POTSDAM INSTITUTE FOR CLIMATE IMPACT RESEARCH

Comprehensive global climate impact assessment for crop yields

Christoph Müller[1],
James Franke[2], Jens Heinke[1], Jonas Jägermeyr[1,2,3], Alexander Ruane[3], Joshua Elliott[2], Elisabeth Moyer[2], Marie Dury[4], Pete Falloon[5], Christian Folberth[6], Louis Francois[4], Tobias Hank[7], Cesar Izaurralde[8], Ingrid Jacquemin[4], Curtis Jones[8], Wenfeng Liu[9], Stefan Olin[10], Thomas A. M. Pugh[11], Ashwan Reddy[8], Karina Williams[5], Florian Zabel[7]

[1] Potsdam Institute for Climate Impact Research, Germany [2] University of Chicago, USA [3] NASA, USA [4] University of Liège, Belgium [5] Met Office Hadley Centre, United Kingdom [6] International Institute for Applied Systems Analysis, Austria [7] Ludwig-Maximilians-Universität, Germany [8] University of Maryland, USA [9] EAWAG, Switzerland [10] Lund University, Sweden [11] University of Birmingham, United Kingdom

Climate change impact assessments are often incomplete

- Sparse sampling of scenarios, models and crops
- Very high computational requirements
- Large uncertainties in drivers (climate scenarios, management) and modeled responses make interpretations of results from sparse sampling difficult
- We here employ potent, light-weight crop model emulators for
  - 9 different global gridded crop models
- to simulate crop yield impacts across the full CMIP5 and CMIP6 climate projections for
  - RCP2.6,
  - RCP4.5, and
  - RCP8.5

Step 1, the basis: the CTWN-A Experiment

The CTWN-A data cube: Regular disturbances of 31-year AgMERRA weather data

- **C**arbon dioxide: 360, 510, 660, 810 ppm (n_C=4)
- **T**emperatures: -1°C to +6°C, skipping 5°C (n_T=7)
- **W**ater supply: -50 to +30, skipping -40 + fully irrigated (n_W=9)
- **N**itrogen supply: 10, 60, 200 kgN/ha (n_N=3)
- **A**daptation: regain lost growing season under warming (yes/no)

The full CTWN-A experiment is described by Franke et al. (2019).

Step 2: The CTWN-A crop yield emulators

$$
\begin{aligned}
Y &= K_1 \\
&+ K_2 C + K_3 T + K_4 W + K_5 N + K_6 C^2 \\
&+ K_7 T^2 + K_8 W^2 + K_9 N^2 + K_{10} CW \\
&+ K_{11} CN + K_{12} TW + K_{13} TN + K_{14} WN \\
&+ K_{15} CT + K_{16} T^3 + K_{17} W^3 + K_{18} C^3 + K_* N^3 \\
&+ K_{19} TWN + K_{20} T^2 W + K_{21} W^2 + K_{22} W^2 N \\
&+ K_{23} CWN + K_{24} CTN + K_{25} CTW + K_{26} N^2 C \\
&+ K_{27} N^2 T + K_{28} N^2 W + K_{29} T^2 N + K_{30} T^2 C \\
&+ K_{31} W^2 C + K_{32} C^2 W + K_{33} C^2 T + K_{34} C^2 N
\end{aligned}
$$

The CTWN-A emulators are trained on the CTWN-A data cube, fitting a 3rd-order polynomial regression model

- for each 0.5°grid cell, crop and crop model with
- C, T, W, and N as regressors and
- fitting individual models for irrigated and rainfed as well as adapted (A1) and non-adapted (A0) systems.

They can well reproduce simulated climate change impact scenarios, including simulations based on GCM projections with inter-annual variability.

The full CTWN-A emulator suite is described by Franke et al. (2020).

Step 3: the CMIP5 and 6 archives

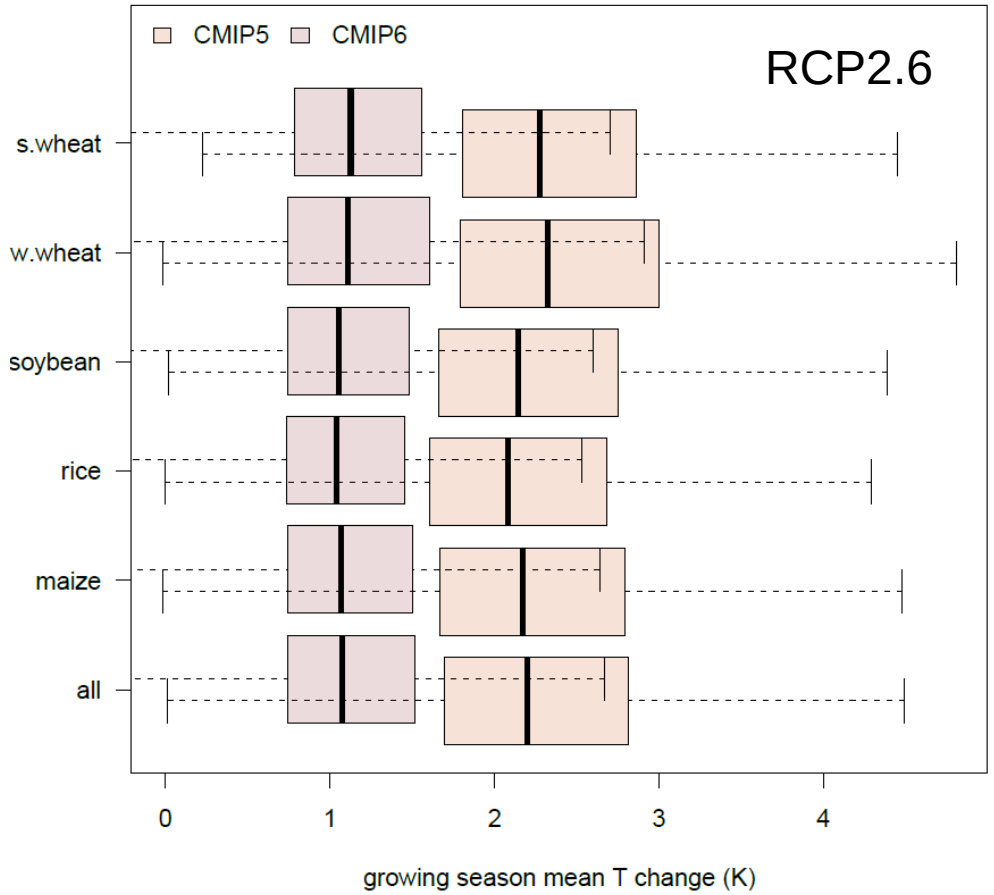
- **All models that provided monthly daily mean near surface air temperature (tas) and monthly precipitation (pr) values**
  - **CMIP5: 45 models, CMIP6: 29 models**

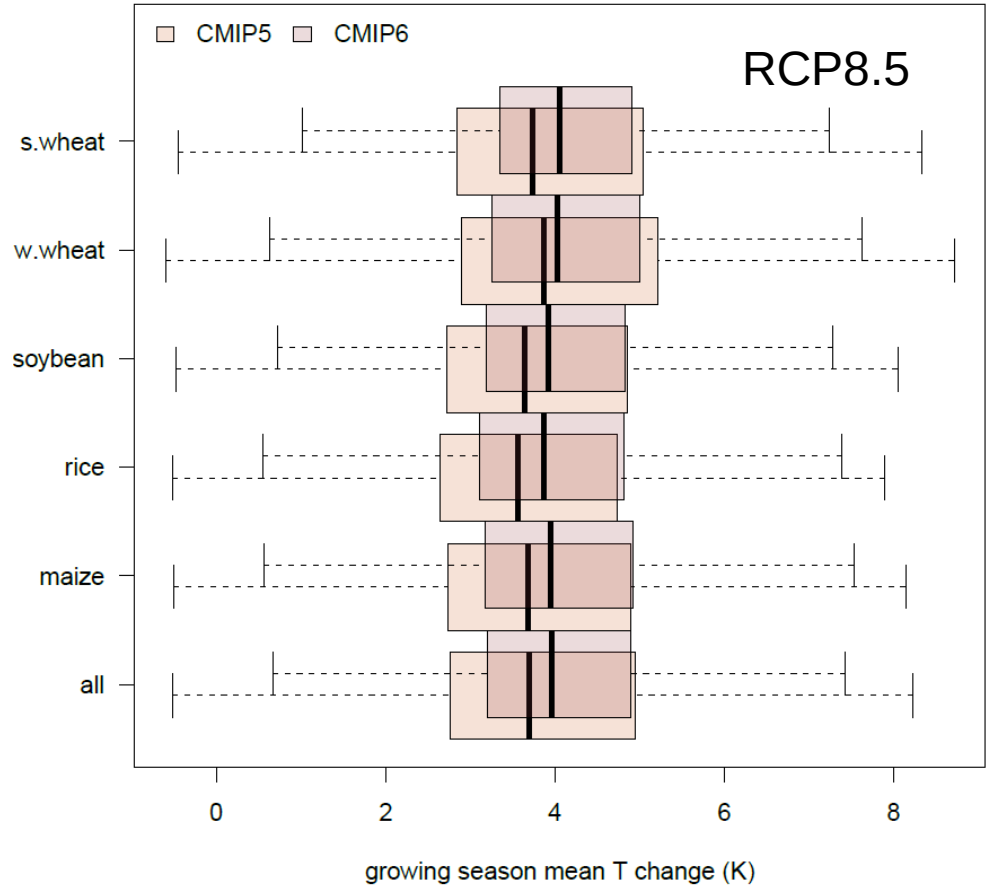
	ACCESS1-0	ACCESS1-3	BCC-CSM1-1	BCC-CSM1-1-M	BNU-ESM	CanESM2	CCSM4	CESM1-BGC	CESM1-CAM5	CESM1-WACCM	CMCC-CESM	CMCC-CM	CMCC-CMS	CNRM-CM5	CSIRO-Mk3-6-0	EC-EARTH	FGOALS-g2	FIO-ESM	GFDL-CM3	GFDL-ESM2G	GFDL-ESM2M	GISS-E2-H	GISS-E2-H	GISS-E2-H	GISS-E2-H-CC	GISS-E2-R	GISS-E2-R	GISS-E2-R	GISS-E2-R-CC	HadGEM2-AO	HadGEM2-CC	HadGEM2-ES	INMCM4	IPSL-CM5A-LR	IPSL-CM5A-MR	IPSL-CM5B-LR	MIROC-ESM	MIROC-ESM-CHEM	MIROC5	MPI-ESM-LR	MPI-ESM-MR	MRI-CGCM3	MRI-ESM1	NorESM1-M	NorESM1-ME
RCP 2.6			X	X	X	X	X		X	X				X	X	X	X	X	X	X	X	X	X	X		X	X	X		X		X		X	X		X	X	X	X	X	X			X	X
RCP 4.5	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X			X	X
RCP 8.5	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X

	ACCESS-CM2	ACCESS-ESM1-5	BCC-CSM2-MR	CAMS-CSM1-0	CESM2	CESM2-WACCM	CNRM-CM6-1	CNRM-ESM2-1	CanESM5p1	CanESM5p2	CanESM5-CanOE	EC-Earth3	EC-Earth3-Veg	FGOALS-f3-L	FGOALS-g3	FIO-ESM-2-0	GFDL-CM4	GFDL-ESM4	GISS-E2-1-G	HadGEM3-GC31-LL	IPSL-CM6A-LR	KACE-1-0-G	MIROC6	MPI-ESM1-2-LR	MRI-ESM2-0	NESM3	NorESM2-LM	NorESM2-MM	UKESM1-0-LL
SSP1 RCP 2.6	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X			X	X	X	X	X	X	X	X	X	X	X
SSP2 RCP 4.5	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X			X	X	X	X	X	X	X	X	X	X	X
SSP5 RCP 8.5	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X

Step 6a: growing season changes (1980-2010 vs. 2069-2099) in T

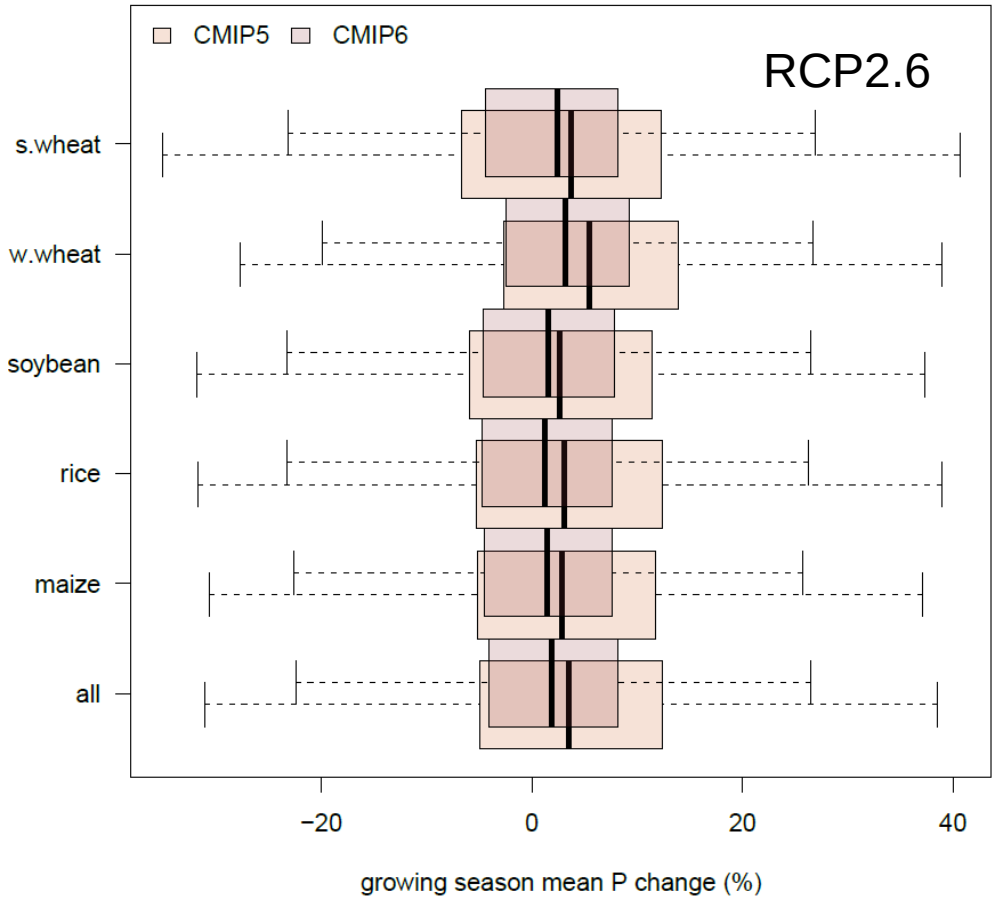
- **CMIP6 cooler in RCP2.6 and warmer in RCP8.5**
- **ensemble and ensemble range smaller in CMIP6**

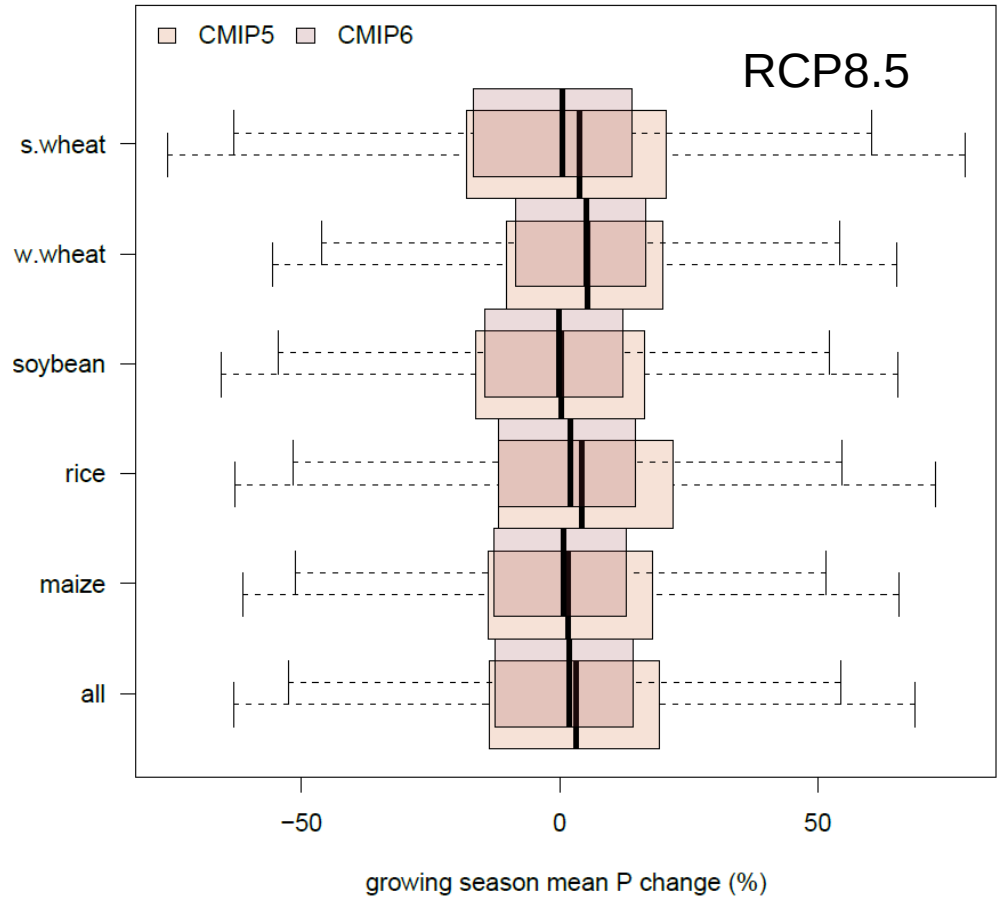




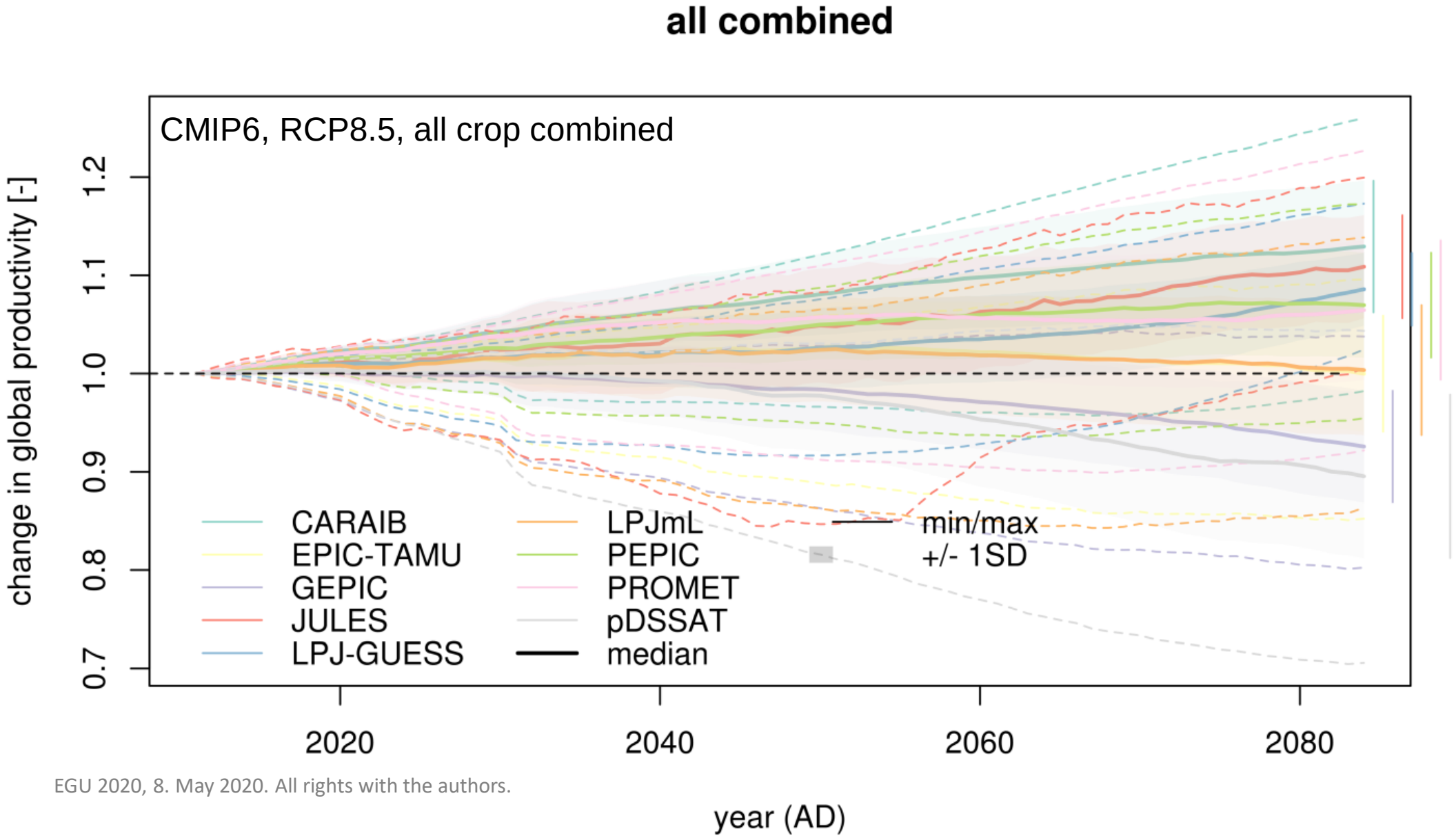
Step 6b: growing season changes (1980-2010 vs. 2069-2099) in P

- **wetter future, but CMIP6 dryer than CMIP5**
- **ensemble and ensemble range smaller in CMIP6**

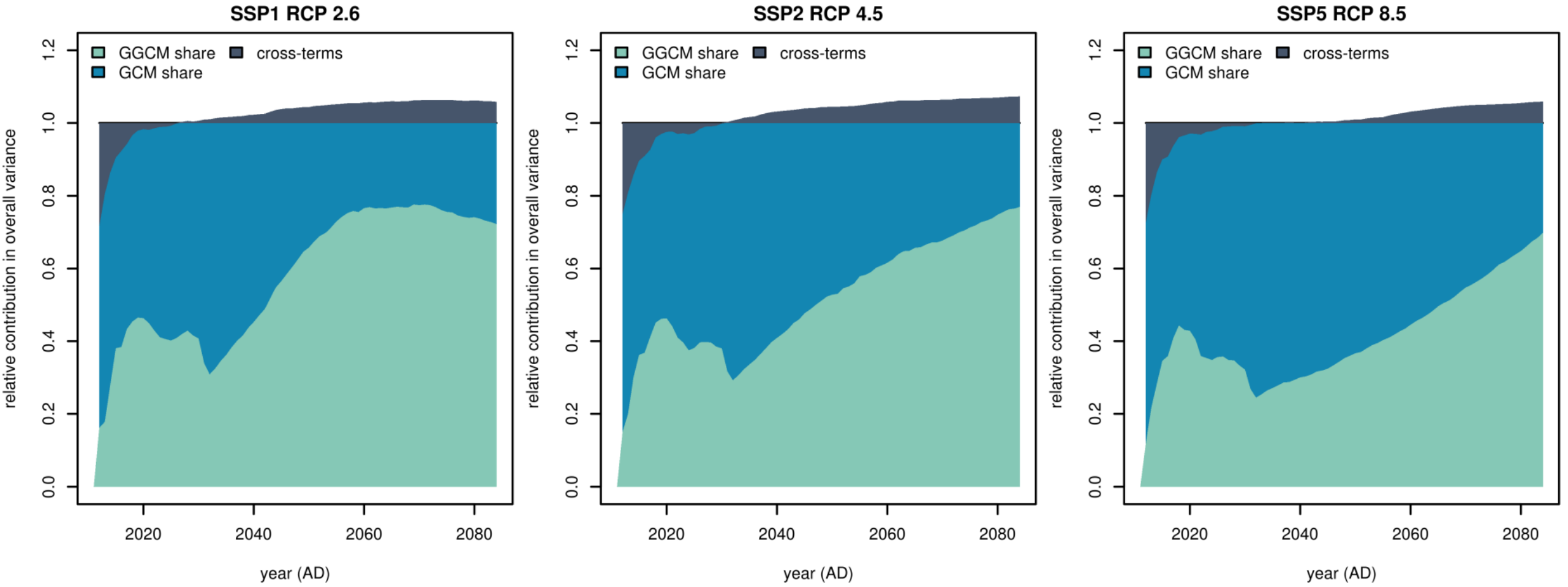




Step 7: emulated yield impacts

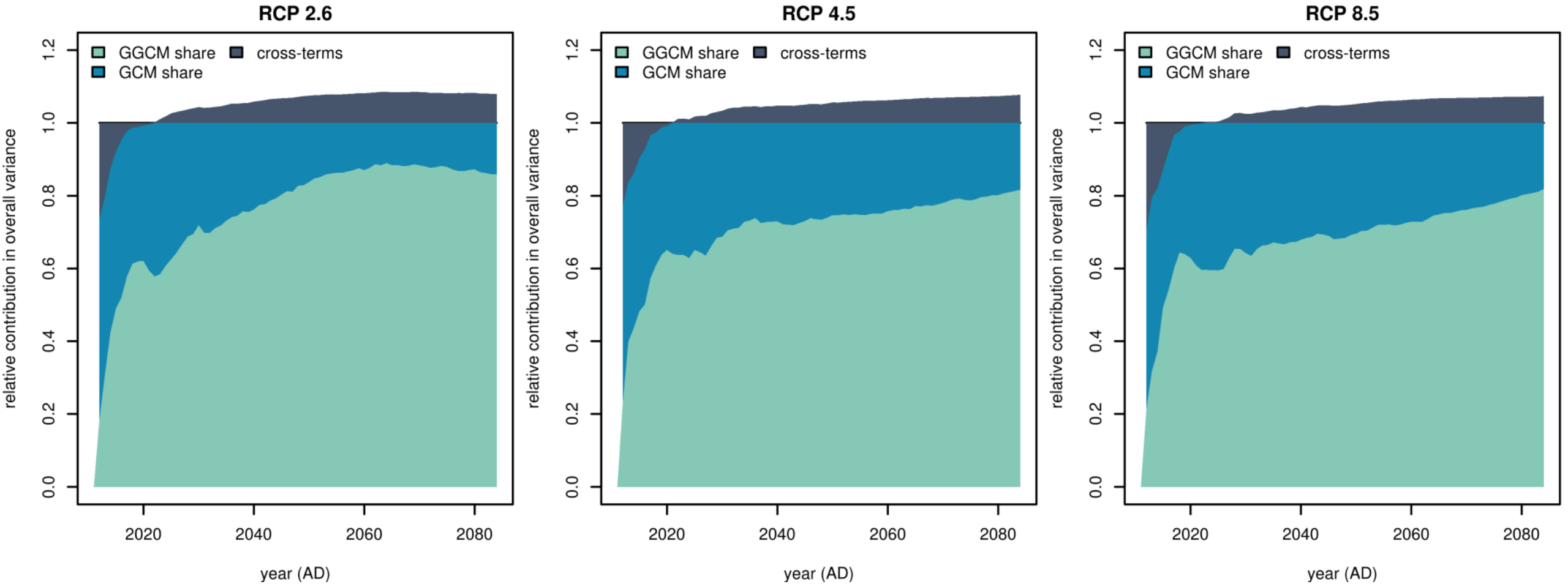


Results: more uncertainty in impact models than in climate projections



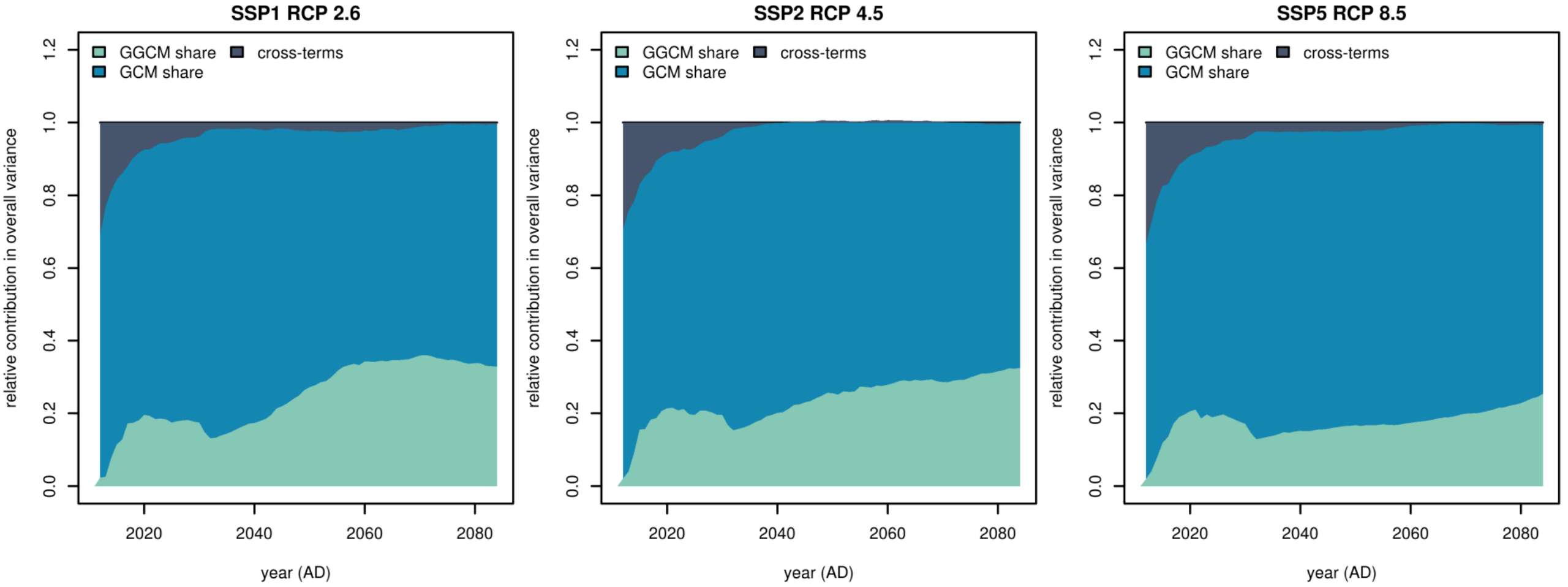
CMIP6

Results: ... and even stronger so in CMIP5



CMIP5

Response to CO_2 strongly affects crop model uncertainty share



CMIP6, static $[CO_2]$

Conclusions

- **The GGCMI CTWN-A experiment-based emulators (Franke et al. 2020) allow for an unprecedentedly large ensemble of crop yield projections, which can be employed to assess the full breadth of future climate scenarios**
- **Broad range of possible climate impacts projected for productivity of major crops**
- **There are substantial differences in**
  - **regional responses**
  - **crop model responses, especially with respect to the effects of elevated [CO_2]**
- **Next steps**
  - **better analysis of crop model specifics that lead to strong deviation in projected impacts**
  - **improve global management data to better represent diverse crop management systems in crop model simulations**

References

- **The GGCMI project**
- **Phase 1:**
  - Elliott J, *et al. The Global Gridded Crop Model Intercomparison: data and modeling protocols for Phase 1 (v1.0). Geoscientific Model Development 8, 10.5194/gmd-8-261-2015 (2015).*
  - Müller C, *et al. Global gridded crop model evaluation: benchmarking, skills, deficiencies and implications. Geoscientific Model Development 10, 10.5194/gmd-10-1403-2017 (2017).*
  - Müller C, *et al. The Global Gridded Crop Model Intercomparison phase 1 simulation dataset. Scientific Data 6, 10.1038/s41597-019-0023-8 (2019).*
- **Phase 2:**
  - Franke J, *et al. The GGCMI Phase II experiment: global gridded crop model simulations under uniform changes in CO2, temperature, water, and nitrogen levels (protocol version 1.0). Geosci Model Dev Discuss 2019, 10.5194/gmd-2019-237 (2019).*
  - Franke J, *et al. The GGCMI phase II emulators: global gridded crop model responses to changes in CO2, temperature, water, and nitrogen (version 1.0). Geosci Model Dev Discuss 2020, 10.5194/gmd-2019-365 (2020).*

Thanks and invite

- **Thanks to all GGCMI participants and data suppliers**
- **Come and join, Phase 3 (improved remake of the ISIMIP fast track in 2012) just starting**
  - **https://agmip.org/ag-grid-2/**
  - **https://www.isimip.org/**
- **We provide access to a very large data set on crop yields, input data and secondary outputs to help with your own analysis**

AgMIP The Agricultural Model Intercomparison and Improvement Project

PIK