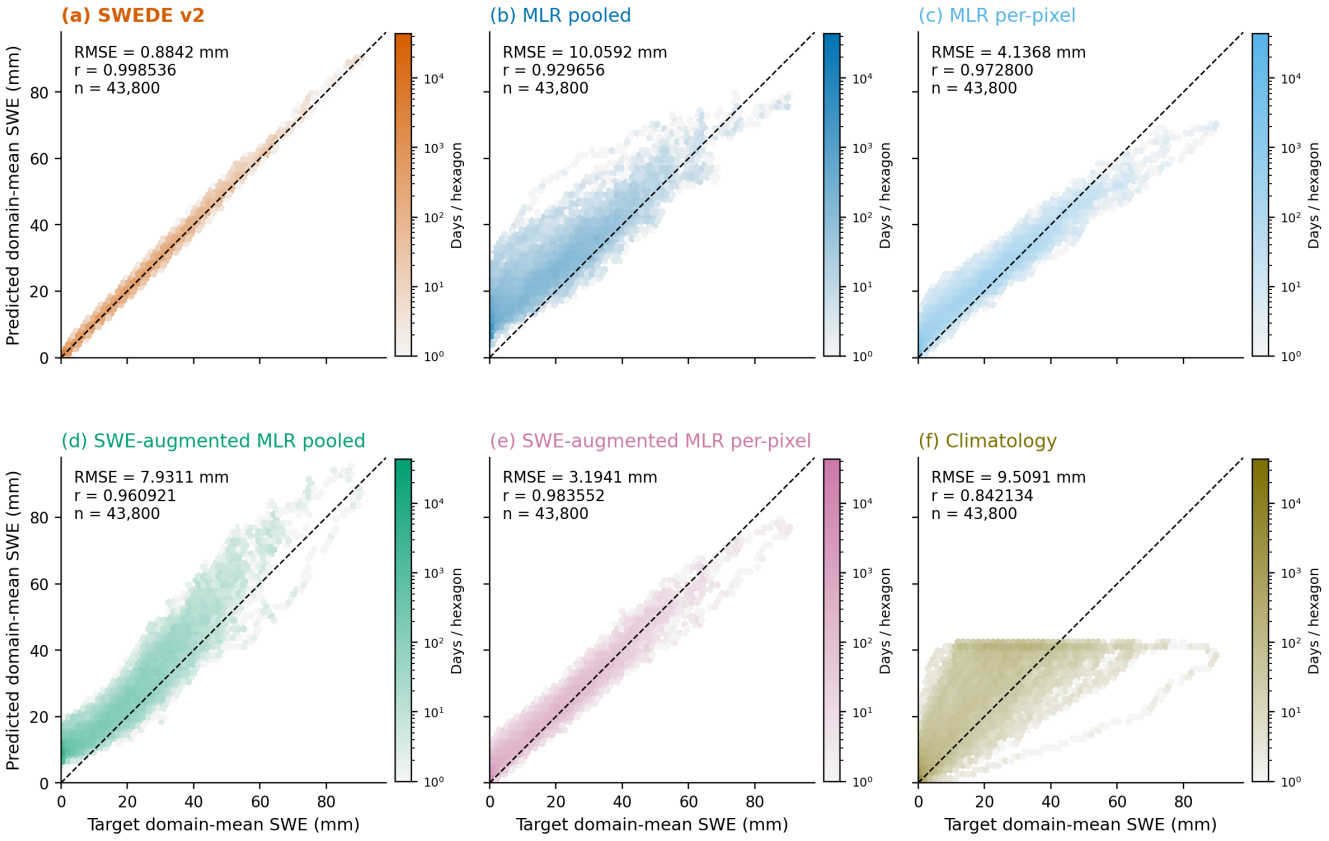

Figure S14. Joint distribution of predicted and target domain-mean daily SWE on the test member for all 43,800 days of 1980 to 2099, for (a) the SWEDE v2 hybrid, (b) pooled MLR, (c) per-pixel MLR, (d) pooled SWE-augmented, (e) per-pixel SWE-augmented, and (f) the training climatology. Color is the number of days per hexagonal bin on a logarithmic scale. The dashed line is the 1:1 line.

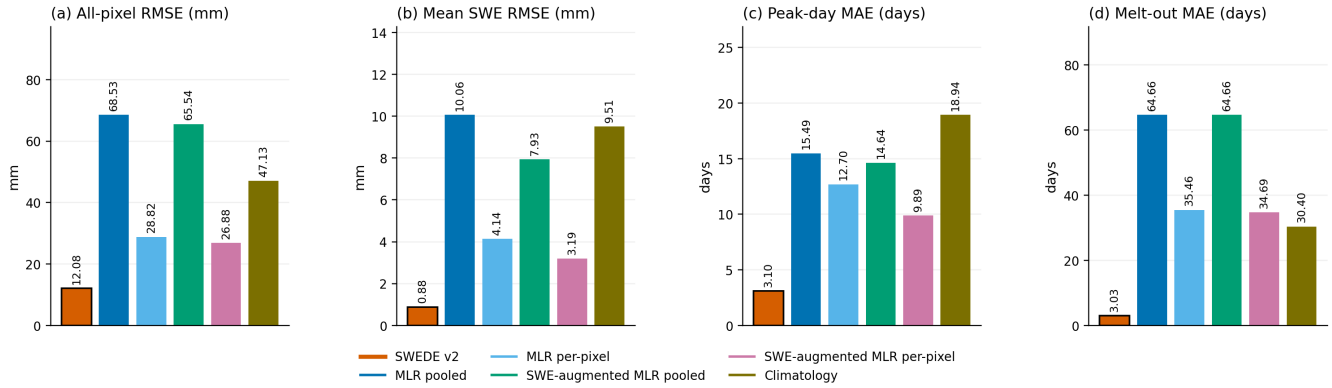

Figure S15. Domain-wide evaluation metrics on the withheld member LE2-1191.010 over 1980 to 2099 for SWEDE v2 (hybrid), the four regression variants, and the training climatology. (a) All-pixel RMSE of daily SWE over all grid cells, (b) RMSE of the domain-mean daily SWE, (c) mean absolute error of the annual peak date, and (d) mean absolute error of the melt-out date. Peak and melt-out dates are computed from domain-mean SWE for each water year (1 September to 31 August) beginning 1980 to 2098; melt-out is the first day after the annual peak on which domain-mean SWE remains at or below 1 mm for five consecutive days. Values are printed above each bar.

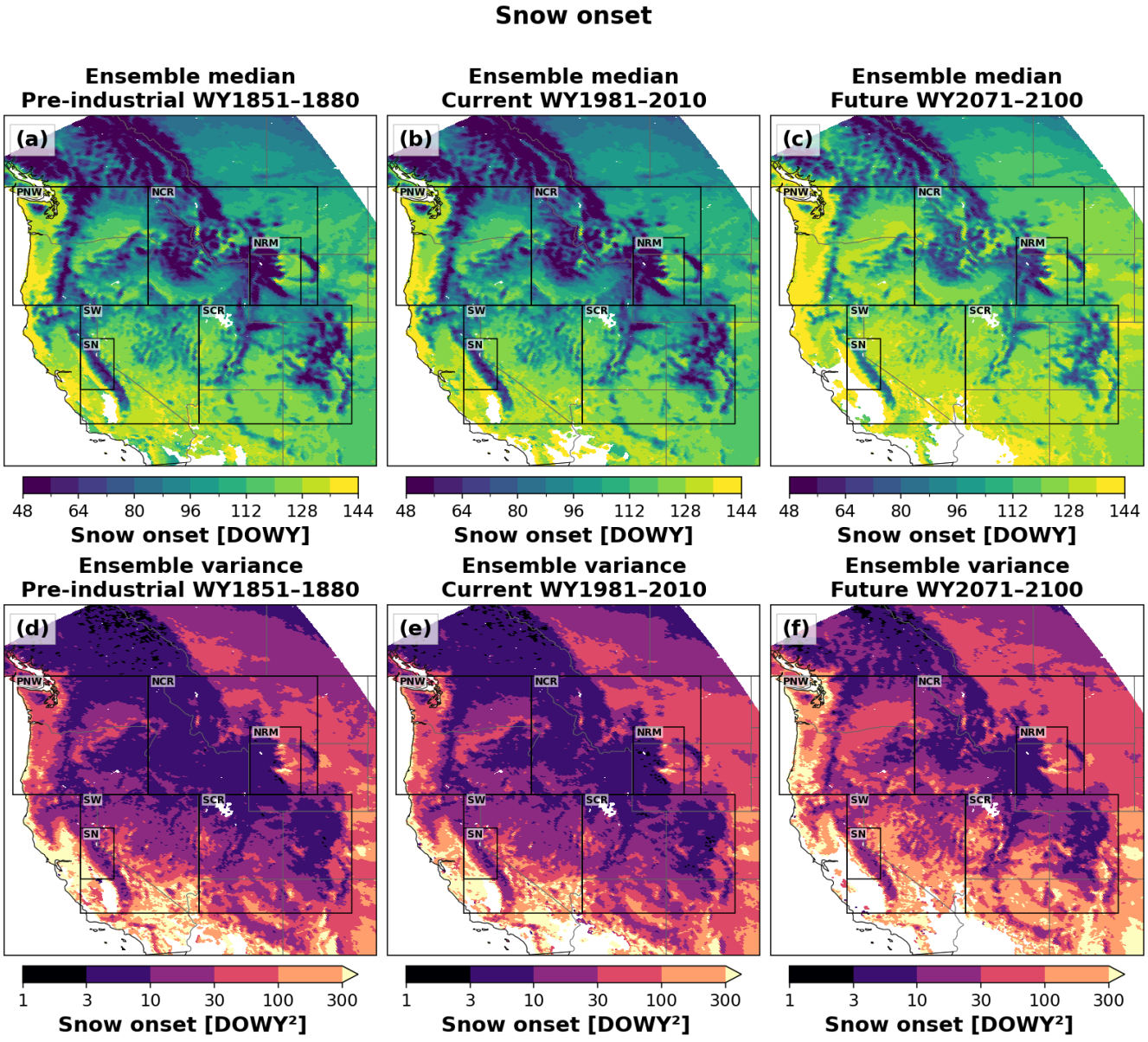

Figure S16. Ensemble median (a to c) and ensemble variance (d to f) of the snow onset date, in day of water year (DOWY), across the 100 SWEDE v2 members for 1851 to 1880, 1981 to 2010, and 2071 to 2100. Onset is defined as the first day of the water year on which SWE exceeds 10 mm.

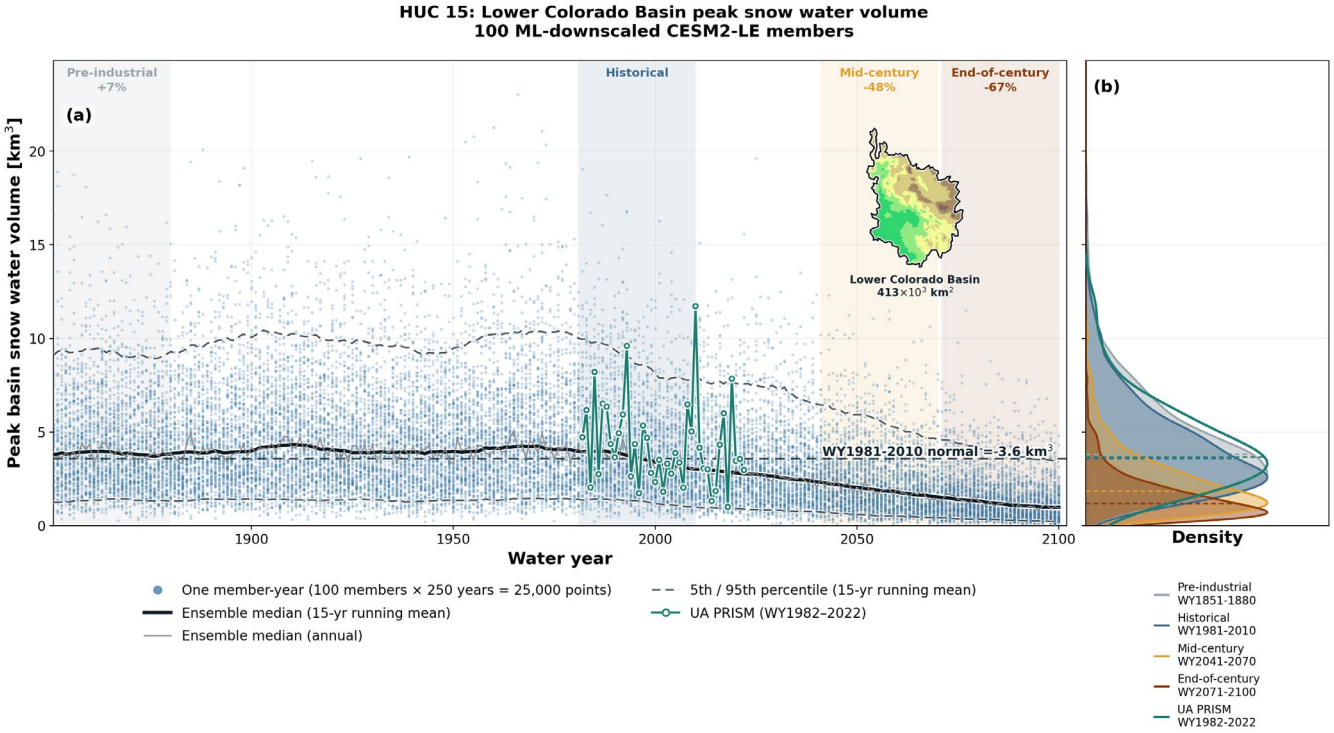

Figure S17. As in Figure 7, annual peak snow water volume over the Lower Colorado basin (HUC2 region 15, basin area 413 × 10^3 km²) in the 100-member SWEDE v2 ensemble.

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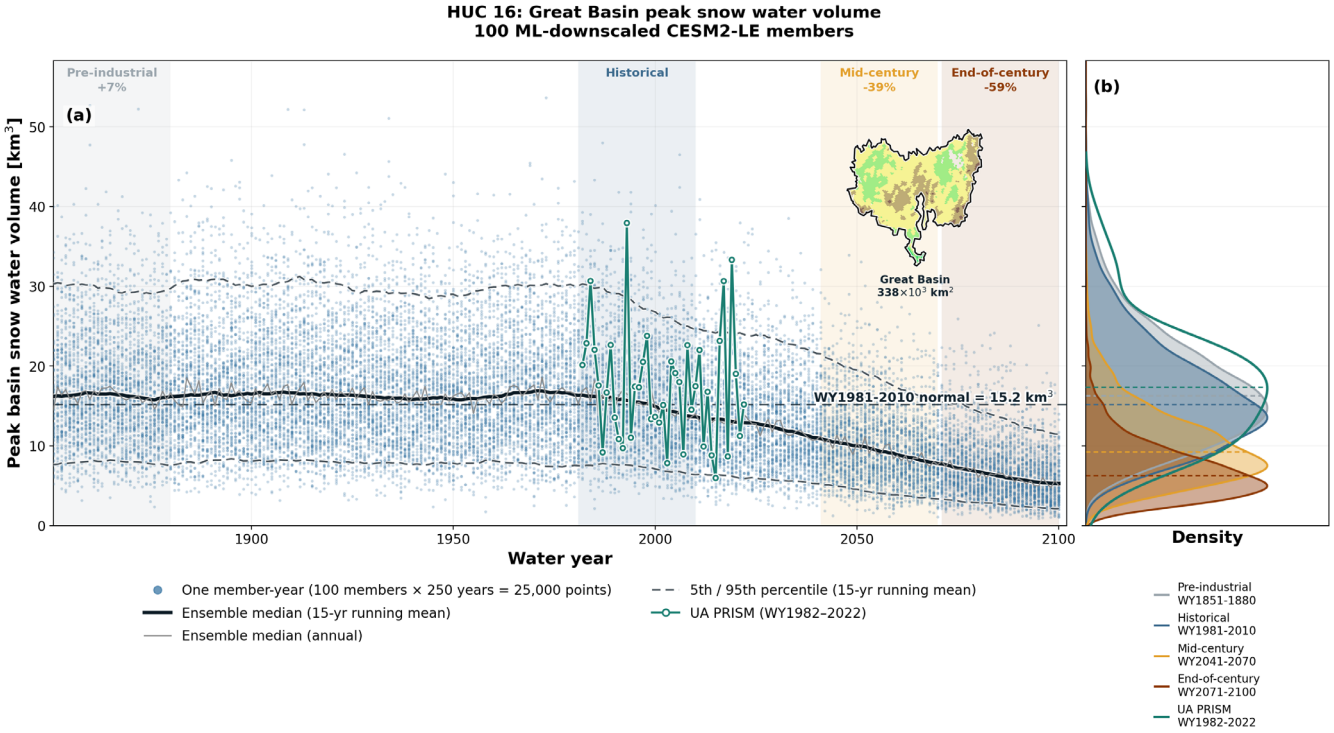

Figure S18. As in Figure 7, annual peak snow water volume over the Great Basin (HUC2 region 16, basin area 338 × 10^3 km²) in the 100-member SWEDE v2 ensemble.

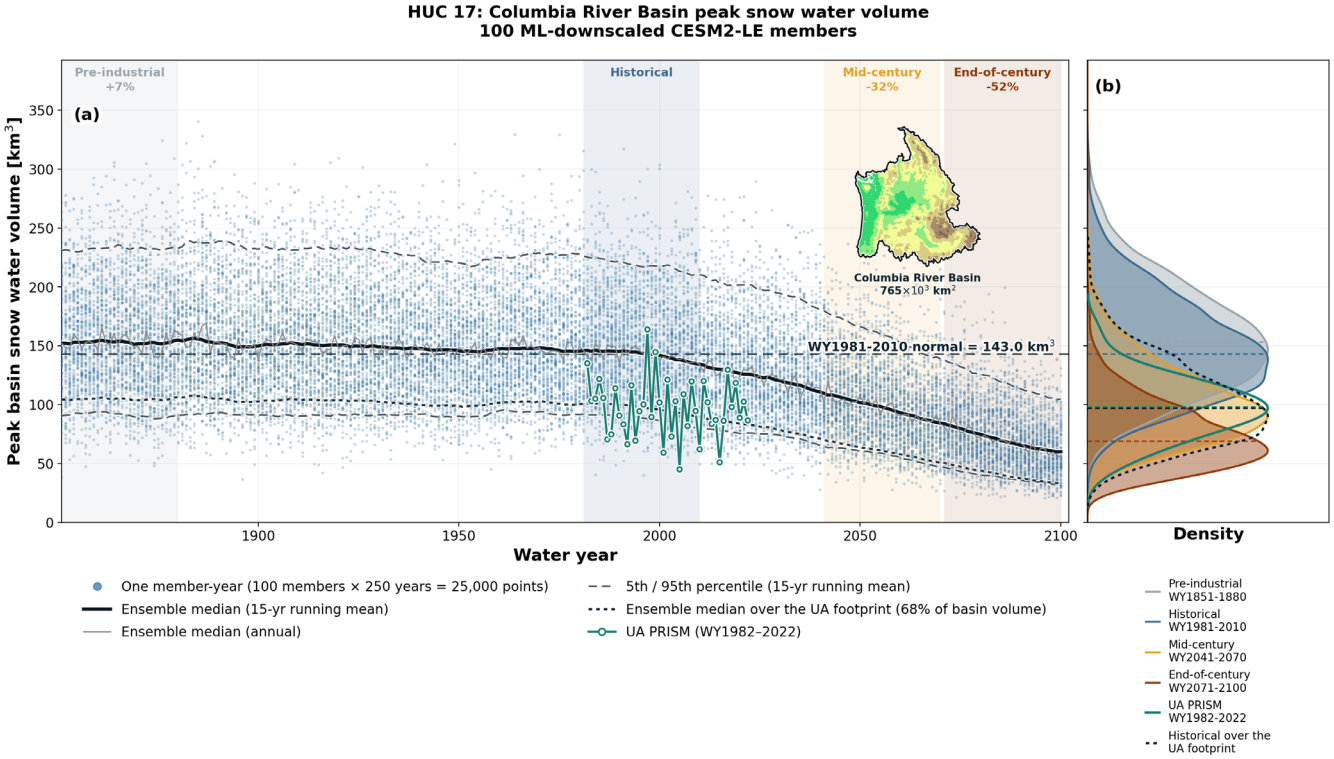

Figure S19. As in Figure 7, annual peak snow water volume over the Columbia River Basin (HUC2 region 17, basin area 765 × 10^3 km²) in the 100-member SWEDE v2 ensemble.

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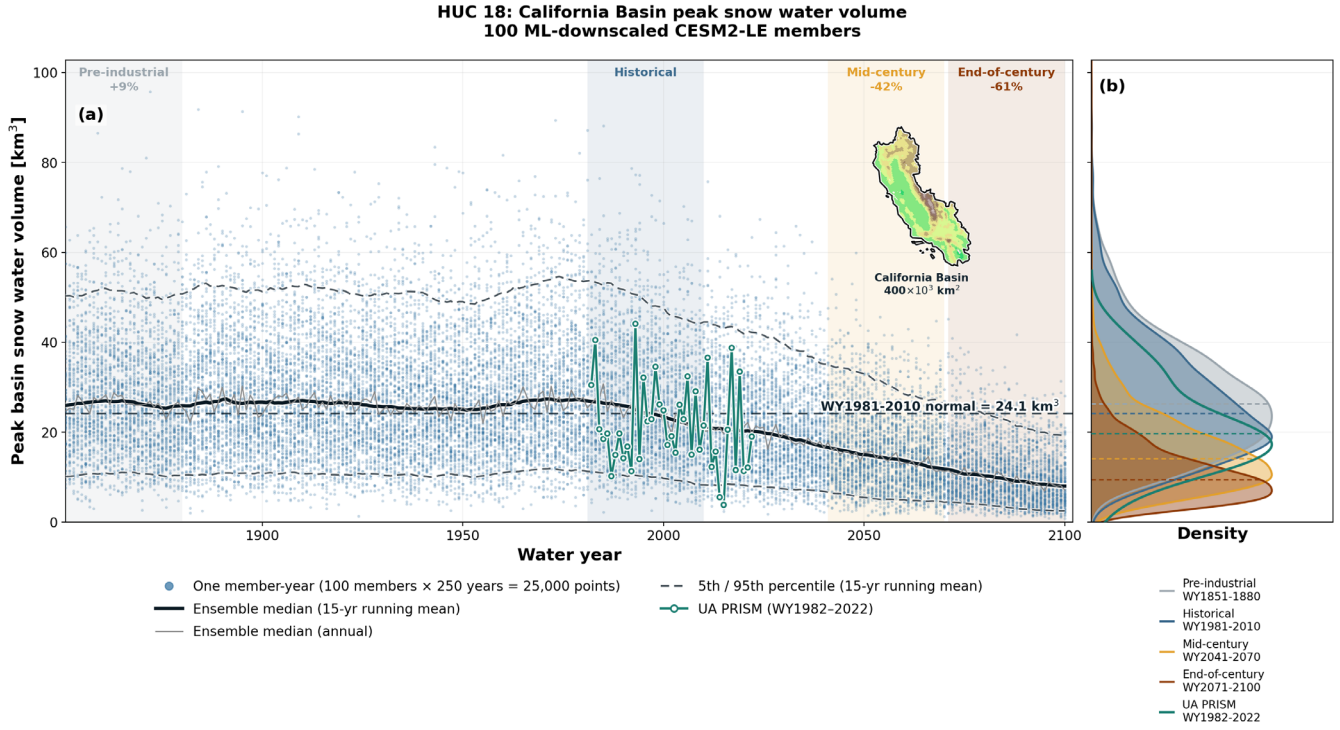

Figure S20. As in Figure 7, annual peak snow water volume over the California Basin (HUC2 region 18, basin area 400 × 10^3 km²) in the 100-member SWEDE v2 ensemble.

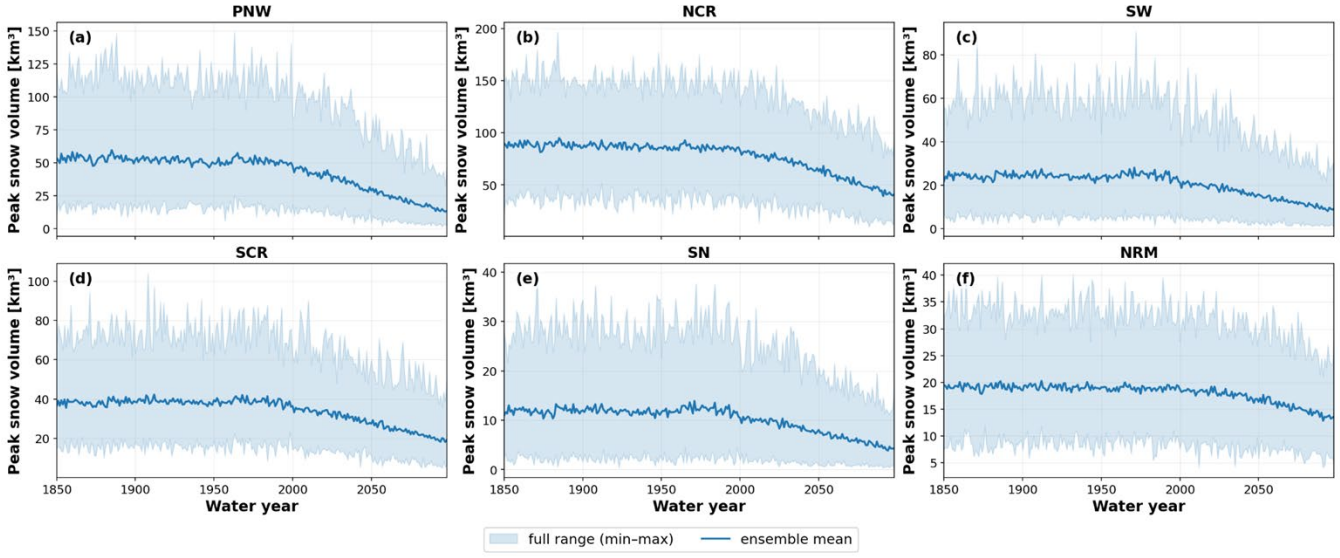

Figure S21. Annual peak snow water volume in each of the six subregions across the 100-member SWEDE v2 ensemble, water years 1850 to 2099. The line is the ensemble mean, and the shaded band is the full range across members (minimum to maximum) in each year.