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Assessing the individual contributions of variations in temperature, solar radiation and precipitation to crop yield in the North China Plain, 1961–2003

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Full Title:

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Abstract: An understanding of the relative impacts of the changes in climate variables on grain yield in the last decades can help develop effective adaptation strategies to cope with climate change. This study was conducted to investigate the effects of the interannual variability and trends in temperature, solar radiation and precipitation during 1961–2003 on wheat and maize yields in the double cropping system at two sites in the North China Plain (NCP), and to examine the relative contributions of the three climate variables in isolation. 129 climate scenarios consisting of all the combinations of these climate variables were designed. Each scenario contained a single daily climate variable of the 43 years (e.g. temperature, 1961–2003), combining with a single year of the other two variables (e.g. solar radiation and precipitation of 1961). An ensemble of crop model simulation driven by these climate scenarios allows assessing the impact of each single climate variable isolated from the other two.

The results showed that year-to-year variations in temperature, solar radiation and precipitation individually resulted in substantial annual differences in crop yield, especially for precipitation. The warming trend alone decreased wheat potential yield at both sites, but not significantly, due to the combined effects of temperature increase during the stages before dormancy (positive effect) and after dormancy (negative effect). Maize potential yield was significantly decreased by 2.7% yr^{-1} at the northern site (Beijing), due to increased temperature during the growing season. The decreasing trend in solar radiation showed the strongest isolated impact on simulated yields. Its decrease caused significant reduction in potential yields at Beijing, at the rate of 5.2% yr^{-1} for wheat and 4.8% yr^{-1} for maize. Although the decreasing trends in rainfed yield of both wheat and maize were large, the large year-to-year variability of precipitation made the trends less prominent.

Key words: Crop modeling; Climate variability; Climate change; Wheat; Maize

1. Introduction

Climate variability and climate change have been documented to have a major impact on agricultural production in many world regions (Rosenzweig and Parry, 1994; Brown and Rosenberg, 1997; Alexandrov and Hoogenboom, 2000; Lobell and Asner, 2003; Parry *et al.*, 2004; Tao *et al.*, 2008), especially in semi-humid and semi-arid areas (Thomson *et al.*, 2006; Tao *et al.*, 2003). This is particularly the case in the North China Plain (NCP), which is vulnerable to climate variability and change. It is one of the largest agricultural production areas in China, covering a total area of 320, 000 km^2 and being home to more than 200 million people (Zhang *et al.*, 2005). The NCP plays an important role in maintaining national food security, providing more than 50% of the wheat and 33% of the maize produced in China (State Statistics Bureau, 1999). However, agricultural production in the NCP is under stress due to water resources shortage and crop land area reduction, as well as climatic effects.

In the past four decades, the NCP has become warmer, drier and dimmer, together with large seasonal/interannual climate variability (Che *et al.*, 2005; Liu *et al.*, 2005; Ren *et al.*, 2008; Fu *et al.*, 2009, Chen *et al.*, 2010a). These variations in climate have been shown to have great impacts on crop production in the region. A simulation study on crop growth and yield of wheat and maize showed that the combined impact of the changes in climate variables (temperature, solar radiation and precipitation) since 1961 has been to reduce potential (i.e. under full irrigation) yield over the NCP (Chen *et al.*, 2010a). In another climate change analysis, Liu *et al.* (2009) found that, if varietal effects were excluded, warming during vegetative stages from 1981–2000 would shorten the length of the growing period of wheat and maize, generally leading to a reduction in crop yields. Wu *et al.* (2006, 2008) reported that climate-related spatial and temporal variability gave rise to substantial yield variability of wheat and maize in the NCP. However, our knowledge on the extent to which crop yield variability and change could be accounted for by the variability and trends in each one of the above climate variables individually still remains unclear.

This is essential for developing strategies to improve adaptation to climate change and ensure sustainable agricultural production in the NCP.

Various approaches, such as statistical regression and simulation models, have been used to investigate crop response to climate variations. Lobell and Asner (2003) used regression statistics to study the relationship between climate variation and crop yield in the United States (1982-1998) and concluded that corn and soybean yields were both significantly correlated with observed temperature trends, while precipitation and solar radiation had little effects. However, the statistical regression approach is usually limited due to the arbitrary selection of the independent variables for multiple regressions (Spaeth *et al.*, 1987). Process-based crop models have been proven to be useful tools to investigate potential impacts of climate variations on crop production (Spaeth *et al.*, 1987; Rosenberg, 1993; Easterling *et al.*, 1996; Rosenzweig and Parry, 1994).

This study aims to separate the impacts of individual climate factors, i.e. temperature, solar radiation and precipitation on grain yields of the winter wheat and maize double cropping system in the NCP by using crop modeling. Specific objectives are to: 1) create climate scenarios for disentangling the impacts of different climate variables on wheat and maize yields, 2) provide a quantitative understanding of the impacts of the variability and trends in temperature, solar radiation and precipitation during 1961–2003 on crop yield, and 3) identify the relative contribution of these factors to variations in crop yield during the study period.

2. Materials and methods

2.1. Study sites

Two study sites, Beijing (39.30ºN, 116.28ºE) and Zhengzhou (34.72ºN, 113.65ºE) were selected (Fig. 1). Beijing is located in the north of the NCP and Zhengzhou is located in the middle and lower reaches of the Yellow River, and they can roughly represent the climate conditions in the northern and southern parts of the NCP, respectively. A major consideration for the site selection is the data availability of daily solar radiation, as well as maximum and minimum temperature and precipitation. Temperature and precipitation in the NCP decrease from the south to the north, while accumulated annual solar radiation increases. The annual mean air temperature was 12.5 and 14.8 ℃ at Beijing and Zhengzhou (1961–2003), respectively; the corresponding annual precipitation at the two sites was 559 and 632 mm, respectively, with more than 75% falling during the summer months (June to September); and accumulated annual solar radiation was 5370 and 5010 MJ m^{-2}, respectively.

Winter wheat-summer maize double crop rotation is the currently dominant cropping system in the NCP, including the two study sites. The growing period for winter wheat is from October to May. There is a long dormant period from the end of November to the beginning of March, after which winter wheat begins growing again. In the present study, winter wheat growth period was divided into two stages: before and after dormancy ("turning green"). The stage before dormancy is from October to February. The stage after dormancy is from March to May. For summer maize, the growth period is from June to September.

2.2. The agricultural system model

The Agricultural Production Systems Simulator, APSIM, (McCown *et al*., 1996; Keating *et al*., 2003) was used to simulate grain yield of the wheat-maize double cropping system affected by the variability and trends in climate variables. APSIM is a modular modeling framework developed by Agricultural Production Systems Research Unit (APSRU) in Australia. It simulates at daily time steps the crop growth and development, yield, soil water and nitrogen dynamics within a single crop or a cropping system. The model allows crop varieties and agronomic management to be kept constant so that the impacts of climate variables can be separated without the joint effects of others. The following main built–in modules were used in this study: wheat crop (WHEAT), maize crop (MAIZE), soil water (SOILWAT2), soil nitrogen (SOILN2), crop residue (RESIDUE) and management specification (MANAGER). Detailed descriptions of the model structure, its crop and soil modules can be found in Keating *et al.* (2003) or at the APSIM website: http://www.apsim.info/apsim/.

The APSIM model has been validated and extensively used to predict crop production in studies of the impacts of climate variations (Reyenga *et al.*, 2001; Asseng *et al.*, 2004; Luo *et al.*, 2005; Ludwig and Asseng, 2006; Wang *et al.*, 2009). In our previous work (Chen *et al.*, 2010a, b, c), we evaluated the model performance in simulating crop growth, development and yield of the wheat and maize double cropping system and simulated the response of crop productivity to climate variability and trends over the NCP. It was found that the APSIM model was able to reasonably reproduce the observed crop growth and yield of wheat and maize in the region. The present study built on the above model calibration and validation work for model performance and application. Wheat variety Zhixuan 1 and maize variety Yedan 22 were planted at the Yucheng experimental station during an experiment conducted from 1997–2001 and the derived cultivar parameters (Chen *et al.*, 2010b) were used in the simulations of this study.

2.3. Simulation approach

We used 43 years (1961–2003) of observed daily climate data from two sites, obtained from the Bureau of Meteorology, China and used as the baseline climate to analyze the combined and interacting effects of temperature, solar radiation and precipitation on wheat and maize grain yield. An ensemble approach was used to separate the impacts of interannual (and long-term) variations of temperature, solar radiation and precipitation on crop yield. A total of 129 climate scenarios were created by constructing synthetic combinations of the three climate variables during 1961–2003. To assess the impact of daily mean temperature, 43 climate scenarios were generated from the 43-year observed time series. In each scenario, temperature was set to its observed values for the period 1961–2003, and it was combined with each historical year’s solar radiation and precipitation copied times (see Table 1). For example, scenario 1 for temperature consisted of the 1961–2003 observed records of temperature, with the solar radiation and precipitation of 1961 and this procedure was used in all 43 years. The crop yields obtained from the 43 climate scenarios were averaged to evaluate the impact of temperature on crop yield under all solar radiation and precipitation conditions of 1961–2003. We also considered the variance ratio:

$$\hat{\rho} = \frac{\sigma_{mean}^{2}}{\sigma_{tot}^{2}} \qquad (1)$$

where σ^2_{mean} is the variance of mean simulated grain yield and σ^2_{tot} is the variance of all simulated grain yields of the 43-member ensembles. Analysis of variance (AMOVA) was used to assess the strength of the forcing by the variance of the isolated climate variable (e.g. temperature), relative to the variability of the other two (e.g. solar radiation and precipitation) (Rowell et al., 1995; Rowell, 1998). The same method was used to create climate scenarios for assessing the impacts of solar radiation and precipitation.

In the simulations, the same wheat cultivar (Zhixuan 1) and maize cultivar (Yedan 22) were used in all the years and at the two study sites, and the impacts of nutrient stress, disease and pests were not considered. Doing so enables to eliminate the effects of other factors, and investigate the impacts of climate factors on crop yield. Winter wheat was planted on October 5th at Beijing and 15th at Zhengzhou, and harvested at physiological maturity. Maize was planted on June 12th at Beijing and June 15th at Zhengzhou. Maize was intercropped into wheat if the crop was not mature at the maize sowing date, and was harvested 1 day before sowing winter wheat.

The soil data at two sites included the soil physical and chemical characteristics in different layers and were obtained from the State Soil Survey Service of China (1998).

Crop yield was simulated under full irrigation conditions (i.e. potential yield) for assessing the impacts of temperature and solar radiation in isolation and of their combined effects. Crop yield without irrigation (i.e. rainfed) was simulated to evaluate the effects of precipitation. Under full irrigation conditions, irrigation water, with the automatic irrigation facility in the APSIM model, was added to the soil up to field capacity when the soil water content within maximum rooting depth (150 cm) fell below field capacity.

Correlation coefficients between the anomalies of simulated wheat and maize yield and the anomalies of temperature, solar radiation and precipitation, and the ratio of the variance of mean simulated grain yield (σ^2_{mean}) and that of all simulated grain yield from the ensemble (σ^2_{all}) were also calculated to detect the relationship between the variability of climate variables and grain yields. Linear regression analysis and Kendall-tau statistic (Lobell and Asner, 2003; Chmielewski *et al.*, 2004) were used to detect trends in climate variables and simulated crop yields.

3. Results

3.1. Variability and trends in climate variables

Anomalies of mean temperature, solar radiation and precipitation and their corresponding trend during the whole year, the wheat growing season, the stages before and after dormancy and the maize growing season from 1961–2003 at Beijing and Zhengzhou were analyzed.

At Beijing, annual mean temperature during the period 1961-1980 varied between 1.7 and 0.2°C lower than the mean for the entire period (1961–2003) (Fig. 2a). The subsequent period (1981–2003) was warmer and included the warmest year (1994), with 1.54 ℃ higher than for 1961–2003. At Zhengzhou, annual mean temperature varied slightly around the values of the normal climate since 1961, except during the last 10 years, when the annual mean temperature was higher than for 1961–2003 (Fig. 2b). Mean temperature during wheat growing season and the stage before dormancy showed similar variations with the annual mean temperature (data not shown). Large variability was observed in in mean temperatures after the wheat dormancy (due to the typical strong variation of general circulation in the spring, Fig. 2c, d) as well as in mean temperatures during the maize growing season (Fig. 2e, f).

Overall, mean temperature during the whole year, the wheat growing season, the stages before and after wheat dormancy and the maize growing seasons increased at the two sites since 1961, except during the maize growing season at Zhengzhou (Table 2). The increases in mean temperature during the whole year, the wheat growing season and March-May were statistically significant ($p < 0.01$ or $p < 0.05$) at the both sites. For the maize season, mean temperatures increased significantly at Beijing, but not at Zhengzhou. In general, mean temperature increased more during the wheat season than during the maize season as a result of a larger increase in mean temperature in the winter months observed in the NCP.

Annual solar radiation at Beijing showed three clear periods (Fig. 3a): the 1960s and 1970s when solar radiation tended to be above the overall mean, the 1980s when the solar radiation showed a negative linear trend, and the 1990s to the end when solar radiation tended to stabilize at values below the overall mean. At Zhengzhou, annual solar radiation showed variations in cycles of 2-5 years (Fig. 3b). The highest solar radiation value was observed in 1978, while the lowest values were observed in 1996 and 2003. The variations found in solar radiation during the wheat growing season, the stages before and after wheat dormancy and the maize growing season were similar to those in annual solar radiation at two sites (data not shown).

In the 43 years of our study, solar radiation during the whole year, the wheat growing season, the stages before and after dormancy and the maize growing season at Beijing showed a significant ($p < 0.001$) decreasing trend at the rate of -29.2, -16.2, -7.7 and -13.1 MJ m^{-2} yr^{-1}, respectively (Table 2). Zhengzhou also showed a decreasing trend in solar radiation, but not significant during the four study periods (Table 2).

Annual precipitation at both Beijing and Zhengzhou showed large year-to-year variability (Fig. 4a, b). At Beijing, the variations of precipitation from 1961 to 1984 were characterized by 2-5 year fluctuations. The wettest years were 1964 and 1969, with precipitation of about 62% higher than the normal (Fig. 4a). The period of 1985–1998 was a long wet period. After that a long dry period was observed and 1999 was the driest year. On the other hand Zhengzhou did not experience obvious dry or wet episodes. Although the rainfall is relative sparse, there were large interannual variations in precipitation during wheat season, and the stages before and after dormancy (Fig. 4g-h). Precipitation during maize growing season varied similarly as annual precipitation (data not shown), because 75% of the annual precipitation falls during the maize season in the NCP. Precipitation during maize growing season showed significant decreasing trend at both Beijing and Zhengzhou, but it did not decrease significantly during the whole year and wheat growing season (Table 2).

3.2. Impact of the climate variability and trends on simulated crop yield

3.2.1. Combined impact of temperature, solar radiation and precipitation

We started by analyzing the crop yield simulations, driven simply by the historical record of temperature, solar radiation and precipitation. This constitutes a baseline for subsequent analysis of the individual contribution of each climate variable in isolation performed with the ensemble approach (see sections 3.2.2-3.2.4 below).

The baseline simulated wheat and maize yields under both potential and rainfed conditions were found to substantially vary from year to year due to the combined effects of climate variables during the study period (Fig. 5, 6). Under fully irrigated conditions, anomalies of simulated wheat yield expressed as percentage of the mean, varied between -25.9% and 20.0% at Beijing and between -18.8% and 35.3% at Zhengzhou, due to combined effects of temperature and solar radiation anomalies (Fig. 5a, b), while those of simulated maize yield ranged from -47.6% to 18.2% and -34.6 to 18.9 at Beijing and Zhengzhou, respectively (Fig. 5c, d). Due to the effects of precipitation anomalies together with anomalies in temperature and solar radiation, simulated rainfed yield of wheat and maize varied greatly, indicating the large impact of rainfall variability. The minimum yield anomalies were -100.0% for both crops at two sites, while the largest yield anomalies were 303.5 and 130.6% for wheat and 73.4 and 60.5% for maize at Beijing and Zhengzhou, respectively (Fig. 6a-d).

Due to effects of temperature increase and solar radiation decrease, simulated yield of both wheat and maize under fully irrigated conditions decreased significantly ($p < 0.01$) in the 43 years of our study period at Beijing (Fig. 5a, b), while that at Zhengzhou decreased slightly (Fig. 5c, d). Simulated yield for wheat and maize decreased by 48.8 kg ha^{-1} yr^{-1} (-22.6% yr^{-1}) and 88.3 kg ha^{-1} yr^{-1} (-31.4% yr^{-1}) at Beijing, respectively. Simulated rainfed yield for both wheat and maize had decreasing trends at Beijing and Zhengzhou (Fig. 6a-d), due to the combined effects of the decrease in precipitation (except Beijing) together with temperature increase and radiation decrease. However, the reduction in rainfed yield for both crops was not significant at either site ($p > 0.05$).

3.2.2. Isolated Impact of temperature

The ensemble of 43 climate scenarios in Table 1 was then used to isolate the impact of temperature in the yield anomalies and trends. Anomalies of simulated wheat yield caused by temperature anomalies alone varied between -10.1% and 9.4% at Beijing and between -12.5% and 12.1% at Zhengzhou (Fig. 7). The relationship between simulated wheat yield anomalies and temperature anomalies indicated that higher temperatures before dormancy (WD1) tended to increase wheat yield (probably due to higher vegetative growth), while a higher temperature after dormancy (WD2) led to wheat yield decrease (probably due to its effect on shortening the grain filling period) (Table 3, 4). Maize yield was also simulated to vary from year to year during the study period due to effects of temperature variability (Fig. 8). Anomalies of simulated maize yield caused by temperature anomalies varied between -16.8% and 13.2% at Beijing and between -9.9% and 12.8% at Zhengzhou. Higher temperature during maize growing season had negative impacts on maize yield probably due to its effect in shortening the grain filling period.

A trend analysis of the simulation is presented in Fig. 9. The simulation results showed that the decrease in mean temperature in the 1960s decreased wheat yields and the increase in temperature since 1971 had slightly affected wheat yield at both Beijing and Zhengzhou. Overall, the warming trend during wheat growing season in the 43 years tended to decrease wheat yields, but the decreasing trend was not significant as a result of the combined positive effects of temperature increase before dormancy and the negative impacts after dormancy. The wheat yield reduction was larger at Zhengzhou than at Beijing. This is mainly due to the fact that the temperature at the former is higher, and therefore wheat growth at this site is more sensitive to temperature stress (Fig. 9). The increased temperature during maize growing season resulted in a significant reduction of maize yield at the rate of 30.6 kg ha^{-1} yr^{-1} (2.7% yr^{-1}) at Beijing, and a slight decrease of maize yield at Zhengzhou (Fig. 9).

3.2.3. Isolated impact of solar radiation

Here an ensemble of 43 climate scenarios was used to investigate the impact of solar radiation, as shown in Table 1. The observed changes in solar radiation resulted in anomalies of simulated wheat yield (ensemble mean of the 43 scenarios) that varied from -16.7% to 20.0% and -18.5% to 36.6% at Beijing and Zhengzhou, respectively (Fig. 10). The simulated results indicate that solar radiation after dormancy plays the key role in final wheat yield (Table 3, 4). Anomalies of simulated maize yield caused by solar radiation anomalies varied between -29.8% and 24.8% at Beijing and between -24.9% and 23.8% at Zhengzhou (Fig. 11). In general, negative anomalies of solar radiation during crop growing season led to lower wheat yield due to reduced photosynthetically active radiation captured by the crops for biomass and yield accumulation.

These results suggest that the reduction in solar radiation observed in the NCP would have decreased grain yields of wheat and maize in the 43 years of our study (Fig. 12). Simulated grain yield of both wheat and maize decreased significantly at Beijing ($P<0.01$) and slightly at Zhengzhou. From 1961–2003, simulated yield decreased by 43.9 kg ha^{-1} yr^{-1} (5.2% yr^{-1}) for wheat and 54.9 kg ha^{-1} yr^{-1} (4.8% yr^{-1}) for maize at Beijing. The greater reduction in solar radiation observed in Beijing (Fig. 3g) caused the greater reduction in crop yield.

3.2.4. Isolated impact of precipitation

The ensemble approach was next applied to isolate the impact of precipitation. Due to the characteristically low precipitation observed in the NCP (Fig. 4), both wheat and maize yields under rainfed conditions are found to be very sensitive to the variations of precipitation (Fig. 13, 14). Wheat yield in high precipitation seasons was found top be three- to four-fold higher than the average, while in some drier seasons, there was no grain yield produced. Compared to wheat, anomalies of maize yield were smaller due to the concentrated precipitation during the maize growing season, but the variations were still large due to inter-seasonal precipitation variability (Fig. 4).

Simulated yield of wheat and maize showed that precipitation decrease in the studied 43 years tended to reduce crop yields under rainfed conditions (Fig. 15). The decreasing trends were large (for wheat: -25.7 kg ha^{-1} yr^{-1} at Beijing and -63.3 kg ha^{-1} yr^{-1} at Zhengzhou; for maize: -38.8 kg ha^{-1} yr^{-1} at Beijing and -41.7 kg ha^{-1} yr^{-1} at Zhengzhou). However, the large variations in rainfed yield due to the interannual variation of precipitation caused the trends to be statistically non significant.

4. Discussion and conclusions

This study used a modeling approach, with climate scenarios built from combinations of observed climate variables and fixed crop cultivars, to disentangle the influence of the observed changes in climate variables on crop yields. This approach enabled us to quantify the changes in crop yield caused by a single weather variable in absence of changes in other climate variables and management options. Compared with some studies using regression analyses to investigate the impacts of climate variables and agronomic management on crop yields (Thompson, 1962; Dirks and Bolton, 1981; Lobell *et al.*, 2007), our approach demonstrates that cropping modeling facilitates the uncoupling.

Overall, the climate has become warmer, drier and solar radiation has decreased during the 43 years of our study at the two sites in the NCP. The variations in temperature reported here correspond well with large-scale patterns reported for China (Ding *et al.*, 2007), as well as with global temperature changes (IPCC, 2007). The variability and trends in solar radiation and precipitation of our study are consistent with the results at regional scale in the NCP and China (Liang and Xia, 2005, Song *et al.*, 2006; Fu *et al.*, 2009). Thus, the simulation results based on the observed climate data at the two study sites are representative of the NCP. Solar radiation variations might be caused by increased air pollution related to human activity (Qian *et al.*, 2006), while the precipitation variability and trends in the NCP have been linked to global drivers (Zhang *et al.*, 2003).

Variations in temperature, solar radiation and precipitation in our study period altered simulated yields, and the impacts on crop yield were not uniform during different crop stages and across the NCP. Higher temperatures before the wheat dormancy stage had a positive effect on yields, especially in the northern part of the NCP, while increased temperatures after dormancy decreased wheat yield. In the NCP, the growth and yield of winter wheat is often affected by frost damage during the winter (Jin, 1996). The higher temperatures during the winter lessen the frost impacts on winter wheat and lead to high grain yields. However, temperature increase during the stage after dormancy shortens the growing period for winter wheat which results less time for photosynthesis including shorter grain-filling stage, accumulation of biomass and hence grain yield, which is inherently detrimental to final yield (Song *et al.*, 2006). Maize was negatively impacted by higher temperatures during its growing season. High levels of solar radiation had significant impacts on achieving high yields for both wheat and maize. The variability of wheat yield was mainly caused by the variability of solar radiation during the stage after dormancy. Under rainfed conditions, precipitation is the most important climate factor affecting crop yield in the NCP. Rainfed grain yield for both wheat and maize varied greatly due to precipitation variability, with very low yields in many seasons due to low precipitation, especially for wheat.

Previous studies (Tao *et al.*, 2003; Liu *et al.*, 2009) showed that climate change in the past few decades led to negative impacts on crop yield potential in the NCP and especially emphasized the role played by the warming trend. Tao et al. (2003) reported that maximum and minimum temperatures in winter and spring during 1981-2000 at Zhengzhou in the NCP were negatively related to wheat yields based on Pearson correlation analyses. Fig. 16 shows the statistical relationship of temperature and baseline wheat yield for the WD1 and WD2 period at Beijing. From our baseline yield simulations, obtained from the combined effects of climate variables (see section 3.2.1), a similar relationship between mean temperature during WD1 and WD2 and simulated wheat yield was also found here. However, these results may be seriously misleading since the effects of other factors (such as solar radiation) were not excluded. Our ensemble simulations show that the changes in solar radiation exert a much stronger impact on the variability and trend on crop yield (Fig. 10-12, Table 3). The temperature increase in 1961-2003 resulted in slightly reduced wheat yield due to the joint effects of temperature increase during the stages before and after dormancy, and in decreased maize yield, especially in the northern location of the NCP. The decline in solar radiation decreased significantly crop yields by 5.2% yr^{-1} for wheat and 4.8% yr^{-1} for maize at Beijing, respectively. Compared with the impact of temperature increase, the magnitude of reduction in crop yield caused by solar radiation decrease was larger. The decrease in wheat yield caused by solar radiation was 53.8 times and 1.8 times larger than that caused by temperature at Beijing and Zhengzhou, respectively. The corresponding decrease in maize yield was 1.8 times at Zhengzhou (the decreased maize yield caused by solar radiation in Beijing was similar to that caused by temperature). Although the decreasing trend in rainfed yield was large as a result of precipitation decrease, the huge year-to-year variability of precipitation made the rainfed yield trends less prominent.

The simulation results indicated that failure to take into account the effects of solar radiation might result in inaccurate estimates of crop production affected by climate change in the study area. It should be kept in mind that the simulated crop yield change caused by temperature should be interpreted cautiously. The current simulations conducted did not consider the impact of extreme temperature (e.g. heat stress during grain filling) on crop yield. Considering this, the impacts of temperature increase on crop yield might be underestimated.

Climate variability and change in the NCP during the last four decades may be partly driven by global warming, and to a large extent, by rapid regional industrial development. The warming trend is predicted to continue in the future 20 to 100 years, with a warming rate that will depend on emission scenarios (Ding *et al.*, 2007). There are many uncertainties regarding future changes in precipitation and solar radiation. One scenario would be that environmental conditions are not improved due to industrial development. In that case, the decreased solar radiation would further reduce the crop potential yields in the future. If environmental conditions are improved in the future and emissions of aerosols are reduced (Wild *et al.*, 2005), solar radiation would increase. However, an increase in solar radiation, together with the projected warmer environment, would lead to worsen water shortages in the NCP, which may ultimately result in decreased crop yield due to crop water stress.

Attempting to assess the impacts of each climate variable, i.e. temperature, solar radiation and precipitation, this study created climate scenarios consisting of possible combinations of observed climate variations. Although these scenarios are not real, the conclusions drawn from the study help to understand how the variations in climatic factor affected crop production in the NCP. The results also have several implications for evaluating the impacts of future climate variability and change on crop production. The combinations of one climate variable with other variables during the study period were considered because only one scenario cannot prescribe long-term climate mean due to large interannual climate variability, such as precipitation. While only temperature, solar radiation and precipitation were considered in this study, it is necessary to include other factors, such as CO_2 concentration and relative humidity to provide more accurate information for assessing the impact of climate change on crop production. It is essential to further consider how the changes in these climate variables and their interactions affect agriculture in the future. The characteristics of the change in climatic factors during different crop growth stages might have different effects on final grain yield, which also needs further research.

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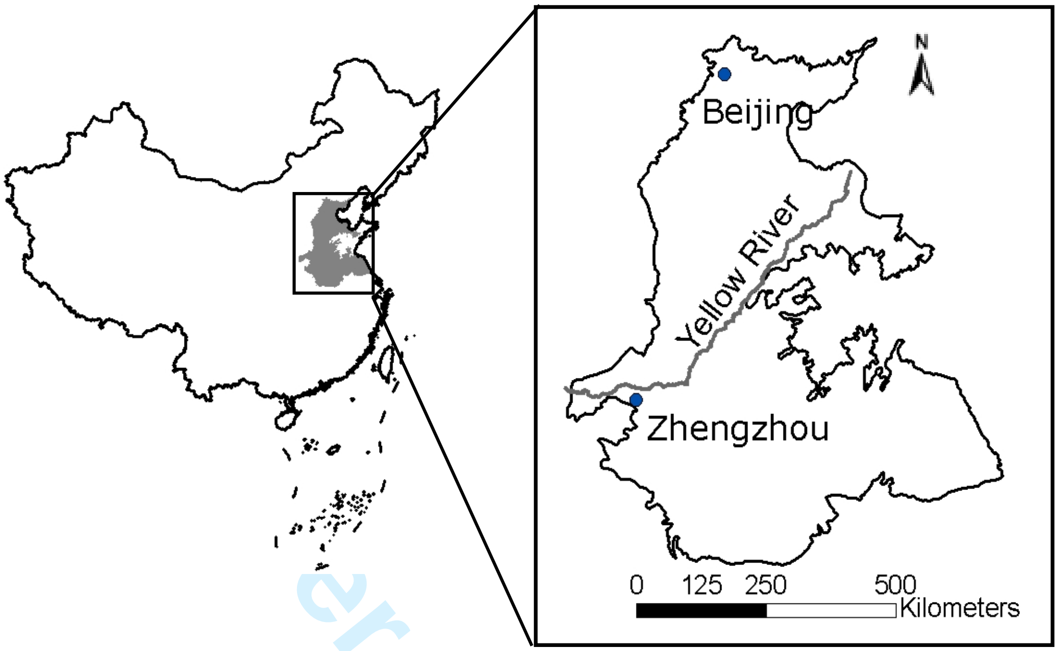
515 

516 Fig. 1. The North China Plain and the two study sites: Beijing and Zhengzhou.

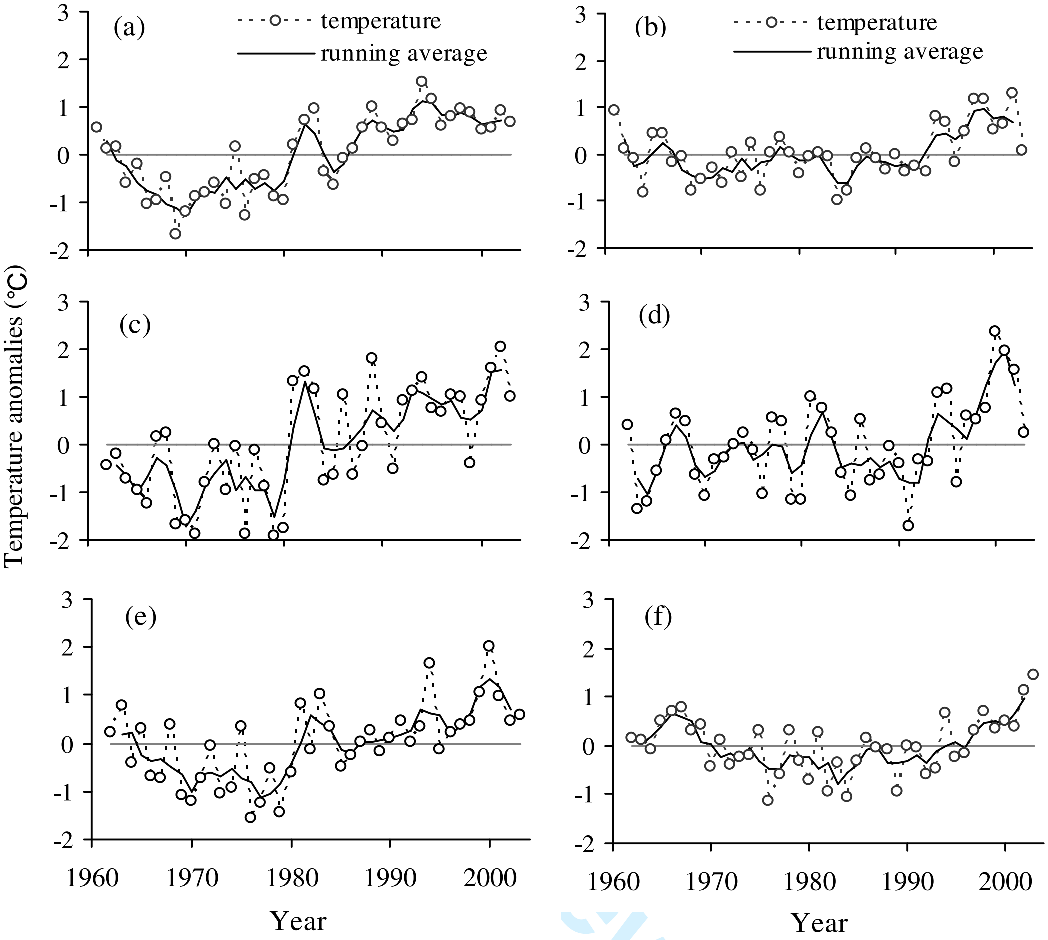
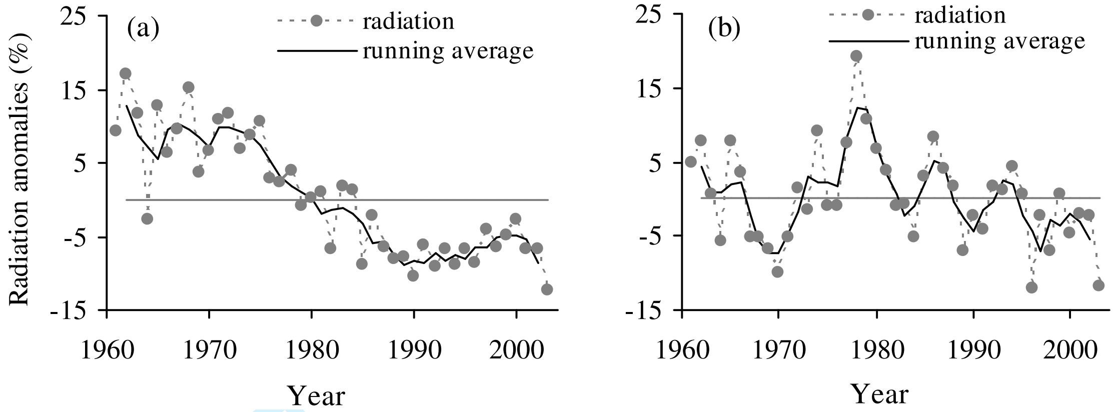


Fig. 2. Anomalies of mean temperature during the whole year (a, b), the stage after wheat dormancy (c, d) and maize growing season (e, f) from 1961–2003 at Beijing (left panel) and Zhengzhou (right panel) in the NCP. Obtained time series of temperature anomalies were smoothed by a 3-yr running average.



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523 Fig. 3. Anomalies of annual solar radiation (a, b) during 1961–2003 at Beijing (left panel) and
524 Zhengzhou (right panel) in the NCP. Obtained time series of solar radiation anomalies were
525 smoothed by a 3-yr running average.

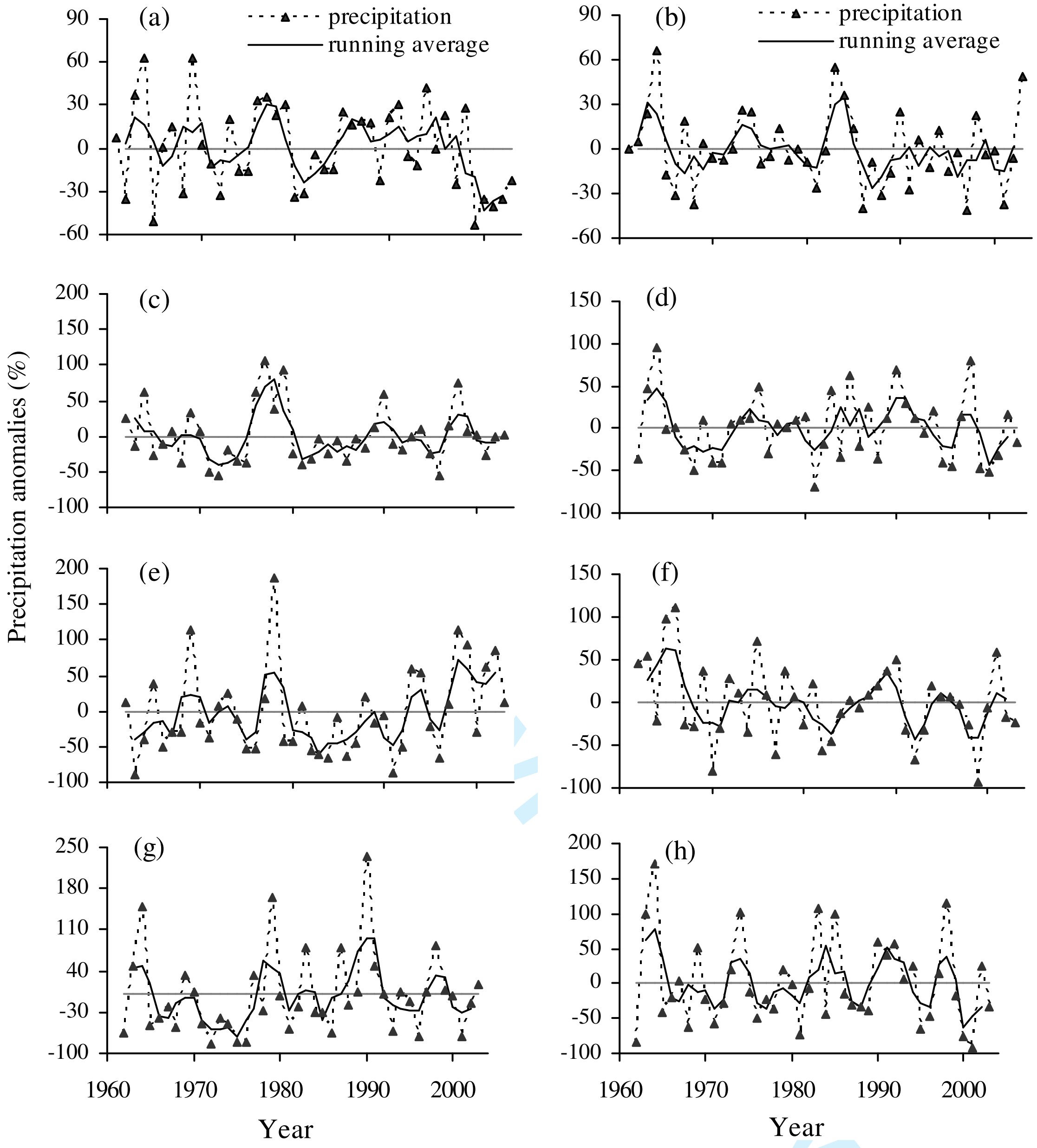


Fig. 4. Anomalies of precipitation during the whole year (a, b), wheat growing season, (c, d), the stage before wheat dormancy (e, f), the stage after wheat dormancy (g, h) from 1961–2003 at Beijing (left panel) and Zhengzhou (right panel) in the NCP. Obtained time series of precipitation anomalies were smoothed by a 3-yr running average.

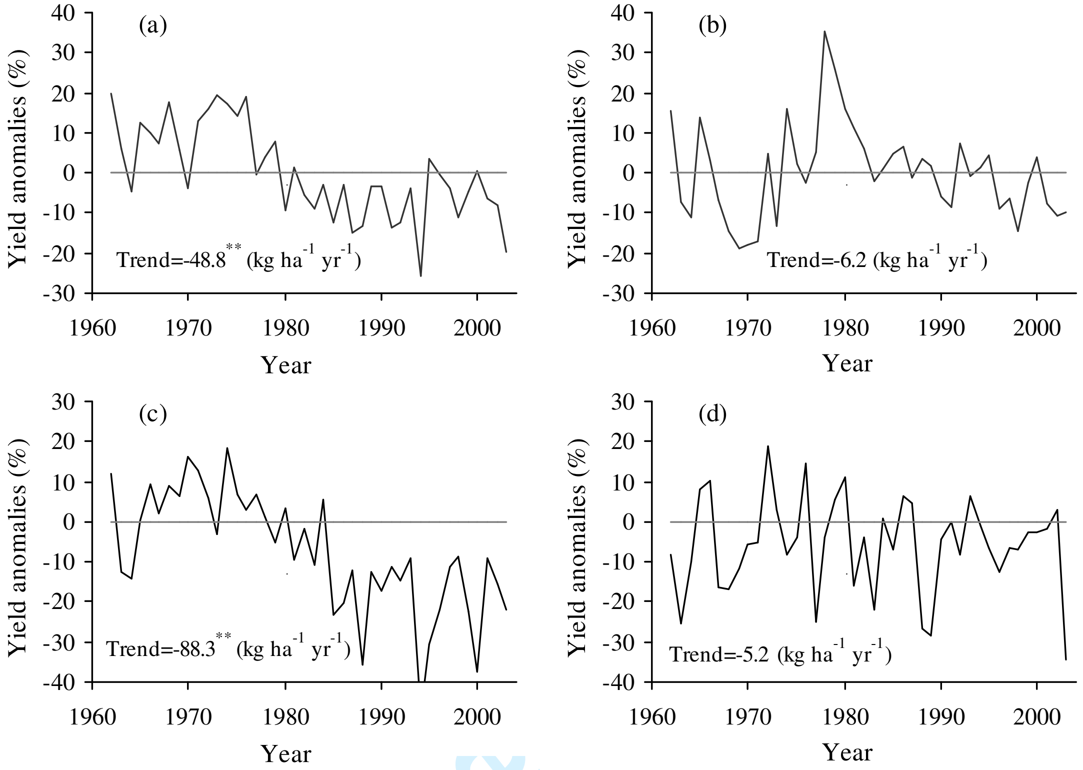


Fig. 5. Anomalies of baseline yield from crop model driven by combined effects of temperature, solar radiation and precipitation under potential conditions for wheat (panels a, b) and maize (panels c, d) at Beijing (a, c) and Zhengzhou (b, d).

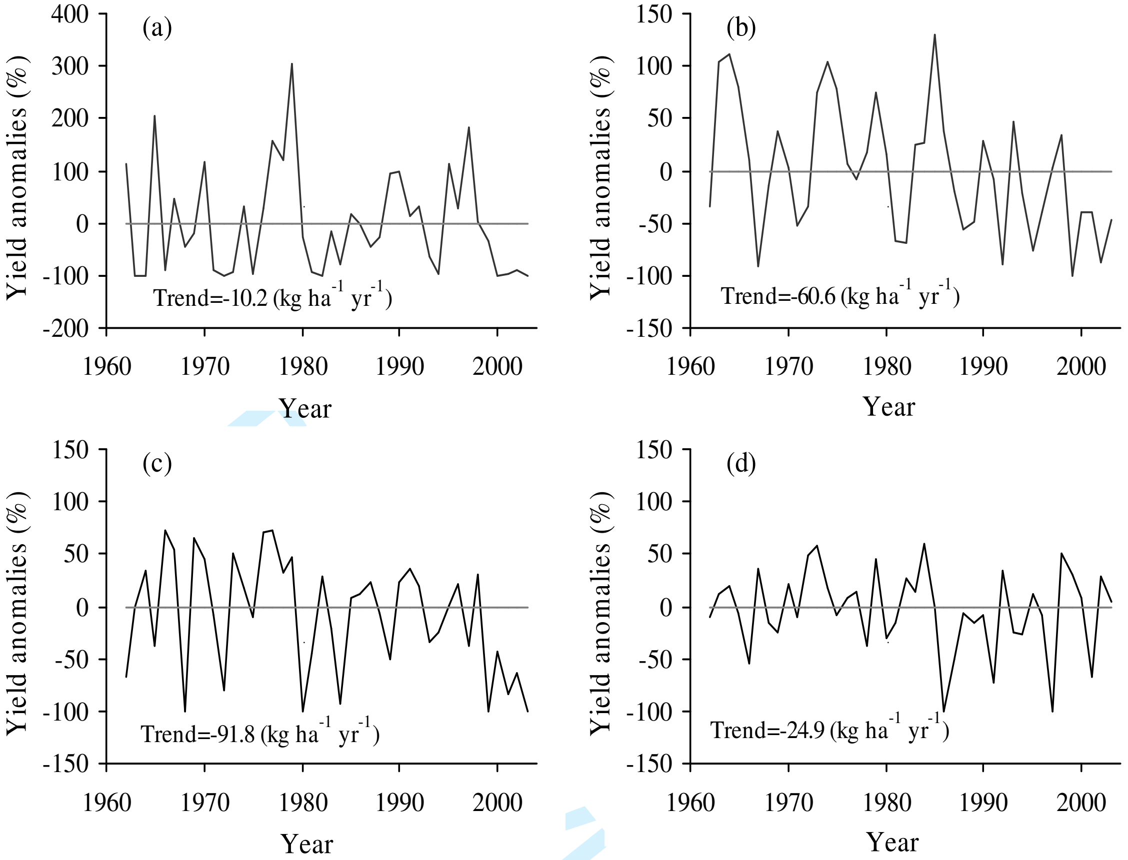


Fig. 6. Anomalies of baseline yield from crop model driven by combined effects of temperature, solar radiation and precipitation under rainfed conditions for wheat (panels a, b) and maize (panels c, d) at Beijing (a, c) and Zhengzhou (b, d).

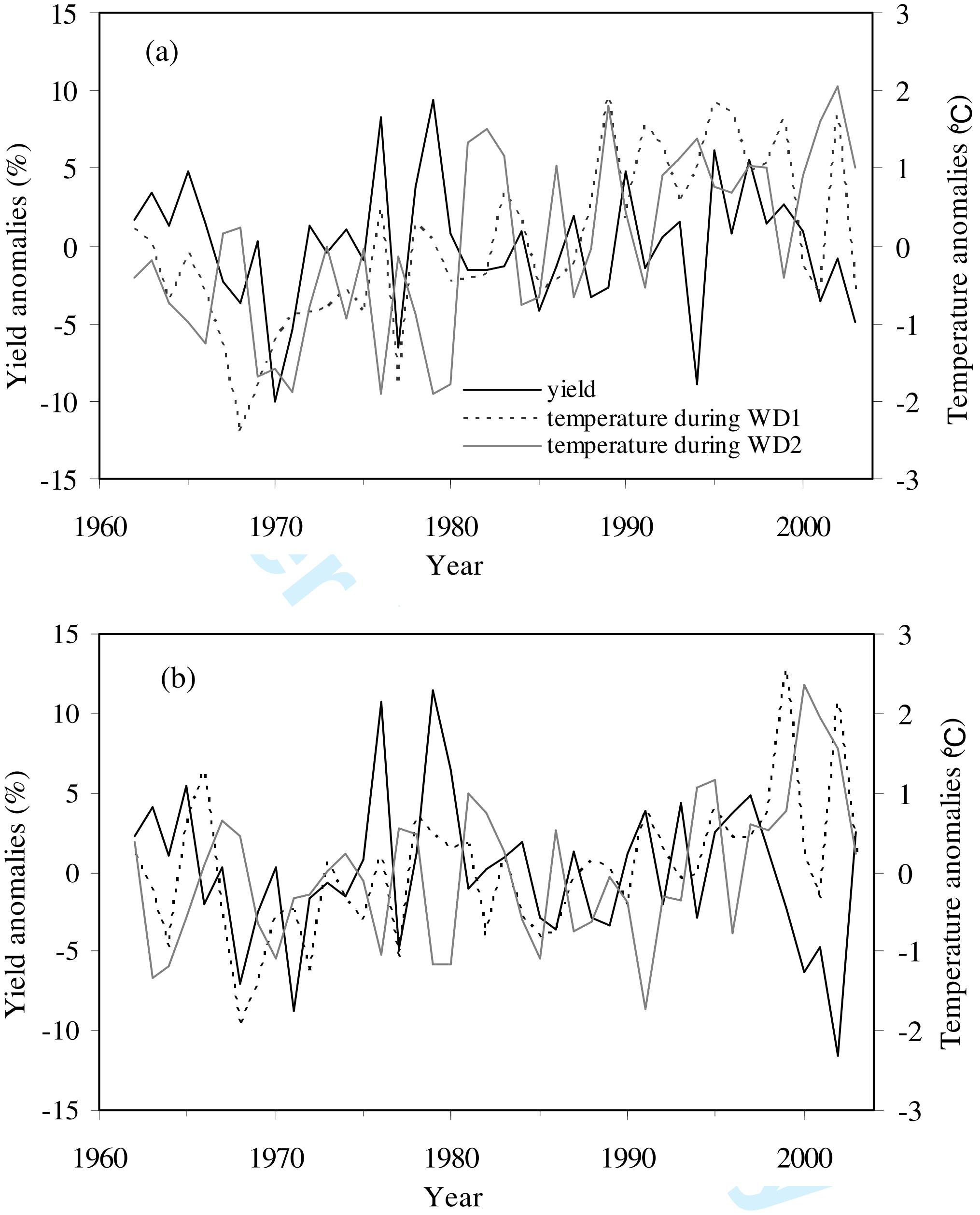


Fig. 7. Isolated impact of temperature on anomalies of wheat yield (%) and temperature anomalies (℃) during the stages before wheat dormancy (WD1) and after wheat dormancy (WD2) at Beijing (a) and Zhengzhou (b).

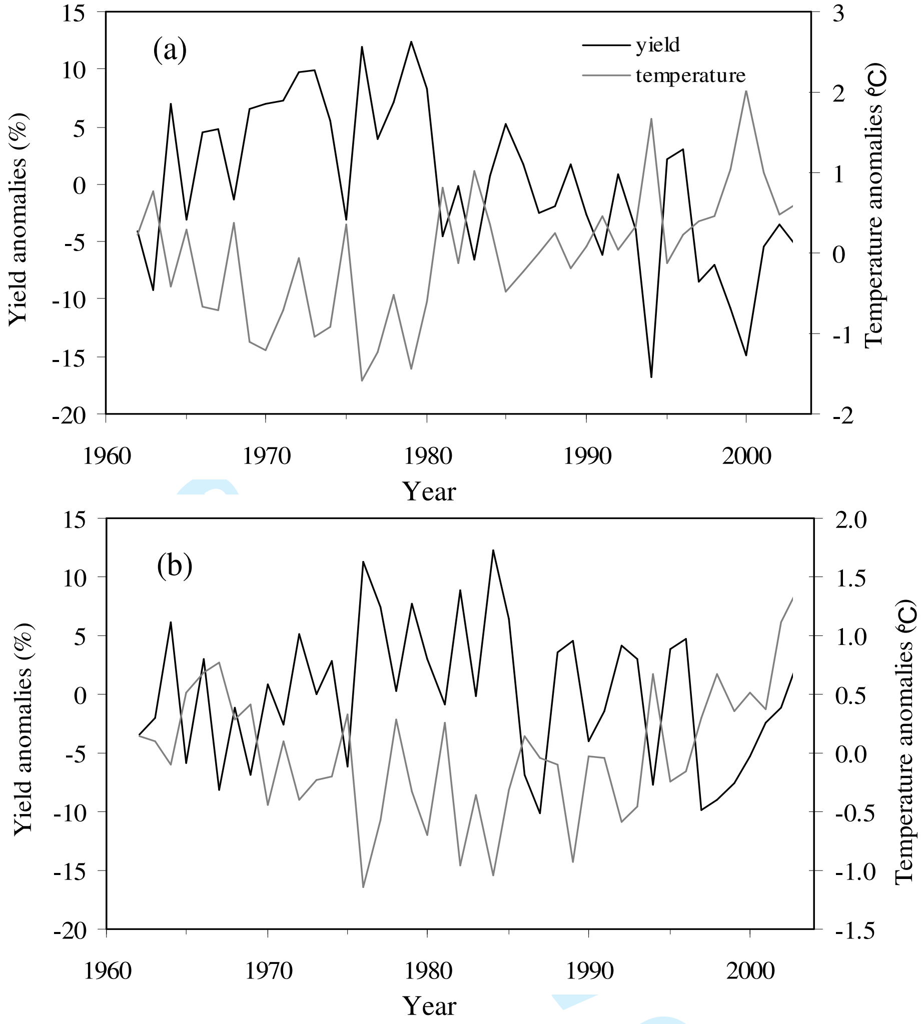


Fig. 8. Isolated impact of temperature on anomalies of maize yield (%) and temperature anomalies (℃) during maize growing season at Beijing (a) and Zhengzhou (b).

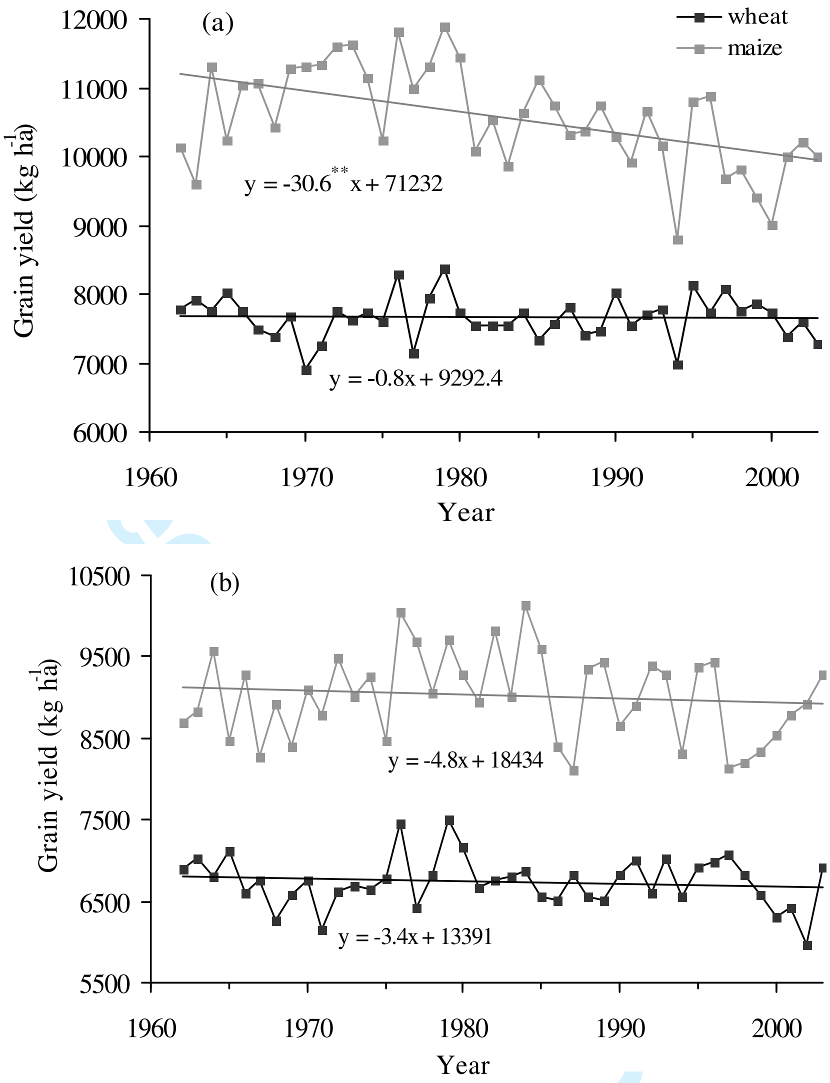


Fig. 9. The simulated yield of wheat and maize under fully irrigated conditions affected by the changes in temperature from 1962–2003 at Beijing (a) and Zhengzhou (b). Straight lines show the linear trends. **Significant at $p < 0.01$.

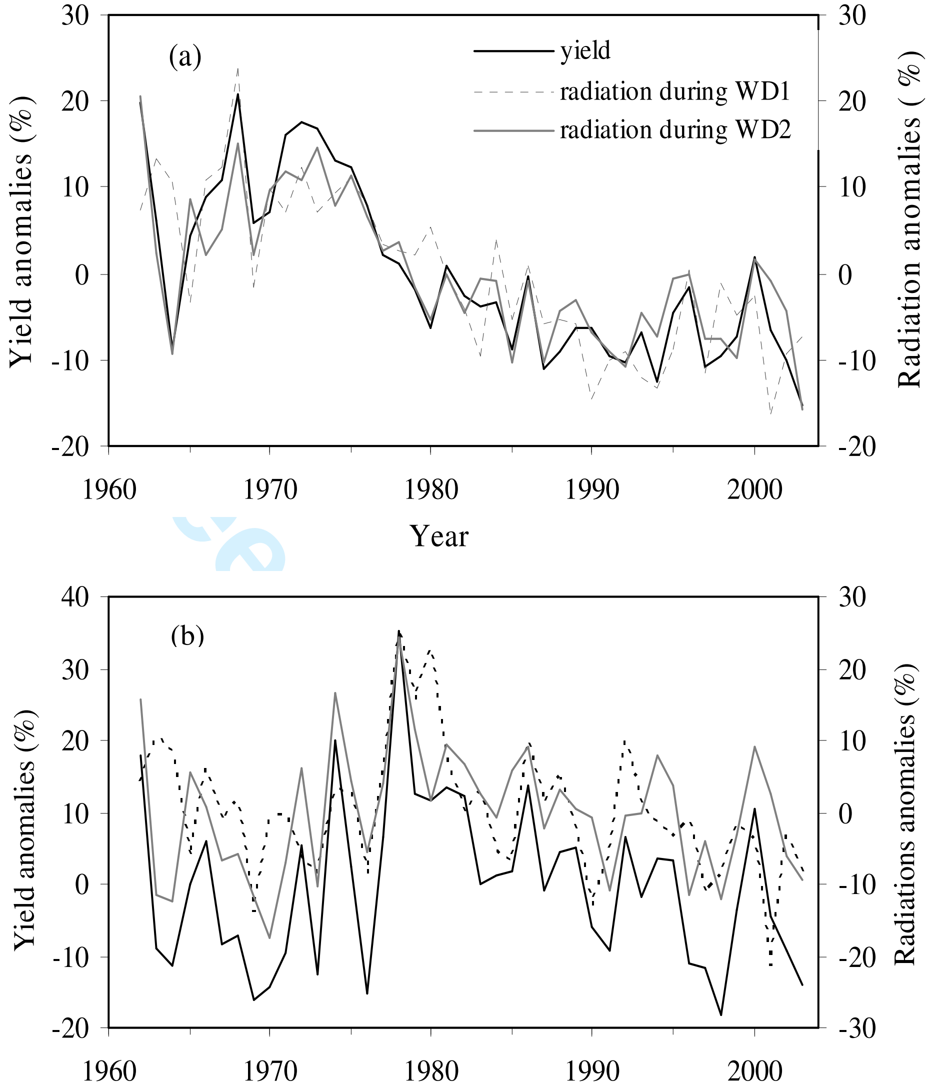
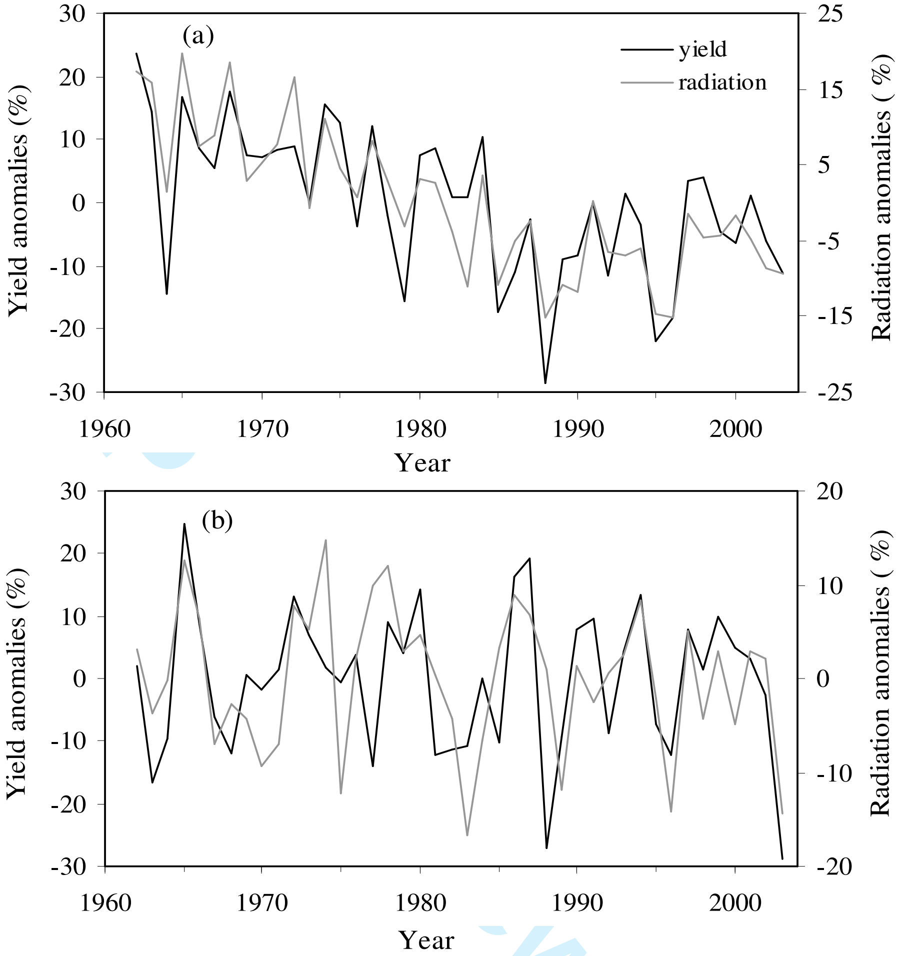


Fig. 10. Isolated impact of solar radiation on anomalies of wheat yield (%) and solar radiation anomalies (%) during the stages before wheat dormancy (WD1) and after wheat dormancy (WD2) at Beijing (a) and Zhengzhou (b).



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556 Fig. 11. Isolated impact of solar radiation on anomalies of maize yield (%) and solar radiation
557 anomalies (%) during maize growing season at Beijing (a) and Zhengzhou (b).

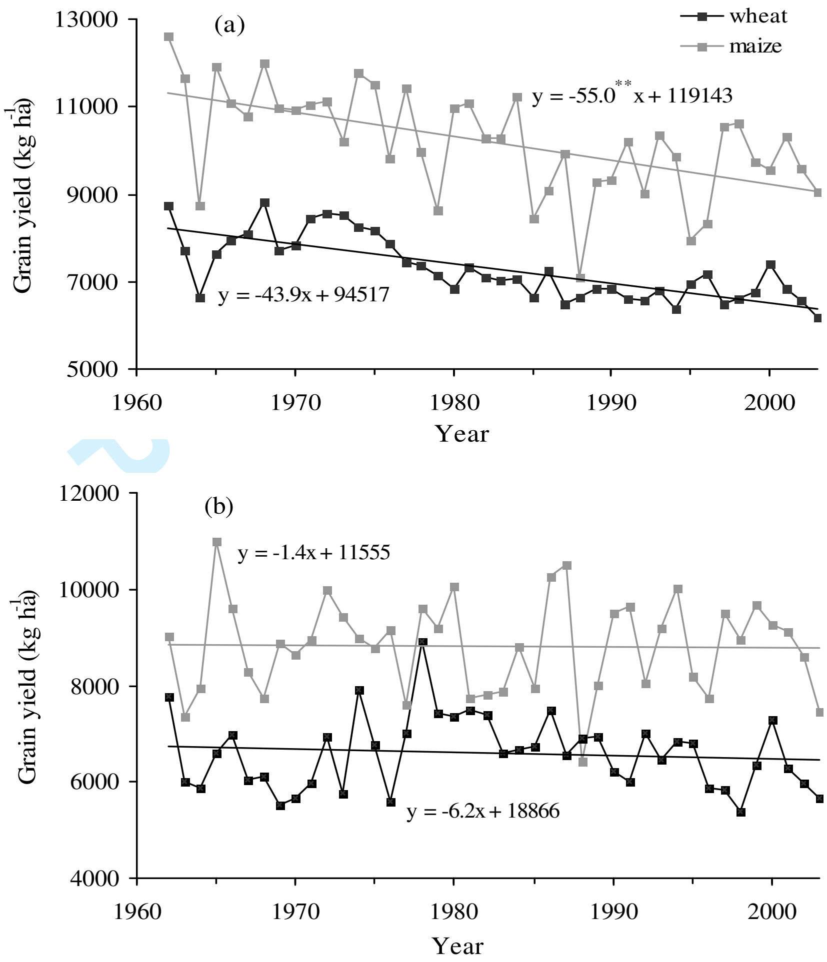


Fig. 12. The simulated yield of wheat and maize under fully irrigated conditions affected by the trends in solar radiation from 1962–2003 at Beijing (a) and Zhengzhou (b). Straight lines show the linear trends. **Significant at $p < 0.01$.

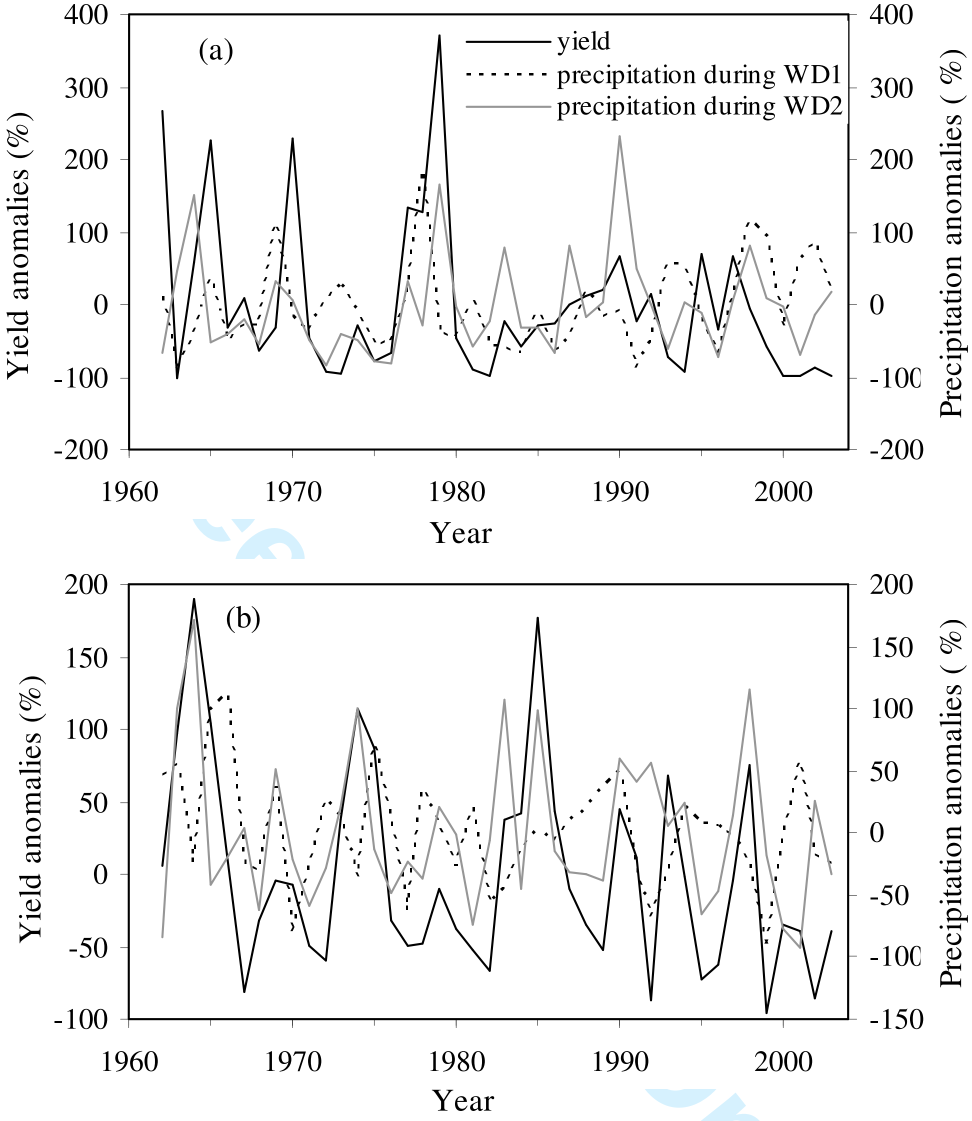
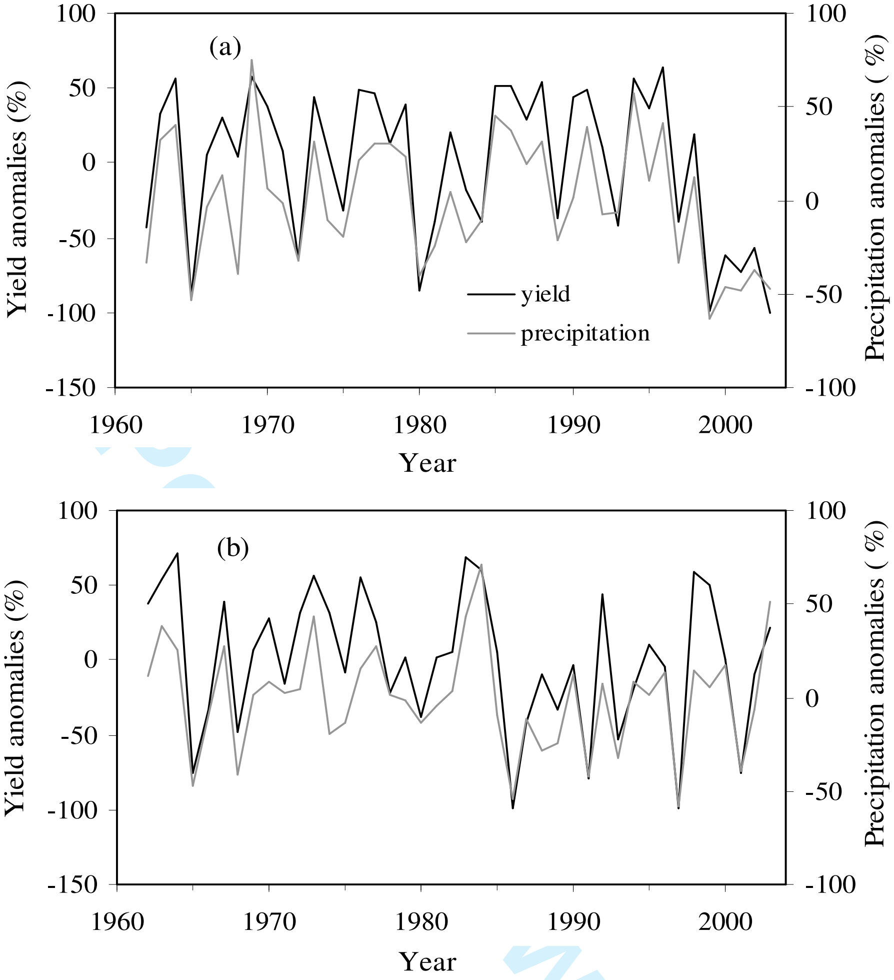


Fig. 13. Isolated impact of precipitation on anomalies of wheat yield (%) and precipitation anomalies (%) during the stages before wheat dormancy (WD1) and after wheat dormancy (WD2) at Beijing (a) and Zhengzhou (b).



566

567 Fig. 14. Isolated impact of precipitation on anomalies of maize yield (%) and precipitation

568 anomalies (%) during maize growing season at Beijing (a) and Zhengzhou (b).

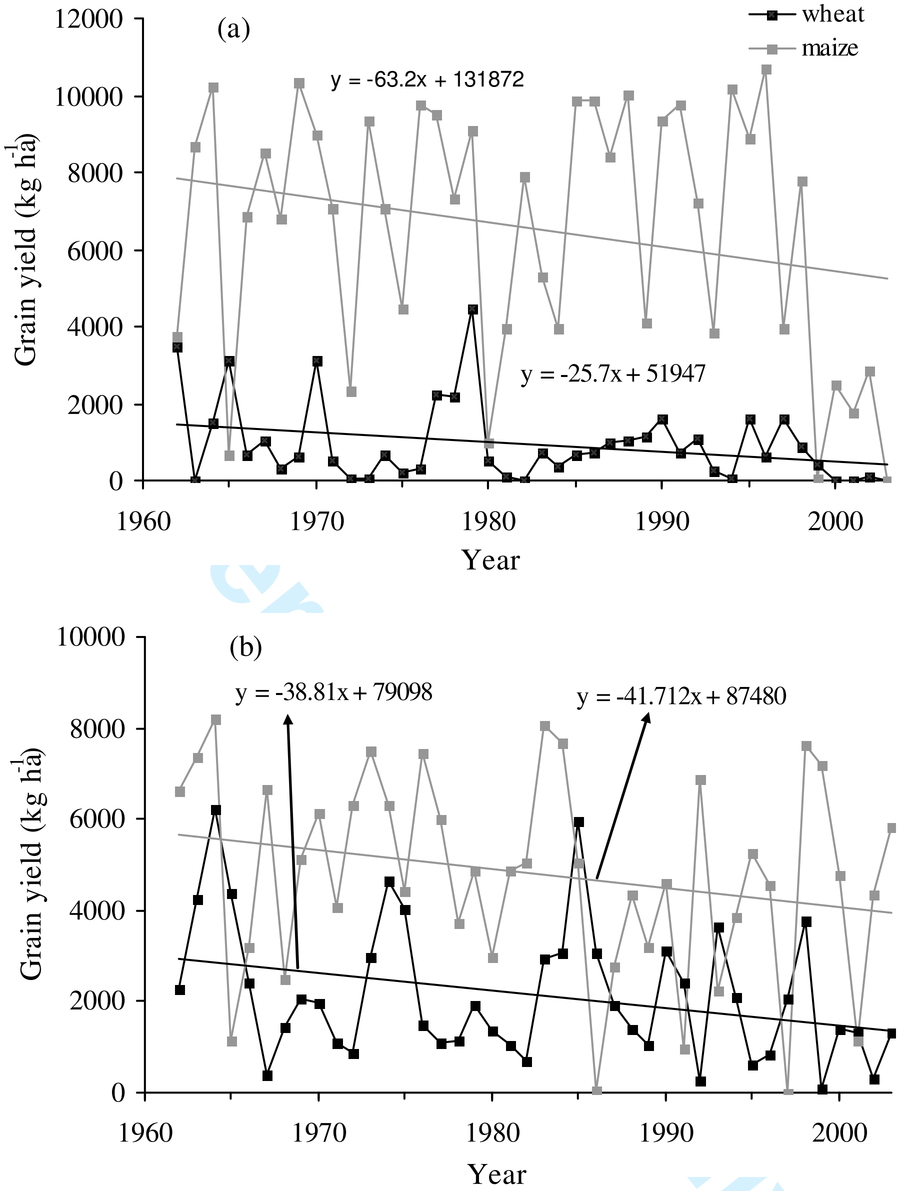


Fig. 15. The simulated yield of wheat and Maize under rainfed conditions affected by the changes in precipitation from 1962–2003 at Beijing (a) and Zhengzhou (b). Straight lines show the linear trends. **Significant at $p < 0.01$.

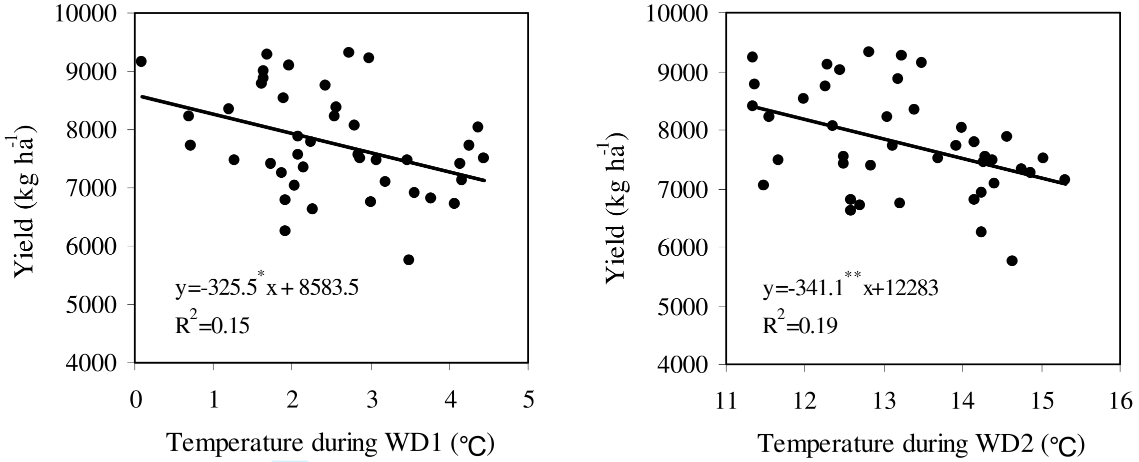


Fig. 16. Relationship between simulated wheat potential yield and mean temperature during the stages before wheat dormancy (WD1) (a) and after wheat dormancy (WD2) (b) at Beijing.

576 Table 1 Climate scenarios designed to analyze the effects of the variations in temperature on crop
577 yield in the simulation study

Scenarios	Time series of Temperature (maximum and minimum)	Time series of Solar radiation	Time series of precipitation
1	1961–2003	1961	1961
2	1961–2003	1962	1962
3	1961–2003	1963	1963
4	1961–2003	1964	1964
5	1961–2003	1965	1965
6	1961–2003	1966	1966
7	1961–2003	1967	1967
8	1961–2003	1968	1968
9	1961–2003	1969	1969
10	1961–2003	1970	1970
11	1961–2003	1971	1971
12	1961–2003	1972	1972
13	1961–2003	1973	1973
14	1961–2003	1974	1974
15	1961–2003	1975	1975
16	1961–2003	1976	1976
17	1961–2003	1977	1977
18	1961–2003	1978	1978
19	1961–2003	1979	1979
20	1961–2003	1980	1980
21	1961–2003	1981	1981
22	1961–2003	1982	1982
23	1961–2003	1983	1983
24	1961–2003	1984	1984
25	1961–2003	1985	1985
26	1961–2003	1986	1986
27	1961–2003	1987	1987
28	1961–2003	1988	1988
29	1961–2003	1989	1989
30	1961–2003	1990	1990
31	1961–2003	1991	1991
32	1961–2003	1992	1992
33	1961–2003	1993	1993
34	1961–2003	1994	1994
35	1961–2003	1995	1995
36	1961–2003	1996	1996
37	1961–2003	1997	1997
38	1961–2003	1998	1998
39	1961–2003	1999	1999
40	1961–2003	2000	2000
41	1961–2003	2001	2001
42	1961–2003	2002	2002
43	1961–2003	2003	2003

Table 2 Trends in mean temperature, solar radiation and precipitation in the whole year, wheat season, the stage before dormancy (WD1), the stage after dormancy (WD2) and maize season during 1961–2003 at the two study sites in the NCP.

Site	Period	Mean temperature		Solar radiation		Precipitation	
		Trend (℃/decade)	R^2	Trend (MJ/m^2/ decade)	R^2	Trend (mm/ decade)	R^2
Beijing	Annual	0.43**	0.46	–291.8**	0.72	–15.2	0.01
	Wheat season	0.55**	0.51	–161.5**	0.63	7.2	0.03
	WD1	0.53**	0.40	–86.0**	0.61	3.6	0.01
	WD2	0.58**	0.37	–76.6**	0.46	3.5	0.03
	Maize season	0.34**	0.27	–131.4**	0.59	–24.1*	0.14
Zhengzhou	Annual	0.17**	0.14	–57.3	0.02	–5.6	0.02
	Wheat season	0.32**	0.30	–36.4	0.04	–4.1	0.001
	WD1	0.31**	0.20	–34.4*	0.10	–9.7	0.07
	WD2	0.31**	0.17	–2.5	0.001	–6.0	0.01
	Maize season	0.08	0.03	–18.2	0.02	–1.1*	0.06

**Significant at $P<0.01$;

*Significant at $P<0.05$.

Table 3 Correlation coefficients between the anomalies of simulated wheat and maize yield and the anomalies of temperature in isolation, solar radiation in isolation and precipitation in isolation at Beijing and Zhengzhou. AWH and AMZ represent the anomalies of wheat yield and maize yield, respectively. ATBD, ATAD, ARBD, ARAD, APBD and APAD represent the anomalies of temperature before dormancy, temperature after dormancy, radiation before dormancy, radiation after dormancy, precipitation before dormancy and precipitation after dormancy respectively during wheat growing season. AT, AR, and AP represent the anomalies of temperature, radiation and precipitation during maize growing season

Factors	AWH		Factors	AMZ	
	Beijing	Zhengzhou		Beijing	Zhengzhou
ATBD	0.27*	0.26*	AT	-0.75**	-0.55**
ATAD	-0.21*	-0.33**			
ARBD	0.57**	0.44**	AR	0.66**	0.44**
ARAD	0.79**	0.74**			
APBD	0.07	0.17	AP	0.79**	0.65**
APAD	0.25*	0.31**			

**Significant at P<0.01;

*Significant at P<0.05.

Table 4 The ratio of variance of mean simulated grain yield (σ^2_{mean}) and that of all simulated grain yield from the ensemble (σ^2_{all}) during 1961-2003. $\sigma^2_{\text{mean,T}}/\sigma^2_{\text{all, T}}$ represents the ratio of σ^2_{mean} and σ^2_{all} where grain yield was affected by temperature; $\sigma^2_{\text{mean, SR}}/\sigma^2_{\text{all, SR}}$ represents the ratio of σ^2_{mean} and σ^2_{all} where grain yield was affected by solar radiation; $\sigma^2_{\text{mean, P}}/\sigma^2_{\text{all, P}}$ represents the ratio of σ^2_{mean} and σ^2_{all} where grain yield was affected by precipitation.

Site	$\sigma^2_{\text{mean,T}}/\sigma^2_{\text{all, T}}$		$\sigma^2_{\text{mean, SR}}/\sigma^2_{\text{all, SR}}$		$\sigma^2_{\text{mean, P}}/\sigma^2_{\text{all, P}}$	
	Wheat	Maize	Wheat	Maize	Wheat	Maize
Beijing	0.11	0.22	0.39	0.62	0.75	0.88
Zhengzhou	0.13	0.16	0.48	0.61	0.88	0.80