Robust future changes in meteorological drought in CMIP6 projections despite uncertainty in precipitation

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Table S1. CMIP5 and CMIP6 models used in this study. Where possible, the equivalent models from CMIP5 and CMIP6 were chosen and otherwise available models by the same institution were matched. Resolution shows the model resolution as degrees latitude and longitude, respectively. For CMIP6 models, *gn* indicates native resolution and *gr* regridded resolution. Ensembles shows the individual model ensemble members used in this study for all historical and future simulations.

CMIP6			**CMIP5**		
Model	**Resolution**	**Ensembles**	**Model**	**Resolution**	**Ensembles**
BCC-CSM2-MR	1.12, 1.13 (gn)	r1i1p1f1	BCC-CSM1-1	2.79, 2.81	r1i1p1
CanESM5	2.79, 2.81 (gn)	r1i1p1f1	CanESM2	2.79, 2.81	r1i1p1, r2i1p1, r3i1p1, r4i1p1, r5i1p1
CESM2-WACCM	0.94, 1.25 (gn)	r1i1p1f1	CESM1-WACCM	1.88, 2.5	r2i1p1, r3i1p1, r4i1p1
CNRM-CM6-1	1.40, 1.41 (gr)	r1i1p1f2, r2i1p1f2, r3i1p1f2, r4i1p1f2, r5i1p1f2, r6i1p1f2	CNRM-CM5	1.40, 1.41	r1i1p1
GFDL-CM4	1.00, 1.25 (gr)	r1i1p1f1	GFDL-CM3	2.00, 2.50	r1i1p1
IPSL-CM6A-LR	1.27, 2.50 (gr)	r1i1p1f1	IPSL-CM5A-LR	1.89, 3.75	r1i1p1, r2i1p1, r3i1p1, r4i1p1
MIROC6	1.40, 1.41 (gn)	r1i1p1f1	MIROC5	1.40, 1.41	r1i1p1, r2i1p1, r3i1p1
MRI-ESM2-0	1.12, 1.13 (gn)	r1i1p1f1	MRI-CGCM3	1.12, 1.13	r1i1p1
UKESM1-0-LL	1.25, 1.86 (gn)	r1i1p1f2, r2i1p1f2, r3i1p1f2, r4i1p1f2, r8i1p1f2	HadGEM2-ES	1.25, 1.88	r1i1p1, r2i1p1, r3i1p1, r4i1p1

Table 2: Additional CMIP5 models used in Supplementary Figure S1. Resolution shows the model resolution as degrees latitude and longitude, respectively. Ensembles shows the individual model ensemble members used in this study for all historical and future simulations.

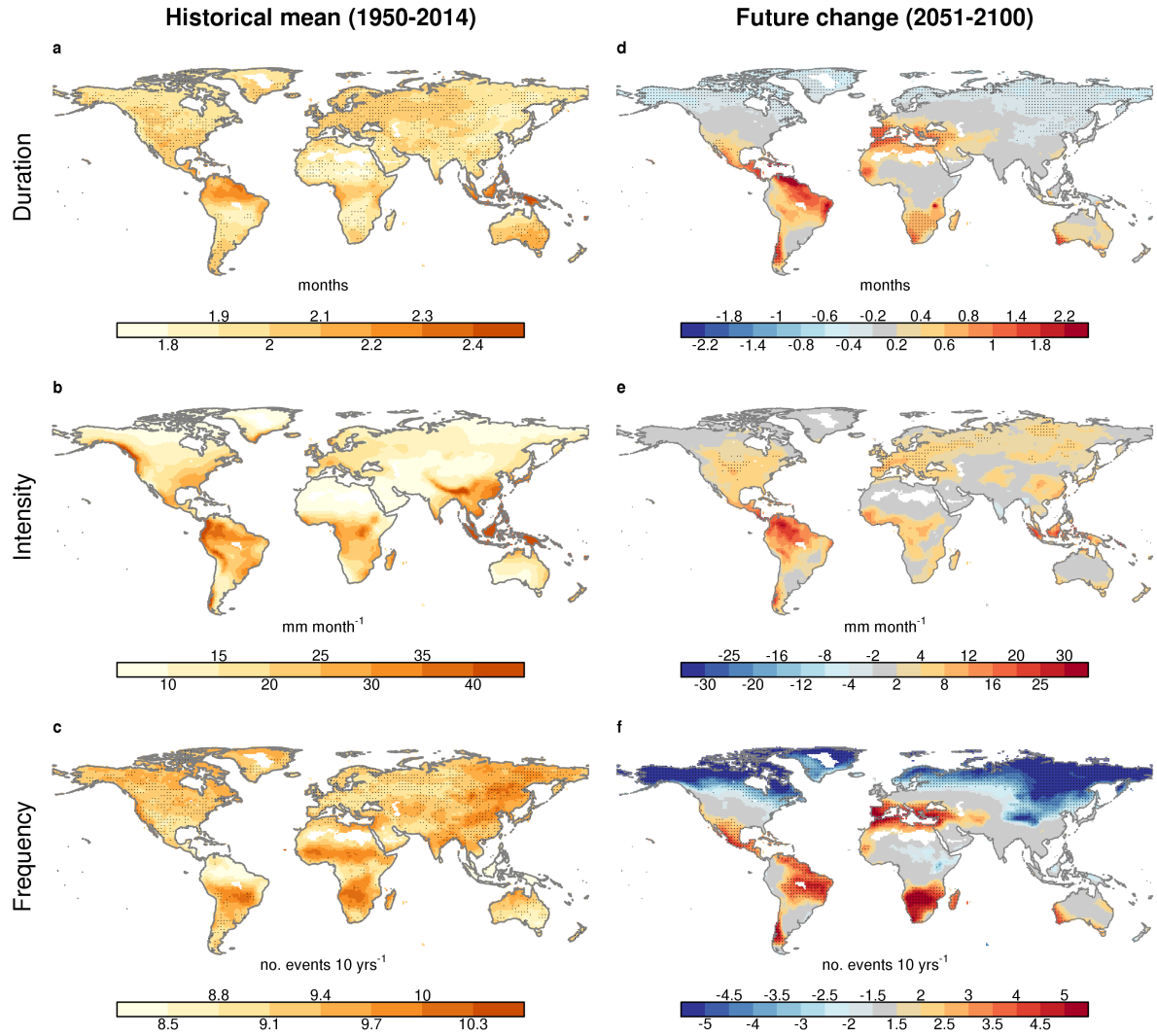| Model	Resolution	Ensembles
ACCESS1-0	1.25, 1.88	r1i1p1
ACCESS1-3	1.25, 1.88	r1i1p1
BNU-ESM	2.79, 2.81	r1i1p1
CCSM4	0.94, 1.25	r1i1p1, r2i1p1, r3i1p1, r4i1p1, r5i1p1, r6i1p1
CESM1-BGC	0.94, 1.25	r1i1p1
CESM1-CAM5	0.94, 1.25	r1i1p1, r2i1p1, r3i1p1
CSIRO-Mk3-6-0	1.87, 1.88	r1i1p1, r2i1p1, r3i1p1, r4i1p1, r5i1p1, r6i1p1, r7i1p1, r8i1p1, r9i1p1, r10i1p1
FGOALS-g2	2.79, 2.81	r1i1p1
GFDL-ESM2G	2.02, 2.00	r1i1p1
GFDL-ESM2M	2.02, 2.50	r1i1p1
GISS-E2-H	2.00, 2.50	r1i1p1, r1i1p2, r1i1p3, r2i1p1, r2i1p3
GISS-E2-R	2.00, 2.50	r1i1p1, r1i1p2, r1i1p3, r2i1p1, r2i1p3
HadGEM2-CC	1.25, 1.88	r1i1p1
INMCM4	1.50, 2.00	r1i1p1
IPSL-CM5A-MR	1.27, 2.50	r1i1p1
IPSL-CM5B-LR	1.89, 3.75	r1i1p1
MIROC-ESM	2.79, 2.81	r1i1p1
MIROC-ESM-CHEM	2.79, 2.81	r1i1p1
MPI-ESM-LR	1.87, 1.88	r1i1p1, r2i1p1, r3i1p1
MPI-ESM-MR	1.87, 1.88	r1i1p1
NorESM1-M	1.89, 2.50	r1i1p1
NorESM1-ME	1.89, 2.50	r1i1p1

Fig. S1. Projected changes in drought metrics in the full CMIP5 archive. (a,b,c) the multi-model mean historical drought duration, intensity and frequency, respectively, for 31 CMIP5 models during the 1950-2014 baseline period. Stippling indicates where ≥75% of models are within 10% of the observed mean (27% of land area in a, 0% in b and 26% in c) (see Figure S3 for observed metrics). (d,e,f) projected future change in drought duration, intensity and frequency, respectively, relative to the historical mean using the 8.5 W m^{-2} scenario. Stippling indicates where the magnitude of the multi-model mean future change exceeds the inter-model standard deviation (26% of land area in d, 8% in e and 46% in f).
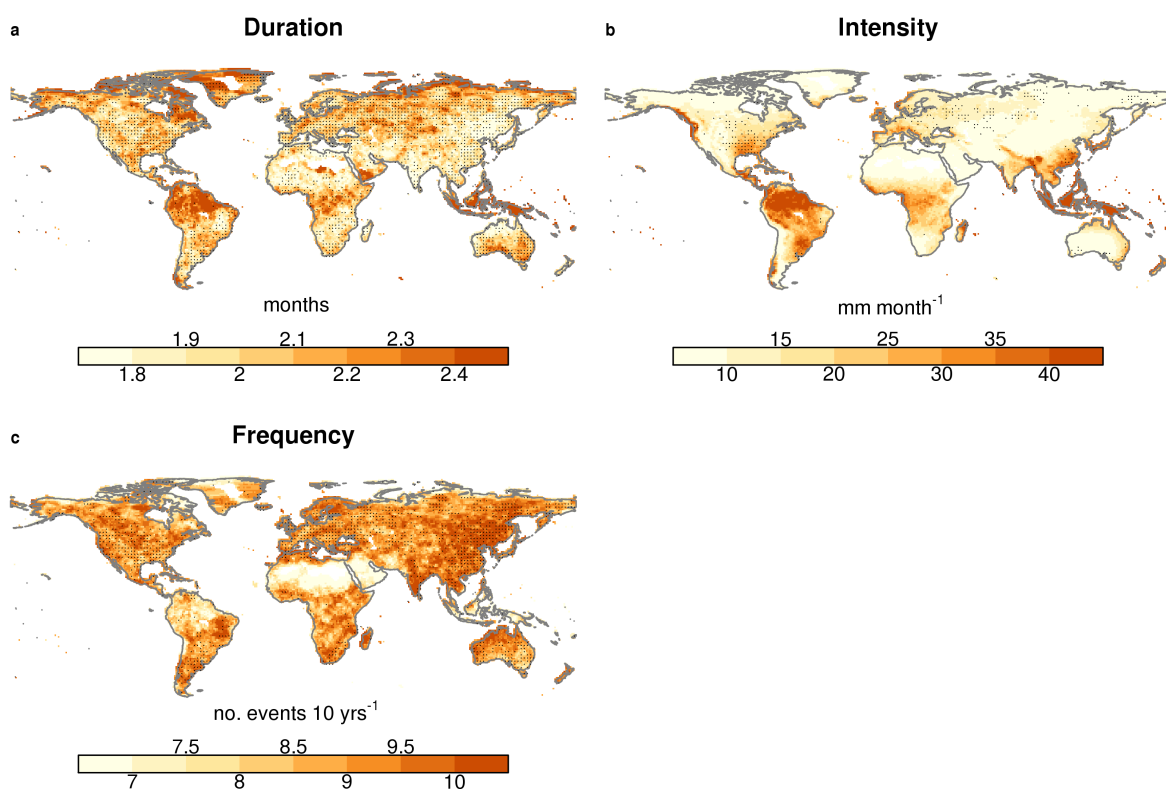
Fig. S2. Projected changes in drought frequency. (a) multi-model mean historical drought frequency for nine CMIP6 and (b) CMIP5 models during the 1950-2014 baseline period. Stippling indicates where ≥75% of models are within 10% of the observed mean (33% of land area in a and 29% in b) (see Figure S3c for observed mean frequency). (c) projected future change in drought frequency relative to the historical mean for CMIP6 and (d) CMIP5 using the 8.5 W m⁻² scenario. Stippling indicates where the magnitude of the multi-model mean future change exceeds the inter-model standard deviation (57% of land area in c and 51% in d).

Fig. S3. Mean observed drought metrics during the 1950-2014 baseline period. Mean historical drought (a) duration (b) intensity and (c) frequency for the three observed precipitation products. Stippling indicates where all three observed datasets are within 10% of the mean.
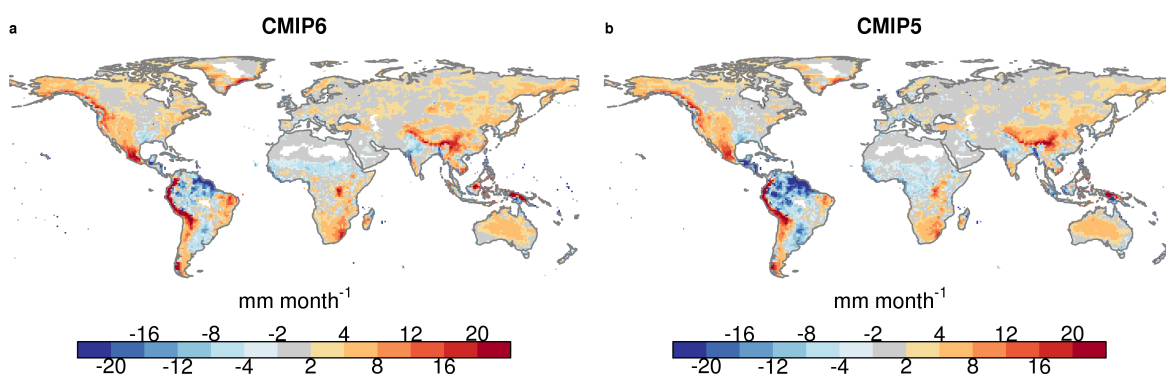

Fig. S4. Bias in historical mean drought intensity. Difference in (a) CMIP6 and (b) CMIP5 ensemble mean drought intensity compared to the mean of the three observational products during the 1950-2014 baseline period.
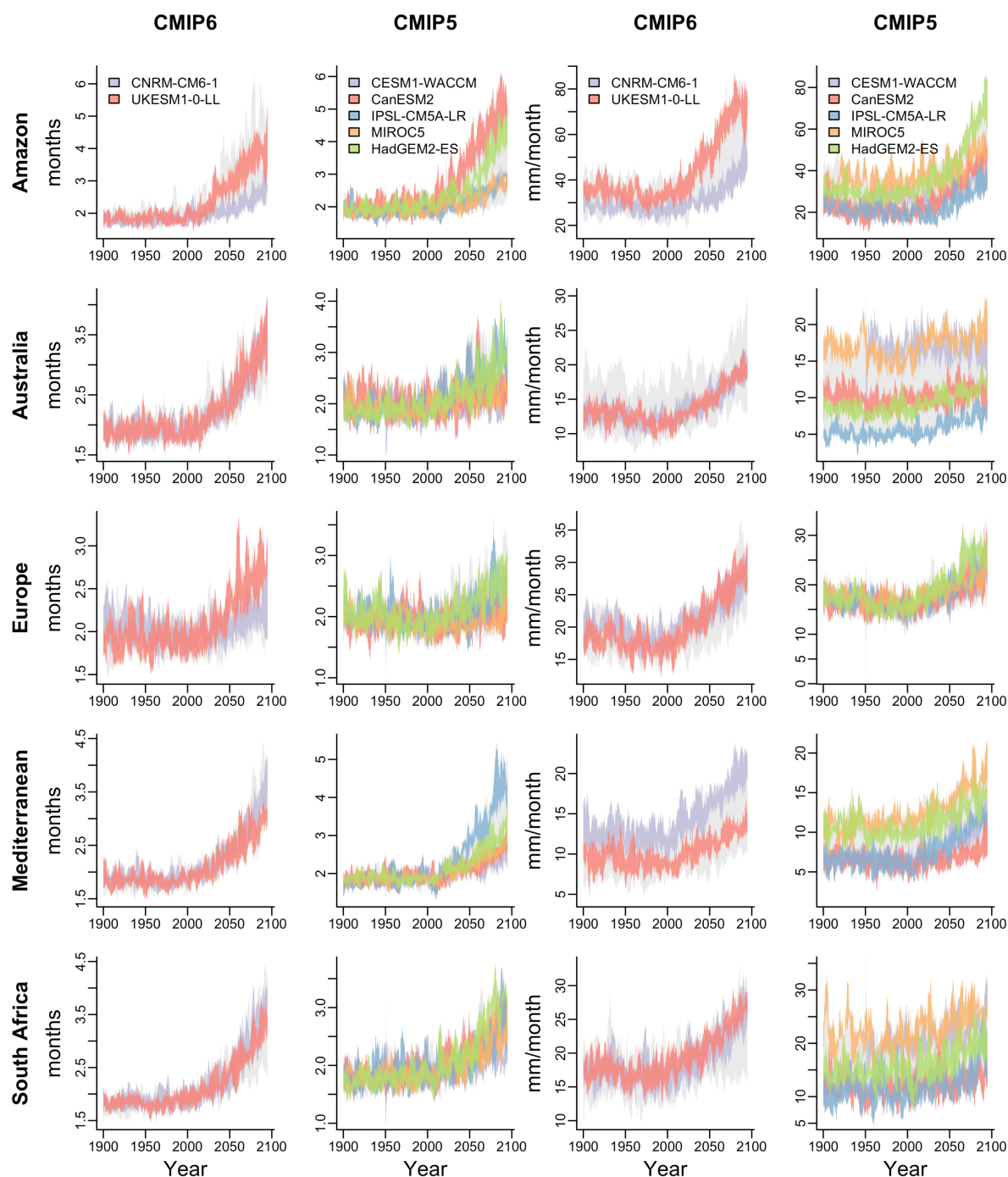
Fig. S5. Range in drought projections due to internal variability in five key regions. The two left-hand panels show time series in drought duration for CMIP6 and CMIP5, respectively, and the two right-hand panels that for drought intensity for the SSP5-8.5 and RCP8.5 emissions scenarios. The coloured shading shows the range across individual ensemble members for each model and the grey shading shows the full range across all models and ensembles. See Table S1 for ensemble members and Figure 3 for regions.
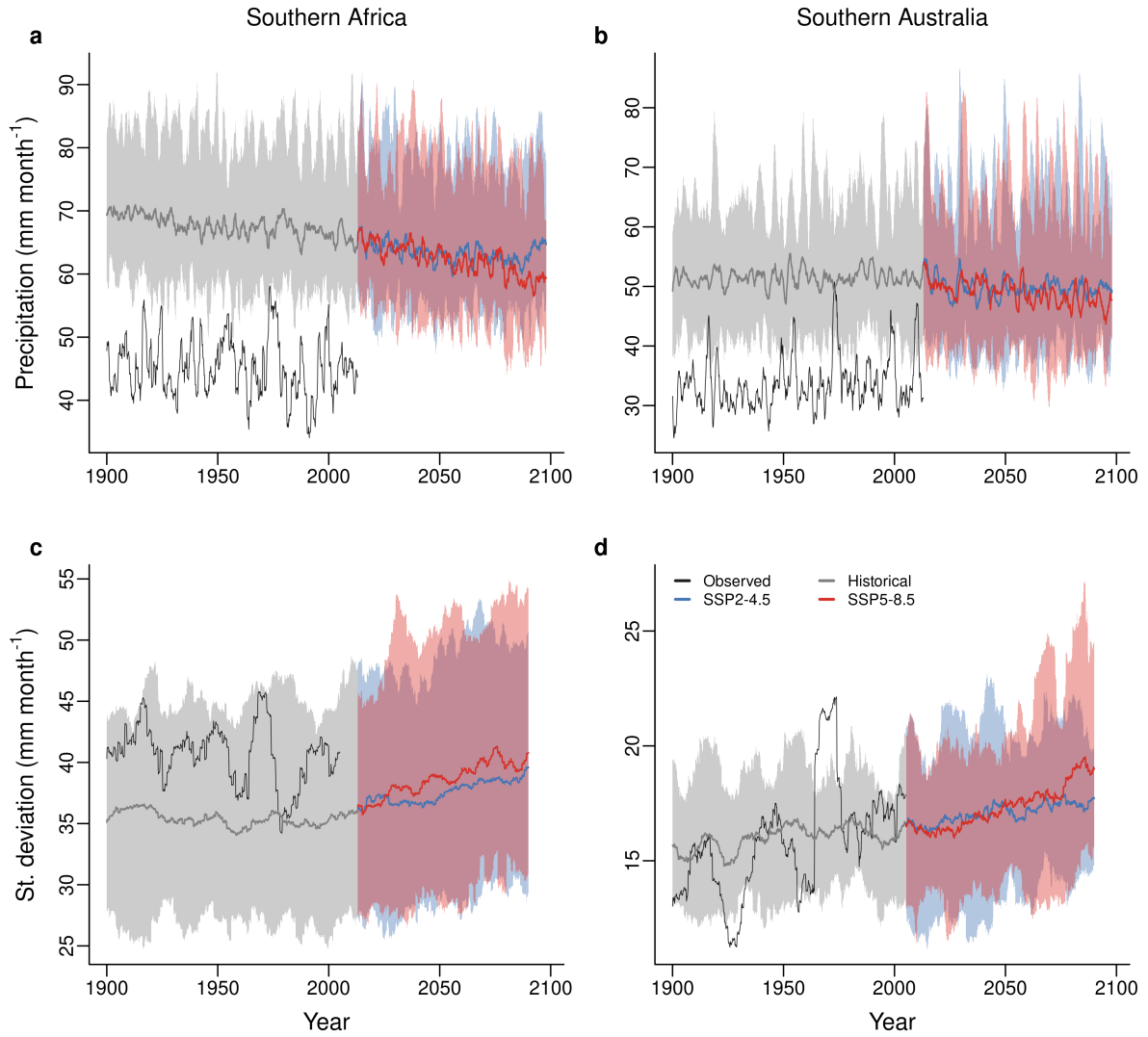
Fig. S6. Projected changes in monthly precipitation mean and variability in southern African and Australian regions. (a-b) show a time series of monthly mean precipitation for the southern African and southern Australian regions, respectively, smoothed using a 24-month running window. (c-d) show a time series of 10-year running standard deviation for the same regions. In (a-d) the shading shows the full model range and the solid lines the multi-model means. For observations, the mean of the three observed products is shown.

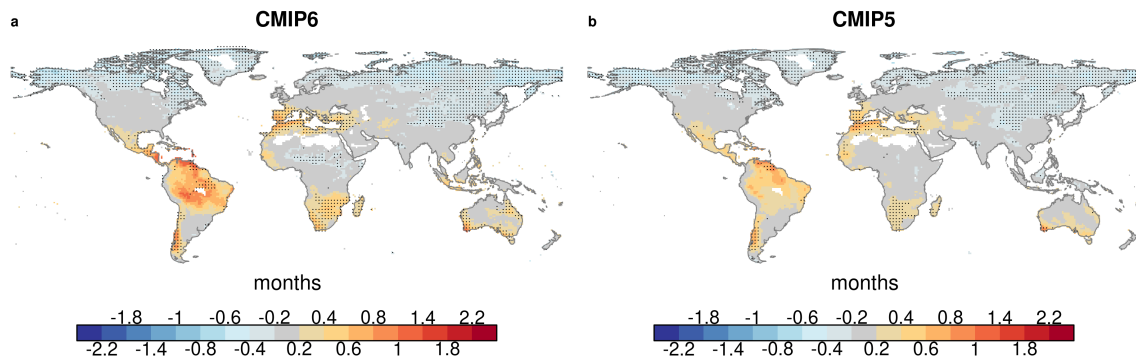# Future projections of drought for the 4.5 W m⁻² emissions scenario

Fig. S7. Projected changes in drought duration for the 4.5 W m⁻² emissions scenario. Projected future change in drought duration relative to the historical mean for a) CMIP6 SSP2-4.5 scenario and b) CMIP5 RCP4.5 scenario. Stippling indicates where the magnitude of the multi-model mean future change exceeds the inter-model standard deviation (36% of land area in a and 29% in b).
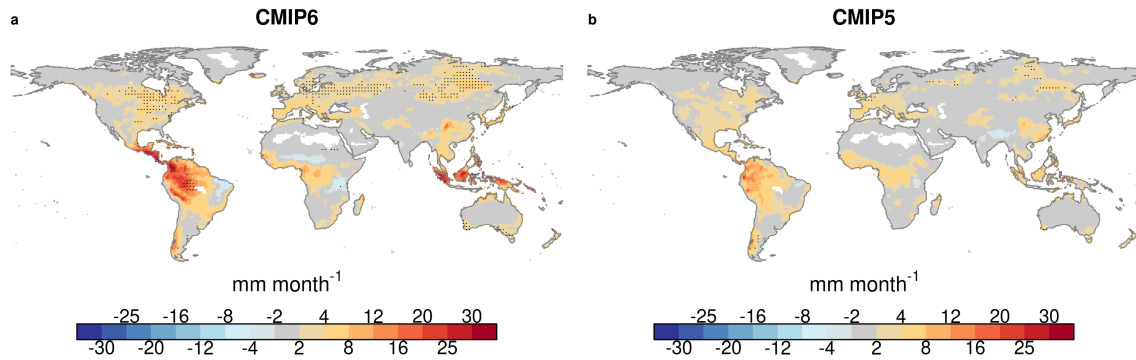

Fig. S8. Projected changes in drought intensity for the 4.5 W m⁻² emissions scenario. Projected future change in drought intensity relative to the historical mean for a) CMIP6 SSP2-4.5 scenario and b) CMIP5 RCP4.5 scenario. Stippling indicates where the magnitude of the multi-model mean future change exceeds the inter-model standard deviation (10% of land area in a and 2% in b).
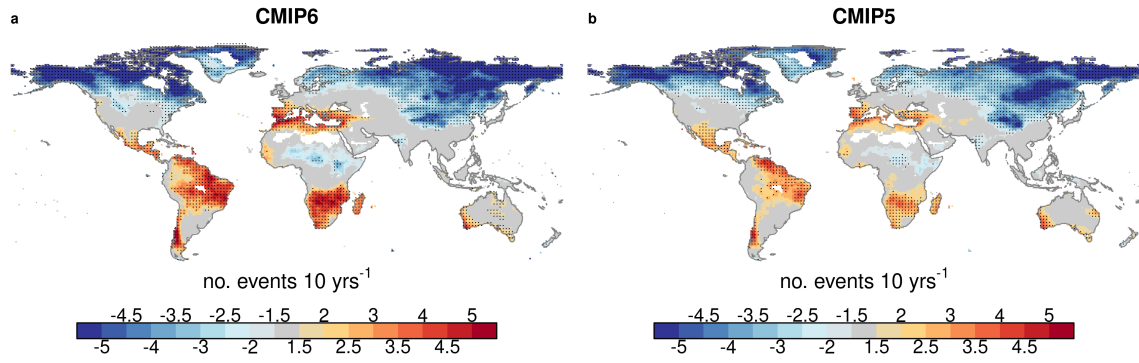
Fig. S9. Projected changes in drought frequency for the 4.5 W m^{-2} emissions scenario. Projected future change in drought frequency relative to the historical mean for a) CMIP6 SSP2-4.5 scenario and b) CMIP5 RCP4.5 scenario. Stippling indicates where the magnitude of the multi-model mean future change exceeds the inter-model standard deviation (52% of land area in a and 45% in b).

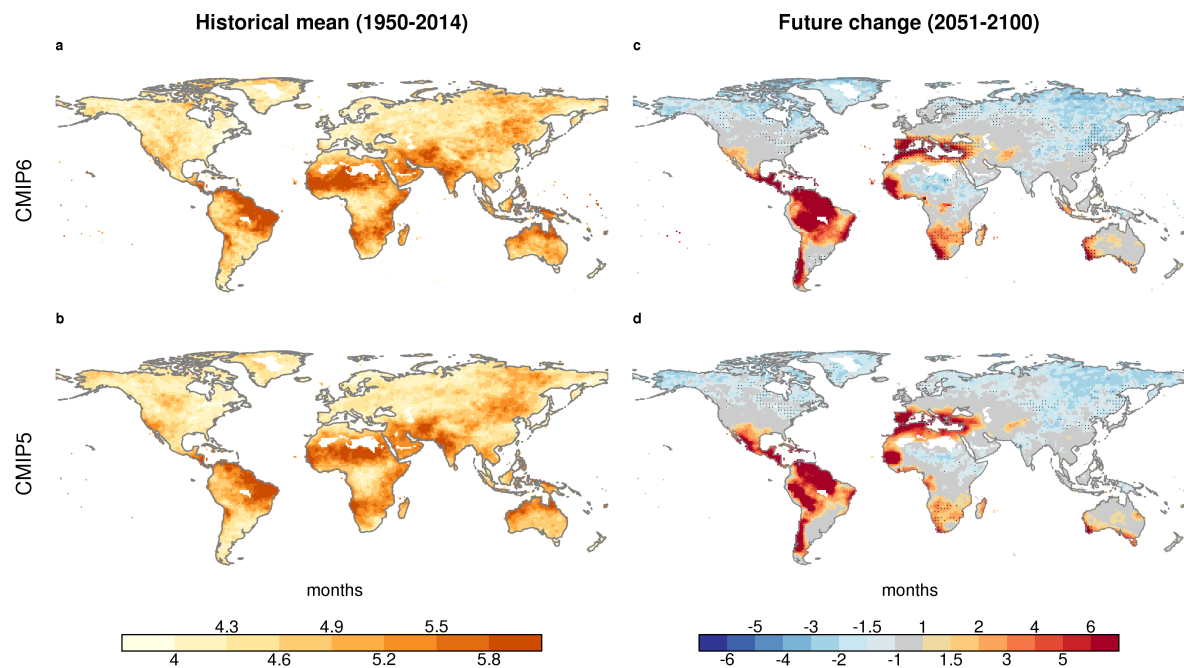# Future projections of drought using 12-month running means

Fig. S10. Projected changes in drought duration using 12-month running means. (a) mean historical drought duration for nine CMIP6 and (b) CMIP5 models during the 1950-2014 baseline period. Stippling indicates where ≥75% of models are within 10% of the observed mean. (c) projected future change in drought duration relative to the historical mean for CMIP6 and (d) CMIP5 using the 8.5 W m^{-2} emissions scenario. Stippling indicates where the magnitude of the multi-model mean future change exceeds the inter-model standard deviation.
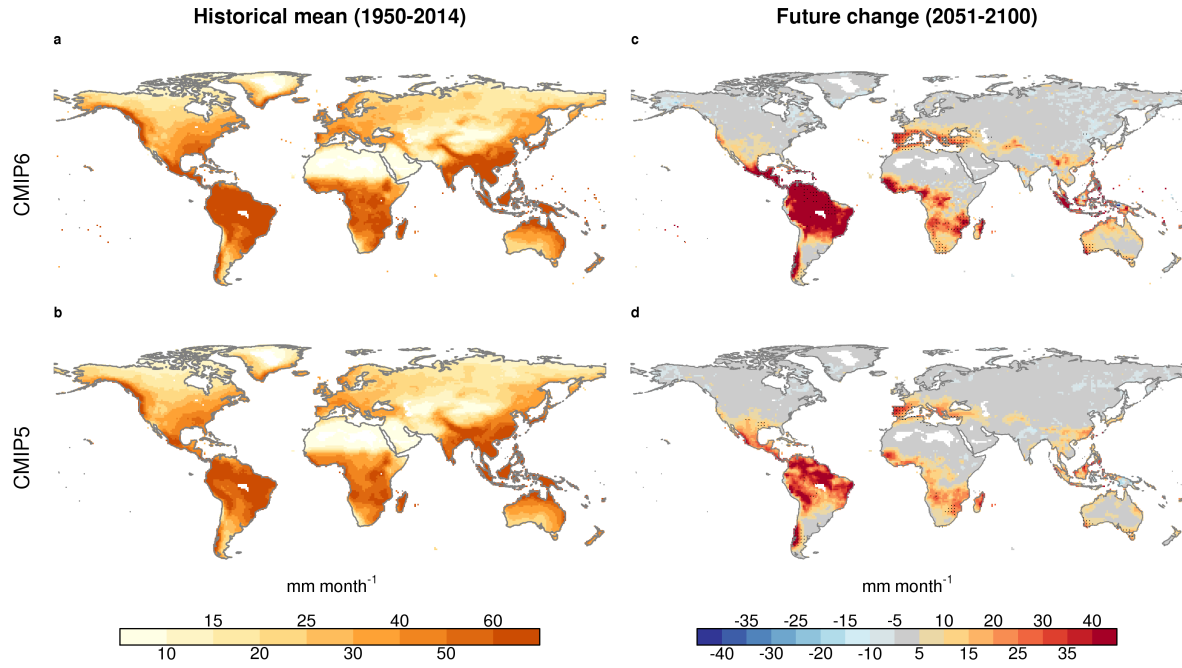
Fig. S11. Projected changes in drought intensity using 12-month running means. (a) mean historical drought intensity for nine CMIP6 and (b) CMIP5 models during the 1950-2014 baseline period. Stippling indicates where ≥75% of models are within 10% of the observed mean. (c) projected future change in drought intensity relative to the historical mean for CMIP6 and (d) CMIP5 using the 8.5 W m^{-2} emissions scenario. Stippling indicates where the magnitude of the multi-model mean future change exceeds the inter-model standard deviation.

Historical mean (1950-2014)   **Future change (2051-2100)**

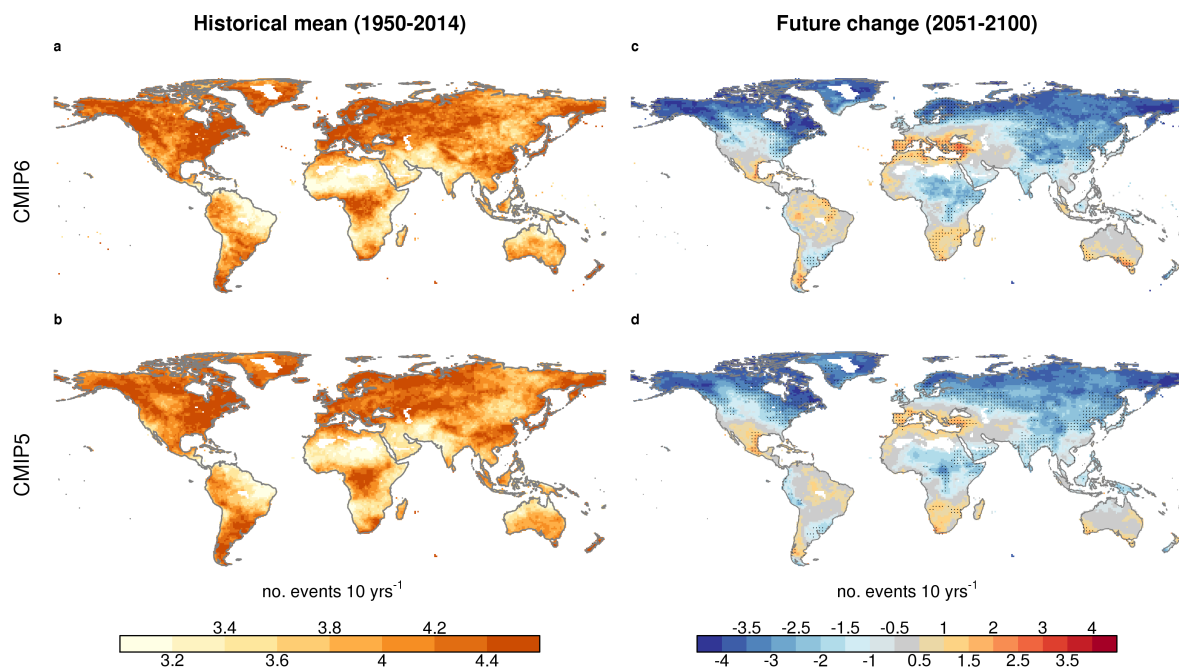no. events 10 yrs⁻¹   no. events 10 yrs⁻¹

Fig. S12. Projected changes in drought frequency using 12-month running means. (a) mean historical drought frequency for nine CMIP6 and (b) CMIP5 models during the 1950-2014 baseline period. Stippling indicates where ≥75% of models are within 10% of the observed mean. (c) projected future change in drought frequency relative to the historical mean for CMIP6 and (d) CMIP5 using the 8.5 W m⁻² emissions scenario. Stippling indicates where the magnitude of the multi-model mean future change exceeds the inter-model standard deviation.