

# Fast emulator of changes in crop yields at different levels of global warming

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**Abstract.** This is the Online Supplement to the following publication: Ostberg, S., Schewe, J., Childers, K., and Frieler, K.: Changes in crop yields and their variability at different levels of global warming, *Earth System Dynamics*, 9, 2018. The Supplement contains a number of additional figures as well as the emulator coefficients needed to apply the emulators presented in the paper to derive yield changes for any given pair global mean temperature change ( $\Delta\text{GMT}$ ) and atmospheric  $\text{CO}_2$  concentration ( $\text{pCO}_2$ ).

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## 1 Contents

The Supplement is divided into two parts:

1. a collection of additional figures (`figures.zip`)
2. an archive containing the emulator coefficients (`emulator_coefficients.zip`)

### 1.1 Collection of additional figures

Figures that represent alternative versions of the figures in Ostberg et al. (2018) are named corresponding to their number in the article. Their captions are printed below.

Figures 6–10 are provided for two versions of the emulator:

- directory `emulator_multi_scenario` contains figures for the emulator trained on all available scenario data
- directory `emulator_RCP8p5_only` contains figures for the emulator trained on data from RCP8.5 only.

The file `HadGEM2-ES_significance_test.pdf` shows for all five crop models and each crop the fraction of year-2000 cropland for which regression methods (a) (top) and (b) (bottom) yield significant fits using a  $p$ -value of 0.05. This fraction is calculated for each of ten  $\Delta\text{GMT}$  bins, and using either all available scenarios or RCP8.5 only for the regression. Note that regression method (a) cannot be calculated for pDSSAT using only RCP8.5, as explained in Ostberg et al. (2018).

## General figures

**Figure 1.** GMT projections from five GCMs (HadGEM2-ES, IPSL-CM5A-LR, MIROC-ESM-CHEM, GFDL-ESM2M, NorESM1-M) for the four RCPs. The horizontal line and shading indicate a  $0.5^{\circ}\text{C}$  wide  $\Delta\text{GMT}$  bin. The original annual GMT values (thin lines) are smoothed (thick lines) in order to obtain a contiguous time interval for each  $\Delta\text{GMT}$  bin. The smoothing is based on a Singular Spectrum Analysis with a time window of 20 years (R-Package Rssa). Years where the thick line falls within the shaded area are associated with the respective bin, and the corresponding time interval is delineated by the dashed vertical lines. File names contain the name of the GCM and the central temperature of the  $\Delta\text{GMT}$  bin.

**Figure 2.** Average yield change at  $\Delta\text{GMT}=2.5^{\circ}\text{C}$  compared to the mean historical yield (1980–2010 average) for each crop model forced by HadGEM2-ES. The average is calculated across all RCPs which reach the global mean warming interval from  $2.25$  to  $2.75^{\circ}\text{C}$ , namely RCP4.5, RCP6.0, and RCP8.5. Note that pDSSAT is run over a limited domain excluding areas north of  $60^{\circ}\text{N}$ . In the file names, *mai*, *ric*, *soy*, and *whe* denote the four crops maize, rice, soybeans, and wheat; *firr* and *noirr* denote fully irrigated and rain-fed conditions. Yield changes are expressed either in absolute terms ( $\text{t/ha/yr}$ ), denoted by *absolute*, or as a percentage of the mean historical yield, denoted by *relative* in the file names. In the figures showing relative changes, regions with marginal historical yields (defined as lying below the 2.5% quantile of historical yields on year-2000 cropland) are masked to avoid exaggerated relative yield increases.

**Figure 3.** Percentage of crop model simulations (combination of a single GCM, GGCM, and RCP scenario) indicating an increase (blue) or decrease (red) in yield of greater than 5% at each grid point at  $2.5 \pm 0.25^{\circ}\text{C}$   $\Delta\text{GMT}$  as compared to the historical period for maize, rice, soybeans, and wheat. White indicates either a less than 5% change or disagreement between the models in the direction of yield change. Note that only four out of five GGCMs provided results for rice. Two versions of this figure are provided, for rain-fed and irrigated conditions, denoted by *noirr* and *firr*, respectively.

**Figure 4.** Fraction of total variance attributable to the impact models (GGCMs, left), climate models (GCMs, middle), and scenarios (RCPs, right), for each crop at  $\Delta\text{GMT} = 2.5 \pm 0.25^\circ\text{C}$  warming. Two versions of this figure are provided, for rain-fed and irrigated conditions, denoted by `noirr` and `firr`, respectively.

**Figure 5.** Difference in global mean yield change (sum of rain-fed and irrigated, and weighted by year-2000 growing areas) between the default ( $Y_{\text{varCO}_2}$ ) and fixed  $\text{CO}_2$  simulations ( $Y_{\text{fixedCO}_2}$ ), for each crop over the range of  $p\text{CO}_2$  associated with a  $0.5^\circ\text{C}$  wide  $\Delta\text{GMT}$  bin. Each color represents an emission scenario. Points mark individual years while dotted lines and shaded areas indicate the linear best fit and its 95% confidence interval for each scenario. If more than one RCP reaches the respective warming level, the black dotted line indicates the linear best fit through all available scenarios. File names contain the GCM (HadGEM2-ES), one of the five `crop` models, and one of ten  $\Delta\text{GMT}$  bins.

**Figure 11.** Percentage of crop model simulations (combination of a single GCM, GGCM, and RCP scenario) in the  $2.5^\circ\text{C}$  warming bin indicating an increase (blue) or decrease (red) in yield variance of greater than 5% compared to the historical period (1980–2010), for maize, rice, soy, and wheat. White indicates either a less than 5% change or disagreement between the models in the direction of change. Note that only four out of five GGCMs provided results for rice. Two versions of this figure are provided, for rain-fed and irrigated conditions, denoted by `noirr` and `firr`, respectively.

Figures available for emulators trained on all available scenario data or trained on RCP8.5 only

**Figure 6.** Climate change-induced yield changes at  $\Delta\text{GMT}=2.5^\circ\text{C}$  of global warming and year 2000  $\text{pCO}_2$  level (370 ppm). Left column: Patterns of  $\Delta Y_{\text{clim}}(i)$  derived at each grid point  $i$  by approach (a) (see Eq. 1 in Ostberg et al. (2018)). Right column: Corresponding patterns of  $\Delta Y_{\text{clim}}(i)$ , derived by approach (b) (see Eq. 3 in Ostberg et al. (2018)). Both types of patterns are derived from crop model simulations forced by HadGEM2-ES and expressed as differences compared to the historical period (1980–2010). Rows: different crop types. The file name follows the pattern:

`fig6_HadGEM2-ES_[CROP MODEL]_2.5K_climeffect_[irrigation setting]_[absolute|relative].pdf`.  
 [CROP MODEL] denotes one of the five crop models; [irrigation setting] is either rain-fed (noirr) or fully irrigated (firr). Yield changes are expressed either in absolute terms (t/ha/yr), or as a percentage of the mean historical yield, denoted by relative. In the figures showing relative changes, regions with marginal historical yields (defined as in Figure 2) are masked to avoid exaggerated relative yield increases.

**Figure 7.**  $\text{CO}_2$ -induced yield changes at  $2.5^\circ\text{C}$  of global warming for crop models forced by HadGEM2-ES. Analogous to Figure 6, but showing the scaling coefficients  $a_1(i)$  from approach (a) (left column) and approach (b) (right column), multiplied by the average  $\text{pCO}_2$  change compared to year 2000 (370 ppm) across all years falling into the GMT bin. Rows: different crop types. The file name follows a similar pattern as Figure 6:

`fig7_HadGEM2-ES_[CROP MODEL]_2.5K_CO2effect_[irrigation setting]_[absolute|relative].pdf`.  
 In the figures showing relative changes, regions with marginal historical yields (defined as in Figure 2) are masked to avoid exaggerated relative yield increases.

**Figure 8.** Validation of the three emulator approaches. Maps show the difference (emulated minus simulated) between the simulated yield from each crop model forced by HadGEM2-ES climate and the corresponding emulated yield for all years falling into the  $\Delta\text{GMT}$  bin of  $2.5^\circ\text{C}$  under either RCP4.5, RCP6.0, or RCP8.5. Different columns: emulated yields based on approach (a) (left), approach (b) (middle), approach (c) (right). Rows: different crop types. The file name follows a similar pattern as Figure 6:

`fig8_HadGEM2-ES_[CROP MODEL]_2.5K_emulator_diff_[irrigation setting]_[absolute|relative]_[RCP].pdf`.  
 [RCP] is one of `rcp45`, `rcp60`, or `rcp85` and specifies the scenario that the emulator attempted to reproduce. In files showing absolute yield change (absolute), MAD is mean absolute difference, regardless of sign, averaged across all grid points.

**Figure 9.** Root mean square difference (in %) between emulated and simulated regional decadal production (yields multiplied by year-2000 growing areas) for each crop model forced by HadGEM2-ES climate projections. The emulator was used to reproduce yield changes in all four RCPs. For comparison, point symbols illustrate the average simulated yield change for 2091–2099 (same horizontal axis), using red crosses or blue circles depending on whether the error between emulated and simulated production is larger or smaller than the simulated change. The file name follows the pattern:

HadGEM2-ES\_[CROP MODEL]\_aggregated\_perf\_[irrigation setting].pdf

[irrigation setting] is either rain-fed (rf), irrigated (irr) or the combination of both (no file name identifier). Corresponding .csv files give the values plotted in the respective figures.

**Figure 10.** Comparison of simulated and emulated time series of regionally aggregated crop production changes for each crop model forced by HadGEM2-ES climate projections. These figures are available for all three emulator approaches in separate directories named fig10\_emulator\_regional\_timseries\_method\_[a|b|c]. The file name follows the pattern:

HadGEM2-ES\_[CROP MODEL]\_emulator\_perf\_regional\_co2\_[m1|m2|m3]\_[CROP]\_[irrigation setting].pdf.

[m1|m2|m3] is an internal identifier for the emulator approaches. [CROP] is one of mai, ric, soy, or whe, and [irrigation setting] is as in Figure 9.

## 1.2 Archive containing emulator coefficients

The archive contains only the coefficients for the emulators trained on all available scenario data. As shown in Figures 8 and 9, these emulators generally provide a better performance in reproducing simulated yield change than the emulators trained on RCP8.5 only.

### Note of caution

Please note that the crop model simulations forming the basis of the emulators are subject to considerable uncertainties, as discussed in Ostberg et al. (2018). We strongly advise that you familiarize yourself with the specific assumptions made by the modelling groups and their implications on simulated yield changes before using any of the emulators.

While crop yields are often subject to substantial inter-annual variability due to weather fluctuations in the real world, the emulators are only designed to capture multi-annual yield trends, not yield variability.

Emulator coefficients are provided as NetCDF files, with file names following the pattern:

HadGEM2-ES\_[CROP MODEL]\_emulator\_method\_[a|b|c]\_[CROP].nc4

All five crop models provide results for maize (mai), soybeans (soy), and wheat (whe). Crop models except PEGASUS also provide results for rice (ric).

### Emulator method (a) and (b)

These NetCDF files contain the following variables:

- [CROP]\_Yhist\_[firr|noirr] provides the average yield during the historical period (1980–2010), differentiated by irrigation setting
- [CROP]\_dYclim\_[firr|noirr] provides the pure climate-change-induced yield change (compared to the historical yield) for each of ten  $\Delta$ GMT bins, differentiated by irrigation setting
- [CROP]\_a1\_[firr|noirr] provides the added CO<sub>2</sub>-induced yield change per ppm for each of ten  $\Delta$ GMT bins, differentiated by irrigation setting
- [CROP]\_a1\_pval\_[firr|noirr] provides the *p*-value corresponding to values of a1, for each of ten  $\Delta$ GMT bins, differentiated by irrigation setting

Yield change for a given pair of  $\Delta$ GMT and pCO<sub>2</sub> can be emulated using the following two-step interpolation process:

1. linear interpolation of dYclim between the two neighbouring warming bins to the desired  $\Delta$ GMT value,
2. addition of the CO<sub>2</sub> pattern described by  $a1 \cdot (pCO_2 - 370\text{ppm})$ , where a1 is also interpolated linearly between the respective coefficients from the neighbouring warming bins.

Do not mix coefficients from different crop models or different methods. Add yield change calculated by the two-step interpolation process to historical yield to derive absolute yield. For details, please refer to Ostberg et al. (2018).

### Emulator method (c)

These NetCDF files contain the following variables:

- `[CROP]_Yhist_[firr|noirr]` provides the average yield during the historical period (1980–2010), differentiated by irrigation setting
- `[CROP]_dYvarCO2_[firr|noirr]` provides the average yield change (compared to the historical yield) driven by both climate and CO<sub>2</sub> change, for each of ten  $\Delta$ GMT bins, differentiated by irrigation setting

Yield change for a given  $\Delta$ GMT can be emulated by a linear interpolation of `dYvarCO2` between the two neighbouring warming bins to the desired  $\Delta$ GMT value. Add yield change to historical yield to derive absolute yield. For details, please refer to Ostberg et al. (2018).

### References

Ostberg, S., Schewe, J., Childers, K., and Frieler, K.: Changes in crop yields and their variability at different levels of global warming, *Earth System Dynamics*, 9, 2018.