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ORIGINAL PAPER

Exposure, vulnerability, and adaptation of major maize-growing areas to extreme temperature

Liangliang Zhang[1] · Zhao Zhang[1] · Yi Chen[1,2] · Xing Wei[1] · Xiao Song[1]

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Abstract Driven by increasing demand for food and industrial consumption, world's maize supply is under stress. Besides, the extreme temperature events are now exposing more threat to maize yield with ongoing climate change. Thus, a comprehensive analysis on maize exposure (exposure is defined as the cultivated area which is exposed to extreme temperature stress), vulnerability (here it means how much yield losses with each temperature increase/decrease at a national scale), and adaptation to extreme temperature is essential to better understand the effects on global maize production, especially in major production countries. It was found that warming trends during the growing season have extensively dominated the main maize-growing areas across the globe. And along with this mean temperature trend was the increasing heat stress and decreasing cold stress among most regions. Moreover, from 1981 to 2011, maize yield losses caused by heat stress in China, India, and the USA were 1.13, 0.64 and 1.12% per decade, respectively, while Mexico has been experiencing a reduction of yield loss due to decreased cold stress of 0.53% per decade. Furthermore, during the period of 2021–2051, the extreme heat stress would increase substantially, while the low temperature was estimated to drop slightly during the growing seasons. Such pattern had also been found over the key reproductive stage of maize. Accordingly, through the sensitivity test of two adaption measures, improved high-temperature-tolerant varieties and changing maize calendar earlier could both mitigate extreme meteorological stress on maize, while the former method would be the most effective way to do so. Our study could provide a paradigm for other crops and other countries in the world to analyze their exposure and vulnerability to the temperature stress and make corresponding adaptation measures.

✉ Zhao Zhang
zhangzhao@bnu.edu.cn

[1] State Key Laboratory of Earth Surface Processes and Resources Ecology/Academy of Disaster Reduction and Emergency Management, Faculty of Geographical Science, Beijing Normal University, Beijing 100875, China

[2] Institute of Geographical Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China

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1 Introduction

World population is expected to keep increasing and soon enough, and in 2050, there would be 9.6 billion people altogether sharing the limited resources of food and energy on earth (Godfray et al. 2010; Pinstrup-Andersen 2009). It is almost unlikely to stabilize because of the lower yield potential and the higher population fertility in some developing countries, booming the size of population to 10.9 billion in 2100 (Gerland et al. 2014). And some developing countries bear the heaviest population burden while being exposed to more severe food insecurity coming along with climate change (Füssel and Klein 2006; Rosenzweig and Parry 1994; Watson et al. 1998; Wheeler and Von Braun 2013).

Extreme temperature usually defined as the highest or lowest temperature of a period of time in a certain area. While a temperature exceeding a given threshold at critical stages of crop development (e.g., the flowering or reproductive stage), it could cause physiological damage and eventually resulted in yield loss (Gourdji et al. 2013). Warmer temperatures, increased frequency, and severity of extreme weather events pose great challenges to agriculture production. Despite the increased yield from field management, like technology development and fertilizer utilization, climate change somehow has offset substantial proportion of those benefits in countries like India and China (Ladha et al. 2003; Lobell et al. 2011; Tao et al. 2012; Wei et al. 2015a). Meanwhile, mean growing season temperature and critical temperature in reproductive stage are both important but differ in their contribution to crop yield (Hatfield et al. 2011; Stone 2001; Wahid et al. 2007; Wang et al. 2015). Therefore, their different influences among crops ask for particular concerns and separate analysis so as to identify specific shackles on promoting production for each crop (Gourdji et al. 2013; Lobell et al. 2008).

Maize, one of the most important food crops in the world, serving as the preferred staple to the poor, is especially important for the developing world (Shiferaw et al. 2011). For the past few decades, its demand has been increasing dramatically with rapid economic growth and calling for more maize production to feed livestock. This deficiency between limited global maize supply and tremendous feeding demand, along with increasing input cost, consequently, have brought great fluctuation in global maize price (FAO 2013). Moreover, in terms of production efficiency, maize generally underperforms in current cultivation system compared with rice and wheat in countries like China (Wei et al. 2015a). Therefore, there is still plenty of room left for investing adaptation solutions to upgrade medium- and low-yield maize fields to further increase cereal yields under climate change.

Adaptation is a key factor that will shape the future severity of climate change impacts on food production and has caused wide attention. Many adaptations (e.g., changing the sowing dates, switching crop variety, expanding irrigation) need to be implemented to face such challenges. For example, Tubiello et al. (2000) put forward incorporate longer maturing hybrids to balance the effect of warmer temperatures. Additionally, early sowing dates is also an effective measure to cope with climate change in maize production. But such alternative is not be equally effective in all regions, and it is necessary to identify the effective adaptations for different areas.

In the study, yield loss to extreme temperature stress at global maize cultivation area was analyzed. Moreover, to investigate and compare the spatiotemporal patterns of maize cultivation at national scale, due to the substantial significance of country in implementing adaptation measures, countries with higher planted area were also taken into consideration. Therefore, the main objectives are: (1) to identify spatiotemporal patterns of extreme temperature stress at global scale; (2) to assess national yield loss to extreme temperature stress in mainly growing countries of maize; (3) and to seek a potential road for maize to adapt climate change. The potential findings would inform us the changes of maize production in global maize market and would provide a paradigm for other crops to research the response to extreme weather and for other countries to take the adaptive measures in the world.

2 Materials and methods

2.1 Data sources

We used ERA-Interim reanalysis as our historical meteorological data input, with a spatial resolution of 1 arc degree, which provides daily maximum, mean, and minimum temperature from 1981 to 2011 (Dee et al. 2011). Future data were obtained from BCC_AGCM_2.2, with a T106 global resolution, daily temperature from 2021 to 2051 produced under the RCP4.5 emission scenario which we needed as moderate simulation for the future climate change (Li 2014; Thomson et al. 2011).

Global maize-planting area data were collected from MIRCA-2000 datasets, with a spatial resolution of 5 arc min (about 9.2 km at the equator), which provides maize area for each month of the year (Portmann et al. 2010). Crop calendar we used in this study was collected from the center for Sustainability And the Global Environment (SAGE), with a spatial resolution of 5 arc min, covering planting and harvesting dates of maize over the globe (Sacks et al. 2010).

Different resolutions among these datasets are all converted to coordinate with the reanalysis data, which is $1° \times 1°$. To make sure there was enough maize cultivation area in certain grid for comprehensive analysis and comparison, we picked grids with at least 10 thousand ha area planting maize.

2.2 Extreme temperature indices

In this study, regarding thermal differences among countries, we chose the percentile extreme temperature indices to analyze the variation of temperature extremes during the growing season. These indices and their definition are shown in Table 1 (Wang et al. 2013).

Table 1 Definition of the percentile extreme temperature indices

ID	Indicator name	Definition	Units
Warm extremes			
TN90p	Warm nights	Percentage of days when TN > 90th percentile	Days
TX90p	Warm days	Percentage of days when TX > 90th percentile	Days
Cold extremes			
TN10p	Cool nights	Percentage of days when TN < 10th percentile	Days
TX10p	Cool days	Percentage of days when TX < 10th percentile	Days

In addition to the extreme temperature indices, growing degree days is used to quantify the yield loss from temperature stress presents time sequence analysis at main national scale due to its good performance (Zhang et al. 2014; Wang et al. 2015). According to the previous studies of thresholds for extreme temperature events, they were set as 16 °C (T_c) and 30 °C (T_h) for low temperature and high temperature, respectively (Hatfield et al. 2011; Wei et al. 2015b). Because various experimental and observed evidences had indicated that the decrease in the pollen viability can be induced by temperature over 30 °C at booting stage and the temperature below 16 °C directly leads to the cessation of physiological activity during grain filling. Correspondingly, the heating degree days (HDD) and cooling degree days (CDD) are given as:

$$\mathrm{HDD} = \frac{1}{d}\sum_{i=1}^{d} \mathrm{HD}_i \quad \mathrm{HD}_i = \begin{cases} 0 & T_i < T_h \\ T_i - T_h & T_i \geq T_h \end{cases}$$

$$\mathrm{CDD} = \frac{1}{d}\sum_{i=1}^{d} \mathrm{CD}_i \quad \mathrm{CD}_i = \begin{cases} 0 & T_i > T_c \\ T_c - T_i & T_i \leq T_c \end{cases}$$

where d is the number of hours during the productive period; T_i, HD_i and CD_i denote the temperature, heating degree, and cooling degree, respectively, at hour i.

2.3 Obtaining yield data and weather variables in a country

National maize yield data from 1981 to 2011 were obtained from production dataset of FAO (2013). The growing season of maize in each grid started at the planting date and ended by the harvesting date. And the starting date of reproductive period was assumed to occur a fixed proportion of the season back from the harvesting date, for maize, of which the proportion is 0.55 based on average state-wide crop calendars from the United States National Agricultural Statistics Service (NASS; www.nass.usda.gov/Data_and_Statistics/) (Gourdji et al. 2013). Thus, to better capture the reproductive period globally, while taking spatial variability into consideration, the date was centered around 10 days prior to the assumed starting date, which extended the time window for reproductive period to 40 days in this study (Gourdji et al. 2013).

When analyzing the national patterns of maize cultivation, each nation was taken as one entity, suggesting the weather data for all grids in a nation should be integrated to represent the whole nation. Here the equation for calculating the national averaged weather input is given as:

$$P(X)=\sum_{i=1}^{n}\left(\frac{A_i}{A}X_i\right),$$

where $P(X)$ is a certain generated meteorological variable (X) at the national level; n denotes the number of grids covering the nation; A_i represents the planting area in grid i; A is the total planting area in all grids of which the nation consists; and X_i represents one certain meteorological variable (X) records at grid i.

2.4 De-trending method for maize yield

Four models, including an intercept-only model, a linear model, a quadratic model, and a cubic model, were used to estimate the trend yield (meaning to separate the trend yield and climatic fluctuant yield from the actual yield), which were shown in the following functions.

$$\begin{aligned} Yield &= k \\ Yield &= at + k \\ Yield &= at^2 + bt + k \\ Yield &= at^3 + bt^2 + ct + k \end{aligned}$$

where *Yield* denoted yield in kg ha^{-1} $year^{-1}$; k was the intercept of regression; a, b, and c were the coefficients of regression. Akaike information criterion (Akaike 1974) and incorporating F test were also applied for each model to identify the best fit model for each yield–time relationship.

2.5 Determining yield contribution from temperature variables

The time sequence analysis, for detecting yield loss caused by the temperature stress, included indices of both mean growing season temperature and critical temperature in reproductive stage. The use of semilogarithmic model made comparison of vulnerability available among different nations. The model is given as:

$$\log(Y_{i,t}) = \beta_0 + \beta_1 \cdot \mathrm{HDD}_{i,t} + \beta_2 \cdot \mathrm{CDD}_{i,t} + \varepsilon_{i,t},$$

where $Y_{i,t}$, $\mathrm{HDD}_{i,t}$, $\mathrm{CDD}_{i,t}$ and $\varepsilon_{i,t}$ denote the detrended national maize yield, heating stress, cooling stress, and error term, respectively, of nation i at year t; β_x is coefficient of different variable in the model (Lobell et al. 2011).

2.6 Selecting study scale and the major production countries

Adaptation decisions occur on a range of temporal and spatial scales, from the crop management choices to the policy decisions. To make adaptive solutions available and accessible, great effort needs to be made within the scope of country based on the following three reasons: (1) within each country, strategies and policies on food security, either increasing food supply or stabilizing food price, are issued by the nation's central government, and carried out top-down to province/county scale, where agricultural policies are ultimately implemented (Demeke et al. 2008; Pinstrup-Andersen 2009; Wei et al. 2015a); (2) bringing the issue to broader discussion, global supply of agricultural commodities serves as determinate dominator to food market in individual countries (Hertel et al. 2010); (3) every international agriculture investment strategy generally targets some foreign country to deal with internal food insecurity, where market works as the driving stimulation to national market structure (Hallam 2011). Therefore, assessing regional food supply should be combined with national adaptation solutions to climate change as global food supply is generally the goal of interest for many specific countries.

The top five countries of maize-planting area are the USA, China, Brazil, Mexico, and India, in descending order of maize-planting area. Clearly, maize has its largest cultivation domination in the USA, which exceeds 28.99 million hectares on average (during 1981–2011), accounting for 21.79% of the global maize-growing area, followed by China with 23.96 million hectares in cultivation size and 17.94% of global occupation. The other three countries each makes up 9.41, 5.37, and 5.00% of the global share. Beside the importance of planting area, quantities of production also play a great role in world commodity trade. In addition, due to the substantial importance of France maize production within the Europe continent, concerns are to be addressed. Altogether, these six countries occupy over 60.84% of global maize-growing areas and provide 57.71% of its production, comprising samples from Americas, Asia and Europe, archetypes for both developed and developing countries (FAO 2013).

3 Results

3.1 Extreme temperature stress during the maize-growing season

Major maize-growing regions experienced significant warming ($p < 0.05$) during 1981 and 2011, especially for some mass production countries such as Eastern Europe, western China, northern Mexico, and northwestern Brazil (with an increased trend of more than 0.2%/a (Fig. 1a). Being consistent with the TX90p, patterns of trends for TN90p had the similar distribution worldwide (Fig. 1b). However, such consistency broke down for cool temperature indices, which significantly decreased ($p < 0.05$) (Fig. 1c, d). Significant negative historical trends existed in areas like Western Europe, northern Mexico, and Brazil, with trends of TX10p $\geq$ 0.2%/a (Fig. 1c). All the increase in high-temperature threat and decrease in low-temperature threat were consistent with the fact of profound global warming.

Among the six nations we compared, for TX90p, median of India was the only one with negative trend during this period (− 0.24%/a), while other nations' medians of TX90p were relatively close from 0.20%/a (France) to 0.41%/a (the USA) (Fig. 2). The range of TN90p in Brazil was from − 0.42 to 1.00%/a, with 30.60% of its maize-growing area experiencing

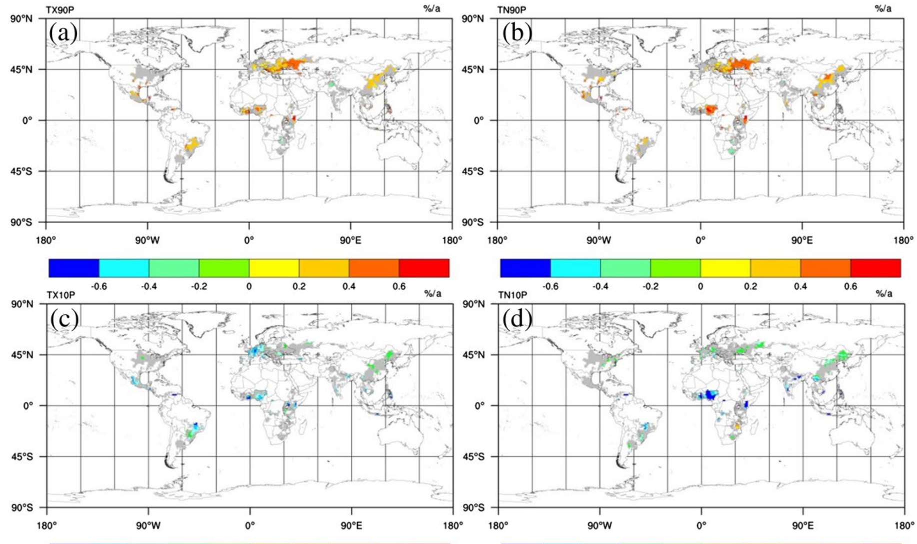


Fig. 1 Global spatial distribution of trends for warm days (TX90p, **a**), warm nights (TN90p, **b**), cool days (TX10p, **c**), and cool nights (TN10p, **d**) during 1981–2011

decreasing warming nights. Besides, France saw the most significant decrease in TX10p (– 0.33%/a), while TN10p in most areas of Brazil and Mexico was increasing (Fig. 2).

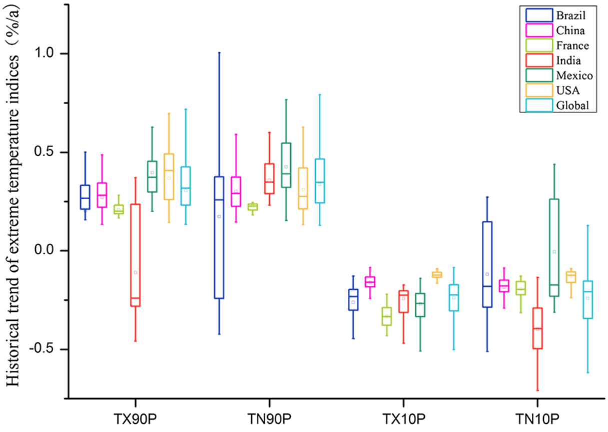
3.2 Extreme temperature stress during the reproductive period

Areas experiencing severe high-temperature stress were located across the world, including Eastern Europe, western India, Northeast China, northern China, major America, and southwestern Brazil. Especially significant areas were like western India, northern China, southern America, and southwestern Brazil, with average at least 5 heat days above critical high-temperature threshold (T_h) (Fig. 3a). And accordingly, historical trends in most of these areas were also positive, more than 0.1 day/a (Fig. 3b). The pattern of global cold days (reproductive days below T_c) is shown in Fig. 3c. With more sever exposure in high latitudes, cold days in the mid and low latitudes were relatively fewer (most with a negative historical trend of cold days (Fig. 3d). The negative trends were pronounced in the Europe, where the average decreasing rate of cold days has exceeded 0.1 day/a.

Table 2 summarizes the comparison among six nations and the global average percent of harvest area with at least 3 or 5 reproductive days above T_h or below T_c. For the period of 1981–2011, China and India were facing the most remarkable heat stress, of which about one quarter of their maize-growing areas (22.09 and 26.40%, respectively) under the exposure of at least 3 heat days during reproductive stage. Similar results were indicated for 5 heat days. Making the situation even worse were the positive historical trends. More and more areas were exposed to such stress (Table 2). In the case of low-temperature stress, it clearly had more important role in Europe, making half growing area in France exposure in cold risk. However, the negative trends for most of these countries and global maize cultivation would alleviate the stress to some extent.

Maize-growing areas were widely spreading from 60°N to 40°S, peaking at 40°N (Fig. 4). Areas affected by heat stress were mainly located in continental regions at mid to high latitudes in the Northern Hemisphere. When the heat days were extended from 3 to 5 days, areas under risk reduced and concentrated to latitudes from 20 to 40°N. Difference among median, 25th and 75th percentiles showed the high annual fluctuation of affected areas among the mid latitudes (38–45°N) in the Northern Hemisphere (Fig. 4a–b). Comparatively speaking, areas affected by cold stress were located in regions of higher

Fig. 2 National historical trends for warm days (TX90p), warm nights (TN90p), cool days (TX10p) and cool nights (TN10p) from 1981 to 2011



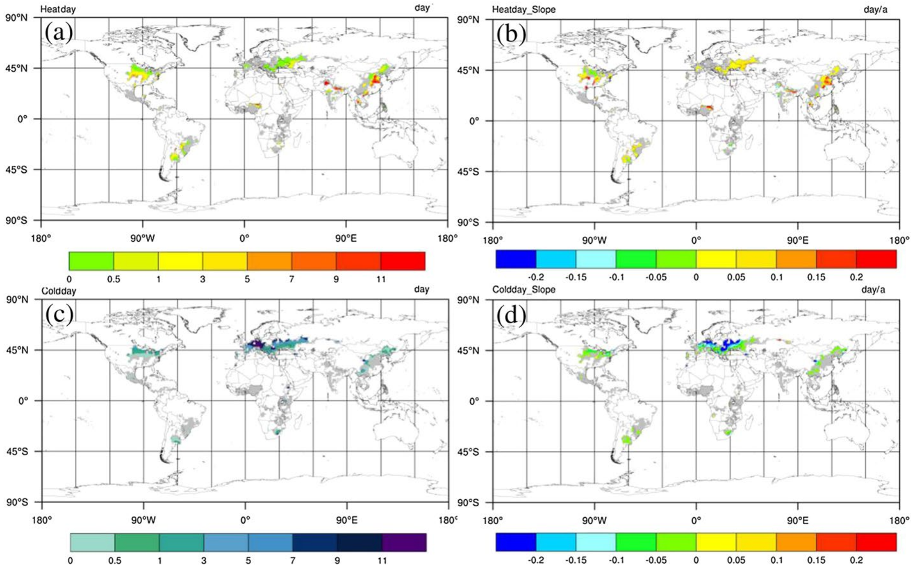


Fig. 3 Number of heat days (reproductive days above T_h, **a**) and cold days (reproductive days below T_c, **c**) and their historical trends (**b**, **d**) during reproductive stage, from 1981 to 2011

Table 2 Percent of harvest area with at least 3 or 5 reproductive days above critical high-temperature threshold (T_h) and below critical low-temperature threshold (T_c) and their historical trends (%/a) from 1981 to 2011

Country	High-temperature stress				Low-temperature stress			
	3 days		5 days		3 days		5 days	
	Average	Trend	Average	Trend	Average	Trend	Average	Trend
Brazil	0.64	0.05**	0.13	0.01	0.01	0.00	0.00	0.00
China	22.09	0.40*	16.04	0.29	5.79	– 0.13*	3.15	– 0.06*
France	0.71	0.06	0.33	0.03	47.37	– 0.19*	34.23	– 0.18
India	26.40	0.18	21.09	0.24	3.44	0.00	0.00	0.00
Mexico	1.17	0.06**	0.83	0.04**	8.58	– 0.05	7.74	– 0.05
USA	14.76	0.26	8.46	0.14	10.17	– 0.31*	4.42	– 0.05
Global	10.81	0.19*	7.43	0.12	12.77	– 0.25**	8.45	– 0.16*

**$p < 0.01$; *$p < 0.05$

latitudes. The continental regions at mid to high latitudes (40–60°N) were more vulnerable to threat of cold days. There was also a large inter-annual variability in areas affected by cold stress, as shown by the different ranges between the 25th and 75th percentiles.

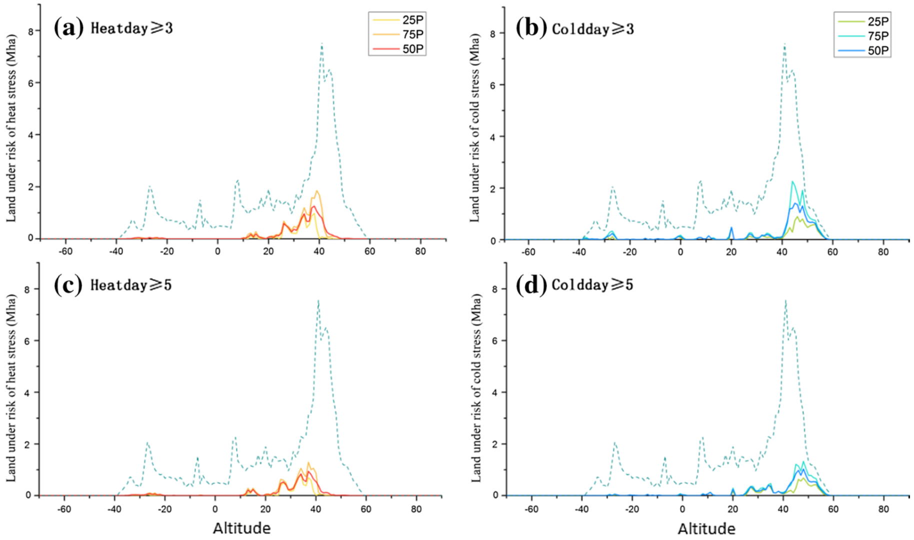
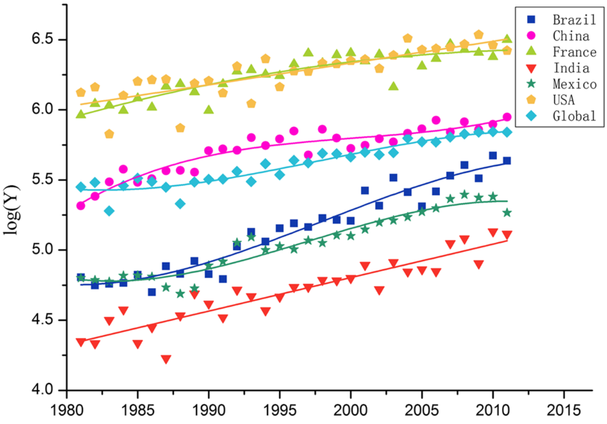


Fig. 4 Area under risk of heat stress (Mha) with heat days ≥ 3 (**a**) and 5 (**c**) and area under risk of cold stress (Mha) with cold days ≥ 3 (**b**) and 5 (**d**) for each 1° latitude-band from 1981 to 2011. Dotted line illustrated the total area of maize-growing area at one certain latitude. 25p, 75p, and 50p represented the 25 percentile, 75 percentile and median respectively

3.3 The yield contributions from temperature variables for maize

Figure 5 shows the detrended national average maize yield patterns from 1981 to 2011. Global maize yield has increased dramatically through these years. Great differences in yield, however, existed among these countries. With the clear advantage of developed counties, average maize yield in the USA and France was much higher than the other four countries, achieving 536.52 and 526.21 kg annually. Except for China, average yield of which was 307.96 kg, slightly above the global average, maize yield in Brazil, Mexico, and

Fig. 5 Detrended national average maize yield patterns from 1981 to 2011



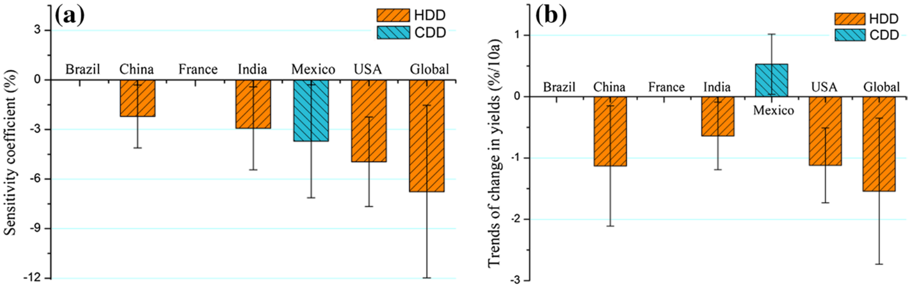


Fig. 6 Sensitivity coefficient of maize yield to extreme temperature stress (high-temperature stress index, HDD; low-temperature stress index, CDD (**a**) and trends of change in yield (**b**)

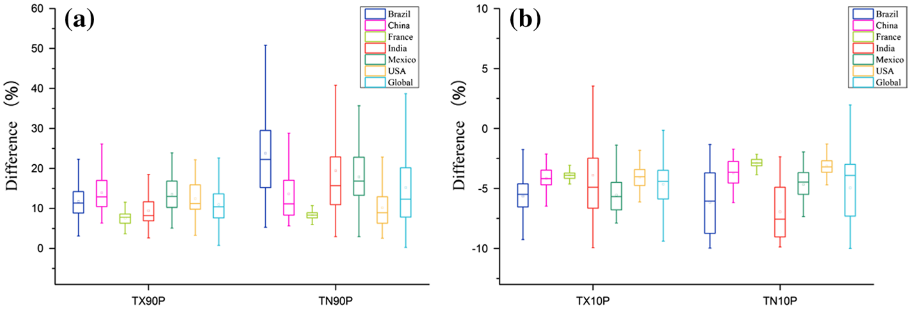


Fig. 7 Difference of TX90p and TN90p (**a**), TX10p and TN10p (**b**) between projected data of 2021–2051 and historical data of 1981–2011

India were even lower than one-third of yield in the USA, only reached 180.05, 158.99 and 113.84 kg, respectively.

Figure 6a shows how sensitive of maize in each country responded to the change of HDD and CDD. With every degree increase in HDD, maize yield in China, India, the USA and global average yield would decrease 2.21% (0.30–4.11%), 2.93% (0.41–5.44%), 4.95% (2.24–7.66%), and 6.76% (1.54–11.99%), respectively. On the other hand, maize yield in Mexico was constrained by low-temperature stress, with every degree increase in CDD, its yield would decrease 3.71% (0.28–7.13%). Thus, yield loss to the temperature stress could be calculated (Fig. 6b). Increase in temperature would bring decrease in yield in China, India, the USA and the globe for 1.13% (0.15–2.11%), 0.64% (0.09–1.19%), 1.12% (0.51–1.73%), and 1.54% (0.35–2.73%) per decade, while increase Mexico maize yield 0.53% (0.04–1.01%) for per decade.

3.4 The extreme temperature stress on maize yield in the future

An increased heat stress would be expected during the growing season from 2021 to 2051 (Fig. 7a). Both differences of TX90p and TN90p between 2021–2051 and 1981–2011 were positive in the six countries and in global extent. For TX90p, China had the largest increment (13.90%), while the increase in TX90p in France (7.52%) was much lower than the other countries. And for TN90p, increase in France (8.29%) was still the lowest, while temperature in Brazil rose much more at daytime (23.79%). Difference in the consistent change in heat stress and difference in cold stress were more complicated in some region (Fig. 7b), India, for example, where the spatial variance were most significant during the period.

Comparison for the projected percent of harvest area with at least 3 or 5 reproductive days above T_h or below T_c is shown in Table 3. For the period of 2021–2051, India would be the country where the heat stress of over 3 days affects most (38.83%) severely, followed by China (35.12%) and the USA (32.30%). Even the other three countries that we tested of lower heat stress exposure during the historical period would be exposed increasing heat stress in future scenarios. The country with the largest increase in percent harvest area under heat threat over 3 days would be the USA, which is 17.54%, and then comes China (13.03%) and India (12.44%). When the heat days were extended to 5 days, except for France, all other countries and the global average percent harvested area would all increase to some extent. Among all these countries, the USA would still face the most significant increase in exposure to heat stress by 14.20%, raising its proportion of the heat risk to 22.66%. Though the rising rate would not be as high as the USA, about one-third cultivation area in China and India would also be affected by severe high-temperature stress. In the case of low-temperature stress, it would continue its dominating role in Europe, making 19.91% of France harvest area under risk. However, it would be 27.46% less than the historical period. And the globe as a whole would also experience a decrease in cold stress by 5.77%.

3.5 Adaptation of maize production in main growing countries

The vulnerability assessment we conducted for each country in the study could help us to target adaptation strategies toward key vulnerability factors, to monitor its exposure to climatic stress and to characterize present and future risks. Hence, our adaptation solutions could be prioritized based on the vulnerability assessment. Without adaptation solutions, maize production would decrease in the maize cultivation zone and seems undisputed (Lobell et al. 2011; Tao et al. 2012). Attention needs to be directed at the generation of high-yielding, stress-tolerant, and widely adapted maize varieties through judicious

Table 3 Percent of harvest area with at least 3 or 5 reproductive days above critical high-temperature threshold (T_h) and below critical low-temperature threshold (T_c) from 2021 to 2051 and its difference to historical period (%)

Country	High-temperature stress				Low-temperature stress			
	3 days		5 days		3 days		5 days	
	Average	Diff	Average	Diff	Average	Diff	Average	Diff
Brazil	3.24	2.60	1.94	1.82	0.00	− 0.01	0.00	0.00
China	35.12	13.03	29.47	13.43	3.59	− 2.20	1.81	− 1.34
France	1.15	0.44	0.00	− 0.33	19.91	− 27.46	11.48	− 22.75
India	38.84	12.44	33.45	12.35	3.29	− 0.16	0.00	0.00
Mexico	3.47	2.29	2.38	1.55	4.65	− 3.94	3.25	− 4.49
USA	32.30	17.54	22.66	14.20	3.28	− 6.88	0.54	− 3.88
Global	19.97	9.16	15.34	7.90	7.00	− 5.77	4.14	− 4.31

Table 4 Percent of harvest area of two type of cultivars affected under different high-temperature threshold (T_h) from 2021 to 2051 and their difference (%) when the T_h was set to be 30 °C

Country	High-temperature stress (over 3 days)			
	Cultivar A ($T_h = 31$ °C)		Cultivar B ($T_h = 32$ °C)	
	Average	Diff	Average	Diff
Brazil	0.12	– 3.12	0.00	– 3.24
China	23.36	– 11.76	16.14	– 18.97
France	0.00	– 1.15	0.00	– 1.15
India	17.98	– 20.86	8.64	– 30.21
Mexico	2.21	– 1.26	0.99	– 2.48
USA	7.72	– 24.58	3.99	– 28.30
Global	9.42	– 10.54	5.98	– 13.99

Table 5 Percent of harvest area affected by high-temperature stress under different adaptation strategies from 2021 to 2051 and their difference (%) to original calendar

Country	High-temperature stress (over 3 days)							
	Scenario I		Scenario II		Scenario III		Scenario IV	
	4 days/°C earlier		6 days/°C earlier		4 days/°C later		6 days/°C later	
	Average	Diff	Average	Diff	Average	Diff	Average	Diff
Brazil	3.22	– 0.02	3.19	– 0.05	3.33	0.08	3.24	0.00
China	33.88	– 1.24	32.92	– 2.20	36.86	1.74	37.16	2.05
France	0.00	– 1.15	0.00	– 1.15	0.20	– 0.94	0.20	– 0.94
India	37.62	– 1.22	37.26	– 1.59	39.11	0.27	39.06	0.21
Mexico	3.64	0.17	3.69	0.22	3.03	– 0.43	2.88	– 0.58
USA	35.05	2.76	35.86	3.56	27.70	– 4.60	24.87	– 7.43
Global	20.42	0.45	20.46	0.49	19.14	– 0.83	18.49	– 1.48

combination of conventional and molecular breeding approaches (Shiferaw et al. 2011). For example, using high-temperature-tolerant varieties and early planting have been proved to be effective in increasing maize production at control experiments (Tao and Zhang 2010). Depending on the climate and variety properties, these adaptation options could result in geographically different contributions to regional maize yield.

Tables 4 and 5 show the two options and corresponding scene we designed based on the future temperature simulation for the six major production countries and global average. In these scenarios, we adopted two easily accessible adaptation options, utilizing the high-temperature-tolerant varieties and changing maize calendar. By increasing high-temperature threshold (T_h) from 30 to 31 °C and 32, we could simulate how two varieties of higher tolerance response to projected temperature stress. And such new variety promotion in each country could result in reduction in yield loss to different extent (Table 4). If Cultivar A, T_h of which was 31 °C, could be widely spread in these regions, then the size of affected areas of each would all be dropped by at least 1.15% (in France, where heat stress was the least severe). In that case, China and India would be the two countries suffered from the most severe heat stress over 3 days, with 23.36 and 17.98% of harvested area under threat, respectively. On the other hand, France could totally get rid of high-temperature stress, while the USA would experience the largest reduction to heat stress where the affected area will be decreased by 24.58% with Cultivar A. Further enhance such tolerance in variety, increasing its T_h to 32 °C, we found that the India and USA would benefit most from the high-temperature cultivar, reducing its affected area to 8.64 and 3.99%, with 30.21 and 28.33% dropped from normal cultivar scenarios, respectively (Table 4).

In the second simulation design, we changed the calendar by moving the reproductive periods few days earlier or later to the normal calendar. The results showed that such changes would do limited but different effects to each country compared with previous method. To elaborate, each trial would result in both benefits to some countries and damages to some other countries. Generally, for the whole global average, moving the reproductive stage earlier for either 4 or 6 days for every warming degree could increase areas affected by heat stress to some extent, while postpone the stage would bring about less loss to the heat damage. Brazil, China, France, and India have all showed positive response to the advanced reproductive stage, while Mexico and the USA would suffer a little more from such advance. Though all the differences were relatively small, the USA was estimated to be the most sensitive to this adaptation option (Table 5).

To conclude here, adopting the suitable adaptation option could effectively help local maize production to resist the specific climatic stress that has been captured in the vulnerability assessment.

4 Discussion

4.1 Global warming and its impact on maize production

Concerns are rising from the deficit between food supply and demand, and its ensuing fluctuation in food price, especially its damage effect on food security in developing countries (Rosenzweig and Parry 1994; Wei et al. 2015a). Also worth great concern of the public is the warming trend of global temperature. The warming was expected to continue at an even faster pace of about 0.2 °C over the next few decades. However, the rising global average temperatures and its impact on agriculture are not well understood (Lobell et al. 2011). To investigate such warming effect, in this study, we analyzed extreme temperature indices during the maize-growing season and the reproductive period. Consistent with some previous studies, heat stress indices in these regions have all increased substantially during the past few decades, and would continue to increase for the following years in the future. While, the cold stress indices, on the other hand, was estimated to keep decreasing over the study time period (Gourdji et al. 2013; Lobell et al. 2011; Teixeira et al. 2013; Wang et al. 2013). Better understanding of the warming impact would help us to identify the particular regions and countries that would be most affected by the trends and assist to make efforts to adapt such trends.

Regression analysis we used could relate historical data of past maize yield to the extreme temperature indices we selected. Because our models have separated the critical extreme temperature impact during the reproductive period from the whole maize-growing season, and related it directly to the detrended maize yield (the climate-induced yield), we could estimate these impacts quantitatively (− 1 to − 12% with each additional degree in temperature stress). Our results are lower than the previous studies (− 1 to − 2.4%) which was based on filed trials without any adaptation measures (Lobell et al. 2011). In the result, the greater the coefficient of the factor, the faster corresponding adaptation measures should be applied to offset its potential losses.

4.2 Importance of adaptation measures in developing countries

It is more important for developing countries to address the significance of adaptation to climate change. They are probably witnessing the rapid construction of various infrastructures like irrigation, transportation systems, and at the same time experiencing severe natural resources degrading such as desertification, soil deterioration, water quality, and scarcity (Lim et al. 2005). Meanwhile, they bear the heaviest burden of population. And the key issue here, for developing countries, is to identify the effective adaptations, where the greatest risk persists (Adger et al. 2003). As we have discussed, between the two options we compared, except for France where their impacts were the same, using new varieties that could bear high-temperature stress would be more effective in dealing with the warming trend and its potential threat to maize production. Several studies also supported our findings, e.g., Tao's study conducted in Northern China by crop model (Tao and Zhang 2010), and Gabaldón-Leal et al.'s study (Gabaldón-Leal et al. 2015) in Spain. For developing countries, like China and India, its effects were especially productive.

Adaptation to climate change, in developing countries, might serve as new opportunities to better improve their infrastructure conditions and would consequently promote economic development. Because the autonomous adaptation that individually undertaken might not be the most effective, suitable for the local resource, governments should take the responsibility to lead the research for characterizing the major risk at present and in the future in sub-national scale, and applying specific adaptation solutions to cope with its risk.

5 Conclusions

In this study, through a thorough analysis of historical and future climatic variables, we focused on the supply of maize and its potential yield loss to warming climate of major production areas. Results show that for both historical period of 1981–2011 and future period 2021–2051, global mean temperature was estimated to increase substantially, accounting for the increasing high-temperature stress and decreasing low-temperature stress in most maize-growing regions. The contribution of mean temperature over the growing season and temperature extremes during the reproductive periods was analyzed via regression analysis, directly associating HDD and CDD with the climate-induced yield we separated from the actual yield. Among the six major maize production countries, yield losses caused by the heat stress in China, India, and the USA were most significant, which were 1.13, 0.64, and 1.12% per decade, respectively, while Mexico experienced 0.53% yield increase per decade due to reduction in cold stress. Additionally, when focusing on heat stress, countries with the largest heat affected area percentage were India, China, and the USA, far more than the other countries. To cope with local threat, which was geographically different among temporal and spatial scales, specific adaptation option should be chosen carefully corresponding to individual situation. Utilizing high-temperature-tolerant varieties and changing maize calendar few days earlier were both effective method to mitigate extreme temperature stress for maize.

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