



Historical data provide new insights into response and adaptation of maize production systems to climate change/variability in China



Fulu Tao^{a,*}, Zhao Zhang^b, Shuai Zhang^a, Reimund P. Rötter^c, Wenjiao Shi^a, Dengpan Xiao^a, Yujie Liu^a, Meng Wang^a, Fengshan Liu^a, He Zhang^a

^a Institute of Geographical Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China

^b State Key Laboratory of Earth Surface Processes and Resource Ecology, Beijing Normal University, Beijing 100875, China

^c Natural Resources Institute Finland (Luke), FI-01301 Vantaa, Finland

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ABSTRACT

Extensive studies had been conducted to investigate the impacts of climate change on maize growth and yield in recent decades; however, the dynamics of crop husbandry in response and adaptation to climate change were not taken into account. Based on field observations spanning from 1981 to 2009 at 167 agricultural meteorological stations across China, we found that solar radiation and temperature over the observed maize growth period had decreasing trends during 1981–2009, and maize yields were positively correlated with these climate variables in major production regions. The decreasing trends in solar radiation and temperature during maize growth period were mainly ascribed to the adoption of late maturity cultivars with longer reproductive growth period (RGP). The adoption of late maturing cultivars with longer RGP contributed substantially to grain yield increase during the last three decades. The climate trends during maize growth period varied among different production areas. During 1981–2009, decreases in mean temperature, precipitation and solar radiation over maize growth period jointly reduced yield most by 13.2–17.3% in southwestern China, by contrast in northwestern China increases in mean temperature, precipitation and solar radiation jointly increased yield most by 12.9–14.4%. Our findings highlight that the adaptations of maize production system to climate change through shifts of sowing date and genotypes are underway and should be taken into account when evaluating climate change impacts.

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1. Introduction

Global maize production and consumption have shown constant increases in the past few decades (FAO, 2012). However, maize yield has been documented to be quite vulnerable to climate change/variability in global major maize production regions, using both crop models (Challinor et al., 2007; Tao et al., 2009; Tao and Zhang, 2011) and statistical approaches (Tao et al., 2004, 2012; Schlenker and Roberts, 2009; Cairns et al., 2012; Lobell et al., 2011a,b, 2013; Wang et al., 2014). Therefore, the ability to maintain rates of yield increase in the face of climate change has increasingly been of concern (Cassman, 2007; IPCC 2014; Schlenker and Roberts, 2009; Battisti and Naylor, 2009; de Lattre-Gasquet et al., 2009; Godfray et al., 2010; Olesen et al., 2011; Elsgaard et al., 2012; Lobell et al., 2013). China produces more than 20% of global annual

maize and is the second consumer of maize in the world. Hence, the impacts of climate change on maize production in this country have global effects.

Extensive studies document that temperature has increased significantly whereas precipitation trends have been smaller during crop growing season since 1980 at broad regions of the world (Lobell et al., 2011), including China (Tao et al., 2012; Zhang et al., 2015). Increases in mean temperature, extreme high temperature (above 30 °C) stress and drought stress have been indicated to be the major challenges for maize productivity in the face of climate change (Bolanos and Edmeades, 1996; Crafts-Brandner and Salvucci, 2002; IPCC, 2014; Battisti and Naylor, 2009; Lobell et al., 2011b, 2013; Olesen et al., 2011; Tao et al., 2012). Increase in mean temperature can reduce crop growth period and subsequently reduce grain yield (IPCC, 2014). Extreme high temperature stress can desiccate pollen and increase kernel abortion during flowering (Bolanos and Edmeades, 1996; Rattalino Edreira et al., 2011), reduce net photosynthesis rates (Crafts-Brandner and Salvucci, 2002), increase vapor pressure deficit and aggravate drought stress

* Corresponding author.

E-mail address: taofl@igsrr.ac.cn (F. Tao).

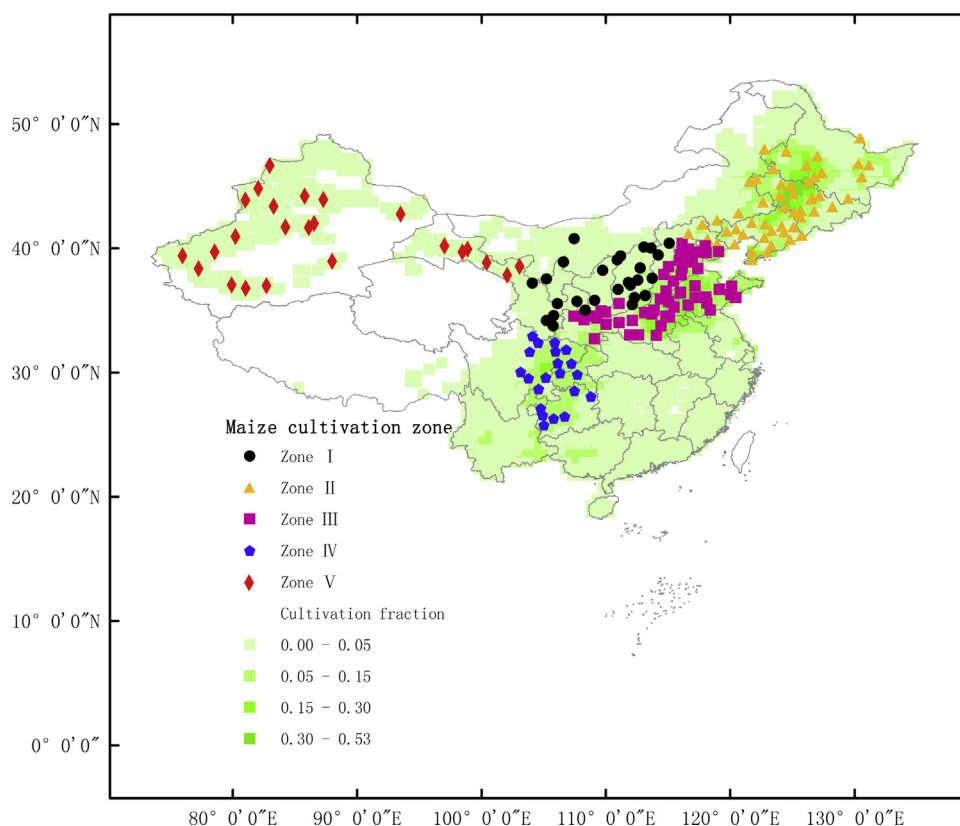


Fig. 1. Maize production zones of China. Each symbol represents the agricultural meteorological stations used in the study. The different intensity of green color indicates the contribution of each zone (in cultivation fraction) to maize production in China. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

(Lobell et al., 2013). The latter mechanism has been indicated to play an important role in affecting maize productivity in some regions of U.S. (Lobell et al., 2013), Africa (Lobell et al., 2011b) and China (Tao et al., 2012) in the past decades.

Nevertheless, the mechanisms, extent and degree of climate impacts on crop growth and productivity under contrasting environments and climate conditions are still imperfectly understood (Lobell et al., 2011b, 2013; Butler and Huybers, 2013; Licker et al., 2013). This particularly applies to the continuous adjustments and adaptations of farmers to climate change such as shifts of sowing dates and cultivars (Welch et al., 2010; Siebert and Ewert, 2012, 2014; Tao et al., 2014a). Crop models and statistical approaches are commonly used to address climate impacts on crop growth and grain yield, both of which, however, have some shortcomings. Crop models do not include potentially relevant processes such as impacts of extremely high temperatures (Lobell and Burke, 2009; Tao et al., 2009; Rötter et al., 2011; Asseng et al., 2013; Ruane et al., 2013; Bassu et al., 2014). Statistical approaches are frequently limited by the quantity and quality of data (Lobell and Burke, 2009). Furthermore, most statistical studies assess climate change and its potential impacts by correlating crop yields at a state or nation from census data with seasonal climate for the same calendar period throughout the whole time series without accounting for the dynamics of cropping systems (i.e., changes of agronomic management practices) (Reidsma et al., 2010; Welch et al., 2010; Tao et al., 2014a). In fact, many farmers select crop cultivars, shift sowing dates and agronomic practices based on the expected meteorological conditions (Tao et al., 2014b). The actual impacts of climate change and variability are largely dependent on farm level response, to accurately understand impacts and adaptation, assessments should consider responses at different levels of organization (Reidsma et al., 2010; Welch et al., 2010).

Historical data from farmer-managed fields would allow us to establish how farmers made changes of agricultural practices based on the weather they observed (Welch et al., 2010; Tao et al., 2014a). In the present study, field observations at 167 agricultural meteorological stations across China (Fig. 1, Table 1) spanning from 1981 to 2009 were used to quantify maize grain yield response considering changes of maize husbandry at different regions of China in the past three decades. We aim to quantify (1) changes of maize phenology and growth durations under the combined effects of climate change, cultivar shifts and sowing dates; (2) climate change during the observed maize growth period; (3) the impacts of climate change on maize yield at different production zones of China accounting for the adaptations (Fig. 1). We try to quantify climate impacts on crop growth and yield under the interactions between climate warming and crop system dynamics, instead of climate warming per se or climate warming impacts without adaptations.

2. Materials and methods

2.1. Experimental stations and data

Experimental observations data on maize cultivars, phenology, yields and management practices during 1981–2009 were from China agricultural meteorological experiment stations, which were maintained by China Meteorological Administration (CMA). There were total 167 geographically and climatologically different agricultural meteorological experiment stations across the major maize production regions (Fig. 1). Based on the maize cultivation zones in China (Tong, 1992), the agricultural meteorological stations were grouped into five zones, i.e., Zone I, Zone II, Zone III, Zone IV, and Zone V (Fig. 1). The information of the dominant cropping system, typical sowing date and maturity date at each zone was presented

Table 1

The dominant cropping system, typical sowing date and maturity date at each maize production zone of China in the last years.

Zones	Abbreviation	Dominant cropping system	Sowing date	Maturity date
Zone I	Zone I.SP	Spring maize	April 20th	September 15th
Zone II	Zone II.SP	Spring maize or rice	April 30th	September 20th
Zone III	Zone III.S	Rotation between summer maize and winter wheat	June 10th	September 20th
Zone IV	Zone IV.SP	Spring maize	March 30th	August 1st
	Zone IV.S	Rotation between spring cereals and summer maize	May 15th	September 10th
Zone V	Zone V.SP	Spring maize	April 25th	September 20th
	Zone V.S	Rotation between winter wheat and summer maize	June 30th	October 5th

Table 2Mean values of air temperature (T_{mean}), maximum temperature (T_{max}), minimum temperature (T_{min}), daily solar radiation (SRD), and precipitation during the vegetative (VGP), reproductive (RGP) and the whole growth period (GPw) at each maize production zone during 1981–2009. Mean grain yield and grain yield trend along this period is also included.

Zone	Period	Mean Yield(kg/ha)	Yield trend (kg/ha/year)	T_{mean} (°C)	T_{max} (°C)	T_{min} (°C)	Precipitation (mm)	SRD (MJ/m ² /day)
Zone I.SP	VGP			21.26	27.88	15.15	165.81	19.43
	RGP			21.28	27.41	16.32	165.66	16.74
	GPw	6242.13	125.56	21.22	27.63	15.60	328.68	18.26
Zone II.SP	VGP			20.92	26.49	15.63	239.15	19.12
	RGP			20.55	26.14	15.66	195.60	16.47
	GPw	6420.10	164.38	20.70	26.29	15.58	430.02	17.94
Zone III.S	VGP			26.02	31.04	21.75	241.66	16.99
	RGP			23.56	28.65	19.48	150.48	15.17
	GPw	5249.92	109.58	24.86	29.92	20.67	388.18	16.17
Zone IV.SP	VGP			21.23	25.93	17.83	342.24	12.07
	RGP			25.74	30.40	22.43	285.43	13.57
	GPw	4818.59	12.74	22.86	27.54	19.49	624.08	12.61
Zone IV.S	VGP			22.91	27.58	19.59	425.46	14.03
	RGP			23.54	28.35	20.27	296.15	14.88
	GPw	4349.41	85.19	23.13	27.85	19.83	715.22	14.33
Zone V.SP	VGP			22.19	29.57	14.93	42.58	23.32
	RGP			21.87	29.72	14.75	28.64	20.70
	GPw	6931.92	243.07	22.02	29.61	14.82	70.71	22.19
Zone V.S	VGP			25.90	33.24	18.78	13.86	21.70
	RGP			20.43	28.50	12.95	6.39	18.24
	GPw	3711.82	161.37	23.18	30.88	15.90	20.18	20.00

in Table 1. The dominant cropping system in Zone I was spring maize (thereafter, Zone I.SP), in Zone II was spring maize (thereafter, Zone II.SP) or rice, in Zone III was rotation between summer maize (thereafter, Zone III.S) and winter wheat, in Zone IV was spring wheat (thereafter, Zone IV.SP) or rotation between spring cereals and summer maize (thereafter, Zone IV.S), in Zone V was spring maize (thereafter, Zone V.SP) or rotation between winter wheat and summer maize (thereafter, Zone V.S). The general information of maize yields and climate during growth period at each zone was presented in Table 2. There were 24, 50, 48, 11, 9, 18 and 7 agricultural meteorological experiment stations for Zone I.SP, Zone II.SP, Zone III.S, Zone IV.SP, Zone IV.S, Zone V.SP and Zone V.S, respectively.

Daily mean temperature (T_{mean}), maximum temperature (T_{max}), minimum temperature (T_{min}), solar radiation (SRD), precipitation and sunshine duration at the agricultural meteorological stations from 1981 to 2009 were also obtained from CMA. SRD was estimated using sunshine duration observation and the Angstrom–Prescott equation (Prescott, 1940) when SRD was not recorded. There was very few missing data in the daily weather data series, which were filled using the corresponding values at the nearest neighboring station.

2.2. Methods

Station-specific analyses showed that crop phenology and grain yields, as well as their responses to climate change, were relatively

heterogeneous across the stations within a zone. Statistical models that relied on information from multiple stations, namely panel models, were documented to be better at predicting crop responses to temperature change than time-series statistical models at each station (Lobell and Burke, 2009). Therefore, the 24, 50, 48, 11, 9, 18 and 7 stations for Zone I.SP, Zone II.SP, Zone III.S, Zone IV.SP, Zone IV.S, Zone V.SP and Zone V.S were combined to conduct a panel analysis for each zone, respectively.

Across the stations for Zone I.SP, Zone II.SP, Zone III.S, Zone IV.SP, Zone IV.S, Zone V.SP and Zone V.S, respectively, time trends in sowing dates, anthesis dates, maturity dates (expressed in Julian days) and yields during 1981–2009 were analyzed using the linear regression method. Likewise, time trends in T_{mean} , T_{max} , T_{min} , SRD and precipitation during maize vegetative growth period (VGP, from sowing to anthesis), reproductive growth period (RGP, from anthesis to maturity), and whole growth period (GPw, from sowing to maturity) were analyzed. Seasonal mean T_{mean} , T_{max} , T_{min} , SRD , precipitation and crop growing degree days (GDD) during VGP, RGP and GPw in each year at each station were computed based on the observed records of sowing, anthesis and maturity dates, which accelerated careful matching of weather variables with farm-specific planting and harvesting dates and crop-growth phases. By this way, the adaptation options such as the shifts of sowing, anthesis, maturity date, and cultivars were implicitly taken into account in the analyses. GDD during a growth period was calculated from hourly temperature obtained by fitting a sine curve to daily T_{max} and T_{min} as done in some previous studies (Jones et al.,

2003), with the cardinal base temperature, optimum temperature and maximum temperature of 8 °C, 30 °C and 34 °C, respectively.

To investigate the correlations between annual yields with climate variables during VGP, RGP and GPw across the stations for Zone I.SP, Zone II.SP, Zone III.S, Zone IV.SP, Zone IV.S, Zone V.SP and Zone V.S, respectively, the yields were firstly linearly de-trended to get the de-trended yield series that were mainly affected by seasonal climate variability. Then the climate variables were also linearly de-trended, and the partial correlation analysis was applied to investigate the correlation between the de-trended yields series (residuals) and the de-trended climate variables series (residuals) during 1981–2009. Statistical significance was tested using the two-tailed *t*-test.

There was no single regression model that performed best for all the zones. As in Tao et al. (2014a), to avoid the confounding effects of highly correlated climate variables, four panel regression models with different predictors were estimated for Zone I.SP, Zone II.SP, Zone III.S, Zone IV.SP, Zone IV.S, Zone V.SP and Zone V.S, respectively, to quantify the uncertainties in estimating yield sensitivity to each of three climate variable, i.e., T_{mean} , precipitation and *SRD* (total seven panel regression models for each growth period at each zone). The Huber–White robust standard errors clustered by station were conducted, which showed the error term in the regression model was identically and independently distributed. For GPw, the seven panel regression models as follows were estimated:

$$Yd_{i,t} = \beta_{i,0} + \beta_1 t + \beta_2 \Delta T_{\text{mean},i,t} + \epsilon_{i,t} \quad (1)$$

$$Yd_{i,t} = \beta_{i,0} + \beta_1 t + \beta_2 \Delta T_{\text{mean},i,t} + \beta_3 \Delta P_{i,t} + \epsilon_{i,t} \quad (2)$$

$$Yd_{i,t} = \beta_{i,0} + \beta_1 t + \beta_2 \Delta T_{\text{mean},i,t} + \beta_4 \Delta SRD_{i,t} + \epsilon_{i,t} \quad (3)$$

$$Yd_{i,t} = \beta_{i,0} + \beta_1 t + \beta_2 \Delta T_{\text{mean},i,t} + \beta_3 \Delta P_{i,t} + \beta_4 \Delta SRD_{i,t} + \epsilon_{i,t} \quad (4)$$

$$Yd_{i,t} = \beta_{i,0} + \beta_1 t + \beta_3 \Delta P_{i,t} + \epsilon_{i,t} \quad (5)$$

$$Yd_{i,t} = \beta_{i,0} + \beta_1 t + \beta_3 \Delta P_{i,t} + \beta_4 \Delta SRD_{i,t} + \epsilon_{i,t} \quad (6)$$

$$Yd_{i,t} = \beta_{i,0} + \beta_1 t + \beta_4 \Delta SRD_{i,t} + \epsilon_{i,t} \quad (7)$$

where $Yd_{i,t}$ is annual yield observations at station *i* in year *t*, $\beta_{i,0}$ represents an intercept, for each station *i*. β_1 represents the linear time trend of observed yields mainly due to the long-term climatic and no-climatic trends including improvements in varieties, technology, management and policy during the study period. β_{1-4} are model parameters to be fit, and $\epsilon_{i,t}$ is an error term. $\Delta T_{\text{mean},i,t}$, $\Delta P_{i,t}$ and $\Delta SRD_{i,t}$ represents the linearly de-trended growing season average for T_{mean} , precipitation and *SRD*, respectively, at station *i* in year *t*.

Among the seven panel regression models, Eqs. (1)–(4) were used to quantify yield sensitivity to T_{mean} . Eqs. (5), (2), (6) and (4), were used to quantify yield sensitivity to precipitation. And Eqs. (7), (3), (6) and (4) were used to quantify yield sensitivity to *SRD*. The parameter β_2 represents yield sensitivity to T_{mean} during GPw. Likewise, the parameter β_3 represents yield sensitivity to precipitation during GPw. And the parameter β_4 represents yield sensitivity to *SRD* during GPw.

Likewise, for VGP and RGP together, total seven panel regression models as follows were estimated:

$$Yd_{i,t} = \beta_{i,0} + \beta_1 t + \beta_2 \Delta T_{\text{mean},i,t,\text{VGP}} + \beta_5 \Delta T_{\text{mean},i,t,\text{RGP}} + \epsilon_{i,t} \quad (8)$$

$$Yd_{i,t} = \beta_{i,0} + \beta_1 t + \beta_2 \Delta T_{\text{mean},i,t,\text{VGP}} + \beta_3 \Delta P_{i,t,\text{VGP}} + \beta_5 \Delta T_{\text{mean},i,t,\text{RGP}} + \beta_6 \Delta P_{i,t,\text{RGP}} + \epsilon_{i,t} \quad (9)$$

$$Yd_{i,t} = \beta_{i,0} + \beta_1 t + \beta_2 \Delta T_{\text{mean},i,t,\text{VGP}} + \beta_4 \Delta SRD_{i,t,\text{VGP}} + \beta_5 \Delta T_{\text{mean},i,t,\text{RGP}} + \beta_7 \Delta SRD_{i,t,\text{RGP}} + \epsilon_{i,t} \quad (10)$$

$$Yd_{i,t} = \beta_{i,0} + \beta_1 t + \beta_2 \Delta T_{\text{mean},i,t,\text{VGP}} + \beta_3 \Delta P_{i,t,\text{VGP}} + \beta_4 \Delta SRD_{i,t,\text{VGP}} + \beta_5 \Delta T_{\text{mean},i,t,\text{RGP}} + \beta_6 \Delta P_{i,t,\text{RGP}} + \beta_7 \Delta SRD_{i,t,\text{RGP}} + \epsilon_{i,t} \quad (11)$$

$$Yd_{i,t} = \beta_{i,0} + \beta_1 t + \beta_3 \Delta P_{i,t,\text{VGP}} + \beta_6 \Delta P_{i,t,\text{RGP}} + \epsilon_{i,t} \quad (12)$$

$$Yd_{i,t} = \beta_{i,0} + \beta_1 t + \beta_3 \Delta P_{i,t,\text{VGP}} + \beta_4 \Delta SRD_{i,t,\text{VGP}} + \beta_6 \Delta P_{i,t,\text{RGP}} + \beta_7 \Delta SRD_{i,t,\text{RGP}} + \epsilon_{i,t} \quad (13)$$

$$Yd_{i,t} = \beta_{i,0} + \beta_1 t + \beta_4 \Delta SRD_{i,t,\text{VGP}} + \beta_7 \Delta SRD_{i,t,\text{RGP}} + \epsilon_{i,t} \quad (14)$$

where $Yd_{i,t}$, $\beta_{i,0}$ and β_1 are the same as in Eq. (1); β_{2-4} and β_{5-7} are model parameters to be fit for VGP and RGP, respectively. $\Delta T_{\text{mean},i,t,\text{VGP}}$, $\Delta P_{i,t,\text{VGP}}$ and $\Delta SRD_{i,t,\text{VGP}}$ represents the linearly de-trended growing season average for T_{mean} , precipitation and *SRD* during VGP, respectively, at station *i* in year *t*. $\Delta T_{\text{mean},i,t,\text{RGP}}$, $\Delta P_{i,t,\text{RGP}}$ and $\Delta SRD_{i,t,\text{RGP}}$ represents the linearly de-trended growing season average for T_{mean} , precipitation and *SRD* during RGP, respectively, at station *i* in year *t*.

Among the seven models, Eqs. (8)–(11) were used to quantify yield sensitivity to T_{mean} . Eqs. (12), (9), (13) and (11) were used to quantify yield sensitivity to precipitation. And Eqs. (14), (10), (13) and (11) were used to quantify yield sensitivity to *SRD*. The parameters β_2 and β_5 represent yield sensitivity to T_{mean} during VGP and RGP, respectively. The parameters β_3 and β_6 represent yield sensitivity to precipitation during VGP and RGP, respectively. The parameters β_4 and β_7 represent yield sensitivity to *SRD* during VGP and RGP, respectively.

The Durbin–Watson statistic was conducted to test the null hypothesis that the residuals from an ordinary least-squares regression are not autocorrelated (Table S1). A set of model parameters for each panel model was estimated using multiple regression method, based on the field observations on yield and climate from 1981 to 2009, across all the stations for Zone I.SP, Zone II.SP, Zone III.S, Zone IV.SP, Zone IV.S, Zone V.SP and Zone V.S, respectively. The estimates of model parameters (i.e., β_{1-7}), expressed in percentage of average yield across these stations, represented the common sensitivity of yield change to T_{mean} , precipitation and *SRD* change, respectively, across these stations and during the growth period. The impact of change in a climate variable (i.e., T_{mean} , precipitation and *SRD*) on crop yields during 1981–2009 (expressed as a percentage of mean yield) was estimated by multiplying the sensitivity of yield change to the climate variable (expressed as a percentage of mean yield) with the magnitude of change in the climate variable across these stations during the study period. The later was estimated by a linear trend. The joint impacts of climate change on crop yields during 1981–2009 (expressed in percentage of mean yield) were computed by summing the impacts of changes in T_{mean} , precipitation and *SRD* on crop yields during the study period. The climate-related changes in the crop yield were compared with the actual mean yield across the stations during the study period.

3. Results

3.1. Climate change during maize growth period in the past three decades

During 1981–2009, climate change during maize growth period showed a spatially explicit pattern across the major maize production zones in China (Fig. 2). T_{mean} increased significantly during

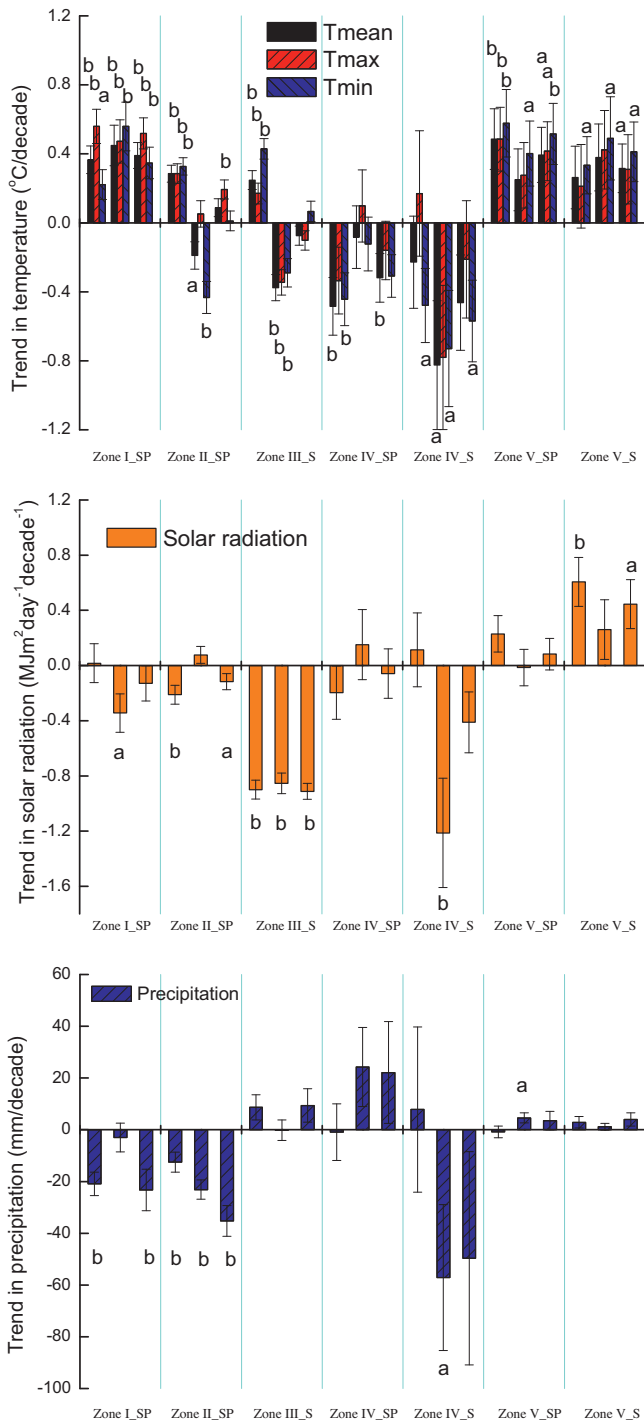


Fig. 2. Trends in mean temperature, solar radiation and precipitation during VGP (left), RGP (middle) and GPw (right) of maize during 1981–2009 at each maize production zone of China. The trends with a mark 'a' are significant at 0.05 level, and with a mark 'b' are significant at 0.01 level. The error bars represent the standard deviations of the means.

VGP, RGP and GPw for Zone I.SP, Zone V.SP and Zone V.S, and during VGP of Zone II.SP and Zone III.S. In contrast, it decreased significantly during RGP of Zone II.SP, Zone III.S, Zone IV.SP and Zone IV.S. Generally T_{max} and T_{min} had the same trends as T_{mean} during each growth period at each zone. SRD decreased significantly during VGP, RGP and GPw of Zone III.S, during VGP of Zone II.SP, and during RGP of Zone I.SP and Zone IV.S. In contrast, it increased significantly during VGP and GPw of Zone V.S. Precipitation decreased

significantly during GPw of Zone I.SP, Zone II.SP and Zone IV.S, in contrast increased significantly during GPw of Zone V.SP (Fig. 2).

3.2. Changes in phenological dates and the durations of maize growth periods in relation to air temperature

During 1981–2009, maize sowing date, anthesis date and maturity date were all significantly advanced for Zone I.SP, in contrast significantly delayed for Zone III.S (Table 3). Sowing date was significantly delayed, while anthesis date was significantly advanced for Zone V.SP. Duration of VGP was shortened significantly for Zone III.S, Zone IV.SP and Zone V.SP, in contrast duration of RGP was significantly prolonged for Zone II.SP, Zone III.S, and Zone V.SP. Finally, duration of GPw increased significantly for Zone II.SP, Zone III.S and Zone IV.S (Table 3). The GDD during VGP, RGP and GPw generally increased except for Zone IV.SP. Durations of VGP, RGP and GPw were negatively correlated to T_{mean} in all the zones except the VGP and GPw of Zone IV.SP (Table 4).

3.3. Correlations between changes in yields and climate during each growth period

Yield was generally positively correlated to T_{mean} in all the zones except Zone IV.SP and Zone V.SP, where yield was negatively correlated to T_{mean} during RGP and VGP, respectively (Table 5). The correlations between yields and T_{max} , as well as between yields and T_{min} , were generally same as those between yields and T_{mean} at each zone. Yield was also significantly positively correlated to SRD at all the zones except Zone I.SP and Zone II.SP (Table 5), where yield was significantly positively correlated to T_{mean} and precipitation during RGP and GPw (Table 5).

3.4. Sensitivity of yield change to climate variables during maize growth period

The estimates on sensitivity of yield change to climate variables using four different models were generally comparable; suggesting the methods and estimates were generally sound (e.g., not affected much by the potential collinearity among climate variables). Yield response of spring maize crops to T_{mean} and SRD during VGP and RGP in Zone I.SP (Fig. 3a) was similar to those of Zone II.SP (Fig. 3b) and Zone V.SP (Fig. 3f). By contrast yield response to these meteorological conditions of Zone IV.SP (Fig. 3d) was opposite to those of mentioned zones. For summer maize crops such as those of Zone III.S (Fig. 3c), Zone IV.S (Fig. 3e) and Zone V.S (Fig. 3g), changes of climate variable during RGP had the highest impact of yield variations. Yield for Zone I.SP increased by 2.2% (2.0%) for each 1 °C increase in T_{mean} , and by 1.0% (1.1%) if precipitation increased by 10% during RGP (GPw) (Fig. 3a). Yield for Zone II.SP increased by 2.7% (3.1%) for each 1 °C increase in T_{mean} during RGP (GPw) (Fig. 3b). For Zone III.S, yield was most sensitive to T_{mean} and SRD during RGP (Fig. 3c), which increased by 2.0% (2.1%) for each 1 °C increase in T_{mean} , and by 3.9% (4.2%) if SRD increased by 10% during RGP (GPw) (Fig. 3c). For Zone IV.SP, yield increased by 0.9% for each 1 °C increase in T_{mean} , and by 4.6% if SRD increased by 10% during GPw; however decreased by 5.5% for each 1 °C increase in T_{mean} during RGP (Fig. 3d). For Zone IV.S, yield increased by 1.6% (2.2%) for each 1 °C increase in T_{mean} , and by 6.4% (11.1%) if SRD increased by 10% during RGP (GPw) (Fig. 3e). For Zone V.SP, yield increased by 4.1% (decreased by 2.1%) for each 1 °C increase in T_{mean} , however increased by 11.9% (11.4%) if SRD increased by 10% during RGP (GPw) (Fig. 3f). For Zone V.S, yield was most sensitive to T_{mean} during RGP, which increased by 7.0% (7.4%) for each 1 °C increase in T_{mean} , and by 0.7% (9.8%) if SRD increased by 10% during RGP (GPw) (Fig. 3g).

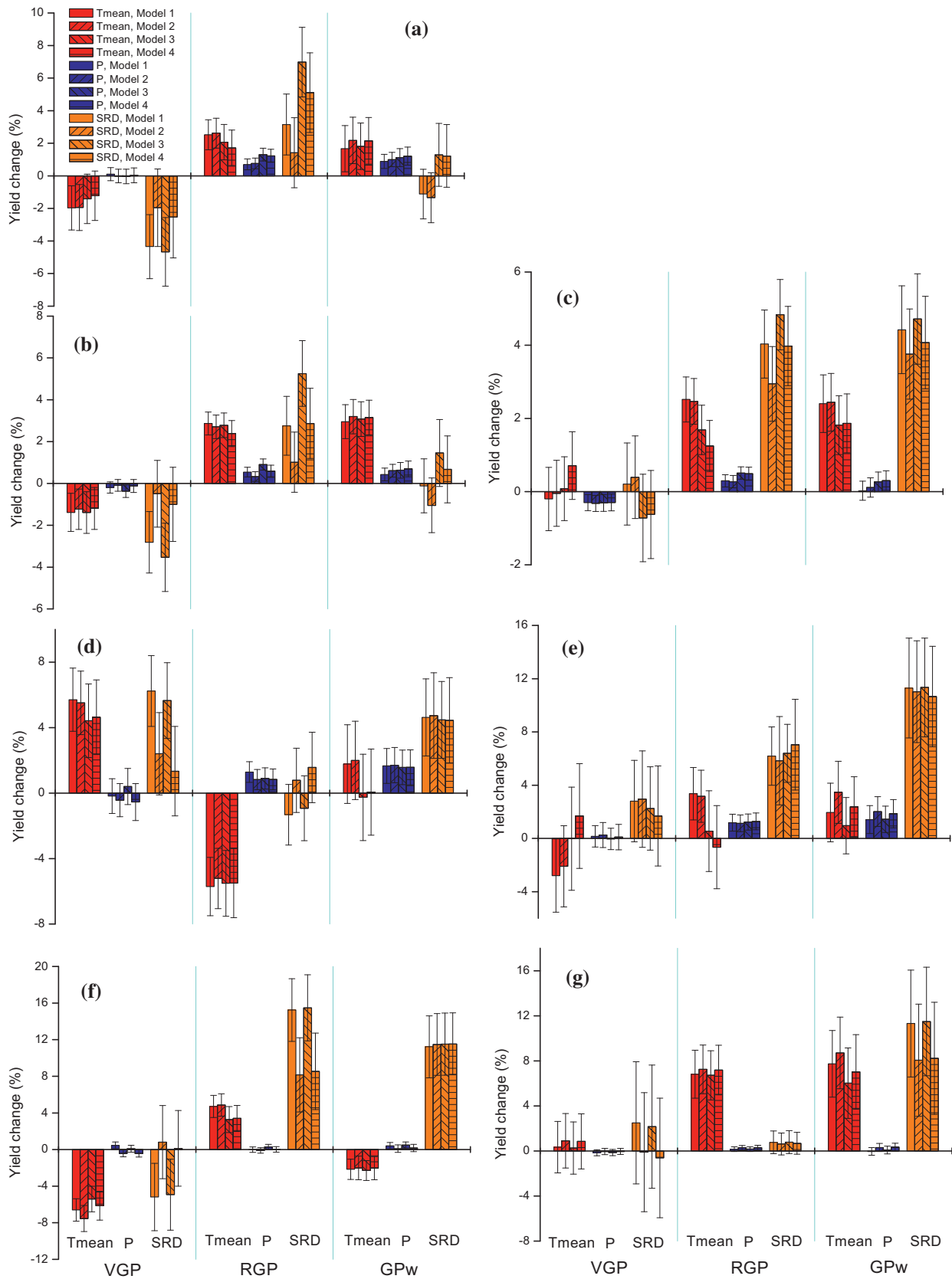


Fig. 3. Estimated maize yield changes by four panel models for each 1 °C increase in T_{mean} (red), 10% increase in precipitation (P) (blue), and 10% increase in SRD (orange) during VGP, RGP and GPw, respectively, for zone I.SP (a), zone II.SP (b), zone III.S (c), zone IV.SP (d), zone IV.S (e), zone V.SP (f), zone V.S (g). The error bars represent the standard deviations of the means. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 3

Trends in maize sowing, anthesis and maturity date, the durations of VGP, RGP and GPw (expressed in days and degree days) during 1981–2009, at each maize production zone of China. The trends with ‘*’ and ‘***’ are significant at the 0.05 and 0.01 level, respectively.

	Zone I.SP	Zone II.SP	Zone III.S	Zone IV.SP	Zone IV.S	Zone V.SP	Zone V.S
Sowing date (days/decade)	-1.73**	0.16	2.12**	-0.20	-1.72	1.92*	-1.68
Anthesis date (days/decade)	-1.53**	0.24	1.30**	-2.59	1.93	-1.43*	-1.07
Maturity date (days/decade)	-1.81**	3.58**	3.92**	-1.81	4.48	0.58	0.29
VGP duration (days/decade)	0.20	0.08	-0.82**	-2.40*	3.64**	-3.35**	0.62
RGP duration (days/decade)	-0.28	3.34**	2.63**	0.79	2.55	2.01**	1.35
GPw duration (days/decade)	-0.08	3.42**	1.80**	-1.61	6.19**	-1.35	1.97
VGP.GDD (degree days/decade)	22.12**	21.81**	5.94*	-22.18	26.55*	6.04	25.49**
RGP.GDD(degree days/decade)	18.10**	15.66**	13.66**	8.48	-0.23	27.86**	21.17**
GPw.GDD(degree days/decade)	39.88**	37.46**	19.56**	-13.39	26.56*	33.80**	46.57**

Table 4

Correlations between durations of VGP, RGP, GPw and T_{mean} , as well as between the durations of VGP, RGP, GPw and yields, at each maize production zone of China. The correlations with ‘*’ and ‘***’ are significant at the 0.05 and 0.01 level, respectively.

	Zone I.SP	Zone II.SP	Zone III.S	Zone IV.SP	Zone IV.S	Zone V.SP	Zone V.S
Duration of VGP & T_{mean}	-0.32**	-0.22**	-0.37**	0.13	-0.44**	-0.57**	-0.21*
Duration of RGP & T_{mean}	-0.41**	-0.37**	-0.44**	-0.39**	-0.71**	-0.32**	-0.47**
Duration of GPw & T_{mean}	-0.41**	-0.28**	-0.41**	0.10	-0.77**	-0.67**	-0.34**
Duration of VGP & yield	-0.14**	0.01	-0.12**	0.29**	0.02	-0.16**	-0.04
Duration of RGP & yield	0.05	0.25**	0.26**	0.37**	0.19	0.27**	0.08
Duration of GPw & yield	-0.07	0.17**	0.08*	0.41**	0.14	0.00	0.03

3.5. Impacts of climate change over maize growth period on yields during 1981–2009

Climate change over maize growth period during 1981–2009 had caused measurable impacts on maize yields. For Zone I.SP, increase in T_{mean} had negative impacts on yields during VGP but had positive impacts during RGP (Fig. 4a). Decreases in SRD and precipitation had negative effects on yield formation during RGP. Yields increased by 2.5% due to increase in T_{mean} , however decreased by 2.5% due to decrease in precipitation, during GPw. For Zone II.SP, yields decreased due to decreases in T_{mean} and precipitation during RGP, however increased due to increase in SRD (Fig. 4b). Finally changes in T_{mean} , precipitation and SRD jointly had only small impacts on maize yields for Zone I.SP and Zone II.SP during 1981–2009 (Fig. 5).

For Zone III.S, decreases in T_{mean} and SRD during RGP reduced yields by 2.5% and 7%, respectively (Fig. 4c). Decreases in T_{mean} and SRD, and small change in precipitation, during RGP, jointly reduced maize yields by 8% (Fig. 5).

For Zone IV.SP, decreases in T_{mean} and SRD had negative impacts on yields during VGP and GPw, however increase in precipitation

had slight positive impacts during RGP and GPw (Fig. 4d). Decreases in T_{mean} and SRD, together with increase in precipitation, jointly had negative impacts on yields during VGP, positive impacts during RGP, and eventually the impacts were almost balanced out during GPw (Fig. 5). For Zone IV.S, decreases in T_{mean} , precipitation and SRD during RGP reduced yields by 7%, 6% and 15%, respectively (Fig. 4e). Decreases in T_{mean} , precipitation and SRD jointly reduced yields by 25% and 15% during RGP and GPw, respectively (Fig. 5).

For Zone V.SP, increase in T_{mean} had negative impacts on yields during VGP; however had positive impacts during RGP. Yield decreased by 2% due to increase in T_{mean} , however increased slightly due to increases in precipitation and SRD during GPw (Fig. 4f). Increases in T_{mean} , precipitation and SRD jointly had negative impacts on yields during VGP, positive impacts during RGP, and the impacts were eventually balanced out during GPw (Fig. 5). For Zone V.S, increases in T_{mean} and SRD during GPw increased yields by 7% and 7%, respectively (Fig. 4g). Increases in T_{mean} , precipitation and SRD jointly increased yields by 9% and 15% during RGP and GPw, respectively (Fig. 5).

Table 5

Correlations between yield and T_{mean} , T_{max} , T_{min} , precipitation, SRD during VGP, RGP, GPw at each maize production zone of China. The correlations with ‘*’ and ‘***’ are significant at the 0.05 and 0.01 level, respectively.

Growing period	climate variables	Zone I.SP	Zone II.SP	Zone III.S	Zone IV.SP	Zone IV.S	Zone V.SP	Zone V.S
VGP	T_{mean}	-0.042	0.004	0.050	0.216**	-0.007	-0.222**	0.046
	T_{max}	-0.042	0.043	0.035	0.202*	-0.047	-0.225**	0.053
	T_{min}	-0.065	-0.012	0.022	0.222*	0.060	-0.231**	0.077
	Precipitation	0.046	-0.003	-0.041	0.002	0.016	0.084	-0.066
	SRD	-0.067	-0.031	0.055	0.247**	0.089	0.109	0.059
RGP	T_{mean}	0.124*	0.150**	0.146**	-0.241**	0.164	0.043	0.306**
	T_{max}	0.100*	0.159**	0.138**	-0.193*	0.133	0.023	0.273**
	T_{min}	0.115*	0.145**	0.121**	-0.262**	0.187	-0.023	0.250**
	Precipitation	0.115*	0.067*	0.056	0.183*	0.222	0.037	0.064
	SRD	0.025	0.030	0.155**	0.017	0.320**	0.274**	0.110
GPw	T_{mean}	0.060	0.109**	0.103**	0.067	0.106	-0.120	0.253**
	T_{max}	0.033	0.125**	0.091**	0.074	0.059	-0.128*	0.198*
	T_{min}	0.046	0.100**	0.072*	0.076	0.157	-0.158*	0.218*
	Precipitation	0.103*	0.042	0.003	0.140	0.343**	0.073	-0.023
	SRD	-0.037	-0.005	0.124**	0.176	0.208	0.200**	0.226*

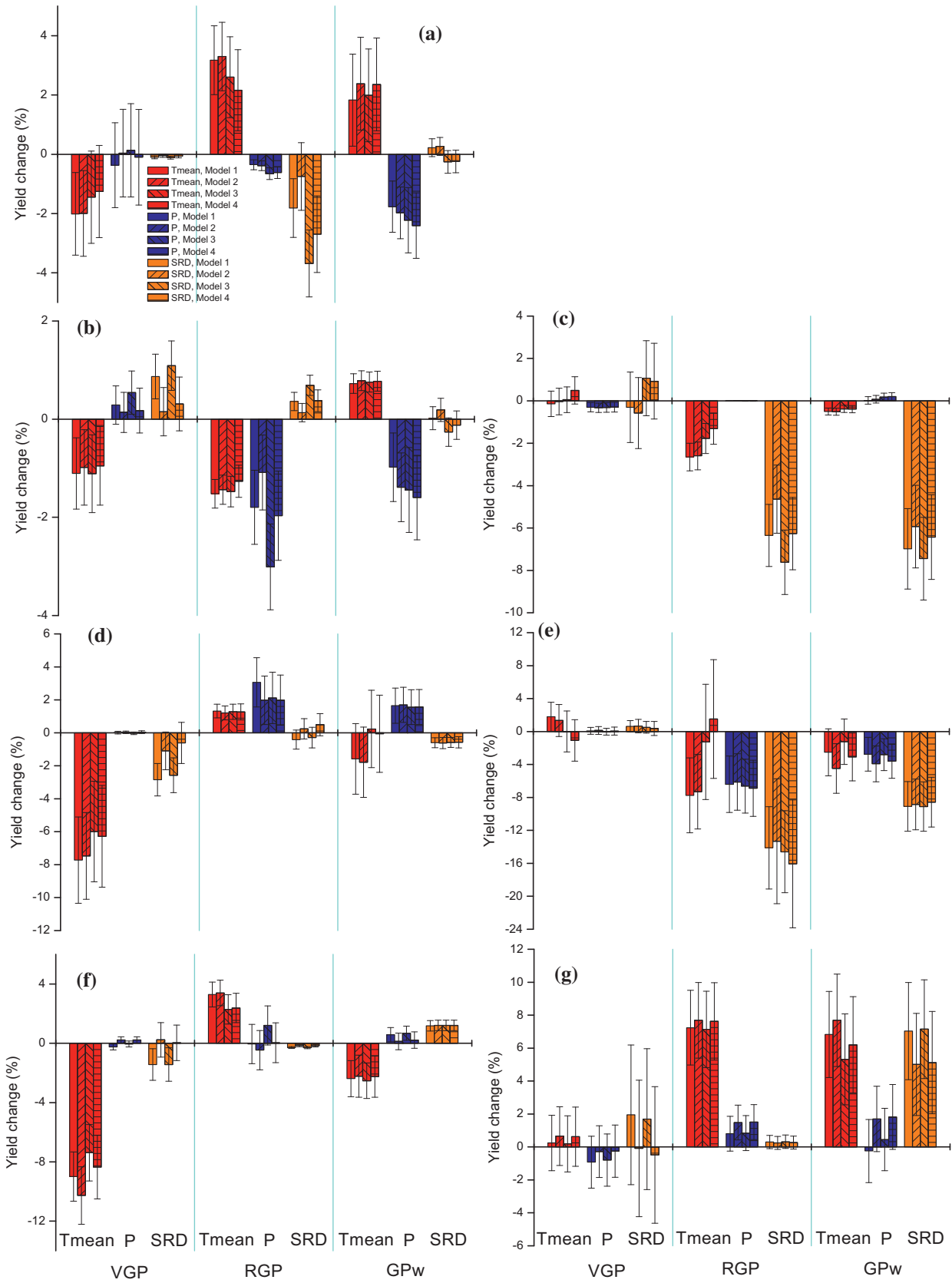


Fig. 4. Estimated maize yield changes by four panel models due to changes in T_{mean} (red), precipitation (P) (blue), and SRD (orange) during VGP, RGP and GPw between 1981 and 2009, respectively, for zone I.SP (a), zone II.SP (b), zone III.S (c), zone IV P (d), zone V.S (e), zone V.SP (f), zone V.S (g). The error bars represent the standard deviations of the means. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

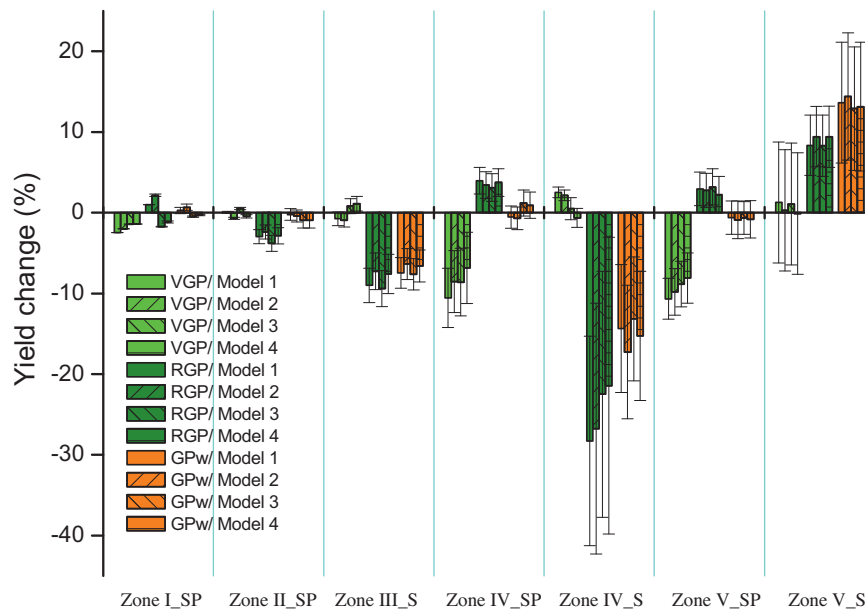


Fig. 5. Estimated maize yield changes by four panel models due to joint changes in T_{mean} , precipitation, and solar radiation during VGP, RGP and GPw between 1981 and 2009, respectively, at each maize production zone of China. The error bars represent the standard deviations of the means.

4. Discussions

4.1. Spatial patterns of climate impacts on maize yield during 1981–2009

Mean temperature during maize growth period in the major maize production regions of China generally lies within the optimum temperature range (18–25 °C; Muchow et al., 1990) for maize growth and yield (Table 2). Hence maize yields were generally positively correlated to T_{mean} in most of these zones, as was observed for maize regions of US (Schlenker and Roberts, 2009). Nevertheless, temperature was above the optimum range in some zones. For example, T_{mean} and T_{max} during RGP of Zone IV.SP were 25.74 °C and 30.40 °C, respectively, above the optimum temperature range for reproductive yield. High temperature and drought stress during RGP were the major challenges for maize productivity for Zone IV.SP (Hu, 1993), hence maize yield was negatively correlated to T_{mean} and T_{max} . Due to advancement of phenological dates for Zone IV.SP (Table 3), T_{mean} during RGP decreased during 1981–2009 (Fig. 2), which reduced the negative impacts of temperature to some extent. In addition, the negative correlation between maize yield and temperature during VGP of Zone V.SP can be ascribed to increasing temperature-induced drought stress, considered that the little precipitation and the positive correlation between yield and precipitation in the zone.

The impacts of climate change on maize yields in China showed a spatially explicit pattern. The yields of Zone IV.S and Zone III.S were most negatively affected due to the significant decreasing trends in T_{mean} and SRD during growth period. By contrast, the yields of Zone V.S were most positively affected because of maturity date changed little and both T_{mean} and SRD during growth period had increased during 1981–2009. The Zone I.SP experienced the highest increase in temperature and less human intervention, as a result, maize sowing dates, anthesis dates and maturity dates of Zone I.SP were most affected by climate change. In comparisons with spring maize, changes of climate variable during RGP had the highest impact of yield variations for summer maize. This was because summer maize usually had shorter growing durations and later maturity dates than spring maize, and the climate during the RGP of summer maize was crucial however subjected to high variability and frost risk (Zhang et al., 2014).

Differences with previous studies of grain yield response to climatic trends (Lobell et al., 2011a; Tao et al., 2012) could be based on the temporal frame used at each study. In this work changes of sowing date and cultivar along time modified not only the length of growing season, but also the period occupied by maize crops along a year.

4.2. Yield change due to genetic and agronomic management improvements

In the past three decades, maize cultivars were shifted frequently, which contributed notably to yield increase, together with improvement of agronomic management practices (Ci et al., 2011; Chen et al., 2013). Recent genetic improvements in grain yield were primarily due to increased stress tolerance of new hybrids, as well as increased efficiency in grain production by maize plants (Ci et al., 2011). A field experimental study showed that the genetic gain in maize yield in China from 1970s to 2000s averaged 94.7 kg ha⁻¹ per year and 53% of this was attributable to breeding (Ci et al., 2011), and the modern hybrids showed increased tolerance to multiple stresses. Another study showed the potential yield of individual hybrids increased by 118.5 kg ha⁻¹ per year with increasing year of release in northeastern China from 1973 to 2000 (Chen et al., 2013). Modern breeding increased ear fertility and grain-filling rate, and delayed leaf senescence without modification in net photosynthetic rate. Recently, Liu et al. (2013) indicated that earlier sowing dates and introduction of cultivars with higher thermal time requirements in northeastern China had overcome the negative effects of climate change during 1981–2007, through a crop model analyses. These results support our findings that observed yield trend ranged from 12.74 kg ha⁻¹ (0.26%) to 243.07 kg ha⁻¹ (4.3%) per year, with an average of 128.84 kg ha⁻¹ (2.4%) per year, mainly due to cultivars turnover and advance in agronomic management (Table 3).

4.3. Implications for adaptation of maize production to climate change

Maize maturity was delayed, GDD of cultivars increased and durations of RGP and GPw were prolonged mainly due to cultivars turnover (Tao et al., 2014b; Xiao et al., 2015), particularly for Zone

II.SP and Zone III.S. Decrease in T_{mean} during growth period can further extend the duration of RGP to some extent (Fig. 2, Table 4). The duration of RGP was positively related to yield in all the maize cultivation zones, although the duration of VGP was negatively related to yield for Zone I.SP, Zone III.S and Zone V.SP (Table 4). Our results suggest that the late maturing cultivars with higher GDD and longer RGP duration were increasingly adopted to take advantage of increasing photo-thermal resource from climate change, which indeed boosted yield substantially in the past three decades, particularly for Zone II.SP and Zone III.S. The findings are supported by field experiments, which showed grain weight and yield increased by more than 10% if maturity dates were extended by 8–10 days (Li et al., 2008; Lu et al., 2011) because a higher biomass accumulated during the effective grain filling period lead to larger kernel weights and yield. In addition, the delay of anthesis date and maturity date can also reduce the risk of extreme high temperature stress. However, the trade-off associated with delay in maturity was that T_{mean} had a decreasing trend during RGP during 1981–2009, which reduced photosynthesis rate and had a negative impact on yield, particularly for Zone II.SP, Zone III.S and Zone IV.S; and even increased frost risk during RGP for Zone II.SP (Zhang et al., 2014).

The potential yields can be further promoted by selecting suitable sowing date and cultivars to avoid the negative impacts of climate change. For Zone I.SP, yield was negatively correlated to duration of VGP and positively correlated to duration of RGP (Table 4). However duration of VGP was slightly prolonged and duration of RGP was slightly shortened during 1981–2009 partly due to advancement of sowing date and maturity date (Table 3). Therefore, late maturing cultivars with longer growth period, together with late sowing, should be adopted in the zone so that duration of VGP can become shorter and duration of RGP can become longer. For Zone IV.SP, yield was significantly positively correlated to duration of RGP (Table 4), and duration of RGP was prolonged insignificantly during 1981–2009 (Table 3), therefore, late maturing cultivars with longer growth period, together with late sowing, should be adopted in the zone to extend duration of RGP further. For Zone V.SP, yield was negatively correlated to duration of VGP and positively correlated to duration of RGP (Table 4). During 1981–2009, duration of VGP was indeed shortened and RGP was indeed prolonged due to delay of sowing date and maturity date, as well as advancement of anthesis date (Table 3). Early sowing can be an effective adaptation option to reduce the negative impacts of climate warming during VGP. For Zone IV.S and Zone V.S, phenology date was not significantly shifted and yield was not significantly correlated with duration of growth period (Table 4), although duration of growth period was prolonged (Table 3). Climate had relatively large positive impacts on yields in Zone V.S, however, had relatively large negative impacts on yields in Zone IV.S (Fig. 5). To reduce the negative impacts of decreases in T_{mean} and SRD, early maturing cultivars with medium growth period, as well as early sowing, should be adopted for Zone IV.S.

The findings have important implications not only for Chinese crop production but also for global crop production to adapt to future climate change. The insights gained from historical data suggest that adaptations of crop production to climate change through shifts of genotype and cropping system optimization will have large potentials to cope with climate risk in future. The historical experiences can be further combined with model-based studies to develop future climate change adaptation strategies through designing crop ideotype and climate-resilient cropping system (Rötter et al., 2015). Some model-based assessments have been conducted in recent years together with long-term historical trial data (e.g., Tao and Zhang, 2010; Martín et al., 2014; Xiao and Tao, 2014). These studies point towards need for cultivars with longer reproductive phases and higher thermal requirements under future climate scenarios in many regions. These studies also indicate that

cropping system can be optimized to prevent anthesis stage from heat and drought stress and to make full use of improved photo-thermal resource under climate change conditions.

5. Conclusions

The detailed field observations at 167 agricultural meteorological stations across China spanning from 1981 to 2009 were used to investigate the response and adaptation of maize production to climate change in the past three decades. We found that once the crop systems dynamics were taken into account, solar radiation and temperature had decreasing trend during the period, and maize yields were positively correlated with solar radiation and temperature in major production regions. The decreases in solar radiation and temperature during growth period were mainly ascribed to adoption of late maturing cultivars with higher thermal requirements and longer RGP duration, which contributed substantially to yield increase. The historical experiences in the past three decades reveal insights into response and adaptation of maize growth and yield to climate change at different climate zones regions of China. Our findings highlight that the shifts between early and late maturity cultivars and sowing dates have mitigated the impact of climate change during the last three decades. These strategies could be further developed for future agricultural adaptation to climate change through designing crop ideotype and climate-resilient cropping system.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.fcr.2015.10.013>.

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