Research Article

Received: 23 April 2011 | Revised: 26 September 2011 | Accepted: 23 October 2011 | Published online in Wiley Online Library:

(wileyonlinelibrary.com) DOI 10.1002/jsfa.5523

Impacts of climate change and inter-annual variability on cereal crops in China from 1980 to 2008

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Abstract

BACKGROUND: Negative climate impacts on crop yield increase pressures on food security in China. In this study, climatic impacts on cereal yields (rice, wheat and maize) were investigated by analyzing climate-yield relationships from 1980 to 2008.

RESULTS: Results indicated that warming was significant, but trends in precipitation and solar radiation were not statistically significant in most of China. In general, maize is particularly sensitive to warming. However, increase in temperature was correlated with both lower and higher yield of rice and wheat, which is inconsistent with the current view that warming results in decline in yields. Of the three cereal crops, further analysis suggested that reduction in yields with higher temperature is accompanied by lower precipitation, which mainly occurred in northern parts of China, suggesting droughts reduced yield due to lack of water resources. Similarly, a positive correlation between temperature and yield can be alternatively explained by the effect of solar radiation, mainly in the southern part of China where water resources are abundant.

CONCLUSION: Overall, our study suggests that it is inter-annual variations in precipitation and solar radiation that have driven change in cereal yields in China over the last three decades.

Supporting information may be found in the online version of this article.

Keywords: China; cereal crops; climate change; climate variability

INTRODUCTION

China has experienced significant climate change over the last century. For example, the annual mean air temperature increased by 1.1 °C from 1951 to 2001.[1] Precipitation in the basins in western China has increased by 10–15% per decade, while a decrease in precipitation has been observed in northern China.[2] A climatic model has projected that by 2050 the annual mean temperature could rise by 2.3–3.3 °C and precipitation could increase by 5–7%.[2] Additionally, heavy rain could increase along the Yangtze River and in parts of southern, northwest and northeast China.[1]

Agricultural land in China accounts for only 7% of the world's arable land area but feeds about 22% of the global population. An increase in crop yields will be required to meet demands of an increasing population.[3,4] Agricultural productivity is dependent upon land resources and climate. Thus, given a finite amount of land, negative impacts of climate change on crop yield will increase stress on food security in China.

A number of studies using historical climate and crop data have indicated climatic impacts on cereal yields in Australia,[5] China,[6,7] England,[8] the Philippines,[9] and the USA.[10,11] A reduction in yields with higher temperature has been found worldwide.[12,13] However, in analyzing observed crop yields over time, it was found that negative correlations between yield and temperature were only predominant for maize, but both positive and negative correlations were detected for rice and wheat cultivated in China.[14]

Peng *et al.*[9] found that an increase in the minimum temperature reduced rice yields on farms at the International Rice Research Institute (IRRI), but Sheehy *et al.*[15] pointed out that the yield decrease may be due to reduced radiation, coinciding with a rise in minimum temperature. Several previous studies[16,17] have suggested that covariant climatic variables should be taken into account when evaluating climate–yield relationships. However, most current studies are more likely to focus on changes in yield with increasing temperature, which is the most significant feature of climate change.

Besides the significant warming trend, a climate model projected that climate change is likely to result in an increase in heavy downpours, while rising air temperature tends to increase evapotranspiration and contribute to dry conditions,[18] suggesting more serious impacts of flood and drought hazards triggered

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by climate change. In the past few decades, both of the two hazards have been reported to adversely affect crop production in China.[19,20]

Rice, wheat, and maize are the three major cereal crops in China, accounting for approximately 54% of the total sowing area and 89% of the total grain yield.[21] The study examined the correlations between climate and cereal yields (rice, wheat, and maize), effects of climatic variables on cereal yields, and impacts of flood and drought on Chinese agriculture from 1980 to 2008 on a provincial scale, when the most significant warming trend of the last six decades was detected.[22]

MATERIALS AND METHODS

Study region and crops

Rice is grown throughout China. Rice cultivated in the north yields one harvest per year; however, most rice is produced in the south, where double-harvest rice (early and late rice) can be cultivated as well. Wheat and maize are cultivated mostly in the north, while a small portion is produced in the south. Winter wheat is common in most of the study area, while spring wheat is only concentrated in northeast and northwest China. The majority of maize is grown in summer. Harvest area and grain production of cereal crops are illustrated as supporting information Appendix S1a. Our study area is highlighted in Appendix S1b, containing approximately 95% of the total national harvest area.

Data sources

Crop data were obtained from China's agricultural statistics[21] and the Data Sharing Infrastructure of Earth System Science,[23] extracted from agricultural yearbooks. Data included province-level acreage and yield of rice (including early, late, and single rice), wheat (including spring and winter wheat) and maize. Additionally, areas affected by droughts and floods, as well as the total cultivated area from 1980 to 2008, were also collected from China's agricultural statistics.[21] The crop calendar was derived from the *Chinese Agricultural Phenology* Atlas.[24] Calendar details are provided in supporting information Appendix S2.

Climate data were obtained from the China Meteorological Administration. A total of 418 weather stations are distributed across the study region (supporting information Appendix S3). Climatic variables included daily minimum temperature ($T_{\min}$), maximum temperature ($T_{\max}$), sunshine duration and precipitation (Pre). Sunshine duration was converted to solar radiation (Rad) using the Ångström formula.[25]

Statistical analysis

Correlations between yield and climate

Grain yield was correlated with climatic variables using a first-difference time series[5] (Eqn (1)):

$$\Delta X_t = X_t - X_{t-1} \tag{1}$$

where X represents climatic variables ($T_{\min}$, $T_{\max}$, Pre and Rad) or grain yield (Y). Subscript t denotes the year and includes 1981–2008.

On a provincial scale, each climatic variable ($T_{\min}$, $T_{\max}$, Pre and Rad) was averaged for each crop season in each year. Using Eqn (1), $\Delta T_{\min}$, $\Delta T_{\max}$, ΔRad, ΔPre and ΔY were obtained for each year and province. First-difference values of yield and climatic variables were correlated using a linear regression model for each pair of datasets, including ΔY with $\Delta T_{\min}$, $\Delta T_{\max}$, ΔRad and ΔPre. Because provincial yields of rice and wheat may include more than one season per year in some provinces (i.e., single, early or late rice, and spring or winter wheat), a weighted average of climatic variables and yields was calculated for each season. Weights were determined by the proportion of cultivated areas in seasons of each year.

Correlation between agricultural drought and flood with climate

The cultivated area affected by droughts and floods as well as total cultivated area for each province were documented by agricultural statistics, but data on corresponding losses in grain yield due to droughts and floods were not recorded. Therefore, the percentage of areas affected by droughts or floods (drought/flood-affected area divided by total cultivated area) for each province was calculated to represent their impacts on agriculture.

A drought indicator (DI), calculated as the difference between annual potential evapotranspiration and precipitation (Eqn (2)), was used to represent surface dryness:

$$\mathrm{DI} = \mathrm{ET_p} - P_{\mathrm{annual}} \tag{2}$$

where ET_p is the potential evapotranspiration (mm y^{-1}) calculated by Hargreaves' equation;[26] P_{annual} is the annual amount of precipitation (mm y^{-1}).

To denote annual downpours, a heavy rain index (HRI) was calculated, which was defined as total annual rainfall with a rate greater than 50 mm d^{-1}.[27]

Using a linear regression model, the percentage of drought-affected areas (%drought) was correlated using DI and the percentage of flood-affected areas (%flood) was correlated with HRI.

RESULTS

Climate change and variability from 1980 to 2008

Temperature records from 1980 to 2008 show a significant warming trend in China, which is consistent with the national assessment report for climate change.[22] Warming was more significant in northern parts of China than in southern parts (Table 1). Moreover, in northeast, northern and northwest China, the slopes of $T_{\min}$ trend are greater than those of $T_{\max}$ in nine provinces of 12 in the regions, whereas, in eastern, central, southwest and southern China, the increases in $T_{\min}$ are lower than $T_{\max}$ in 10 provinces of 12 in these areas (Table 1).

Solar radiation from 1980 to 2008 was not statistically significant in most provinces; however, in five provinces in northern and northwest China, radiation significantly decreased by 105–305 MJ m^{-2} y^{-1} per decade (Table 1). Annual precipitation in the study region did not show a significant trend. However, a reduction of approximately 30 mm per decade was observed in the Heilongjiang and Sichuan Provinces (Table 1). These results suggest that the time trend in radiation and precipitation in most areas of China over the past three decades was not pronounced.

Yield correlations with climate

Rice

In general, increases in the minimum and maximum temperatures did not always reduce rice yield (supporting information Appendix S4). It is noteworthy that rice yield was only significantly reduced as $\Delta T_{\min}$ increased in Shaanxi Province but it increased with rising

Table 1. Average, standard deviation, and trend in climate over the period 1980–2008 in each province

Province	ID[a]	T_{min} Ave. ± SD[b] (°C)	T_{min} Trend[c] (°C 10 y^{-1})	T_{max} Ave. ± SD (°C)	T_{max} Trend (°C 10 y^{-1})	Annual Rad Ave. ± SD (MJ m^{-2})	Annual Rad Trend (MJ m^{-2} 10 y^{-1})	Annual Pre Ave. ± SD (mm)	Annual Pre Trend (mm 10 y^{-1})
Northeast									
Heilongjiang	1	−2.3 ± 0.7	0.59**	9.0 ± 0.8	0.51**	4388 ± 131	4	530 ± 74	−32*
Jilin	2	−0.2 ± 0.7	0.56**	11.6 ± 0.7	0.54**	4596 ± 135	−30	627 ± 74	−20
Liaoning	3	3.8 ± 0.6	0.54**	14.6 ± 0.7	0.43**	4862 ± 149	−48	662 ± 114	−13
North									
Beijing	4	8.0 ± 0.7	0.67**	18.3 ± 0.6	0.37**	5035 ± 256	−211**	529 ± 149	−46
Hebei	5	5.3 ± 0.8	0.75**	16.8 ± 0.6	0.40**	5086 ± 180	−152**	497 ± 86	−2
Tianjin	6	9.1 ± 0.4	0.29**	17.8 ± 0.6	0.44**	4979 ± 314	−305**	524 ± 123	−16
Shandong	7	8.1 ± 0.6	0.53**	17.2 ± 0.6	0.38**	5156 ± 213	−164**	669 ± 149	42
Henan	8	10.0 ± 0.6	0.51**	20.1 ± 0.7	0.45**	4683 ± 212	−91	761 ± 135	4
Northwest									
Shanxi	9	3.1 ± 0.9	0.81**	15.8 ± 0.9	0.71**	5074 ± 170	−105**	471 ± 71	−8
Shaanxi	10	7.0 ± 0.5	0.44**	17.6 ± 0.8	0.69**	4734 ± 216	128**	656 ± 109	−46
Ningxia	11	2.6 ± 0.7	0.57**	15.4 ± 0.7	0.57**	5518 ± 141	−20	269 ± 53	1
Gansu	12	1.3 ± 0.6	0.58**	14.6 ± 0.7	0.54**	5449 ± 128	56*	271 ± 34	4
East									
Anhui	13	11.4 ± 0.6	0.60**	20.1 ± 0.7	0.61**	4661 ± 160	−36	1194 ± 171	−17
Jiangsu	14	11.8 ± 0.8	0.76**	19.8 ± 0.7	0.62**	4831 ± 164	−42	1050 ± 158	−5
Zhejiang	15	14.0 ± 0.6	0.62**	21.1 ± 0.7	0.74**	4688 ± 165	−2	1405 ± 180	−25
Central									
Hubei	16	12.8 ± 0.5	0.55**	21.2 ± 0.7	0.68**	4389 ± 169	−51	1193 ± 187	−46
Hunan	17	13.8 ± 0.4	0.38**	21.4 ± 0.6	0.51**	4282 ± 132	4	1442 ± 167	−3
Jiangxi	18	14.4 ± 0.5	0.42**	22.5 ± 0.6	0.58**	4561 ± 160	0	1686 ± 227	−23
Southwest									
Guizhou	19	12.4 ± 0.3	0.22**	20.2 ± 0.5	0.27**	3969 ± 114	−59*	1136 ± 100	6
Sichuan	20	7.9 ± 0.4	0.37**	18.3 ± 0.6	0.47**	4388 ± 118	−42	960 ± 67	−30*
Yunnan	21	11.9 ± 0.4	0.37**	22.9 ± 0.4	0.20**	5159 ± 141	−22	1128 ± 88	12
South									
Fujian	22	15.7 ± 0.5	0.39**	23.6 ± 0.6	0.52**	4677 ± 198	−4	1580 ± 219	14
Guangdong	23	18.8 ± 0.5	0.33**	26.3 ± 0.5	0.45**	4841 ± 181	−8	1793 ± 265	−13
Guangxi	24	18.1 ± 0.4	0.28**	25.6 ± 0.5	0.30**	4566 ± 163	−13	1621 ± 227	6

[a] Same as in Appendix S1b.
[b] Averaged over the period 1980–2008. SD, standard deviation.
[c] Slope of the linear regression of climate variable with time in 10 years. Asterisks indicate significance at confidence levels of * 5% and ** 1%, respectively.

ΔT_{min} in Heilongjiang, Yunnan, and Guangxi Province (Fig. 1(a)). An increase in ΔT_{max} significantly decreased rice yield in four provinces and improved yield in two provinces (Fig. 1(b)). Yield was significantly correlated with ΔRad (Fig. 1(c)) and ΔPre (Fig. 1(d)) in four of the 24 provinces (Appendix S4). Importantly, there is a clear spatial distribution for correlation between yield and ΔPre. The positive correlations mainly occurred in the provinces of northern and northwest China as well as Sichuan and Guizhou Provinces in southwest China, even through these correlations are insignificant. For other regions, yields became lower with higher precipitation (Fig. 1(d)).

Correlations between yield and climatic variables (Appendix S4 for rice) were plotted on a province-by-province basis (Fig. 2). It is observed that when the correlation between yield and temperature (ΔT_{min} and ΔT_{max}) was positive, yields were also positively correlated with ΔRad (quadrant I in Fig. 2(a,b)) and negatively correlated with ΔPre (quadrant IV in Fig. 2(c,d)). Conversely, for the data points with negative correlation between yield and temperature, a negative correlation between yield and ΔRad (quadrant III in Fig. 2(a,b)) and a positive correlation between yield and ΔPre (quadrant II in Fig. 2(c,d)) tended to occur simultaneously. These results indicated that correlations between yield and temperature could be alternatively explained by effects of radiation and precipitation.

Wheat

In general, the correlation between wheat yield and ΔT_{min} was not statistically significant (Fig. 3(a)); however, an increase in ΔT_{max} appeared to reduce wheat yield in northeast China (Fig. 3(b)). Wheat yield in three provinces in eastern China and one province in southern China was significantly correlated with radiation in a positive manner (Fig. 3(c)). In contrast, an increase in precipitation generally reduced wheat yield in eastern, central and southern China (Fig. 3(d)).

Figure 4 plots the correlation coefficients between wheat yield and climatic variables (Appendix S4 for wheat) in one graph.

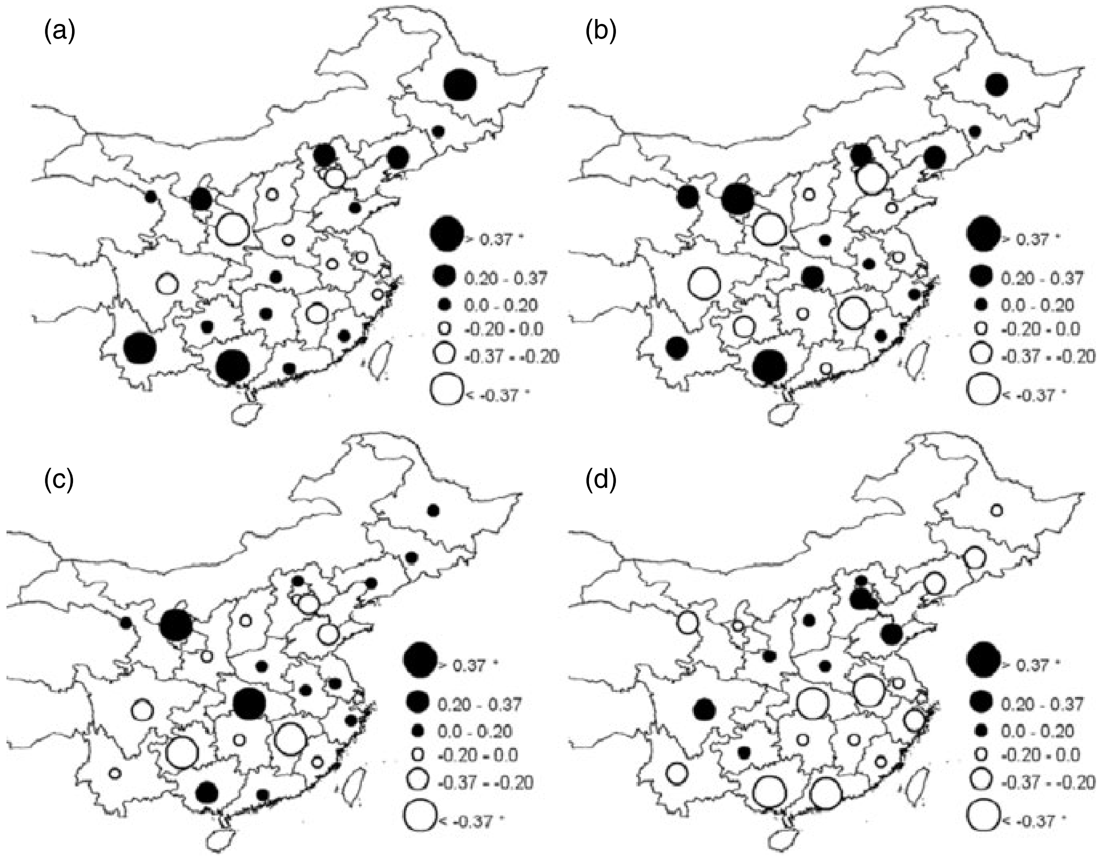

Figure 1. Spatial distribution of correlation coefficient between yield and climate for rice: (a) ΔY vs. ΔT_{min}; (b) ΔY vs. ΔT_{max}; (c) ΔY vs. ΔRad; (d) ΔY vs. ΔPre. *Statistical significance at $P < 0.05$. See Appendix S4 for details.

There is a positive correlation between wheat yield and ΔT_{max} when yields were also positively correlated with ΔRad (quadrant I in Fig. 4(b)) and negatively correlated with ΔPre (quadrant IV in Fig. 4(d)), and vice versa (data points fell into quadrant III in Fig. 4(b) and into quadrant II in Fig. 4(d), respectively). Such covariant climatic effects are unclear, however, for ΔT_{min} (Fig. 4(a,c)).

Maize

Maize yield was significantly reduced (Fig. 5(a,b)) in approximately 50% of provinces (Appendix S4) with an increase in temperature. Maize yield was more negatively correlated with ΔT_{max} than ΔT_{min} (Fig. 5(a,b)). Additionally, yield was negatively correlated with radiation (Fig. 5(c)) and positively correlated with precipitation (Fig. 5(d)) in most areas, with six and seven provinces, respectively, showing a significant relationship (Appendix S4).

A negative correlation between maize yield and ΔT_{min} or ΔT_{max} was coincident with a negative correlation between yield and ΔRad (quadrant III in Fig. 6(a,b)) and a positive correlation between yield and ΔPre (quadrant II in Fig. 6(c,d)). These results suggest that a lower maize yield is accompanied by a decrease in precipitation, an increase in radiation or an increase in temperature.

Correlations between climatic variables

Correlations between climatic variables are quite significant in China (Appendix S4). For the growing season of the three crops, on an inter-annual basis, higher ΔT_{max} is accompanied by higher ΔRad and lower ΔPre in a significant manner in most areas, while the correlations for ΔT_{min} are relative weak. ΔRad is significantly correlated with ΔPre in a negative manner in most areas.

Percentage of cultivated area significantly impacted by climate

The percentage of cultivated area significantly impacted by climate was estimated by correlations between yield and climatic variables (Appendix S4) and the cultivated area (the mean from 1980 to 2008) of rice, wheat, and maize in each province.

An increase in minimum temperature did not lead to a significant reduction in rice and wheat yields; in particular, rice yield increased in 14.8% of the sowing areas due to an increase in T_{min} (Table 2). An increase in the maximum temperature caused a lower yield in 20.7% of the rice-growing areas and 10.3% of the wheat-growing areas (Table 2). Maize was more sensitive to warming than rice and wheat: 16.2% and 35.5% of maize-cultivated areas showed significant negative correlations with T_{min} and T_{max}, respectively (Table 2).

Precipitation had a stronger impact on yield than temperature. Lower yield with higher precipitation occurred in 32.5% of rice and 18.4% of wheat but higher precipitation increased maize yield in 44.4% of the cultivated area (Table 2). The reduction in rice and wheat yields occurred mainly in central and southern China, where annual precipitation was greater than 1000 mm y^{-1} (Table 1). Positive effects of precipitation on maize yield appeared in the northern part of China (Fig. 5(d)), where annual precipitation is generally lower than 700 mm (Table 1). Thus maize yield in these provinces was more vulnerable to precipitation than to temperature.

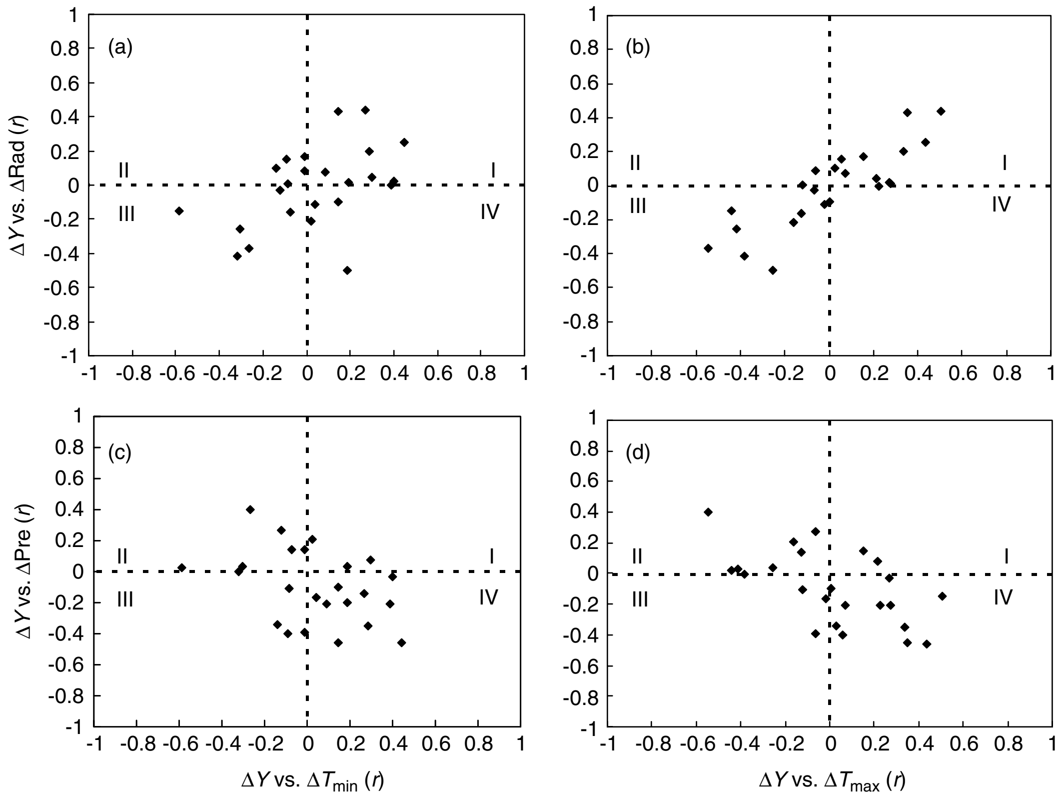

Figure 2. Pattern of rice yield correlations to climatic variables. Values show the Pearson correlation coefficient between rice yield and climate variables. I, II, III, IV denote the quadrant.

Table 2. Percentage of cultivated area (%, mean from 1980 to 2008) with insignificant, significant positive and negative ($P < 0.05$) impact of climatic parameter on yield

Climatic variable	Correlation with ΔY	Rice	Wheat	Maize
ΔT_{min}	Insignificant	84.7	98.9	83.8
	Positive	14.8	0.0	0.0
	Negative	0.5	1.1	16.2
ΔT_{max}	Insignificant	71.0	81.5	64.5
	Positive	8.3	8.3	0.0
	Negative	20.7	10.3	35.5
ΔPre	Insignificant	67.5	76.7	55.6
	Positive	0.0	5.0	44.4
	Negative	32.5	18.4	0.0
ΔRad	Insignificant	79.4	77.4	58.4
	Positive	7.9	17.2	0.0
	Negative	12.7	5.3	41.6

An increase in radiation reduced maize yield in 41.6% of the cultivated area (Table 2). Although this appears counterintuitive, radiation was negatively correlated with precipitation (Appendix S4); thus lower annual precipitation was accompanied by higher solar radiation. The resultant water stress conditions caused a reduction in yield (Appendix S4).

Impact of droughts and floods

At a regional level, droughts affected a larger cropland area than floods, with an average of 22.5 ± 6.9 Mha and 11.5 ± 4.8 Mha, respectively, affected by drought, which encompasses approximately 16 ± 5% and 8 ± 3% of the total area (Table 3). In the northern part of China, upland crops were dominant and drought was more significant than in other regions of China. Areas affected by drought accounted for 24 ± 14% of the total cultivated area. For floods, impacts were stronger in northeast, central and southeast provinces, where a rotation of rice with upland crops or double rice systems was common. Areas affected by floods accounted for 11 ± 10% of the total cultivated area in the study region (Table 3).

No significant trends in the percentage of drought- and flood-affected areas were observed from 1980 to 2008 at the national level (Table 3). At the provincial level, percentage of drought-affected areas decreased in Hebei, Shandong, Henan, and Hunan Province, while the percentage of flood-affected areas decreased in Heilongjiang Province over the period (Table 3).

In general, DI tended to increase over time throughout the region. However, it was only statistically significant in three provinces (Heilongjiang, Shaanxi, and Sichuan). HRI decreased in Beijing and increased in Fujian, but no significant trends were detected in other provinces (Table 3).

The percentage of areas affected by drought (%drought) correlated significantly with DI (Table 3). An increase in evapotranspiration or a decrease in precipitation (Eqn (2)) tended to enhance drought stress, with the largest impacts in northeast and northwest regions. According to correlations between %drought and DI, a 100 mm increase in DI caused an additional 4–15% of the total cultivated area to be affected by drought in the regions. However, a 100 mm increase in the DI of eastern, central, southwest

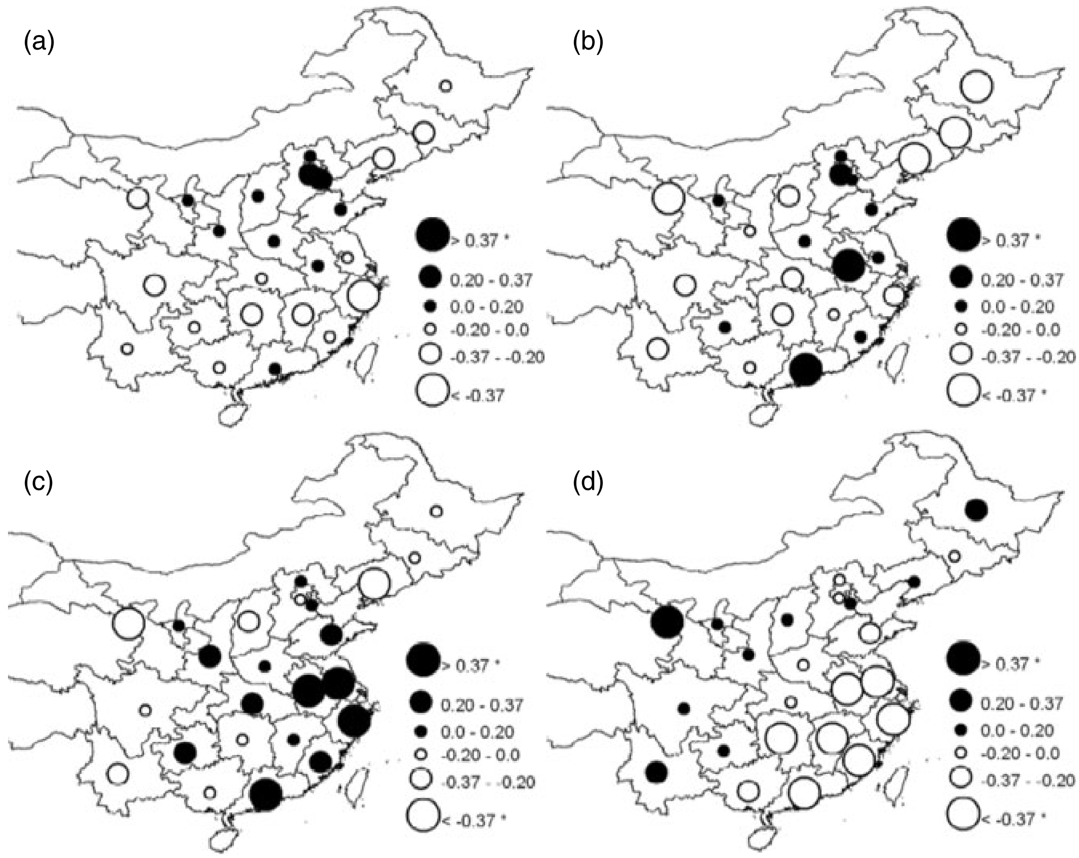

Figure 3. Spatial distribution of correlation coefficient between yield and climate for wheat: (a) ΔY vs. ΔT_{min}; (b) ΔY vs. ΔT_{max}; (c) ΔY vs. ΔRad; (d) ΔY vs. ΔPre. *Statistical significance at $P < 0.05$. See Appendix S4 for details.

and southern provinces only led to an increase in drought-affected area by 1–4% (Table 3).

The percentage of areas affected by floods (%flood) was positively correlated with HRI. Crops in northeast China were most sensitive to heavy downpours: a 100 mm y^{-1} increase in heavy rain affected an additional 15–43% of the cultivated area (Table 3). Although annual precipitation was quite high, the crop area in the south was less sensitive to heavy downpours (Table 1).

The above results give us a general picture of drought and flood impacts in China. In northern parts, drought impacts are much stronger than floods; in southern parts, drought impacts are weaker but floods show no significantly higher effect than droughts.

DISCUSSION

It is often thought that an increase in temperature causes a decrease in the yields of Chinese cereal crops.[6,28] However, data obtained in the present study revealed that an increase in temperature had no significant effect on cereal yields at a national scale and were associated with both an increase and decrease in yields from 1980 to 2008. Of the three crops in this investigation, maize seemed most vulnerable to higher temperatures, while rice and wheat were not so sensitive (Table 2). Thus the often cited result that warming has a negative impact on yield does not explain the observations of this study.

Correlations between yield and temperature obtained by this study are consistent with the results of Tao *et* al.[14] However, our analysis suggests that the varying correlation of yield with temperature is due to covariant effects of other climatic variables intertwined with temperature. During the growing season, a higher temperature was generally accompanied by less precipitation in the majority of areas (Appendix S4). Consequently, a negative correlation between yield and temperature can be interpreted as a positive correlation with precipitation, mainly in northern provinces (Figs 2, 4, and 6), especially for maize. This result indicates that drought significantly limits yield.[29] Moreover, data obtained in this study revealed that most drought-affected areas were located in the northern part of China (Table 3), which is consistent with above climate–yield correlations.

Significant impacts on yield due to drought have been reported in other regional scale assessments. Lobell and Burke[30] found that crop yields in most countries were negatively correlated with temperature but they were also positively correlated with precipitation in a more significant manner. This reflects that precipitation has a more significant impact on crop yield than temperature. In Australia, Nicholls[5] found a negative correlation between wheat yield and diurnal temperature range. However, Gifford *et al.*[31] indicated that this negative correlation may be due to droughts. In China, significant droughts in north have been widely recognized (Table 3) and are clearly due to a lack of water resources.[32–35] For example, droughts highly constrained the production of rice,[36,37] wheat,[38,39] and maize[40,41] in the region.

Warmer temperatures also coincided with higher levels of solar radiation (Appendix S4). Improved photosynthesis associated with an increase in radiation has a positive effect on yield,[42] which could explain an increase in yield with higher temperatures (Figs 2, 4, and 6). Radiation driving crop yield is not new. For instance, Peng

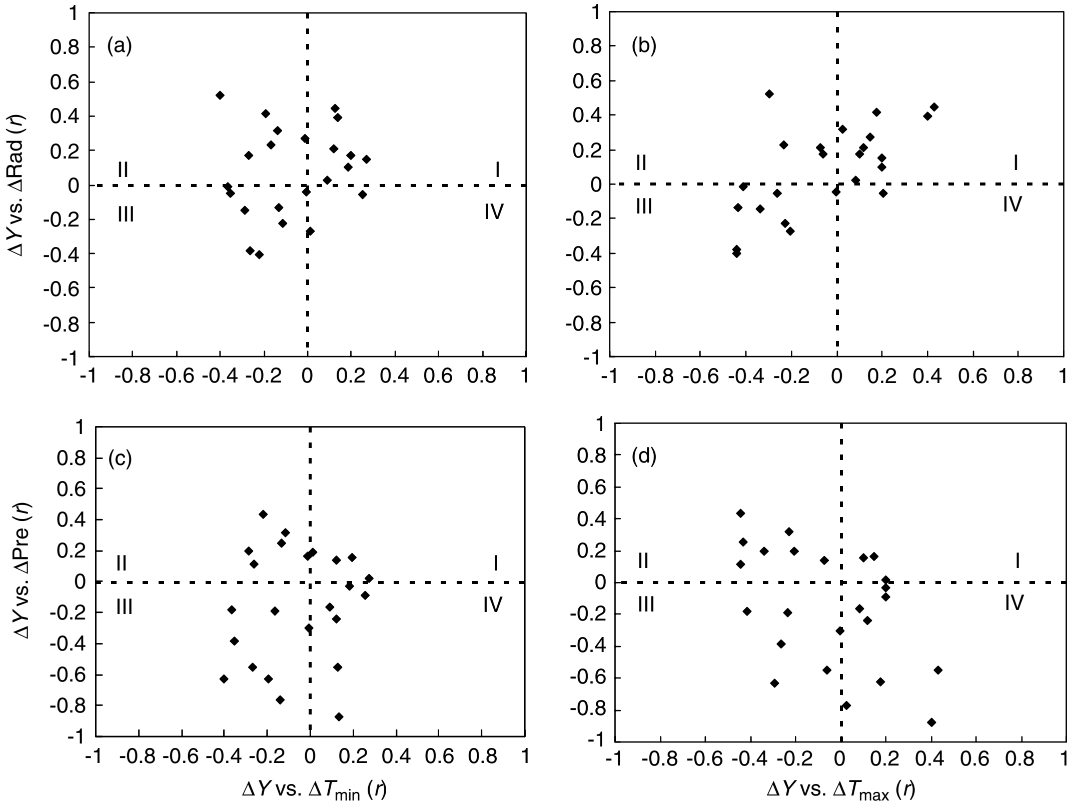

Figure 4. Pattern of wheat yield correlations to climatic variables. Values show the Pearson correlation coefficient between wheat yield and climate variables. I, II, III, IV denote the quadrant.

et al.[9] suggested a strong negative minimum temperature effect on rice yield from long-term experiments at IRRI that maintained good growing conditions for crop development. However, Sheehy *et al.*[15] pointed out that the observed reduction in yield at IRRI in Peng's study could be largely explained by a significant negative correlation between T_{min} and Rad; thus an effect due exclusively to minimum temperature was not necessary to explain observed trends in yield, and radiation is largely responsible for change in yield. In our study, there are seldom significant negative correlations between T_{min} and Rad in most provinces of China (Appendix S4), which is in contrast to the aforementioned situation at IRRI and validates Sheehy's hypothesis. In China, recent studies based on long-term field experiments also found that radiation has a stronger correlation with yield than temperature,[43] which is in accordance with the effects of radiation on yield when positive correlations between yield and temperature were presented (Figs 2, 4, and 6).

The above analysis reveals that changes in precipitation and solar radiation drove variations in yields of cereal crops. Yields of rice, wheat, and maize were sensitive to drought in the northern part of China. Maize was most sensitive to droughts (Fig. 5(d)), while rice was least sensitive (Fig. 1(d)), which can be explained by rice having nearly twice as large an irrigated area (95%) as maize (45%) allocated in China.[44] In southern parts, however, yields tended to decrease with greater amounts of precipitation (negative correlation), which is especially evident in rice (Fig. 1(d)) and wheat (Fig. 3(d)). The decrease in yield with higher precipitation is not due to floods since impacts of floods were shown to be not very strong in the south relative to drought (Table 3). This is probably due to lower radiation accompanied by higher precipitation (Appendix S4). In summary, variations in yield related to climate showed a strong inter-annual variability, where changes in precipitation and radiation were significant (Table 1), even though an increase in temperature is the most significant feature of climate change.

CONCLUSIONS

In China, a significant warming trend was observed from1980 to 2008, but trends in annual precipitation and solar radiation were not statistically significant for a majority of the region. In general, maize was relatively sensitive to increasing temperatures, while an increase in temperature was correlated not only with lower but also with higher yields of rice and wheat. The observation suggests that the current view that warming adversely affects cereal yield cannot be held to be universally true. Further investigation found that negative correlation between yields and temperature tended to be coincident with positive yield correlations with precipitation, mainly in the northern part of China where water resources are limiting and droughts have affected a large area. On the other hand, a positive correlation between yield and temperature was generally accompanied by positive yield correlations with radiation, primarily in southern parts where much richer water resources meet the water requirements of crops but flood impacts are not strong. This reflects that effects of precipitation (via drought) and radiation (via photosynthetic processes) intertwined with temperature variation explain change in yields of the three crops in China, suggesting a covariant impact of climatic variables. Moreover, no significant trends in the percentage of drought- and flood-affected areas were observed over the period. In summary,

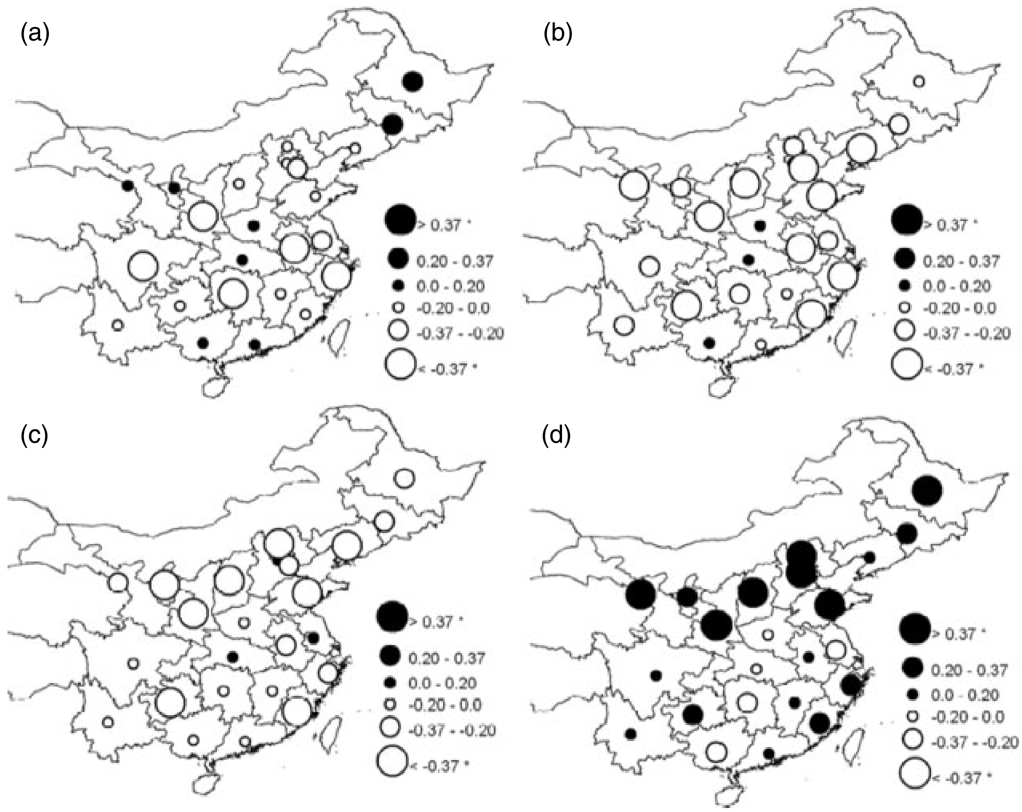

Figure 5. Spatial distribution of correlation coefficient between yield and climate for maize: (a) ΔY vs. ΔT_{min}; (b) ΔY vs. ΔTmax; (c) ΔY vs. ΔRad; (d) ΔY vs. ΔPre. *Statistical significance at $P < 0.05$. See Appendix S4 for details.

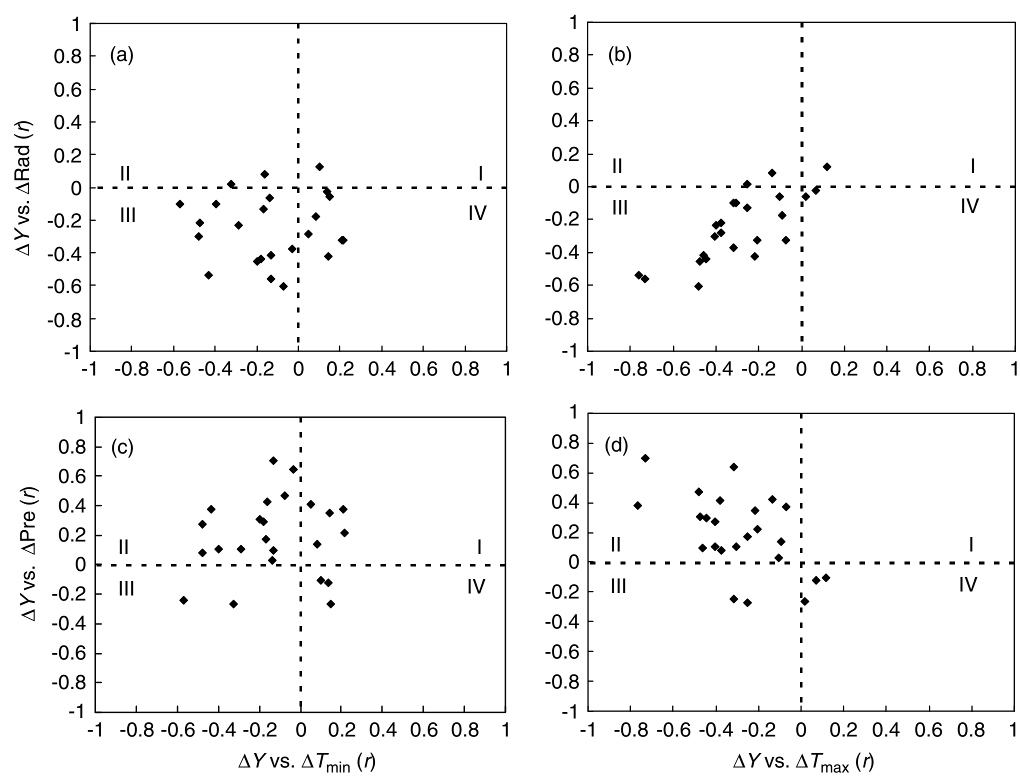

Figure 6. Pattern of maize yield correlations to climatic variables. Values show the Pearson correlation coefficient between maize yield and climate variables. I, II, III, IV denote the quadrant.

Table 3. Percentage of drought- and flood-affected areas, trend and correlation with DI and HRI

		% drought			% drought vs. DI[d]		% flood			% flood vs. HRI[d]	
Region and province	ID[a]	Ave. ± SD[b] (%)	Trend[c] (% 10 y^{-1})	DI Trend (mm 10 y^{-1})	Slope (% 100 mm^{-1})	r	Ave. ± SD (%)	Trend (% 10 y^{-1})	HRI Trend (mm 10 y^{-1})	Slope (% 100 mm^{-1})	r
Northeast											
Heilongjiang	1	20 ± 14	4.5	44.9*	9	0.61**	12 ± 11	−5.6*	−1.7	43	0.62**
Jilin	2	26 ± 19	5.2	35.3	12	0.57**	11 ± 14	−5.1	2.5	20	0.46*
Liaoning	3	29 ± 18	2.0	21.5	10	0.69**	9 ± 13	−3.0	−3.2	15	0.76**
North											
Beijing	4	16 ± 10	0.1	48.8	3	0.48**	3 ± 4	−1.0	−55.1*	2	0.76**
Hebei	5	21 ± 8	−3.9*	5.3	5	0.61**	3 ± 3	0.0	−4.1	5	0.60**
Tianjin	6	22 ± 15	−2.3	31.9	6	0.55**	7 ± 7	−2.0	−17.3	2	0.26
Shandong	7	20 ± 12	−7.2**	−38.3	6	0.76**	5 ± 4	0.9	18.3	4	0.70**
Henan	8	16 ± 9	−5.3**	8.7	3	0.56**	6 ± 6	−0.4	4.4	7	0.70**
Northwest											
Shanxi	9	38 ± 18	−0.8	30.9	11	0.62**	5 ± 5	0.1	0.6	14	0.56**
Shaanxi	10	27 ± 11	1.1	81.5**	4	0.59**	8 ± 6	−1.1	−6.0	9	0.50**
Ningxia	11	22 ± 15	3.5	18.6	15	0.73**	3 ± 3	0.2	4.6	10	0.43*
Gansu	12	29 ± 14	5.0	15.9	12	0.42*	4 ± 2	−0.4	1.4	13	0.33
East											
Anhui	13	12 ± 10	0.4	36.4	3	0.59**	12 ± 12	−0.9	2.8	9	0.81**
Jiangsu	14	10 ± 9	−1.6	18.7	3	0.52**	10 ± 12	−0.8	4.1	12	0.79**
Zhejiang	15	7 ± 5	−0.7	54.0	1	0.32	9 ± 6	−1.5	20.9	4	0.53**
Central											
Hubei	16	13 ± 10	−0.1	74.6	3	0.66**	13 ± 9	2.3	−20.6	6	0.71**
Hunan	17	13 ± 8	−4.0*	24.0	2	0.55**	12 ± 7	1.6	23.2	5	0.71**
Jiangxi	18	8 ± 6	−0.7	47.2	2	0.70**	10 ± 8	1.9	18.5	4	0.68**
Southwest											
Guizhou	19	17 ± 17	−3.8	2.9	2	0.12	8 ± 5	1.2	16.9	4	0.37*
Sichuan	20	12 ± 8	1.9	53.1**	4	0.38*	8 ± 4	0.9	−12.8	4	0.41*
Yunnan	21	12 ± 7	0.8	−12.8	4	0.50**	6 ± 3	0.7	−2.1	1	0.11
South											
Fujian	22	7 ± 8	−0.9	6.5	2	0.62**	10 ± 9	−0.4	59.3*	3	0.49*
Guangdong	23	8 ± 6	−1.0	33.3	1	0.46*	9 ± 6	−1.8	5.2	2	0.51**
Guangxi	24	12 ± 7	−2.5	0.5	2	0.73**	8 ± 6	1.9	25.8	3	0.66**
National total		16 ± 5	−0.8	–	–	–	8 ± 3	−0.3	–	–	–

[a] Same as in Appendix S1b.
[b] Averaged over the period 1980–2008. SD, standard deviation.
[c] Slope of the linear regression with time in 10 years.
[d] A linear regression of % droughts with DI, or % floods with HRI.
Significant at confidence levels of * 5% and ** 1%, respectively.

this study revealed that inter-annual variation in precipitation and solar radiation are the major climatic drivers of the three cereal crop yields in China over the last three decades.

Supporting information

Supporting information may be found in the online version of this article.

ACKNOWLEDGEMENTS

This research was jointly supported by the External Cooperation Program of the Chinese Academy of Sciences (Grant No. GJHZ1204), China Meteorological Administration (Grant No. 200806026) and the Ministry of Finance People's Republic of China (Grant No. GYHY200806008). We also thank Data Sharing Infrastructure of Earth System Science and China Meteorological Administration for providing agricultural and climate data, and anonymous reviewers for insightful suggestions.

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