Leibniz-Gemeinschaft

Final report

Title of the project:

Where to stop? - Efficient projections of correlated impacts at different levels of global warming

Leibniz-Institute: Potsdam Institute for Climate Impact Research
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EXECUTIVE SUMMARY

The Paris Agreement ratified by 171 countries includes the decision to limit global warming to "well below 2°C". With the request for an IPCC Special Report "on the impacts of global warming of 1.5 °C [...]" it also includes a call for research differentiating the impacts of climate change at low levels of global mean warming. At the same time global warming associated with current National Determined Contributions (NDC) to emission reductions is still expected to exceed 2°C and an assessment of the related risks is urgently required.

The EXPACT project comprises three work packages (WPs). The first one is dedicated to the development of highly efficient impact emulators allowing for a synthesis of complex bio-physical impact simulations in terms of global mean temperature (GMT) change and the second one comprises the evaluation and improvement of the underlying process-based impact models. The third WP pioneers the translation of the considered biophysical impacts into economic and societal risks by the development of models allowing for the representation of i) short term price fluctuations at the global agricultural market and ii) cross-sectoral price effects induced by production failures propagating along global supply chains.

Primarily based on the synchronized multi-model climate impact projections generated within the Inter-Sectoral-Impact Model Intercomparison Project ISIMIP we provide a spatially explicit synthesis of long-term average changes in maize, wheat, rice and soy yields, areas affected by and people exposed to crop yield failure, river floods, wildfires, tropical cyclones, droughts and heat waves at different levels of global warming. The considered indicators show a quasi instantaneous response to GMT change that can be approximated by averaging complex simulations across all years falling into individual intervals of GMT change. In contrast, the developed approximation of sea level rise uses observational data to constrain the temporal delay in reaching equilibrium levels of sea level associated with different levels of GMT. In addition, we used GMT and the ENSO index to expand dynamical simulations of tropical cyclone tracks from a range of climate simulations to individual years not originally covered by high resolution cyclone simulations.

The evaluation of the underlying process-based impact model simulations was focused on the representation of i) annual yield fluctuations and yield responses to heat in global gridded crop models as well as ii) peak flows in the hydrological models used for flood projections. The ISIMIP crop model ensemble is shown to generally reproduce the observed response of maize, soy and wheat yields in the USA. Based on the LPJmL crop model we could demonstrate that the correlation between simulated and reported annual crop yield fluctuations can be substantially increased at national scale by improving the irrigation scheme and the spatial representation of crop varieties. Both adjustments also allow for a close reproduction of observed yield reductions induced by heat waves and droughts.

Within the third work package we developed two agent based models describing annual and biannual variations in crop prices induced by fluctuations in global or regional production, respectively. Forced by historical production and demand as well as information about national trade interventions in response to production shortages both models allow for a close reproduction of reported price time series. Our analysis supports the hypothesis that recent price peaks were triggered by these “internal” drivers rather than external influences from other markets. The new tools were used to demonstrate the effectiveness of an international grain reserve in dampening extreme price peaks on the agricultural market.

In addition to the sectoral price models we also developed an implementation of prices within the global supply chain model Acclimate permitting to describe price inflation in the aftermath of production losses induced by different types of extreme events. We show that indirect losses along the supply chains have the potential to significantly increase direct losses.

MAIN REPORT

The project was intended to

1. Develop an impact emulator allowing for i) a highly efficient representation of crop yields in terms of GMT and ii) a consistent integration of other types of impacts,
2. Improve the underlying process-based crop models simulations by the LPJmL model, and
3. Pioneer the representation short term price fluctuations on the global crop market in an economic model forced by variations in crop production.

With the generation of synchronized process-based impact simulations spanning multiple sectors within the Inter-Sectoral-Impact Model Intercomparison Project (ISIMIP) the first task was substantially simplified: The originally planned two step approach of developing a simplified representation of i) regional climate change in terms of GMT (original WP1.1 and 1.2) and ii) regional impacts in terms of regional climate change (see WP2.1 in Figure 1) would have allowed to expand impact simulations forced by one specific Global Circulation Model (GCM) to climate simulations provided by another GCM. In this way simulations generated by different impact models forced by different climate projections could have been harmonized, i.e. transferred to common scenarios of climate change. However, as the impact simulations generated within ISIMIP are consistent by design (e.g. Frieler et al., 2017) the two step approach was reduced to one step, i.e. the synthesis of the available spatial explicit impact simulations in terms of GMT change (see new WP2 in Figure 2). This simplification has freed some capacity for an expansion of the analyses from the agriculture sector to other types of impacts covered by ISIMIP. Thus, runoff simulations by the hydrological models were translated into inundation areas and depths by the inundation scheme CaMaFlood (Yamazaki et al., 2011) allowing for a synthesis of areas affected by river floods and people exposed to flooding in terms of GMT change. In addition, we provide emulators for areas affected by and the number of people exposed to wildfires, crop failure, droughts, tropical cyclones, and heat waves including a first analysis of the co-occurrence of events across categories and on annual scale (Lange et al., 2017). While the underlying impact simulations were generally consistent in the sense that they were all forced by the same daily climate projections the sample of potential tracks and intensities of tropical cyclones generated within ISIMIP2b was incomplete. To fill the gaps the sample of available simulations was expanded to other years based on the associated level of global warming and their ENSO index (Frieler et al., 2017a). The method was similar to the originally planned two-step approach of building the impact emulator. Beyond the analyses of extreme events we also developed a simplified representation of sea level rise in terms of GMT pathways. Here, long-term equilibrium responses of main sea level rise contributions are combined with their last century's observed contributions to constrain projections of future sea level rise. The methodology was applied to provide sea level projections for the GMT pathways considered within ISIMIP2b, an important input for the estimation of impacts on coastal infrastructure planned within the intercomparison project (Frieler et al., 2017a).

Within work package 2 we did not only evaluate the representation of crop yield responses to weather fluctuations within the ISIMIP crop models but also assessed the representation of peak flows in the hydrological models participating in ISIMIP (see new WP2 compared to original WP2.2).

In addition, the planned cost estimates were expanded from the analysis of short-term price fluctuations on the global crop market to a multi-sectoral approach allowing for the quantification of price responses to production failures potentially caused by different types of weather extremes and propagating along global supply chains.

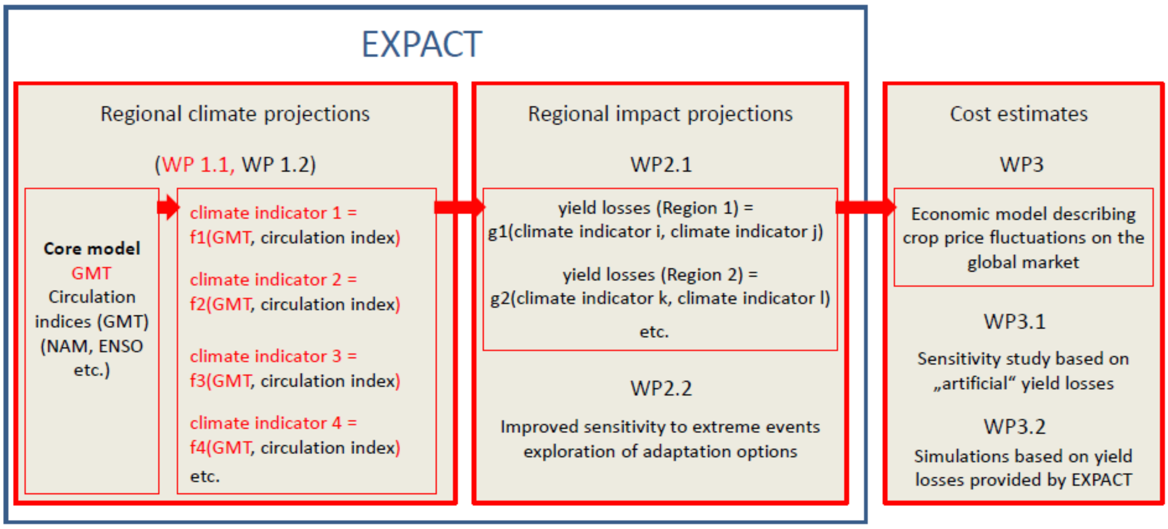


Figure 1: Original work package structure described in the EXPACT proposal

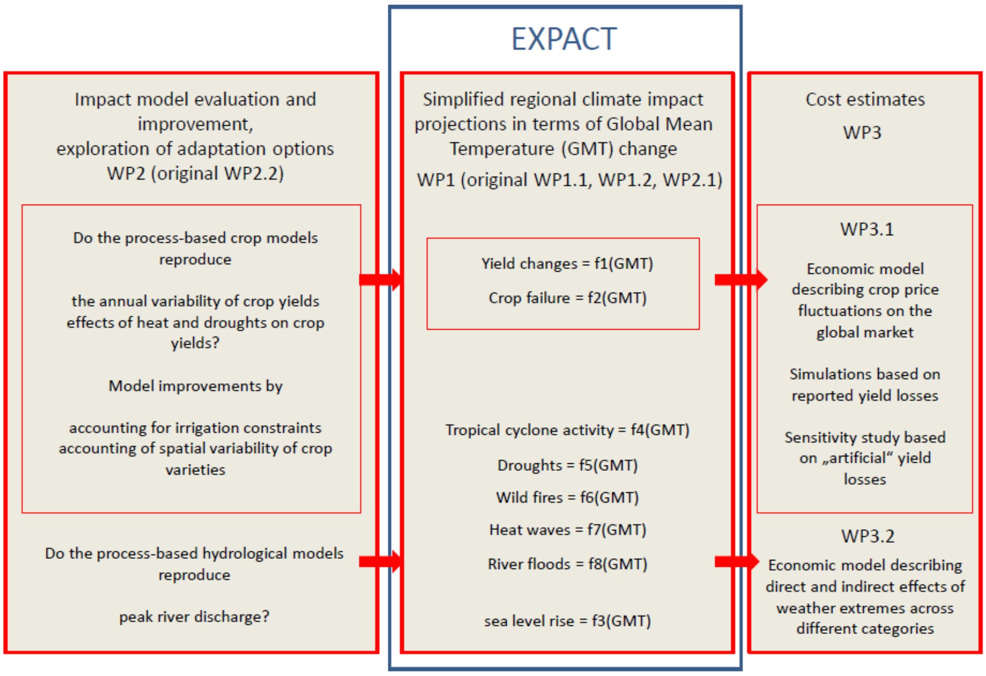


Figure 2: Adjusted work package structure

The economic models developed within EXPACT do not capture the full effect of weather fluctuations on national Gross Domestic Product (GDP). However, in the course of the project new empirical estimates of the effect of annual temperature variations on national GDP have been published (Burke et al., 2015). The method opened the opportunity to address the project’s central question “Where to stop global warming?” from a cost-benefit point of view. An associated analysis was added to WP2 (Ueckerdt et al., 2017).
In the following we discuss the results of the individual studies in the context of their WP according to Figure 2. Figures, captions and individual text elements were directly taken from the associated papers that received support from the EXPACT project. The titles of the papers are used at the headlines of the associated sections. In the reference list the papers that acknowledge EXPACT are marked in black while other references are listed in grey.

1 CLIMATE CHANGE IMPACTS IN TERMS OF GMT CHANGE

1.1 Change of crop yields in terms of GMT change (Ostberg et al., 2017)

In this study we developed and applied simple emulators of agricultural crop yields under global warming. The emulators were derived from an ensemble of five global gridded crop models, each driven by climate simulations of five GCMs under four Representative greenhouse gas Concentration Pathways (RCPs). Using this multi-dimensional simulation ensemble, we showed that the changes in yields of the four major staple crops in terms of GMT change depend only little on the choice of scenario (RCP), and much more on the choice of crop model (see Figure 3). In other words, yield changes for a specific GMT pathway can be approximated by the GMT specific changes derived from process-based simulations for another scenario, at least on an aggregated spatial scale. In addition to the very basic approach building on a linear interpolation between GMT specific patterns of yield changes derived by averaging across process-based yield projections for all years falling into a considered GMT interval we presented and tested two approaches including atmospheric CO_2 concentration as an additional predictor. We found overall little improvement by including CO_2 as a predictor, although results varied regionally and between models. Thus, the most basic emulator approach based only on GMT appeared to be a good choice in the considered setting. The underlying GMT specific patterns of crop changes for each crop and climate model were provided in netCDF format ready for further use by the larger scientific community for a simplified description of yield changes under arbitrary pathways of GMT (and CO_2) changes, without the need for additional climate and crop model simulations.

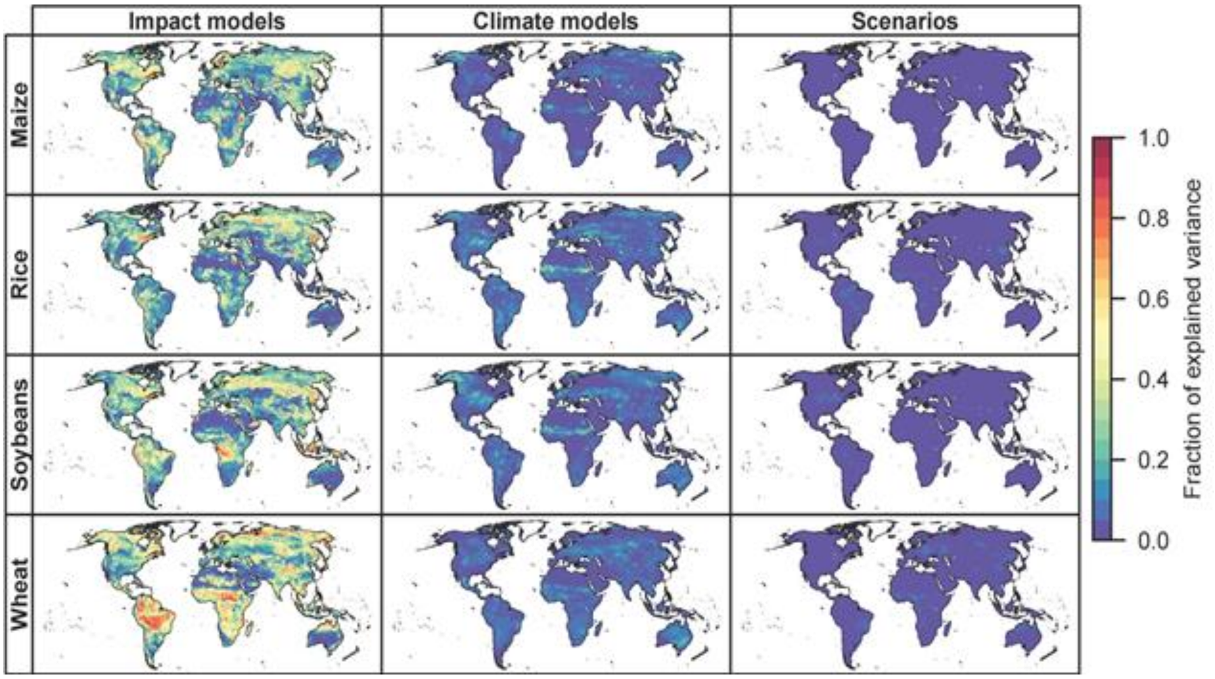


Figure 3: Fraction of total variance attributable to the global gridded crop models (impact models, left), climate models (GCMs, middle), and scenarios (RCPs, right) for each crop under rainfed conditions and for a GMT increase of 2.5°C compared to historical levels.

As a further result, we also showed that the variability of crop yields is expected to increase with increased warming in many world regions, while decreases were found in some other regions. This indicated a sensitivity of the global food production system to both climate change and changes in cultivation patterns, and provides additional motivation to study the implications of these biophysical changes for agricultural prices and, by extension, food security (see WP3).

1.2 The climate change signal in natural disasters (Lange et al., 2017)

The synchronized climate impact model simulations newly-released within ISIMIP2b allowed for an expansion of the emulator approach to a temporally and spatially explicit assessment of future weather-related threats induced by the occurrence of different types of extreme events. Here, we estimate the area affected by and the number of people exposed to different types of extremes assuming fixed present day population and land use patterns. As the relationship between GMT change and the considered impact indicators turned out to be quasi-independent of the underlying emission scenario the basic emulator approach applied to long-term changes in crop yields was also applied to the considered indicators of extreme events. The cross-sectoral consistent design of the multi-impact model simulations allowed for the first time to aggregate the areas affected by or the number of people exposed to weather extremes across different types of events. In total, the population exposed to confined events (floods, tropical cyclones, wildfire, and crop failure) showed a purely climate driven increase of 67 mn people at 1.5°C compared to pre-industrial levels, and 95 mn people at 2°C of global warming. The population exposed to extensive events (droughts and heat waves) increased by 455 mn people at 1.5°C and 781 mn people at 2°C. In addition, it became possible to estimate the frequency of extreme events across the considered types of events at each grid cell. Even meeting the Paris Agreement will expose some tropical regions to more than one extreme event per year, compared to fewer than 3 events per decade occurring under pre-industrial climate conditions.

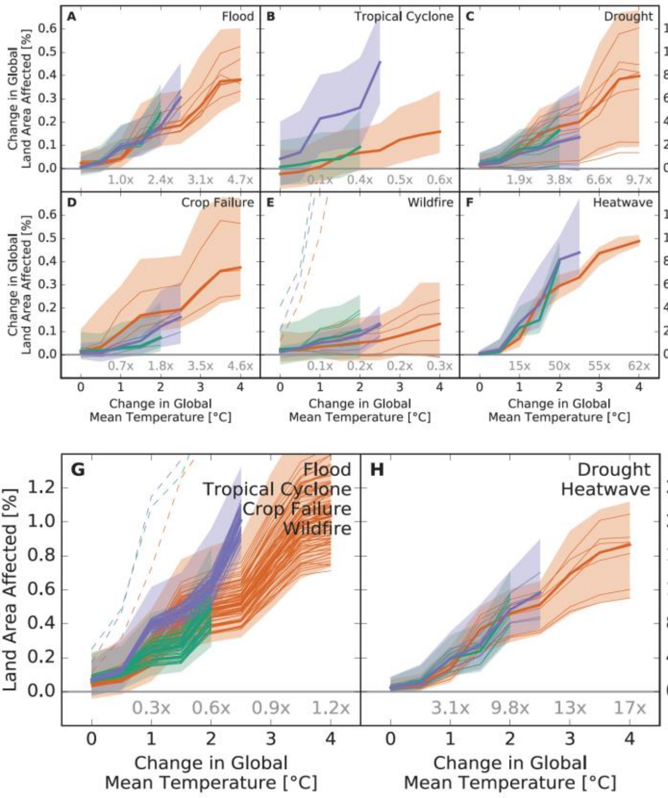
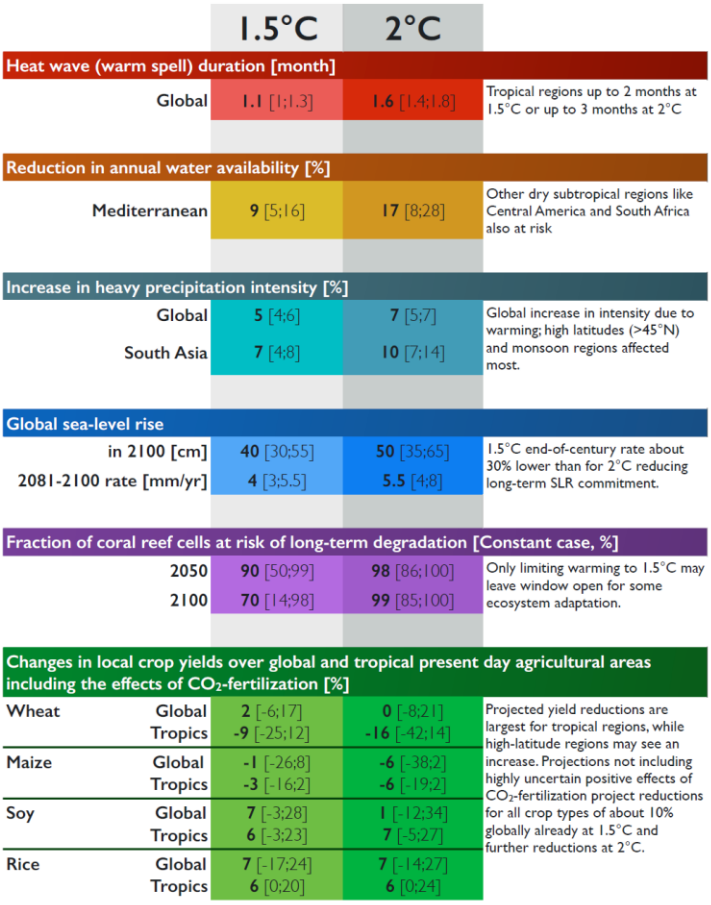


Figure 4: Change in annual global land area affected by extremes compared to pre-industrial climate conditions. Panel A: Changes in annual global land area affected by floods. Thin curves: Difference between the average of annual global land area affected by floods of all years falling into a ± 0.5°C range around the indicated level of global warming and the average areas under pre-industrial climate conditions for one GCM-impact model combination; Brown lines and shading: impacts derived for climate simulations by IPSL-CM5A-LR; green: GFDL-ESM2M; blue: MIROC5. Thick curves: Median of all impact simulations forced by the considered climate model. Shaded areas: Range between the 20th and 80th percentile of the sample of all annual changes in areas affected by floods compared to associated pre-industrial average areas from all impact models forced by the same GCMl indicated by the color. Panels B-F: Same as Panel A but for tropical cyclones, droughts, crop failure, wildfires and heat waves, respectively. For tropical cyclones, 100 realisations per year are handled as different impact models without showing the individual curves. For wildfires, results from VISIT (dashed lines) strongly deviate from the results of the other models and are not included in the ensemble estimate. The scale on the left side refers to panels A, B, D, and E while the scale on the right side refers to panel C and F. Panels G-H: Changes in areas affected by at least one of the confined extremes or extensive extremes, respectively. Thin curves: Results of individual impact model combinations (one model per extreme). Thick curves: Median changes across all impact model combinations. Here the ensemble medians based on VISIT wildfire simulations are shown as individual dashed curves in panel E and not included in the ensemble estimates. Color coding and shaded areas are analogous to Panel A. The numbers reported at the bottom of each panel indicate the relative change in affected areas compared to pre-industrial reference conditions.



		1.5°C	2°C	
Heat wave (warm spell) duration [month]				
	Global	**1.1** [1;1.3]	**1.6** [1.4;1.8]	Tropical regions up to 2 months at 1.5°C or up to 3 months at 2°C
Reduction in annual water availability [%]				
	Mediterranean	**9** [5;16]	**17** [8;28]	Other dry subtropical regions like Central America and South Africa also at risk
Increase in heavy precipitation intensity [%]				
	Global	**5** [4;6]	**7** [5;7]	Global increase in intensity due to warming; high latitudes (>45°N) and monsoon regions affected most.
	South Asia	**7** [4;8]	**10** [7;14]	
Global sea-level rise				
	in 2100 [cm]	**40** [30;55]	**50** [35;65]	1.5°C end-of-century rate about 30% lower than for 2°C reducing long-term SLR commitment.
	2081-2100 rate [mm/yr]	**4** [3;5.5]	**5.5** [4;8]	
Fraction of coral reef cells at risk of long-term degradation [Constant case, %]				
	2050	**90** [50;99]	**98** [86;100]	Only limiting warming to 1.5°C may leave window open for some ecosystem adaptation.
	2100	**70** [14;98]	**99** [85;100]	
Changes in local crop yields over global and tropical present day agricultural areas including the effects of CO_2-fertilization [%]				
Wheat	Global	**2** [-6;17]	**0** [-8;21]	Projected yield reductions are largest for tropical regions, while high-latitude regions may see an increase. Projections not including highly uncertain positive effects of CO_2-fertilization project reductions for all crop types of about 10% globally already at 1.5°C and further reductions at 2°C.
	Tropics	**-9** [-25;12]	**-16** [-42;14]	
Maize	Global	**-1** [-26;8]	**-6** [-38;2]	
	Tropics	**-3** [-16;2]	**-6** [-19;2]	
Soy	Global	**7** [-3;28]	**1** [-12;34]	
	Tropics	**6** [-3;23]	**7** [-5;27]	
Rice	Global	**7** [-17;24]	**7** [-14;27]	
	Tropics	**6** [0;20]	**6** [0;24]	

Figure 5: Summary of key differences in climate impacts between a warming of 1.5°C and 2°C above pre-industrial levels or stylized 1.5°C and 2°C sea level scenarios over the 21st century. Square brackets give the likely (66 %) range.

Compared to previous simulations rounds simulations generated within ISIMIP2b comprise a large sample of impact simulations assuming pre-industrial climate conditions, thus allowing for the estimation of changes in the occurrence of extreme impacts compared to this reference. Prior to the ISIMIP2b simulations we contributed to an assessment of differences in regional climate change impacts based on simulations generated within the ISIMIP Fast Track (Schleussner et al., 2016a). The study reveals substantial differences in impacts between 1.5 °C and 2 °C warming that are highly relevant for the assessment of dangerous anthropogenic interference with the climate system (see Figure 5). The analysis was complemented by a perspective on the "Science and policy characteristics of the Paris Agreement temperature goal" (Schleussner et al., 2016b).

1.3 High-income does not protect against hurricane losses (Geiger et al., 2016)

In addition to the areas affected by and the number of people exposed to extreme events we also developed a damage function allowing for a translation of hurricane hazards into direct economic losses accounting for their intensity, exposure and vulnerabilities. So far, historical losses due to tropical cyclones were found to increase less than linearly with a nation's affected GDP. We showed that for the United States this scaling was caused by a sub-linear increase with affected population while relative losses scaled super-linearly with per capita income. The separation of both socio-economic predictors was shown to strongly affect the projection of potential future hurricane losses. Separating the effects of growth in population and per-capita income, per hurricane losses with respect to national GDP were projected to triple by the end of the century under unmitigated climate change, while they were estimated to decrease slightly without the separation. The paper was the basis for Tobias Geiger's nomination for the "Brandenburger Postdoc-Preis 2017.

1.4 Non-linear intensification of Sahel rainfall as a possible dynamic response to future warming (Schewe and Levermann, 2017)

The basic emulator approach used to describe changes in crop yields and the occurrence of extreme events in terms of GMT change did not make any assumption about the functional relationship between global warming and the considered impacts indicator. Instead the relationship was directly derived from the underlying process-based impact simulations. By the example of changes in Sahel rainfall we showed that assuming a linear scaling with GMT may indeed be too restrictive if the underlying processes are e.g. subject to a self-amplifying feedback.

The Sahel region in Africa is especially vulnerable to climate impacts on agricultural livelihoods. Rainfall was very variable over the past decades, including devastating droughts, but also flooding. In this study, we showed that while some climate models project just minor, gradual changes in Sahel rainfall under climate change, there are other models in which a proper monsoon regime developed in the continental interior of the region, bringing intense rainfall to the Sahel. We showed that this effect can be understood in terms of the internal dynamics of the monsoon circulation, and that the critical point for the monsoon "switch-on" in these models lies near 1.5-2°C of global warming, i.e., the Paris Agreement targets. We thus revealed a climatic tipping point that, if these models properly reflect real atmospheric dynamics, could profoundly change the Sahel's climate regime even under ambitious climate change mitigation. This has important implications for future agriculture, water resources, flood risk, etc.. The paper was selected as EGU Highlight Article in July 2017.

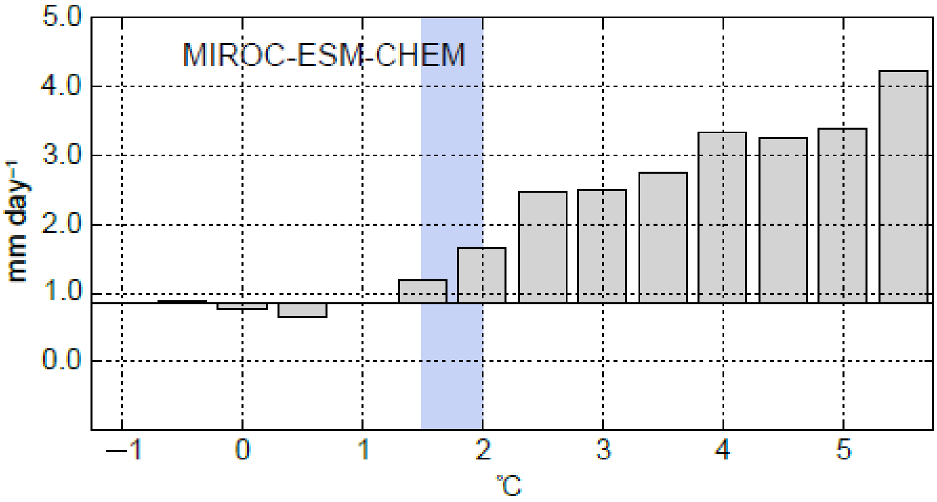


Figure 6: Median Sahel July–September rainfall for different intervals of GMT change. Bars illustrate the deviation from the 1900–1999 rainfall average (horizontal black line). Blue

shading marks global warming levels consistent with the Paris Agreement. Shown here is an example for the MIROC-ESM-CHEM GCM.

1.5 Future sea-level rise constrained by observations and long-term commitment (Mengel et al., 2016)

The developed model of sea level rise in terms of GMT change combined estimates of the equilibrium response of the main sea level rise contributions with their last century's observed contribution to constrain projections of future sea level rise. The model was calibrated to a set of observations for each contribution. In this way the tool in is consistent both with the past observations of sea-level rise and the long-term physical processes in the different elements of the Earth system that are more easily computed with currently available process-based models than are decadal to centennial variations. As the individual calculations are fast observational and climate uncertainties could be sampled and combined to produce uncertainty ranges for 21st century sea level rise. The method projected anthropogenic sea level rise of 28–56 cm, 37–77 cm, and 57–131 cm in 2100 for the greenhouse gas concentration scenarios RCP2.6, RCP4.5, and RCP8.5, respectively. The derived uncertainty ranges for total sea level rise overlap with the process-based estimates of the Intergovernmental Panel on Climate Change. The “constrained extrapolation” approach generalized earlier global semiempirical models. The separate representation of each individual contribution to sea level rise (thermal expansion, mountain glaciers, Greenland and Antarctica) may lead to a better understanding of the discrepancies with process-based projections.

2 MODEL EVALUATION AND IMPROVEMENT

2.1 Spatial variations in cultivars pivotal to understand global fluctuations in maize and wheat yields (Jägermeyr and Frieler, 2017)

Comparing model simulations to observational data is an essential test for our understanding of the observed system. Regarding our understanding of crop yield responses to weather fluctuations at global scale this test was notoriously hampered by limited information about direct human influences on agricultural yields. The historical crop model simulations generated within ISIMIP2a only account for yield fluctuations induced by weather variations and, depending on the crop model, on potential adjustments of growing seasons or cultivars in response to changes in weather. However, they do not account for management adjustments driven e.g. by price fluctuations or policies. Therefore, in a first study, we used the correlation between observed and simulated crop yields to estimate the fraction of the observed variance in national crop yields that can be explained by weather variations based on the available state-of-the-art, process-based crop model simulations (Frieler et al., 2017b). We found that the fraction was larger than 50% for wheat yields in Australia, Canada, Spain, Hungary, and Romania. For maize, weather sensitivities exceeded 50% in seven countries, including the United States. The explained variance exceeded 50% for rice in Japan and South Korea and for soy in Argentina. Avoiding water stress by simulating yields assuming full irrigation showed that water limitation was a major driver of the observed variations in most of these countries.

In a second study based on the LPJmL crop model we demonstrated that the fraction of reported annual fluctuations in maize and wheat yields on national level could be substantially increased by accounting for spatial variations in crop cultivars derived from reported growing seasons (Jägermeyr and Frieler, 2017). Compared to assuming spatially homogeneous cultivars the improved model version increased the explained variance of historical yield fluctuations from 34.5% to 58% for maize and from 46.5% to 51.4% for wheat on average across the top-10 main producer countries (see Figure 7).

Compared to a reference model version assuming a spatially homogeneous distribution of cultivars and full irrigation on areas equipped for irrigation the main increase in variance was due to the cultivar adjustment but for some countries a newly developed implementation of

irrigation schemes accounting for constraints in water availability (Jägermeyr et al., 2016) also lead to substantial increases in explained variances. In addition, the representation of spatial variations in cultivars allowed for a quantitative reproduction of the observed global average impact of extreme heat and drought on national yields. Improvements were most pronounced regarding heat effects on maize - in particular for the 2003 heat wave in Europe.
Our results underline the importance of an adequate representation of human management for the projection of potential adverse climate change impacts on crop yields. Moreover, we showed that integrated crop water management is pivotal to buffer negative climate change impacts and to halve the global food gap on a sustainable basis (Jägermeyr et al., 2016).

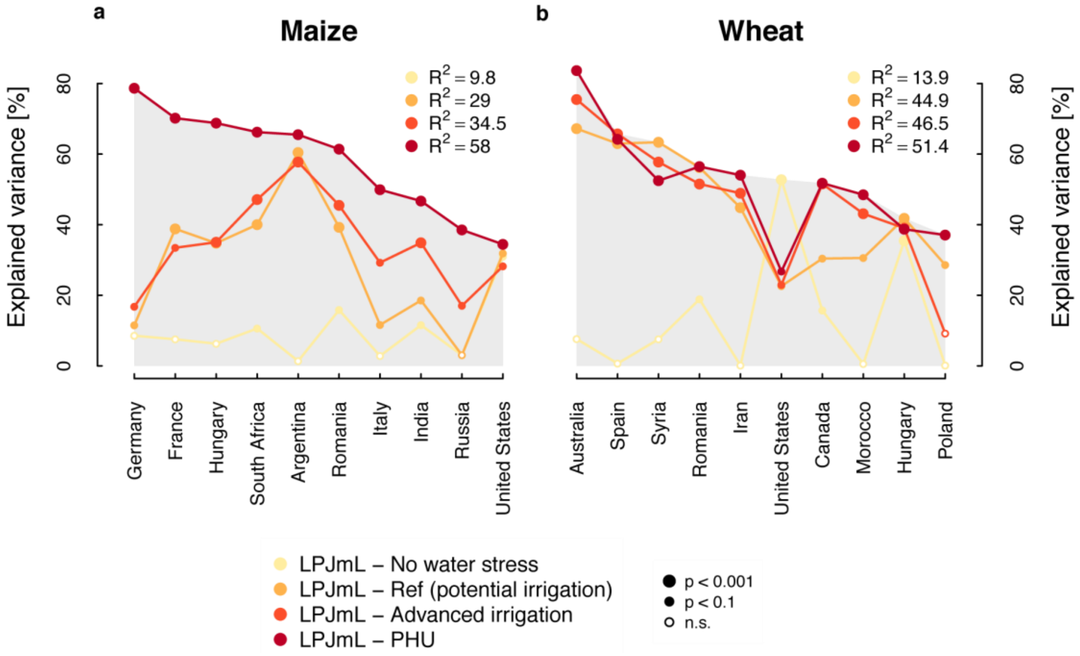


Figure 7: Explained variance of country-level yield anomalies for maize (a) and wheat (b). Explained variances were derived from correlations between different LPJmL simulations and observed FAO time series (1980 – 2010) for the top-10 performers among main producer countries. Yellow: LPJmL simulation assuming full irrigation on entire cropland; light orange: LPJmL simulation assuming full irrigation on areas currently equipped for irrigation; dark orange: LPJmL simulations with advanced mechanistic representation of water-constrained irrigation (as in Jägermeyr et al., 2016), all three simulations assumed homogeneous cultivars; red: LPJmL simulations accounting for water constraints and spatial variations in cultivars. Statistical significance of the explained variance is indicated through chart symbols (large dots if p-value < 0.001; small dots if p-value < 0,1; circle if not significant, i.e. p-value 0≥1). R2 values in the top-right corner are mean value across displayed countries.

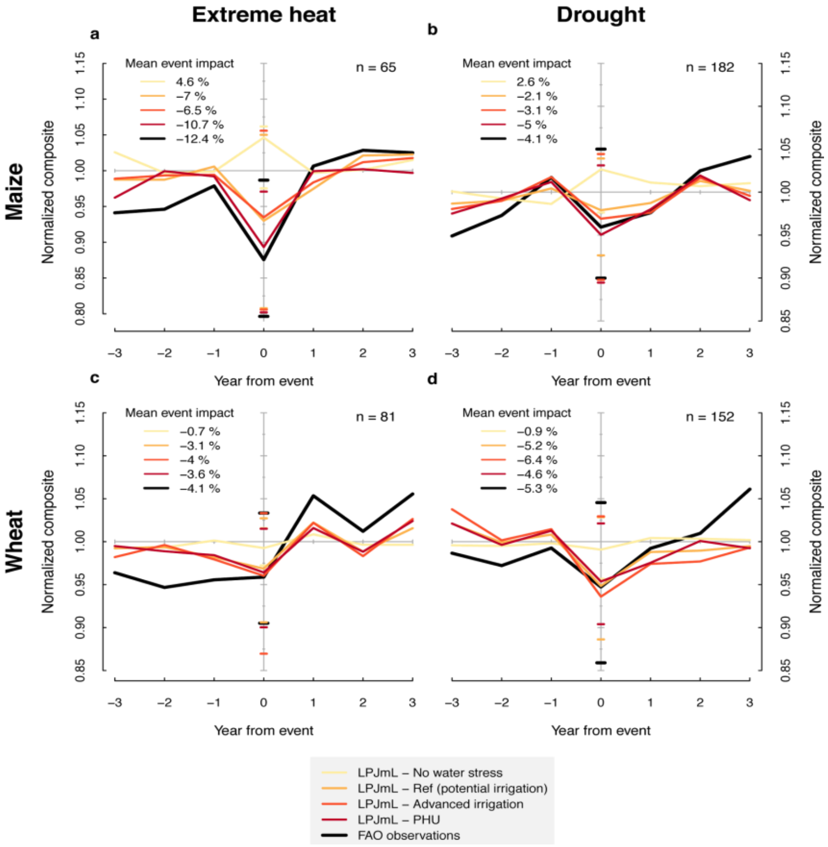


Figure 8: Observed and simulated influences of extreme weather on global crop yields. The composite figure shows the average impact of worldwide extreme heat events (first column) and droughts (second column) on maize (top row) and wheat (bottom row) yields (1964 – 2007; EMdat database). Seven-year time windows of country-level yields were centered on the respective event, including three years before and after the event for reference. Black line: observed FAO time series; remaining simulation protocol same as in Fig. 7. n = number of extreme events. Dashes along the y-axis indicate the 75%–25% quantile range of both observations and simulations during extreme events. LPJmL simulations were based on three different observational climate input datasets.

2.2 Consistent negative response of US crops to high temperatures in observations and crop models (Schauberger et al., 2017)

Alternatively a statistical model can be used to separate weather responses from other types of crop yield variations. These observed responses can then be compared to simulated responses. Within the project we used this approach to evaluate the representation of heat effects in the crop model simulations considered within ISIMIP and to construct the emulator of long term yield changes (see section 1.1). The considered ensemble of nine process-based crop models was shown to reproduce the observed average temperature responses of US maize, soybean and wheat yields including the observed strong negative responses of maize and soybean when exposed to temperatures above 30°C (Schlenker and Roberts, 2009): Each day > 30°C diminished maize and soybean yields by up to 6% under rainfed conditions. Under irrigation simulated and observed heat effects were weak. This supports the hypothesis that the observed decline was induced by temperature induced water stress (Lobell et al., 2013). For wheat a negative response to high temperature was neither observed nor simulated under historical conditions, since critical temperatures were rarely exceeded during the growing season. Under high levels of warming, crop model simulations showed a pronounced drop in yields at high temperatures for all three crops, that was only weakly reduced by the associated elevated levels of atmospheric CO2.

2.3 The critical role of the routing scheme in simulating peak river discharge in global hydrological models (Zhao et al., 2017)

Within the project global hydrological models (GHMs) have been applied to assess flood hazards. Within WP2 we evaluated their capacity to capture the timing and amplitude of peak river discharge. Though crucial in flood simulations, model evaluation studies have traditionally not focused on this indicator. We evaluated to what degree the choice of the river routing scheme affects simulations of peak discharge and may help to provide better agreement with observations. To this end we used runoff and discharge simulations of nine GHMs forced by observational climate data (1971–2010) within the ISIMIP2a project. The runoff simulations were used as input for the global river routing model CaMa-Flood. The simulated daily discharge was compared to the discharge generated by each GHM using its native river routing scheme. For each GHM both versions of simulated discharge were compared to monthly and daily discharge observations as a benchmark. The CaMa-Flood routing applied within the project showed a general reduction of peak river discharge and a delay of about two to three weeks in its occurrence, likely induced by the buffering capacity of floodplain reservoirs as CaMa-Flood routing accounts for floodplain storage and backwater effects that were not represented in most other GHMs. For a majority of river basins, discharge produced by CaMa-Flood resulted in a better agreement with observations. In particular, maximum daily discharge was adjusted, with a multi-model averaged reduction in bias over about 2/3 of the analysed basin area. The increase in agreement was obtained in both managed and near-natural basins. Overall, the study demonstrated the importance of routing scheme choice in peak discharge simulation. In addition to the emulators developed in WP1, the flood projections derived from the ISIMIP runoff simulations within this project were applied to estimate the adaptation required to preserve future high-end flood risk at present level (Willner et al., 2017).

2.4 Simulating the compound impacts of climate extremes: Lessons from the 2003 European heat wave and drought (Schewe et al., 2017a)

As part of WP2, we used the 2003 European heat wave and drought (EHWD) as a historical analogue for comparable events in the future, and evaluated whether a multi-sectoral ensemble of state-of-the-art impacts models (run within the ISIMIP project) could reproduce the severity of the event’s compound impacts. Our study combined, for the first time, impacts on agriculture, freshwater resources, terrestrial and marine ecosystems, energy, and human health in a consistent multi-model framework. We found that the intensity of the EHWD’s impacts on agriculture, terrestrial ecosystem productivity, and heat-related mortality was underestimated by most of the respective models. In contrast, the multi-model mean of global hydrological models reproduced the severest impacts on surface water resources, but exhibited false alarms in many less-impacted river basins. Further, a hydropower capacity model matched reported hydropower generation anomalies in some but not all of the affected countries. Finally, estimates of heat-related excess mortality from a set of statistical models were consistent with literature reports for some of the cities investigated, but much lower for other cities. Thus, if a future climate scenario contains an event like the 2003 EHWD, its compound impacts may be seriously underestimated by the present impacts model ensemble. This means that presently, a precautionary approach is advisable when assessing potential impacts of future extreme events. Our study revealed important shortcomings of present models, and highlighted ways to address them.

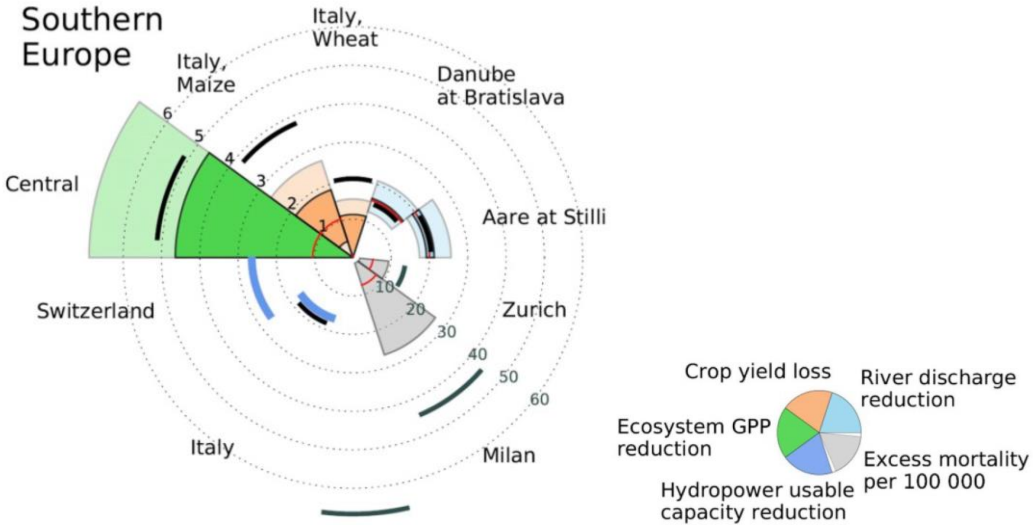


Figure 9: Multi-sector impacts of the 2003 EHWD in models (colors) and observations/literature (black arcs). Units are standard deviations (black axis labels), except for human mortality which is given in excess deaths per 100,000 (grey axis labels). For river discharge, crop yields, and ecosystem GPP, the thin red line marks the multi-model median; the dark-colored segment marks the interquartile range; and the light-colored segment marks the full range of model results. For hydropower, only one model was available which is marked by the thick blue arcs. For mortality, the red line and colored segments mark the median and the full range, respectively, across three climate forcing data sets and three different heat-mortality relations. Further regions and locations in Europe were analyzed in the study.

3 ECONOMIC EVALUATION

3.1 The role of storage dynamics in annual wheat prices (Schewe et al., 2017c)

Identifying the drivers of global crop price fluctuations is essential for estimating the risks of unexpected weather-induced production shortfalls and for designing optimal response measures. While agricultural economic models exist that capture the long-term response of crop prices to weather conditions, demand, and land-use change, so far no model was available that could successfully and consistently capture short-term price fluctuations. In this project, we developed such a model. The explicit representation of storage dynamics turned out to be key as on short time scales it acts as a buffer between production, consumption, and prices. We showed that a simple supply–demand model with storage could explain most of the observed variations in wheat prices over the last 40 years solely based on time series of annual production and long term demand trends. Even the most recent price peaks in 2007/08 and 2010/11 - which had serious implications for food security in many developing countries - could be explained by additionally accounting for documented changes in countries' trade policies and storage strategies, without the need for external drivers such as oil prices or speculation across different commodity or stock markets. This underlines the critical sensitivity of global prices to fluctuations in production. The model now forms the basis for exploring potential responses to future crop yield variability under climate and land-use change.

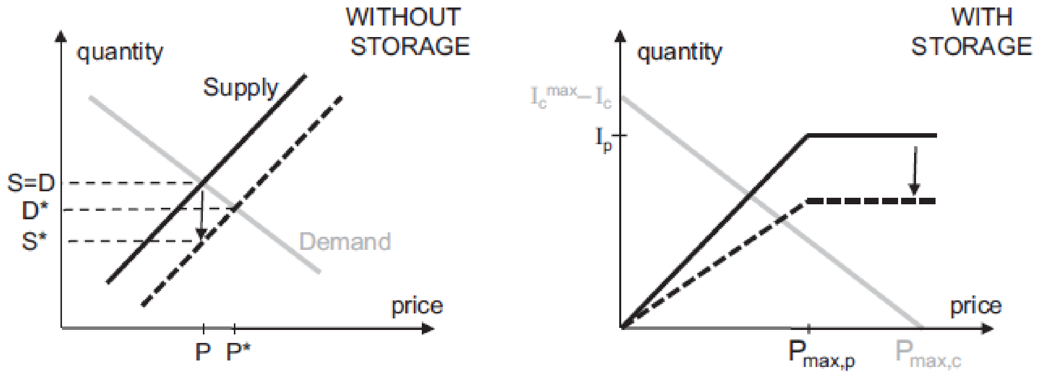


Figure 10: Schematic illustration of the supply and demand functions in an exemplary equilibrium model without storage (left), and in our model with storage (right). In each case the implementation of a negative production shock is indicated by the arrow and the dashed supply curve. Without storage, a production shock cannot be implemented without creating an inconsistency between supply and demand. In the model with storage, the supply curve represents total available goods including both new production and carryover stocks. Here, the balance of goods is conserved through the producer-side and consumer-side inventories, Ip and Ic, respectively. Therefore this model is suitable for long-term projections

3.2 The potential of an international wheat reserve to improve global food security
(Otto et al., 2017b)

Based on the experiences with the global model, we developed a multi-regional agent-based model that accounts for commercial and strategic stock keeping. It enabled us to simulate prices at agricultural world markets (WM) and stocks in the world's breadbaskets with sub-annual resolution. Thus, price spikes could be traced back to regional harvest failures and policy measures in the various world agricultural regions. The model accounted for long-term changes in national stockkeeping policies such as transitions from public to commercial inventory management schemes as well as national policy responses to tight markets such as restocking attempts of import dependent countries and export restrictions of net exporters.

The two recent world food crises have revived a long-standing debate if an international grain reserve could be a viable means to improve global food security. However, to date reliable quantitative estimates on the efficiency of such a reserve to suppress damaging price spikes and the associated costs are still missing. Our quantitative modeling approach permitted us to study for the case of wheat - arguably the most important food grain - the efficiency and financial viability of an international price stabilization reserve. We demonstrated that a strategic reserve of 70 million metric tons would have been sufficient to significantly dampen past price extremes. The reserve's annual operational costs were estimated to be with 0.7 to 1.4 bn USD substantial, but still small compared to the expenses for other present national agricultural support programs. Our findings suggest that an international reserve could be a viable tool to limit the effects of production shortfalls on global crop prices even in the presence of price driving real-world market interventions. As such, it could become an important option to mitigate the risks of climate change and social instability.

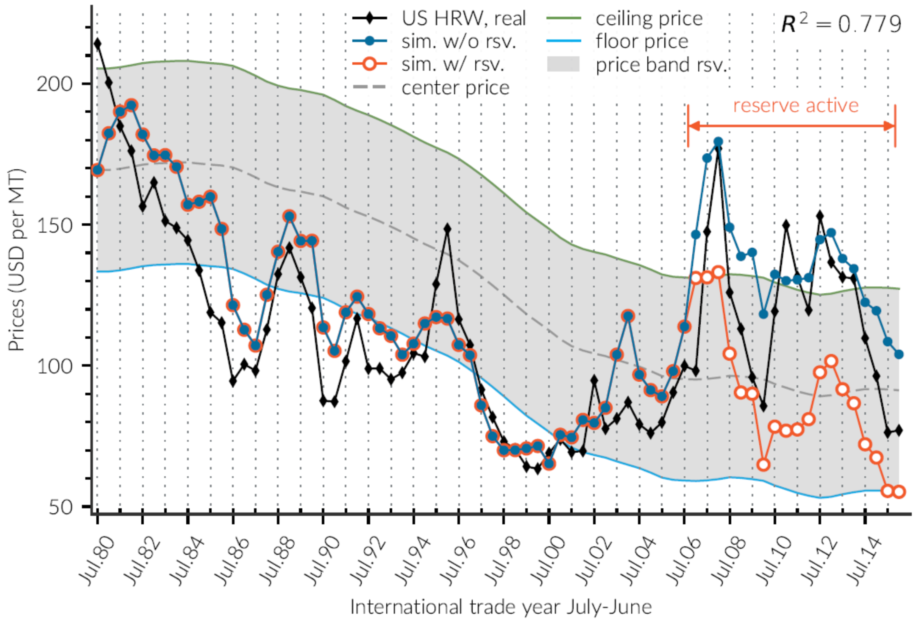


Figure 11: Simulated price dynamics at the world market for wheat from 1980 to 2016. Time series of real wheat prices (black diamonds), simulated prices without (blue dots) and with international wheat reserve (open orange circles) of 70 million metric tons. The gray shaded area indicates the price band of the reserve; the reserve was restocked (released), if prices dropped below (increase above) the floor price (thin light-blue line) (ceiling price (thin green line)).

3.3 The influence of future climate and land use changes on global crop price fluctuations (Schewe et al., 2017b)

Using the global price model developed in Schewe et al., 2017c, we set out to investigate whether and how the variability of annual food grain prices may change in the future. The underlying hypothesis was that increases in the occurrence of droughts and other damaging climate events in major food producing regions would render global grain production more volatile, thus increasing the risk of food price spikes and entailing effects on food security and social stability. With its explicit representation of grain storage, our model was ideally suited to explore this question, and also to test potential adaptation measures involving storage strategies.

In order to construct consistent future scenarios of crop yields under climate change and changes in growing areas, it is important that agricultural land-use scenarios were harmonized between historical and future periods. This process, tackled in cooperation with a leading land-use research group in the USA (George Hurtt, University of Maryland), took much longer than expected due to unforeseen challenges related, among others, to future bioenergy crop production. The land-use scenarios were finally completed in fall 2017 (Frieler et al., 2017a). We have subsequently started the crop price analysis and obtained initial results for wheat, which are being prepared for publication. The analysis will subsequently be expanded to other important food crops.

3.4 Acclimate - A dynamic model for economic loss propagation (Otto et al., 2017c)

Due to globalization, the global economy has become increasingly interlinked within the last decades forming a complex network of firms and regional consumers. In consequence, local climate extremes can have global repercussion, because local production disruptions can cause cascading indirect losses spreading along global supply chains. For large scale disaster such as tropical cyclones these indirect losses, exacerbated by price inflation in the disaster aftermath, can be of the same order of magnitude as direct losses and therefore have to be accounted in a comprehensive disaster impact analysis.

In this project, we extended the disaster impact model Acclimate to account for price dynamics. Acclimate is an agent-based dynamic model of the global economy designed to describe direct and indirect production losses caused by localized unpremeditated production disruptions. The new model version combines an adaptive production system with high regional, sectoral, and temporal resolution permitting to capture short-term market imperfections. It temporally resolves the propagation of indirect production losses spreading along the global supply chains in the disaster aftermath as well as subsequent economic recovery phase. Firms and regional consumers are modeled as bounded rational agents, which base their expectations on future market developments on past information, and adapt them successively according to their gain in information. In each timestep, they decide on their optimal production or consumption level by local utility maximization. Accounting for price dynamics enabled us to describe price inflation in the disaster aftermath which significantly increases overall costs for large scale disasters (Otto et al., 2017c).

In an ongoing effort (Otto et al., 2017a), we calibrated the model to describe the indirect economic effects of hurricane Katrina on the economy of the United States. Figure 12 shows direct and indirect impacts of hurricane Katrina on the economy of the USA. Our analysis suggests that overall, indirect losses dominated indirect gains. However, indirect losses and gains were distributed very heterogeneously between the states. Whereas California and Texas suffered the highest indirect losses, other states profited from the disaster, at least temporarily. Price effects increased these trends. The highest, indirect gains were observed in the directly affected states where scarcity driven price inflation is strongest. In response to high incoming demand and high reservation prices of their clients, the non affected firms in these regions activated idle capacities to extend their productions above their pre-disaster baseline levels. However, the different scales of direct losses and indirect gains in Figure 12 reveal, that indirect effects could somewhat mitigate total losses in the affected states, but not compensate them. Overall, total losses in the USA exceeded direct losses by 50%. Our analysis will permit us to estimate the overall economic damage caused by Harvey and Irma, the two major hurricanes making landfall in the USA mainland in 2017.

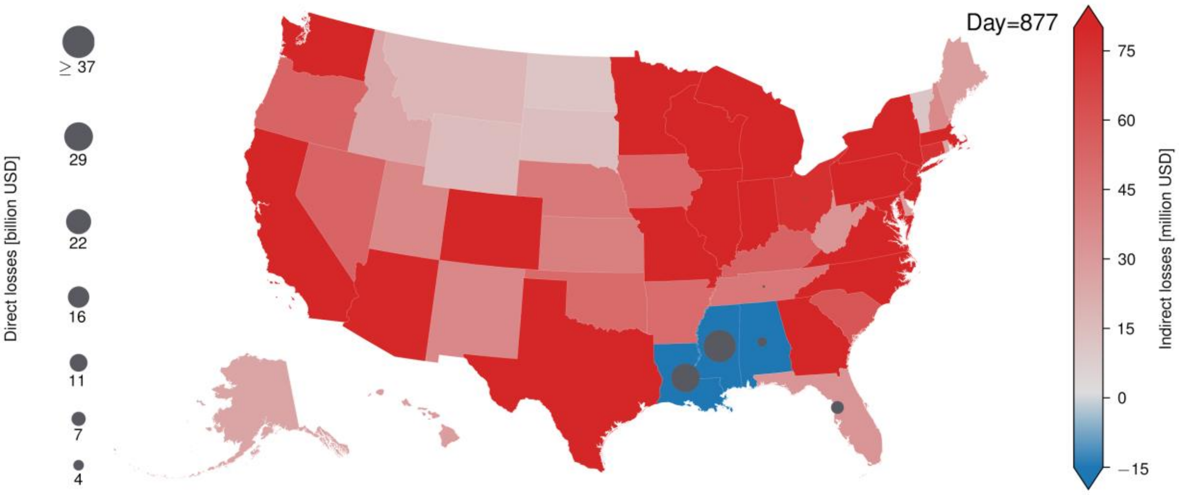


Figure 12 Importance of indirect losses and gains in the aftermath of hurricane Katrina. Direct (gray circles) and indirect (color map) production losses with price effects in the aftermath of hurricane Katrina. Shown are direct (gray circles) cumulative production losses and indirect production losses and gains (color code) after the economic recovery phase.

3.5 The economically optimal warming of the planet (Ueckerdt et al., 2017)

Both climate-change damages and climate-change mitigation will incur economic costs. While the risk of severe damages increases with the level of global warming (IPCC, 2014a), mitigating costs increase steeply with more stringent warming limits (IPCC, 2014b; Rogelj et al., 2015)

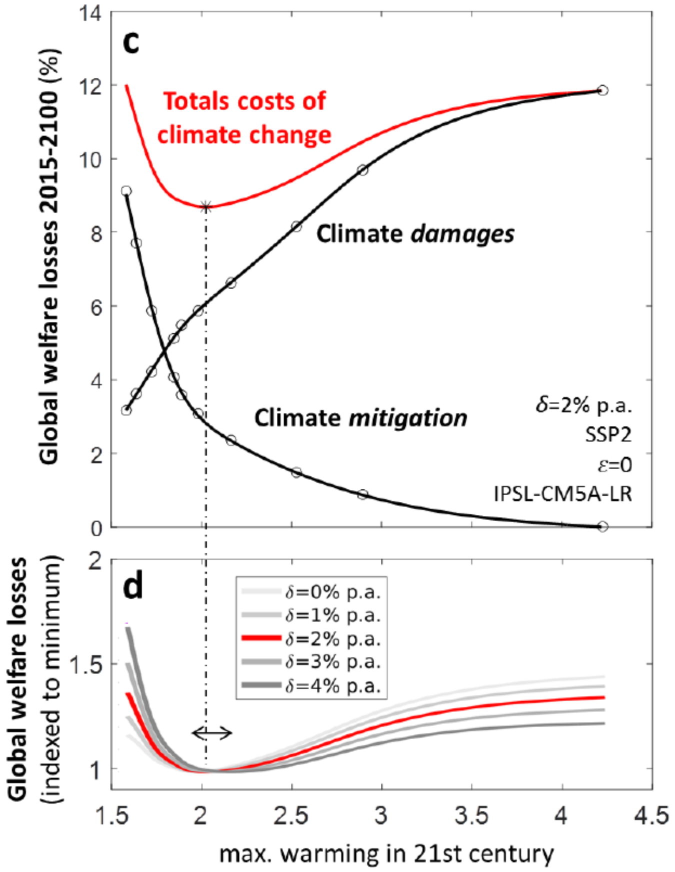


Figure 13: Cumulated global welfare losses (2015–2100) from climate damages, climate mitigation and their combined effect (total costs), as a function of global warming limits illustrated from an example scenario (SSP2, GCM: IPSL-CM5A-LR, inequality aversion ε=0, pure rate of time preference δ=2% p.a.). Total costs are derived in 3 steps: Climate impacts and climate mitigation are combined by reducing the reference GDP (without climate change) successively by the two relative annual country-specific GDP losses; resulting country-specific GDP pathways (with and without climate change) are translated to per-capita utility via an isoelastic utility function with varying inequality aversion; resulting utilities are globally and temporally (2015–2100) aggregated to a social welfare function varying the pure rate of time preference. (d) Dependence of total cumulative welfare losses on pure rates of time preference. Losses are normalized by the minimum loss of each curve. Red line for d = 2% corresponds to red line in panel c (dashed vertical line). Cost-minimizing global warming limits slightly shift towards higher values with increasing pure rate of time preference (range indicated by arrow).

A new empirical study published in the course of the project (Burke et al., 2015) showed that - building on the historical relationship between annual temperature fluctuations and variations in national economic growth - future damages induced by global warming may be considerably larger than assumed by previous cost-benefit analysis. We built on the empirical findings to estimate climate change impacts on economic growth for 186 countries and combined this information with mitigation costs derived from the state-of-the-art energy-economy-climate model Remind (Luderer et al., 2013; Rogelj et al., 2015) representing a wide range of highly-resolved mitigation options (see Figure 13). The assessment showed that the global warming limit that minimizes this century's total economic costs of climate change lies between 1.9 and 2°C if temperature changes continue to impact national economic growth rates as observed in the past. The result was shown to be robust across a wide range of normative assumptions on the valuation of future welfare and inequality aversion. Our purely economic assessment, even though it omits non-monetary damages, provides support for the international Paris Agreement on climate change.

4 DATA ACCESS

The climate impacts simulations generated within the ISIMIP project are freely available (see www.isimip.org for a documentation how to access the data). We are currently in the process to establish an open repository providing access to associated "secondary" data derived from ISIMIP simulations. The repository is planned to include e.g. the inundation areas and depth derived from ISIMIP runoff simulations by CaMaFlood and the patterns of climate change impacts at different levels of global warming generated within the study by Lange et al., 2017 Patterns of yield changes at different levels of global warming (Ostberg et al., 2017) will be added and are currently already available as supplementary online material to the paper. The source code for future sea-level rise approximation tool is available via github. Socio-economic impact data underlying the tropical cyclone emulator is currently prepared for publication and annually aggregated exposed population and exposed assets by tropical cyclones and will be available on country- and regional-level as a function of global mean temperature, c.f. the equivalent freely available database for observed historical tropical cyclone exposure TCE-DAT. These datasets are generated using the open-source climate adaptation toolbox climada and all modeling steps are freely available online.

5 LIST OF PRESS RELEASES AND MEDIA CONTRIBUTIONS

- The study of Mengel et al. (2016) was covered by leading international newspapers, e.g. Washington Post and The Guardian, as well as by Climate Central. The press release can be found here.
- The study by Jägermeyr et al. (2016) was covered in various print and online newspaper outlets, e.g. Time Magazine, Deutsche Welle, or Märkische Allgemeine. The press release can be found here. The paper was awarded ERL Highlights 2016 by editors.
- The study by Geiger et al. (2016) was covered in various international media outlets (Reuters, mashable, climatewire, Liberation). Find PIK press release here. The paper was awarded ERL featured article.
- The Schewe & Levermann (2017) study was covered in German daily Süddeutsche Zeitung, German radio programme RadioEins, as well as by Reuters, AFP, and others. Press release see PIK website.
- The Schewe et al. (2017) study was covered in German daily Der Tagesspiegel. Press release see PIK website.
- The press release for the study by Schauberger et al., 2017 can be found here.

6 LIST OF PUBLICATIONS GENERATED WITHIN THE PROJECT

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8 LIST OF QUALIFICATIONS

Jonas Jägermeyr defended his dissertation (May 29, 2017) with summa cum laude at the Geography Department of Humboldt-Universität zu Berlin. The paper “Integrated crop water management might sustainably halve the global food gap”, which is part of this project, was a central chapter of his doctoral studies.
Bernhard Schauberger will defend his dissertation at the Albrecht Daniel Thaer-Institute of Agricultural and Horticultural Sciences of Humboldt-Universität zu Berlin in January 2018. The paper “Consistent negative response of US crops to high temperatures in observations and crop models” generated within this project is an integral chapter of his doctoral studies.

7 FURTHER UTILISATION

The methods and results will become central inputs for the ISIpedia portal.

The methodology to project future global sea level rise (Mengel et al. 2016) has been regionalized to serve as input for the ISIMIP2b impact assessments. The methodology was the basis of a publication that links the Paris Agreement goals with future sea level rise (Mengel et al., 2017)

The methodology developed for the tropical cyclone emulator has been implemented within the open-source climate adaptation toolbox climada that provides an economic assessment of climate impacts by linking the hazard with economic impacts and potential adaptation strategies. Together with the planned implementation of other additional hazards in an ongoing collaboration with partners from ETH Zurich the climada tool will make impact assessments available to and reproducible by a broad community.

Dr. Michael J. Puma (Director of the Center for Climate Systems Research at NASA Goddard Institute for Space Studies in New York and a Climate and Life Fellow at the Center for Climate and Life at Columbia University, New York), who is an expert for global food security, significantly contributed to our study on the food security improvements by a global wheat reserve. Building upon NASA's existing food security efforts, we plan to integrate our price volatility models in an broader operational setting combing remote sensing, crop modeling, seasonal forecasting, nutrition, and socioeconomic analysis to integrate Earth information into decision support products that will appeal to a broad array of international stakeholders. This project aims at designing application products to provide early warning and rapid response to emergent food security challenges.

With respect to the modelling of supply-chain losses, we were invited to a kick-off workshop in October 2017 at the World Bank in Washington DC on the supply-chain risks of climate extremes organized by Dr. Stephane Hallegatte, lead economist with the Global Facility for Disaster Reduction and Recovery (GFDRR). The goal of the workshop was to initialize a more formal assessment of the World Bank on the importance of disaster induced supply-chain losses. The results of this ongoing effort are planned to be summarized in a GFDRR report to inform multinational bodies such as Green Climate Fund as well as national governments and stakeholders on the economic risks of climate change.

The tools used to estimate the heat response of crop yields in the USA provide the basis of further analysis expanding the existing study (Schauberger et al., 2017) to other world regions to explore whether they show a similar characteristic of crop yield variations and whether the differences in the responses can be explained by our current understanding of the underlying processes as represented in the global gridded crop model LPJmL. The work is part of the PhD by Elisabeth Vogel in the framework of the Australian-German Climate and Energy College.

A further PhD project by Caroline Park in the framework of the college is intended to estimate the effect of extreme events on fruit and vegetable production and availability. A first analysis will build on the developed tools to estimate the effects of droughts and heat waves (Jägermeyr and Frieler, 2017) on crop yields and apply it to reported data of fruit and vegetable production.