Supplemental Methods

S1. Models

We analyze global climate model output archived in Phase 5 of the Coupled

Model Intercomparison Project (CMIP5) (Taylor et al. 2012). The CMIP5 ensemble is

similar to the CMIP3 ensemble analyzed by Giorgi (2006), with a number of notable

advances. First, whereas the CMIP3 ensemble was forced by atmospheric constituent

concentrations from the SRES scenarios (IPCC 2000), the CMIP5 ensemble is forced by

Representative Concentration Pathways (RCPs) (Moss et al. 2010). Second, whereas the

CMIP3 ensemble was limited to atmosphere-ocean general circulation models

(AOGCMs), the CMIP5 ensemble includes AOGCMs and "Earth system models"

(ESMs) in which AOGCMs have been expanded to include interactive vegetation,

biogeochemical cycles, and/or atmospheric chemistry. Third, a number of the models in

the CMIP5 ensemble have been run at higher spatial resolution than the models in the

CMIP3 ensemble.

Here we quantify climate change hotspots in 3 periods of the 21st century of

RCP8.5 and RCP4.5 (2016-2035, 2046-2065, and 2080-2099). The suite of available

RCP8.5 and RCP4.5 simulations includes realizations from 20 models, including 86

realizations of the baseline period (1986-2005), 51 realizations of the 21st century in the

RCP8.5 pathway, and 51 realizations of the 21st century in the RCP4.5 pathway (Table

S1).

S2. Hotspot Quantification

We extend the statistical approach of Diffenbaugh et al. (2008) and Williams et al. (2007) to quantify global climate change hotspots in the CMIP5 ensemble. Diffenbaugh et al. (2008) calculated the hotspot pattern in the United States using both the Standard Euclidean Distance (SED) and the Squared Chord Distance (SCD), and found the pattern to be robust to quantification method.

Here we focus on the SED, which quantifies the distance between two points in multi-dimensional space (Williams et al. 2007). We use the SED to calculate the total change in multi-dimensional climate space at each grid point between the present and future periods:

$$\text{SED}_{total} = \left(\sum_v \text{SED}_v\right)^{1/2} \quad\quad\quad\quad (\text{Eq.1})$$

for

$$\text{SED}_v = \left(\text{abs}(\Delta_v) \,/\, \max[\text{abs}(\Delta_v)]_{ij}\right)^2 \quad\quad\quad\quad (\text{Eq.2})$$

where $\text{abs}(\Delta_v)$ is the absolute value of change in climate indicator v at each grid point between the present and future periods, and $\max[\text{abs}(\Delta_v)]_{ij}$ is the maximum land-grid-point absolute value change in climate indicator v over all land grid points ij in the 2080-2099 period of RCP8.5.

S3. Climate Indicators

We include 7 climate indicators in our quantification: mean surface air temperature (T), mean precipitation (P), interannual standard deviation of surface air temperature (Tvar), interannual coefficient of variation of mean precipitation (Pvar), occurrence of years above the baseline maximum surface air temperature (Hot), occurrence of years below the baseline minimum precipitation (Wet), and occurrence of

years above the baseline maximum precipitation (Dry). We treat each climate indicator separately in each of four seasons (DJF, MAM, JJA, SON), yielding 28 total climate dimensions for the SED calculation.

We calculate these 28 Δ_v changes between the baseline (1986-2005) and future periods (2016-2035, 2046-2065, and 2080-2099) at each grid point using the long-term ensemble mean of seasonal temperature (T_{mean-e}), seasonal precipitation (P_{mean-e}), interannual standard deviation of seasonal temperature (T_{SD-e}), interannual standard deviation of seasonal precipitation (P_{SD-e}), ensemble mean extreme hot years (T_{hot-e}), ensemble mean extreme wet years (P_{wet-e}), and ensemble mean extreme dry years (P_{dry-e}) for the DJF, MAM, JJA, and SON seasons at each 1-degree grid point for the baseline period (1986-2005) and each of the three future periods (2016-2035, 2046-2065, and 2080-2099):

Mean temperature: $\Delta_T = (T_{mean-e})_{future} - (T_{mean-e})_{baseline}$ (Eq.4)

Mean precipitation: $\Delta_P = ((P_{mean-e})_{future} - (P_{mean-e})_{baseline}) / (P_{mean-e})_{baseline}$ (Eq.5)

Temperature variability: $\Delta_{Tvar} = ((T_{SD-e})_{future} - (T_{SD-e})_{baseline}) / (T_{SD-e})_{baseline}$ (Eq.6)

Precipitation variability: $\Delta_{Pvar} = (((P_{SD-e})_{future} / (P_{mean-e})_{future}) - ((P_{SD-e})_{baseline} / (P_{mean-e})_{baseline})) / ((P_{SD-e})_{baseline} / (P_{mean-e})_{baseline})$ (Eq.7)

Extreme hot occurrence: $\Delta_{Hot} = (T_{hot-e})_{future}$ (Eq.8)

Extreme wet occurrence: $\Delta_{Wet} = (P_{wet-e})_{future}$ (Eq.9)

Extreme dry occurrence: $\Delta_{Dry} = (P_{dry-e})_{future}$ (Eq.10)

S4. Normalization of Climate Indicators

Because our goal is to identify climate change hotspots over the inhabited land areas, we mask out all grid points south of 60˚S and all ocean grid points north of 60˚S from each of the 28 climate indicators. We create a land mask from the soil moisture field of one model (CSIRO-Mk3-6-0) gridded to the common 1-degree grid (see description of regridding in section S5 below). We note that while this land mask is representative of the common 1-degree grid, it does not represent the exact land mask of each model gridded to the 1-degree grid.

Further, in order to treat the change in each of the 28 climate indicators equally in the SED calculation, we normalize the change in each climate indicator v to the maximum land-grid-point change in that climate indicator that is found in the 2080-2099 period of RCP8.5.

To execute this normalization, we first calculate the Δ_v for each climate indicator in each of the three future periods, as described above in section S3.

We then calculate the absolute value of the Δ_v for each climate indicator v in each of the three future periods:

$$(\Delta_v)_{abs} = \text{abs}(\Delta_v) \tag{Eq.11}$$

We then calculate the maximum land-grid-point change $\max[\text{abs}(\Delta_v)]_{ij}$ found in the 2080-2099 period of RCP8.5 for each climate indicator v over all land grid points ij north of 60˚S:

$$(\Delta_v)_{max} = (\max[\text{abs}(\Delta_v)]_{ij})_{2080\text{-}2099} \tag{Eq.12}$$

We then calculate the SED value for each climate indicator at each grid point as the square of the ratio between the absolute value of change in each climate indicator v and the maximum land-grid-point absolute value change in that climate indicator in the 2080-2099 period of RCP8.5:

$$SED_v = ((\Delta_v)_{abs} / (\Delta_v)_{max})^2 \qquad\qquad (Eq.13)$$

We then calculate the total SED as the square root of the sum of the 28 SED_v values:

$$SED_{total} = (sum(SED_v))^{1/2} \qquad\qquad (Eq.14)$$

S5. Calculation of the Ensemble Mean Climate Indicators

As described above, we calculate the aggregate climate change from the ensemble mean of seasonal temperature (T_{mean-e}), interannual standard deviation of seasonal temperature (T_{SD-e}), seasonal precipitation (P_{mean-e}), and interannual standard deviation of seasonal precipitation (P_{SD-e}). We take the following steps to calculate these ensemble means from the individual realizations of the 20 models (Table S1):

1. First, following Giorgi (2006), Diffenbaugh et al. (2007), and Diffenbaugh et al. (2008), we interpolate the output from each realization r of each model m to a common 1-degree geographical grid. For models with horizontal resolution that is more coarse than 1 degree, we interpolate to the common 1-degree grid using bilinear interpolation. For models with horizontal resolution that is more fine than 1 degree, we interpolate to the common 1-degree grid using local area averaging (in order to account for fractional contributions from the high-resolution grid to the low-resolution grid).

2. Second, for each realization r of each model m, we calculate the yearly seasonal temperature (T_{y-r}) and precipitation (P_{y-r}) at each 1-degree grid point for the DJF, MAM, JJA, and SON seasons of each year y of the baseline period (1986-2005) and each year y of the three future periods (2016-2035, 2046-2065, and 2080-2099). (In order to maintain coherence of DJF seasons, we begin each year with the December of the preceding year.)

3. Third, for each realization r of each model m, we calculate the mean and standard deviation of the T_{y-r} and P_{y-r} values across the y years of that realization, yielding the long-term realization mean temperature (T_{mean-r}), realization mean precipitation (P_{mean-r}), realization interannual standard deviation of temperature (T_{SD-r}), and realization interannual standard deviation of precipitation (P_{SD-r}) for the DJF, MAM, JJA, and SON seasons at each 1-degree grid point in the baseline period (1986-2005) and each of the three future periods (2016-2035, 2046-2065, and 2080-2099):

$$T_{mean-r} = mean(T_{y-r}) \qquad\qquad\qquad\qquad (Eq.15)$$

$$P_{mean-r} = mean(P_{y-r}) \qquad\qquad\qquad\qquad (Eq.16)$$

$$T_{SD-r} = stddev(T_{y-r}) \qquad\qquad\qquad\qquad (Eq.17)$$

$$P_{SD-r} = stddev(P_{y-r}) \qquad\qquad\qquad\qquad (Eq.18)$$

Prior to calculating the interannual standard deviation of DJF, MAM, JJA, and SON seasonal temperature and precipitation, we remove the least squares linear trend of the 20-year seasonal timeseries (T_{y-r} and P_{y-r}) at each 1-degree grid point.

4. Fourth, for each model m, we calculate the mean of the T_{mean-r}, P_{mean-r}, T_{SD-r} and P_{SD-r} values across all of the r realizations of that model, yielding the long-term model

mean temperature (T_{mean-m}), model mean precipitation (P_{mean-m}), model interannual standard deviation of temperature (T_{SD-m}), and model interannual standard deviation of precipitation (P_{SD-m}) for the DJF, MAM, JJA, and SON seasons at each 1-degree grid point for the baseline period (1986-2005) and each of the three future periods (2016-2035, 2046-2065, and 2080-2099):

$$T_{mean-m} = mean(T_{mean-r}) \qquad (Eq.19)$$

$$P_{mean-m} = mean(P_{mean-r}) \qquad (Eq.20)$$

$$T_{SD-m} = mean(T_{mean-r}) \qquad (Eq.21)$$

$$P_{SD-m} = mean(P_{mean-r}) \qquad (Eq.22)$$

5. Fifth, we calculate the mean of the T_{mean-m}, P_{mean-m}, T_{SD-m} and P_{SD-m} values across all of the *m* models in the CMIP5 ensemble, yielding the long-term ensemble mean temperature (T_{mean-e}), ensemble mean precipitation (P_{mean-e}), ensemble interannual standard deviation of temperature (T_{SD-e}), and ensemble interannual standard deviation of precipitation (P_{SD-e}) for the DJF, MAM, JJA, and SON seasons at each 1-degree grid point for the baseline period (1986-2005) and each of the three future periods (2016-2035, 2046-2065, and 2080-2099):

$$T_{mean-e} = mean(T_{mean-m}) \qquad (Eq.23)$$

$$P_{mean-e} = mean(P_{mean-m}) \qquad (Eq.24)$$

$$T_{SD-e} = mean(T_{mean-m}) \qquad (Eq.25)$$

$$P_{SD-e} = mean(P_{mean-m}) \qquad (Eq.26)$$

6. Sixth, for each realization r of each model m, we calculate the baseline maximum seasonal temperature (T_{max-r}), maximum seasonal precipitation (P_{max-r}), and minimum seasonal precipitation (P_{min-r}) at each 1-degree grid point for the DJF, MAM, JJA, and SON seasons from the baseline (1986-2005) T_{y-r} and P_{y-r} seasonal timeseries described in (2):

$$T_{max-r} = max(T_{y-r}) \qquad\qquad (Eq.27)$$

$$P_{max-r} = max(P_{y-r}) \qquad\qquad (Eq.28)$$

$$P_{min-r} = min(P_{y-r}) \qquad\qquad (Eq.29)$$

7. Seventh, for each model m, we calculate the mean of the T_{max-r}, P_{max-r}, and P_{min-r} values across all of the r realizations of that model, yielding the long-term model mean maximum temperature (T_{max-m}), model mean maximum precipitation (P_{max-m}), and model mean minimum precipitation (P_{min-m}) for the DJF, MAM, JJA, and SON seasons at each 1-degree grid point for the baseline period (1986-2005):

$$T_{max-m} = mean(T_{max-r}) \qquad\qquad (Eq.30)$$

$$P_{max-m} = mean(P_{max-r}) \qquad\qquad (Eq.31)$$

$$P_{min-m} = mean(P_{min-r}) \qquad\qquad (Eq.32)$$

8. Eighth, for each realization r of each model m, we calculate: (a) the number of years in which the DJF, MAM, JJA, and SON seasonal temperature T_{y-r} is greater than the respective model mean baseline T_{max-r} value at each 1-degree grid point in each of the three future periods (2016-2035, 2046-2065, and 2080-2099), yielding the long-term realization mean extreme hot seasons (T_{hot-r}); (b) the number of years in which the DJF,

MAM, JJA, and SON seasonal precipitation P_{y-r} is greater than the respective model mean baseline P_{max-m} value at each 1-degree grid point in each of the three future periods (2016-2035, 2046-2065, and 2080-2099), yielding the long-term realization mean extreme wet years (P_{wet-r}); and (c) the number of years in which the DJF, MAM, JJA, and SON seasonal precipitation Py-r is less than the respective model mean baseline P_{min-m} value at each 1-degree grid point in each of the three future periods (2016-2035, 2046-2065, and 2080-2099), yielding the long-term realization mean extreme dry years (P_{dry-r}):

$$T_{hot-r} = sum(T_{y-r} > T_{max-m}) \tag{Eq.33}$$

$$P_{wet-r} = sum(P_{y-r} > P_{max-m}) \tag{Eq.34}$$

$$P_{dry-r} = sum(P_{y-r} < P_{min-m}) \tag{Eq.35}$$

9. Ninth, for each model *m*, we calculate the mean of the T_{hot-r}, P_{wet-r}, and P_{dry-r} values across all of the *r* realizations of that model, yielding the long-term model mean extreme hot years (T_{hot-m}), model mean extreme wet years (P_{wet-m}), and model mean extreme dry years (P_{dry-m}) for the DJF, MAM, JJA, and SON seasons at each 1-degree grid point for each of the three future periods (2016-2035, 2046-2065, and 2080-2099):

$$T_{hot-m} = mean(T_{hot-r}) \tag{Eq.36}$$

$$P_{wet-m} = mean(P_{wet-r}) \tag{Eq.37}$$

$$P_{dry-m} = mean(P_{dry-r}) \tag{Eq.38}$$

10. Tenth, we calculate the mean of the T_{hot-m}, P_{wet-m}, and P_{dry-m} values across all of the *m* models of the CMIP5 ensemble, yielding the long-term ensemble mean extreme hot years (T_{hot-e}), ensemble mean extreme wet years (P_{wet-e}), and ensemble mean extreme

dry years ($P_{dry\text{-}e}$) for the DJF, MAM, JJA, and SON seasons at each 1-degree grid point

for each of the three future periods (2016-2035, 2046-2065, and 2080-2099):

$$T_{hot\text{-}e} = mean(T_{hot\text{-}m}) \qquad\qquad\qquad (Eq.39)$$

$$P_{wet\text{-}e} = mean(P_{wet\text{-}m}) \qquad\qquad\qquad (Eq.40)$$

$$P_{dry\text{-}e} = mean(P_{dry\text{-}m}) \qquad\qquad\qquad (Eq.41)$$

These ten steps yield the ensemble mean of the 28 climate indicators from which

we calculate the aggregate climate change between the baseline (1986-2005) and future

periods (2016-2035, 2046-2065, and 2080-2099).

Supplemental References

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Table S1. Available models in the CMIP5 RCP8.5 ensemble archiving monthly surface air temperature (tas) and precipitation (pr) data for both the historical and 21st century periods. *

Model	Historical Realizations	RCP8.5 Realizations	RCP4.5 Realizations
ACCESS1-0	1	1	1
bcc-csm1-1	3	1	1
CanESM2	5	5	5
CCSM4	6	6	5
CNRM-CM5	10	5	1
CSIRO-Mk3-6-0	10	10	10
FGOALS-g2	4	1	1
GFDL-ESM2G	1	1	1
GFDL-ESM2M	1	1	1
GISS-E2-R	16	1	5
HadGEM2-CC	3	3	1
HadGEM2-ES	4	1	4
inmcm4	1	1	1
IPSL-CM5A-LR	4	4	4
MIROC5	4	3	3
MIROC-ESM-CHEM	1	1	1
MIROC-ESM	1	1	1
MPI-ESM-LR	3	3	3
MRI-CGCM3	5	1	1
NorESM1-M	3	1	1

* see Supplemental Information for description of approach to averaging across the ensemble
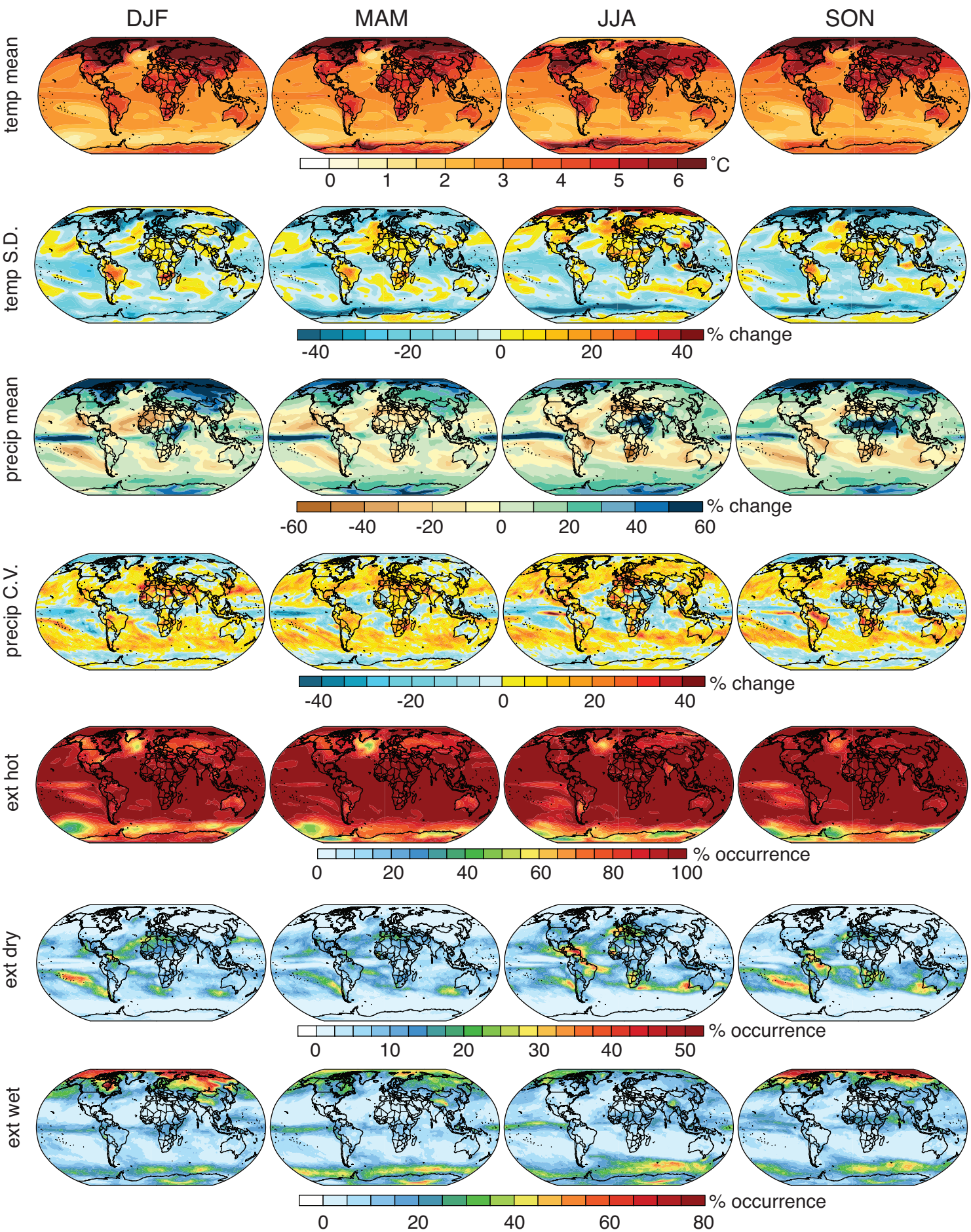
RCP8.5 2080-2099

Figure S1. The change in each variable between the 1986-2005 and 2080-2099 periods.
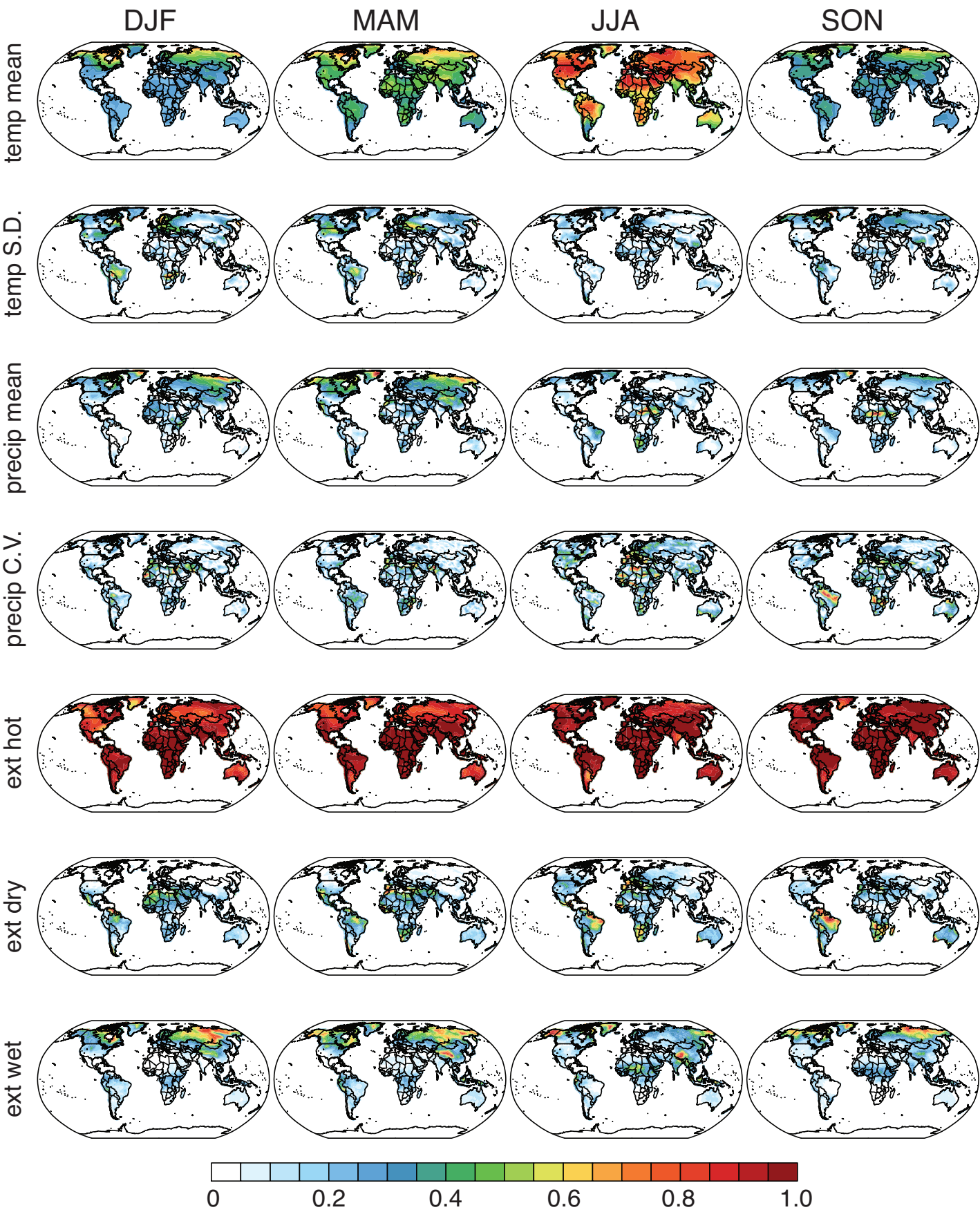
RCP8.5 2080-2099

Figure S2. The absolute value of change in each variable between the 1986-2005 and 2080-2099 periods. The absolute values of change at each grid point are normalized to the maximum absolute value of all land grid points north of 60˚S.
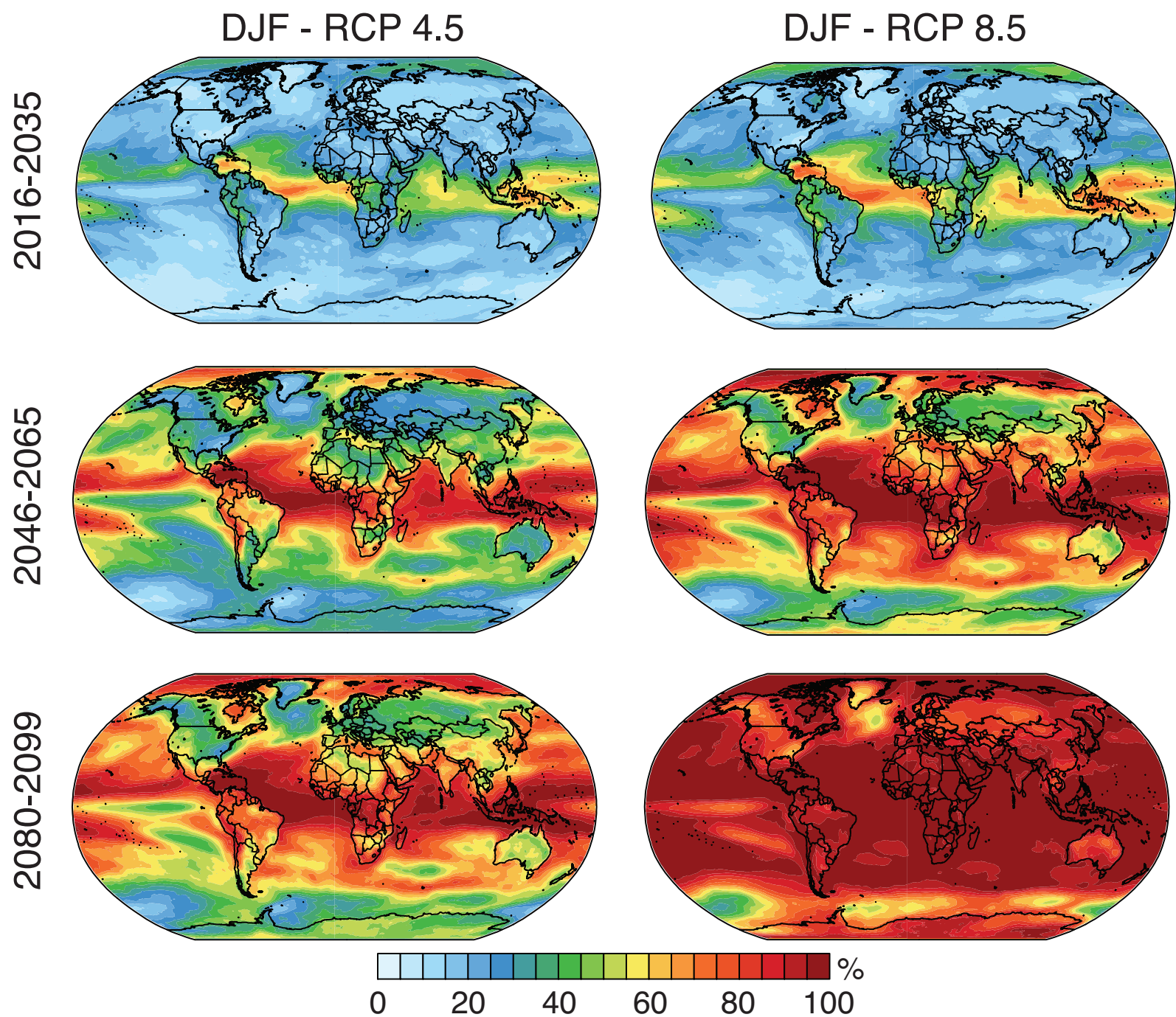
Figure S3. The occurrence of the 1986-2005 maximum December-January-February (DJF) seasonal temperature in the 2016-2035, 2046-2065 and 2080-2099 periods of RCP8.5 (left) and RCP4.5 (right). The panels show the absolute occurrences as the percent of years in each 20-year period. The frequency of occurrence of the 1986-2005 maximum JJA seasonal temperature value is, by definition, 5% at each grid point during the 20-year 1986-2005 period.