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Impacts of climate change and climate extremes on major crops productivity in China at a global warming of 1.5℃ & 2.0℃

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Abstract. A new temperature goal of "holding the increase in global average temperature well below 2℃ above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5℃ above pre-industrial levels" has been established in Paris Agreement, which calls for understanding of climate risk under 1.5℃ & 2.0℃ warming scenarios. Here, we evaluated the effects of climate change on growth and productivity of three major crops (i.e., maize, wheat, rice) in China during 2106-2115 at warming scenarios of 1.5℃ & 2.0℃ using the method of ensemble simulation with well-validated MCWLA family crop models, their 10 sets of optimal crop model parameters, and 70 climate projections from four global climate models. We presented the spatial patterns of changes in crop growth duration, crop yield, impacts of heat and drought stress, as well as crop yield variability and probability of crop yield decrease. Results showed that the decrease of crop growth duration and the increase of extreme events impacts in the future would have major negative impacts on crop production, particularly for wheat in north China, rice in south China and maize across the cultivation areas. By contrast, with the moderate increases in temperature, solar radiation, precipitation, and atmospheric CO_2 concentration, agricultural climate resources such as light and thermal resource could be ameliorated which enhance canopy photosynthesis, and consequently biomass accumulations and yields. The moderate climate change would slightly deteriorate maize growth environment but result in much more appropriate growth environment for wheat and rice. As a result, the wheat and rice yields could increase by 3.9% and 4.1%, respectively, and maize yield could increase by 0.2%, at a warming scenario of 1.5℃. At the warming scenario of 2.0℃, wheat and rice yield would increase by 8.6% and 9.4%, respectively, but maize yield could decrease by 1.7%. In general, the warming scenarios would bring more opportunities than risks for the crop development and food security in China. Moreover, although variability of crop yield would increase with the change of climate scenario from 1.5℃ warming to 2.0℃ warming, the probability of crop yield decrease would decrease. Our findings highlight that the 2.0℃ warming scenario would be more suitable for crop production in China, but the expected increase in extreme events impacts should be paid more attention to.

1 Introduction

In the past decades, global warming has markedly shifted the spatial-temporal patterns of temperature and precipitation (Gourdji et al., 2013; Liu and Allan, 2013). Moreover, the warming trend is expected to go on in the following decades with the increase of greenhouse gas emissions (Zhao et al., 2017), especially in cultivated areas (Lobell et al., 2011).The effects of climate changes and climate extreme on growth and yields of crops have been highly concerned(Porter et al., 2014; Asseng et al., 2015).Researchers have extensively demonstrated the crop responses to climate factors through conducting environment-controlled experiments(e.g., Ottman et al., 2012; Chen et al., 2016),analysing historical records (e.g., Lobell et al., 2011; Tao et al., 2012; Tao et al., 2014), and crop model simulations (Porter et al., 2014; Asseng et al., 2015). These studies have documented that increasing temperature could shorten crop growth duration and reduce crop yields at broad regions(Porter et al., 2014). Meanwhile, with climate warming, the frequency and intensity of climate extreme events, for example heat stress, are projected to increase, and substantially threaten the crop growth and food security, especially for some susceptible areas (Wahid et al., 2007; Asseng et al., 2011; Gourdji et al., 2013). Besides the negative impacts, the warmer environment could also improve the crop productions in some areas that suffered from heat deficit(Tao et al., 2008a; Tao et al., 2012; Tao et al., 2014; Zhang et al., 2014). In addition, elevated CO_2 concentration could inhibit the stomatal conductance and reduce the transpiration rates (Brown and Rosenberg, 1997), enhance photosynthesis and have fertilization effects on crop productivity(Ainsworth et al., 2008; Leakey, 2009).

With the progresses on impact mechanisms, crop model improvements and impacts assessment approaches such as ensemble simulations, climate change impact assessments have been elaborated in recent decade (Porter et al., 2014). The results of these studies have stressed the remarkable increase of extreme events and the decrease of major food crop yields, particularly under those scenarios with relatively higher temperature increase (Lobell et al., 2014; Porter et al., 2014). These results alerted the food crisis and highlighted the importance of mitigating the impacts of human activities on climate change. Recently, a new temperature goal of “holding the increase in global average temperature well below 2℃ above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5℃ above pre-industrial levels” have been established in Paris Agreement for the purpose of significantly reducing the risks and impacts that caused by climate change(UNFCCC, 2015). This goal implied a more moderate climate scenario in the future, requiring more focuses on the impacts evaluation in a warming world with ambitious mitigation strategies, and thus called for climate change impact assessments under the 1.5℃ warming and 2.0℃ warming scenarios(Mitchell et al., 2016).

China is one of the main planting countries of staple food (maize, rice and wheat). The crop productions in China have accounted for roughly 21%, 28% and 17% of global total production of maize, rice and wheat, respectively during the past decade. So far there has not had study about the impacts of 1.5℃ warming and 2.0℃ warming on national crop production in China, and has no information for the question of “What may probably happen to the future crop production in China with moderate temperature increase?” Here, we tried to conduct a study to evaluate the influences of climate change and climate extremes on these major crop yields in China at the warming scenarios of 1.5℃ & 2.0℃. We aimed to provide the spatial patterns of changes in crop growth duration, crop yield, yield decrease probability, and impacts of heat and drought stress for three major crops under these warming scenarios across China at spatial resolution of 0.5°×0.5°.

2 Materials and methods

2.1 Study area

This study focused on the cultivation area of maize, wheat and rice across China. The crop cultivation areas were shown in Fig. 1. The study was conducted at a grid scale with spatial resolution of 0.5°×0.5°. The maize was mainly sown in the northeast China, North China Plain (NCP) and some areas of southwest China (Fig. 1b). The major cultivation areas of winter wheat were across the NCP and Sichuan Basin, and the spring wheat was sown above the 40th degree of Northern Latitude (Fig. 1c). The rice was widely cultivated in the northeast, southwest and south China (Fig. 1d). The double rice (early rice and later rice) was cultivated in six provinces in south China, while single rice was cultivated in other regions.

2.2 Data

The climate dataset used in this study were the outputs of the “half a degree additional warming, projections, prognosis and impacts (HAPPI) experiment”, which provided historical climate datasets during 2006-2115 and the projected climate scenarios that were 1.5℃ and 2.0℃ warmer than pre-industrial level during 2106-2115 (Mitchell et al., 2017). Data from four global climate models (GCMs) including the CAM4, ECHAM6, MIROC5and NorESM1with 1.5℃ warming and 2.0℃ warming scenarios were published by the National Energy Research Scientific Computing Center (NERSC) at http://portal.nersc.gov/c20c/data.html. These datasets had been bias corrected using the methods in Hempel et al. (2013) and Frieler et al. (2016) and the dataset EWEMBI (Frieler et al., 2016; Lange, 2016). Among datasets, the CAM4, ECHAM6 and NorESM1 provided 20 runs of simulation results and the MIROC5 provided 10 runs of simulation results. All these runs were used as input data for crop models. In this study, the period of 2006-2015 was regarded as historical period and the period of 2106-2115 was regarded as future period.

2.3 MCWLA model and its parameterization

The MCWLA model family, including MCWLA-Maize model (Tao et al., 2009a; Tao et al., 2009b), MCWLA-Wheat model (Tao and Zhang, 2013a) and MCWLA-Rice model(Tao and Zhang, 2013b), were used as tools to simulate crop growth in this study. The MCWLA models were designed for the crop growth simulation at a daily step and the crop yields estimation. Briefly, the MCWLA models take the temperature and photoperiods into account to drive the simulation of daily crop development. Meanwhile, the growth rate that driven by heat and the water stresses were considered during estimating the LAI growth. In addition, the models adopted the methods in Lund–Potsdam–Jena (LPJ) model to represent the coupled CO_2 and H_2O exchanges. The MCWLA models have been widely used to simulate the effects of climate change and climate extreme on crop growth and yields at broad areas of the world (Asseng et al., 2013; Bassu et al., 2014; Asseng et al., 2015; Li et al., 2015; Tao et al., 2015; Shuai et al., 2016; Wang et al., 2016; Chen et al., 2017a; Chen et al., 2017b; Zhang et al., 2017). In general, the MCWLA models could fairly well capture the effects of climate change, climate extreme and elevated CO_2 on crop growth and yields.

In this study, the MCWLA models were used to simulate the yields of maize, wheat and rice in China at a grid scale under different climate scenarios. The model parameters have been well calibrated and validated in different regions of China in previous studies for maize (Shuai et al., 2016),rice(Wang et al., 2016) and wheat (Chen et al., 2017b). The model parameters calibrated and validated in these previous studies were applied in current study. Ensemble simulations using 10 optimal sets of parameters were conducted to reduce the uncertainties caused by crop model parameters.

2.4 Methods to evaluate the impacts of climate change and climate extreme

For each grid cell across the cultivation areas of each crop, the bias-corrected climate datasets were used as input data to drive the well-validated MCWLA models. According to the protocol of HAPPI, the emission scenario of 1.5℃ warming was close to that of RCP 2.6, and the emission scenario of 2.0℃ warming was weighted between RCP 2.6 and RCP 4.5(Mitchell et al., 2017). In this study, the simulation during 2006-2015 used the CO_2 concentration of 390.5 ppm. Meanwhile, the CO_2 concentration during 2106-2115 was set as 416.1 ppm and 490.5 ppm for warming scenarios of 1.5℃ & 2.0℃, respectively. The irrigation was considered during simulation. For maize and wheat, we assumed automatic irrigation in simulation settings, that is, an irrigation of 50 mm would be conducted if the ratio between transpiration and potential transpiration was lower than 0.5. For rice, full irrigation was assumed when necessary during simulation.

The annual average simulation results during 2006-2015 and 2106-2115 were compared at grid scale. Because we used 70 runs of climate data and 10 sets of parameters, thus we could obtain an ensemble of 700 sets of comparison results for each grid under a single warming scenario. Then the median of these results was used to demonstrate the changes between the two periods for a certain variable such as crop growth duration and crop yield.

In this study, we evaluated the changes in growth duration, yield and the impacts of climate extreme events on crop yield for each grid with crop cultivation across China at the warming scenarios of 1.5℃& 2.0℃, respectively. For growth duration and yield in each grid under one set of climate data, the changes were identified as Eq. (1):

$$S_c = \frac{S_f - S_h}{S_h} \times 100\% \qquad (1)$$

Where S_c was the change percentage between two periods, S_h and S_f were annual average simulation result for the historical and the future period, respectively. Meanwhile, standard deviation (SD) of S_c for yield was also calculated at grid scale to represent yield variability. Moreover, we also computed the yield decrease probability by calculating the percentage of simulation results that showed yield decrease among the 700 simulated results at each grid.

Furthermore, to evaluate the impact of climate extreme event, we selected heat stress on rice and wheat and the drought stress on wheat and maize as typical extreme events. The impacts of climate extreme event on crop yield were identified as the changes between the simulated yields with and without considering the stresses of the extreme event as shown in Eq. (2):

$$YL = \frac{Y_1 - Y_0}{Y_1} \times 100\% \tag{2}$$

Where *YL* was the yield loss percentage caused by extreme events, Y_0 and Y_1 were simulated yields with and without considering stresses of the extreme event, respectively, for a time period. Then the differences of *YL* between two periods were used to evaluate the changes in the impacts of extreme event on crop yield.

Besides the analysis at a grid scale, we also aggregated the simulated yields to country scale using the cultivation areas-weighted-mean based on the crop cultivation ratios for each grid to present the impact of climate change on national food supply.

3 Results

3.1 Changes in critical climate factors at the warming scenarios of 1.5℃ & 2.0℃

The spatial patterns of projected annual changes in average temperature, precipitation and solar radiation during 2106-2115, relative to 2006-2015, were shown in Fig. 2. These changes were the median changes based on the 70 sets of climate projections. The spatial patterns of climate change at the warming scenarios of 1.5℃ & 2.0℃ were similar. Increase of temperature was projected by approximately 0.7 ~ 1.05℃ and 1.2 ~ 1.9℃, respectively, at the warming scenarios of 1.5℃ & 2.0℃ (Fig. 2a, b). Temperature would increase relatively slighter in the northeast China, NCP, southwest China and the Qinghai-Tibet Plateau. The precipitation would increase during 2106-2115 in most parts of China (Fig. 2c, d). In general, the increase of precipitation at warming scenario of 2.0℃ would be larger than that at warming scenario of 1.5℃ except some areas in southwest China. For most of the cultivation areas of major crops in China, increase of precipitation would range from 2% ~ 6%. Increase of precipitation would be greater in southeastern parts of China by more than 6%. Solar radiation would increase in nearly the whole country (Fig. 2e, f). Under 1.5℃ warming scenario, it was expected to increase by more than 7% in the southern parts of China, particularly the Sichuan Basin. Moreover, solar radiation in these areas would increase more significantly under 2.0℃ warming scenario. In other regions, the increase of solar radiation would be similar under two warming scenarios by less than 6%.

3.2 Impacts of climate change on major crops growth durations

Increase in temperature would accelerate crop development rate and consequently reduce crop growth duration. Results showed that increase in temperature would ubiquitously shorten the growth duration of the three major crops (Fig. 3). The most prominent decrease in maize growth duration could be expected in northeast China, southwest China and Loess plateau by up to 6% and 10% at the warming scenarios of 1.5℃ & 2.0℃, respectively (Fig. 3a, b). The decrease in maize growth duration would be relatively slighter (4% ~ 8%) in south China. In addition, the impacts of climate change on maize growth duration would be the smallest in NCP where was expected to reduce by less than 2% in most of areas. The decrease in growth durations of wheat would be slighter than that of maize (Fig. 3c, d). In most of regions, wheat growth duration would decrease slightly by less than 4%, particularly in the NCP (less than 2%). Wheat growth duration could decrease more in the northeast, southwest and northwest China. Under 2.0℃ warming scenario, it would decrease by approximately 2% more than that under 1.5℃ warming scenario in most of cultivation areas, except the NCP. Rice phenology would change more apparently in the double rice region (Fig. 3e, f). Rice growth duration was projected to decrease by 4% ~ 8% and 6% ~10% at the warming scenarios of 1.5℃ & 2.0℃, respectively. By contrast, it was projected to reduce by less than 2%, with slight differences between two warming scenarios, in other regions.

3.3 Impacts of climate change on major crops yields

Climate change would have major impacts on major crops yields in China. The impacts of climate changes on the three major crops yields were investigated without (Fig. 4) and with taking CO_2 fertilization effect into account(Fig. 5). Without taking CO_2 fertilization effect into account, maize yield in most of the cultivation areas would decrease by less than 10% under 1.5℃ warming scenario (Fig. 4a). It would decrease more under 2.0℃ warming scenario by less than 15% in most of areas and more than 15% at 5.6% of the grids with maize cultivation (Fig. 4b). Maize yield was expected to increase mainly in the northeast China and some portions in northwest China. The proportion of grids with yield increase would be 45.5% under 1.5℃ warming scenarios and reduce to 35.1% under 2.0℃ warming scenarios. As for wheat, the areas with yield increase would be in the southern parts of the cultivation areas (Fig. 4c, d), where yield was expected to increase by less than 10% under both warming scenarios. The regions with yield decrease were located in the northern parts of China and Yunnan province in southwest China, where yield was expected to decrease by up to 15% and 25% at the warming scenarios of 1.5℃ & 2.0℃, respectively. Under 2.0℃ warming scenario, the areas with yield increase would slightly shrink. Moreover, the yield decrease would obviously aggravate by approximately 5% in most of areas with yield decrease under 1.5℃ warming scenario. For rice, there was a spatially explicit pattern of yield changes (Fig. 4e, f). Rice yield would increase by 5% ~ 15% or even larger than 30% in the northeast and southwest China. The yield increase in these areas would be greater at warming scenario of 2.0℃ than that at 1.5℃. However, in the central parts of rice cultivation areas and the double rice cultivation region, rice yield was projected to decrease widely by less than 10% and 15% at the warming scenarios of 1.5℃ & 2.0℃, respectively.

When considering the CO_2 fertilization effect, the spatial pattern of yield changes would change substantially (Fig. 5). The effects of CO_2 fertilization could enhance crop photosynthesis and increase crop productivity to some extent for all the three major crops. For maize, the differences between the simulated yields with and without considering CO_2 fertilization effect were slight (Fig. 5a, b). The contribution of CO_2 fertilization effect to maize yields was generally less than 6%, and it would be more obvious at warming scenario of 2.0℃ than that at 1.5℃. In regions such as the NCP and middle and low reaches of Yangtze River (MLYR), maize yield would increase at more areas than those without CO_2 fertilization effect. However, yield would still decrease in more than half of grids with maize cultivation. In comparison with maize, the yields of wheat and rice were more benefited from the elevated CO_2 concentrations. The contribution of CO_2 fertilization effect to wheat yield could reach 4% and 15% at the warming scenarios of 1.5℃ & 2.0℃, respectively (Fig. 5c, d). With CO_2 fertilization effect, the decrease in wheat yield in the northeast China and NCP could be totally compensated. As a result, yield could be expected to increase by approximately 5% ~ 15% in most of the wheat cultivation areas (Fig. 5c, d). The increase of wheat yield under 2.0℃ warming scenario would be 5% larger than those under 1.5℃ warming scenario. In addition, wheat yield decrease in Inner Mongolia and Yunnan Provinces would be less than 10%, suggesting that the risks of yield decrease caused by climate change could be reduced by the rising of CO_2 concentration in these areas. As for rice, the contribution of CO_2 fertilization effect could be 2% ~ 5% and 8% ~ 16% at the warming scenarios of 1.5℃ & 2.0℃, respectively (Fig. 5e, f).Yield decrease in central China and double rice regions could be compensated and the widespread yield increase would be expected across the entire rice cultivation areas. Yield increase under 2.0℃ warming scenario would be 5% ~ 10% larger than that under 1.5℃ warming scenario.

To evaluate the possible effects of climate change on country-level crop productivities, the simulation results at grid scale were aggregated to country scale. The yield changes for the three major crops at country scale under different climate scenarios were shown in Fig. 6. Without CO_2 fertilization effect, maize yields at country level would decrease by 0.1% and 2.6% at the warming scenarios of 1.5℃ & 2.0℃, respectively (Fig. 6a, b). By contrast, wheat and rice would slightly benefit from climate change at warming scenario of 1.5℃ but suffer from negative impacts at warming scenario of 2.0℃(Fig. 6a, b). Wheat yield would increase by 1.2% but decrease by 0.9% at the warming scenarios of 1.5℃ & 2.0℃, respectively. Rice yield would increase by 0.7% under 1.5℃ warming scenario but decrease by 2.4% under 2.0℃ warming scenario. When considering the CO_2 fertilization effect, crops would obtain a larger yield increase or less yield decrease(Fig. 6c, d). Maize yield would increase by 0.2% under 1.5℃ warming scenario and the yield decrease would reduce to 1.7% under 2.0℃ warming scenario. Wheat and rice yields would increase by 3.9 % and 4.1%, respectively, under warming scenario of 1.5℃ (Fig. 6c); and by 8.6% and 9.4%, respectively, under warming scenario of 2.0℃(Fig. 6d).

3.4 Impacts of climate extremes on major crops yields

The influences of climate extreme events, including heat stress and drought stress, on yield have been explicitly accounted for in this study. The impacts of heat stress on wheat and rice (Fig. 7), and the impacts of drought stress on wheat and maize(Fig. 8) were shown here. Without considering CO_2 fertilization effects, wheat yield loss caused by heat stress would increase in the northern parts of China by up to 8% under warming scenario of 1.5℃ (Fig. 7a), particularly in the Inner Mongolia, Loess Plateau and NCP, and it would become larger at warming scenario of 2.0℃ (Fig. 7b). In other regions such as the southwest China, the risk of heat stress would not change much. As for rice, yield loss caused by heat stress would increase by less than 2% and 5% under 1.5℃ and 2.0℃ warming scenario, respectively, mainly in the MLYR (Fig. 7e, f). In other regions such as the northeast China and southwest China, the risk of heat stress would not change much. When taking CO_2 fertilization effect into account, the results were quite similar to those without considering CO_2 fertilization effect (Fig. 7c, d, g, h).

The impacts of drought stress on wheat and maize yield were shown in Fig. 8. The impacts of drought stress on wheat yield would be more severe at nearly the entire cultivation areas(Fig. 8a, b). Under 1.5℃ warming scenario, wheat yield loss due to drought stress would increase by less than 4% in most of areas (Fig. 8a). Yield loss would increase by larger than 2% in 45.5% of the grids with wheat cultivation. Under 2.0℃ warming scenario, the yield loss would increase more than that under 1.5℃ warming scenario except some areas in the southern parts of NCP(Fig. 8b). The yield loss would increase by more than 2% in 50.8% of the grids with wheat cultivation. As for maize, the impacts of drought stress would decrease in the southeast China by approximately 2% (Fig. 8e, f). By contrast, in most parts of maize cultivation areas, maize yield loss due to drought stress would increase byup to 8%, mainly in the Loess Plateau, NCP and some areas in northeast China and southwest China. Impacts of drought would further aggravate under 2.0℃ warming scenario. Grids with yield loss increase by more than 2% would be expected in 31.6% and 53.5% of all grids at the warming scenarios of 1.5℃ & 2.0℃, respectively.

Elevated CO_2 concentration would reduce drought stress to crop, consequently reduce yield loss. This would be much more obvious under warming scenario of 2.0℃ than 1.5℃ (Fig. 8c, d, g, h). For wheat, percentage of grids with yield loss that increase by more than 2% would reduce to 18.8% at warming scenario of 1.5℃ (Fig. 8c). Meanwhile, yield loss under 2.0℃ warming scenario was expected to decrease in nearly 60% of the grids (Fig. 8d), which was only 5.7% when CO_2 fertilization effect was not taken into accounted. For maize, yield loss due to drought stress could be expected to decrease in a larger area, particularly the northeast China and southwest China (Fig. 8g, h). The Loess Plateau would still be the hotspot areas suffered from increased drought stress, however the increase of yield loss would be less than 6% generally.

3.5 Yield variability and yield decrease probability at the warming scenarios of 1.5℃ & 2.0℃

The SD of simulated yield changes was shown in Fig. 9. For maize, the SD was relatively larger in south China and some marginal areas of northeast China, where it could be larger than 20%. By contrast, it was generally less than 10% in most parts of northeast China, NCP, Loess Plateau and southwest China (Fig. 9a, b). The SD under 2.0℃ warming scenario would generally be larger than that under 1.5℃ warming scenario except the areas with relatively smaller SD in NCP and Loess Plateau. For wheat, under both warming scenarios, the SD of simulated yield changes was less than 9% in most of the cultivation areas. However, it could be up to 12% and 18%, respectively, in the NCP and Inner Mongolia (Fig. 9c, d). The SD under two warming scenarios was similar in most of cultivation areas, while SD under 2.0℃ warming scenario would increase in some areas of NCP and southern parts of cultivation areas. As for rice, the simulated yield changes in double rice region and most parts of southwest China were relatively stable with SD generally less than 9% under both warming scenarios(Fig. 9e, f);by contrast, the SD would range from 9% to more than 20% in the northeast China, central China and the Sichuan Basin (Fig. 9e, f). The SD in MLYR at warming scenario of 2.0℃ would be larger than that at 1.5℃. In other regions, the variability of rice yield changes was similar under two warming scenarios.

Based on the ensemble simulations, the probability of major crops yields decrease was estimated and presented in Fig. 10. For maize, yield would decrease with probability of more than 60% at warming scenario of 1.5℃ in the southwest China, southeast coast areas, some portions in the north China, NCP, and northeast China (Fig. 10a). Moreover, the probability of yield decrease in these areas would increase at warming scenario of 2.0℃ (Fig. 10b). In contrast, the probability of maize yield decrease would be less than 40% in the MLYR, and the northeast China (Fig. 10a). In addition, the yield decrease probability in these areas would decrease to less than 30% at warming scenario of 2.0℃ (Fig.10b). For wheat, probability of yield decrease was projected to generally less than 30% in more than half of the wheat cultivation areas at warming scenario of 1.5℃(Fig.10c). However, yield would decrease with probability of more than 60% in the southwest China, north China, and some portions in marginal areas in northeast China. At warming scenario of 2.0℃, the probability of yield decrease would reduce in the areas with low decrease probability (Fig. 10d). 66% of grids would have yield decrease probability less than 30%, while number of grids with yield decrease probability larger than 70% would not change much. For rice, the probability of yield decrease was projected to be less than 30% generally across most of the cultivation areas under 1.5℃ warming scenario, and the probability would be even less under 2.0℃ warming scenario. But in some areas in the MLYR, the probability of yield decrease could keep ranging from 40% ~ 60% and 40% ~ 50% at the warming scenarios of 1.5℃ & 2.0℃, respectively.

Taking CO_2 fertilization effect into account, at country scale, the SD of simulated yield changes ranged from 1.5% to 4% under different ensemble members (Fig. 6c, d). Meanwhile, the SD under 2.0℃ warming scenario would be generally larger than that under 1.5℃ warming scenario. For maize, wheat and rice, respectively, the probability of yield decrease was 46.1%, 18.3% and 4.3% under 1.5℃ warming scenario, and 70%, 0.6% and 0% under 2.0℃ warming scenario.

4 Discussion

4.1 Impacts of climate change on future crop productivity in China

In this study, we showed a similar spatial pattern between changes of growth duration and that of yield decrease without CO_2 fertilization effect, such as the wheat yields in northern parts of China, rice yield in double rice region, and the maize yields across China, suggesting that growth duration should play a critical role in affecting crop yields. Beside changes in growth duration, varieties in temperature and solar radiation would also impact the crop yields by affecting photosynthesis process. Moderate increase in mean temperature and the increase in solar radiation would promote the yield increase by enhancing crop canopy photosynthesis and consequently biomass accumulation and yield (Tao et al., 2013). These positive effects could underlie the crop responses of yield increase in current study. For example, in cultivation areas of maize with growth duration decrease by less than 2%, the yield would generally increase, which should be due to the increase of solar radiation and the warmer environment that close to optimal temperature for photosynthesis. As for wheat in southern parts of cultivation areas, although the growth duration would obviously decrease because of the relatively larger increase of temperature, the yield loss could be compensated by the positive effects of increasing temperature and solar radiation on photosynthesis. For rice, the contribution of increased temperature and solar radiation would be more distinct for rice production in southwest and northeast China where growth duration would decrease by less than 2%. The large increase of rice yield in these areas indicated a more appropriate environment, particularly a more suitable thermal scenario, for photosynthesis (Tao et al., 2008b; Zhang et al., 2017).

According to the simulation results, impacts from extreme events would still be a critical limitation factor for crop growth in the future. Although their impacts might be slightly mitigated in some areas, the projected increases of stress impacts were always remarkable. The increase of impacts of heat stresses on wheat in the northern parts of China and on rice in south China would significantly aggravate the yield loss in these areas, suggesting the requirement for improving adaptation strategies with higher priority. Meanwhile, the increase of drought impacts indicated that water requirement would widely increase risk of water crisis in most of the cultivation areas.

The elevated atmospheric CO_2 concentration, which is a critical reason for global warming, is also a positive factor that could improve the crop yields. The interactions among moderate increase in temperature, solar radiation and CO_2 concentration would enhance photosynthesis (Sage et al., 1995; Hikosaka et al., 2006; Sage and Kubien, 2007; Zhu et al., 2008). The combination of these effects would consequently benefit the biomass accumulations and yield. In this study, simulation results with CO_2 fertilization effect have compensated the yield decrease in most of the cultivation areas of wheat and rice. As for maize, although less sensitive to the elevated CO_2 concentration, the simulation results with CO_2 fertilization effect could reduce yield loss. In addition, the rising CO_2 could also be expected to effectively reduce drought stress because of the stomatal ‘anti-transpirant’ response of plants and the increase of root density and canopy closure which would reduce the transpiration rates at leaf level and meanwhile increase the water availability(Polley et al., 2007; Jiahong et al., 2010). However, for hotspot areas of drought stress aggravation, particularly the wheat production in north China and maize production in Loess Plateau, the increase of irrigation should be inevitable and more input in agricultural infrastructure would be necessary.

4.2 Risks and opportunities in regard to crop production in China with climate change

Climate change will substantially alter the growing environment of crops and consequently change the yield potential and yield expectation in future periods (Gourdji et al., 2013; Nelson et al., 2014; Rosenzweig et al., 2014; Assenget al., 2015). In past decade, the negative impacts of climate change have been critically focused on since the foreseeable population growth and more frequent extreme events may infer pessimistic conclusion of food shortage (Wheeler and Von Braun, 2013;

Trnkaet al., 2014). However, in this study, the simulation results under 1.5℃ and 2.0℃ warming scenarios presented possible risks to crop production but also suggest the opportunities and potentials for agricultural development. The negative impacts were generally resulted from the decrease of growth duration and aggravation of impacts of extreme events. However, we have found that the negative influence under moderate warming scenarios would be very limited at country scale, suggesting low risks for crop production and food security. On the contrary, the negative impacts of warming scenarios could be compensated by the increase of solar radiation and temperature, the more appropriate temperature environment in some relatively colder areas, and the fertilization effects of elevated atmospheric CO_2 concentration. As a consequence, yield would increase with high probability for rice and wheat under both warming scenarios. The yield of maize, which was not sensitive to CO_2 fertilization effects, would slightly decrease in a 1.5℃ warmer world and decrease more under 2.0℃ warming scenario. However, the contribution of climate change to increasing wheat and rice productivity would be always much larger than the decrease of maize productivity, indicating that the national overall food supply would benefit from the climate change.

Considering the results, we concluded that the 1.5℃ or 2.0℃ warming scenario would bring more opportunities than risks to the food supply in China, particularly for wheat and rice. When comparing the effects between warming scenarios of 1.5℃ and 2.0℃, although the variability of yield changes would be larger under 2.0℃ warming scenario, the probability of wheat and rice yield decrease would be less, and their yields would increase much more at warming scenario of 2.0℃ than that at 1.5℃.

4.3 Uncertainties of study

Uncertainties in GCMs and model parameterization are critical sources of uncertainties in simulation results (Assenget al., 2015). In order to provide more accurate evaluation on climate change impacts, the improvement of input data should be helpful since the simulation results are substantially depend on the climate scenarios. Meanwhile, the adaptations should be more elaborate in future studies. Although multiple sets of parameters have been used to account for the uncertainties in cultivars, the parameter calibration was based on current crop datasets. The changes in cultivars in future may lead to more optimistic results considering the rapid update of adaptive cultivars. In addition, the temporal changes and spatial heterogeneity in adaptation methods, especially the real capacity in coping with extreme events, would be another source of the uncertainties that affect the evaluation on local crop development (Elliott et al., 2014; Lobell et al., 2014). The combination of assessing results across multiple sectors, such as the accurate prediction of changes in climate factors, cultivars, and adaptation capacity, could be expected to help better quantify the future risks and opportunities on agricultural development and provide more accurate and effective suggestions for government and farmers.

5 Conclusions

In current study, using the well-validated MCWLA family crop models, their 10 sets of optimal crop model parameters, and 70 climate projections from four GCMs, we evaluated the potential changes of major crop growth and yields during 2106-2115 relative to2006-2015 under 1.5℃ and 2.0℃ warming scenarios. Results showed that the decrease of crop growth duration and the increase of extreme events impacts would be critical reasons for crop failure in the future. Meanwhile, agricultural climate resources such as light and thermal resource could be ameliorated which enhance canopy photosynthesis, biomass accumulations and yield and could partly compensate the yield decrease or even contribute to the yield increase. In general, without considering CO_2 fertilization effects, the food supply at country scale would not change much under the 1.5℃ warming scenario, while the crop production for all three kinds of major crops would tend to reduce slightly under the 2.0℃ warming scenario. The maize production in most of cultivation areas, wheat production in north and southwest China, and the rice production in south China, would be hotspots that encounter adverse impacts caused by climate change. The combination of moderate increase in temperature, solar radiation, precipitation, and the CO_2 fertilization effects, would result in more appropriate growth environment for wheat and rice and slightly deteriorate the growth environment of maize. Totally, the benefits from climate change would be larger than crop loss caused by the adverse factors in moderate warming environment. Thus we could expect that the 1.5℃ and 2.0℃ warming scenarios would bring more opportunities than risks for agricultural production and food supply in China in general. Moreover, because of the larger increase in crop productivity and the less probability of yield loss, the 2.0℃ warming scenario might be more suitable for crop production in China than the 1.5℃ warming scenario.

Acknowledgements

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Figures

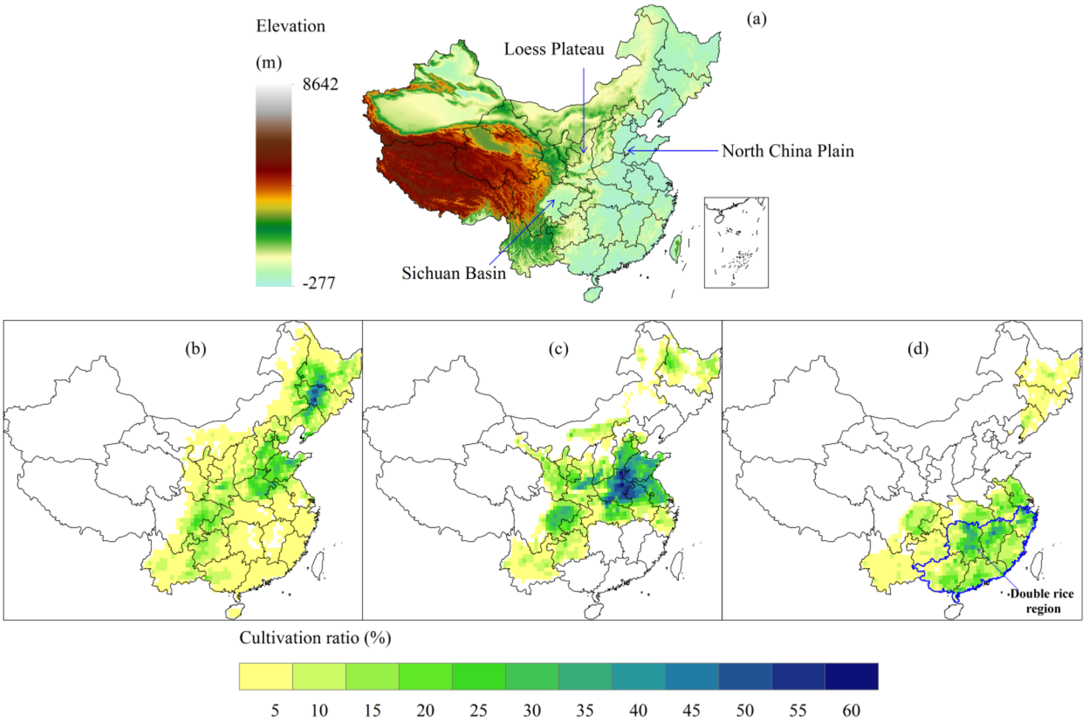

Figure 1: Terrain (a) and cultivation ratios of maize (b), wheat (c) and rice (d) in China.

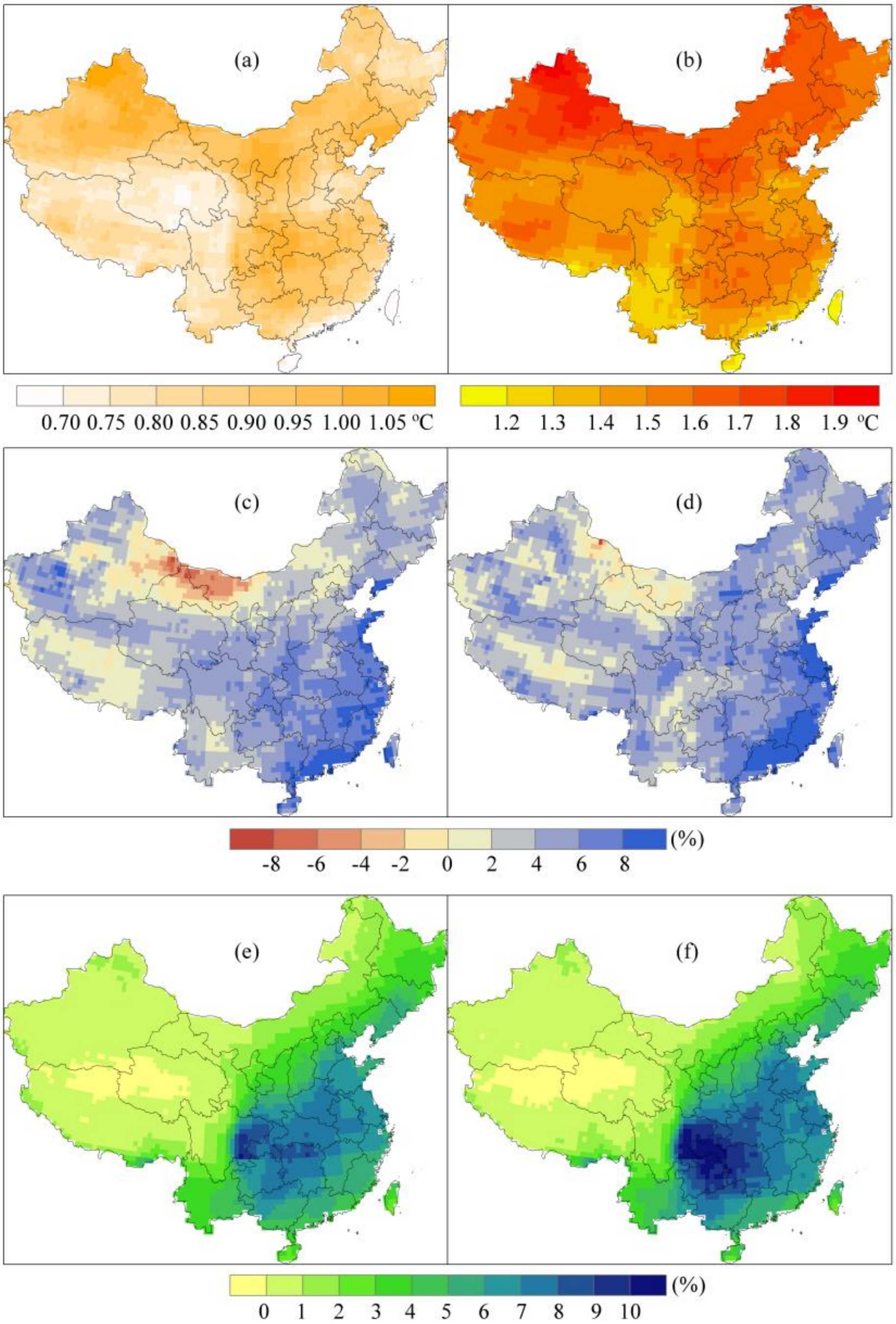

Figure 2: Median changes of mean temperature (a, b), precipitation (c, d), and solar radiation (e, f) during 2106-2115 under 1.5℃ warming (a, c, e) and 2.0℃ warming (b, d, f) scenarios relative to 2006-2015.

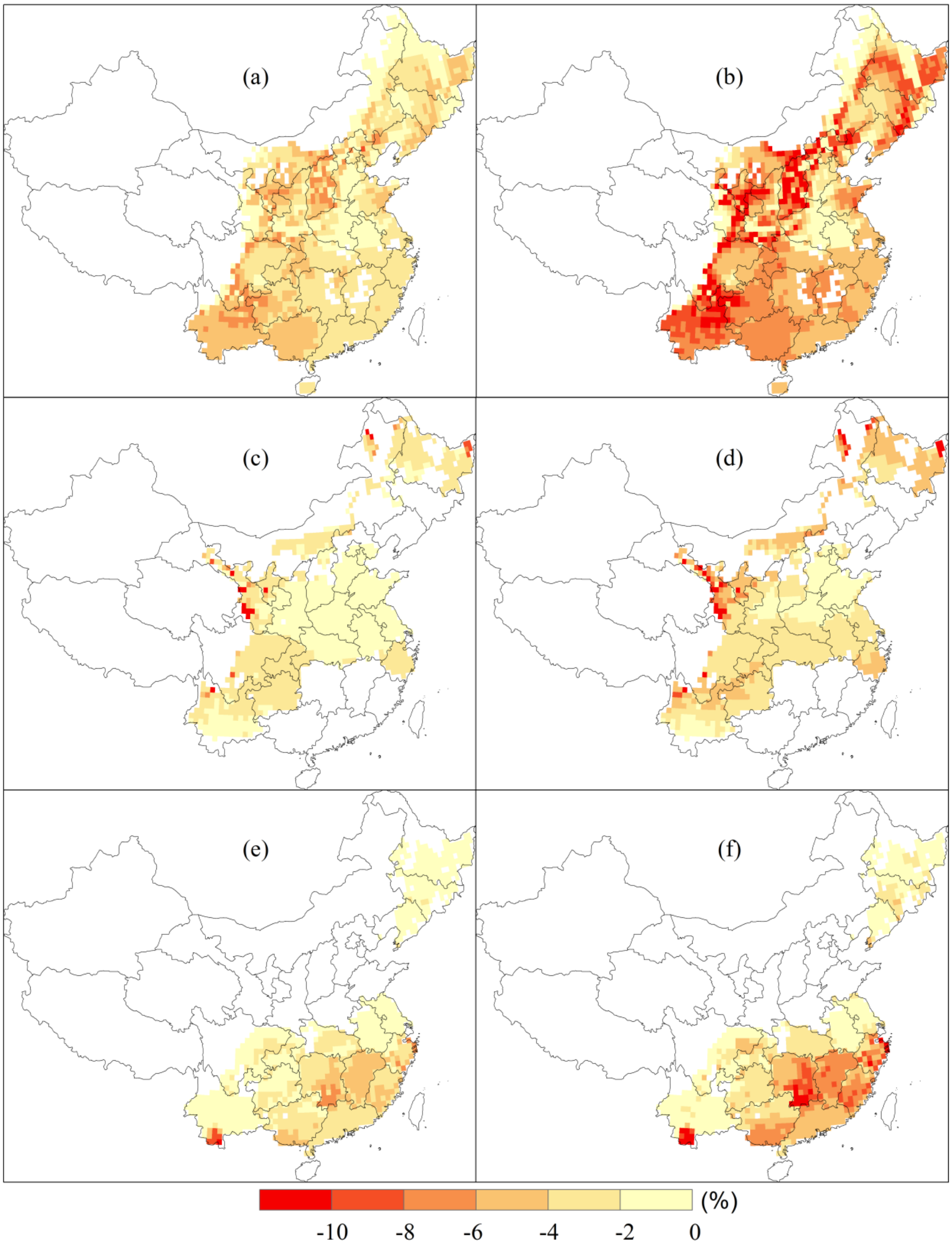

Figure 3: Median changes of growth duration of maize (a, b), wheat (c, d), and rice (e, f) during 2106-2115 under 1.5℃ warming (a, c, e) and 2.0℃ warming (b, d, f)scenarios relative to 2006-2015.

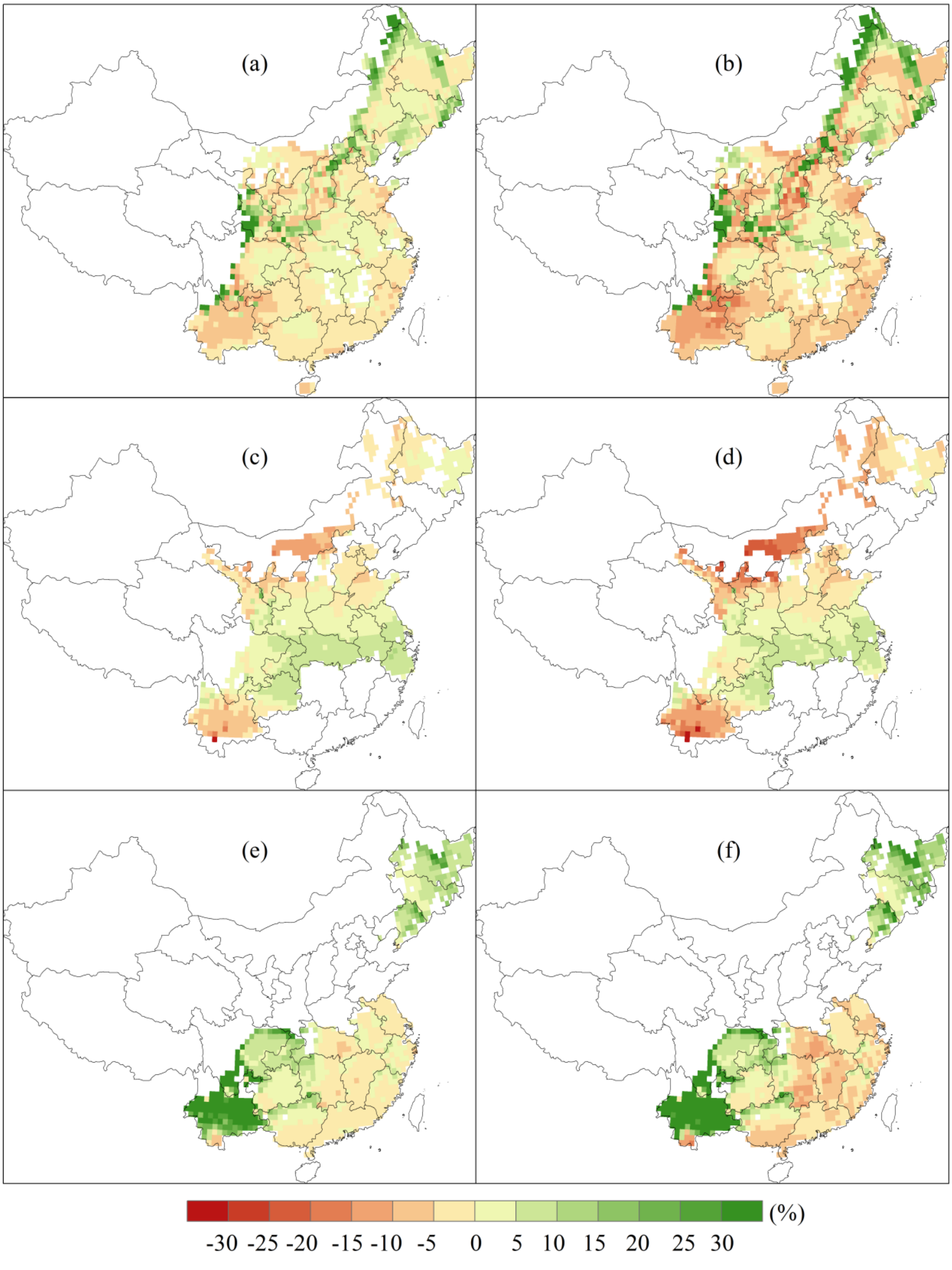

Figure 4: Median changes of yield of maize (a, b), wheat (c, d), and rice (e, f)during 2106-2115 under 1.5℃ warming (a, c, e) and 2.0℃ warming(b, d, f) scenarios relative to 2006-2015, without taking CO_2 fertilization effect into account.

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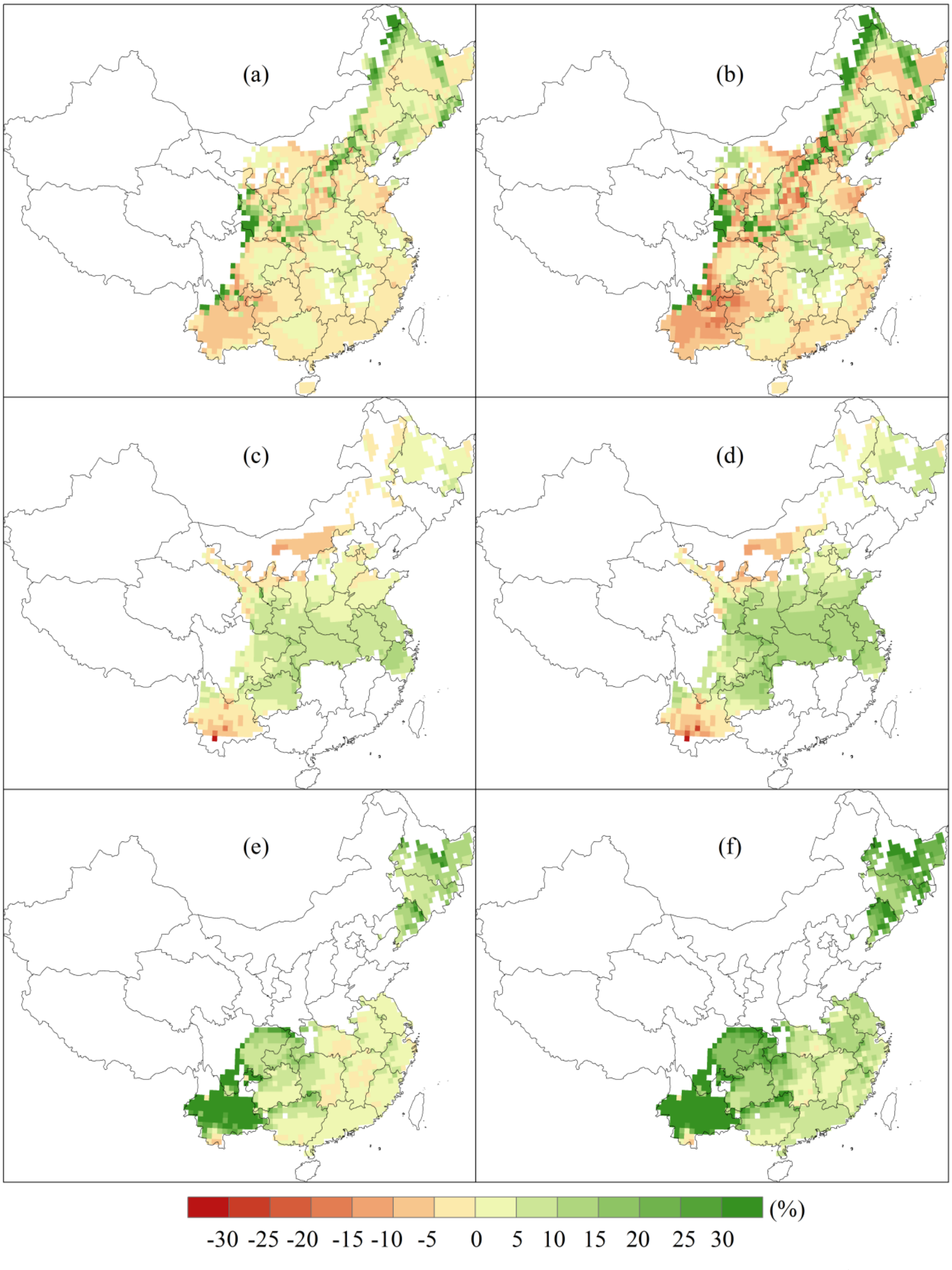


Figure 5: Median changes of yield of maize (a, b), wheat (c, d), and rice (e, f) during 2106-2115 under 1.5℃ warming (a, c, e) and 2.0℃ warming (b, d, f)scenarios relative to 2006-2015, taking CO_2 fertilization effect into account.

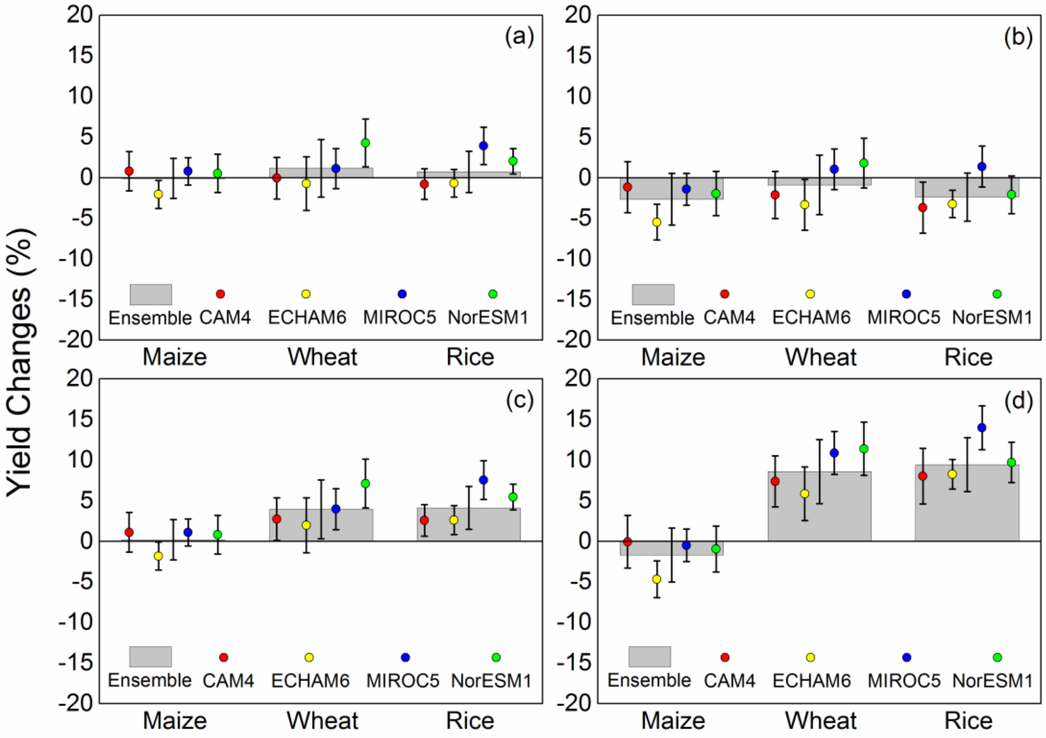


Figure 6: Changes of ensemble simulated yield and of simulated yield using climate data from different GCMs at country scale during 2106-2115 at warming scenarios of 1.5℃ (a, c) and 2.0℃ (b, d) relative to 2006-2015. (a)(b) are results without CO_2 fertilization effect, (c)(d) are results with CO_2 fertilization effect.

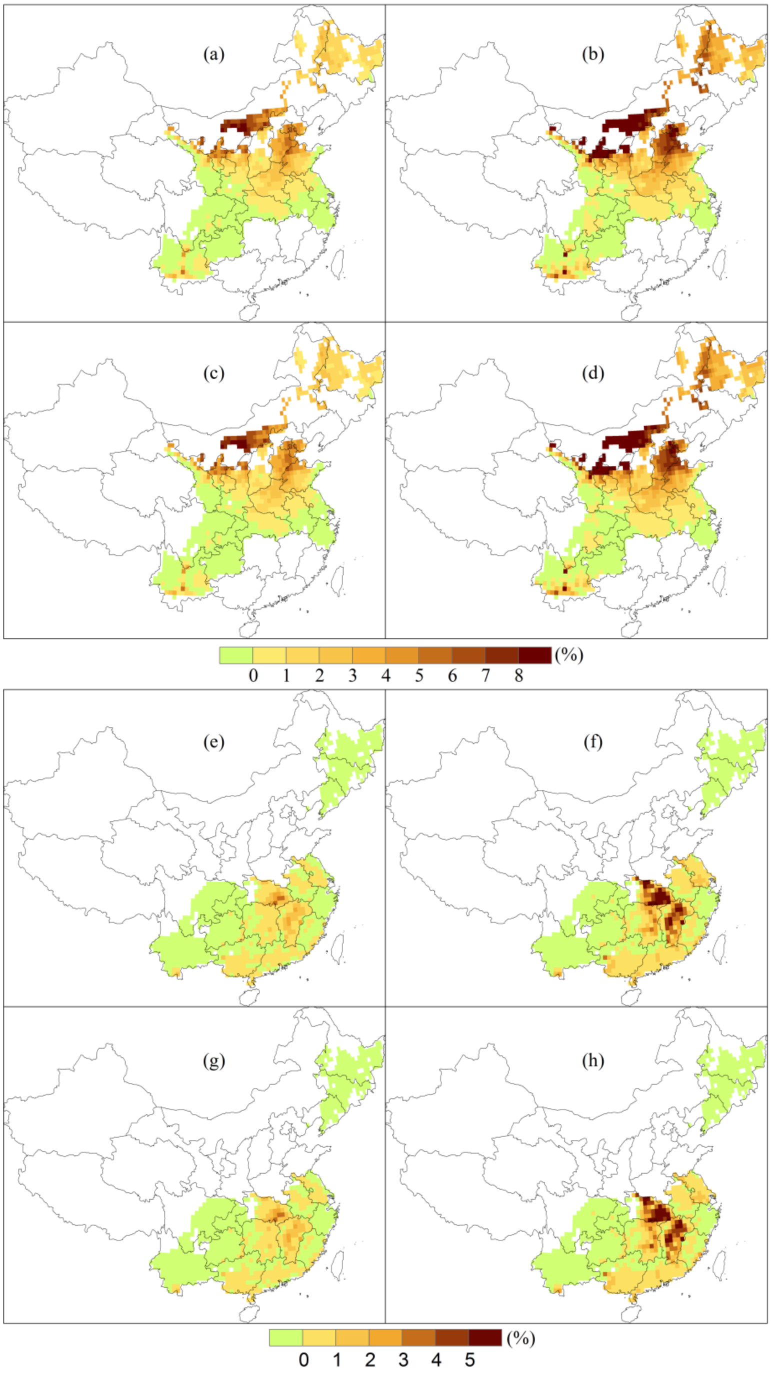


Figure 7: Median changes of yield loss percentage of wheat (a, b, c, d) and rice (e, f, g, h) caused by heat stress during 2106-2115 under 1.5℃ warming (a, c, e, g) and 2.0℃ warming(b, d, f, h)scenarios relative to 2006-2015. (a)(b)(e)(f)are results without CO_2 fertilization effect, (c)(d)(g)(h) are results with CO_2 fertilization effect.

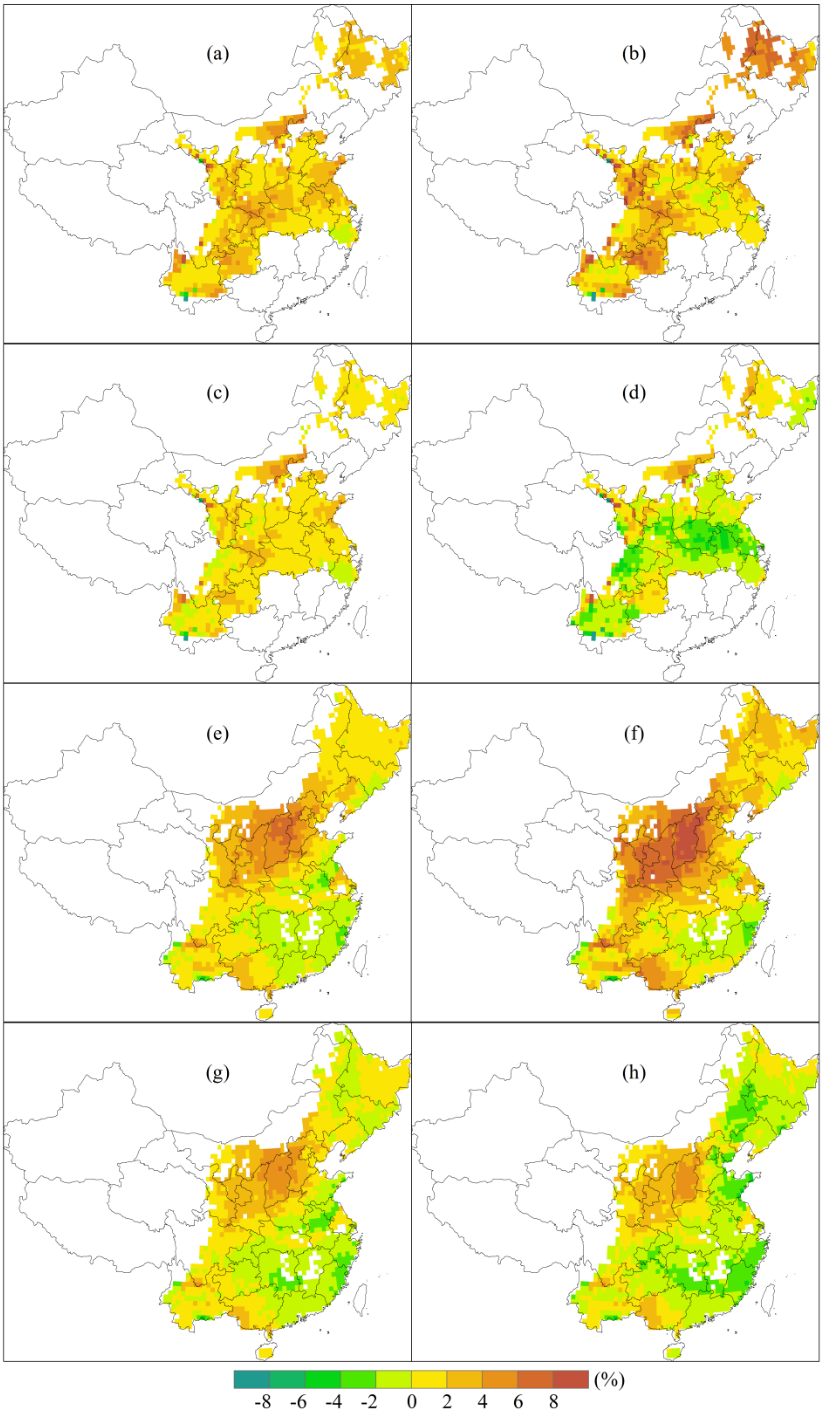


Figure 8: Median changes of yield loss of wheat (a, b, c, d) and maize (e, f, g, h) caused by drought stress during 2106-2115 under 1.5℃ warming (a, c, e, g) and 2.0℃ warming scenarios (b, d, f, h) relative to 2006-2015. (a)(b)(e)(f) are results without CO_2 fertilization effect, (c)(d)(g)(h) are results with CO_2 fertilization effect.

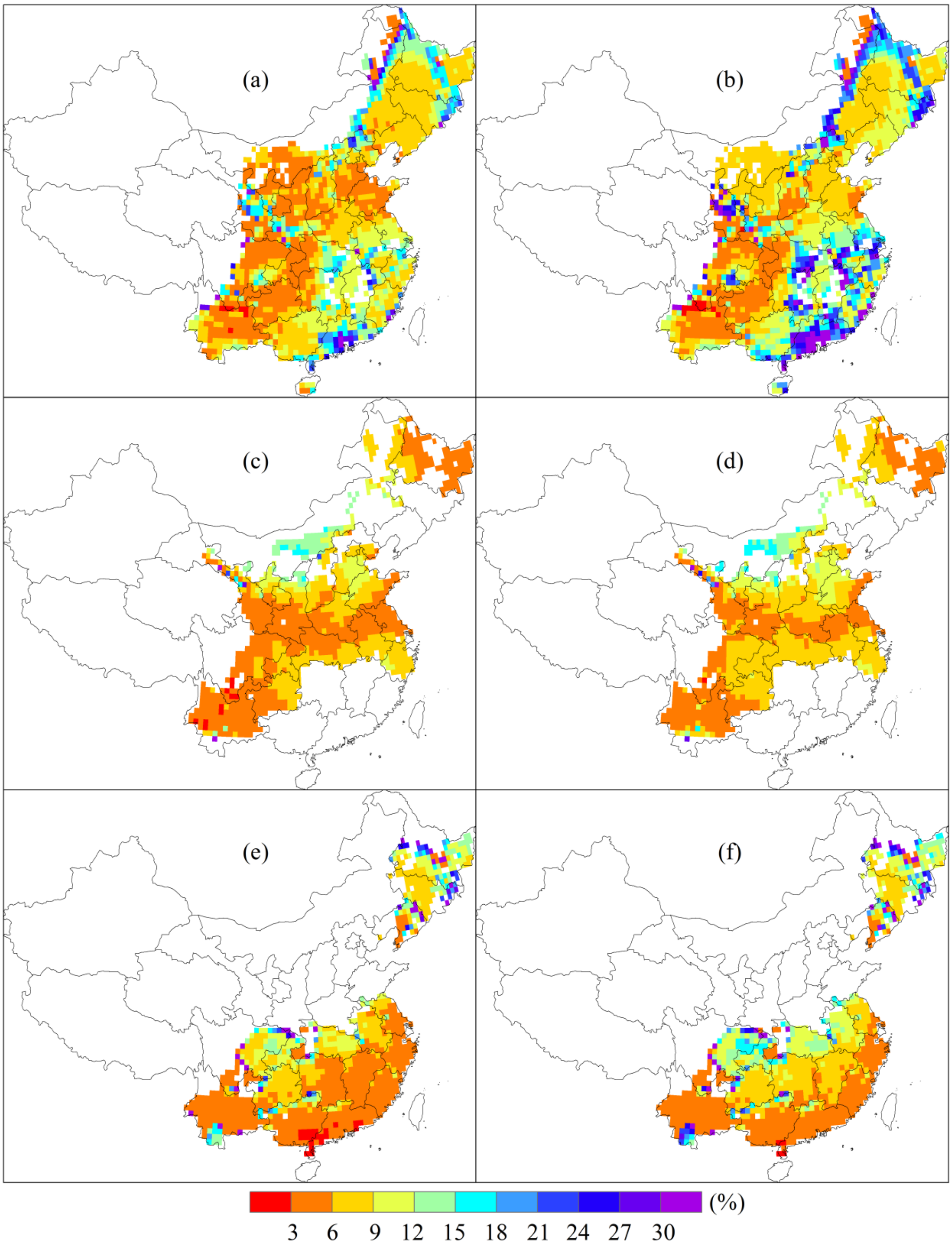
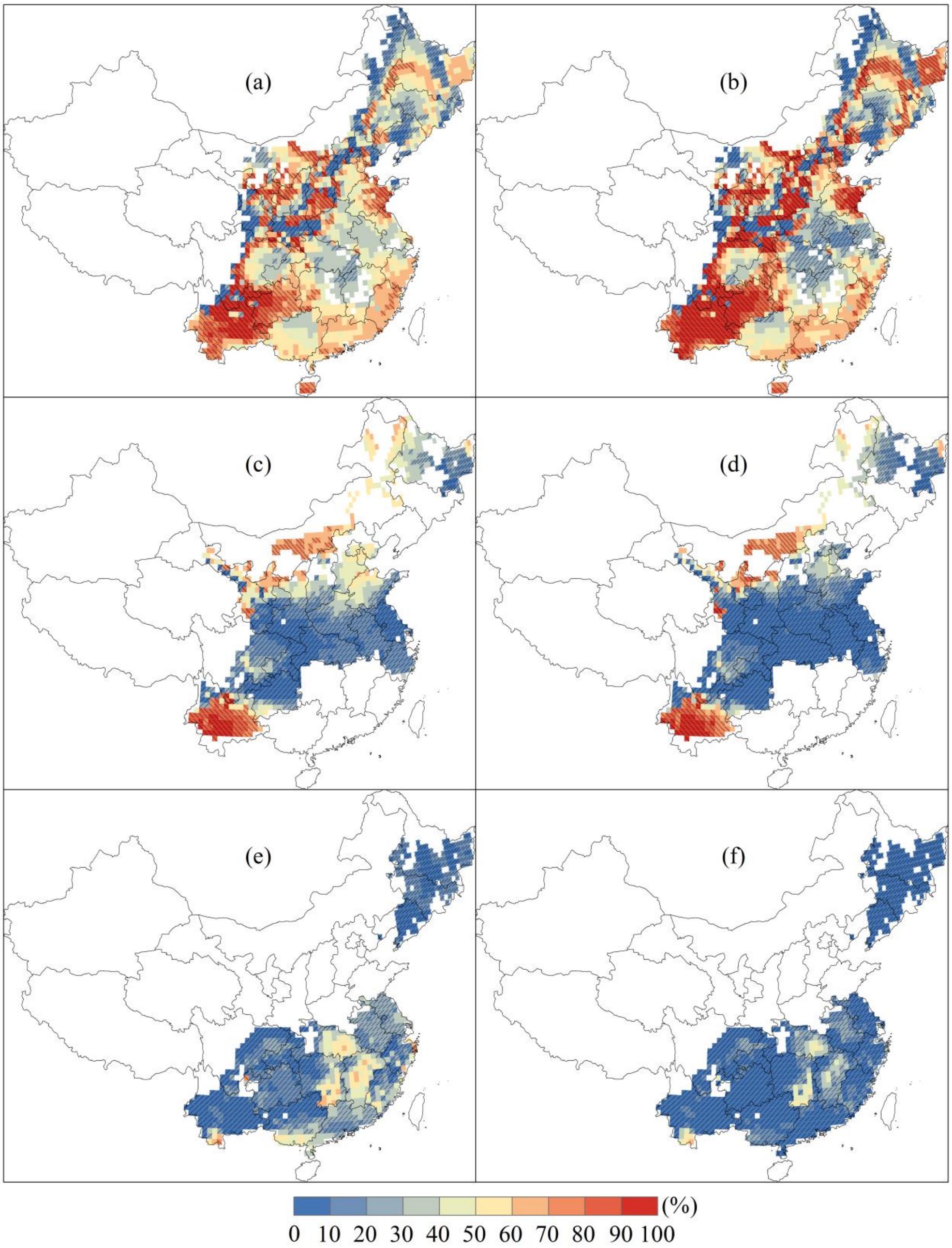


Figure 9: Median standard deviation of the yield changes of maize (a, b), wheat (c, d), and rice (e, f) under 1.5℃ warming (a, c, e) and 2.0℃ warming(b, d, f) scenarios, taking CO_2 fertilization effect into account.



5 **Figure 10: Median of yield decrease probability of maize (a, b), wheat (c, d), and rice (e, f) during 2106-2115 under 1.5℃ warming (a, c, e) and 2.0℃ warming (b, d, f)scenarios, taking CO_2 fertilization effect into account. Hatching indicates areas where more than 70% of the ensemble members agree on the direction of yield changes.**