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Complete List of Authors:	Sultan, Benjamin; Institut de recherche pour le developpement, ESPACE-DEV Parkes, Ben; University of Manchester School of Mechanical Aerospace and Civil Engineering, MACE Gaetani, Marco; Centre National de la Recherche Scientifique, LATMOS-IPSL
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Direct and indirect effects of CO2 increase on crop yield in West Africa

Benjamin Sultan (1), Ben Parkes (2) and Marco Gaetani (3)

(1) ESPACE-DEV, Univ Montpellier, IRD, Univ Guyane, Univ Reunion, Univ Antilles, Univ Avignon, Maison de la Télédétection, 500 rue Jean-François Breton, F-34093 Montpellier Cedex, France

(2) MACE – Manchester, United Kingdom

(3) LATMOS/IPSL, CNRS, Sorbonne Université, Université Paris-Saclay, Paris, France

Abstract

Climate change directly threatens food security in West Africa through a negative impact on productivity of the main staple food crops. However, providing consistent future crop yield projections in the region remain challenging because of uncertainty in the response of the regional climate to the CO2 increase and in the response of the cultivated crop to this altered climate with more CO2 in the atmosphere. Here, we analyse a set of idealised climate simulations to investigate the effect of CO2 concentration increase on the West African monsoon and potential impacts on crop yields of maize. On the one hand, simulations with prescribed SST and quadrupled CO2 concentration are analysed to study the atmospheric response to direct radiative forcing induced by increasing CO2 concentration, not mediated by ocean heat capacity. On the other hand, simulations with prescribed SST augmented by 4 K are analysed to study the atmospheric response to the global ocean warming expected as a consequence of the increasing CO2 radiative forcing. We show that if CO2 concentration increase has a positive impact on crop yield due to the fertilisation effect, it also has a direct effect on the monsoon which acts to increase (decrease) rainfall in the Eastern (Western) part of the Sahel and increase (decrease) crop yields consequently. Finally, we show that SST warming acts to reduce rainfall and increase local temperatures leading to strong reduction of crop yield. The reduction of crop yield is more important in the Eastern part of the Sahel where the warming is more intense than in the Western part of the Sahel. Overall, positive effects are weaker and more uncertain than the negative effects in the analysed simulations.

1. Introduction

Sub-Saharan Africa is particularly vulnerable to climate change which directly threatens food security of the rapidly growing population (IPCC 2014). Here, multiple environmental, political, and socio-economic stressors interact to increase the region's susceptibility and limits its economic and institutional capacity to cope with and adapt to climate variability and change (Connolly-Boutin and Smit 2016; Müller et al. 2010; Challinor et al. 2007). Achieving food security in several African countries will depend partly on the effective adaptation of agriculture to climate change, as crop yields of major staple food crops in the Tropics are expected to decrease in a warmer climate (Challinor et al. 2014). However, one of the limits of adaptation planning — such as breeding more resilient crop varieties or promoting more resistant existing varieties and practices (Barnabás et al 2008)— is the high uncertainty in regional scenarios of crop production under climate change. Indeed, although there are robust evidences of a decrease of crop production due to the global warming (Challinor et al. 2014; Knox et al. 2012), the spread of crop yield responses remains very large as found by Müller et al. (2010) which showed that projected impacts relative to current African production levels range from −100% to +168%. Most of the uncertainty is led by the difficulty to estimate the twofold effect of CO_2 concentration increase, i.e. the response of the regional climate to the CO_2 increase and the response of the cultivated crop to this altered climate with more CO_2 in the atmosphere (Berg et al. 2013). Here we investigate those two effects of CO_2 increase in West Africa where crop yield is projected to decrease under global warming (Roudier et al. 2011) but also where there are large discrepancies in future climate scenarios (Sultan and Gaetani 2016). The variability of the West African climate during the 20th century has been deeply tied to the CO_2 concentration increase, but the response of the regional atmospheric dynamics is particularly complex and still debated (Gaetani et al. 2017). Indeed, the CO_2 concentration increase has a twofold and conflicting effect on the West African monsoon dynamics. Interestingly, whereas the radiative forcing mediated by the Global Ocean warming weakens the monsoonal circulation, the direct radiative forcing at the land surface acts locally to enhance precipitation (Gaetani et al. 2017). Specifically, the Tropical Ocean warming heats the troposphere and imposes stability, reducing moisture transport and deep convection over land, ultimately weakening the monsoonal circulations (Held et al. 2005). Over land, CO_2 radiative forcing leads to local increased evaporation and vertical instability, resulting in enhanced precipitation (Giannini 2010). Climate variability in West Africa during the 20th century was characterised by large variability, alternating wet periods with droughts (Nicholson et al. 2017). After a devastating drought characterising the 70s and peaking in the mid-80s (Held et al. 2005), West Africa experienced a recovery in summer monsoon precipitation during the 90s and at the turn of the 21st century (Fontaine et al. 2011). Dry anomalies were caused by the weakening of the monsoonal circulation in West Africa, driven by the warming of the Tropical Ocean (Giannini et al. 2003). The concomitant negative phase of the Atlantic Multidecadal Oscillation (AMO), which reduced the boreal summer northward migration of the intertropical convergence zone (ITCZ) and its associated rain belt, exacerbated the drying trend, resulting in a long lasting drought (Mohino et al. 2011). Conversely, the recent precipitation recovery has been related to the faster warming of the northern hemisphere, which favoured the northern displacement of the ITCZ (Park et al. 2015), and to the local CO_2 radiative forcing over land (Dong and Sutton 2016). In this context, how the competing effects of ocean-mediated and local CO_2 radiative forcing combine is still unclear, and the likely further future increase in CO_2 concentration casts uncertainties on the rainfall projections for the 21st century (Biasutti 2013).

Rising CO_2 concentration in the atmosphere has an impact of the cultivated crop through a direct and an indirect effect. The direct effect is the potential of atmospheric CO_2 to increase crop water productivity by enhancing photosynthesis and reducing leaf-level transpiration of plants (Tubiello et al. 2007; Leakey 2009; Deryng et al. 2016). Although the amplitude of this effect depends on the region, the scale and the crop, most of the recent modelling studies found significant increases of crop yield in West Africa due to elevated CO2 (Deryng et al., 2016; 2015; Sultan et al. 2014; Muller et al. 2010). It is particularly true for C3 crops such as cotton (Gerardeaux et al. 2013). C4 crops such as maize, sorghum or millet are less sensitive to atmospheric CO2 concentration however there are impacts as a result of stomatal closure and soil moisture conservation (Leakey et al. 2009). The indirect effect is the response of the crop to the altered climate due to atmospheric CO2 concentration increase. Most studies find yield losses under future climate scenarios (Sultan and Gaetani 2016; Challinor et al. 2014; Roudier et al. 2011; Knox et al. 2012; Challinor et al. 2007; Kotir 2010; Müller et al. 2010), because of the adverse role of higher temperatures which reduce the crop cycle duration and increase evapotranspiration (Schlenker and Lobell 2010; Roudier et al. 2011; Berg et al. 2013; Sultan et al. 2013). Although uncertain, changes in rainfall modulate the spatial distribution of climate change impacts on crop yields (Gaetani and Sultan 2016; Sultan et al. 2014). Indeed, yields losses of millet and sorghum are particularly high in the western Sahel as a result of the combination of warming and decreased precipitation at the beginning of the rainy season (Sultan et al. 2014). In the central Sahel, temperature and precipitation operate in opposite directions—warming causes yield loss whereas increased rainfall at the end of the rainy season is favourable for growing millet and sorghum (Sultan et al. 2014). Thus, direct and indirect effects of rising atmospheric CO2 act in a competing way with benefits of elevated levels of CO2 through increased crop water productivity while resulting warmer mean temperatures are likely to lead to crop yield losses.

Here, we use a set of idealised climate simulations of five climate models combined with a crop model to investigate the effect of CO2 concentration increase on the West African monsoon and potential impacts on maize yields. Maize is an important staple crop of West Africa and is grown extensively in Burkina Faso, Mali, Niger and Nigeria. The climate model experimental set-up allows to separate the direct local CO2 radiative forcing on the West African climate from the indirect forcing mediated by global Sea Surface Temperature (SST). The aim of this study is to investigate how these decoupled climate signals propagate through a crop model rather than producing realistic maize simulations. In addition, the crop model experimental set-up allows to evaluate the potential of the CO2 fertilisation effect on the crop water productivity in combination with the impacts of regional climate change in West Africa.

In the next section we introduce the experimental set-up and the crop model (GLAM model) used in this study. In section 3, we analyse the simulations by separating (i) the direct effect of CO2 increase on crop and monsoon and (ii) the effect of SST warming on the regional climate and crop productivity. Finally, in section 4, we discuss our conclusions.

2. Materials and Methods

2.1 AMIP Simulations

The competition between the SST-mediated and direct CO2 effect on the West African climate is studied by analysing idealised numerical experiments from a set of five climate models selected in the CMIP5 archive (Taylor et al. 2012) (see Table 1 for details on the models). Models are run in atmospheric-only configuration, with observed SST and sea ice prescribed for the period 1979 to the 2008. The simulations take into account the observed evolution in the atmospheric composition (including CO2), due to both anthropogenic and natural influences, and the changes in solar forcing, emissions and concentrations of aerosols, and land use. This experimental set-up is used as the control simulation (CTL) for two sensitivity experiments run either by prescribing uniform 4K increase in global SST (4K experiment), or by quadrupling the CO2 atmospheric concentration while maintaining the SST unchanged (4xCO_2 experiment). The use of such an idealised design is intended to isolate in a straightforward manner the climate responses to, respectively, the direct local CO_2 radiative forcing and to the global SST increase, which would not be possible in ocean-atmosphere coupled simulations. Indeed, in coupled simulations, direct and SST-mediated effects of CO_2 forcing on the climate system are mixed, and the competitive aspects of the CO_2 influence on the West African monsoon cannot be disentangled. Specifically, in the 4xCO_2 experiment, the Global Ocean is not allowed to warm and store heat, so that the climate system only responds to the local radiative forcing on land surface induced by the quadrupling of the CO_2 concentration (Fig.S1-S5 in Supplementary Material). Conversely, by fixing CO_2 concentration at present-day values and increasing SST, the climate system only responds to the ocean surface warming, with no direct forcing from increasing CO_2 concentration (Fig.S6-S10 in Supplementary Material). The experimental setup is described in detail in Taylor et al. (2012). Extreme idealised forcing is imposed in the sensitivity experiments to magnify the response of the climate system to the global SST warming (in 4K), and to the local direct CO_2 radiative forcing (in 4xCO_2), respectively. These conditions are comparable with the situation expected in 2100 in the RCP8.5 emission scenario (Riahi et al. 2011), with the CO_2 concentration augmented from 390 ppm in 2011 to more than 1000 ppm (more than +260 %), and more than 3K global SST warming (IPCC 2014). Model selection is based on the experiment availability, thus considering only models for which the three experiments (CTL, 4K and 4xCO_2) are available. Moreover, the availability of daily data for the variables used to force the GLAM model (see Section 2.2) represents a further constraint, leading to the final selection of the model ensemble. Availability of multiple realisations is also limited (for the baseline experiment, 6 members are respectively available for HadGEM2-A and IPSL-CM5A-LR, and 2 members for MIROC5; for sensitivity experiments, 2 members are available for IPSL-CM5A-LR and IPSL-CM5B-LR, respectively). Therefore, one realisation of each experiment is used for each model, not to bias the results toward models for which more realisations are available. However, the analysis of precipitation and temperature outputs from HadGEM2-A and IPSL-CM5A-LR shows that idealised perturbations in the sensitivity experiments are large enough to overcome model internal variability (not shown), and choosing different realisations for baseline and sensitivity experiments would not change the conclusions of the paper. The selected models correctly simulate all the main features of the monsoonal dynamics, although the comparison with observational and reanalysis products shows some biases (see Supplementary Material in Gaetani et al. 2017). Particularly, HadGEM2-A and IPSL-CM5B-LR simulate a significant weaker monsoon, while MIROC5 is affected by significant wet biases. Specific analysis of these biases is beyond the scope of the paper. However, biases in model simulation of the West African monsoon are related to the coarse resolution, which limit the model ability in producing intense and organised convective systems (Vellinga et al. 2015), to the poor representation of the global SST teleconnections (Rowell 2013). The differences in grid resolution among models are harmonised by using a first-order conservative remapping to regrid all the datasets to a 1° regular grid. Although caution should be used when regridding the coarse resolution of the IPSL models to 1°, we consider this choice an appropriate compromise to conserve climate model information and respond to the crop model needs. Finally, we highlight that the purpose of this study is to analyse the sensitivity of crop yield to idealised conditions representing the competing effects of the CO_2 concentration increase, rather than a realistic productivity assessment.

2.2 GLAM Simulations

GLAM is the Global Large Area Model for annual crops (Challinor, et al. 2004). GLAM is a process-based model that was developed for use with climate scale data. GLAM requires soil data, a crop parameter set and meteorological inputs. The soil data is derived from the Digital Soil Map of the World and gridded to the meteorological data grid. The planting dates for the crops were derived from the Global Gridded Crop Model Intercomparison project dates for maize (Elliott et al 2015).

GLAM runs are performed at 1° regular grid resolution using climate simulations outputs as meteorological inputs. These inputs are maximum daily temperature, minimum daily temperature, downwelling shortwave radiation at the surface and precipitation. The maize parameter set is identical to the one used in Parkes, et al. (2018) and based on the parameter set used in Vermulen et al. (2013). In this study GLAM was run with an idealised crop where the yield gap parameter is set to 1 instead of being calibrated to observed crop yields (Challinor, et al. 2015 Parkes, et al. 2015). We are using a maize parameterisation that is idealised in that we are not attempting to replicate observed yields but instead are simulating the theoretical maximum yield value for a crop in those circumstances. This removes the effects of pest/diseases and management techniques. This method was selected to show the meteorological signals consistently across the domain. GLAM uses a triangular profile to determine growth at a given temperature. For these simulations the base, optimum and maximum temperature were set at 8, 34 and 44 C respectively. If the mean daily temperature is above the optimum temperature then reduced growth is expected. A high temperature stress routine is also used and can further reduce yields if temperatures are above 37 C during flowering. The high temperature stress routine is described fully in Challinor et al (2005).

Carbon dioxide fertilisation in C4 crops is less significant than in C3 crops. However, C4 crops do respond to carbon dioxide fertilisation due to stomatal closure and conservation of soil moisture. The relationship between transpiration efficiency and carbon dioxide fraction for C4 grasses increases to a maximum before levelling off. The increased transpiration efficiency values are based on response ratio of the transpiration efficiency to carbon dioxide for water limited maize in GLAM generated by Julian Ramirez-Villegas (personal communication, 2015). The curve of this relationship was modelled using a negative square term to find the maximum transpiration efficiency. This maximum is at 850 ppm CO_2 and results in a transpiration efficiency of 11.06 pa (from 6.5 pa). In addition, the maximum transpiration efficiency was increased from 9.0 g/kg to 15.31 g/kg where the fractional increase in transpiration efficiency (pa) is maintained for the increase in maximum transpiration efficiency (kg).

2.3 The six scenarios

Six scenarios are used in this study to investigate the role of CO_2 concentration increase on crop yield in West Africa (Table 2):

- *The control scenario (t0c1f1):* Here GLAM runs are performed using climate inputs from the most realistic configuration of a set of climate models forced with observed SST and sea ice prescribed for the period 1979 to the 2008 which takes into account anthropogenic and natural influences. It allows to have a realistic climate forcing as a baseline to further sensitivity experiments.

- *The scenario with fertilisation effect of CO2 on the crop (t0c1f4):* Here GLAM runs are performed using baseline climate but the crop is experiencing four times higher levels of CO_2 concentration which increase transpiration efficiency in the GLAM model and thus increase crop yield. When compared to the control scenario, this simulation gives the fertilising effect of CO_2 increase on crop yield in the GLAM model for unchanged climate conditions.

- *The warmer climate scenario with no effect of CO2 on the crop transpiration (t4c1f1):* Here GLAM runs are performed using the +4K climate conditions and atmospheric CO_2 concentration is similar to the control scenario. When compared to the control scenario, this simulation allows to point out the impact on crop yield of the climate system response to the global SST warming.

- *The warmer climate scenario with effect of C02 on the crop transpiration (t4c1f4):* Here GLAM runs are performed using the same +4K climate conditions as in *t4c1f1* but the crop is experiencing four times higher levels of CO_2 concentration which increase transpiration efficiency in the GLAM model. When compared to the control scenario, this simulation gives the combined effects of warmer climate and increase of transpiration efficiency on crop yield in the GLAM model.

- *The direct CO_2 effect on the monsoon with no effect of CO_2 on the crop transpiration (t0c4f1):* Here GLAM runs are performed using climate conditions responding to the quadrupling of CO_2 concentration while SST is unchanged, and CO_2 concentration remains unchanged compared to the control scenario. When compared to the control scenario, this experiment allows to isolate the impact on crop yield of the response of the monsoon to the local direct CO_2 radiative forcing.

- *The direct CO_2 effect on the monsoon added to the effect of CO_2 on the crop transpiration (t0c4f4):* Here GLAM runs are performed using climate conditions responding to quadrupled CO_2 concentration and crop is experiencing four times higher levels of CO_2 concentration which increase transpiration efficiency in the GLAM model. When compared to the control scenario, this experiment simulates the combined effects of the CO_2 increase on the monsoons dynamics and on the transpiration efficiency.

3. Results

3.1. The control simulation

The control simulation reveals important differences in total rainfall and mean temperatures between the five climate models (Table 3). In particular, HadGEM2 simulates the lowest annual precipitation value (461 mm/year) while the MIROC5 model is the wettest (671 mm/year) and the hottest model (29.1C). Even if climate models are forced with observed SST and are thus likely more realistic than coupled model simulations, there are still important biases compared to observations in the control run. Indeed all models are too dry and too hot compared to annual rainfall and mean temperature computed using the reference WFDEI dataset (707 mm/year and 27.1C respectively). As a result of these important differences between climate models, the simulated yield varies strongly from one model to another since yield is highly sensitive to rainfall and temperature variations (Figure 1). In the GLAM crop model, crop yield increases as total rainfall amount during the growing season increases, following an exponential fit, until reaching values where the water constraint is not limiting anymore. Simulated potential crop yield follows a more linear fit with temperature and shows a decrease of crop yield as temperature decreases. As a result, the HadGEM2 model has the lowest mean yield because of its low annual rainfall compared to the four other models.

3.2. The direct effect of CO_2 increase on crop and monsoon

Elevated concentration of CO_2 in the GLAM crop model under the control climate (*t0c1f4* simulation) has a clear positive effect on crop yield (red bars in Figure 2). The multi-model mean shows an increase of +26.79% of simulated potential crop yield compared to the control simulation (*t0c1f1* simulation) when aggregating results over whole West Africa. This crop yield increase is found using any of the five climate models although the amplitude of the yield gain varies across the models. The yield increase exceeds 40% using the IPSL CM5A model while it less than 23% using the CNRM CM5 model. The CO_2 fertilisation effect is linked to the water stress and therefore it can explain why the responses are model dependent.

An increase of atmospheric CO_2 concentration has also a direct effect on the monsoon which has in turn an impact on simulated potential crop yields. The *t0c4f1* simulation isolates this effect by removing the fertilisation effect on the crop model. When aggregating results over whole West Africa, the multi-model mean shows a very weak response of crop yields (-0.67%) which mainly result from a high dispersion across the response of individual models (grey bars in Figure 2). Indeed, the monsoon effect can lead to yield gain of about 22% using the HadGEM2 model while it results to a yield loss of more than 15% in the MIROC5 model. This yield response is mainly driven by the rainfall change in the model with elevated levels of CO2 (Figure 3; Table 4). The HadGEM2 model is highly sensitive to atmospheric CO2 increase which produces more rainfall (+19.82%) while the same CO2 increase lead to a reduction of rainfall of about 2% in the MIROC model. In average over West Africa, there is a positive linear relationship between rainfall changes and yield changes between the *t0c4f1* simulation and the control *t0c1f1* simulation (R^2=0.98; Figure 3).

The combination of the direct effect of CO2 increase on the crop and on the monsoon (*t0c4f4* simulation) leads to a large increase of simulated crop yields (+26.79%) over West Africa in the multi-model mean (Figure 2). It indicates that the fertilisation effect on the crop dominates the yield response rather than the effect of the monsoon. However individual model runs show that the monsoon effect can largely modulate the fertilisation effect (blue bars in Figure 2). The benefits of the fertilisation effect are almost cancelled in the MIROC model (24,04% in *t0c1f4* simulation and 6,39% in *t0c4f4* simulation) which simulates a decrease of rainfall with the CO2 increase. On the opposite, the benefits are doubled in the HadGEM2 model (24,45% in *t0c1f4* simulation and 49,68% in *t0c4f4* simulation) which simulates more rains with the CO2 increase.

The spatial patterns of yield change due to CO2 increase show some important regional disparities (Figure 4). Although the yield increase due to the CO2 fertilisation effect (Figure 4a) is widespread over the Soudano-Sahelian zone, it is slightly less important in the North where water stress is too high for being compensated by the CO2 increase. The CO2 fertilisation effect is also reduced in the wettest areas along the Guinean coast and in southern Atlantic coast where on the opposite there is no water stress and thus where the crop cannot benefit from the reduction of transpiration expected by the CO2 atmospheric concentration increase. In Figure 4b, yield change is driven by the effect of CO2 on the monsoon without taking into account the fertilisation effect (*t0c4f0* simulation). The spatial pattern opposes the western part of West Africa and to a less extent the Guinean Coast where potential crop yield losses are expected with the Central Sahel where crop yield gains are expected. When averaging across West Sahel and East Sahel boxes (see Figure 4b for the localisation of the boxes), we can see that the direct effect of the monsoon leads to potential crop yield losses in the West Sahel (-5.27%) and to yield increases in East Sahel (+12.07%). It is highly variable across model and the response depends on rainfall change (Table 5). This spatial pattern is very close to the precipitation change due to CO2 increase effect on the monsoon (Figure 4c). Gaetani et al. (2017) shows that the response of the WAM precipitation to the quadrupling of the CO2 concentration is the northward migration of the precipitation belt, driven by the intensification of the meridional energy gradient across West Africa, and resulting in positive (negative) precipitation anomalies in the Sahel (Guinean coast). The positive precipitation anomalies in the Sahel are also modulated along the zonal direction, being stronger to the east than to the west (see Figure 2 in Gaetani et al. 2017). This feature is associated with an anomalous zonal cell triggered by strengthened convection over West Africa, which connects with subsidence over Tropical Atlantic. This results in a quasi-zonal anomaly in the monsoonal flow, which favours moisture convergence in central-eastern Sahel (see Figures 4 and 8 in Gaetani et al. 2017). Precipitation patterns in model responses to quadrupled CO2 concentration are then produced by the combination of the circulation response in the zonal and meridional directions, which is in turn driven by the model regional response to the CO2 forcing. When we combine the direct effect of CO2 increase on the crop and on the monsoon (*t0c4f1* simulation), yield is increasing almost everywhere in West Africa (Figure 4d) except in Western part of the Sahel where the reduction of rainfall induced by the CO2 increase dominates the yield benefit of the fertilisation effect.

3.3. The effect of SST warming

A warmer ocean (+4K increased SSTs in the *t4c1f1* experiment) leads to particularly detrimental climate conditions for the crop (Figure 5; Table 6). An important warming is simulated in West Africa with annual temperatures changes ranging between 4K and 5K in the coastal areas of the Atlantic Ocean and reaching +6K, up to +7K in the more continental areas (Figure 5a). The multi-model mean shows that the +4K warming of SSTs leads to a +5.54K local growing season warming in average over West Africa (Table 6). A warmer ocean induces a reduction of rainfall all over West Africa (-18.97% in average) except in the North Eastern part of the Sahel (Niger) where rainfall increases. The rainfall deficit is particularly important in South West Sahel in Senegal, Gambia and Guinea-Bissau where a reduction of rainfall greater than 40% is simulated in the *t4c1f1* experiment (see also Gaetani et al. 2017).

These warm and dry conditions lead to large potential crop yield losses (Figure 6; Table 6) everywhere in West Africa. The multi-model mean shows that a +4K warming of SSTs leads to a reduction of 56% of crop yield in average over West Africa and a shortening of the crop season duration of 9 days. This reduction is only partly (-40.89%) compensated by the fertilisation effect of CO_2.

It is interesting that even if the rainfall deficit is the greatest in the Western part of the Sahel, yield loss is more pronounced in the Eastern part of the Sahel when averaged simulations over the same West and East boxes shown in Figure 4 (Table 7). The reduction of the potential yield is the most important in the East Sahel (-69.8%) and slightly hampered by CO_2 fertilisation effect (-54.7% of crop yield loss). The yield loss is less important in the West Sahel reaching -52.6% without taking into account CO_2 effect on crop and -38.6% with the CO_2 fertilisation effect. Simulations show that if the monsoon rains are more affected in the Western Sahel (a reduction of 12 days and more than 25% of the rainfall) than in the Eastern Sahel (a reduction of 3 days and about 16% of rainfall), the warming is more important in the East Sahel (+5.9K against 5.4K in the West Sahel). With such levels of warming, temperatures changes drive the yield variability in the crop model as illustrated by Figure 7 which depicts a linear relationship between temperatures and yield changes in the simulations. It might explain why even if the monsoon rainfall is less affected in the East Sahel, the impact on crop yield is more important since the warming is more intense.

4. Conclusion

Rising CO_2 concentration in the atmosphere leads to two opposite effects on potential crop yield in West Africa. On one hand, benefits could be expected through an increase of rainfall driven by the direct effect of CO_2 radiative forcing on the monsoonal dynamics. Our simulations showed that, without increase of temperature, positive impacts will be more likely in Central and East Sahel where annual rainfall are strongly enhanced by elevated levels of CO_2. Indeed, monsoonal precipitation in West Africa responds to increasing CO_2 concentration migrating northwards to the Sahel, driven by the strengthened energy meridional gradient associated with the CO_2 radiative forcing over land. Enhanced deep convection triggers an anomalous zonal cell which intensifies the westerly moisture flow from the tropical Atlantic, resulting in a wetter response in central-eastern Sahel (Gaetani et al. 2017). Yield gains are also expected through the CO_2 fertilisation effect which act to reduce crop transpiration in the crop model and thus increase drought resistance. Although the amplitude of the expected benefits of the CO_2 fertilisation is certainly crop model dependent and still debated in the literature (Deryng et al. 2016), we found that they are far greater than those expected from the direct effect on the monsoon. In the Central East Sahel for instance, our simulations showed an increase of +43.5% of crop yield with the fertilisation effect against a yield gain of +12.1% due to the rainfall increase. On the other hand, negative impacts are expected from the elevation of temperatures. Detrimental conditions for the crop were obtained by warming up the ocean of +4K leading to drought conditions in the Western part of the Sahel and to an increase mean surface temperature of more than +5.5K in West Africa with particularly warm conditions in continental regions. This warming could lead to yield loss of more than 56% which can only be partly hampered by the fertilisation effect (-40.9% of yield loss by taking into account the fertilisation effect).

With such competing effects, which are not always additive, providing reliable climate change impacts scenarios on crop yields is challenging. The differences between climate models in the estimation of the effects of direct and SST-mediated effects of CO2 were found to be very large with for instance the HadGEM2 model simulating an increase of +49.7% of the yield through the increase of rainfall (t0c4f4 simulations) and a decrease of -56.1% with the increase of temperatures (*t4c1f4*). Overall we found that positive effects in the analysed simulations are weaker and more uncertain than the negative effects. Indeed, simulated positive effects on crop yield range from +6.4% using the MIROC5 model to +49.7% in the HadGEM2 model while the negative effects range from -51.7% to -62.9% using the same two climate models respectively. We also found that temperatures increase will likely have a more important impacts on crop yield than rainfall changes as shown in previous studies (Schlenker and Lobell 2010; Roudier et al. 2011; Berg et al. 2013; Sultan et al. 2013). We highlight that, by construction, the idealised simulations analysed in this paper do not account for climate feedbacks to the increasing CO2 concentration. In particular, the global SST response to CO2 forcing in past and future climate simulations is far from the homogeneous warming prescribed in the 4K experiment, and this may lead to different results for the monsoonal dynamics and crop productivity. For instance, it has been shown that, in the presence of overall global ocean warming, while the warming of the Tropical belt inhibits precipitation in West Africa, the differential warming of the Northern Hemisphere, and in particular of the North Atlantic and Mediterranean, is favourable to rainfall (Giannini et al. 2013; Park et al. 2014; Park et al. 2016). Ocean-atmosphere coupled simulations of future climate in West Africa include all the climate feedbacks, so that the uncertainties in AMIP idealised simulations discussed in this paper are exacerbated, undermining mitigation and adaptation strategies in the region. Whereby in AMIP simulations the responses to an idealised forcing are concordant, though different in amplitude, coupled model simulations for the end of the 21st century range from dry to very wet projections, characterised by spatial inhomogeneity (Monerie et al. 2017). Coupled climate models are generally skilful in simulating the relationship between the regional atmospheric dynamics and the Sahelian rainfall (Biasutti et al. 2009), while SST teleconnections are poorly simulated (Rowell 2013), mainly because of the model biases in simulating ocean dynamics (Roehrig et al. 2013). Moreover, coupled climate simulations are generally performed not considering dynamic vegetation and land use, which are instead key ingredients of the monsoonal dynamics (Koster et al. 2004). Fixing model shortcomings and improving model design should be then prioritised in the next CMIP6 exercise (Eyring et al. 2016).

Every modelling study has its limitations and we recognize some caveats in our experiments. First of all, we use a limited number of GCMs (only five) within the full list of models participating to the CMIP5 exercise (more than 30). If different results with different or with more models are still possible, Gaetani et al. (2017) showed a general agreement among models in their response to the idealized conditions, which demonstrates the robustness of the mechanisms linking the WAM dynamics to the SST and CO2 idealized forcings, whatever the model physics or performance. Another limitation is the use of only one ensemble member from each GCM which does not ensure that most of the plausible scenarios are captured. However, we are here critically limited by the availability of ensemble members in the CMIP5 archive, which does not allow to perform a full exhaustive analysis of the internal variability within each GCM. Finally, a caution is necessary when interpreting the crop simulation results presented in this study. Crop yields results have to be interpreted as potential crop yield response to two aspects of climate change on the crops grown in West Africa, i.e. the increase in temperatures and the increase in atmospheric carbon dioxide levels, and not as a realistic crop yield prediction for the future. The crop model is simulating potential yields, without calibration. The parameter set is the same as the one used in Parkes et al. (2018), this includes the high temperature stress routine. This routine reduces crop yields as a result of high temperature stress during flowering. The potential yields are much higher than real yields and therefore the magnitude of reductions in yield as a result of high temperature stress is expected to be higher than for calibrated crops. This is expected to reduce the yields in the *t4c1f1* and *t4c1f4* experiments and may lead to an overestimate of the impact of increased temperatures.

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Table 1: Models analysed. CMIP5 model information and outputs are available through the Earth System Grid Federation archive (http://cmip-pcmdi.llnl.gov/cmip5)

Country	Modelling centre	Model	Resolution
France	Centre National de Recherches Météorologiques/Centre Européen de Recherche et Formation Avancée en Calcul Scientifique	CNRM-CM5	T127 (~1.4°)
United Kingdom	Met Office Hadley Centre	HadGEM2-A	1.25 × 1.875°
France	Institut Pierre Simon Laplace	IPSL-CM5A-LR	1.875° × 3.75°
France	Institut Pierre Simon Laplace	IPSL-CM5B-LR	1.875° × 3.75°
Japan	Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine Earth Science and Technology	MIROC5	T127 (~1.4°)

Table 2: The experiments with GLAM and AMIP runs. In control climate (ctl), SST and CO2 are prescribed at the 1979-2008 observed values (Taylor et al. 2012).

		Sea Surface Temperature in AGCM	CO2 atmospheric concentration in AGCM	CO2 concentration in GLAM crop model	Short description of the scenario
Control climate	*t0c1f1*	ctl	ctl	ctl	*The control scenario*
	t0c1f4	ctl	ctl	**ctl x4**	*The scenario of direct effect on CO2 on the crop*
Altered climate with +4K warmer SST but control CO2 concentration	*t4c1f1*	**ctl +4K**	ctl	ctl	*The warmer climate scenario with no effect of CO2 on the crop transpiration*
	t4c1f4	**ctl +4K**	ctl	**ctl x4**	*The warmer climate scenario with direct effect of C02 on the crop transpiration*
Altered climate with 4 times higher levels of CO2 concentration but control SST	*t0c4f1*	ctl	**ctl x4**	ctl	*The direct CO2 effect of the monsoon with no effect of CO2 on the crop transpiration*
	t0c4f4	ctl	**ctl x4**	**ctl x4**	*The direct CO2 effect of the monsoon with no effect of CO2 on the crop transpiration*

Table 3: Simulated yield (kg/ha), annual rainfall (mm/year) and mean surface temperature (degC) in West Africa in the *t0c1f1* control simulations. The values are averaged over the domain: Longitude 15W to 20E and latitude 4N to 15N

Climate model	Mean yield (kg/ha)	Total precipitation (mm/year)	Mean temperature (degC)
CNRM CM5	3994,0	650	27,2
HadGEM2	2921,5	461	28,7
IPSL CM5A	3706,6	645	27,6
IPSL CM5B	3342,6	569	27,4
MIROC5	3480,3	671	29,1

Table 4: Yield and annual precipitation change (%) in West Africa (20W-15E ; 4N-15N) in the *t0c4f1* simulations comparing to CTL simulation. MMM is the multi-model mean.

Climate models	Mean yield change (%)	Total precipitation change (%)
CNRM CM5	-0,57	6,59
HadGEM2	21,91	19,82
IPSL CM5A	1,42	5,43
IPSL CM5B	-7,68	1,60
MIROC5	-15,26	-2,08
MMM	-0,67	5,49

Table 5: Yield and annual precipitation change (%) in West Sahel and East Sahel (see boxes on Figure 4) in the *t0c4f1* simulations comparing to the control CTL simulation. MMM is the multi-model mean.

Domain	Climate models	Total precipitation change (%)	Mean yield change (%)
West Sahel	CNRM CM5	4,29	-6,79
	HadGEM2	16,07	9,21
	IPSL CM5A	6,78	-1,02
	IPSL CM5B	-2,07	-11,94
	MIROC5	-1,81	-14,34
	MMM	4,01	-5,27
East Sahel	CNRM CM5	10,34	8,11
	HadGEM2	33,45	90,31
	IPSL CM5A	13,23	10,09
	IPSL CM5B	12,27	0,86
	MIROC5	1,60	-20,64
	MMM	12,75	12,07

Table 6: Crop season duration (day), annual precipitation (%), mean temperature (K) and yield change (%) in the *t4c1f1* and *t4c1f4* simulations (only yield differs) in West Africa comparing to the control CTL simulation. MMM is the multi-model mean.

Climate models	Growing season duration change (day)	Total precipitation change (%)	Mean temperature change (K)	t4c1f1 Mean yield change (%)	t4c1f4 Mean yield change (%)
CNRM CM5	-14,3	-15,3	5,7	-54,7	-43,1
HadGEM2	-2,9	-16,6	6,0	-62,9	-52,6
IPSL CM5A	-12,7	-18,6	5,3	-55,4	-32,3
IPSL CM5B	-10,9	-27,2	5,5	-57,0	-39,9
MIROC5	-3,5	-17,5	5,2	-51,7	-38,6
MMM	-8,9	-19,0	5,5	-56,1	-40,9

Table 7: Crop season duration (day), annual precipitation (%), mean temperature (K) and yield change (%) in the *t4c1f1* and *t4c1f4* simulations (only yield differs) in West and East Sahel comparing to control CTL simulation. MMM is the multi-model mean.

Domain	Climate models	Growing season duration change (day)	Total precipitation change (%)	Mean temperature change (K)	t4c1f1 Mean yield change (%)	t4c1f4 Mean yield change (%)
West Sahel	CNRM CM5	-15,7	-24,9	5,4	-50,9	-41,6
	HadGEM2	-6,9	-25,8	5,8	-60,9	-51,5
	IPSL CM5A	-14,2	-18,1	5,2	-50,2	-26,0
	IPSL CM5B	-13,8	-28,1	5,3	-51,8	-35,2
	MIROC5	-9,6	-30,6	5,2	-50,4	-40,6
	MMM	-12,0	-25,5	5,4	-52,6	-38,6
East Sahel	CNRM CM5	-10,3	-10,5	6,1	-62,7	-47,8
	HadGEM2	5,4	-10,4	6,4	-85,9	-78,0
	IPSL CM5A	-10,1	-28,0	5,5	-69,2	-50,8
	IPSL CM5B	-5,6	-39,8	5,9	-81,1	-69,7
	MIROC5	6,1	1,6	5,3	-63,4	-44,0
	MMM	-2,9	-16,3	5,9	-69,8	-54,7

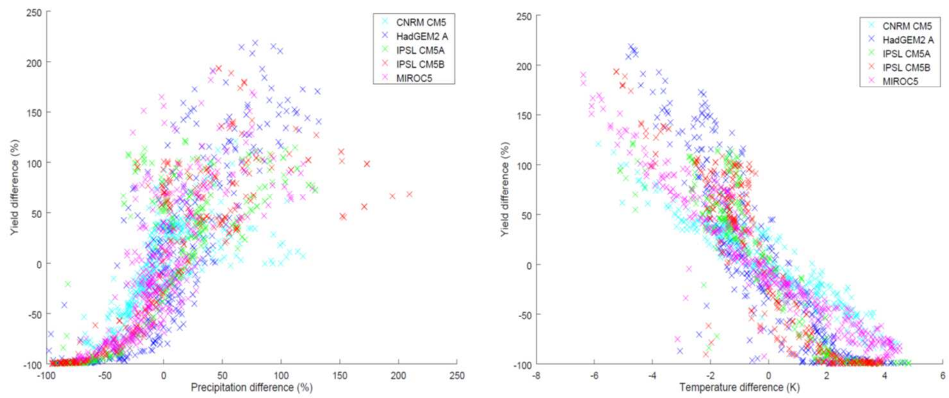

Figure 1: Crop yield response to rainfall and temperature variations in the GLAM model. Pixel by pixel difference against the domain average for mean yield and total growing season rainfall (left) and mean temperature (right). Values are then averaged over the 30 years of the control experiment to give more than 400 values expressed in percentage.

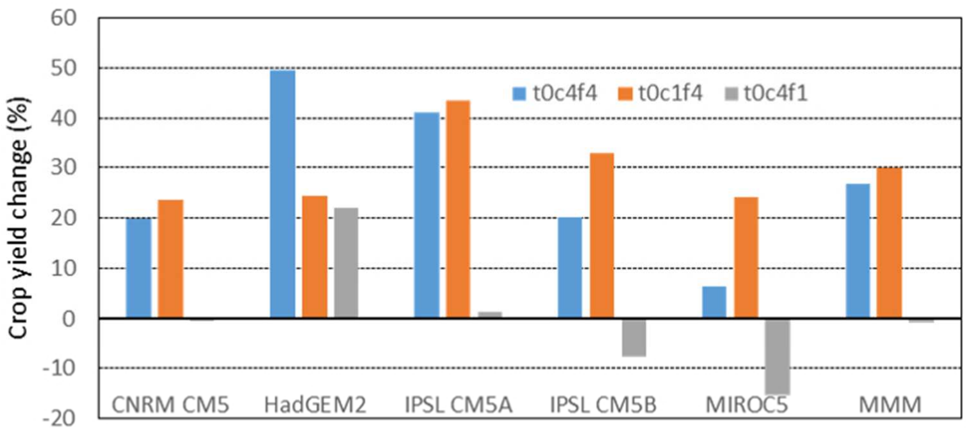

Figure 2: Crop yield response to increased C02 concentration. Simulated yield change (%) are shown as differences with the control run in average over West Africa (20W-15E ; 4N-15N) for the t0c4f4, t0c1f4 and t0c4f1 simulations. MMM is the multi-model mean.

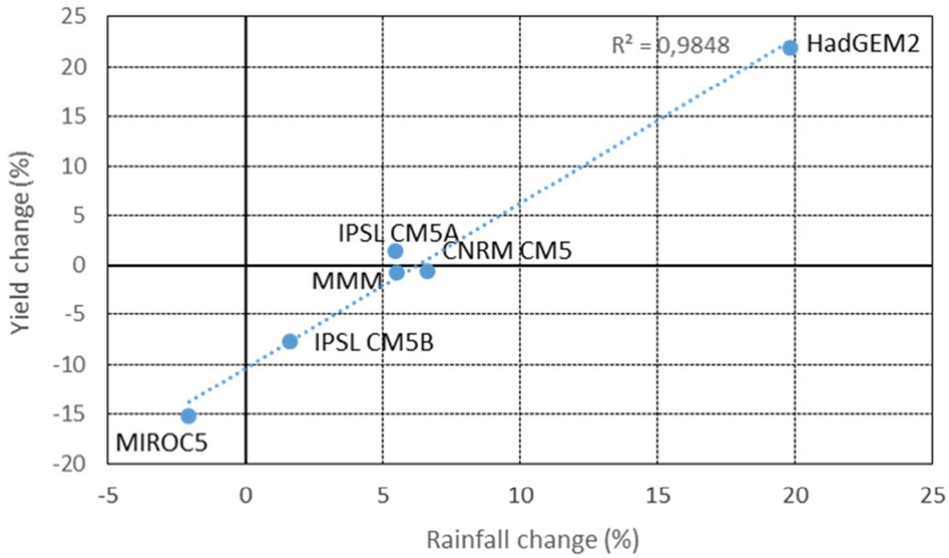

Figure 3: Crop yield response to rainfall variations in the t0c4f1 simulation. Simulated yield and rainfall changes (%) are shown as differences with the control run in average over West Africa for the t0c4f1 simulation. MMM is the multi-model mean.

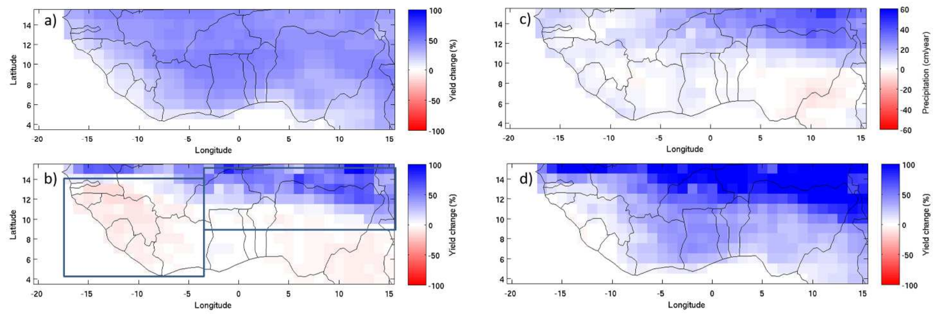

Figure 4: Mean yield and rainfall changes in West Africa in the t0c1f4, t0c4f1 and t0c4f4 simulations. Multi-model mean changes (%) are shown as differences with the control run. Simulated yield change are shown for simulations t0c1f4 (a), t0c4f1 (b) and t0c4f4 (d). Total rainfall change is shown in (c) for the t0c4f1 simulation. A similar map would be obtained for t0c4f4 simulation

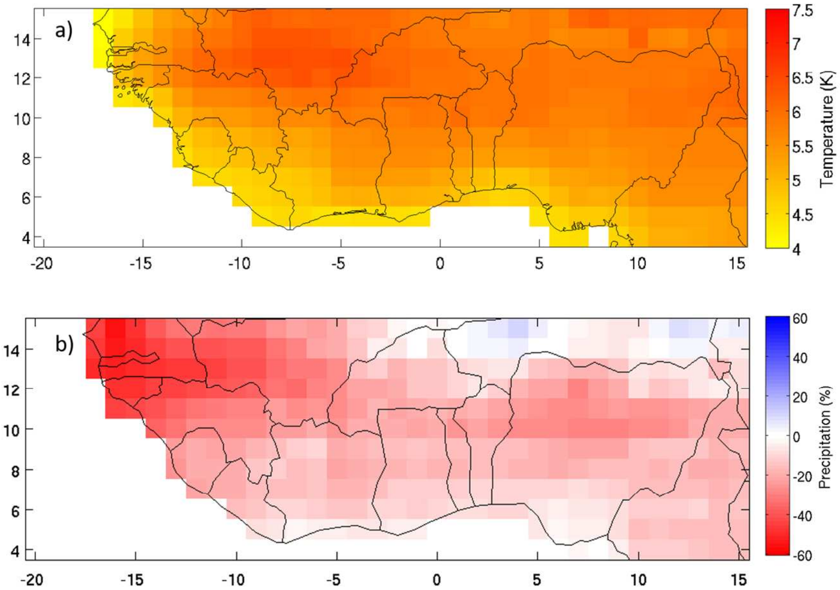

Figure 5: Mean temperature and rainfall response to a SST warming of +4K. Multi-model mean changes of temperature (a) and rainfall (b) are shown as differences between the t4c1f1 simulation and the control run.

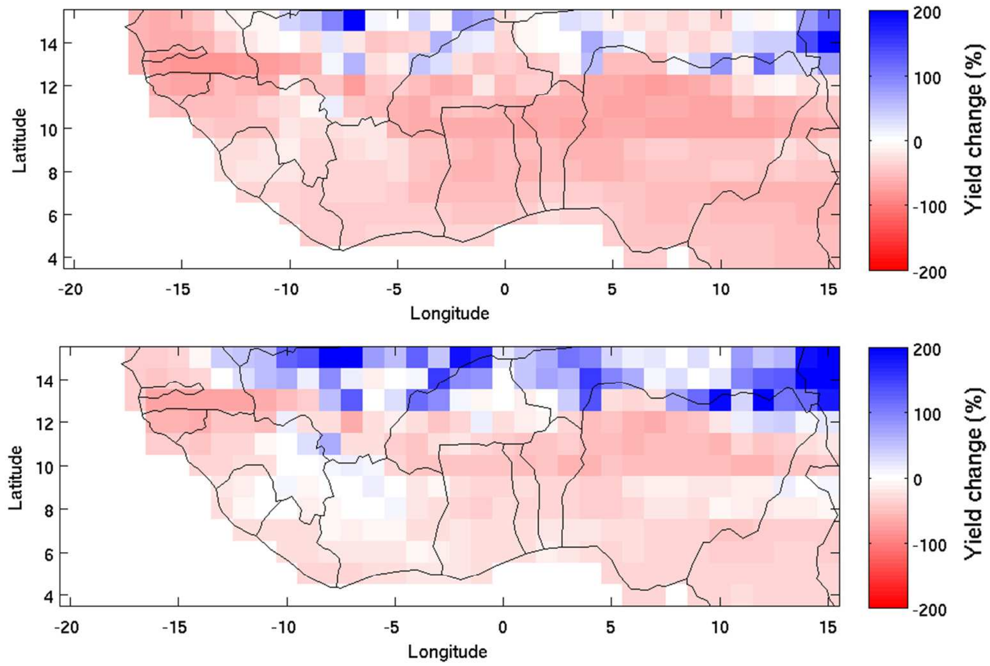

Figure 6: Crop yield response to a SST warming of +4K. Multi-model mean yield changes in West Africa (%) in the t4c1f1 (a) and t4c1f4 (b) simulations.

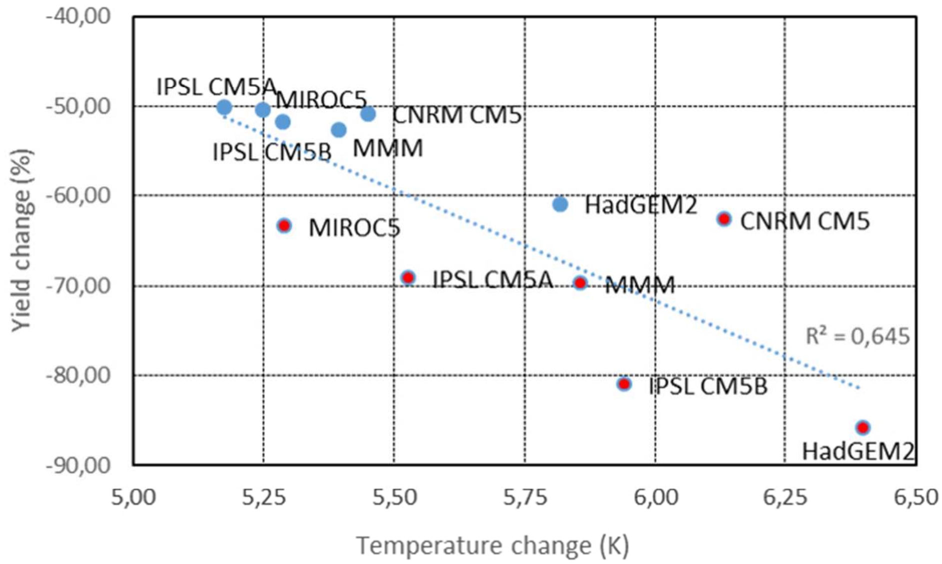

Figure 7: Crop yield response to temperature variations in the t4c1f1 simulation. Simulated yield (%) and temperature (K) changes are shown as differences with the control run in average over West Sahel (blue dots) and East Sahel (red dots) for the t4c1f1 simulation. MMM is the multi-model mean.