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Emerging global freshwater challenges unveiled through observation-constrained projections

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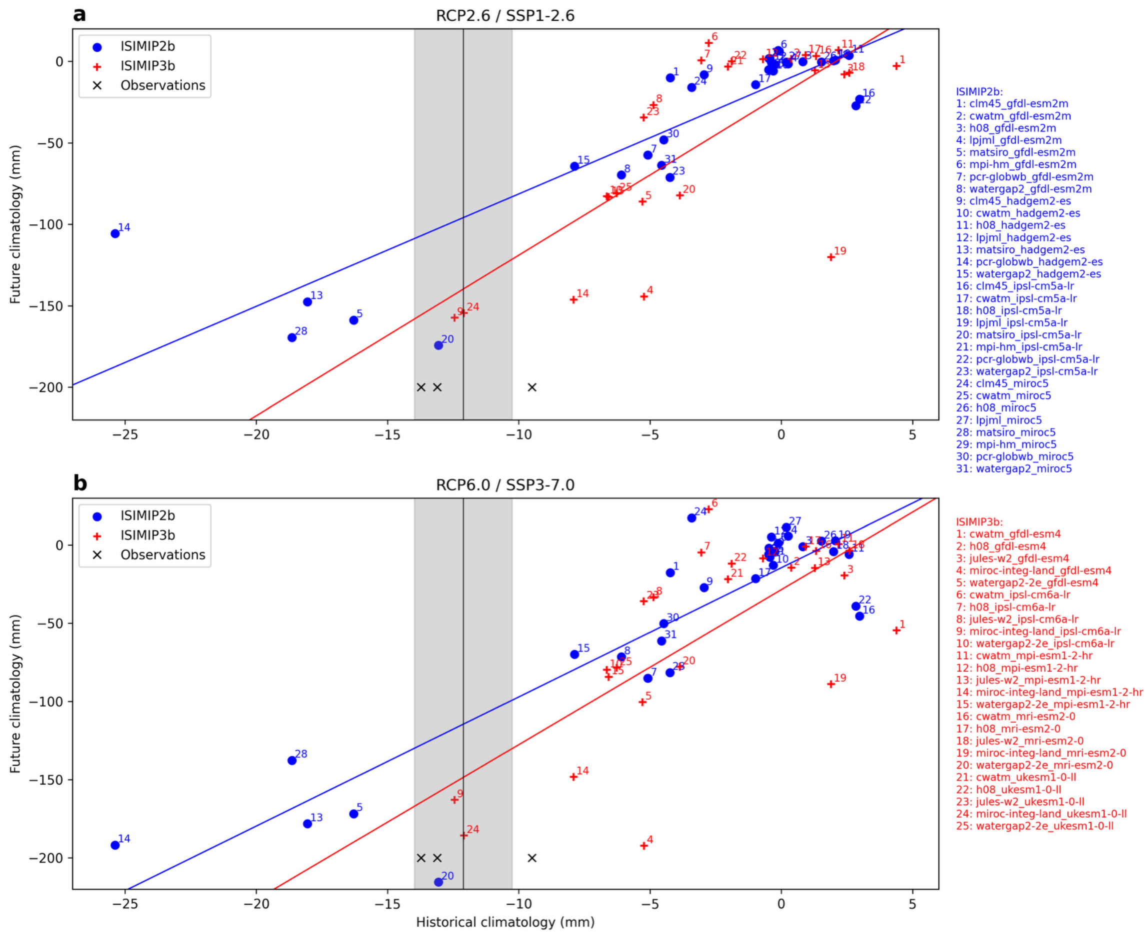

Fig. S1 | Past-future TWS relationships. Inter-model relationships between historical and late century climatologies of TWS anomalies from ISIMIP2b (blue) and ISIMIP3b (red) models under the RCP2.6/SSP1-2.6 (**a**) and RCP6.0/SSP3-7.0 (**b**) scenarios. Blue and red dots and crosses represent global averages from ensemble members. Black crosses represent GRACE observations. Blue and red lines denote the linear regression, black vertical lines indicate the average of three mascon solutions, and grey shading represents the standard deviation. Individual models are identified by numbers.

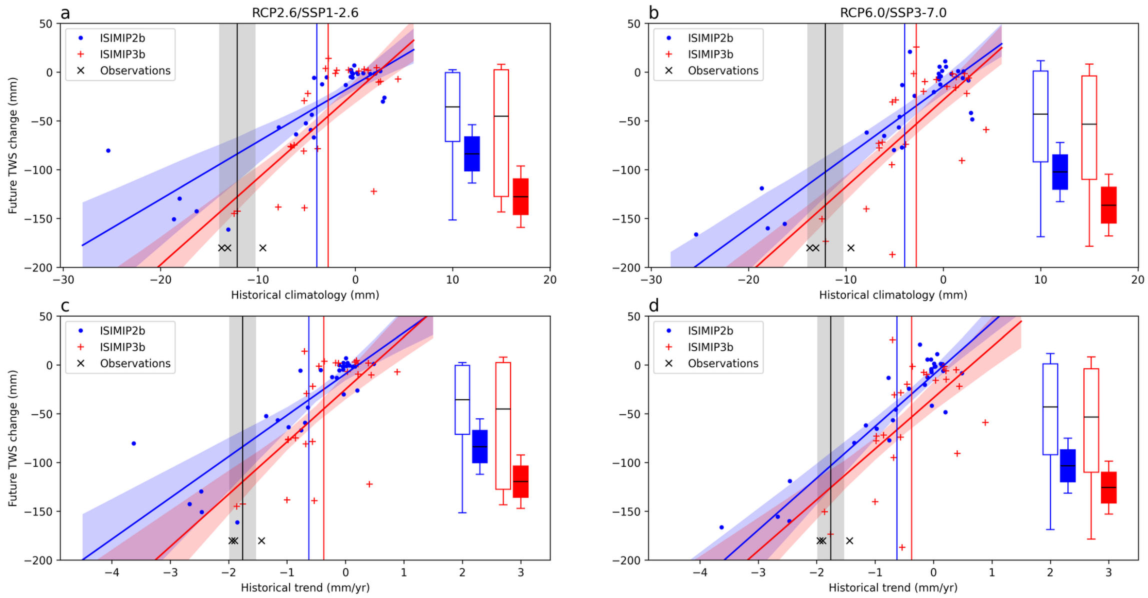

Fig. S2 | Different emergent constraints on future changes in TWS. a,**b**, Upper panels depict inter-model relationships between historical climatologies of TWS anomalies and late century TWS changes from ISIMIP2b (blue) and ISIMIP3b (red) models under the RCP2.6/SSP1-2.6 and RCP6.0/SSP3-7.0 scenarios. **c**,**d**, Lower panels illustrate inter-model relationships between historical trends of TWS anomalies and late century TWS changes for the same scenarios. Blue and red dots and crosses represent global averages from ensemble members. Black crosses represent GRACE observations. Blue and red lines represent linear regression fits, with 90% confidence intervals estimated through bootstrapping. Blue and red vertical lines mark the ensemble mean. Black vertical lines indicate the average of three mascon solutions (black cross), and grey shading represents the standard deviation. Box plots indicate the mean (black line), 66% (box), and 90% (whisker) confidence intervals of future TWS changes before (empty box) and after (filled box) applying observational constraints.

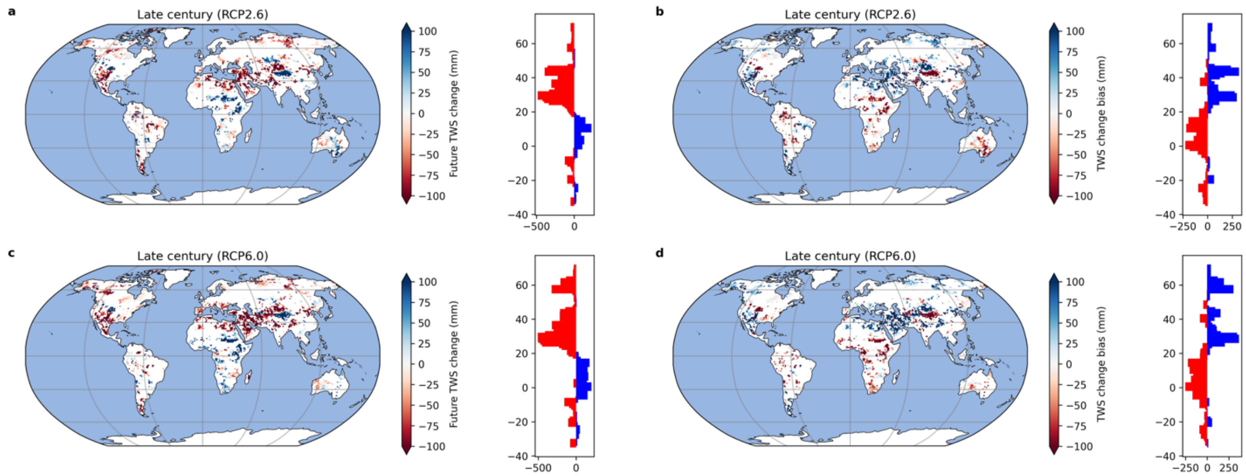

Fig. S3 | EC-calibrated changes in TWS from the ISIMIP2b models at the end of the century. a,**c**, Late century (2080–2099) EC-corrected TWS changes under the RCP2.6 and RCP6.0 scenarios, shown relative to historical (2004–2023) climatologies. **b**,**d**, Biases in projected late century TWS changes (raw model outputs minus EC-corrected values). Only regions with statistically significant positive EC correlations ($R > 0$ and $p < 0.05$) are shown. The histograms on the right represent zonally averaged values, with data shown only for latitudes between 70°N and 35°S due to sparse coverage outside this range.

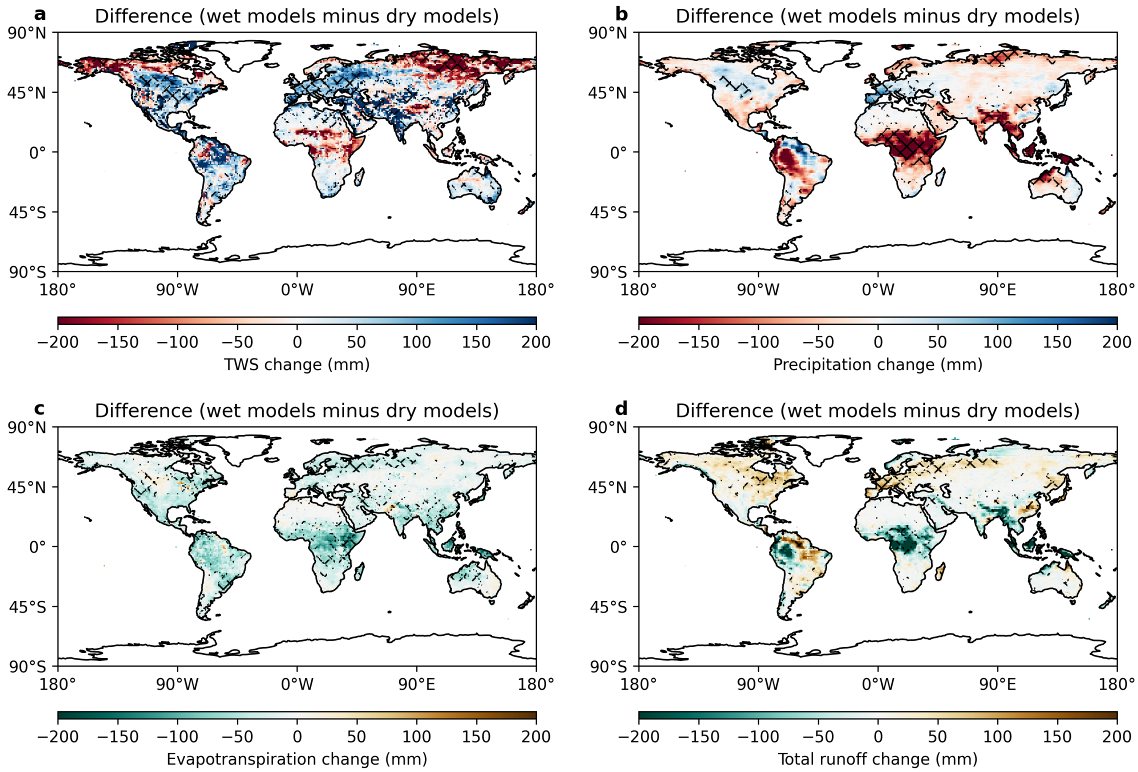

Fig. S4 | Differences in future changes between the wettest and driest models. Differences (the wettest minus the driest models) in late century (2080–2099) changes for TWS (**a**), precipitation (**b**), evapotranspiration (**c**), and total runoff (**d**) under the SSP3-7.0 scenario. Statistically significant differences at the 5% level, as determined by Welch's *t*-test, are indicated by black hatches. A permutation test with 100 random permutations was conducted to estimate the *p*-values.

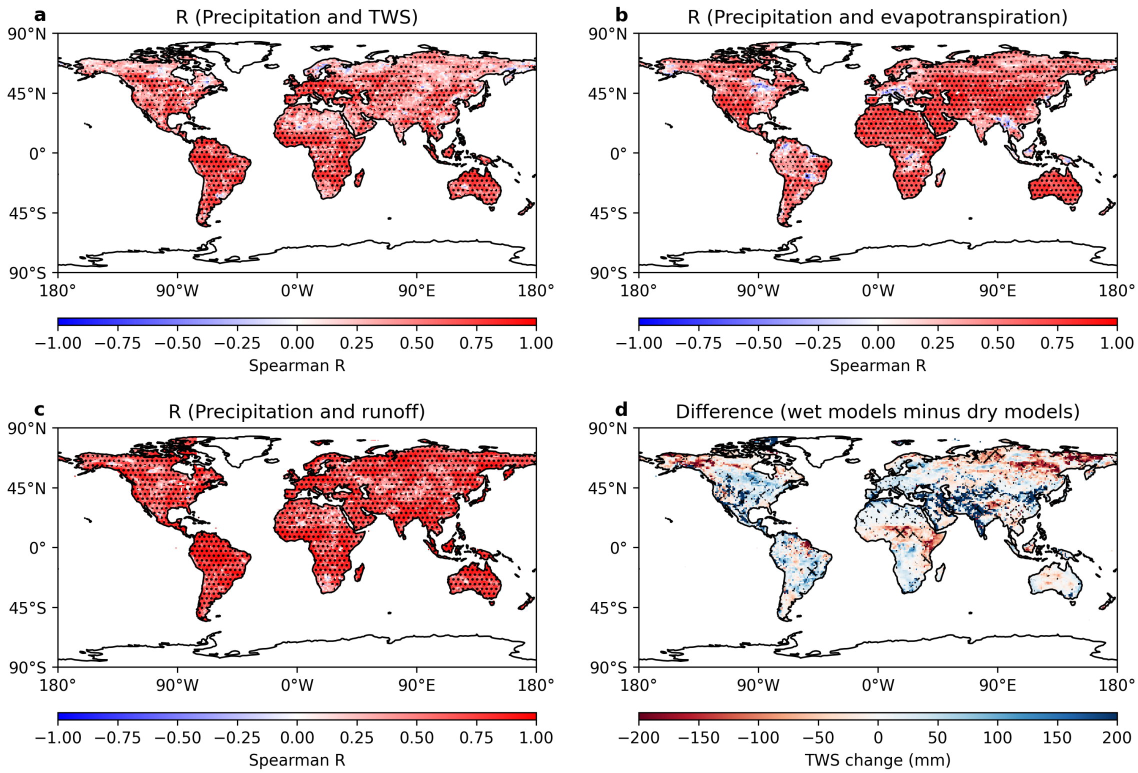

Fig. S5 | Spatial patterns in future changes. Same as Fig. 4 but under the SSP1-2.6 scenario.

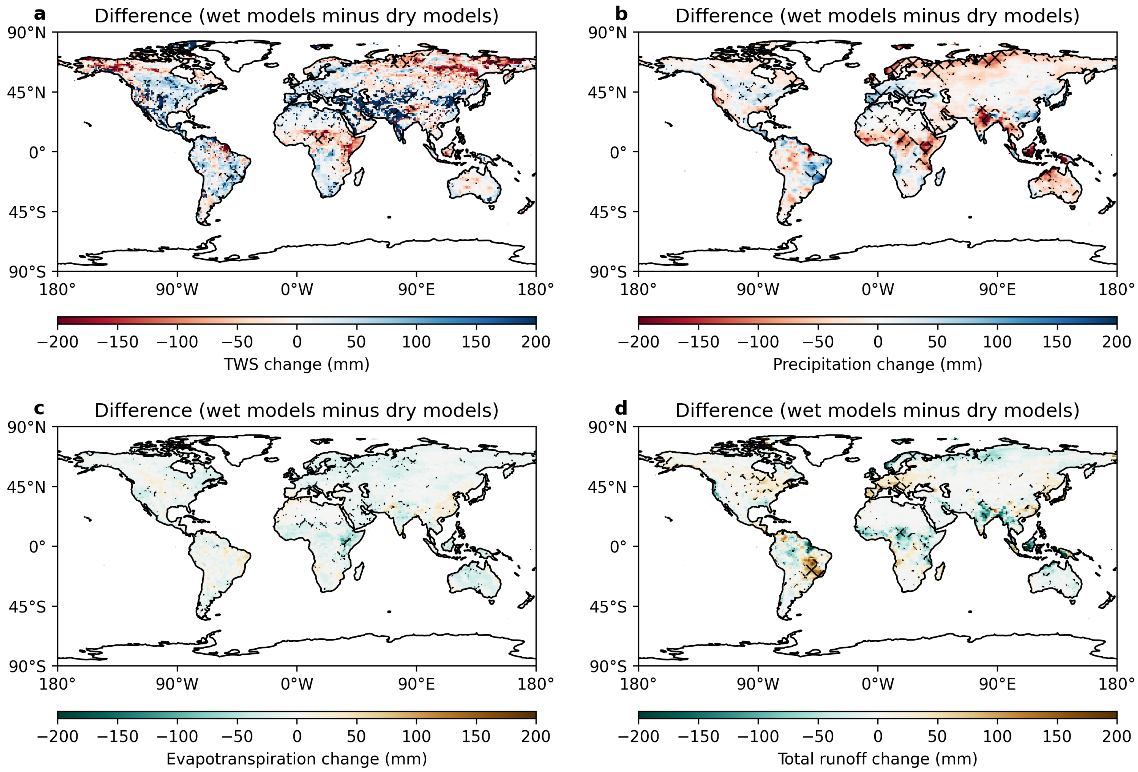

Fig. S6 | Differences in future changes between the wettest and driest models. Same as Fig. S4 but under the SSP1-2.6 scenario.

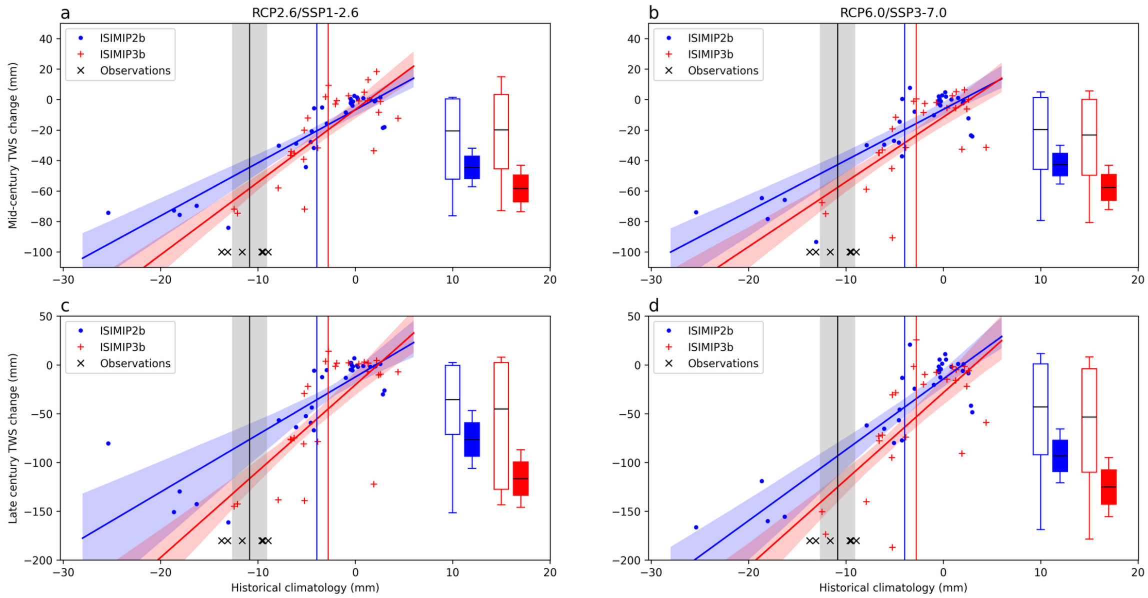

Fig. S7 | Emergent constraints on future changes in TWS. Same as Fig. 1, but replacing the mascon solutions with 7 GRACE-derived TWS products to ensure our results are robust across processing approaches. These include three mascon solutions (i.e., JPL RL06.3M v04, CSR RL0603M, and GSFC RL06 v1.0) and four spherical-harmonic solutions (i.e., JPL RL06, CSR RL06, GFZ RL06, and COST-G RL01), thereby illustrating the robustness of our results across diverse GRACE processing approaches.

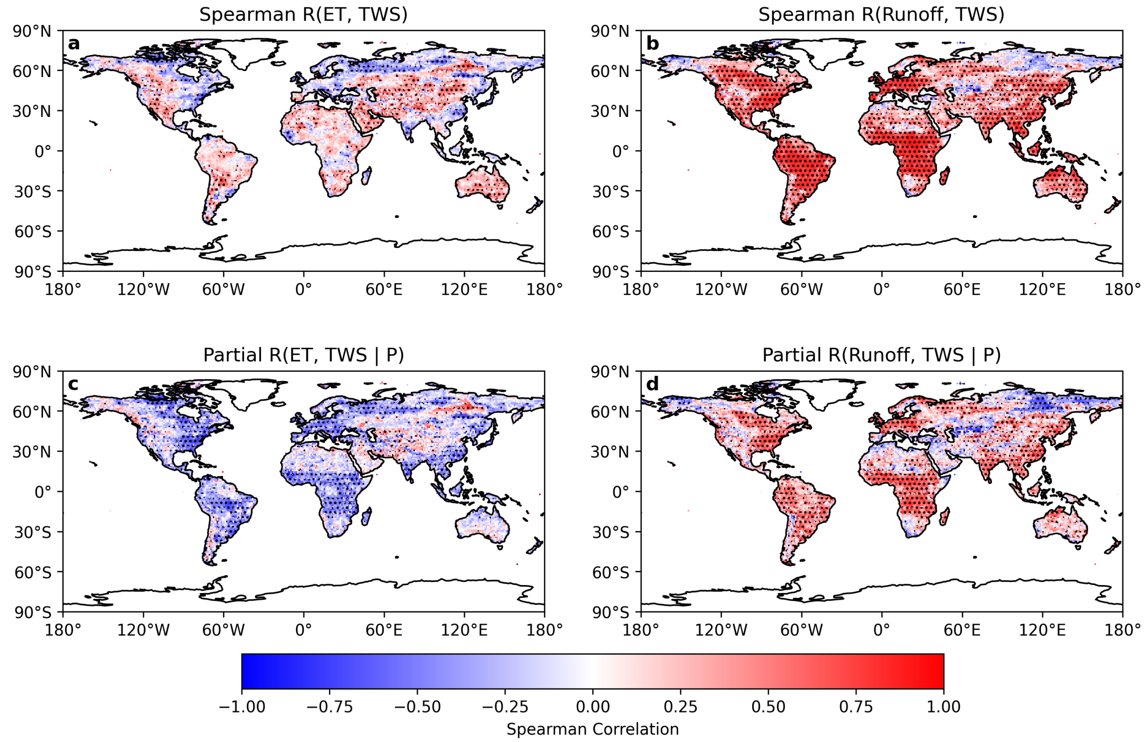

Fig. S8 | Spatial patterns in future changes. Inter-model Spearman's rank correlations between late century (2080–2099) TWS changes and changes in evapotranspiration (a) and total runoff (b) under the SSP3-7.0 scenario. Inter-model partial Spearman's correlations between late century TWS changes and changes in evapotranspiration (c) and total runoff (d), controlling for precipitation. Black stippling marks regions of statistical significance ($p < 0.05$).

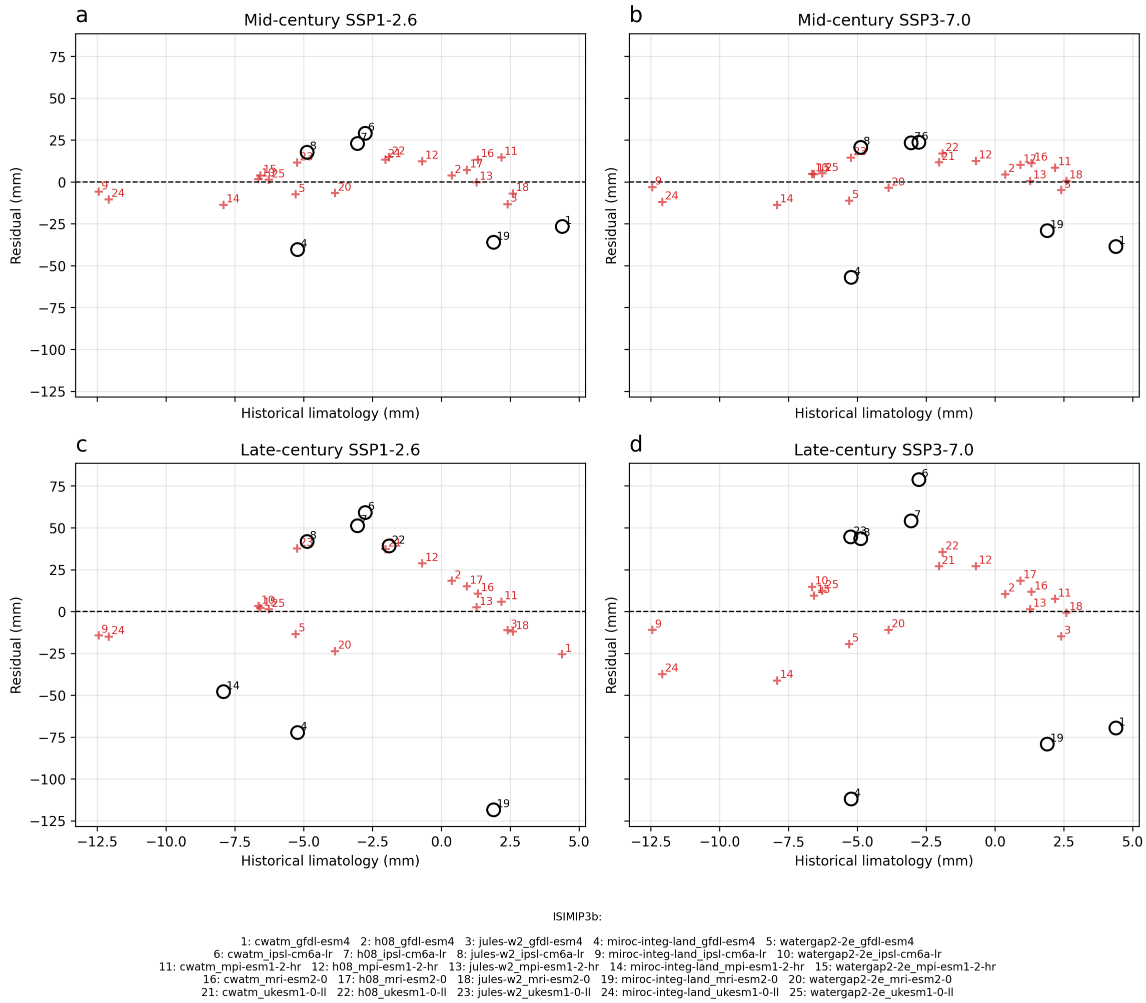

Fig. S9 | Residual plots corresponding to the EC relationships shown in Fig. 1, including only ISIMIP3b models. Outliers, defined as points with residuals exceeding one standard deviation, are marked in black. Individual models are identified by numbers.

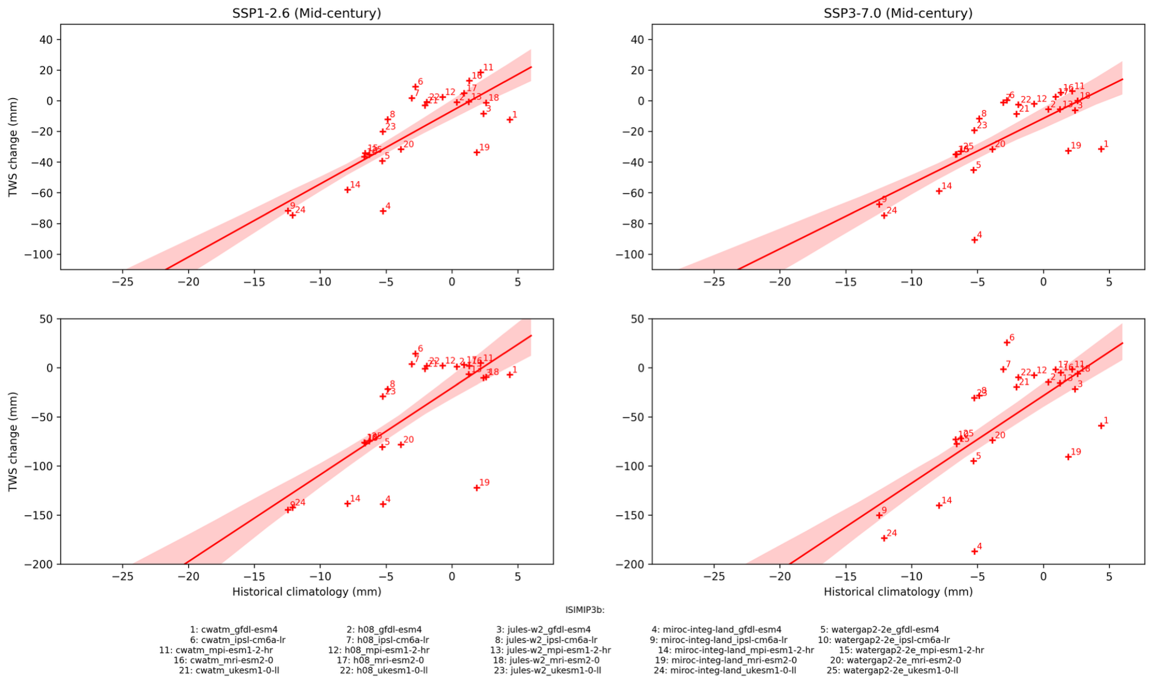

Fig. S10 | Same as Fig. 1, but including only the EC relationships across ISIMIP3b models. Individual models are identified by numbers.

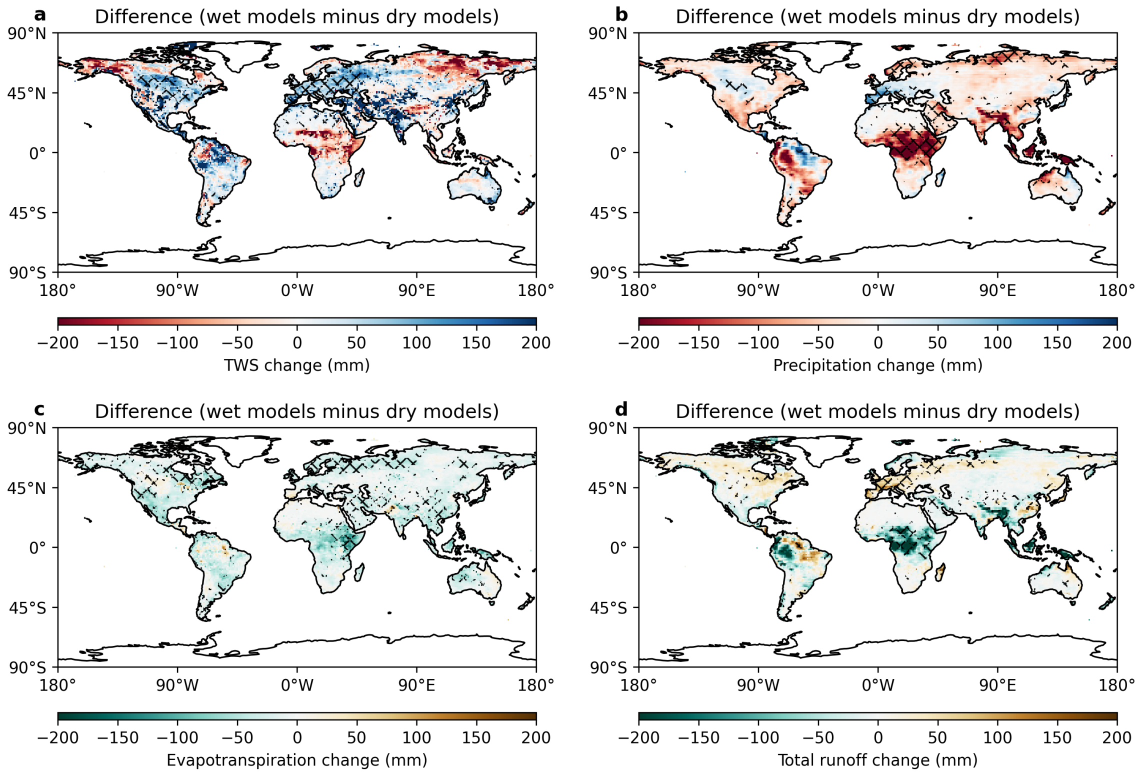

Fig. S11 | Same as Fig. 4, but based on an alternative classification threshold. Dry models include miroc-integ-land_ipsl-cm6a-lr, miroc-integ-land_ukesm1-0-ll, miroc-integ-land_mpi-esm1-2-hr, watergap2-2e_ipsl-cm6a-lr, watergap2-2e_mpi-esm1-2-hr, watergap2-2e_ukesm1-0-ll, watergap2-2e_gfdl-esm4 (newly added), and jules-w2_ukesm1-0-ll (newly added). Wet models include jules-w2_mri-esm2-0, jules-w2_gfdl-esm4, cwatm_mpi-esm1-2-hr, cwatm_mri-esm2-0, jules-w2_mpi-esm1-2-hr, h08_mri-esm2-0, h08_gfdl-esm4 (newly added), and h08_mpi-esm1-2-hr (newly added).

Table S1 | Description of ISIMIP3b settings. All outputs are provided at a monthly temporal resolution and on a 0.5° × 0.5° global grid. Specific storage compartments include canopy water storage (canopystor), groundwater storage (groundwstor), lake storage (lakestor), wetland storage (wetlandstor), reservoir storage (reservoirstor), soil moisture (soilmoist), snow water equivalent (swe), and river storage (riverstor). Ensemble members are classified into the driest (D) and wettest (W) categories based on their historical climatology of global mean TWS anomalies after excluding outliers identified from the residual analysis (Fig. S9) (see Methods).

Model	**Meteorological forcing**	**Radiative forcing scenario**	**Socioeconomic scenario**	**Water storage compartments considered** (Telteu et al., 2021)
CWatM	GFDL-ESM4, IPSL-CM6A-LR, MPI-ESM1-2-HR (W), MRI-ESM2-0 (W), UKESM1-0-LL	HIST, SSP1-2.6, SSP3-7.0	histsoc (HIST), 2015soc-from-histsoc (SSP1-2.6, SSP3-7.0)	groundwstor, soilmoist, lakestor, reservoirstor, riverstor, swe, canopystor
H08	GFDL-ESM4, IPSL-CM6A-LR, MPI-ESM1-2-HR, MRI-ESM2-0 (W), UKESM1-0-LL	HIST, SSP1-2.6, SSP3-7.0	histsoc (HIST), 2015soc (SSP1-2.6, SSP3-7.0)	swe, soilmoist, groundwstor, reservoirstor, riverstor
JULES-W2	GFDL-ESM4 (W), IPSL-CM6A-LR, MPI-ESM1-2-HR (W), MRI-ESM2-0 (W), UKESM1-0-LL	HIST, SSP1-2.6, SSP3-7.0	histsoc (HIST), 2015soc-from-histsoc (SSP1-2.6, SSP3-7.0)	canopystor, swe, soilmoist
MIROC-INTEG-LAND	GFDL-ESM4, IPSL-CM6A-LR (D), MPI-ESM1-2-HR (D), MRI-ESM2-0, UKESM1-0-LL (D)	HIST, SSP1-2.6, SSP3-7.0	histsoc (HIST), 2015soc-from-histsoc (SSP1-2.6, SSP3-7.0)	soilmoist, canopystor, swe, riverst or, reservoirstor
WaterGAP2-2e	GFDL-ESM4, IPSL-CM6A-LR (D), MPI-ESM1-2-HR (D), MRI-ESM2-0, UKESM1-0-LL (D)	HIST, SSP1-2.6, SSP3-7.0	histsoc (HIST), 2015soc-from-histsoc (SSP1-2.6, SSP3-7.0)	canopystor, riverstor, swe, soilmoist, groundwstor, lakestor, wetlandstor, reservoirstor

Table S2 | Description of ISIMIP2b settings. All outputs are provided at a monthly temporal resolution and on a 0.5° × 0.5° global grid. Specific storage compartments include canopy water storage (canopystor), groundwater storage (groundwstor), lake storage (lakestor), wetland storage (wetlandstor), reservoir storage (reservoirstor), soil moisture (soilmoist), snow water equivalent (swe), and river storage (riverstor).

Model	Meteorological forcing	Radiative forcing scenario	Socioeconomic scenario	Water storage compartments considered
CLM4.5	GFDL-ESM2M, HadGEM2-ES, IPSL-CM5A-LR, MIROC5	HIST, RCP2.6, RCP6.0	2005soc (HIST, RCP2.6, RCP6.0)	lakestor, reservoirstor, riverstor, groundwstor, soilmoist, swe, canopystor
CWatM	GFDL-ESM2M, HadGEM2-ES, IPSL-CM5A-LR, MIROC5	HIST, RCP2.6, RCP6.0	histsoc (HIST), 2005soc (RCP2.6, RCP6.0)	groundwstor, soilmoist, lakestor, reservoirstor, riverstor, swe, canopystor
H08	GFDL-ESM2M, HadGEM2-ES, IPSL-CM5A-LR, MIROC5	HIST, RCP2.6, RCP6.0	histsoc (HIST), 2005soc (RCP2.6, RCP6.0)	swe, soilmoist, groundwstor, reservoirstor, riverstor
LPJmL	GFDL-ESM2M, HadGEM2-ES, IPSL-CM5A-LR, MIROC5	HIST, RCP2.6, RCP6.0	histsoc (HIST), 2005soc (RCP2.6, RCP6.0)	soilmoist, lakestor, riverstor, reservoirstor, swe
MATSIRO	GFDL-ESM2M, HadGEM2-ES, IPSL-CM5A-LR, MIROC5	HIST, RCP2.6, RCP6.0	histsoc (HIST), 2005soc (RCP2.6, RCP6.0)	soilmoist, canopystor, swe, riverstor, reservoirstor
MPI-HM	GFDL-ESM2M, IPSL-CM5A-LR, MIROC5	HIST, RCP2.6, RCP6.0	histsoc (HIST), 2005soc (RCP2.6, RCP6.0)	riverstor, wetlandstor, reservoirstor, groundwstor, soilmoist, canopystor
PCR-GLOBWB	GFDL-ESM2M, HadGEM2-ES, IPSL-CM5A-LR, MIROC5	HIST, RCP2.6, RCP6.0	histsoc (HIST), 2005soc (RCP2.6, RCP6.0)	riverstor, reservoirstor, soilmoist, swe, canopystor
WaterGAP2	GFDL-ESM2M, HadGEM2-ES, IPSL-CM5A-LR, MIROC5	HIST, RCP2.6, RCP6.0	histsoc (HIST), 2005soc (RCP2.6, RCP6.0)	canopystor, riverstor, swe, soilmoist, groundwstor, lakestor, wetlandstor, reservoirstor