2016-11

Increasing ambient temperature reduces emotional well-being

Supplementary Information

Simulated vs. Empirical Weather Responsiveness of Crop Yields:

U.S. Evidence and Implications for the Agricultural Impacts of Climate Change

Malcolm N. Mistry[1,2], Ian Sue Wing[3], Enrica De Cian[2]

[1] Dept. of Economics, Università Ca' Foscari, Venice, Italy.

[2] Fondazione Eni Enrico Mattei (FEEM), Centro Euro-Mediterraneo sui Cambiamenti Climatici (CMCC),Venice, Italy

[3] Dept. of Earth and Environment, Boston University, Boston MA, USA

Email: malcolm.mistry@unive.it, malcolm.mistry@feem.it

S1. Global Gridded Crop Models (GGCMs) from ISIMIP-Fastrack used in this study along with the contact details of the modelling groups

(i) Geographic Information System (GIS)-based Environmental Policy Integrated Climate (GEPIC) (Liu *et al* 2007)

(ii) Global Agro-Ecological Zone model in the Integrated Model to Assess the Global Environment (GAEZ-IMAGE) (Van Vuuren *et al* 2006)

(iii) Lund-Potsdam-Jena General Ecosystem Simulator (LPJ-GUESS) (Bondeau *et al* 2007)

(iv) Lund Potsdam-Jena managed Land (LPJmL) (Bondeau *et al* 2007, Sitch *et al* 2003)

(v) parallel Decision Support System for Agro-technology Transfer (pDSSAT) (Elliott *et al* 2013, Jones *et al* 2003)

(vi) Predicting Ecosystem Goods And Services Using Scenarios (PEGASUS) (Deryng *et al* 2011)

Table S1. GGCMs used in this study, with the home institution and contact details.

Model	Institution	Contact Person/Web address
GEPIC	EAWAG (Switzerland)	Christian Folberth/Hong Yang christian.folberth@eawag.ch hong.yang@eawag.ch
GAEZ-IMAGE	Netherland Environmental Assessment Agency, PBL (Netherland)	Elke Stehfest/Kathleen Neumann elke.stehfest@pbl.nl kathleen.neumann@pbl.nl
LPJ-GUESS	Lund University (Sweden), IMK-IFU, Karlsruhe Institute of Technology (Germany)	Stefan Olin/Thomas Pugh stefan.olin@nateko.lu.se thomas.pugh@imk.fzk.de
LPJmL	PIK (Germany)	Christoph Muller christoph.mueller@pik-potsdam.de
pDSSAT	University of Chicago (USA)	Joshua Elliott, jelliott@ci.uchicago.edu
PEGASUS	Tyndall Centre, University of East Anglia (UK)	Delphine Deryng d.deryng@uea.ac.uk

S2. Data

S2.1 GGCMs' simulated crop yields

We utilize the annual gridded rainfed crop yields from the six GGCMs of ISI-MIP Fastrack (Hempel *et al* 2013, Rosenzweig *et al* 2014) listed in table S1, over the GGCMs' historical simulation period spanning 1981-2004 (24 years)[1]. The number of grid-cells, counties and observations used in each crop~GGCM combination regression are summarized in table S3.

S2.2 USDA historical observed data

For comparison of the GGCMs' annual yields with the factual yields, we employed historical observed annual county level production ($bushel, bu$) and harvested areas ($acre, a$), made available by the U.S. Department of Agriculture (USDA)–National Agricultural Statistics Service (NASS): Quickstats 2.0 database[2]. The total (irrigated + rainfed) production and harvested area data utilized in this study covers ~90-1200 counties in the U.S. over the period 1981–2004 (24 years). Crop yields (bu/a) for each county are calculated as the ratio of production to harvested area. The conversion from bu/a to tons/hectare (t/ha) for each crop (for consistency with GGCMs' yield units in t/ha) is described as below in table S2.

Table S2. Conversion from bu/a to t/ha

Crop	bu/a	t/ha
Maize	1	0.0628
Wheat	1	0.0673
Soybeans	1	0.0673

To ensure comparability with the rainfed GGCMs' crop yields, we need to formulate a methodology to differentiate between the irrigated and rainfed crop production by county for the USDA crop yields. We utilized crop harvested area data from the 2012 USDA census of agriculture[3], and define rainfed counties for each of the three crops meeting the below criteria.

County (for crop type) is deemed as 'rainfed' county if

the share of crop harvested area is > 10 %, AND < 10 % of that harvested area is irrigated.

[1] Each GGCM panel is unbalanced. However, the time period (1981-2004) is consistent with USDA panel.

[2] http://quickstats.nass.usda.gov/ (accessed on 13 February 2017)

[3] https://www.agcensus.usda.gov/Publications/2012/Online_Resources/Ag_Census_Web_Maps/Data_download/index.php (accessed on 13 February 2017)

The final counties retained in regression analyses for each crop are shown in fig, S1 (USDA panel). The result is an unbalanced panel spanning years 1981-2004 (see details of observations and number of counties in table S3 under USDA).

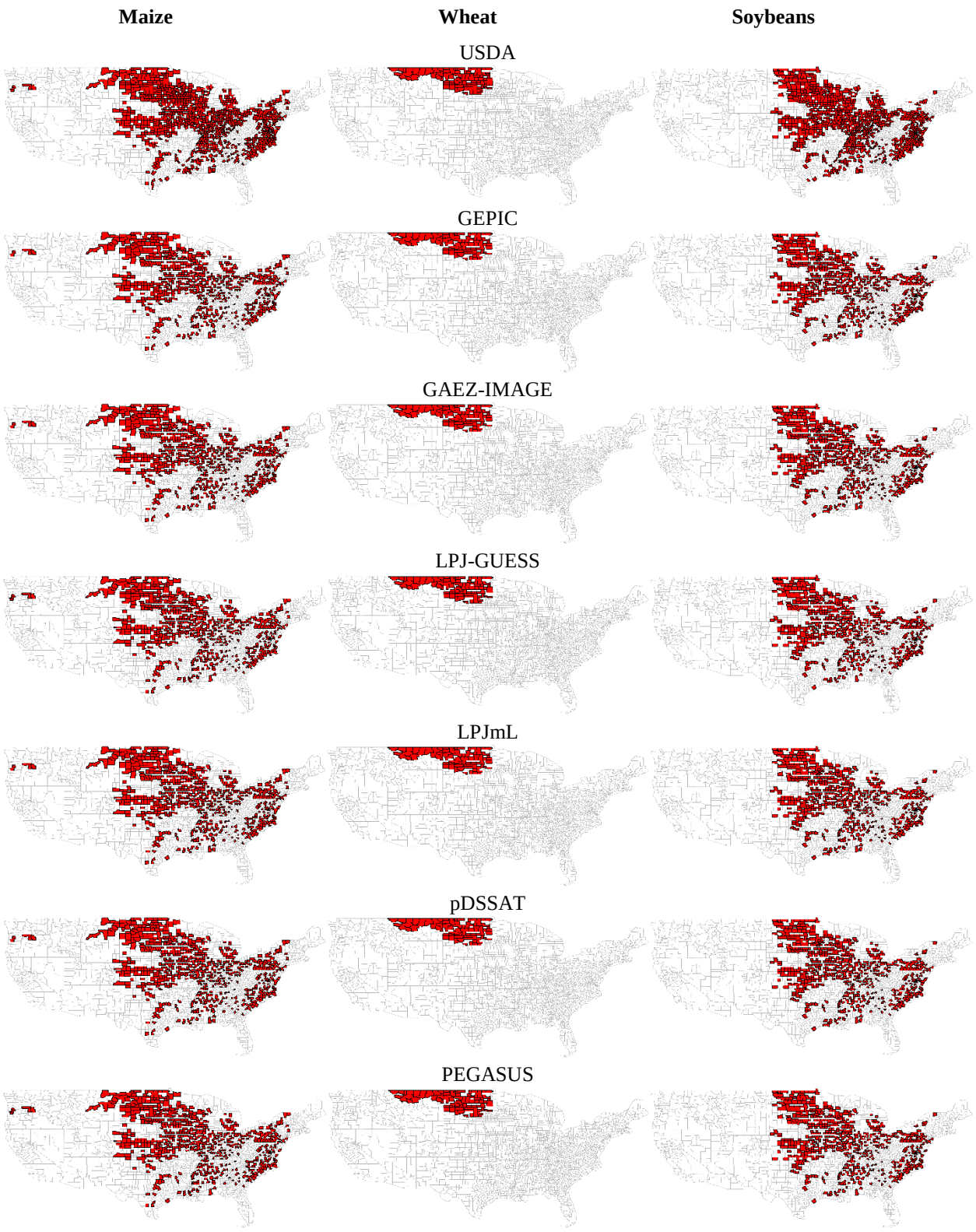

Fig. S1. Maps of USDA and GGCMs' rainfed counties used in this study for (i) maize (ii) wheat and (iii) soybeans.

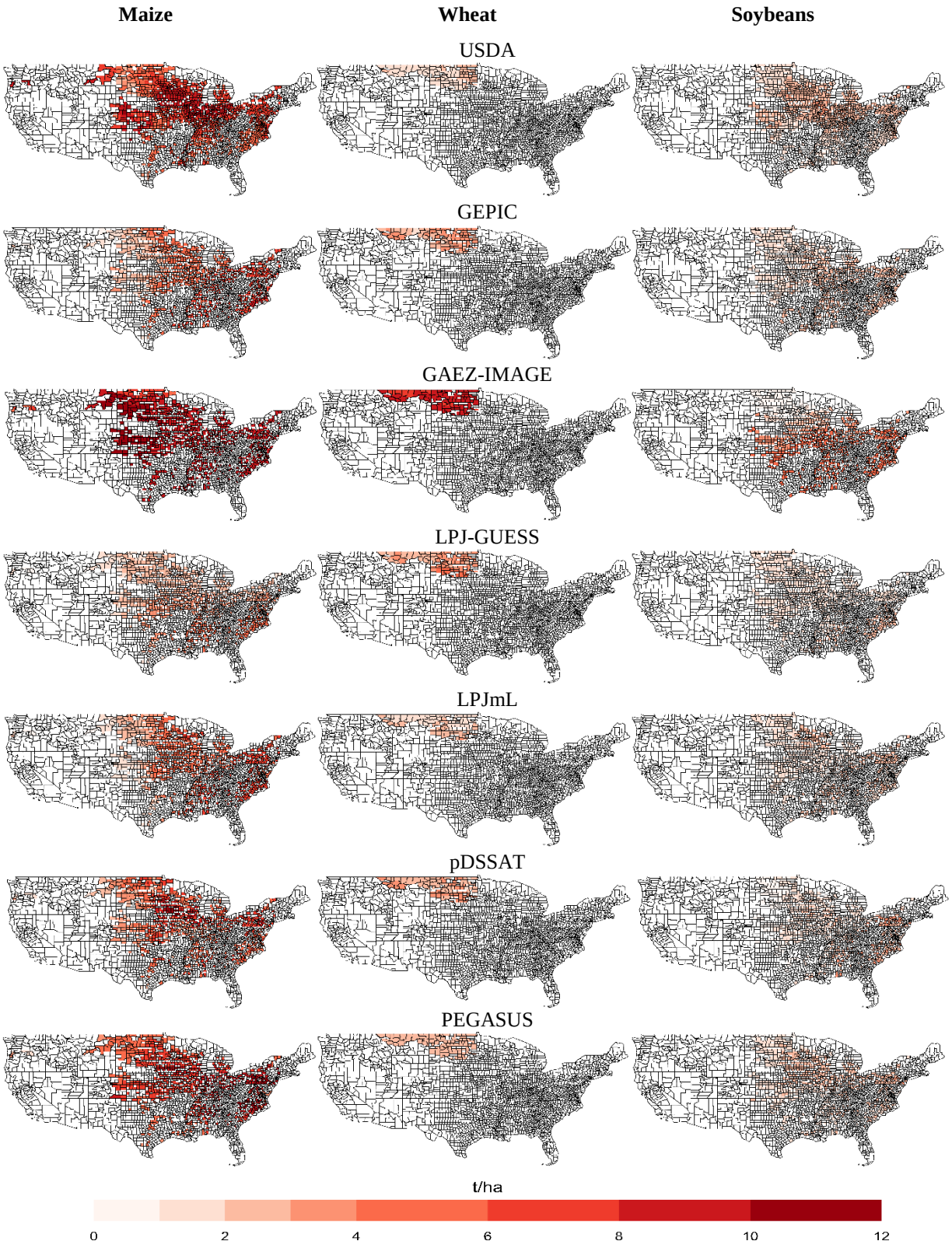

Fig. S2. Maps of USDA and GGCMs' historical (1981~2004) mean rainfed county yields (t/ha) for (i) maize (ii) wheat and (iii) soybeans.

Table S3. Number of observations, counties (in braces) and total grid-cells (in square braces) used in GGCMs and USDA regressions. The grid-cells and counties were retained for analyses if they reported yields in at least 10 of the total 24 years.

GGCM	Maize	Soybeans	Wheat
GEPIC	21,453 (728) [910]	18,123 (667) [777]	4,645 (88) [196]
GAEZ-IMAGE	21,939 (733) [919]	14,789 (670) [777]	4,800 (88) [200]
LPJ-GUESS	21,924 (730) [914]	18,672 (669) [778]	4,800 (88) [200]
LPJmL	21,851 (733) [919]	18,702 (786) [673]	4,800 (88) [200]
pDSSAT	20,926 (725) [912]	17,677 (771) [663]	4,773 (88) [200]
PEGASUS	21,819 (726) [910]	17,724 (772) [664]	4,799 (88) [200]
Multi-GGCM	129,912 (733) [919]	105,687 (786) [673]	28,617 (88) [200]
USDA, rainfed panel	27,370 (1,187)	24,606 (1,103)	1,855 (102)

S2.3 Crop growing seasons

In ISIMIP-FT simulations, the crops growing season (CGS) varies marginally not only for each crop-GGCM combination historical simulation, but also in the historical and future periods of GGCMs' simulated data (e.g. LPJ-GUESS and LPJmL mimic planting dates according to climatic conditions, see Rosenzweig *et al* 2014 SI for further details). To keep our analyses tractable, we subsume this heterogeneity and adopt the key simplification of a common fixed, four-month CGS as May-August (*MJJA*) for both USDA and GGCMs' crop panels; except for crop wheat for which April-August (*AMJJA*) was adopted.

Our definition of CGS by and large encapsulates the broader CGS across the GGCMs and crops. Moreover, by adopting a common CGS, we avoid the potential endogeneity problem with crop modellers' definition of when planting and harvesting begin in each year. Nevertheless, it is important to highlight that the definition of CGS may not likely be consistent with the actual CGS for the USDA data (e.g. 'spring + durum' wheat in some individual years of analyses could be partly grown outside the CGS ($AMJJA$) in our study area). The overall results of wheat could therefore be marginally influenced by this assumption (for e.g., see Lobell and Field 2007, Schauberger *et al* 2017)where in the results are fairly insensitive to the choice of CGS months for multiple crops examined in their study)

S3. Historical weather exposure for empirical analyses.

S3.1 GGCMs

All GGCM historical (1981-2004) crop yield simulation runs are forced with bias-corrected climate inputs (Hempel *et al* 2013) from HadGEM2-ES (Jones *et al* 2011). Here we matched the bias-corrected HadGEM2-ES frequency of days (bins) in the CGS, for daily mean temperature ($°C$) and total precipitation (mm) to GGCMs' generated realizations of yield in each year of the historical period. For consistency, we used the identical CGS truncations across the different GGCMs (i.e. $MJJA$ for crops maize and soybeans, and $AMJJA$ for wheat).

S3.2 USDA

Historical weather exposures (bins of daily mean temperature and total precipitation) for our empirical model are calculated from the 2.5 arcmin scale (~4 km) gridded Parameter-elevation Regressions on Independent Slopes Model (PRISM)[4] forcing files, spatially interpolated to county boundaries[5]. The PRISM model has been well documented in Daly *et al* (2008), has been widely used in earlier studies focusing on U.S. (such as Schlenker and Roberts 2006b, 2009, Roberts *et al* 2013, Auffhammer *et al* 2013), and more recently in Heft-Neal et al (2017). It is developed using climate observations from a wide range of monitoring networks, accounts for climate and elevation, and has highlighted by Schlenker and Roberts 2006a, is widely regarded as one of the best geographic interpolation procedures.

[4] PRISM daily mean temperature and total precipitation (1981~2004) were downloaded from http://www.ocs.orst.edu/prism/ (accessed on 13 February 2017)

[5] https://www.census.gov/geo/maps-data/data/cbf/cbf_counties.html (accessed on 13 February 2017)

S4. Binning structure of temperature and precipitation in regressions

For our base specifications (eq. 1 in main text), our meteorological covariates are defined as the cumulative exposure to intervals ("bins") of T and P during the annual CGS in both USDA and GGCMs' regression specifications.

The bins $\{T_1, \dots, T_J, P_1, \dots, P_K\}$ are counts of number of days in the CGS at each GGCM grid-cell (county for USDA regression) spent in j intervals[6] of $T(Degree\ Celcius, °C)$ and k intervals of $P(millimiter\ per\ day, mm/d)$, where:

$j = \{< 7.5, 7.5\sim10, 10\sim12.5, 12.5\sim15, 15\sim17.5, 17.5\sim20, 20\sim22.5, 22.5\sim25, 25\sim27.5, 27.5\sim30, > 30\}$

and

$k = \{< 5, 5\sim10, 10\sim15, > 15\}$

The bins $j = 22.5\sim25\ °C$ and $k = 10\sim15\ mm/d$ were omitted in regressions as reference category. Thus with reference to eq. (1) in main text, each coefficient of T (P) indicates the impact on $log\ yield$ of an additional day in the j^{th} (k^{th}) interval, relative to a day in the dropped T (P) bin. All our regression specifications were run in R package Linear Fixed Effects (LFE) (Gaure 2013), which can handle arbitrary number of factors (fixed effects) and is tailored for fixed effect estimation on large panel data. To account for heteroscedasticity and autocorrelation in the error term $\varepsilon_{i,t,m}$ (eq. 1 in main text), we use robust standard errors (S.E.)[7] clustered by cross-sectional units (grid-cells/counties).

[6] For each T and P bin except the extreme lower and upper values, the lower range is included in the count. The extreme bins are open-ended.

[7] The S.E.s calculated by R LFE are adjusted for the reduced degrees of freedom (DOF) coming from the dummies which are implicitly present. They are also small-sample corrected.

Table S4: Regression summary with Clustered Robust S.E. (in parenthesis, S.E. clustered by cross-sectional unit; in square braces clustered by cross-sectional unit and time): (i) maize, (ii) soybeans, (iii) wheat. Because two S.E.s are provided for each estimate, the stars denoting significance level are marked on the S.E. instead of on the estimates

	(i) Dependent variable: log yield (Maize)							
	USDA	GEPIC	GAEZ-IMAGE	LPJ-GUESS	LPJmL	pDSSAT	PEGASUS	Multi-GGCM
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
$\overline{T} < 7.5°C$	−0.006	0.076	0.005	0.003	0.024	0.007	−0.0124	0.017
	(0.001)***	(0.003)***	(0.001)***	(0.001)**	(0.002)***	(0.002)***	(0.002)***	(0.001)***
	[0.005]	[0.025]***	[0.004]	[0.006]	[0.018]	[0.007]	[0.007]*	[0.008]**
(7.5-10°C)	−0.006	0.030	−0.005	0.001	0.011	0.004	−0.025	0.002
	(0.001)***	(0.003)***	(0.001)***	(0.001)	(0.002)***	(0.001)***	(0.002)***	(0.001)**
	[0.004]	[0.022]	[0.003]	[0.005]	[0.007]	[0.007]	[0.006]***	[0.006]
(10-12.5°C)	−0.007	0.031	0.000	0.006	0.009	0.002	−0.020	0.005
	(0.001)***	(0.003)***	(0.001)	(0.001)***	(0.002)***	(0.001)**	(0.001)***	(0.001)***
	[0.003]**	[0.011]***	[0.002]	[0.002]***	[0.007]	[0.004]	[0.005]***	[0.003]
(12.5-15°C)	−0.006	0.023	−0.002	0.004	0.004	0.001	−0.016	0.002
	(0.001)***	(0.002)***	(0.001)***	(0.001)***	(0.001)***	(0.001)	(0.001)***	(0.001)***
	[0.002]***	[0.008]***	[0.001]	[0.002]*	[0.005]	[0.003]	[0.004]***	[0.002]
(15-17.5°C)	−0.002	0.025	−0.002	0.005	0.014	−0.001	−0.008	0.0069
	(0.000)***	(0.002)***	(0.000)***	(0.001)***	(0.001)***	(0.001)	(0.001)***	(0.001)***
	[0.002]	[0.009]***	[0.002]	[0.002]***	[0.003]***	[0.003]	[0.004]**	[0.003]**
(17-20°C)	−0.001	0.027	0.000	0.006	0.014	0.005	−0.003	0.008
	(0.000)***	(0.001)***	(0.000)	(0.001)***	(0.001)***	(0.001)***	(0.001)***	(0.001)***
	[0.001]	[0.008]***	[0.001]	[0.001]***	[0.005]***	[0.003]**	[0.003]	[0.002]***
(20-22.5°C)	0.002	0.019	0.000	0.005	0.008	0.005	0.002	0.007
	(0.000)***	(0.001)***	(0.000)***	(0.001)***	(0.001)***	(0.001)***	(0.001)***	(0.001)***
	[0.001]**	[0.005]***	[0.001]	[0.001]***	[0.002]***	[0.001]***	[0.002]	[0.001]***
(25-27.5°C)	−0.006	−0.021	0.000	−0.007	−0.009	−0.009	−0.009	−0.009
	(0.000)***	(0.001)***	(0.000)***	(0.000)***	(0.001)***	(0.001)***	(0.001)***	(0.000)***
	[0.001]***	[0.004]***	[0.001]	[0.001]***	[0.003]***	[0.001]***	[0.002]***	[0.001]***
(27.5-30°C)	−0.016	−0.025	0.000	−0.009	−0.016	−0.010	−0.010	−0.012
	(0.000)***	(0.002)***	(0.000)	(0.001)***	(0.001)***	(0.001)***	(0.001)***	(0.001)***
	[0.002]***	[0.007]***	[0.001]	[0.002]***	[0.003]***	[0.003]***	[0.003]***	[0.002]***
$\overline{T} > 30°C$	−0.018	−0.030	0.001	−0.013	−0.020	−0.017	−0.022	−0.017
	(0.001)***	(0.002)***	(0.000)***	(0.001)***	(0.001)***	(0.001)***	(0.001)***	(0.000)***
	[0.003]***	[0.009]***	[0.001]	[0.002]***	[0.006]***	[0.003]***	[0.004]***	[0.004]***
$\overline{P} < 5$ mm/day	−0.006	−0.020	0.000	−0.005	−0.015	−0.012	−0.002	−0.009
	(0.001)***	(0.002)***	(0.000)	(0.001)***	(0.001)***	(0.001)***	(0.001)	(0.001)***
	[0.003]**	[0.007]***	[0.001]	[0.002]***	[0.004]***	[0.003]***	[0.003]	[0.002]***
(5-10 mm/day)	−0.001	−0.010	0.000	−0.003	−0.007	−0.005	0.000	−0.004
	(0.001)	(0.003)***	(0.000)	(0.001)***	(0.002)***	(0.001)***	(0.002)	(0.001)***
	[0.001]	[0.006]*	[0.001]	[0.001]***	[0.003]**	[0.002]**	[0.003]	[0.002]**
$\overline{P} > 15$ mm/day	−0.001	0.020	0.001	0.010	0.017	0.008	−0.005	0.009
	(0.001)	(0.003)***	(0.001)***	(0.001)***	(0.002)***	(0.001)***	(0.002)***	(0.001)***
	[0.002]	[0.010]**	[0.002]	[0.003]***	[0.007]**	[0.004]*	[0.004]	[0.004]**
State time trends	Yes	No	No	No	No	No	No	No
Time dummies	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Location FE	County FE	Grid-cell FE	Grid-cell FE	Grid-cell FE	Grid-cell FE	Grid-cell FE	Grid-cell FE	Grid-cell FE
Observations	27,370	21,453	21,939	21,924	21,851	20,926	21,819	129,912
Adjusted R^2	0.682	0.766	0.373	0.846	0.770	0.689	0.554	0.675
Residual SE	0.21 (df = 26134)	0.75 (df = 20507)	0.13 (df = 20984)	0.22 (df = 20974)	0.48 (df = 20896)	0.36 (df = 19979)	0.38 (df = 20873)	0.56 (df = 124393)

	(ii) Dependent variable: log yield (Soybeans)							
	USDA	GEPIC	GAEZ-IMAGE	LPJ-GUESS	LPJmL	pDSSAT	PEGASUS	Multi-GGCM
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
$\overline{T} < 7.5°C$	−0.004	0.031	0.004	0.018	0.047	0.008	−0.060	0.008
	(0.001)***	(0.001)***	(0.003)	(0.001)***	(0.003)***	(0.005)	(0.003)***	(0.001)***
	[0.007]	[0.006]***	[0.012]	[0.008]**	[0.013]***	[0.024]	[0.025]**	[0.008]
(7.5-10°C)	−0.003	0.012	−0.011	0.011	0.007	0.011	−0.024	0.002
	(0.001)***	(0.001)***	(0.002)***	(0.001)***	(0.002)***	(0.004)***	(0.003)***	(0.001)**
	[0.004]	[0.006]**	[0.009]	[0.007]	[0.012]	[0.016]	[0.011]**	[0.006]
(10-12.5°C)	−0.008	0.015	−0.006	0.020	0.008	−0.003	−0.022	0.004
	(0.001)***	(0.001)***	(0.002)***	(0.001)***	(0.002)***	(0.003)	(0.002)***	(0.001)***
	[0.003]**	[0.004]***	[0.008]	[0.004]***	[0.008]	[0.010]	[0.008]***	[0.003]
(12.5-15°C)	−0.007	0.006	−0.004	0.017	0.006	−0.015	−0.024	−0.001
	(0.001)***	(0.001)***	(0.001)***	(0.001)***	(0.001)***	(0.002)***	(0.001)***	(0.001)**
	[0.002]***	[0.003]**	[0.006]	[0.003]***	[0.005]	[0.010]	[0.007]***	[0.003]
(15-17.5°C)	−0.003	0.008	−0.003	0.015	0.017	−0.014	−0.009	0.005
	(0.000)***	(0.001)***	(0.001)***	(0.001)***	(0.001)***	(0.002)***	(0.001)***	(0.001)***
	[0.002]	[0.003]***	[0.003]	[0.003]***	[0.006]***	[0.010]	[0.005]*	[0.002]*
(17-20°C)	−0.001	0.009	−0.002	0.012	0.018	−0.003	−0.002	0.007
	(0.000)***	(0.000)***	(0.007)**	(0.001)***	(0.001)***	(0.002)	(0.001)***	(0.001)***
	[0.002]	[0.003]***	[0.003]	[0.002]***	[0.006]***	[0.008]	[0.003]	[0.002]***
(20-22.5°C)	0.001	0.006	−0.002	0.008	0.014	0.006	−0.001	0.006
	(0.000)	(0.001)***	(0.001)***	(0.001)***	(0.001)***	(0.001)***	(0.001)*	(0.001)***
	[0.001]	[0.002]***	[0.002]	[0.001]***	[0.003]***	[0.006]	[0.002]	[0.002]***
(25-27.5°C)	−0.003	−0.011	−0.001	−0.010	−0.008	−0.023	−0.007	−0.010
	(0.000)***	(0.000)***	(0.000)***	(0.001)***	(0.001)***	(0.001)***	(0.001)***	(0.000)***
	[0.001]***	[0.001]***	[0.001]	[0.002]***	[0.003]**	[0.004]***	[0.002]***	[0.001]***
(27.5-30°C)	−0.010	−0.016	0.002	−0.013	−0.018	−0.0223	−0.008	−0.012
	(0.000)***	(0.000)***	(0.000)***	(0.001)***	(0.001)***	(0.001)***	(0.001)***	(0.000)***
	[0.002]***	[0.003]***	[0.002]	[0.002]***	[0.004]***	[0.005]***	[0.003]***	[0.002]***
$\overline{T} > 30°C$	−0.019	−0.017	0.001	−0.021	−0.015	−0.045	−0.020	−0.017
	(0.001)***	(0.000)***	(0.001)***	(0.001)***	(0.001)***	(0.002)***	(0.001)***	(0.000)***
	[0.003]***	[0.003]***	[0.003]	[0.004]***	[0.009]*	[0.015]***	[0.003]***	[0.003]***
$\overline{P} < 5$ mm/day	−0.006	−0.006	−0.002	−0.006	−0.004	−0.060	0.008	−0.011
	(0.001)***	(0.001)***	(0.001)*	(0.001)***	(0.002)**	(0.003)***	(0.002)***	(0.001)***
	[0.002]***	[0.002]**	[0.003]	[0.003]*	[0.004]	[0.008]***	[0.004]*	[0.003]***
(5-10 mm/day)	−0.001	−0.003	0.000	−0.002	−0.005	−0.015	0.009	−0.003
	(0.001)	(0.001)***	(0.001)	(0.001)*	(0.002)***	(0.003)***	(0.001)***	(0.001)***
	[0.001]	[0.001]*	[0.003]	[0.002]	[0.003]	[0.008]*	[0.003]***	[0.002]
$\overline{P} > 15$ mm/day	0.000	0.005	0.000	0.016	0.014	0.014	0.003	0.009
	(0.001)	(0.001)***	(0.001)	(0.001)***	(0.002)***	(0.003)***	(0.002)	(0.001)***
	[0.002]	[0.003]*	[0.003]	[0.005]***	[0.008]*	[0.009]	[0.005]	[0.003]***
State time trends	Yes	No	No	No	No	No	No	No
Time dummies	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Location FE	County FE	Grid-cell FE	Grid-cell FE	Grid-cell FE	Grid-cell FE	Grid-cell FE	Grid-cell FE	Grid-cell FE
Observations	24,606	18,123	14,789	18,672	18,702	17,677	17,724	105,687
Adjusted R^2	0.653	0.851	0.325	0.845	0.654	0.672	0.478	0.586
Residual Std. Error	0.19 (df = 23459)	0.21 (df = 17310)	0.28 (df = 14083)	0.26 (df = 17858)	0.51 (df = 17880)	0.80 (df = 16870)	0.41 (df = 16916)	0.59 (df = 101097)

	(iii) Dependent variable: log yield (Wheat)							
	USDA	GEPIC	GAEZ-IMAGE	LPJ-GUESS	LPJmL	pDSSAT	PEGASUS	Multi-GGCM
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
$\overline{T} < 7.5°C$	0.003	0.003	−0.001	0.014	0.041	0.003	−0.014	0.008
	(0.002)**	(0.002)	(0.001)***	(0.001)***	(0.005)***	(0.003)	(0.002)***	(0.002)***
	[0.006]	[0.011]	[0.002]	[0.005]***	[0.017]**	[0.006]	[0.013]	[0.005]
(7.5-10°C)	0.004	0.025	−0.002	0.014	0.040	0.018	−0.008	0.014
	(0.003)	(0.002)***	(0.000)***	(0.001)***	(0.004)***	(0.002)***	(0.002)***	(0.001)***
	[0.007]	[0.009]***	[0.002]	[0.004]***	[0.012]***	[0.004]***	[0.010]	[0.004]***
(10-12.5°C)	−0.006	0.026	0.000	0.015	0.026	0.009	0.004	0.013
	(0.002)***	(0.001)***	(0.001)	(0.001)***	(0.002)***	(0.002)***	(0.001)***	(0.001)***
	[0.006]	[0.007]***	[0.001]	[0.003]***	[0.008]***	[0.005]**	[0.006]	[0.003]***
(12.5-15°C)	0.003	0.019	0.000	0.013	0.011	0.005	0.001	0.008
	(0.002)	(0.001)***	(0.000)	(0.001)***	(0.002)***	(0.001)***	(0.002)	(0.001)***
	[0.004]	[0.005]***	[0.001]	[0.002]***	[0.009]	[0.004]	[0.004]	[0.002]***
(15-17.5°C)	−0.003	0.019	0.000	0.013	0.012	0.007	0.005	0.009
	(0.002)*	(0.001)***	(0.000)	(0.001)***	(0.002)***	(0.001)***	(0.002)***	(0.001)***
	[0.004]	[0.004]***	[0.001]	[0.002]***	[0.006]*	[0.004]**	[0.006]	[0.002]***
(17-20°C)	−0.006	0.011	−0.001	0.006	0.000	0.000	0.003	0.003
	(0.002)***	(0.001)***	(0.000)*	(0.001)***	(0.002)	(0.001)	(0.002)*	(0.001)***
	[0.004]	[0.004]***	[0.001]	[0.002]***	[0.008]	[0.003]	[0.006]	[0.002]
(20-22.5°C)	−0.009	0.003	−0.001	−0.001	−0.009	−0.004	0.000	−0.002
	(0.002)***	(0.001)***	(0.000)***	(0.001)	(0.002)***	(0.001)***	(0.001)	(0.001)***
	[0.004]**	[0.003]	[0.001]	[0.002]	[0.005]*	[0.004]	[0.004]	[0.002]
(25-27.5°C)	−0.026	0.004	−0.001	−0.002	−0.011	0.002	−0.004	−0.002
	(0.003)***	(0.002)**	(0.000)**	(0.001)*	(0.002)***	(0.002)	(0.002)**	(0.001)**
	[0.009]***	[0.006]	[0.001]	[0.002]	[0.006]*	[0.005]	[0.006]	[0.002]
(27.5-30°C)	−0.037	−0.022	0.001	−0.009	−0.011	−0.016	−0.040	−0.016
	(0.005)***	(0.003)***	(0.000)***	(0.001)***	(0.003)***	(0.003)***	(0.002)***	(0.001)***
	[0.013]***	[0.009]**	[0.001]	[0.004]**	[0.008]	[0.008]*	[0.012]***	[0.003]***
$\overline{T} > 30°C$	−0.075	−0.004	−0.002	−0.003	−0.059	−0.017	−0.028	−0.019
	(0.017)***	(0.006)	(0.001)**	(0.003)	(0.011)***	(0.007)**	(0.007)***	(0.003)***
	[0.026]***	[0.009]	[0.002]	[0.008]	[0.014]***	[0.006]***	***	[0.004]***
$\overline{P} < 5$ mm/day	−0.016	−0.017	0.001	−0.019	−0.011	−0.006	−0.006	−0.010
	(0.003)***	(0.002)***	(0.001)*	(0.001)***	(0.004)***	(0.002)***	(0.002)***	(0.001)***
	[0.007]**	[0.006]***	[0.001]	[0.004]***	[0.012]	[0.005]	[0.007]	[0.003]***
(5-10 mm/day)	−0.010	−0.005	0.001	−0.008	0.008	0.007	−0.007	−0.001
	(0.004)**	(0.002)**	(0.001)**	(0.001)***	(0.004)**	(0.002)***	(0.002)***	(0.001)
	[0.006]*	[0.003]*	[0.001]	[0.002]***	[0.009]	[0.004]*	[0.005]	[0.002]
$\overline{P} > 15$ mm/day	−0.015	0.010	0.001	0.010	−0.016	0.001	0.000	0.001
	(0.005)***	(0.003)***	(0.001)*	(0.001)***	(0.004)***	(0.002)	(0.002)	(0.001)
	[0.007]*	[0.010]	[0.001]	[0.004]***	[0.008]**	[0.004]	[0.010]	[0.004]
State time trends	Yes	No	No	No	No	No	No	No
Time dummies	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Location FE	County FE	Grid-cell FE	Grid-cell FE	Grid-cell FE	Grid-cell FE	Grid-cell FE	Grid-cell FE	Grid-cell FE
Observations	1,855	4,645	4,800	4,800	4,800	4,773	4,799	28,617
Adjusted R^2	0.431	0.752	0.3706	0.829	0.620	0.580	0.695	0.734
Residual Std. Error	0.28 (df = 1736)	0.24 (df = 4413)	0.07 (df = 4564)	0.13 (df = 4564)	0.34 (df = 4564)	0.22 (df = 4537)	0.23 (df = 4563)	0.32 (df = 27385)

S5. Variation in historical observed (USDA) and simulated (GGCMs) yields empirically attributed to weather (T and P bins)

The adjusted R^2 (in table S4) derived from our regression specifications track how much of the cross-section/time-series variation in yields is explained by not only the predictors[8] (T and P), but also by the grid-cell fixed effects (μ_i) and the time effects ($f(t) = \tau_t$), or the county fixed effects (μ_i) and the state specific time trend ($f(t) = \lambda_s t$).

To gauge how much on average the weather variables (T and P) explain the cross-section/time-series variation in yields, table S5 summarizes the adjusted R^2 by stripping out the influencing effects of the idiosyncratic unobserved shocks (μ_i and $f(t)$) in eq. 1. These are obtained directly from R LFE package 'Projected Model $adj - R^2$'

Table S5. Percentage of variation explained by the covariates (T and P), for base specification with time effects, and with state specific time trend in lieu of time effects (in braces)

GGCM	Maize	Wheat	Soybeans
GEPIC	30% (61%)	29% (51%)	53% (74%)
GAEZ-IMAGE	2% (4%)	0% (1%)	0% (11%)
LPJ-GUESS	39% (58%)	43% (63%)	53% (74%)
LPJmL	31% (49%)	15% (24%)	22% (43%)
pDSSAT	27% (48%)	9% (21%)	32% (50%)
PEGASUS	20% (35%)	22% (49%)	17% (32%)
Multi-Model	10% (19%)	4% (7%)	10% (22%)
USDA	16% (46%)	13% (30%)	15% (32%)

Focusing on GGCMs (table S5), GAEZ-IMAGE is not well captured by the regression specifications (eq. 1 in main text). This could be partly attributed to the low inter-annual variation in crop yields as GAEZ-IMAGE simulates yields at 5-yearly time step in contrast to the yield simulated annually by other GGCMs[9]. It then interpolates the crop yields for the missing years. This results in lower inter-annual

[8] There are total 13 weather response parameters (10 temperature bins and 3 precipitation bins) in our regressions model (eqs.1 of main text). See table S4 for details on number of fixed effects, time effects and state specific time trends.

[9] https://www.isimip.org/outputdata/caveats-fast-track/

variation of yields vis-à-vis other GGCMs, thereby resulting in low residual variation for the weather variables to capture.

Compared to the $adj - R^2$ for maize and soybean, the $adj - R^2$ for wheat is generally low across all GGCMs, except for LPJ-GUESS and PEGASUS. GGCMs in ISIMIP-FT decide internally on the type of wheat to simulate. Preference to grow spring or winter wheat in GGCMs depend on temperature thresholds etc. (with some exceptions, e.g. LPJmL has preference for winter wheat, and PEGASUS simulates only spring wheat). Therefore, it is plausible that some variation in GGCMs' wheat yields can be attributed to weather exposure outside the choice of our growing season months ($AMJJA$). Nevertheless, by and large our specification (eq. 1 in main text) explain between one-fifth to half of the variance in each of the three crops and six GGCMs, and slightly lower in the multi-model regression specification.

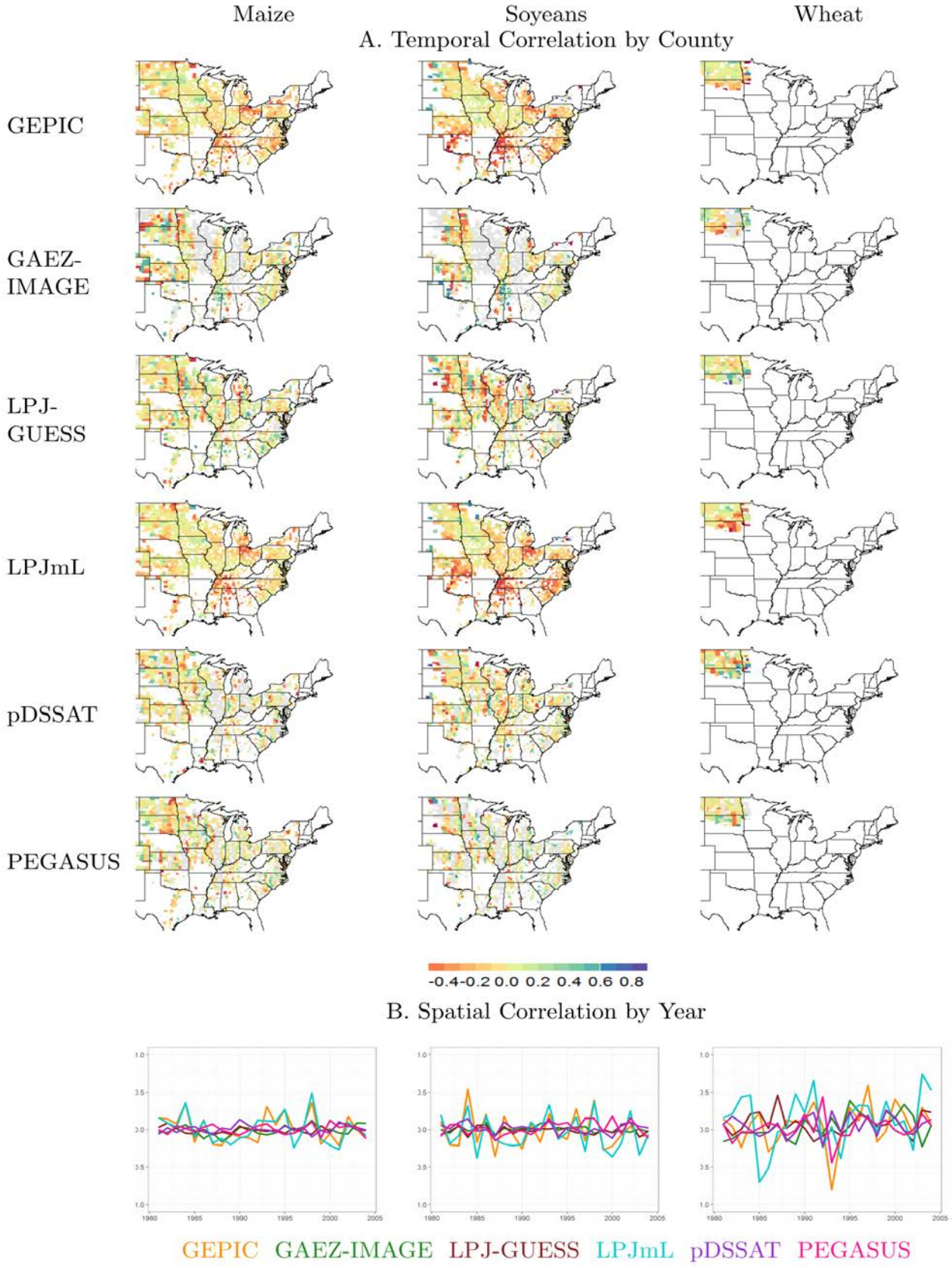

Fig. S3: Correlations between GGCM simulated and USDA recorded percentage anomalies in de-trended yields for maize, soybeans and wheat. Anomalies are calculated as the % deviation of each county's de-trended yield from its own 1981-2004 mean.

S6. Sensitivity checks using different regression specifications

To ensure that the estimate coefficient responses of GGCMs summarized in fig. 3 of main text did not depend on an overly specific choice of regression specification, and in line with common practice in statistical modelling (e.g. Urban *et al* 2015, Schlenker and Roberts 2009, Baylis *et al* 2011, Lobell *et al* 2011, Blanc 2016, Schauberger *et al* 2017), we consider two further suites of regression specifications.

S6.1 Mean responses of simulated yield using state time-trend specification for all GGCMs

Fig. S4 shows the mean responses of GGCMs' log $yields$ to temperature and precipitation exposure, using a specification with state specific time trend in lieu of time dummies. As highlighted in main text, GGCMs hold management practices and technology parameter constant to the year 2000 (although some GGCMs do include some endogenous form of adaptation (see table S6 for details), and therefore time effects are considered more appropriate for GGCMs. Nevertheless, for comparability with the empirical specification for USDA, we re-examine the GGCMs' estimated coefficient responses using state-specific time trends.

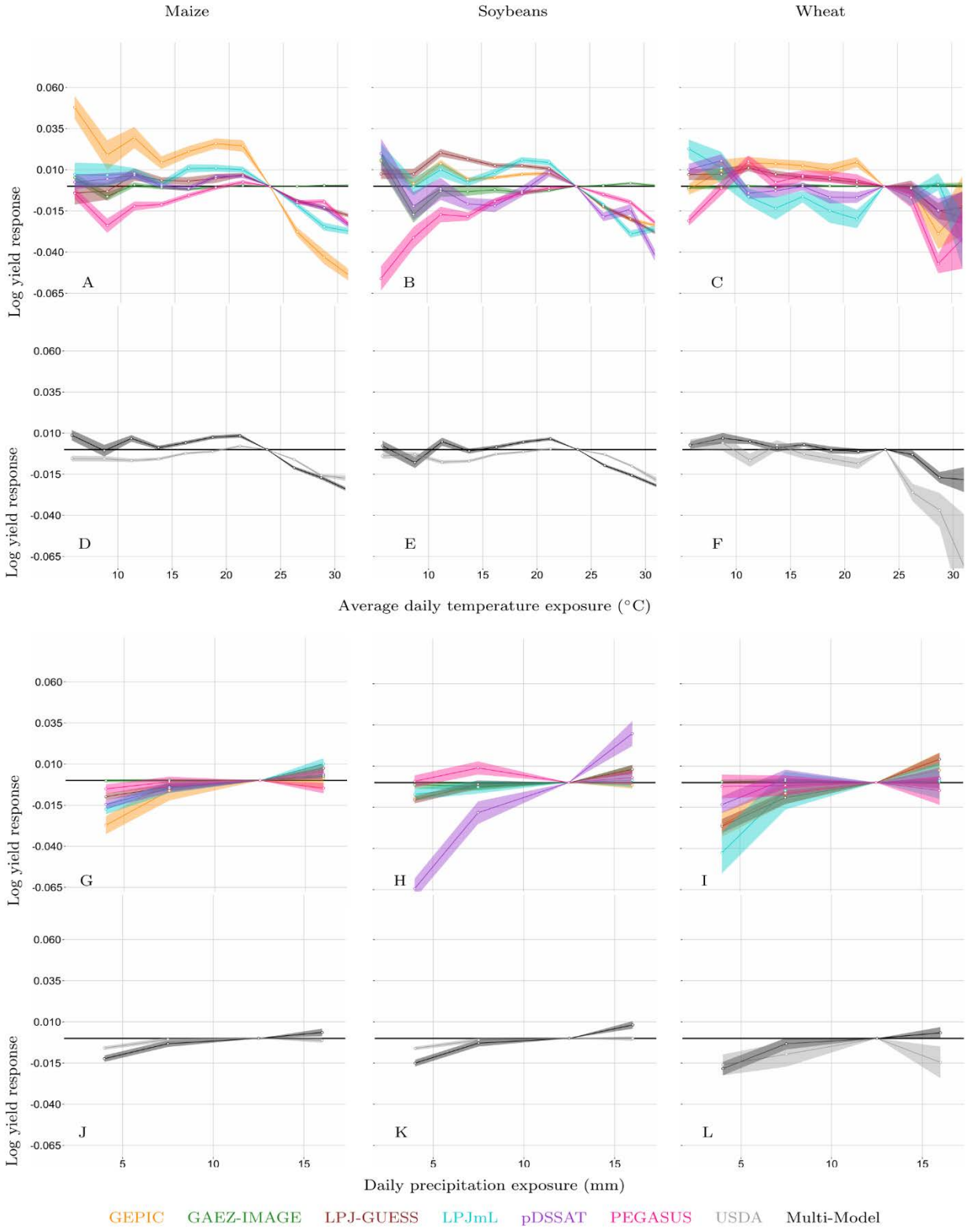

Fig. S4. Mean responses (solid lines) and confidence intervals (95%) (shaded areas) of log yield to temperature and precipitation exposure for maize, soybeans and wheat, with state time trends. Responses are normalized relative to the number of days with temperatures $22.5 - 25°C$ and precipitation $10 - 15\ mm/day$, represented by the heavy horizontal axis. Shaded confidence intervals are computed from robust standard errors clustered at the cross-sectional units. For USDA, the mean responses are from the same specification as in fig. 3 of main text.

As noted by other studies (e.g. Schlenker and Roberts 2009, Lobell *et al* 2011, Schauberger *et al* 2017); comparing figures 3 (main text) and S4, the responses of GGCMs' crop yields are robust to modification in econometric specifications.

S6.2 Mean responses of simulated yield using mean growing season temperature and precipitation

A similar pattern of nonlinear effects of temperature and precipitation remain if a commonly used parsimonious specification is utilized, instead of our semi-parametric binning approach. The use of mean growing season temperature (T), mean (or total) growing season precipitation (P) (eq. S1[10]), show that the generally heterogeneous responses of GGCMs' $log\ yield$ responses to the weather variables used in our study, generally disagree both in magnitude and response thresholds (figure S5) with the observed.

$$y_{i,t,m} = \mu_i + f(t) + \beta_1 T_{i,t,m} + \beta_2 T_{i,t,m}^2 + \beta_3 P_{i,t,m} + \beta_4 P_{i,t,m}^2 + \beta_5 T_{i,t,m} * P_{i,t,m} + \varepsilon_{i,t,m} \qquad \text{(S1)}$$

where T is the mean growing season (MJJA for maize and soybeans, AMJJA for wheat) temperature ($°C$), P is mean growing season precipitation (mm), and the remaining terms as per the nomenclature used in eq. 1 of main text. In lieu of mean growing season precipitation, total growing season precipitation was also examined (results are near similar and available upon request).

[10] For instance, see Lobell and Burke 2010, Lobell *et al* 2011, Blanc 2017 for a good discussion on the underlying reasons of choosing specifications with mean growing season variables and their quadratic terms, along with interactions between T and P.

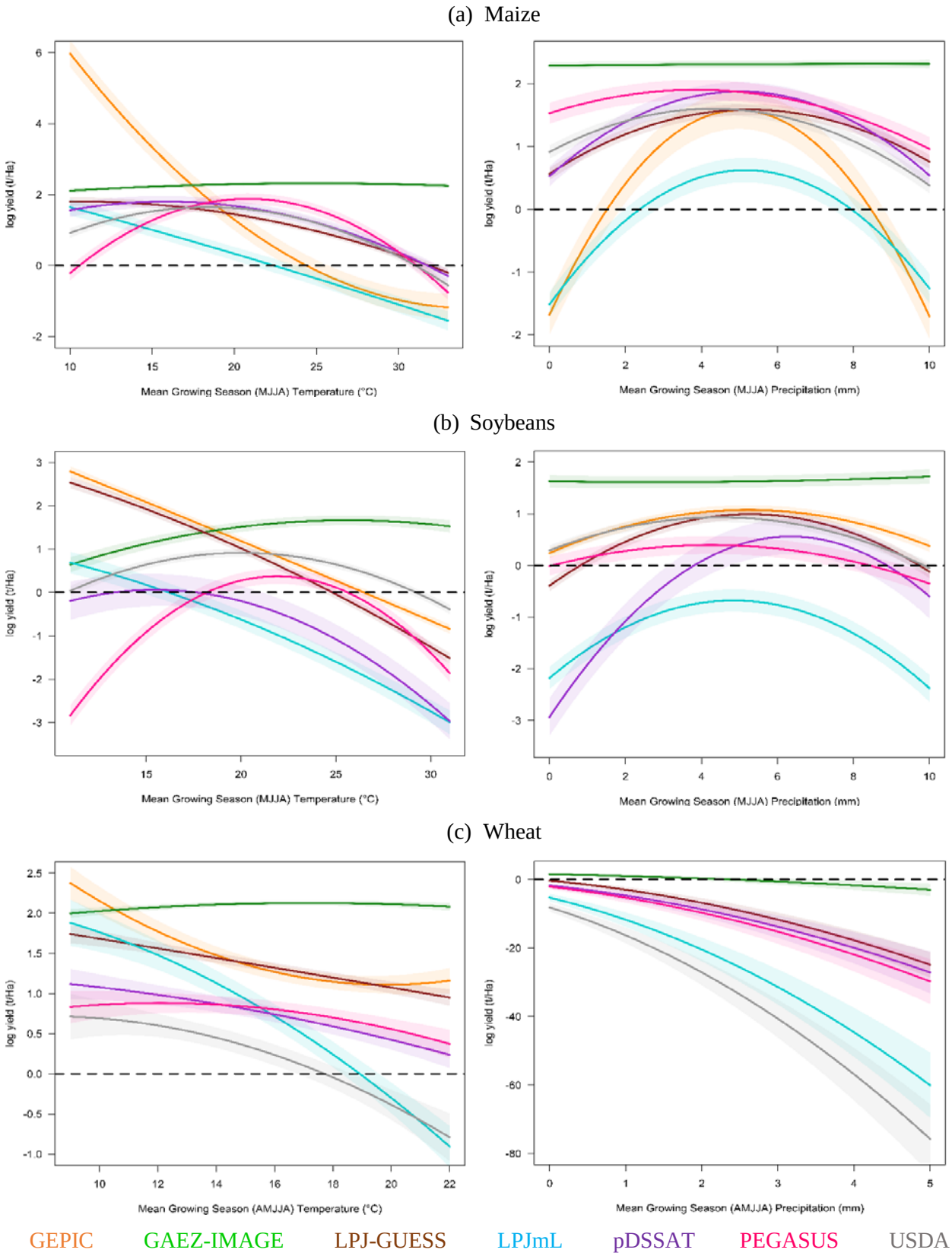

Fig. S5. Mean log *yields* responses (solid lines) and confidence intervals (95%) (shaded areas) to mean growing season temperature ($°C$) and precipitation (mm) exposure for (a) maize, (b) soybeans and (c) wheat (eq. S1). Horizontal dashed line (at y=0) shown for reference. Shaded confidence intervals are computed from robust standard errors clustered at the cross-sectional units. Growing seasons are defined as in main text (May-August for maize and soybeans, and April-August for wheat)

S7. Meta-Analyses

Using the five sets of characteristics (illustrated in bold in table S6), we construct binary variables for explanatory variables in the meta-analysis regression (eq. 5 in main text).

Table S6: Heterogeneity in GGCMs used in this study, adapted from Rosenzweig *et al* (2014).

Parameters	**GEPIC**	**GAEZ-IMAGE**	**LPJ-GUESS**	**LPJmL**	**pDSSAT**	**PEGASUS**
Model Type	Site-based	Agro-ecological zone (AEZ)	Agro-ecosystem	Agro-ecosystem	Site-based	Agro-ecosystem
Crop Yield	Actual	Potential	Potential	Actual	Actual	Actual
Crop Cultivars	Yes	Yes	Yes	No	No[a]	Yes
Planting window	Dynamic[b] (climate adaptation)	Implicit Planting dates (climate adaptation)	Fixed[c]	Fixed planting date	Fixed (by taking the historical average, for all years in future)	Dynamic (climate adaptation)
Nitrogen (N)[d] fertilization	Yes	No	No	No	Yes	Yes
Type of stress[e]	W, T, **H**, O_2, N, P, BD, Al	W, T, BD	W, T	W, T	W, T, **H**, O_2, N	W, T, **H**, N, P, K
Light Utilization (Photosynthesis)	Radiation use efficiency (RUE)	RUE	Leaf	Leaf	RUE (Leaf for Soybeans)	RUE
Model Calibration and Type_*SpatialResolution*	Yes Site-specific_*National*	No	No	Yes Global_*National*	Yes Site-specific_*Field-scale*	Yes Global_*Gridcell*
Method used in Evapotranspiration (ET) calculation	Penman-Monteith	Priestly-Taylor	Priestly-Taylor	Priestly-Taylor	Priestly-Taylor	Priestly-Taylor

[a] For pDSSAT, cultivar choice, fertilizer application etc. are fixed by the historical average of all future years.

[b] Dynamic: Automatic adjustments of planting and harvesting dates due to annual weather conditions; an internal model process.

[c] Fixed: planting windows are determined using historical values based on literature. LPJ-GUESS allows planting dates adaptation within +/-15 days of calculated optimum values, but planting window is fixed.

[d] For GEPIC, fertilizer application rate is adjusted flexibly according to Nitrogen (N) stress. pDSSAT and PEGASUS hold fertilizer application rates constant.

[e] Water (W), Temperature (T), Heat (H), Oxygen (O_2), Phosphorous (P), Bulk Density (BD), Aluminum (Al), Potassium (K)

We regress the vector of differences in combined set of estimated semi-elasticities from GGCMs and USDA, $\Delta\zeta(\widehat{\boldsymbol{\beta}}^T, \widehat{\boldsymbol{\beta}}^P) = \zeta\left(\widehat{\boldsymbol{\beta}}^T, \widehat{\boldsymbol{\beta}}^P\right)^{GGCM} - \zeta\left(\widehat{\boldsymbol{\beta}}^T, \widehat{\boldsymbol{\beta}}^P\right)^{USDA}$, using the set of parameters describing models' dimensions as a vector of dummies (Specification 1)[11]. We also test i) two additional models in which only the vector of differences in temperature (Specification 2) and precipitation (Specification 3) semi-elasticities are used as dependent variables[12] and ii) three additional models in which model parameter dummies are interacted with the extreme high temperature (*hi_t*) and low precipitation (*lo_p*) bins, namely as $\{25\sim27.5, 27.5\sim30, >30\}℃$ and $\{<5, 5\sim10\}mm/day$ (Specifications 4, 5, and 6). Specifications (1) and (4) enable us to examine the influence of GGCMs key parameter dimensions averaged across all temperature and precipitation bins. Specifications (4), (5), and (6) enable us to attribute the key parameters that influence the divergence in GGCMs' responses to the extreme temperature or precipitation bins.

[11] The dependent variable is the difference in the estimated coefficient of the 13 temperature and precipitation bins from eq. 1 of main text, for each of the 6 GGCMs (thus totalling 72 observations using the parameters in bold from table S6).

[12] Specifications 2 and 3 have 60 and 18 observations for the six GGCMs for temperature and precipitation, respectively.

Table S7: Effects of model characteristics on GGCM-USDA divergence in (A) soybeans and (B) wheat $log\ yield$ responses. Robust standard errors (S.E.) are reported in parenthesis

A. Soybeans

	(1) $\Delta\zeta[\widehat{\boldsymbol{\beta}}^P, \widehat{\boldsymbol{\beta}}^T]$	(2) $\Delta\zeta[\widehat{\boldsymbol{\beta}}^T]$	(3) $\Delta\zeta[\widehat{\boldsymbol{\beta}}^P]$	(4) $\Delta\zeta[\widehat{\boldsymbol{\beta}}^P, \widehat{\boldsymbol{\beta}}^T]$	(5) $\Delta\zeta[\widehat{\boldsymbol{\beta}}^T]$	(6) $\Delta\zeta[\widehat{\boldsymbol{\beta}}^P]$
Potential yield	-0.012*	-0.011*	0.002	-0.011**	-0.020***	0.003
	(0.006)	(0.006)	(0.003)	(0.005)	(0.006)	(0.007)
Endog. cultivar	0.022***	0.022***	0.001	0.029***	0.038***	0.005
	(0.007)	(0.007)	(0.002)	(0.006)	(0.007)	
Endog. sowing date	-0.007*	-0.008*		-0.018***	-0.018***	
	(0.004)	(0.005)		(0.003)	(0.003)	
Heat stress	-0.023***	-0.026***	0.008**	-0.025***	-0.037***	-0.002
	(0.008)	(0.008)	(0.003)	(0.009)	(0.009)	
Site calibration	-0.007	-0.004		0.004	-0.004	
	(0.005)	(0.004)		(0.004)	(0.004)	
$T > 30°C$						
× Potential yield				0.007	0.031***	
				(0.009)	(0.007)	
× Endog. cultivar				-0.028***	-0.053***	
				(0.009)	(0.008)	
× Endog. sowing date				0.033***	0.033***	
				(0.006)	(0.006)	
× Heat stress				0.008	0.035***	
				(0.010)	(0.009)	
× Site calibration				-0.023***		
				(0.005)		
$P < 5$mm						
× Potential yield				-0.020		-0.001
				(0.017)		(0.007)
× Endog. cultivar				0.002		-0.006***
				(0.017)		(0.001)
× Endog. sowing date				0.020***		
				(0.003)		
× Heat stress				0.004		0.014***
				(0.018)		(0.002)
× Site calibration				-0.037**		
				(0.016)		
Adj. F	4.289***	4.885***	1.553	42.577***	24.052***	2.325*
	(df = 4;77)	(df = 4;59)	(df = 2;17)	(df = 14;77)	(df = 8;59)	(df = 5;17)
Obs.	78	60	18	78	60	18
Adj R Sq.	0.128	0.190	-0.110	0.390	0.319	-0.339

*$p < 0.1$; **$p < 0.05$; ***$p < 0.01$

B. Wheat

	(1) $\Delta\zeta[\widehat{\boldsymbol{\beta}}^P, \widehat{\boldsymbol{\beta}}^T]$	(2) $\Delta\zeta[\widehat{\boldsymbol{\beta}}^T]$	(3) $\Delta\zeta[\widehat{\boldsymbol{\beta}}^P]$	(4) $\Delta\zeta[\widehat{\boldsymbol{\beta}}^P, \widehat{\boldsymbol{\beta}}^T]$	(5) $\Delta\zeta[\widehat{\boldsymbol{\beta}}^T]$	(6) $\Delta\zeta[\widehat{\boldsymbol{\beta}}^P]$
Potential yield	0.010	0.007	0.002	-0.006	0.0003	-0.004
	(0.009)	(0.011)	(0.008)	(0.005)	(0.007)	(0.004)
Endog. cultivar	0.008	0.014	0.009	0.020***	0.012	0.024***
	(0.010)	(0.013)	(0.007)	(0.005)	(0.007)	(0.000)
Endog. sowing date	-0.003	-0.006		-0.011***	-0.011***	
	(0.008)	(0.010)		(0.003)	(0.003)	
Heat stress	0.003	-0.0005	0.00004	-0.007	-0.0005	-0.010***
	(0.008)	(0.010)	(0.007)	(0.006)	(0.008)	(0.000)
Site calibration	0.015***	0.016***		0.008***	0.016***	
	(0.004)	(0.005)		(0.002)	(0.006)	
$T > 30°C$						
× Potential yield				0.049**	0.023	
				(0.023)	(0.020)	
× Endog. cultivar				-0.022	0.006	
				(0.027)	(0.024)	
× Endog. sowing date				0.015	0.015	
				(0.019)	(0.019)	
× Heat stress				0.027	-0.00002	
				(0.023)	(0.020)	
× Site calibration				0.027**		
				(0.011)		
$P < 5$mm						
× Potential yield				0.032***		0.009
				(0.006)		(0.006)
× Endog. cultivar				-0.046***		-0.023***
				(0.007)		(0.002)
× Endog. sowing date				0.025***		
				(0.005)		
× Heat stress				0.025***		0.015***
				(0.007)		(0.004)
× Site calibration				0.005		
				(0.003)		
Adj. F	4.289***	4.885***	1.553	42.577***	24.052***	2.325*
	(df = 4;77)	(df = 4;59)	(df = 2;17)	(df = 14;77)	(df = 8;59)	(df = 5;17)
Obs.	78	60	18	78	60	18
Adj. R Sq.	0.350	0.342	0.283	0.564	0.530	0.401

*$p < 0.1$; **$p < 0.05$; ***$p < 0.01$

Table S8. Two-sided Welch t-test for significant difference in regression coefficients (GGCM – USDA), based on robust standard errors clustered at the cross-sectional units. Test results in parenthesis are based on two-way clustered robust standard errors (Cameron *et al* 2011), clustered by the cross-sectional units and time.
H_0: Coefficients are not different

(a) **GEPIC**

T, P bins	Maize (Coeff diff)	t	Soybeans (Coeff diff)	t	Wheat (Coeff diff)	t
tas_7p5lo	0.081	25.430*** (3.117)***	0.035	23.979*** (3.841) ***	-0.001	-0.298 (-0.055)
tas_7p5_10	0.036	11.838*** (1.613)*	0.015	11.307*** (2.118) **	0.021	6.740*** (1.921) **
tas_10_12p5	0.037	14.664*** (3.120)***	0.023	22.413*** (4.107) ***	0.032	12.463*** (3.677) ***
tas_12p5_15	0.030	16.323*** (3.368)***	0.013	18.235*** (3.920) ***	0.017	8.209*** (2.501) ***
tas_15_17p5	0.028	18.182*** (2.943)***	0.011	17.989*** (3.425) ***	0.022	10.678*** (3.785) ***
tas_17p5_20	0.029	20.495*** (3.461)***	0.010	19.469*** (2.992) ***	0.017	8.582*** (2.818) ***
tas_20_22p5	0.016	11.850*** (3.285)***	0.006	10.478*** (2.600) ***	0.012	5.865*** (2.287) **
tas_25_27p5	-0.015	-11.570*** (-3.626)***	-0.008	-15.624*** (-4.884) ***	0.030	9.530*** (2.879) ***
tas_27p5_30	-0.009	-4.793*** (-1.229)	-0.006	-9.948*** (-1.721) *	0.015	2.496* (0.913)
tas_g30	-0.013	-7.272*** (-1.359)	0.003	2.858*** (0.598)	0.071	3.862*** (2.583) ***
p_5lo	-0.014	-5.821*** (-1.852)*	0.001	0.608 (0.173)	-0.001	-0.286 (-0.117)
p_5_10	-0.010	-3.632*** (-1.672)*	-0.002	-1.728* (-1.095)	0.004	0.973 (0.680)
p_15up	0.021	6.885*** (2.111)**	0.005	4.535*** (1.461)	0.024	4.360*** (1.968) **

(b) **GAEZ-IMAGE**

tas_7p5lo	0.010	8.082*** (1.573)	0.008	2.648*** (0.537)	-0.005	-2.786*** (-0.785)
tas_7p5_10	0.000	0.247 (0.054)	-0.008	-3.413*** (-0.817)	-0.006	-2.239* (-0.815)
tas_10_12p5	0.007	8.697*** (1.727)*	0.002	0.998 (0.191)	0.007	3.165*** (1.163)
tas_12p5_15	0.004	7.924*** (2.304)**	0.003	2.388** (0.461)	-0.003	-1.503* (-0.615)
tas_15_17p5	0.000	0.263 (0.055)	-0.005	-0.454 (-0..119)	0.003	1.671** (0.677)
tas_17p5_20	0.001	2.294** (0.534)	0.000	-0.058 (-0.011)	0.005	3.293*** (1.134)
tas_20_22p5	-0.002	-4.996*** (-1.512)	-0.003	-4.133*** (-1.176)	0.008	4.601*** (1.940) ****
tas_25_27p5	0.006	17.519*** (4.697)***	0.002	3.868*** (1.299)	0.025	9.287*** (2.954) ****
tas_27p5_30	0.016	35.298*** (8.543)***	0.012	21.418*** (4.374) ****	0.038	7.085*** (2.846) ****
tas_g30	0.018	20.674*** (5.645)***	0.021	20.476*** (5.248) ****	0.073	4.205*** (2.846) ****
p_5lo	0.006	9.092*** (2.061)**	0.004	3.528*** (1.035)	0.017	5.195*** (2.292) ****
p_5_10	0.001	1.289 (0.552)	0.001	0.614 (0.322)	0.011	2.806*** (1.907) ***
p_15up	0.003	2.818*** (0.895)	0.000	0.032 (0.013)	0.016	3.218*** (2.106) ****

$* p < 0.1; ** p < 0.05; *** p < 0.01$

(c) **LPJ-GUESS**

T, P bins	Maize (Coeff diff)	t	Soybeans (Coeff diff)	t	Wheat (Coeff diff)	t
tas_7p5lo	0.009	5.258*** (1.109)	0.022	12.752*** (2.116) **	0.011	5.037*** (1.463)
tas_7p5_10	0.007	4.997*** (1.005)	0.014	8.980*** (1.708) *	0.010	3.473*** (1.233)
tas_10_12p5	0.013	12.948*** (3.266)***	0.028	25.534*** (5.449) ***	0.021	9.453*** (3.297) ***
tas_12p5_15	0.010	10.204*** (3.766)***	0.024	27.641*** (7.043) ***	0.011	5.767*** (2.245) **
tas_15_17p5	0.007	9.749*** (2.938)***	0.018	24.705*** (5.820) ***	0.015	8.865*** (3.513) ***
tas_17p5_20	0.008	9.467*** (3.773)***	0.014	21.745*** (5.468) ***	0.012	6.996*** (2.421) **
tas_20_22p5	0.003	4.644*** (1.946)**	0.008	12.542*** (3.840) ***	0.008	4.337*** (1.809) *
tas_25_27p5	-0.001	-2.242** (-0.671)	-0.007	-11.706*** (-3.129) ***	0.024	8.499*** (2.761) ***
tas_27p5_30	0.006	9.137*** (2.674)***	-0.003	-3.795*** (-0.890)	0.028	5.028*** (1.972) **
tas_g30	0.004	4.408*** (1.129)	-0.002	-1.690*** (-0.317)	0.072	4.054*** (2.684) ***
p_5lo	0.001	0.566*** (0.161)	0.001	0.506 (0.149)	-0.003	-0.827 (-0.358)
p_5_10	-0.003	-2.372** (-1.613)*	-0.001	-0.800 (-0.495)	0.002	0.510 (0.342)
p_15up	0.011	9.233*** (3.058)***	0.016	12.330*** (2.961) ***	0.025	4.806*** (2.925) ***

(d) **LPJmL**

tas_7p5lo	0.029	11.194*** (1.562)*****	0.051	17.244*** (3.505) ***	0.038	6.950*** (2.142) **
tas_7p5_10	0.016	7.220*** (1.953)**	0.010	4.247*** (0.810)	0.036	8.351*** (2.662) *******
tas_10_12p5	0.015	9.835*** (2.027)**	0.016	8.577*** (1.792) **	0.032	10.327*** (3.295) *******
tas_12p5_15	0.010	8.498*** (1.992)**	0.013	10.827*** (2.653) ***	0.008	3.248*** (0.852)
tas_15_17p5	0.017	17.117*** (4.636)***	0.019	17.759*** (3.293) ***	0.014	6.301*** (2.026) ******
tas_17p5_20	0.015	14.451*** (2.948)***	0.019	18.798*** (3.112) ***	0.005	2.202** (0.565)
tas_20_22p5	0.006	7.886*** (2.628)***	0.014	15.460*** (3.780) ***	-0.001	-0.299 (-0.110)
tas_25_27p5	-0.003	-4.021*** (-0.896)	-0.005	-7.0346*** (-1.504)	0.015	4.419*** (1.416)
tas_27p5_30	-0.000	-0.248 (-0.073)	-0.008	-8.042*** (-1.648) *	0.026	4.382*** (1.691) *****
tas_g30	-0.002	-1.852* (-0.353)	0.004	3.353*** (0.433)	0.016	0.792 (0.559)
p_5lo	-0.009	-6.164*** (-1.827)**	0.003	1.458 (0.554)	0.005	0.950 (0.338)
p_5_10	-0.006	-3.526*** (-1.749)**	-0.004	-2.102** (-1.119)	0.018	3.272*** (1.656) *****
p_15up	0.018	10.533*** (2.601)***	0.0144	6.593*** (1.679) *	-0.001	-0.192 (-0.109)

$* p < 0.1; ** p < 0.05; *** p < 0.01$

(e) **pDSSAT**

T, P bins	Maize (Coeff diff)	t	Soybeans (Coeff diff)	t	Wheat (Coeff diff)	t
tas_7p5lo	0.012	6.584*** (1.350)	0.011	2.418** (0.456)	0.000	-0.233 (-0.088)
tas_7p5_10	0.010	6.025*** (1.265)	0.014	3.836*** (0.884)	0.014	4.902*** (1.868) *
tas_10_12p5	0.009	7.405*** (1.875)**	0.004	1.457*** (0.422)	0.015	6.274*** (2.186) **
tas_12p5_15	0.006	6.622*** (1.799)**	-0.008	-3.997 (-0.800)	0.002	0.974 (0.352)
tas_15_17p5	0.001	1.316*** (0.308)	-0.011	-5.509*** (-1.117)	0.009	5.0493*** (1.907) *
tas_17p5_20	0.007	8.705*** (2.230)**	-0.001	-0.676 (-0.148)	0.005	3.041*** (1.090)
tas_20_22p5	0.003	4.218*** (1.895)*	0.006	4.451*** (0.966)	0.004	2.130*** (0.759)
tas_25_27p5	-0.003	-3.679*** (-1.470)	-0.020	-15.169*** (-4.568) ***	0.027	8.022*** (2.840) ***
tas_27p5_30	0.006	6.349*** (1.657)*	-0.012	-8.231*** (-2.160) **	0.021	3.468*** (1.361)
tas_g30	0.000	0.104 (0.027)	-0.026	-14.603*** (-1.731) *	0.058	3.078*** (2.210) **
p_5lo	-0.006	-4.697*** (-1.405)	-0.054	-18.059*** (-6.630) ***	0.010	2.925*** (1.198)
p_5_10	-0.004	-2.907*** (-1.566)*	-0.014	-4.291*** (-1.739) *	0.016	3.755*** (2.385) **
p_15up	0.009	5.756*** (1.885)*	0.014	4.061*** (1.493)	0.0152	2.788*** (1.797) *

(f) **PEGASUS**

tas_7p5lo	-0.007	-3.913*** (-0.781)	-0.056	-17.536*** (-2.172) **	-0.017	-6.157*** (-1.199)
tas_7p5_10	-0.020	-11.593*** (-2.676)***	-0.021	-7.791*** (-1.886) *	-0.012	-4.099*** (-0.996)
tas_10_12p5	-0.013	-9.563*** (-2.276)**	-0.014	-7.192*** (-1.652) *	0.011	4.340*** (1.316)
tas_12p5_15	-0.010	-10.809*** (-2.116)**	-0.016	-14.101*** (-2.221) **	-0.001	-0.765 (-0.296)
tas_15_17p5	-0.005	-6.872*** (-1.402)	-0.006	-6.292*** (-1.137)	0.008	3.509*** (1.152)
tas_17p5_20	-0.001	-1.956*** (-0.448)	-0.001	-1.306 (-0.326)	0.008	3.805*** (1.157)
tas_20_22p5	0.000	-0.416*** (-0.126)	-0.001	-2.259** (-0.658)	0.008	3.809*** (1.410)
tas_25_27p5	-0.003	-4.365*** (-1.338)	-0.004	-4.998*** (-1.765) *	0.022	6.280*** (2.056)**
tas_27p5_30	0.006	6.139*** (1.835)*	0.002	2.331** (0.512)	-0.003	-0.456 (-0.146)
tas_g30	-0.004	-3.794*** (-0.883)	-0.001	-0.563 (-0.134)	0.046	2.485** (1.693)*
p_5lo	0.004	2.935*** (0.938)	0.014	7.655*** (2.844) ***	0.010	2.608** (0.998)
p_5_10	0.000	0.451 (0.264)	0.010	5.128*** (2.947) ***	0.003	0.679 (0.410)
p_15up	-0.003	-1.879* (-0.656)	0.003	1.566 (0.560)	0.014	2.665** (1.162)

$* p < 0.1; ** p < 0.05; *** p < 0.01$

(g) **Multi-GGCM**

T, P bins	Maize (Coeff diff)	t	Soybeans (Coeff diff)	t	Wheat (Coeff diff)	t
tas_7p5lo	0.022	15.798*** (2.291)**	0.012	7.301*** (1.082)	0.004	2.013** (0.548)
tas_7p5_10	0.008	6.082*** (1.084)	0.005	4.089*** (0.695)	0.010	4.062*** (1.327)
tas_10_12p5	0.011	11.623*** (2.374)**	0.012	10.623*** (2.373)**	0.019	9.122*** (3.156)**
tas_12p5_15	0.008	11.104*** (2.728)***	0.005	7.000*** (1.661)*	0.005	3.167*** (1.199)
tas_15_17p5	0.008	12.405*** (2.583)***	0.007	10.719*** (2.490)***	0.012	7.014*** (2.808)**
tas_17p5_20	0.009	16.146*** (3.470)***	0.007	13.917*** (3.098)***	0.009	5.265*** (1.788)*
tas_20_22p5	0.004	7.808*** (2.964)***	0.005	9.263*** (2.560)***	0.007	3.615*** (1.490)
tas_25_27p5	-0.003	-5.794*** (-1.645)*	-0.007	-13.102*** (-4.670)***	0.024	8.455*** (2.703)***
tas_27p5_30	0.003	6.133*** (1.473)	-0.003	-4.329*** (-0.831)	0.021	3.829*** (1.538)*
tas_g30	0.001	0.673 (0.161)	0.002	2.530** (0.686)	0.055	3.153*** (2.153)**
p_5lo	-0.003	-3.152*** (-0.887)	-0.004	-4.613*** (-1.381)	0.006	1.877* (0.794)
p_5_10	-0.003	-3.097*** (-1.557)*	-0.002	-1.286 (-0.695)	0.009	2.263** (1.484)
p_15up	0.010	7.916*** (2.113)**	0.009	7.337*** (2.692)***	0.015	3.072*** (1.760)*

$*\,p < 0.1; **\,p < 0.05; ***\,p < 0.01$

Table S9. Mid (2033~2065)- and end-century (2067~2099) (in parenthesis) % change in aggregated production under RCP 8.5 warming scenario simulated by HadGEM2-ES, due to extreme high temperature ($T > 30\ °C$) days. The projected % change in production is aggregated for the sample of counties shown in maps of Fig. 5 (main text).

GGCM	Maize	Soybeans	Wheat
GEPIC	-47% (-72%)	-35% (-55%)	-9% (-52%)
GAEZ-IMAGE	1% (3%)	4% (7%)	0% (-4%)
LPJ-GUESS	-26% (-45%)	-42% (-63%)	-7% (-42%)
LPJmL	-35% (-59%)	-33% (-52%)	-46% (-66%)
pDSSAT	-32% (-54%)	-64% (-86%)	-30% (-35%)
PEGASUS	-38% (-62%)	-40% (-61%)	-37% (-44%)
Multi-GGCM	-32% (-53%)	-35% (-56%)	-33% (-42%)
USDA	-32% (-54%)	-39% (-60%)	-53% (-73%)

S8. Average change in exposure across HadGEM2-ES temperature and precipitation bins in RCP 8.5 scenario, relative to historical (1981-2004)

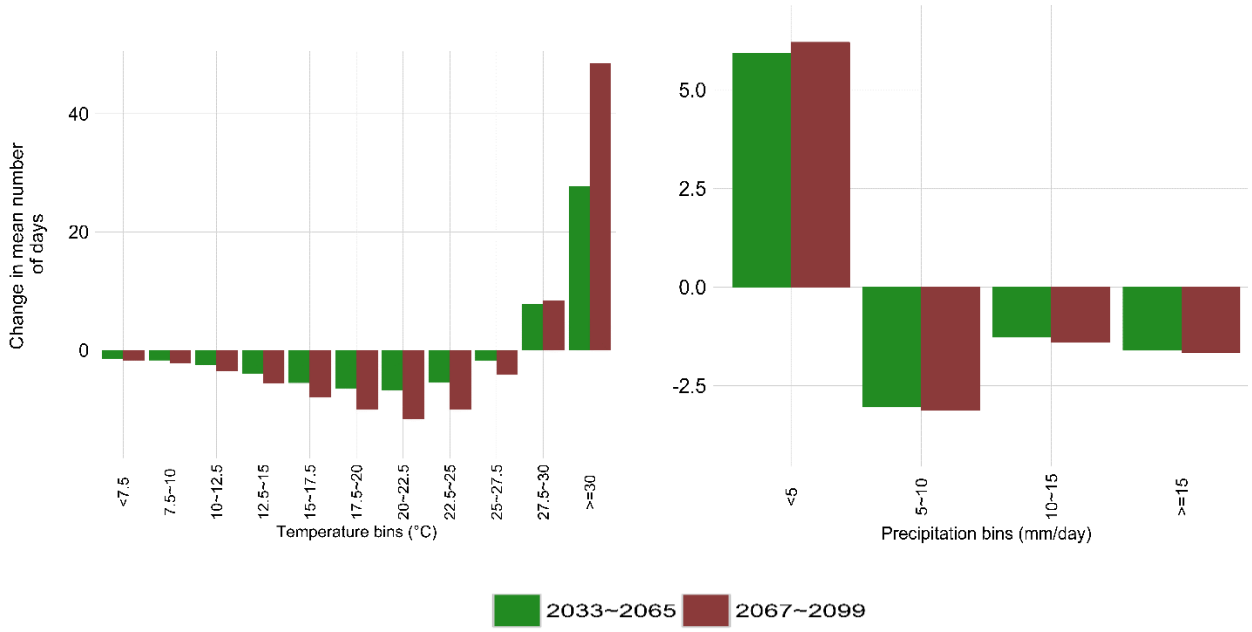

Fig. S6. Change in distribution of HadGEM2-ES temperature and precipitation bins, for two mean future periods in RCP 8.5 scenario.

The change in number of days is computed by first averaging the number of days (in each bin) in each USDA crop county, for the historical and future periods. The average number of days (in each bin) are then computed over all counties. The difference is calculated as future period – historical period.

Supplementary References

Auffhammer M, Hsiang S M, Schlenker W and Sobel A 2013 Using Weather Data and Climate Model Output in Economic Analyses of Climate Change *Rev. Environ. Econ. Policy* **7** 181–98 Online: http://reep.oxfordjournals.org/content/7/2/181.abstract

Baylis K, Paulson N D and Piras G 2011 Spatial Approaches to Panel Data in Agricultural Economics : A Climate Change Application **3** 325–38

Blanc É 2017 Statistical emulators of maize, rice, soybean and wheat yields from global gridded crop models *Agric. For. Meteorol.* **236** 145–61 Online: http://linkinghub.elsevier.com/retrieve/pii/S0168192316307493

BONDEAU A, SMITH P C, ZAEHLE S, SCHAPHOFF S, LUCHT W, CRAMER W, GERTEN D, LOTZE-CAMPEN H, MÜLLER C, REICHSTEIN M and SMITH B 2007 Modelling the role of agriculture for the 20th century global terrestrial carbon balance *Glob. Chang. Biol.* **13** 679–706 Online: http://doi.wiley.com/10.1111/j.1365-2486.2006.01305.x

Bouwman A.F., Kram T. and G K K 2006 *Integrated modelling of global environment change. An overview of IMAGE 2.4.*

Cameron A C, Gelbach J B and Miller D L 2011 Robust Inference With Multiway Clustering *J. Bus. Econ. Stat.* **29** 238–49 Online: http://www.tandfonline.com/doi/abs/10.1198/jbes.2010.07136

Daly C, Halbleib M, Smith J I, Gibson W P, Doggett M K, Taylor G H, Curtis J and Pasteris P P 2008 Physiographically sensitive mapping of climatological temperature and precipitation across the conterminous United States *Int. J. Climatol.* **28** 2031–64 Online: http://doi.wiley.com/10.1002/joc.1688

Deryng D, Sacks W J J, Barford C C C and Ramankutty N 2011 Simulating the effects of climate and agricultural management practices on global crop yield *Global Biogeochem. Cycles* **25**n/a-n/a Online: http://www.agu.org/pubs/crossref/2011/2009GB003765.shtml

Elliott J, Kelly D, Best N, Wilde M, Glotter M and Foster I 2013 The Parallel System for Integrating Impact Models and Sectors (pSIMS) *Proceedings of the Conference on Extreme Science and Engineering Discovery Environment: Gateway to Discovery* XSEDE '13 (New York, NY, USA: ACM) p 21:1--21:8 Online: http://doi.acm.org/10.1145/2484762.2484814

Gaure S 2013 lfe: Linear Group Fixed Effects *R J.* **5** 104–117 Online: http://journal.r-project.org/archive/2013-2/gaure.pdf

Hempel S, Frieler K, Warszawski L, Schewe J and Piontek F 2013 A trend-preserving bias correction – The ISI-MIP approach *Earth Syst. Dyn.* **4** 219–36

Jones C D, Hughes J K, Bellouin N, Hardiman S C, Jones G S, Knight J, Liddicoat S, O'Connor F M, Andres R J, Bell C, Boo K O, Bozzo A, Butchart N, Cadule P, Corbin K D, Doutriaux-Boucher M, Friedlingstein P, Gornall J, Gray L, Halloran P R, Hurtt G, Ingram W J, Lamarque J F, Law R M, Meinshausen M, Osprey S, Palin E J, Parsons Chini L, Raddatz T, Sanderson M G, Sellar A A, Schurer A, Valdes P, Wood N, Woodward S, Yoshioka M and Zerroukat M 2011 The HadGEM2-ES implementation of CMIP5 centennial simulations *Geosci. Model Dev.* **4** 543–70

Jones J W, Hoogenboom G, Porter C H, Boote K J, Batchelor W D, Hunt L A, Wilkens P W, Singh U, Gijsman A J and Ritchie J T 2003 The {DSSAT} cropping system model *Eur. J. Agron.* **18** 235–65 Online: http://www.sciencedirect.com/science/article/pii/S1161030102001077

Liu J, Williams J R, Zehnder A J B and Yang H 2007 GEPIC – modelling wheat yield and crop water productivity with high resolution on a global scale *Agric. Syst.* **94** 478–93

Lobell D B and Burke M B 2010 On the use of statistical models to predict crop yield responses to

climate change *Agric. For. Meteorol.* Online: http://dx.doi.org/10.1016/j.agrformet.2010.07.008

Lobell D B and Field C B 2007 Global scale climate–crop yield relationships and the impacts of recent warming *Environ. Res. Lett.* **2** 14002

Lobell D B, Schlenker W and Costa-Roberts J 2011 Climate trends and global crop production since 1980. *Science* **333** 616–20

Roberts M J, Schlenker W and Eyer J 2013 Agronomic Weather Measures in Econometric Models of Crop Yield with Implications for Climate Change *Am. J. Agric. Econ.* **95** 236 Online: +

Rosenzweig C, Elliott J, Deryng D, Ruane A C, Müller C, Arneth A, Boote K J, Folberth C, Glotter M, Khabarov N, Neumann K, Piontek F, Pugh T a M, Schmid E, Stehfest E, Yang H and Jones J W 2014 Assessing agricultural risks of climate change in the 21st century in a global gridded crop model intercomparison. *Proc. Natl. Acad. Sci. U. S. A.* **111** 3268–73 Online: http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=3948251&tool=pmcentrez&rendertype=abstract

Schauberger B, Archontoulis S, Arneth A, Balkovic J, Ciais P, Deryng D, Elliott J, Folberth C, Khabarov N, Müller C, Pugh T A M, Rolinski S, Schaphoff S, Schmid E, Wang X, Schlenker W and Frieler K 2017 Consistent negative response of US crops to high temperatures in observations and crop models *Nat. Commun.* 8

Schlenker W and Roberts M J 2006a Estimating the impact of climate change on crop yields: The importance of nonlinear temperature effects Online: http://www.nber.org/papers/w13799

Schlenker W and Roberts M J 2006b Nonlinear Effects of Weather on Corn Yields* *Appl. Econ. Perspect. Policy* **28** 391 Online: +

Schlenker W and Roberts M J 2009 Nonlinear temperature effects indicate severe damages to U.S. crop yields under climate change. *Proc. Natl. Acad. Sci. U. S. A.* **106** 15594–8

Sitch S, Smith B, Prentice I C, Arneth A, Bondeau A, Cramer W, Kaplan J O, Levis S, Lucht W, Sykes M T, Thonicke K and Venevsky S 2003 Evaluation of ecosystem dynamics, plant geography and terrestrial carbon cycling in the LPJ dynamic global vegetation model *Glob. Chang. Biol.* **9** 161–85 Online: http://doi.wiley.com/10.1046/j.1365-2486.2003.00569.x

Urban D W, Sheffield J and Lobell D B 2015 The impacts of future climate and carbon dioxide changes on the average and variability of US maize yields under two emission scenarios *Environ. Res. Lett.* **10** 45003 Online: http://stacks.iop.org/1748-9326/10/i=4/a=045003?key=crossref.58e5b11cc0b47418b44a35b4a231f5fc