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# Future water storage changes over the Mediterranean, Middle East, and North Africa in response to global warming and stratospheric aerosol intervention

**Abolfazl Rezaei et al.**

*Correspondence to:* Abolfazl Rezaei (arezaei@iasbs.ac.ir, abolfazlrezaei64@gmail.com)

**This Supplement contains 13 tables and 15 figures as follows:**

**Table S1.** As in Table 1 but for the SSP5-8.5 global warming and SSP5-8.5-SAI scenarios over 2071-2100.

| Region | R1 | | R2 | | R3 | | R4 | | R5 | | R6 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Future climate scenario | SSP5-8.5 | SSP5-8.5-SAI | SSP5-8.5 | SSP5-8.5-SAI | SSP5-8.5 | SSP5-8.5-SAI | SSP5-8.5 | SSP5-8.5-SAI | SSP5-8.5 | SSP5-8.5-SAI | SSP5-8.5 | SSP5-8.5-SAI |
| Precipitation (mm/yr) | 337 | 328 | 219 | 212 | 403 | 419 | 97 | 83 | 50 | 48 | 91 | 103 |
| Temperature ($^0$C) | 19.7 | 14.8 | 26.1 | 21.5 | 21.2 | 17 | 32.3 | 28.6 | 29.4 | 24.8 | 30.8 | 27.4 |
| Real ET (mm/yr) | 470 | 419 | 213 | 205 | 347 | 353 | 89 | 80 | 53 | 50 | 94 | 104 |
| Soil moisture (Kg/m$^2$) | 1756 | 1813 | 1768 | 1792 | 1485 | 1530 | 1428 | 1416 | 1156 | 1164 | 1283 | 1299 |
| TWS (Kg/m$^2$) | 2013 | 2065 | 1773 | 1797 | 1543 | 1586 | 1433 | 1421 | 1171 | 1178 | 1309 | 1325 |
| Potential ET (mm/month) | 116 | 78 | 296 | 150 | 114 | 79 | 686 | 299 | 385 | 183 | 613 | 259 |

**Table S2.** The average correlation between the variables under the available ensembles for global warming SSP5-8.5 scenario in the region R1. Consistently, the values inside the parenthesis are the difference-range values between minimum and maximum correlations. The insignificant correlation coefficients (p-value>0.05) are underlined.

| **SSP-R1** | TWS | Temp | Precip | SM | RET | PET | LAI |
|---|---|---|---|---|---|---|---|
| TWS | 1 | -0.35 (-0.31, -0.37) | 0.61 (0.58, 0.64) | 0.99 (0.98, 1) | 0.18 (0.15, 0.23) | -0.30 (-0.26, -0.32) | 0.77 (0.72, 0.78) |
| Temp | | 1 | -0.61 (-0.60, -0.62) | -0.35 (-0.32, -0.37) | 0.77 (0.76, 0.78) | 0.96 (0.96, 0.96) | 0.05 (0.02, 0.07) |
| Precip | | | 1 | 0.59 (0.56, 0.63) | -0.17 (-0.13, -0.19) | -0.56 (-0.55, -0.57) | 0.42 (0.40, 0.44) |
| SM | | | | 1 | 0.17 (0.14, 0.22) | -0.30 (-0.26, -0.32) | 0.74 (0.70, 0.77) |
| RET | | | | | 1 | 0.75 (0.75, 0.75) | 0.60 (0.58, 0.63) |
| PET | | | | | | 1 | 0.11 (0.08, 0.13) |
| LAI | | | | | | | 1 |

**Table S3.** As Table S2 but for the region R2.

| **SSP-R2** | TWS | Temp | Precip | SM | RET | PET | LAI |
|---|---|---|---|---|---|---|---|
| TWS | 1 | -0.25 (-0.24, -0.26) | 0.50 (0.47, 0.53) | 0.99 (0.99, 1) | 0.54 (0.50, 0.57) | -0.24 (-0.23, -0.25) | 0.72 (0.71, 0.74) |
| Temp | | 1 | -0.48 (-0.47, -0.50) | -0.24 (-0.22, -0.25) | 0.11 (0.10, 0.12) | 0.95 (0.94, 0.96) | -0.18 (-0.15, -0.20) |
| Precip | | | 1 | 0.49 (0.46, 0.51) | 0.53 (0.52, 0.55) | -0.51 (-50, -53) | 0.52 (0.51, 0.53) |
| SM | | | | 1 | 0.53 (0.49, 0.56) | -0.22 (-0.20, -0.24) | 0.71 (0.70, 0.73) |
| RET | | | | | 1 | 0.03 (0.02, 0.04) | 0.85 (0.84, 0.86) |
| PET | | | | | | 1 | 0.16 (0.14, 0.19) |
| LAI | | | | | | | 1 |

**Table S4.** As Table S2 but for the region R3.

| **SSP-R3** | TWS | Temp | Precip | SM | RET | PET | LAI |
|---|---|---|---|---|---|---|---|
| TWS | 1 | -0.67 (-0.65, -0.70) | 0.51 (0.49, 0.52) | 0.98 (0.97, 0.99) | 0.34 (0.33, 0.35) | -0.54 (-0.52, -0.57) | 0.80 (0.78, 0.81) |
| Temp | | 1 | -0.83 (-0.82, -0.84) | -0.68 (-0.66, -0.70) | 0.23 (0.22, 0.24) | 0.97 (0.97, 0.97) | -0.44 (-0.42, -0.46) |
| Precip | | | 1 | 0.49 (0.46, 0.51) | -0.28 (-0.27, -0.30) | -0.82 (-0.81, -0.83) | 0.31 (0.29, 0.32) |
| SM | | | | 1 | 0.34 (0.33, 0.35) | -0.55 (-0.53, -0.57) | 0.80 (0.78, 0.81) |
| RET | | | | | 1 | 0.33 (0.32, 0.34) | 0.69 (0.68, 0.70) |
| PET | | | | | | 1 | -0.29 (-0.26, -0.31) |
| LAI | | | | | | | 1 |

**Table S5.** As Table S2 but for the region R4.

| **SSP-R4** | TWS | Temp | Precip | SM | RET | PET | LAI |
|---|---|---|---|---|---|---|---|
| TWS | 1 | 0.08 (0.03, 0.11) | 0.19 (0.14, 0.23) | 0.99 (0.98, 1) | 0.35 (0.26, 0.42) | 0.08 (0.05, 0.10) | 0.53 (0.43, 0.59) |
| Temp | | 1 | -0.06 (-0.02, -0.11) | 0.08 (0.04, 0.11) | 0.04 (0.03, 0.06) | 0.92 (0.92, 0.92) | -0.07 (-0.02, -0.12) |
| Precip | | | 1 | 0.18 (0.13, 0.22) | 0.71 (0.68, 0.72) | -0.14 (-0.10, -0.20) | 0.25 (0.23, 0.27) |
| SM | | | | 1 | 0.32 (0.21, 0.40) | 0.08 (0.06, 0.10) | 0.53 (0.42, 0.59) |
| RET | | | | | 1 | -0.09 (-0.05, -0.13) | 0.62 (0.60, 0.64) |
| PET | | | | | | 1 | 0.04 (0.01, 0.06) |
| LAI | | | | | | | 1 |

**Table S6.** As Table S2 but for the region R5.

| **SSP-R5** | TWS | Temp | Precip | SM | RET | PET | LAI |
|---|---|---|---|---|---|---|---|
| TWS | 1 | 0.15 (0.14, 0.17) | 0.19 (0.15, 0.23) | 0.74 (0.70, 0.76) | 0.29 (0.24, 0.33) | 0.19 (0.18, 0.21) | 0.33 (0.29, 0.35) |
| Temp | | 1 | 0.17 (0.12, 0.24) | 0.31 (0.24, 0.37) | 0.34 (0.31, 0.39) | 0.96 (0.96, 0.96) | 0.50 (0.46, 0.53) |
| Precip | | | 1 | 0.36 (0.31, 0.38) | 0.91 (0.88, 0.93) | 0.12 (0.07, 0.19) | 0.61 (0.54, 0.70) |
| SM | | | | 1 | 0.49 (0.41, 0.55) | 0.32 (0.25, 0.38) | 0.50 (0.43, 0.55) |
| RET | | | | | 1 | 0.30 (0.27, 0.36) | 0.82 (0.79, 0.85) |
| PET | | | | | | 1 | 0.47 (0.44, 0.50) |
| LAI | | | | | | | 1 |

**Table S7.** As Table S2 but for the region R6.

| **SSP-R6** | TWS | Temp | Precip | SM | RET | PET | LAI |
|---|---|---|---|---|---|---|---|
| TWS | 1 | 0.29 (0.26, 0.31) | 0.29 (0.24, 0.35) | 0.98 (0.97, 1) | 0.46 (0.38, 0.53) | 0.26 (0.21, 0.31) | 0.26 (0.24, 0.31) |
| Temp | | 1 | 0.06 (0.02, 0.11) | 0.29 (0.26, 0.31) | 0.32 (0.27, 0.39) | 0.95 (0.94, 0.96) | 0.35 (0.28, 0.40) |
| Precip | | | 1 | 0.27 (0.22, 0.32) | 0.84 (0.82, 0.85) | 0.04 (0.02, 0.07) | -0.02 (0.00, -0.06) |
| SM | | | | 1 | 0.43 (0.36, 0.50) | 0.28 (0.26, 0.30) | 0.27 (0.24, 0.32) |
| RET | | | | | 1 | 0.26 (0.23, 0.30) | 0.05 (0.03, 0.11) |
| PET | | | | | | 1 | 0.22 (0.12, 0.29) |
| LAI | | | | | | | 1 |

**Table S8.** As Table S2 but under SAI scenario for the region R1.

| **SAI-R1** | TWS | Temp | Precip | SM | RET | PET | LAI |
|---|---|---|---|---|---|---|---|
| TWS | 1 | -0.20 (-0.18, -0.24) | 0.59 (0.58, 0.60) | 0.96 (0.95, 0.97) | 0.13 (0.13, 0.13) | -0.15 (-0.13, -0.18) | 0.52 (0.46, 0.59) |
| Temp | | 1 | -0.51 (-0.49, -0.52) | -0.06 (-0.02, -0.11) | 0.88 (0.87, 0.89) | 0.96 (0.96, 0.96) | 0.44 (0.38, 0.49) |
| Precip | | | 1 | 0.53 (0.52, 0.54) | -0.20 (-0.19, -0.21) | -0.47 (-0.46, -0.49) | 0.26 (0.23, 0.28) |
| SM | | | | 1 | 0.26 (0.25, 0.27) | -0.05 (0.00, -0.08) | 57 (50, 64) |
| RET | | | | | 1 | 0.89 (0.88, 0.90) | 0.76 (0.72, 0.78) |
| PET | | | | | | 1 | 0.52 (0.46, 0.57) |
| LAI | | | | | | | 1 |

**Table S9.** As Table S2 but under SAI scenario for the region R2.

| **SAI-R2** | TWS | Temp | Precip | SM | RET | PET | LAI |
|---|---|---|---|---|---|---|---|
| TWS | 1 | -0.26 (-0.24, -0.28) | 0.53 (0.51, 0.55) | 0.97 (0.96, 1) | 0.54 (0.52, 0.57) | -0.25 (-0.23, -0.26) | 0.73 (0.69, 0.79) |
| Temp | | 1 | -0.53 (0.51, 0.55) | -0.24 (-0.22, -0.26) | 0.27 (0.26, 0.28) | 0.96 (0.96, 0.96) | -0.08 (-0.05, -0.09) |
| Precip | | | 1 | 0.51 (0.50, 0.53) | 0.41 (0.40, 0.42) | -0.57 (-0.54, -0.59) | 0.50 (0.48, 0.51) |
| SM | | | | 1 | 0.53 (0.51, 0.56) | -0.23 (-0.21, -0.24) | 0.72 (0.68, 0.78) |
| RET | | | | | 1 | 0.21 (0.21, 0.22) | 0.84 (0.84, 0.84) |
| PET | | | | | | 1 | -0.04 (-0.03, -0.05) |
| LAI | | | | | | | 1 |

**Table S10.** As Table S2 but under SAI scenario for the region R3.

| **SAI-R3** | TWS | Temp | Precip | SM | RET | PET | LAI |
|---|---|---|---|---|---|---|---|
| TWS | 1 | -0.54 (-0.53, -0.55) | 0.43 (0.42, 0.44) | 0.98 (0.97, 0.99) | 0.25 (0.24, 0.26) | -0.46 (-0.46, -0.47) | 0.76 (0.75, 0.77) |
| Temp | | 1 | -0.78 (0.78, 0.79) | -0.54 (-0.53, -0.55) | 0.55 (0.54, 0.56) | 0.98 (0.96, 0.99) | -0.18 (-0.16, -0.19) |
| Precip | | | 1 | 0.42 (0.41, 0.43) | -0.37 (-0.35, -0.38) | -0.78 (-0.78, -0.78) | 0.18 (0.17, 0.21) |
| SM | | | | 1 | 0.26 (0.25, 0.26) | -0.46 (-0.46, -0.47) | 0.76 (0.75, 0.78) |
| RET | | | | | 1 | 0.59 (0.58, 0.59) | 0.67 (0.66, 0.67) |
| PET | | | | | | 1 | -0.09 (-0.07, -0.10) |
| LAI | | | | | | | 1 |

**Table S11.** As Table S2 but under SAI scenario for the region R4.

| **SAI-R4** | TWS | Temp | Precip | SM | RET | PET | LAI |
|---|---|---|---|---|---|---|---|
| TWS | 1 | 0.03 (0.01, -0.04) | 0.28 (0.27, 0.30) | 0.99 (0.98, 1) | 0.45 (0.37, 0.52) | 0.03 (0.02, 0.04) | 0.56 (0.52, 0.60) |
| Temp | | 1 | -0.05 (-0.02, -0.07) | 0.03 (0.01, 0.04) | 0.09 (0.06, 0.10) | 0.94 (0.94, 0.94) | 0.16 (0.10, 0.24) |
| Precip | | | 1 | 0.27 (0.26, 0.29) | 0.78 (0.76, 0.79) | -0.14 (-0.11, -0.15) | 0.32 (0.26, 0.36) |
| SM | | | | 1 | 0.43 (0.36, 0.50) | 0.03 (0.02, 0.04) | 0.55 (0.51, 0.59) |
| RET | | | | | 1 | -0.02 (0.00, -0.03) | 0.68 (0.67, 0.69) |
| PET | | | | | | 1 | 0.15 (0.08, 0.23) |
| LAI | | | | | | | 1 |

**Table S12.** As Table S2 but under SAI scenario for the region R5.

| **SAI-R5** | TWS | Temp | Precip | SM | RET | PET | LAI |
|---|---|---|---|---|---|---|---|
| TWS | 1 | 0.29 (0.22, 0.34) | 0.15 (0.14, 0.16) | 0.73 (0.64, 0.80) | 0.28 (0.26, 0.31) | 0.33 (0.27, 0.38) | 0.36 (0.28, 0.41) |
| Temp | | 1 | 0.12 (0.12, 0.13) | 0.29 (0.24, 0.34) | 0.36 (0.35, 0.37) | 0.97 (0.97, 0.97) | 0.56 (0.52, 0.59) |
| Precip | | | 1 | 0.37 (0.33, 0.41) | 0.88 (0.88, 0.89) | 0.09 (0.09, 0.10) | 0.56 (0.52, 0.58) |
| SM | | | | 1 | 0.54 (0.50, 0.58) | 0.32 (0.26, 0.37) | 0.50 (0.46, 0.54) |
| RET | | | | | 1 | 0.34 (0.32, 0.35) | 0.80 (0.77, 0.81) |
| PET | | | | | | 1 | 0.56 (0.52, 0.59) |
| LAI | | | | | | | 1 |

**Table S13.** As Table S2 but under SAI scenario for the region R6.

| **SAI-R6** | TWS | Temp | Precip | SM | RET | PET | LAI |
|---|---|---|---|---|---|---|---|
| TWS | 1 | 0.11 (0.06, 0.17) | 0.26 (0.19, 0.31) | 0.99 (0.98, 1) | 0.44 (0.38, 0.50) | 0.11 (0.05, 0.16) | 0.33 (0.31, 0.35) |
| Temp | | 1 | 0.06 (0.05, 0.08) | 0.11 (0.06, 0.17) | 0.35 (0.33, 0.37) | 0.96 (0.96, 0.96) | 0.37 (0.34, 0.40) |
| Precip | | | 1 | 0.24 (0.18, 0.29) | 0.73 (0.72, 0.74) | 0.00 (0.00, 0.00) | 0.08 (0.03, 0.12) |
| SM | | | | 1 | 0.42 (0.36, 0.47) | 0.10 (0.05, 0.16) | 0.33 (0.31, 0.34) |
| RET | | | | | 1 | 0.29 (0.26, 0.31) | 0.26 (0.19, 0.30) |
| PET | | | | | | 1 | 0.32 (0.30, 0.35) |
| LAI | | | | | | | 1 |

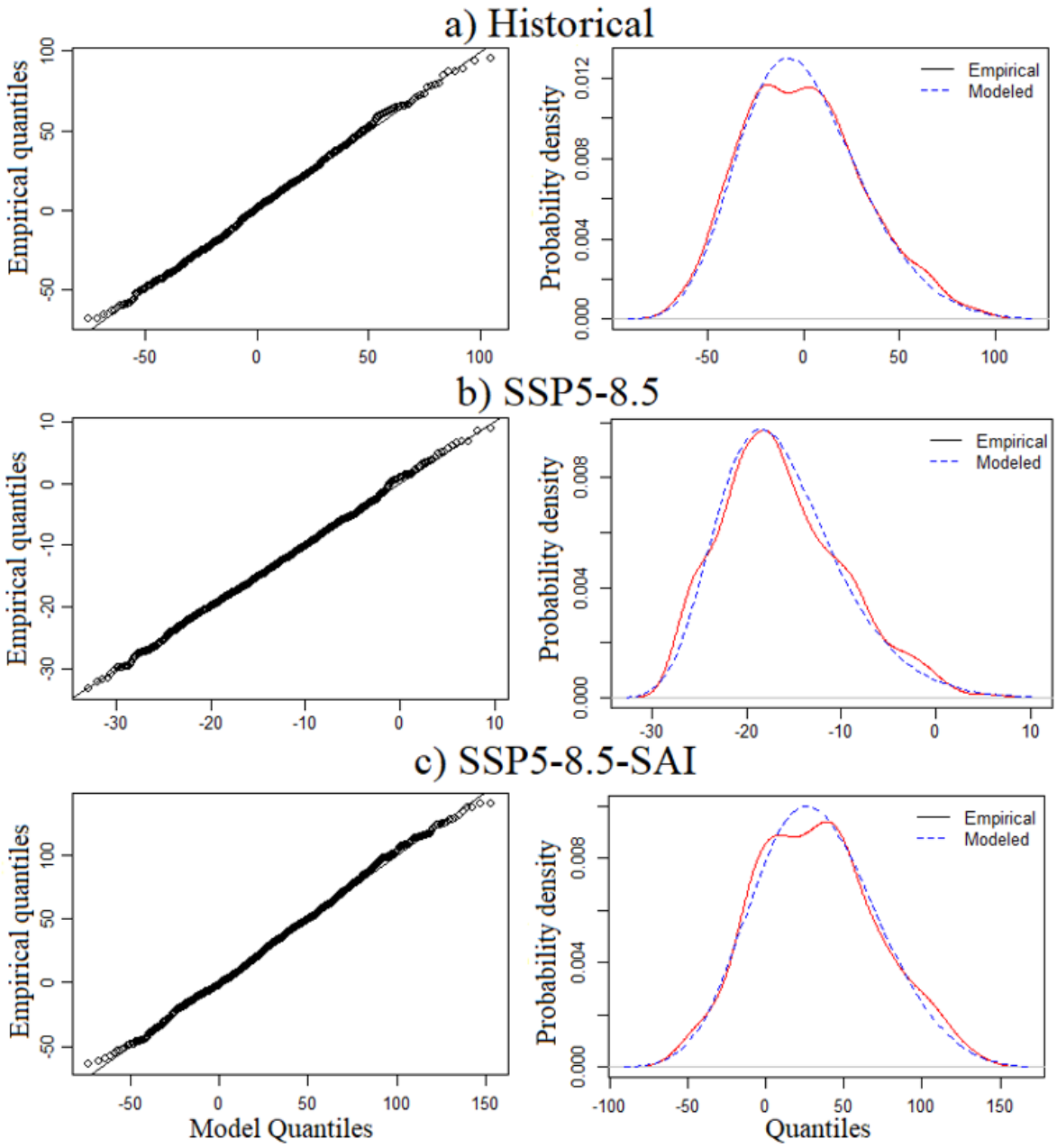


**Figure S1.** In region R2, the graphs illustrate the following scenarios: (a) historical, (b) global warming, and (c) the SAI scenario. In the left column, you can observe the relationship between empirical quantiles and model quantiles. In the right column, the graphs depict the probability density versus quantiles.

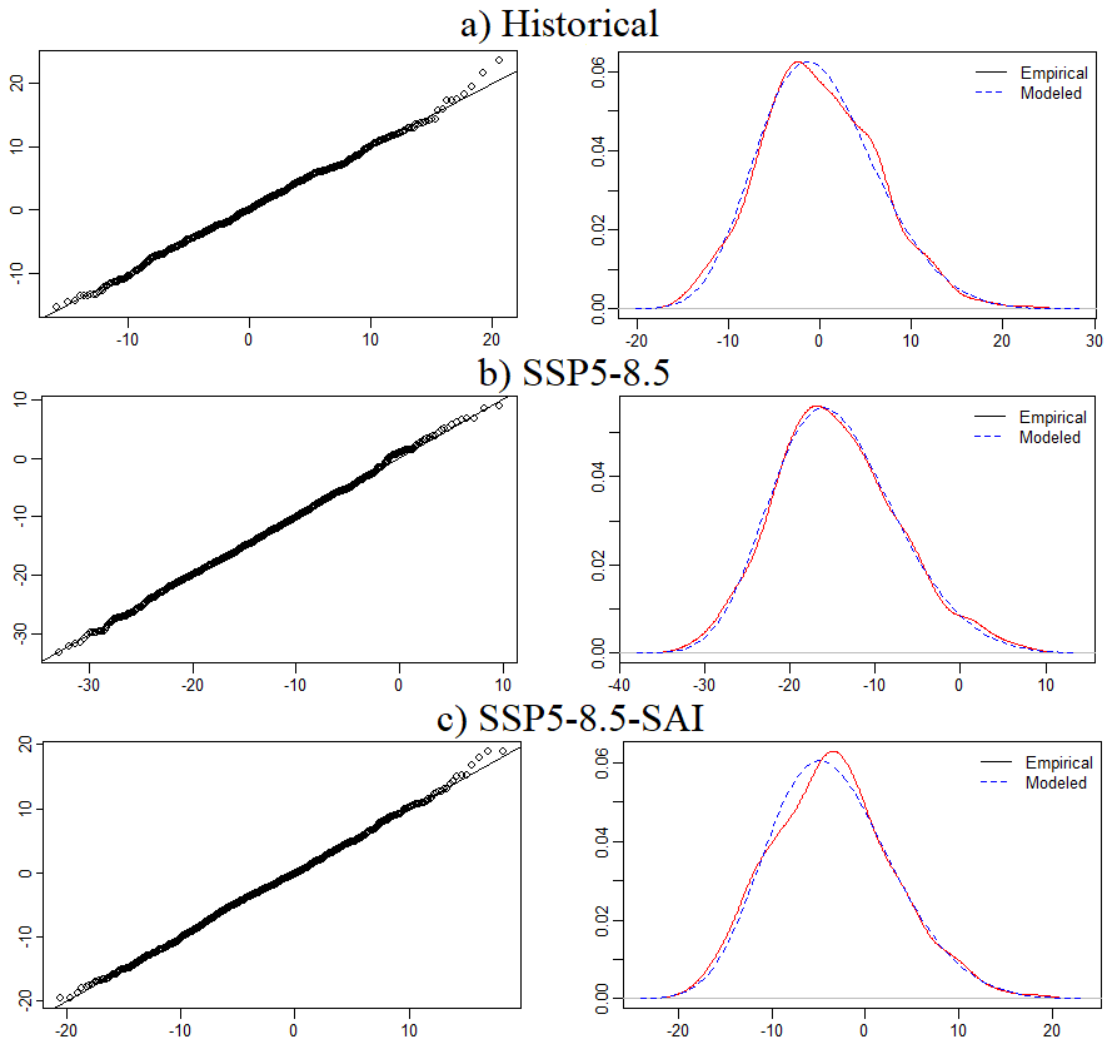


**Figure S2.** As in Fig. S1 but for R5.

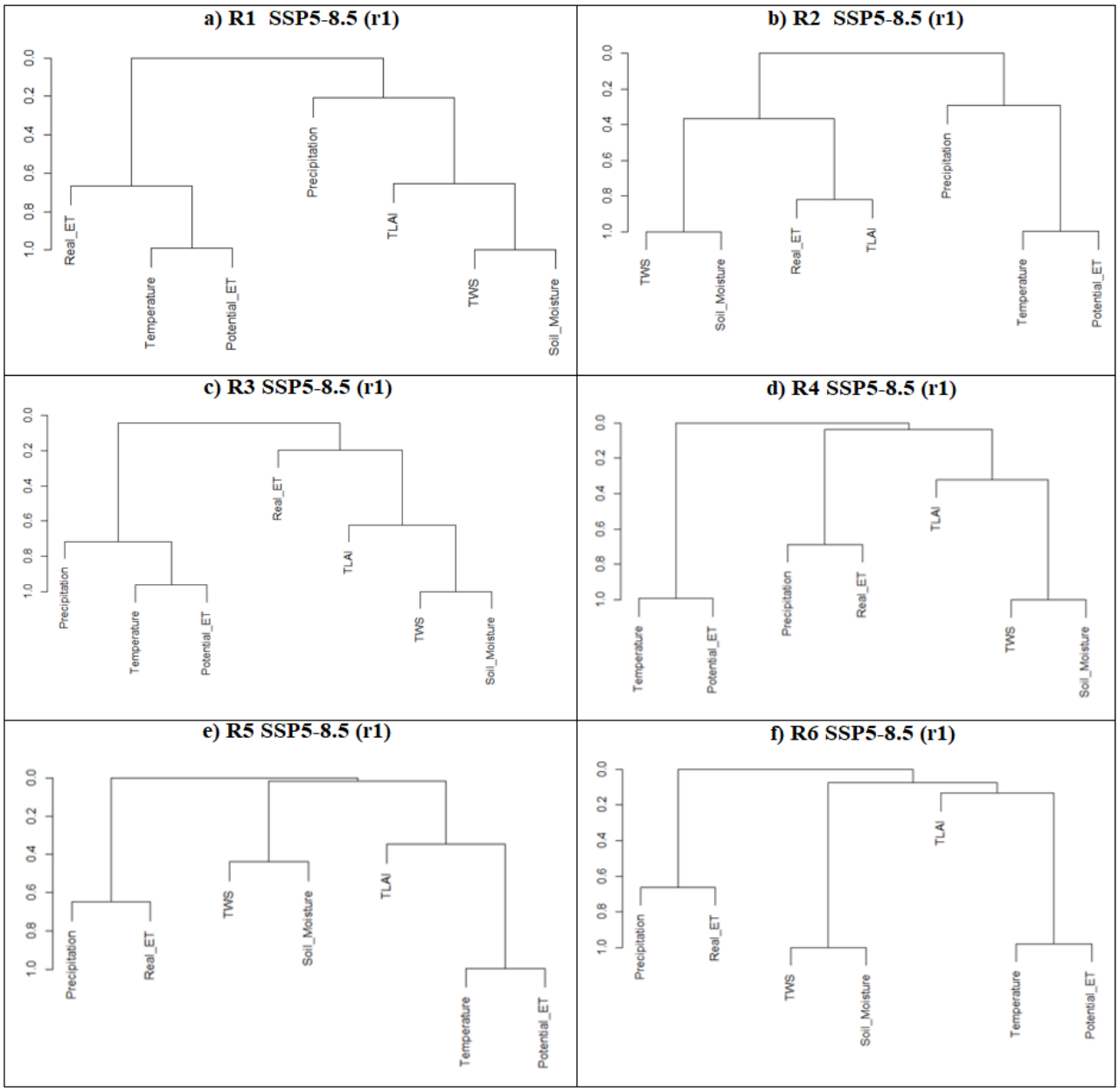


**Figure S3.** This tree diagrams illustrate the cluster hierarchy within ensemble r1 of the SSP5-8.5 scenario across regions R1 to R6. The y-axis represents the proportion of variance explained.

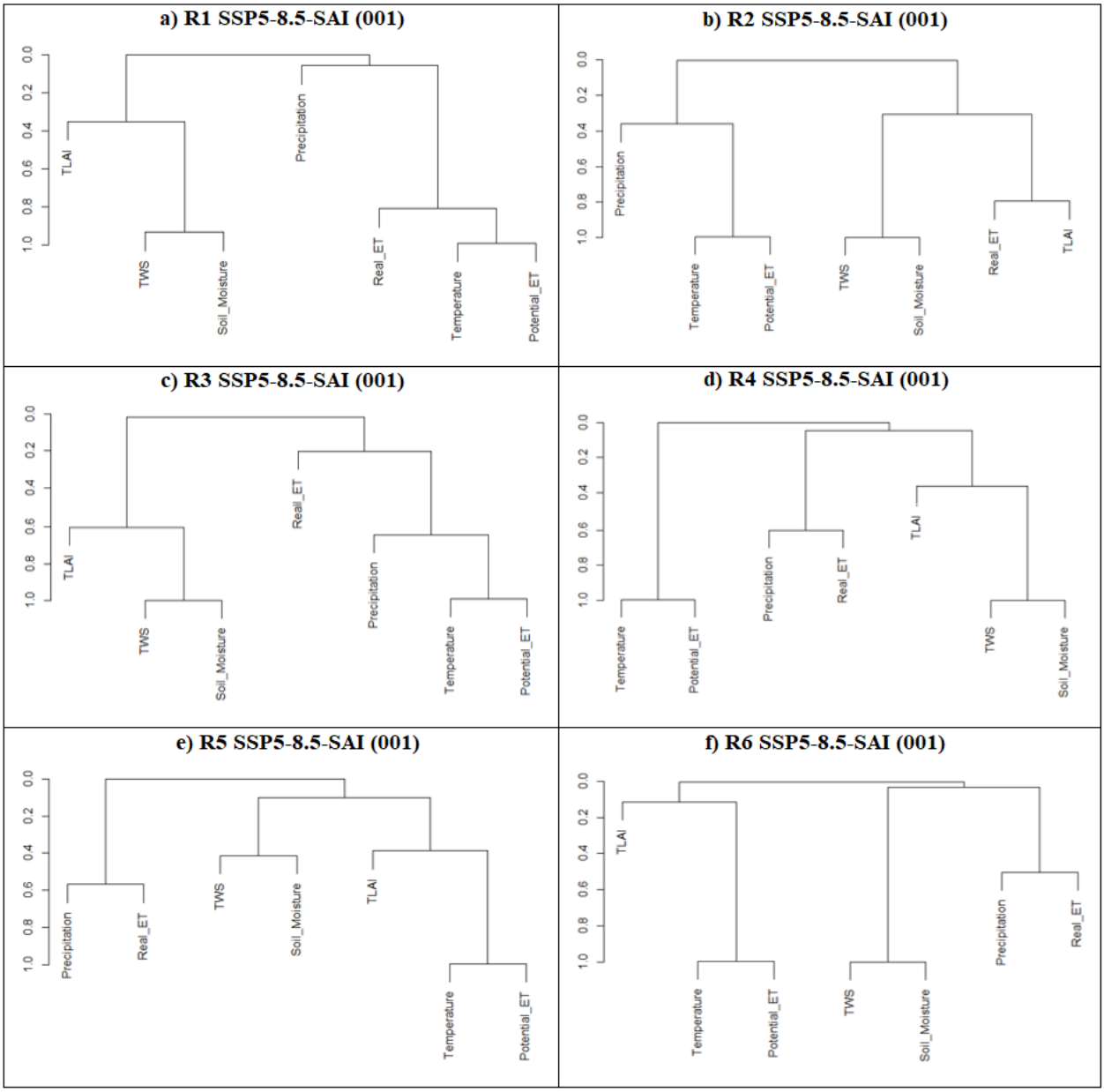


**Figure S4.** As in Fig. S3 but for the SSP5-8.5-SAI scenario.

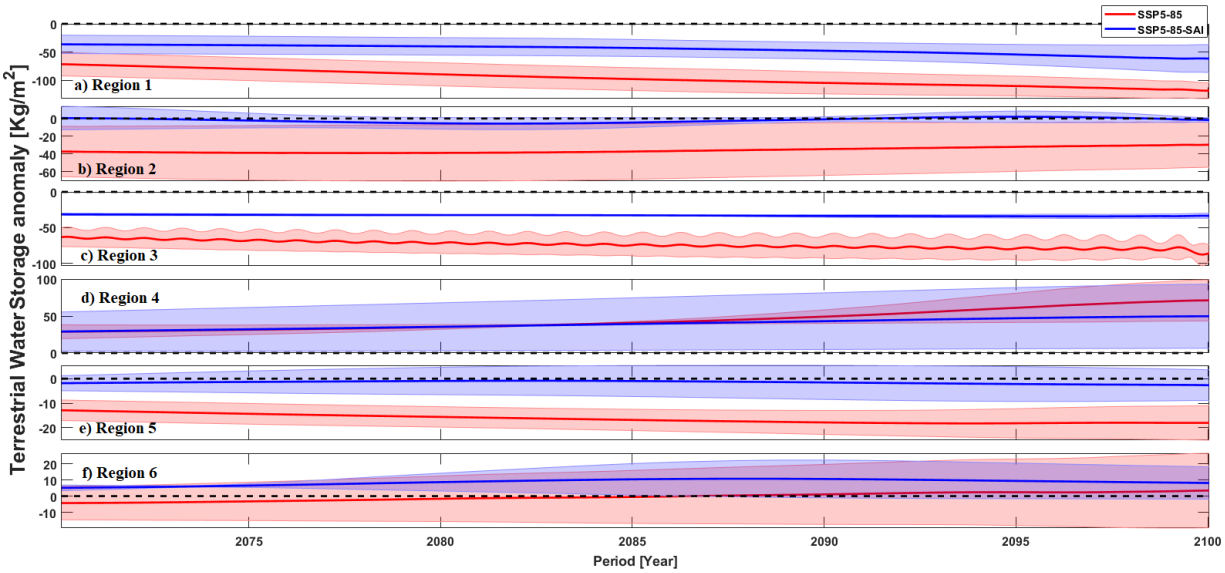


**Figure S5.** The long-term trends of TWS anomaly relative to the TWS averaged over the historical period across MENA and the lands around the Caspian and Mediterranean Seas under global warming without (SSP5-8.5) and with SAI (SSP5-8.5-SAI). Figures a-f respectively are for regions R1 to R6. Shading in each curve shows the across-ensemble range. The dashed line crossing the *y*-axis at zero in each subplot is the ensemble mean of TWS over the historical period (1985-2014).

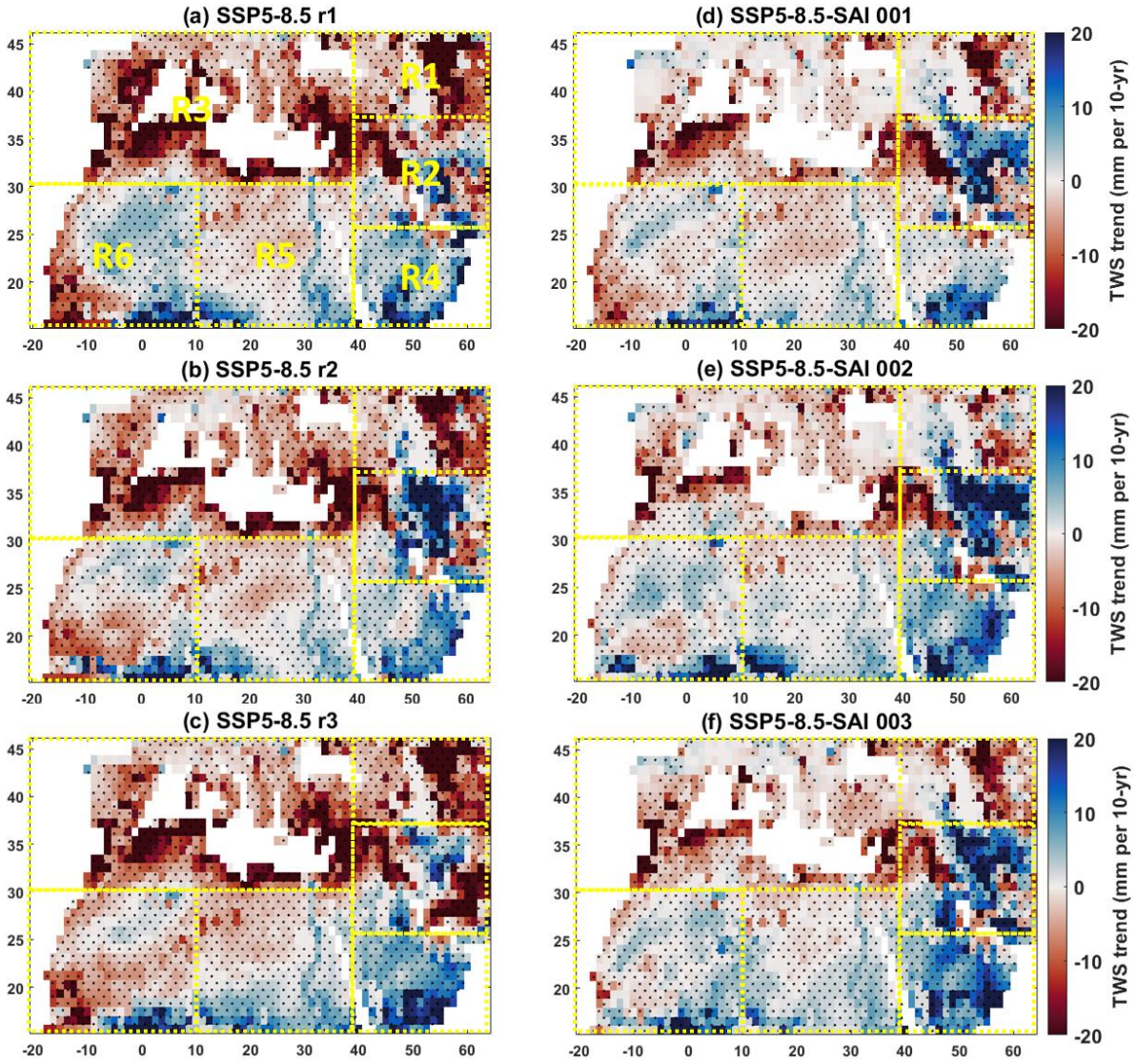


**Figure S6.** The TWS trend maps across MENA over the period (1984–2100) under purely GHG forcing (SSP5-8.5 in a to c) and combined with SAI (SSP5-8.5-SAI in d to f). The dotted regions have trends significant at a 95% confidence level according to the standard simple Mann-Kendall test. R1 to R6 shown in Fig. S6a denote the selected regions 1 to 6, respectively.

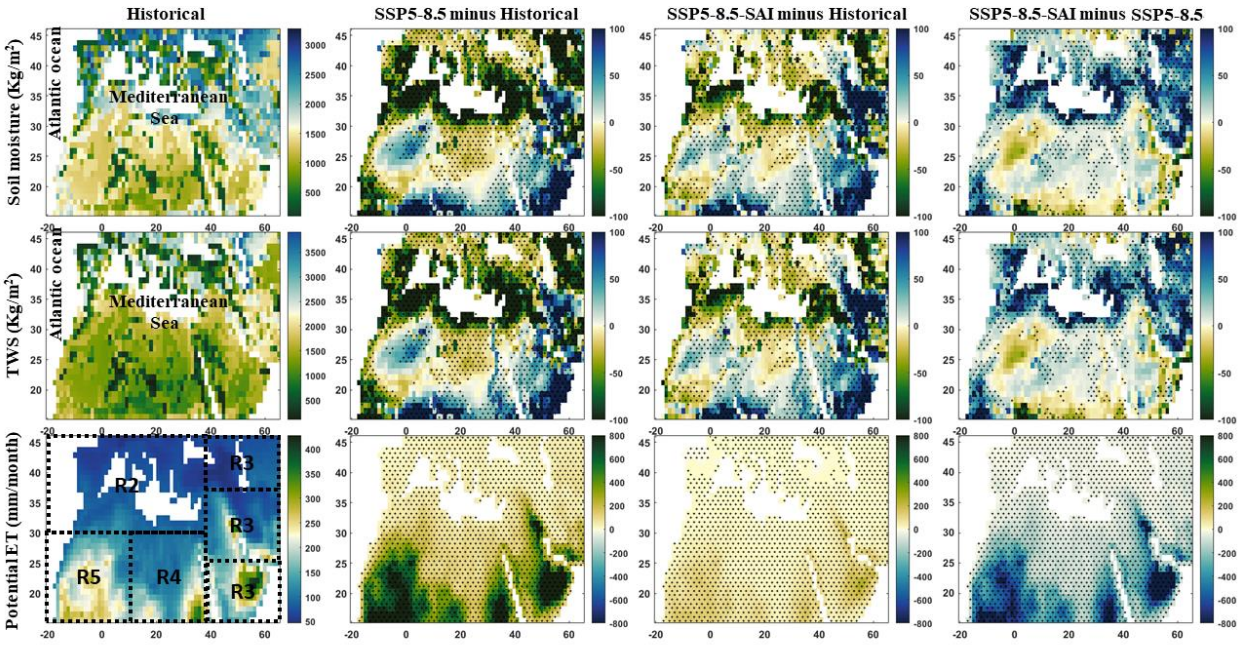


**Figure S7**. The maps of soil moisture (upper row), terrestrial water storage (TWS, middle row), and potential evapotranspiration (ET, bottom row) over MENA in the historical climate (1984-2014) and their projected future changes in the period (2071–2100) under the SSP5-85 scenario without and with SAI (SSP5-8.5 minus historical and SAI minus historical, respectively). The extent to which the SAI impacts the global warming effects on the climate variables is further shown (SAI minus SSP5-8.5). The cross sign (+) highlights where all ensemble members agree on the sign of the changes. R1 to R6 denote to the selected regions 1 to 6, respectively.

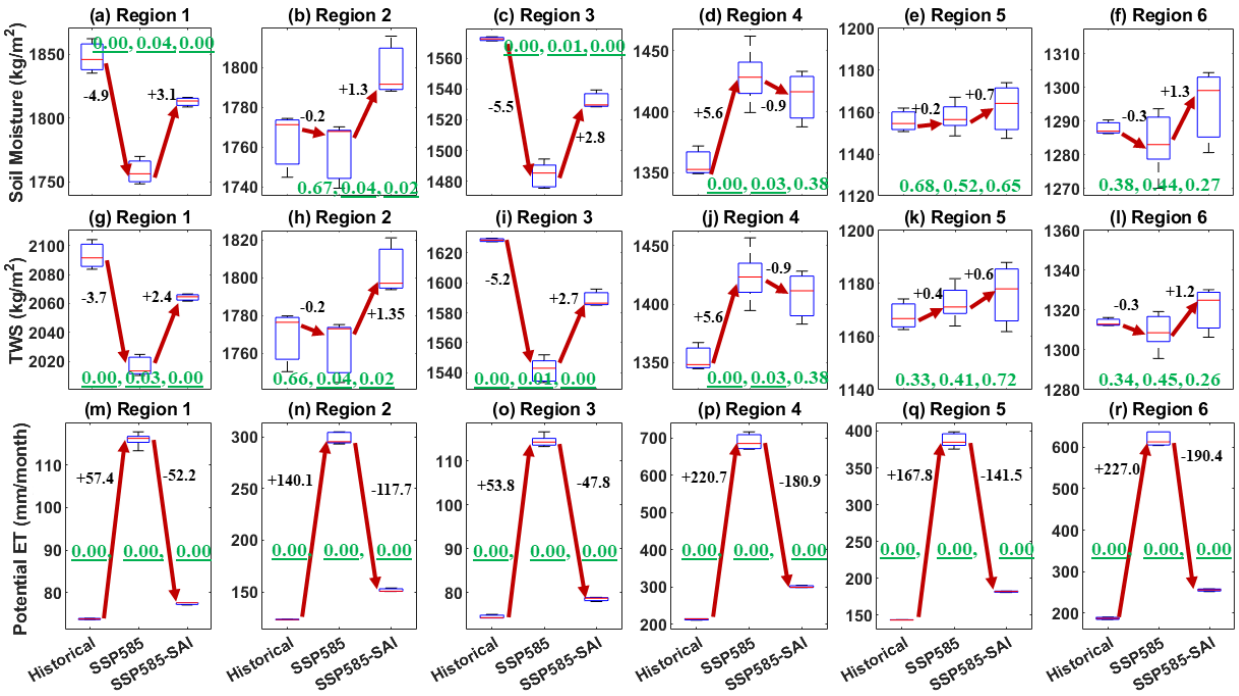


**Figure S8.** Box and whiskers plot of the changes in soil moisture (upper row), terrestrial water storage (TWS, middle row), and potential evapotranspiration (ET, bottom row) in each region from R1 to R6 row). The titles of subplots refer to the regions. The median for each experiment is denoted by the red line, the upper (75$^{th}$) and lower (25$^{th}$) quartiles by the top and bottom of the box and ensemble limits by the whisker extents. The positive/negative values in black are the change percent relative to the median of the historical period for each variable. The three values refer to *p*-values between historical and global warming, historical and SAI, and global warming and SAI, respectively, obtained from *t*-test analysis in which the underlined *p*-values are statistically significant.

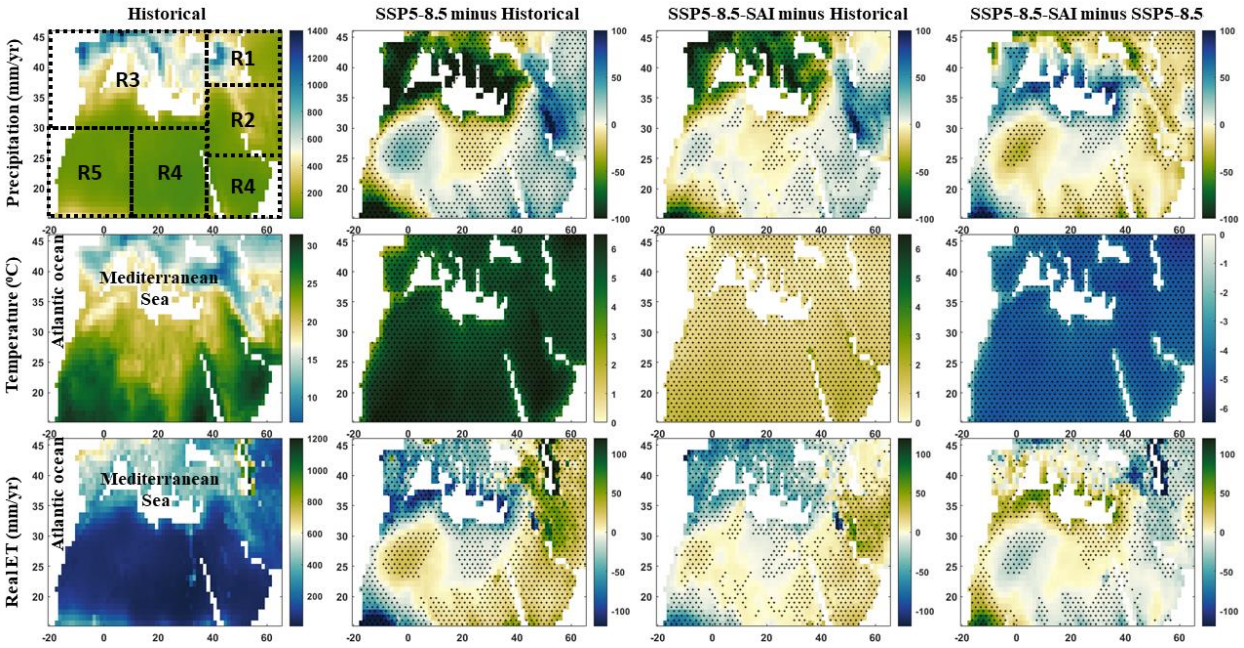


**Figure S9**. As in Fig. S7, but for the variables of precipitation (upper row), surface temperature (middle row), and real evapotranspiration (ET, bottom row).

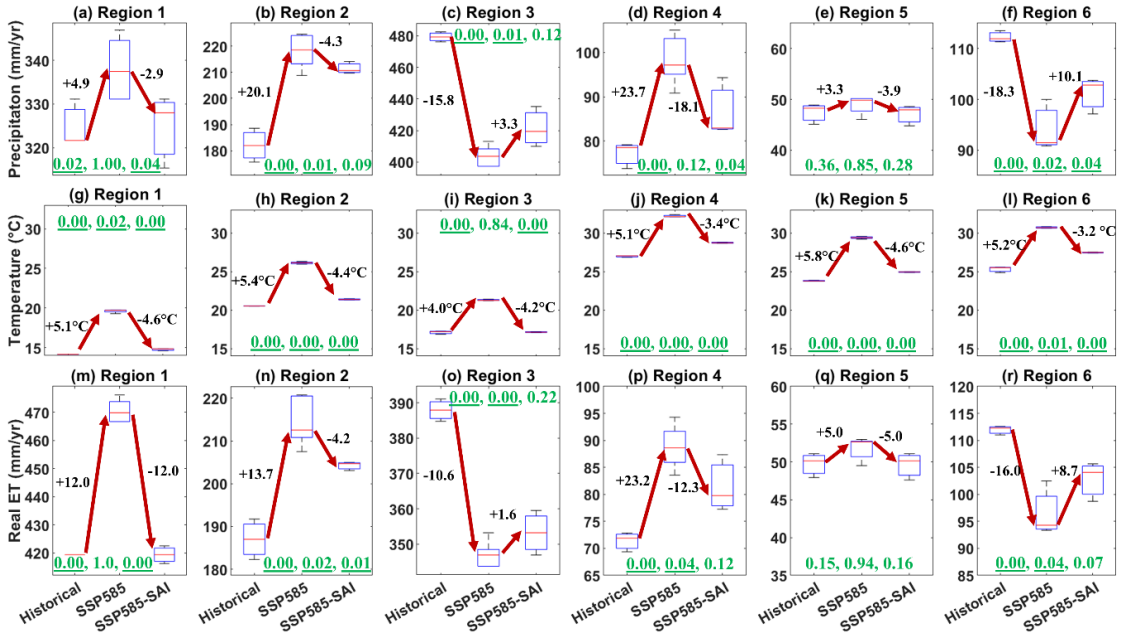


**Figure S10**. As Fig. S8, but for the variables of precipitation (upper row), surface temperature (middle row), and real evapotranspiration (ET, bottom row).

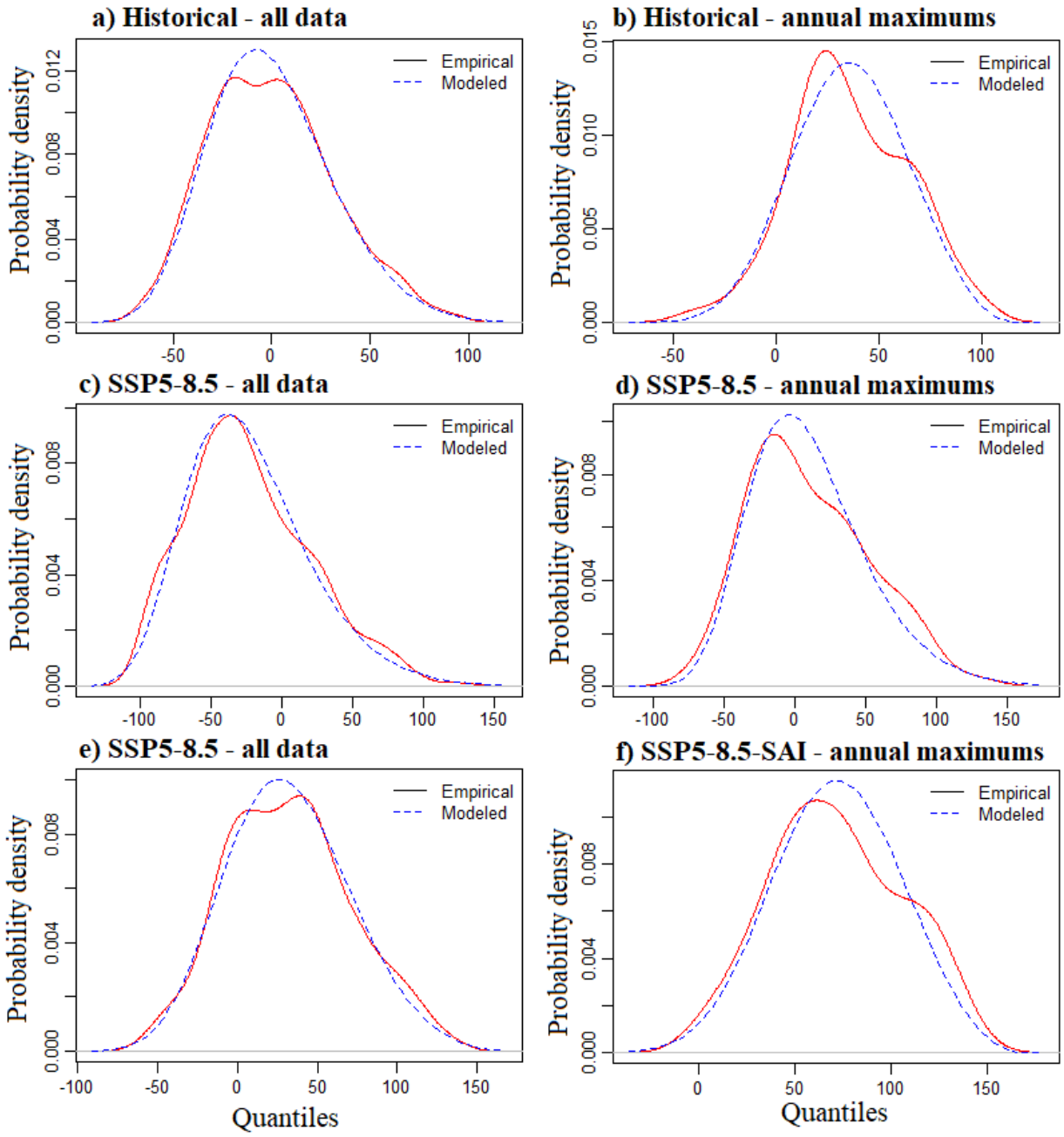


**Figure S11.** Probability density curves for the region R2, comparing two scenarios: one using all available data (left column) and the other using annual maximum values (right column) under the historical conditions (upper row) as well as the GHG emissions (middle row) and SAI (lower row) scenarios.

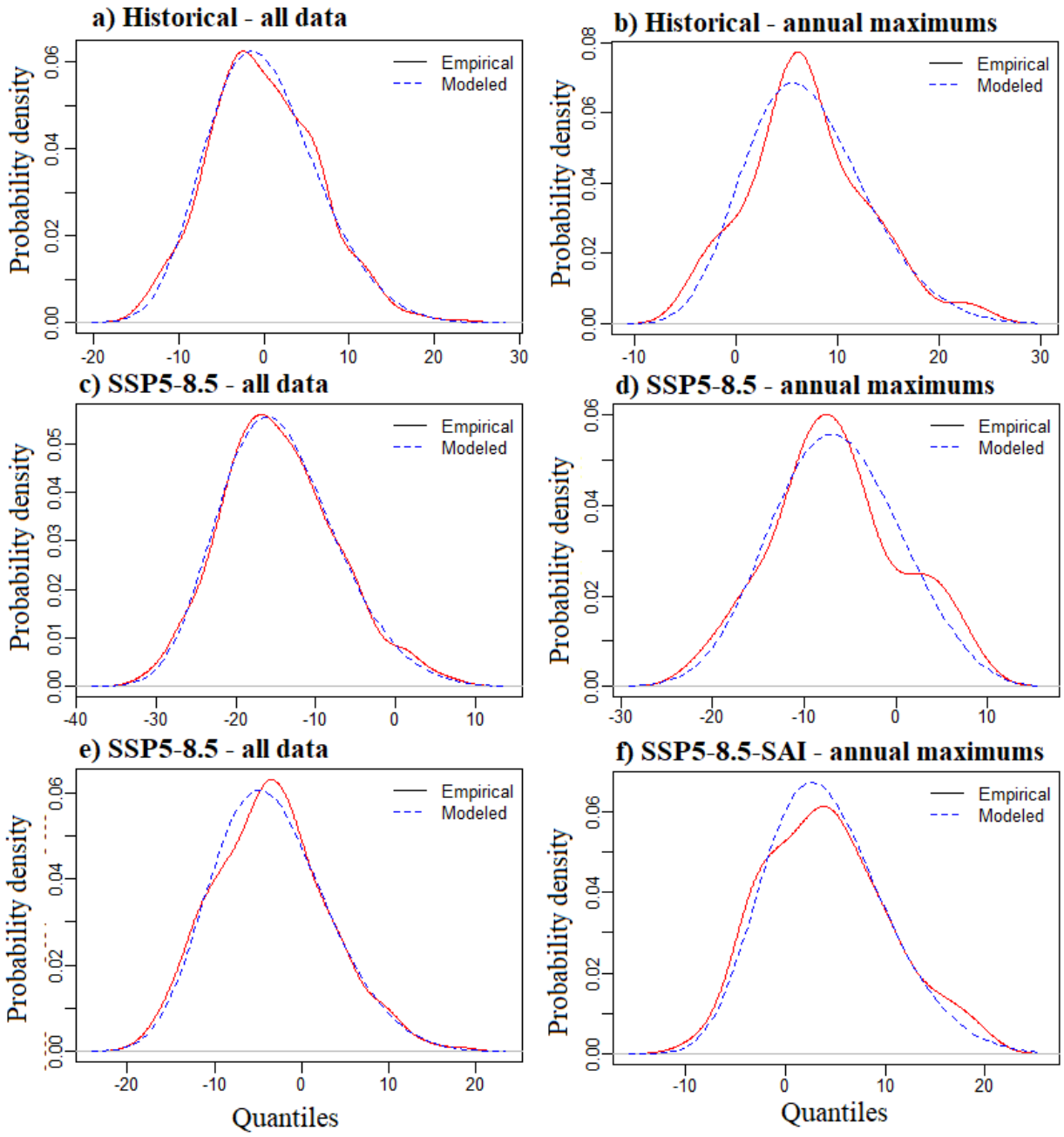


**Figure S12.** As Fig. S11 but for the region R5.

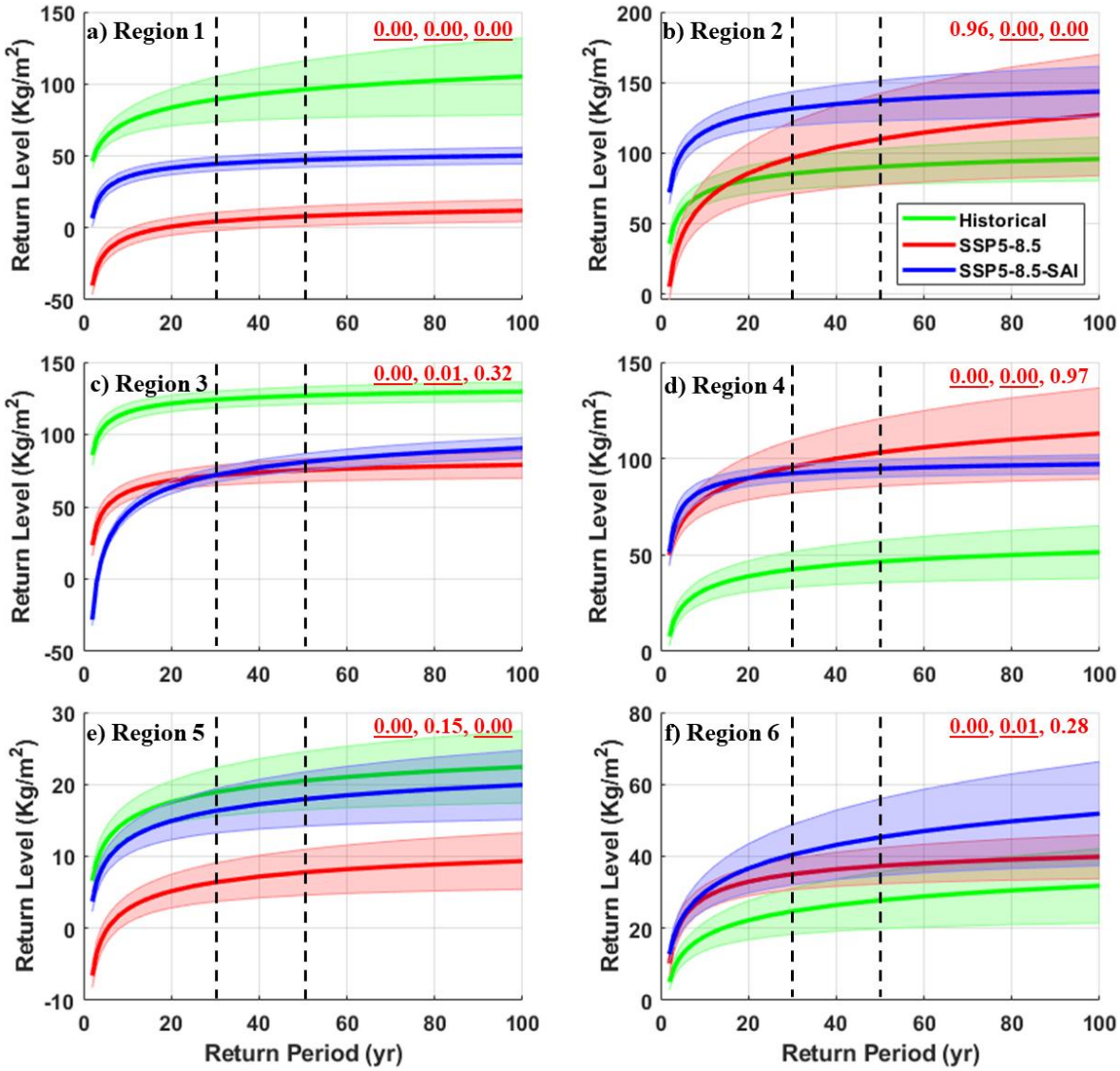


**Figure S13.** As in Fig. 5 but for the annual maximums.

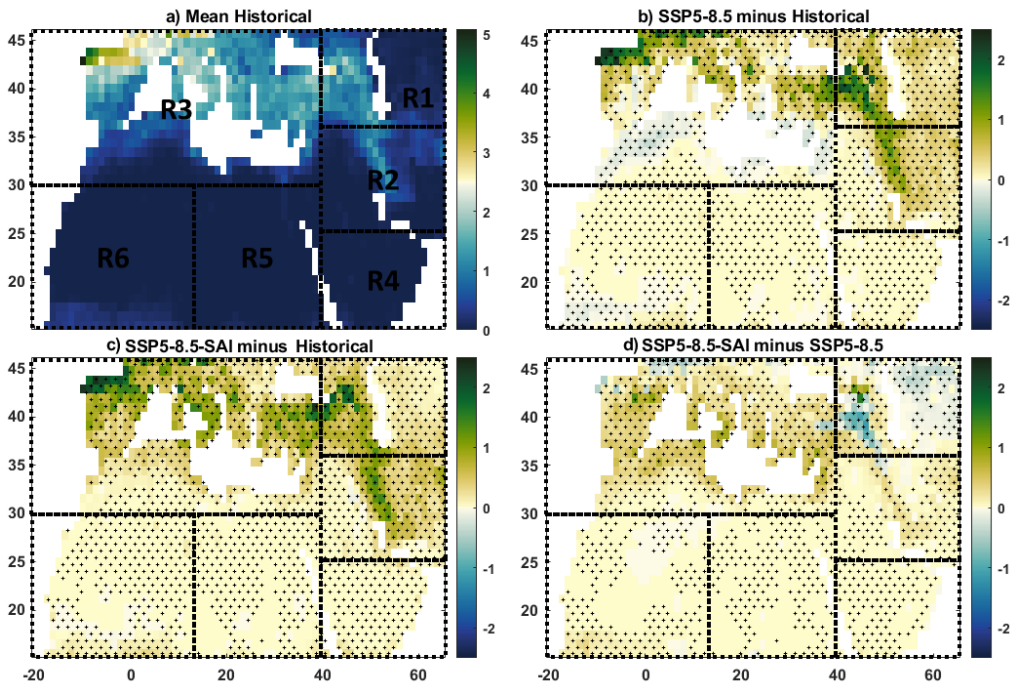


**Figure S14**. As Fig. 3 but for LAI.

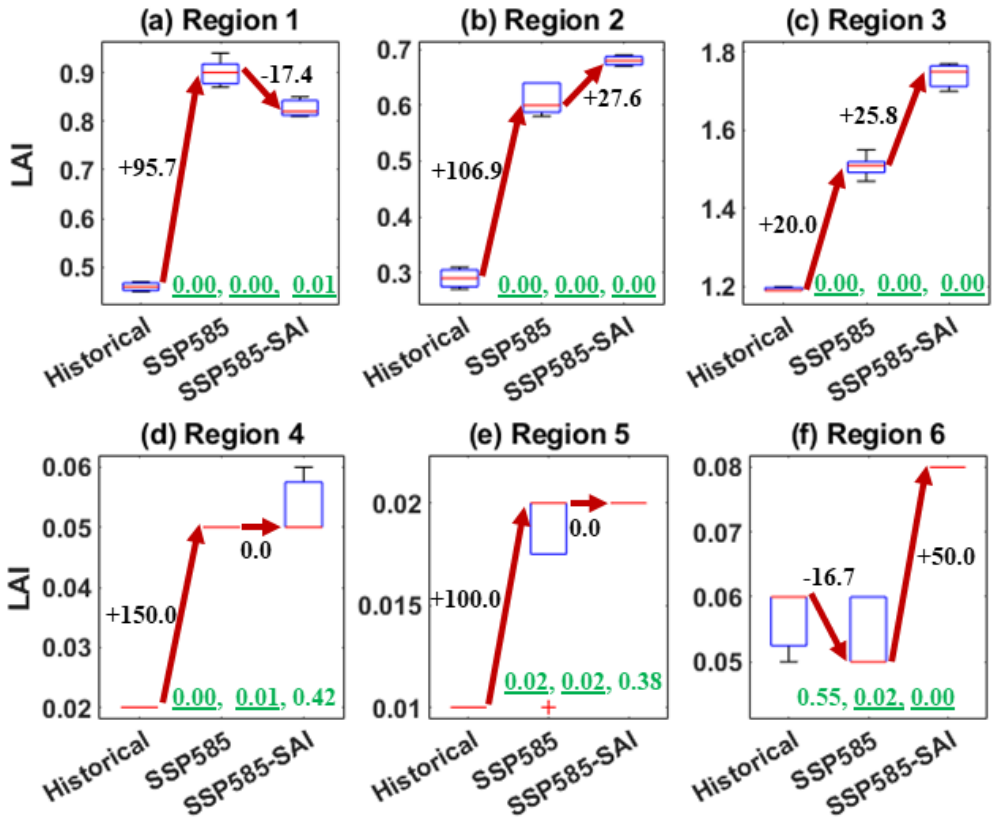


**Figure S15**. As Fig. 4 but for LAI.