

# Large increases of multi-year droughts in north-western Europe in a warmer climate

## SUPPORTING INFORMATION

Additional figures and tables that support the results of the main text.

Section S1 - Makkink reference evapotranspiration

Section S2 - Model evaluation

Section S3 - Comparison observational (based) data sets

Section S4 - Simulated mean climate change

### S1 | MAKKINK REFERENCE EVAPOTRANSPIRATION

We use the formula of Makkink to compute reference evapotranspiration. There are slight variations on this formula, for clarity we therefore include the computation used here (from KNMI operational use).

$$ET_0 = \frac{0.65 \times \delta}{(\delta + \gamma) \times \rho \times \lambda} \times Q \times (86400 \times N_{days}) \times 1000,$$

with

$$\delta = \left( \frac{7.5 \times 237.3}{(T + 237.3)^2} \times \log(10) \times e_s, \right.$$

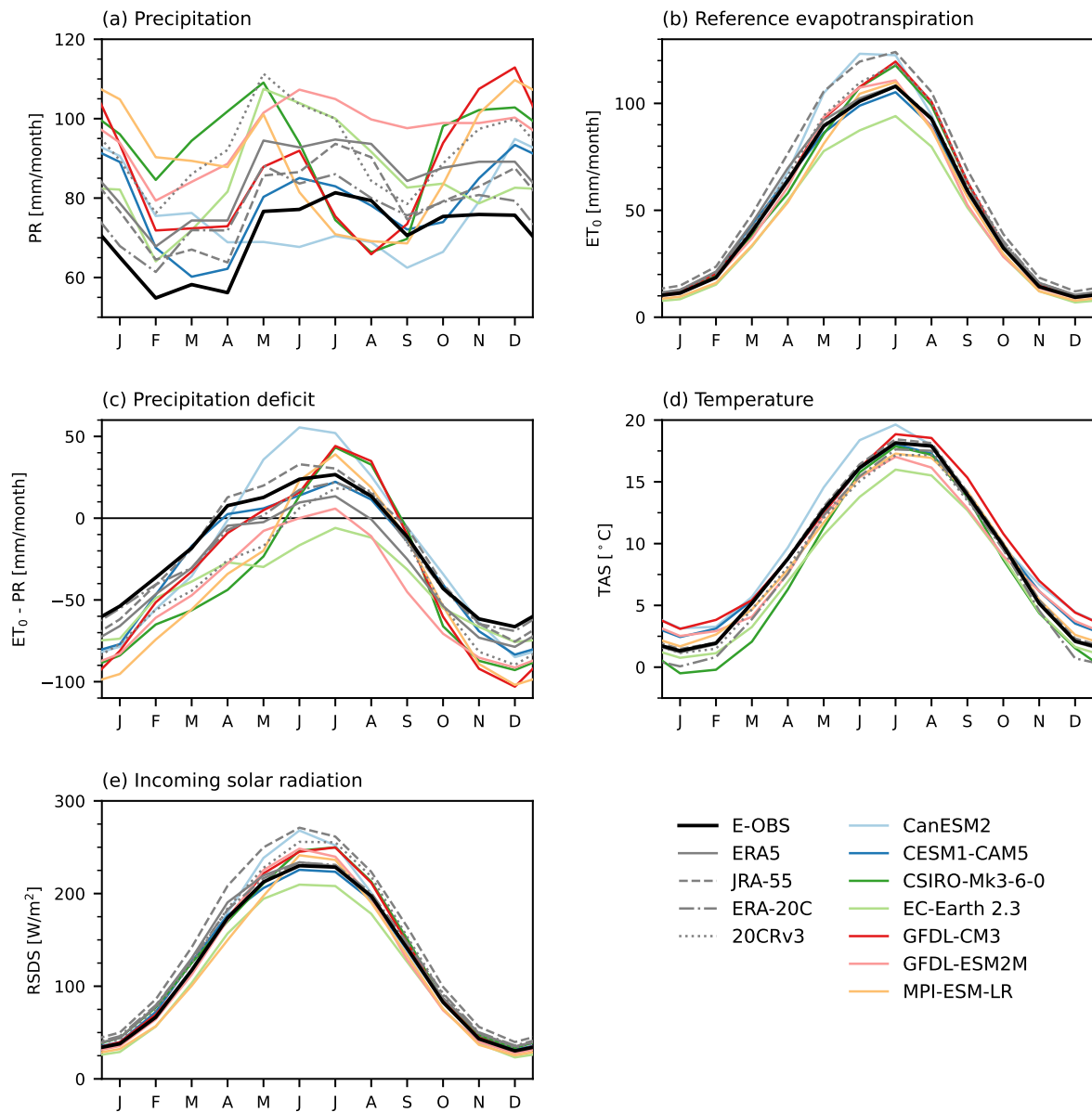
$$e_s = 6.107 * 10 * \left( 7.5 * \frac{T}{237.3 + T} \right),$$

$$\gamma = 0.646 + (0.0006 \times T),$$

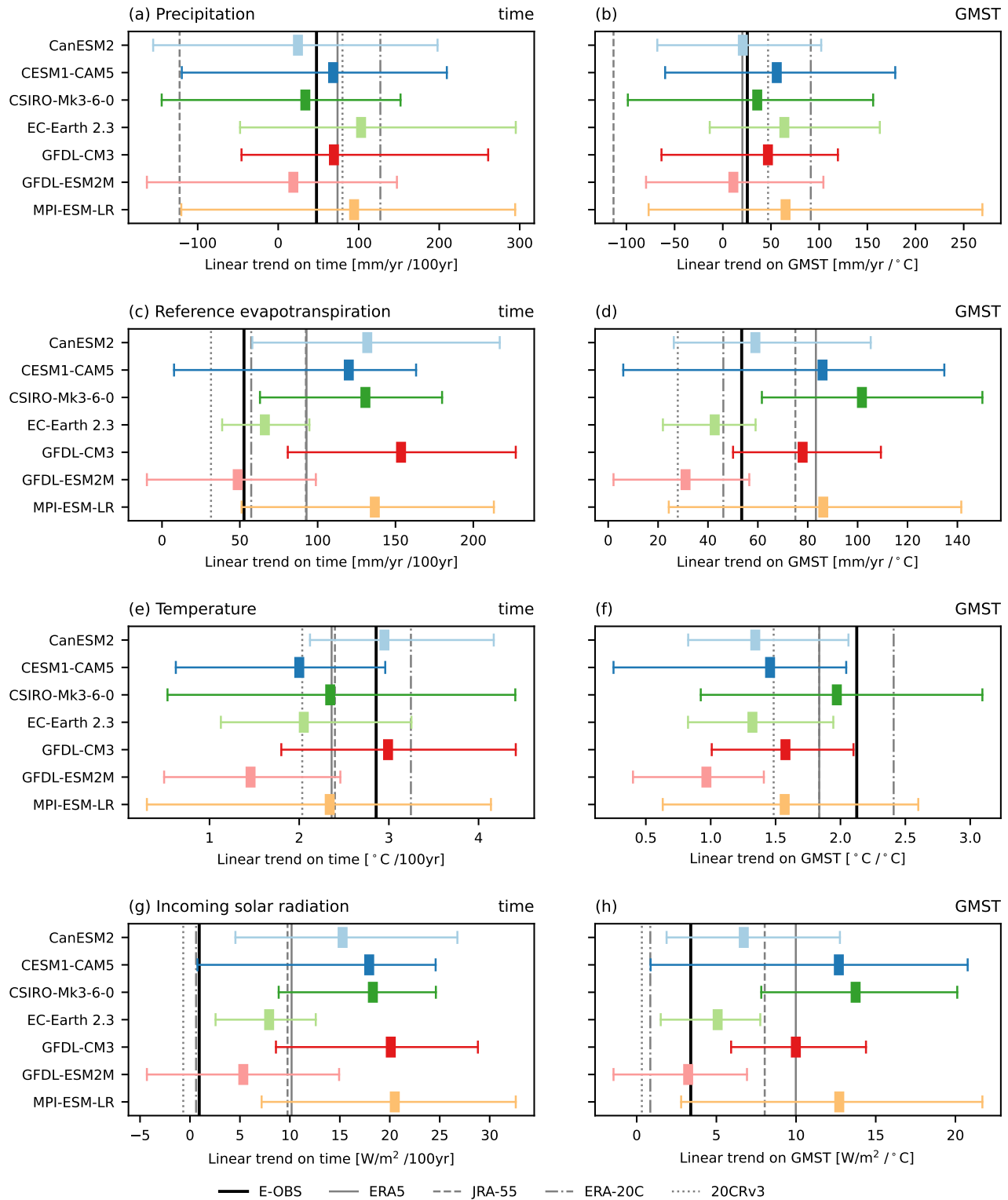
$$\lambda = 1000 * (2501 - (2.375 \times T)).$$

In which  $ET_0$  is the reference evapotranspiration in [mm/month],  $Q$  is incoming solar radiation [ $\text{W/m}^2$ ],  $T$  is temperature in [C].  $e_s$  describes the saturated vapour pressure above water [hPa],  $\gamma$  is the psychrometric constant [hPa/C],  $\lambda$  is the enthalpy of vaporization of water [J/kg], and  $\rho = 1000 \text{ kg/m}^3$  is the density of water,  $N_{days}$  refers to the number of days in a month.

## S2 | MODEL EVALUATION



**FIGURE S1** Mean annual cycle of (a) precipitation, (b) reference evapotranspiration, (c) 2 m temperature, (d) incoming solar radiation, (e) precipitation deficit. Coloured lines show the seven models, black lines the reanalysis products. Evaluation period 1961-2010.



**FIGURE S2** Linear trends in annual mean (a,b) precipitation and (c,d) reference evapotranspiration, (e,f) 2 m temperature, (g,h) incoming solar radiation over the period 1958-2010, with time as a covariate in (a,c,e,g) and a smoothed Global Mean Surface Temperature (GMST) as covariate in (b,d,f,h). Horizontal bars show the range of trends in individual ensemble members of the different climate models, with the ensemble mean value as a thick line in the middle. Vertical lines show the trend in the reanalysis data sets, in which Berkeley GMST is used as covariate (Rohde et al. 2020). GMST smoothing by means of a five year running mean.

**TABLE S1** Reproduction of first part of Table 2 in the main text, but with additional variables.

| Observations   | PR [mm/month] |       |       | ET <sub>0</sub> [mm/month] |       |       | ET <sub>0</sub> - PR [mm/month] |       |       | TAS [°C] |      |       | RSDS [W/m <sup>2</sup> ] |       |       |
|----------------|---------------|-------|-------|----------------------------|-------|-------|---------------------------------|-------|-------|----------|------|-------|--------------------------|-------|-------|
|                | Bias          | RMSE  | Corr. | Bias                       | RMSE  | Corr. | Bias                            | RMSE  | Corr. | Bias     | RMSE | Corr. | Bias                     | RMSE  | Corr. |
| E-OBS          | 0.00          | 0.00  | 1.00  | 0.00                       | 0.00  | 1.00  | 0.00                            | 0.00  | 1.00  | 0.00     | 0.00 | 1.00  | 0.00                     | 0.00  | 1.00  |
| Reanalyses     |               |       |       |                            |       |       |                                 |       |       |          |      |       |                          |       |       |
| ERA5           | 14.57         | 14.68 | 0.98  | 1.91                       | 2.52  | 1.00  | -12.67                          | 12.73 | 1.00  | -0.05    | 0.07 | 1.00  | 6.37                     | 8.07  | 1.00  |
| JRA-55         | 8.85          | 9.24  | 0.96  | 9.67                       | 10.98 | 1.00  | 0.81                            | 5.73  | 1.00  | 0.18     | 0.21 | 1.00  | 24.23                    | 26.25 | 1.00  |
| ERA-20C        | 5.03          | 6.74  | 0.87  | 2.03                       | 2.23  | 1.00  | -3.01                           | 5.70  | 0.99  | -0.54    | 0.66 | 1.00  | 7.96                     | 8.64  | 1.00  |
| 20CRv3         | 21.06         | 23.35 | 0.50  | 4.41                       | 5.51  | 1.00  | -16.64                          | 20.40 | 0.95  | -0.33    | 0.48 | 1.00  | 12.72                    | 14.93 | 1.00  |
| Climate models |               |       |       |                            |       |       |                                 |       |       |          |      |       |                          |       |       |
| CanESM2        | 3.56          | 14.33 | -0.12 | 5.04                       | 9.00  | 0.99  | 1.48                            | 18.61 | 0.97  | 1.14     | 1.43 | 0.99  | 8.27                     | 15.12 | 0.99  |
| CESM1-CAM5     | 6.92          | 10.23 | 0.70  | -0.19                      | 2.09  | 1.00  | -7.11                           | 10.03 | 0.98  | 0.31     | 0.72 | 1.00  | 0.48                     | 4.70  | 1.00  |
| CSIRO-Mk3-6-0  | 20.51         | 26.98 | -0.16 | 1.50                       | 4.54  | 0.99  | -19.02                          | 28.60 | 0.90  | -1.25    | 1.55 | 0.99  | 7.64                     | 10.50 | 1.00  |
| EC-Earth 2.3   | 15.36         | 17.44 | 0.74  | -7.60                      | 8.79  | 1.00  | -22.96                          | 25.79 | 0.97  | -1.46    | 1.62 | 1.00  | -13.50                   | 14.50 | 1.00  |
| GFDL-CM3       | 14.38         | 20.15 | 0.37  | 3.28                       | 4.81  | 1.00  | -11.10                          | 20.28 | 0.98  | 0.95     | 1.27 | 0.99  | 5.97                     | 9.22  | 1.00  |
| GFDL-ESM2M     | 25.72         | 25.94 | 0.94  | -0.75                      | 3.71  | 1.00  | -26.47                          | 26.86 | 0.99  | -0.31    | 1.15 | 0.99  | 0.19                     | 8.72  | 1.00  |
| MPI-ESM-LR     | 17.53         | 25.01 | -0.20 | -3.17                      | 4.87  | 0.99  | -20.69                          | 28.44 | 0.94  | -0.23    | 0.67 | 1.00  | -7.07                    | 11.59 | 0.99  |

**TABLE S2** As Table S1, but here only considering the summer half year (April-September).

| Observations   | PR [mm/month] |       |       | ET <sub>0</sub> [mm/month] |       |       | ET <sub>0</sub> - PR [mm/month] |       |       | TAS [°C] |      |       | RSDS [W/m <sup>2</sup> ] |       |       |
|----------------|---------------|-------|-------|----------------------------|-------|-------|---------------------------------|-------|-------|----------|------|-------|--------------------------|-------|-------|
|                | Bias          | RMSE  | Corr. | Bias                       | RMSE  | Corr. | Bias                            | RMSE  | Corr. | Bias     | RMSE | Corr. | Bias                     | RMSE  | Corr. |
| E-OBS          | 0.00          | 0.00  | 1.00  | -0.00                      | 0.00  | 1.00  | 0.00                            | 0.00  | 1.00  | 0.00     | 0.00 | 1.00  | 0.00                     | 0.00  | 1.00  |
| Reanalyses     |               |       |       |                            |       |       |                                 |       |       |          |      |       |                          |       |       |
| ERA5           | 7.77          | 15.62 | 0.98  | 0.86                       | 2.70  | 0.99  | -6.91                           | 13.81 | 1.00  | -0.02    | 0.05 | 1.00  | 2.52                     | 7.66  | 0.98  |
| JRA-55         | 4.47          | 9.27  | 0.98  | 7.17                       | 14.60 | 1.00  | 2.70                            | 5.92  | 0.98  | 0.11     | 0.23 | 1.00  | 16.32                    | 33.16 | 0.99  |
| ERA-20C        | 2.57          | 7.70  | 0.70  | 0.87                       | 2.01  | 1.00  | -1.70                           | 7.02  | 0.90  | -0.19    | 0.45 | 1.00  | 3.08                     | 6.85  | 1.00  |
| 20CRv3         | 9.85          | 23.67 | 0.16  | 3.55                       | 7.57  | 1.00  | -6.31                           | 19.28 | 0.57  | -0.30    | 0.63 | 1.00  | 9.64                     | 20.13 | 0.99  |
| Climate models |               |       |       |                            |       |       |                                 |       |       |          |      |       |                          |       |       |
| CanESM2        | -2.87         | 10.03 | 0.21  | 4.66                       | 12.69 | 0.97  | 7.53                            | 20.20 | 0.90  | 0.52     | 1.37 | 0.96  | 7.74                     | 21.33 | 0.99  |
| CESM1-CAM5     | 1.61          | 4.44  | 0.93  | -0.95                      | 2.36  | 1.00  | -2.56                           | 5.78  | 0.98  | -0.09    | 0.27 | 1.00  | -1.60                    | 4.39  | 1.00  |
| CSIRO-Mk3-6-0  | 6.12          | 24.61 | -0.40 | 1.44                       | 6.34  | 0.98  | -4.68                           | 28.09 | 0.51  | -0.46    | 1.22 | 0.99  | 4.87                     | 13.44 | 0.97  |
| EC-Earth 2.3   | 10.53         | 22.22 | 0.71  | -5.81                      | 11.79 | 1.00  | -16.34                          | 33.54 | 0.77  | -1.01    | 2.05 | 0.99  | -9.16                    | 18.38 | 1.00  |
| GFDL-CM3       | 2.13          | 11.91 | 0.20  | 2.83                       | 6.71  | 0.99  | 0.70                            | 14.01 | 0.75  | 0.20     | 0.70 | 0.99  | 5.50                     | 12.93 | 0.99  |
| GFDL-ESM2M     | 13.21         | 26.72 | 0.90  | -0.01                      | 4.79  | 0.99  | -13.21                          | 27.11 | 0.97  | -0.54    | 1.14 | 0.99  | 2.20                     | 11.45 | 1.00  |
| MPI-ESM-LR     | 3.10          | 17.47 | -0.28 | -1.74                      | 6.04  | 0.98  | -4.84                           | 22.32 | 0.67  | -0.35    | 0.83 | 0.99  | -2.87                    | 13.47 | 0.97  |

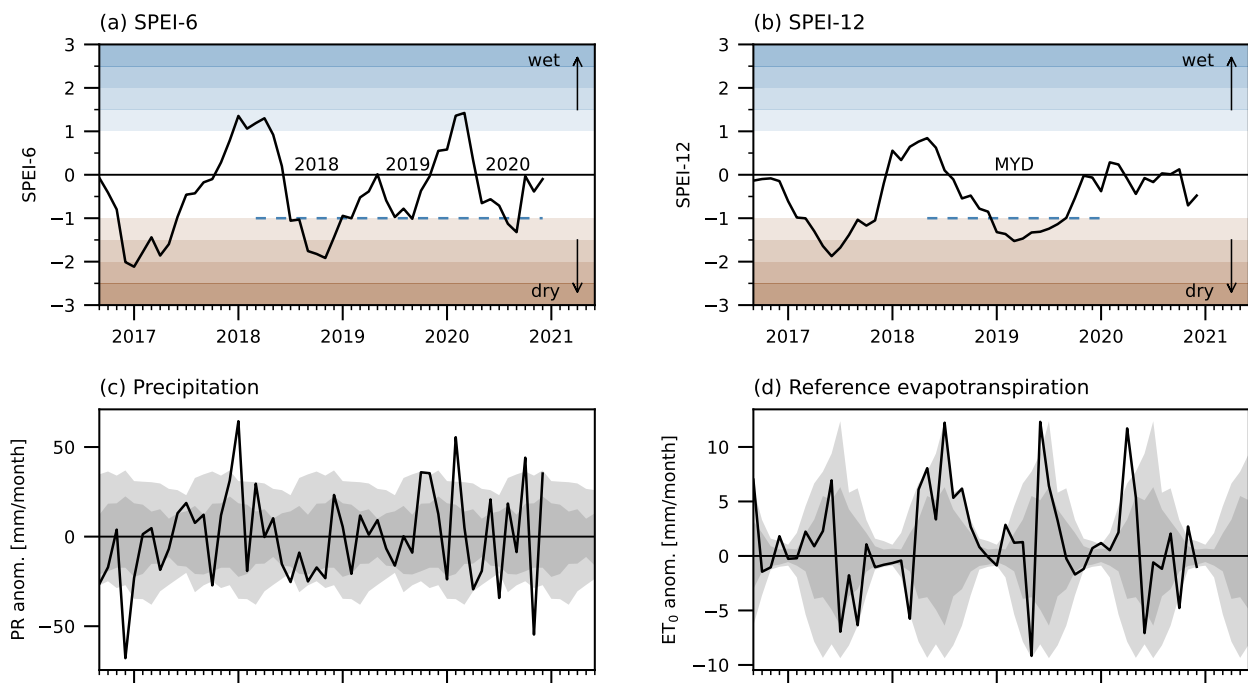
**TABLE S3** Reproduction of second part of Table 2 in the main text, but with additional variables and including a regression with time as covariate.

| Observations   | PR [mm/yr]      |                | ET <sub>0</sub> [mm/yr] |                | TAS [°C]        |                 | RSDS [W/m <sup>2</sup> ] |                   |
|----------------|-----------------|----------------|-------------------------|----------------|-----------------|-----------------|--------------------------|-------------------|
|                | Time [/100yr]   | GMST [/°C]     | Time [/100yr]           | GMST [/°C]     | Time [/100yr]   | GMST [/°C]      | Time [/100yr]            | GMST [/°C]        |
| E-OBS          | 48              | 25             | 53                      | 54             | 2.9             | 2.1             | 0.9                      | 3                 |
| Reanalyses     |                 |                |                         |                |                 |                 |                          |                   |
| ERA5           | 74              | 20             | 93                      | 83             | 2.4             | 1.8             | 10.2                     | 10                |
| JRA-55         | -122            | -113           | 92                      | 75             | 2.4             | 1.8             | 9.8                      | 8                 |
| ERA-20C        | 127             | 91             | 57                      | 46             | 3.2             | 2.4             | 0.6                      | 0                 |
| 20CRv3         | 80              | 47             | 31                      | 28             | 2.0             | 1.5             | -0.7                     | 0                 |
| Climate models |                 |                |                         |                |                 |                 |                          |                   |
| CanESM2        | 25 (-155 - 198) | 21 (-68 - 102) | 132 (58 - 217)          | 59 (26 - 105)  | 3.0 (2.1 - 4.2) | 1.3 (0.8 - 2.1) | 15.3 (4.5 - 26.8)        | 6.7 (1.9 - 12.8)  |
| CESM1-CAM5     | 68 (-120 - 209) | 56 (-60 - 179) | 120 (8 - 163)           | 86 (6 - 135)   | 2.0 (0.6 - 3.0) | 1.5 (0.3 - 2.0) | 17.9 (0.7 - 24.6)        | 12.7 (0.9 - 20.8) |
| CSIRO-Mk3-6-0  | 34 (-145 - 152) | 36 (-99 - 156) | 131 (63 - 180)          | 102 (62 - 150) | 2.3 (0.5 - 4.4) | 2.0 (0.9 - 3.1) | 18.3 (8.9 - 24.6)        | 13.7 (7.8 - 20.1) |
| EC-Earth 2.3   | 103 (-47 - 295) | 64 (-14 - 163) | 66 (39 - 95)            | 43 (22 - 59)   | 2.1 (1.1 - 3.3) | 1.3 (0.8 - 1.9) | 7.9 (2.6 - 12.6)         | 5.1 (1.5 - 7.8)   |
| GFDL-CM3       | 69 (-46 - 261)  | 47 (-64 - 119) | 154 (81 - 227)          | 78 (50 - 109)  | 3.0 (1.8 - 4.4) | 1.6 (1.0 - 2.1) | 20.1 (8.6 - 28.8)        | 10.0 (5.9 - 14.4) |
| GFDL-ESM2M     | 19 (-163 - 147) | 11 (-80 - 104) | 49 (-10 - 99)           | 31 (2 - 57)    | 1.5 (0.5 - 2.5) | 1.0 (0.4 - 1.4) | 5.3 (-4.3 - 14.9)        | 3.2 (-1.5 - 6.9)  |
| MPI-ESM-LR     | 94 (-120 - 294) | 65 (-77 - 269) | 137 (51 - 213)          | 86 (24 - 142)  | 2.3 (0.3 - 4.1) | 1.6 (0.6 - 2.6) | 20.5 (7.2 - 32.6)        | 12.7 (2.8 - 21.7) |

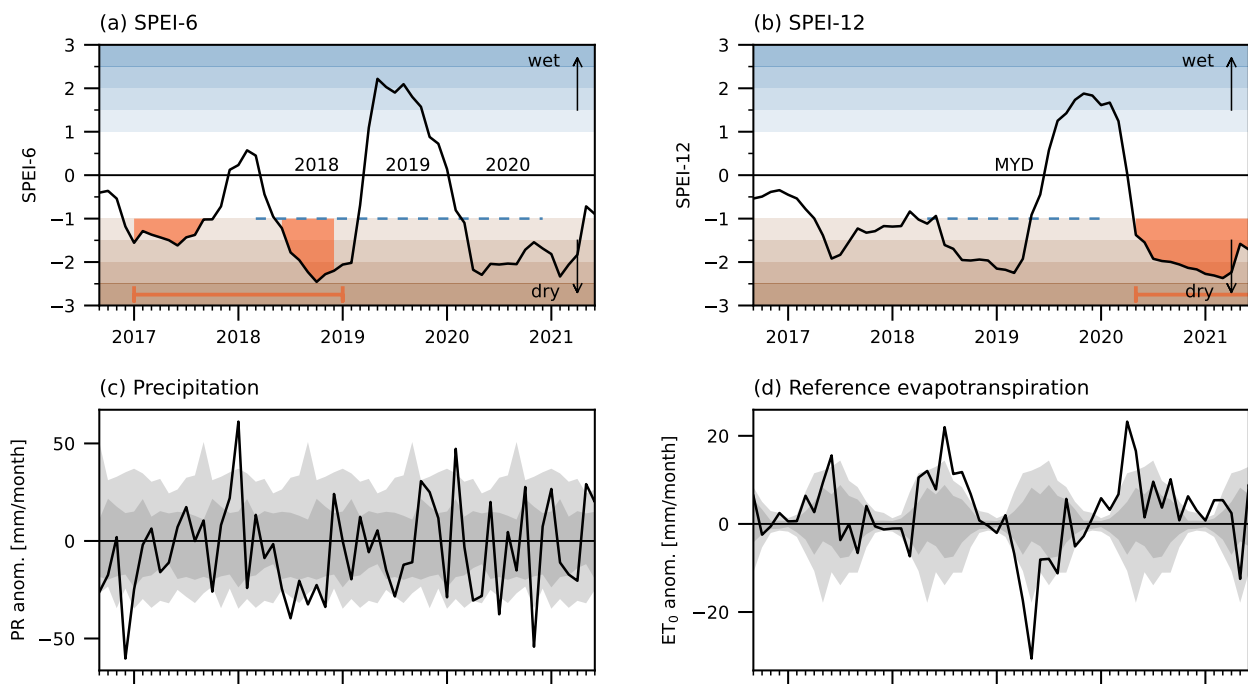
**TABLE S4** Reproduction of the third part of Table 2 in the main text, but with additional variables.

| Observations   | PR   |                 | ET <sub>0</sub> |      | TAS    |         | RSDS   |         |
|----------------|------|-----------------|-----------------|------|--------|---------|--------|---------|
|                | PR   | ET <sub>0</sub> | TAS             | RSDS | SPEI-6 | SPEI-12 | SPEI-6 | SPEI-12 |
| E-OBS          | 0.01 | 0.22            | 0.27            | 0.19 | 0.85   | 0.95    |        |         |
| Reanalyses     |      |                 |                 |      |        |         |        |         |
| ERA5           | 0.03 | 0.30            | 0.27            | 0.23 | 0.86   | 0.94    |        |         |
| JRA-55         | 0.04 | 0.23            | 0.27            | 0.16 | 0.87   | 0.94    |        |         |
| ERA-20C        | 0.05 | 0.19            | 0.29            | 0.12 | 0.87   | 0.94    |        |         |
| 20CRv3         | 0.03 | 0.12            | 0.24            | 0.08 | 0.85   | 0.93    |        |         |
| Climate models |      |                 |                 |      |        |         |        |         |
| CanESM2        | 0.11 | 0.29            | 0.28            | 0.25 | 0.86   | 0.93    |        |         |
| CESM1-CAM5     | 0.05 | 0.29            | 0.28            | 0.22 | 0.85   | 0.92    |        |         |
| CSIRO-Mk3-6-0  | 0.07 | 0.39            | 0.34            | 0.32 | 0.85   | 0.93    |        |         |
| EC-Earth 2.3   | 0.07 | 0.28            | 0.26            | 0.21 | 0.85   | 0.93    |        |         |
| GFDL-CM3       | 0.10 | 0.46            | 0.38            | 0.37 | 0.87   | 0.94    |        |         |
| GFDL-ESM2M     | 0.09 | 0.20            | 0.20            | 0.14 | 0.85   | 0.93    |        |         |
| MPI-ESM-LR     | 0.07 | 0.31            | 0.26            | 0.26 | 0.86   | 0.93    |        |         |

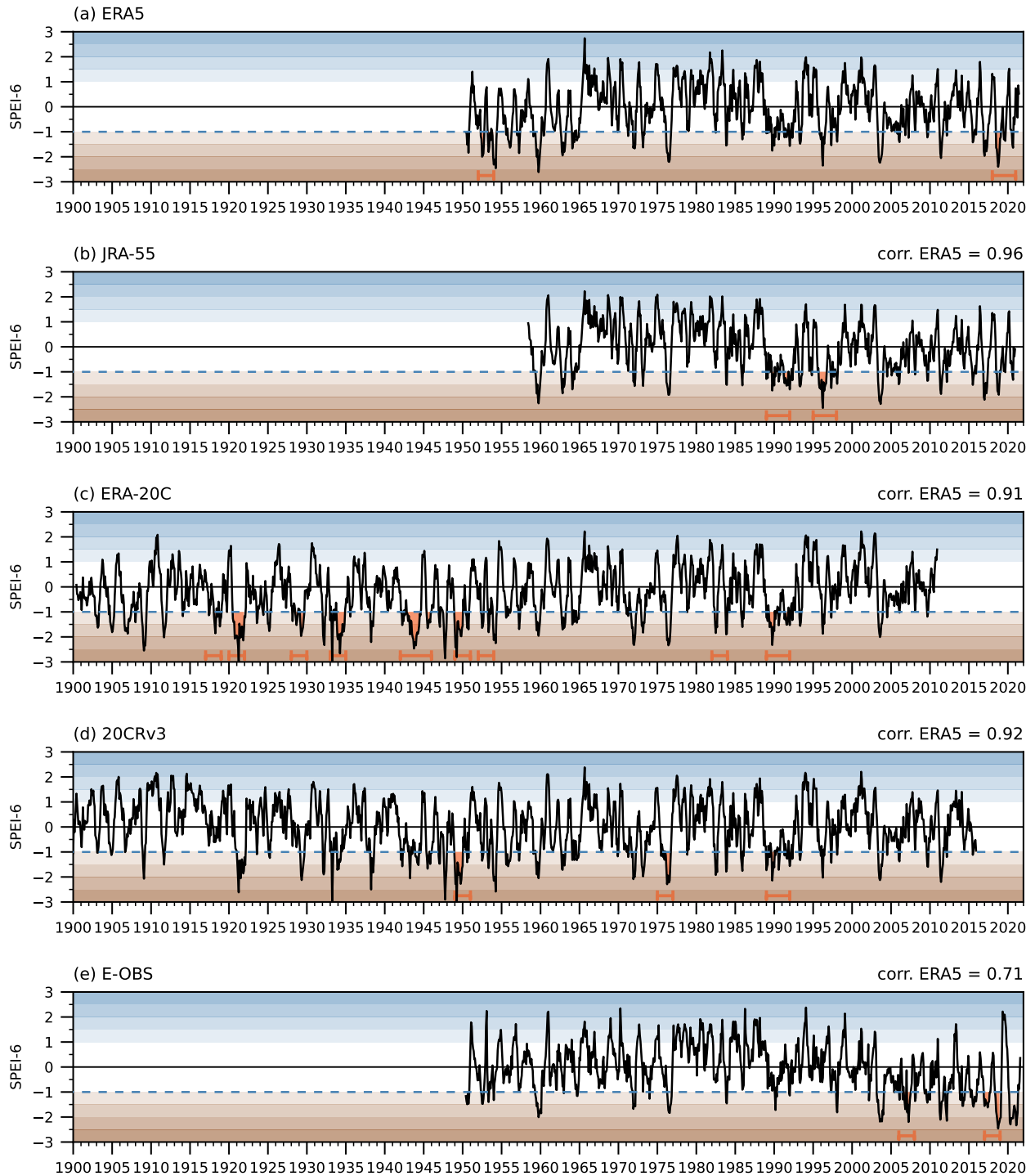
### S3 | COMPARISON OBSERVATIONAL (BASED) DATA SETS



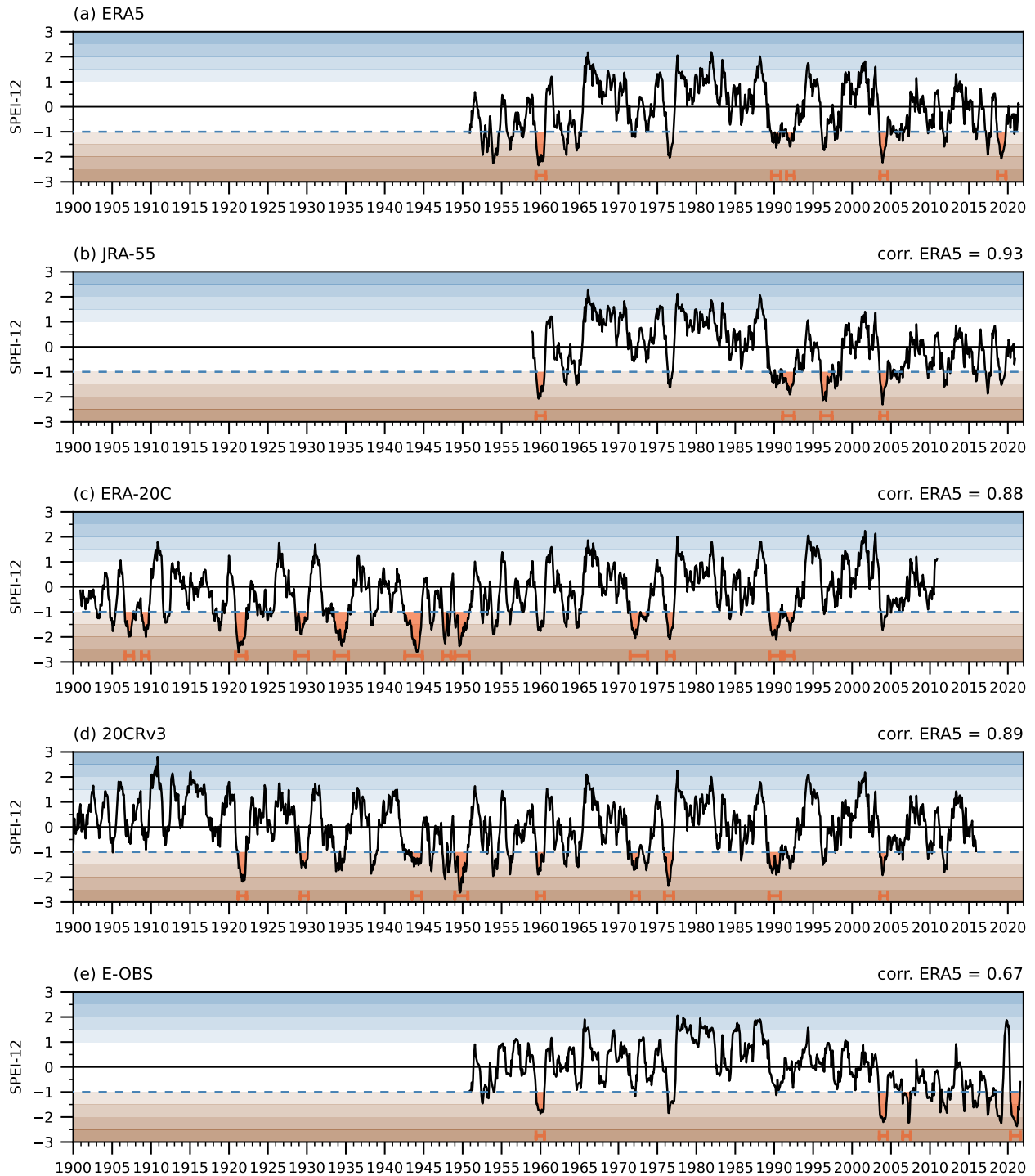
**FIGURE S3** As Fig. 1 of the main text, but here using JRA-55 data.



**FIGURE S4** As Fig. 1 of the main text, but here using E-OBS data. Note consecutive meteorological summer droughts are selected based on calendar years, hence the seemingly weird orange shading.



**FIGURE S5** Time series of SPEI-6 [unitless] as in Fig. 2a of the main text. Comparing four different reanalysis products: (a) ERA5, 1950-2021, (b) JRA-55, 1958-2020, (c) ERA-20C, 1900-2010, (d) 20CRv3, 1836-2015, (e) E-OBS, 1950-2020.



**FIGURE S6** Time series of SPEI-12 [unitless] as in Fig. 2b of the main text. Comparing four different reanalysis products: (a) ERA5, 1950-2021, (b) JRA-55, 1958-2020, (c) ERA-20C, 1900-2010, (d) 20CRv3, 1836-2015, (e) E-OBS, 1950-2020.

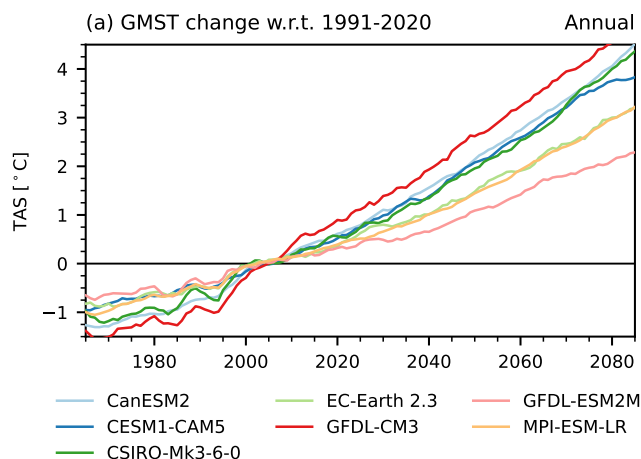
**TABLE S5** Consecutive meteorological drought events in the gridded observations and the different reanalysis products (Fig. S5), shown starting year and length of drought [year]. Dashes (–) note when the reanalysis product doesn't have data for that year.

| Start year | EOBS | ERA5 | JRA-55 | ERA-20C | 20CRv3 |
|------------|------|------|--------|---------|--------|
| 1892       | –    | –    | –      | –       | 2      |
| 1917       | –    | –    | –      | 2       |        |
| 1920       | –    | –    | –      | 2       |        |
| 1928       | –    | –    | –      | 2       |        |
| 1933       | –    | –    | –      | 2       |        |
| 1942       | –    | –    | –      | 4       |        |
| 1949       | –    | –    | –      | 2       | 2      |
| 1952       |      | 2    |        | 2       |        |
| 1975       |      |      |        |         | 2      |
| 1982       |      |      |        | 2       |        |
| 1989       |      |      | 3      | 3       | 3      |
| 1995       |      |      | 3      |         |        |
| 2006       | 2    |      |        |         |        |
| 2017       | 2    |      |        |         |        |
| 2018       |      | 3    | –      | –       | –      |

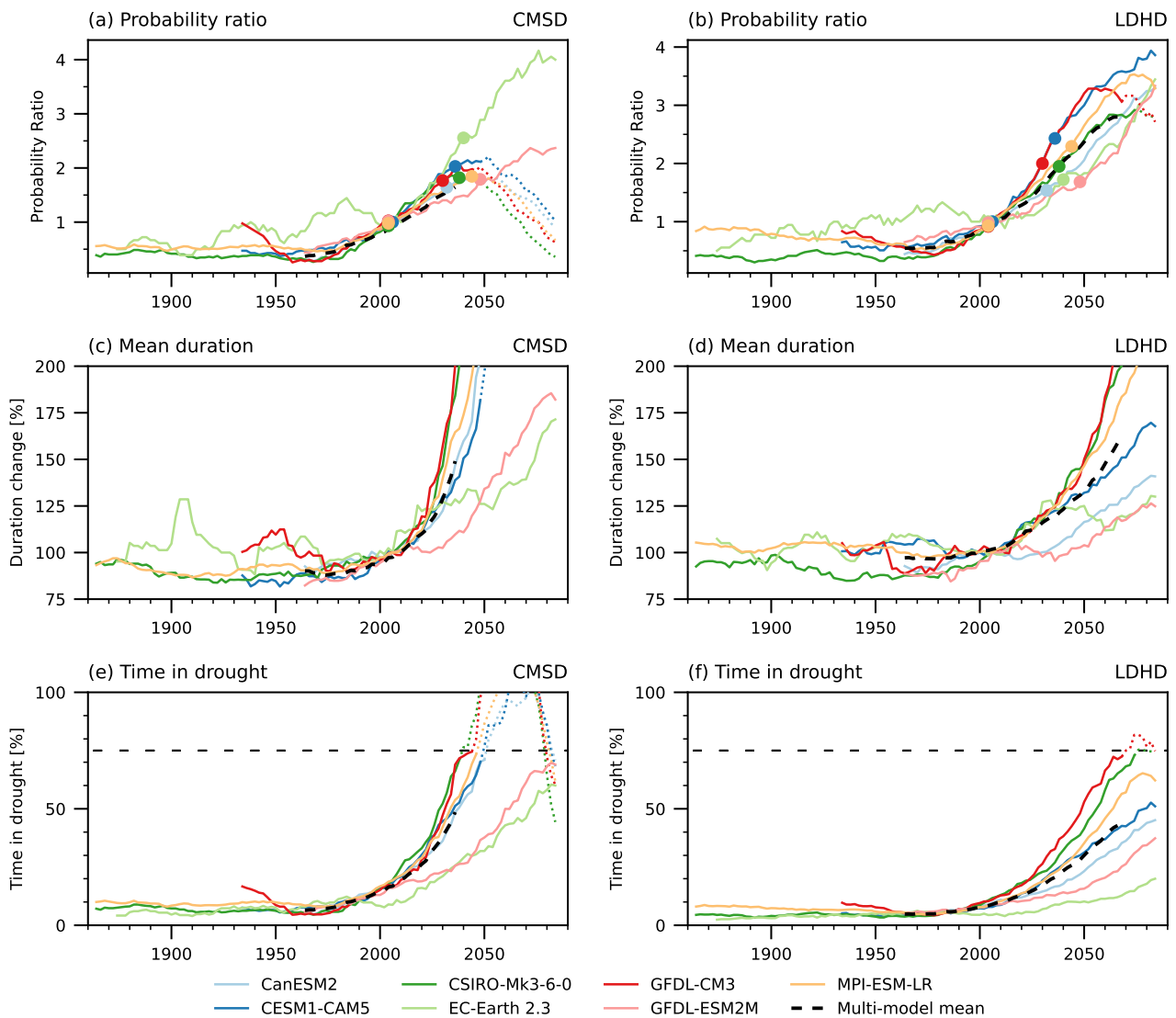
**TABLE S6** Long-duration hydrological drought events in the gridded observations and the different reanalysis products (Fig. S6), shown are starting date [YYYY MM] and length of drought [months]. Events marked with \* in the 20CRv3 column, match other events in the other columns but are mis-matched in starting year. Dashes (–) note when the reanalysis product doesn't have data for that year.

| Start year | EOBS  |        | ERA5  |        | JRA-55 |        | ERA-20C |        | 20CRv3 |        |
|------------|-------|--------|-------|--------|--------|--------|---------|--------|--------|--------|
|            | Month | Length | Month | Length | Month  | Length | Month   | Length | Month  | Length |
| 1857       | –     | –      | –     | –      | –      | –      | –       | –      | 12     | 12     |
| 1906       | –     | –      | –     | –      | –      | –      | 09      | 13     |        |        |
| 1908       | –     | –      | –     | –      | –      | –      | 10      | 12     |        |        |
| 1920       | –     | –      | –     | –      | –      | –      | 11      | 17     |        |        |
| 1921       | –     | –      | –     | –      | –      | –      |         |        | 03     | 13*    |
| 1928       | –     | –      | –     | –      | –      | –      | 07      | 20     |        |        |
| 1929       | –     | –      | –     | –      | –      | –      |         |        | 03     | 12*    |
| 1933       | –     | –      | –     | –      | –      | –      | 07      | 22     |        |        |
| 1938       | –     | –      | –     | –      | –      | –      |         |        |        |        |
| 1942       | –     | –      | –     | –      | –      | –      | 08      | 27     |        |        |
| 1943       | –     | –      | –     | –      | –      | –      |         |        | 07     | 15*    |
| 1947       | –     | –      | –     | –      | –      | –      | 06      | 13     |        |        |
| 1949       | –     | –      | –     | –      | –      | –      | 01      | 22     | 01     | 20     |
| 1953       |       |        |       |        | –      | –      |         |        |        |        |
| 1959       | 06    | 13     | 06    | 15     | 06     | 14     |         |        | 07     | 12     |
| 1971       |       |        |       |        |        |        | 07      | 27     | 09     | 12     |
| 1975       |       |        |       |        |        |        |         |        | 12     | 14     |
| 1976       |       |        |       |        |        |        | 03      | 12     |        |        |
| 1989       |       |        | 09    | 14     |        |        | 06      | 17     | 05     | 18     |
| 1991       |       |        | 08    | 12     | 02     | 18     | 06      | 14     |        |        |
| 1996       |       |        |       |        | 01     | 17     |         |        |        |        |
| 2003       | 07    | 13     | 08    | 12     | 08     | 12     |         |        | 08     | 12     |
| 2006       | 07    | 12     |       |        |        |        |         |        |        |        |
| 2018       |       |        | 09    | 13     |        |        | –       | –      | –      | –      |
| 2010       | 05    | 15     |       |        |        |        |         |        |        |        |

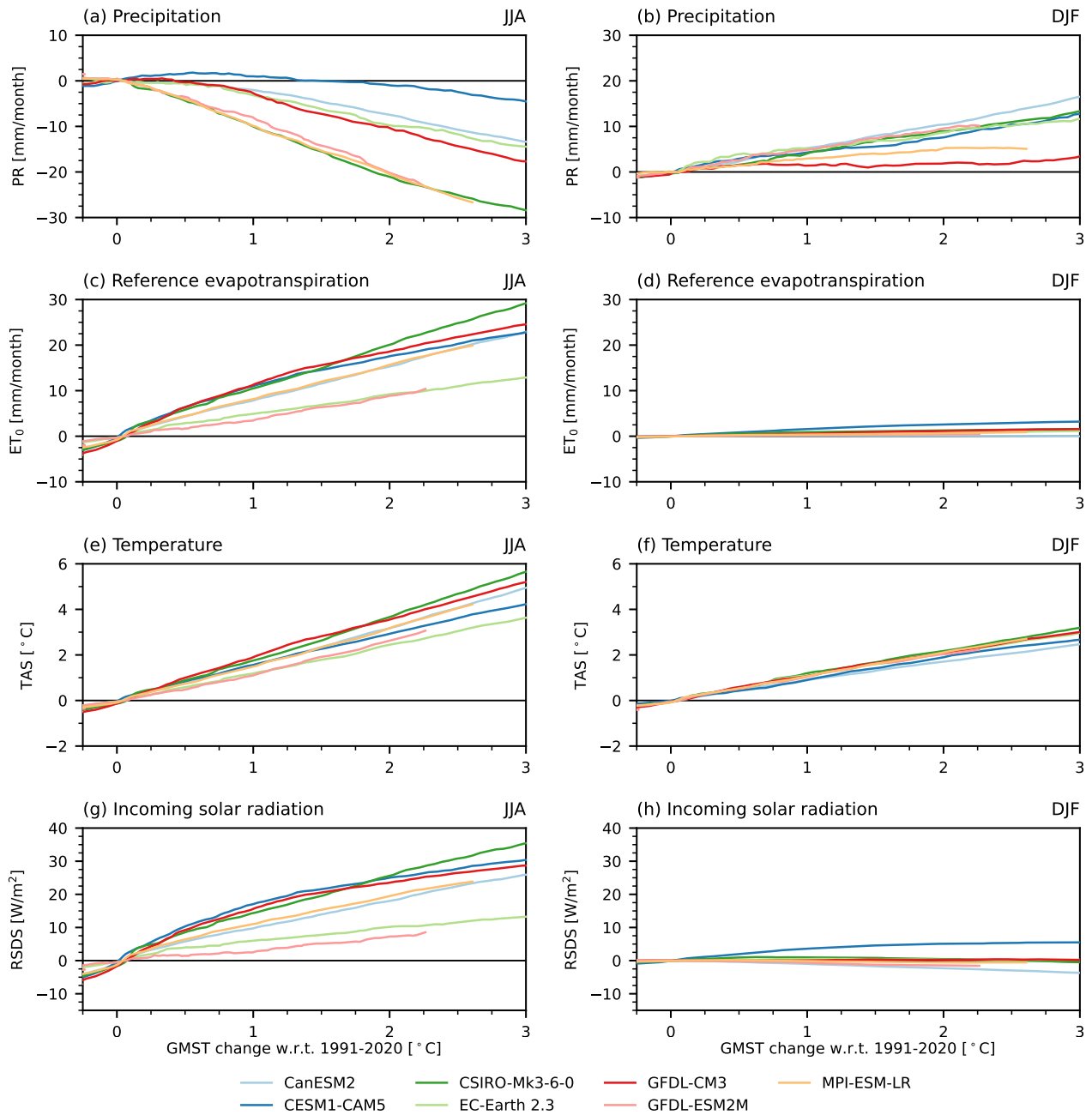
# S4 | SIMULATED MEAN CLIMATE CHANGE



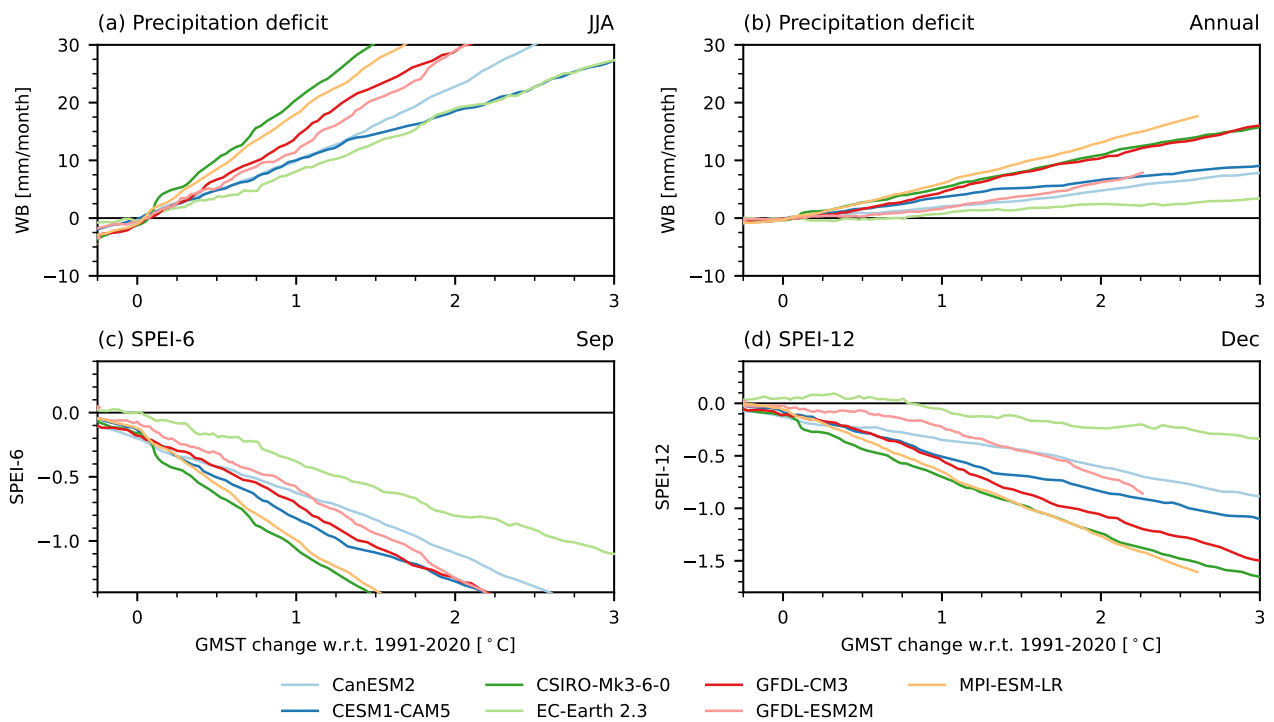
**FIGURE S7** Time series of annual mean global mean surface temperature (GMST) change relative to the period 1991-2020, a 5-year running mean has been applied as smoothing.



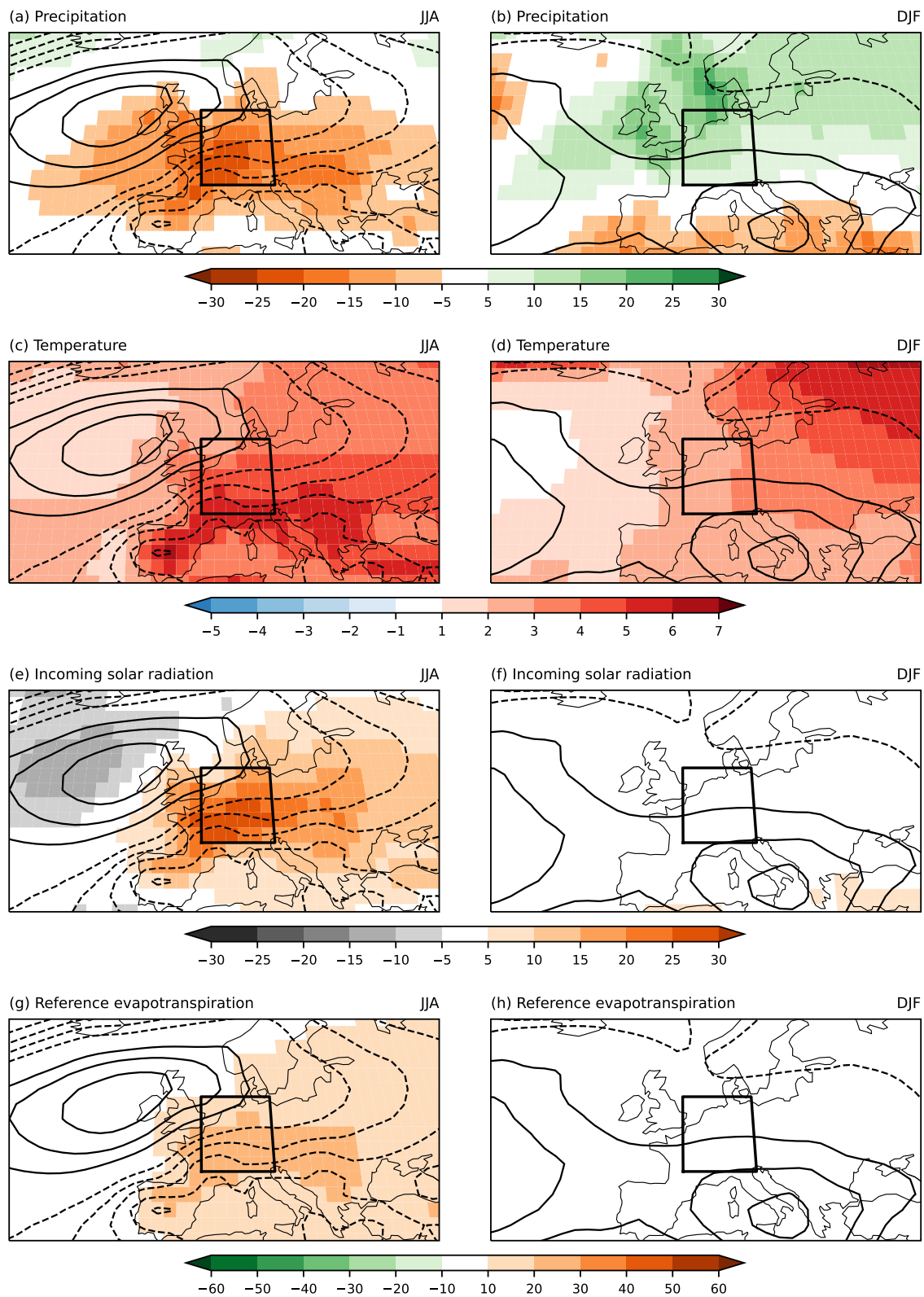
**FIGURE S8** As Fig. 4 in the main text, but here time series plotted against time. The multi-model mean line is only shown for the years in which all models have valid data (simulation exists and time in drought < 75 %).



**FIGURE S9** As Fig. 5 of the main text, but here showing more variables. Time series of ensemble mean (a,b) precipitation [mm/month], (c,d) reference evapotranspiration [mm/month], (e,f) temperature [ $^{\circ}\text{C}$ ], (g,h) incoming solar radiation [ $\text{W}/\text{m}^2$ ]; (a,c,e,g) June-July-August mean, (b,d,f,h) December-January-February mean.



**FIGURE S10** As Fig. 5 of the main text, but here showing more variables. Time series of ensemble mean (a) June-July-August precipitation deficit,  $ET_0 - PR$ , [mm/month], (b) December-January-February precipitation deficit [mm/month] (c) September SPEI-6 [unitless], (d) December SPEI-12 [unitless].



**FIGURE S11** Maps of ensemble mean, multi-model mean, seasonal mean change in (a,b) precipitation [mm/month], (c,d) temperature [ $^{\circ}\text{C}$ ], (e,f) incoming solar radiation [ $\text{W}/\text{m}^2$ ], (g,h) reference evapotranspiration [mm/month], for the periods 2071-2100 minus 1991-2020. Contours show mean change in sea level pressure, contour interval 0.25 hPa, zero contour omitted. (a,c,e,g) June-July-August, (b,d,f,h) December-January-February.