Climate and crop yields impacted by ENSO episodes on the North China Plain: 1956–2006

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Received: 12 September 2012 / Accepted: 30 March 2013 / Published online: 13 April 2013
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Abstract El Niño-Southern Oscillation (ENSO) contributes to climate anomalies, especially those related to regional rainfall, which affect crop production. Although the North China Plain (NCP) is the most important agricultural production region in China, the impact of ENSO events on local climate and crop production has received only limited attention. Therefore, the impact of different phases of ENSO on local climate and production of winter wheat and summer maize, both rain fed and irrigated, was investigated at three sites using the agricultural production systems simulator model. Data on daily temperature, precipitation, and sunshine hours for 50 years (1956–2006) were analysed to build climate scenarios for three categories of ENSO: years with El Niño events, years with La Niña events, and neutral years. The pattern of climate

change was generally similar across the three sites: annual precipitation decreased slightly and annual mean sunshine hours decreased significantly, whereas annual mean minimum temperature increased significantly, leading to a significant increase in mean air temperature. Precipitation decreased and temperature and sunshine hours increased in both El Niño and La Niña years but remained stable in neutral years. Under full irrigation, the probability of exceeding distribution that crop yield would be higher was not markedly affected ($P > 0.05$), although the yields in both El Niño and La Niña years differed markedly from those in neutral years, especially in maize. Under rain-fed conditions, the yield of maize was decreased greatly ($P < 0.05$), the probability distribution of such reduction being the highest in La Niña years at all the sites ($P < 0.05$). At the provincial level, yields from well-managed fields differed ($P > 0.05$) with the ENSO category: production of maize was more vulnerable than that of wheat in El Niño and La Niña years. El Niño and La Niña had similar effects on climatic variables across the NCP: low yields in El Niño and La Niña years due to lower precipitation and high yields in neutral years due to longer sunshine hours and additional irrigation.

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Keywords ENSO · El Niño · La Niña · Crop yield ·
Climate change · North China Plain

Introduction

El Niño-Southern Oscillation (ENSO), the most widely known source of inter-annual variability in climate (Bjerknes 1969; Loon and Rogers 1981; Ropelewski and Halpert 1986; Lin and Yu 1990, 1993), has a significant impact on global rainfall although the extent of impact

varies with the region (Waddington 1994; Stone et al. 1996). ENSO refers to the year-to-year variations in sea surface temperatures (SSTs), surface air pressure, convective rainfall, and atmospheric circulation that occur across the equatorial Pacific Ocean (Philander 1990). Many statistical connections have been found between ENSO events and precipitation anomalies around the world (Ropelewski and Halpert 1987; Cane et al. 1994; Yakir et al. 1996), for example, the established ENSO signal, the ‘Pacific Decadal Oscillation’ (PDO), the ‘Atlantic Multi-decadal Oscillation’ (AMO), and the ‘North Atlantic Oscillation’ (NAO), all of which have been shown to influence the variability of stream flow in the USA (Tootle et al. 2005).

It has been shown that not all severe droughts or floods in China were associated with El Niño or La Niña events (Lau and Weng 2001). On average for the country as a whole, approximately 53 and 49 % of the variation in rainfall in 1997 and 1998, respectively, can be attributed to the anomalies in SST associated with El Niño modes (Lau and Weng 2001). Also, Zhang et al. (1999) found that early summer precipitation in Yunnan was related to the variation in SST across equatorial east Pacific and convective activity over the South China Sea. Furthermore, Chinese researchers have shown that anomalies in summer climate can be traced to ENSO events and are particularly important to agriculture in China (Huang and Wu 1989). In China, temperatures were lower in spring and summer and higher in autumn and winter in El Niño years than in La Niña years (Zhao 1989). Such changes often have a significant impact on crop production.

The impacts of ENSO on crop production have been studied in many countries (Handler 1990; Cane et al. 1994; Carlson et al. 1996; Meinke et al. 1998). In general, yields in La Niña years have been higher in countries west of the Pacific and lower in those east of the Pacific. Simulations

were also conducted to investigate the influence of ENSO phases on yields of peanut in Australia (Meinke and Hammer 1995), maize in Zimbabwe (Phillips et al. 1998), and several crops in other countries (Hansen et al. 1998; Messina et al. 1999). In China, only one study significantly linked rice production in northern and north-western China with ENSO (Zhang et al. 2008). The monthly Southern Oscillation Index (SOI) is widely used as a measure of the strength of ENSO (Gordon 1986; Ropelewski and Halpert 1987) and was also used for measuring the correlation between the SOI and rainfall in Australia (Mcbride and Nicholls 1983). Although the North China Plain (NCP) is agriculturally the most important region in China, the impact of ENSO on climate and crop production in the region has received only limited attention. Because ENSO is the largest signal in the inter-annual variation in the atmosphere–ocean system and affects global climate, the related climatic variability and crop production along with ENSO are among the most important frontiers of research in China. Therefore, the present study sought to: (1) describe the trends in a few climatic variables and analyse the impact of ENSO on them in the NCP and (2) study the effect of three phases of ENSO (years with El Niño events, years with La Niña events, and neutral years) on yields of winter wheat and summer maize.

Materials and methods

Study sites

Three study sites (Fig. 1) were selected from the observational stations of the National Meteorological Network of Central China Meteorological Administration (CMA), namely Nanyang (33.0°N, 112.6°E; 129.2 m) and Zhengzhou

Fig. 1 Location of agricultural experimental stations across the NCP: Nanyang and Zhengzhou in Henan province and Luancheng in Hebei province

Table 1 Basic experimental information on the crop (typical average dates of sowing, anthesis, and maturity) and the weather (annual mean temperature, annual mean sunshine hours, and annual total precipitation) from 1981 to 2005 at the study sites

Event or variable	Nanyang		Zhengzhou		Luancheng	
	Wheat	Maize	Wheat	Maize	Wheat	Maize
Planting date (day/month)	23/10	08/06	15/10	07/06	04/10	05/06
Flowering date (day/month)	06/05	03/08	26/04	01/08	26/04	31/07
Maturity date (day/month)	29/05	14/09	31/05	11/09	08/06	16/09
Mean temperature (°C)	13.8	25.6	13.9	25.0	14.5	25.5
Mean sunshine hours (h)	5.1	5.8	6.1	6.0	6.9	6.4
Precipitation (mm)	229	440	199	360	142	367

(34.8°N, 113.7°E; 80.0 m) in Henan province and Luancheng (37.9°N, 114.6°E; 52.5 m) in Hebei province. These sites were chosen because long-term crop data were available for each and because they were located along the south–north axis of the NCP. Both annual air temperature and annual rainfall decrease from the south to the north. For Nanyang, Zhengzhou, and Luancheng, the mean values of annual mean air temperature are 15.0, 14.4, and 13.4 °C and of annual precipitation are 784, 643, and 528 mm, respectively (Table 1).

Weather and crop data

Daily weather data from 1956 to 2006 on precipitation, sunshine hours, and maximum, average, and minimum temperature were available from CMA. Data on yields of winter wheat and summer maize at the provincial level for 50 years (1956–2006) were collected from the *China Agriculture Yearbook* (China Statistics Press 2007). A wheat–maize double rotation was practised from 1981 to 2005 at each of the agro-meteorological experimental stations. Typical sowing, flowering, and harvest dates for the crops are shown in Table 1.

ENSO phases/years

Detailed categorization of ENSO is shown in Table 2, which is based on an index from the Japan Meteorological Agency. The index is a 5-month running mean of spatially averaged anomalies in SST over the tropical Pacific: 4°S to 4°N and 90°W to 150°W. When the index values were greater than 0.5 °C in a given ENSO year for six consecutive months from October, the year was categorized as an

Table 2 Categorization of ENSO years (1956–2006) based on the Japan Meteorological Agency's tropical Pacific sea surface temperature anomaly (SSTA) index

El Niño years (warm event)	Neutral years		La Niña years (cold event)
1957	1958	1984	1956
1963	1959	1985	1964
1965	1960	1989	1967
1969	1961	1990	1970
1972	1962	1992	1971
1976	1966	1993	1973
1982	1968	1994	1975
1986	1974	1995	1988
1987	1977	1996	1998
1991	1978	2000	1999
1997	1979	2001	
2002	1980	2003	
2006	1981	2004	
	1983	2005	

El Niño year; when lower than -0.5 °C, the year was categorized as a La Niña year (Sittel 1994a). Of the 51 years of the study period, 13 were El Niño years, 10 were La Niña, and 28 were neutral (Table 2).

Data analysis and preparation

For a more reliable comparison of the different climatic indicators, namely temperature, precipitation, and sunshine

Fig. 2 Raw (grey dots 1956–2006) and smoothed (black line 1958–2004) time series (a) and the detrended residuals (1958–2004) (b) of wheat yield across the whole of China

hours, the trends were removed by detrending the time and leaving the year-to-year residuals, as shown in the following equation.

$$Y = \frac{x - \bar{x}}{\bar{x}} \times 100 \% \quad (1)$$

where Y is the residuals (%), x is the actual value, and $\bar{x}$ represents the smoothed 5-year running means. Trend analysis of the climatic variables during the three phases or categories of ENSO was carried out by examining the slope of the linear regression line of the target variable against time using Student's t test at a confidence level above 95 or 99 %. The contrasting cumulative probability distributions of the climatic variables and of crop yield indicators under the three ENSO phases and for the total period were tested by the Kolmogorov–Smirnov (KS) test.

Smoothed time series of observed national yields (for wheat) were calculated with a 5-year running mean (Fig. 2a). Inter-annual residuals were calculated by subtracting the raw

and smoothed time series. It was assumed that these detrended results are free of non-climate-related influences such as improved varieties, better management, more irrigation, and higher doses of fertilizers since 1956 (Fig. 2b). This assumption made it possible to examine inter-annual yield residuals, which are generally considered sensitive to weather variations. Similar transformations were commonly performed at other research stations. The growth period of wheat was divided into two stages: stage 1 (October–February), which spans the autumn and the winter and stage 2 (March–May), which is confined mainly to the spring. Maize season is from June to September and is confined mainly to the summer.

Crop simulations

Agricultural production systems simulator (APSIM) is a farming systems model that can simulate crop rotations

Fig. 3 Trends in annual precipitation (a–c), annual mean temperature (d–f), and annual mean sunshine hours (g–i) from 1956 to 2006 at the three sites. The straight line is the linear regression line against year. **Significant at $P < 0.01$; *significant at $P < 0.05$

Table 3 Trends in standardized climatic parameters at different growth stages according to the three ENSO phases

Crop and stage	Item	Phases	Nanyang trend	Zhengzhou trend	Luancheng trend
Stage 1 Winter wheat	Rainfall	El Niño	-5	-11	38
		Neutral	9	4	-3
		La Niña	-61	-47	-53
	Sunshine hours	El Niño	1.2	-0.9	3.3
		Neutral	-1.1	-0.7	-0.8
		La Niña	10.1	5.6	11.2
	T_{avg}	El Niño	5.7	1.7	3.1
		Neutral	-2.9	-3.1	-5.3
		La Niña	25.7*	37.9**	67.2**
	T_{max}	El Niño	3.8	2.3	-1.4
		Neutral	-2.2	-2.5	-2.2
		La Niña	20.5	28.7*	35.9**
	T_{min}	El Niño	-0.1	-107.8	13.8
		Neutral	-7.0	0.8	7.6
		La Niña	92.1	479.7	150.1**
	T_{diff}	El Niño	2.1	1.7	-3.0
		Neutral	-1.4	-1.8	-0.7
		La Niña	14.8	19.7	18.1
Stage 2 Winter wheat	Rainfall	El Niño	33	22	4
		Neutral	-10	-10	1
		La Niña	24	-16	-28
	Sunshine hours	El Niño	-4.6	-1.6	4.3
		Neutral	0.6	-0.3	-1.1
		La Niña	-2.3	-11.5	-2.1
	T_{avg}	El Niño	1.2	3.4	3.4
		Neutral	-0.7	-0.8	-0.7
		La Niña	-0.2	-0.6	1.9
	T_{max}	El Niño	0.1	1.5	1.4
		Neutral	-0.6	-0.7	-0.8
		La Niña	0	-1.6	4.1
	T_{min}	El Niño	1.5	6.6	7.5
		Neutral	-0.9	-0.9	-0.2
		La Niña	0.8	-4.1	-7.5
	T_{diff}	El Niño	-1.8	-2.8	-2.6
		Neutral	-0.1	-0.5	-1.2
		La Niña	-2.1	4.8	10.7
Summer maize	Rainfall	El Niño	-40	-33	-18
		Neutral	14	9	14
		La Niña	-40	-22	-57
	Sunshine hours	El Niño	5.9	8.3	7.4
		Neutral	-1.8	-2.4	-1.7
		La Niña	5.7	3.1	5.8
	T_{avg}	El Niño	2.2*	3.2*	1.9
		Neutral	-0.9	-0.9	-0.9
		La Niña	3.8*	2.2	4.0
	T_{max}	El Niño	2.9*	3.9*	1.1
		Neutral	-1.3	-1.1	-1.0
		La Niña	4.1*	2.1	4.8
	T_{min}	El Niño	0.4	2.4	3.1
		Neutral	-0.5	-0.4	-0.8
		La Niña	3.0	-0.2	2.3
	T_{diff}	El Niño	9.3	7.4	-2.0
		Neutral	-3.0	-2.3	-1.5
		La Niña	0	6.0	8.7

All units of climatic parameters are percentages of changes per decade due to be standardized. Stage 1 and Stage 2 of winter wheat represent the period from October to February and from March to May, respectively, and the summer maize season is from June to September

P precipitation, SH sunshine hours, T_{max} maximum temperatures, T_{avg} average temperatures, T_{min} minimum temperatures, T_{diff} diurnal

** Significant at $P < 0.01$; * significant at $P < 0.05$

and effects of management practices worldwide (McCown et al. 1996; Asseng et al. 1998, 2000; Southworth et al. 2000; Keating et al. 2003). APSIM is preferably run with a time resolution of 1 day. The model can simulate, in terms of yield, the response to alternative management practices such as irrigation, fertilizer application, and the choice of cultivar over many years of weather data (Meinke and Hammer 1995; Boote et al. 1996; Mavromatis et al. 2002).

Agricultural production systems simulator has been widely tested in many countries including Australia, the Netherlands, Philippines, and the USA, and also in West Asia and North Africa, under a wide range of conditions on both temporal and spatial scales (Asseng et al. 1998, 2000; Nelson et al. 1998; Lyon et al. 2003; Wang et al. 2003). The model has also been calibrated, validated, and used in China. Sun and Feng (2005) assessed the effects of drought on wheat production using APSIM-Wheat in Beijing, China. Wang et al. (2007) evaluated APSIM by simulating the production and water use in a wheat–maize double cropping system in the NCP and found that the model predicted crop growth and yield in

the study areas reasonably well. Chen et al. (2010a, b), who calibrated and validated APSIM using 3 years of experimental data in Luancheng, also concluded that the model was able to simulate crop yields and water use in wheat–maize rotations in the NCP. In general, these applications of APSIM indicate that simulation can explain at least 60 % of the variation in biomass, yield, and water use in these tested areas. In this study, we relied on the model performance based on the earlier work on model validation and also used the model for constructing vulnerability scenarios of current agricultural management practices in China. The wheat–maize rotation was simulated from 1956 to 2006 using the daily weather data. One cultivar of wheat for each location (Zhengyin_1 for Nanyang, Zhengzhou_761 for Zhengzhou, and Pin_39 for Luancheng) and one of maize (Yunong_704 for Nanyang, Zhengdan_2 for Zhengzhou, and Luyuandan_9 for Luancheng) were used for the entire 50-year period to eliminate the impact of varietal changes. All the cultivars of wheat and maize actually grown in 1981—the midpoint of the simulation period—were calibrated and validated using

Fig. 4 Cumulative probability distributions of subsequent simulated potential (a–f) and rain-fed yields (g–l) of wheat and maize under ENSO phases at Nanyang, Zhengzhou, and Luancheng. Solid black

lines show the all-year distribution, Dashed lines show the neutral years, and grey lines with “open square” and “asterisk” show the La Niña and El Niño years, respectively

Fig. 5 Cumulative probability distributions of subsequent yields of wheat and maize under ENSO phases at the national level and at the provincial level. Dashed lines show the neutral years and grey lines with “open square” and “asterisk” show the La Niña and El Niño years, respectively

experimental data for each site. All simulations were conducted assuming a full dose of fertilizers to eliminate the impact of nutrient stress. Two water regimes were assumed for each site, namely full irrigation and no irrigation (rain-fed cultivation). The local mean sowing date for each site and crop (Table 1), planting density, and other management practices were kept constant throughout.

Results

Variability of climatic parameters in ENSO phases

Climate change in China in the twentieth century mainly involved changes in precipitation, sunshine hours, and temperature (Fig. 3). The pattern of changes was generally similar for all the three sites.

Annual precipitation decreased slightly ($P > 0.05$) (Fig. 3a–c), from -19 mm per decade at Luancheng to -4 mm per decade at Zhengzhou, whereas annual mean sunshine hours decreased significantly by about 0.5 h per

decade ($P < 0.01$) at all the sites (Fig. 3g–i). The extent of warming increased from south to north (Nanyang to Luancheng), as seen in the increase in mean temperatures. The annual mean minimum temperature also increased ($P < 0.01$) at each site whereas the annual mean maximum temperature increased only slightly ($P > 0.05$), leading to a significant increase in mean air temperature (Fig. 3d–f), from 0.1 °C per decade at Nanyang to 0.4 °C per decade at Luancheng ($P < 0.01$).

Table 3 shows the trends in standardized climatic variables in each ENSO phase. For wheat, residuals of precipitation tended to decline in both El Niño and La Niña years during pre-flowering compared to those in neutral years at Nanyang and Zhengzhou but not at Luancheng, although in none of the cases was the change significant at 95 % CI. Residuals of precipitation during the post-flowering stage tended to increase markedly during both El Niño and La Niña years and to decrease during neutral years for all sites ($P > 0.05$). Likewise, for all the three sites, the number of sunshine hours increased slightly during both El Niño and La Niña years and decreased during neutral years ($P > 0.05$) in stage 1 of wheat

Table 4 *P* value in the Kolmogorov–Smirnov test for different levels of grain yield of wheat and maize versus ENSO phases

	Potential						Rain fed						Provincial					
	Wheat			Maize			Wheat			Maize			Wheat			Maize		
	NY		LC	NY		LC	NY		LC	NY		LC	National		Hebei	National		Henan
	ZZ	LC	NY	ZZ	LC	NY	ZZ	LC	NY	ZZ	LC	NY	ZZ	LC	NY	ZZ	LC	NY
All years versus El Niño years	1	1	1	1	0.96	0.96	1	0.96	0.54	1	0.96	0.98	1	0.89	1	1	0.96	0.98
All years versus Neutral years	1	1	1	1	1	1	1	1	1	1	1	1	1	0.89	1	1	1	0.98
All years versus La Niña years	1	1	1	1	0.96	1	0.54	0.96	1	0.70	0.70	0.70	0.89	0.89	0.94	1	0.96	0.70
El Niño years versus Neutral years	1	1	1	1	0.96	0.96	0.54	0.96	0.96	0.70	0.98	0.98	0.89	0.89	1	0.89	0.96	0.70
El Niño years versus La Niña years	1	1	1	1	0.96	0.96	1	0.96	1	0.34	0.34	0.34	0.89	0.89	0.94	1	0.63	0.34
Neutral years versus La Niña years	1	1	1	1	0.96	0.96	0.54	0.96	1	0.70	0.70	0.70	0.89	0.89	0.94	0.89	0.96	0.70

** Significant at $P < 0.01$; * significant at $P < 0.05$

production; in stage 2, the pattern was the exact opposite ($P > 0.05$). The mean maximum temperature increased during the vegetative stage (stage 1), significantly so at Zhengzhou ($P < 0.05$) and Luancheng ($P < 0.01$), which led to a significant increase in the mean temperature at all sites ($P < 0.01$). During the reproductive stage (stage 2, from March to May), there was little variation in temperature at any of the sites ($P > 0.05$).

In the case of maize (June–September), residuals of precipitation declined in both El Niño and La Niña years and increased slightly in neutral years at all sites, but none reached the confidence level of 95 %. The number of sunshine hours in both the categories was higher than that in neutral years ($P > 0.05$); temperature followed the same pattern, most significantly the mean and maximum temperature in El Niño years at Nanyang ($P < 0.05$) and Zhengzhou ($P < 0.05$) and the maximum temperature in La Niña years at Nanyang ($P < 0.05$).

Variability in crop yields in ENSO phases

Crop yields in the NCP were affected by the phases of ENSO, and the magnitude of the effect varied with the phase. Figure 4 shows the cumulative probability distributions of grain yields of wheat and maize—assuming either full irrigation or no irrigation (rain-fed cultivation)—under the three ENSO phases and for total years at all the three sites. Probability distributions of wheat yield assuming full irrigation (Fig. 4a–c) did not differ markedly among the three ENSO phases or for total years, being only slightly lower in La Niña years at Zhengzhou and Luancheng, although none of the differences was significant at the 95 % level (Table 4). In the case of maize (Fig. 4d–f), the distributions were different, although not markedly so, for each of the phases, those for both El Niño and La Niña years being slightly higher than those for neutral years and for total years at every site ($P > 0.05$). In other words, different phases of ENSO affect precipitation and even yields to different degrees. However, irrigation can compensate for the loss in yield due to lower precipitation, resulting in only slight differences in the probability that yields would be affected by the ENSO phases.

Cumulative probability distributions of yields of rain-fed wheat and maize under the ENSO phases are shown in Fig. 4g–l. For wheat (Fig. 4g–i), the probability distributions in El Niño and La Niña years were higher than those for total years at each site, although at Nanyang the differences between El Niño and La Niña events were significant only at the 5 % level. For maize (Fig. 4j–l) at all the sites, the lowest probability distributions were seen in El Niño years and reached the confidence level of 95 % in La Niña years.

Probability distributions of wheat and maize yields at the national and provincial levels are shown in Fig. 5. The

Fig. 6 Cumulative probability distributions of subsequent precipitation at different growth stages of wheat and maize under ENSO phases. Solid black lines show the all-year distribution. Dashed lines show the neutral years, and grey lines with “open square” and “asterisk” show the La Niña and El Niño years, respectively. The

growth period of wheat was divided into two stages: stage 1 (October–February) spanned the autumn and the winter and stage 2 (March–May) is confined mainly to the spring. The maize season is from June to September, and is confined mainly to the summer

differences were not significant in Hebei and Henan provinces under any of the four periods and were the lowest in La Niña years ($P > 0.05$). Crop yields on a national or provincial scale, especially in Hebei and Henan provinces, two of the principal production areas, showed little change under the ENSO phases ($P > 0.05$) because other factors compensated for the adverse effects.

Discussion

El Niño and La Niña represent the opposite extremes of the ENSO cycle (Ropelewski and Halpert 1986). However, under these extremes as well as under neutral conditions, the values of SOI are near zero, the long-term average. Studies have shown that La Niña summers tend to be slightly wetter than

normal in the USA (Sittel 1994a, b). ENSO can also affect climate variability, which has been identified as a key driver of agricultural productivity, especially since it affects the extent to which water is available for agricultural production in the NCP (Waddington 1994; Tao et al. 2003). Huang and Wu (1989) discovered that weak convective activity around the South China Sea during the developing stage of ENSO may result in drought in the Indo-China peninsula. Liu and Ding (1995) analysed seasonal precipitation and temperature in China during ENSO events for the last 40 years and found that both were lower than normal on the whole in ENSO years, whereas the anomalies were almost exactly the opposite—higher than average rainfall and temperatures—in the following year in most parts of China.

Climate variability was identified as a major constraint to agricultural productivity (Waddington 1994), and

variability in the availability of water for agriculture in the NCP especially so (Tao et al. 2003). Figure 6 shows the probability of exceeding distributions of higher precipitation in the year following the ENSO phases and in all years, respectively, during the two growth stages of winter wheat, namely stage 1 (pre-flowering) and stage 2 (post-flowering). For stage 1, the probability of higher precipitation differed little among the three ENSO phases and over the total years ($P > 0.05$) at the three sites, although it was a little lower in El Niño and La Niña years than in neutral years and over the total years. For stage 2 of wheat, the probability distribution in La Niña years was significantly higher than that in the other two phases and over the total years ($P < 0.05$) at Nanyang, but differed little ($P > 0.05$) at other sites. The probability of exceedance was the highest in La Niña years and the lowest in El Niño years at the three sites (significantly so at Nanyang and Luancheng; $P < 0.05$), especially for maize, whereas it was intermediate in neutral years and for total years.

Variations in other climatic variables under the three ENSO phases during different stages of crop growth are not discussed here because the variations were not significantly different. Precipitation, which is the key factor influencing crop yield in the NCP, varies between about 470 and 900 mm because of the influence of the monsoon, which is active mainly from June to September (Jin et al. 1999), and is thus critical to the productivity of winter wheat–summer maize rotation system. Crops during the summer monsoon (June–September), especially maize in the present context, are subjected to seasonal variability in rainfall associated with ENSO. Wheat growth and grain yields are typically sensitive to variability in precipitation in the spring (Bai et al. 1999), but the seasonal variability associated with ENSO did not affect wheat yield significantly (Fig. 5a–c). Although ENSO's influence on rainfall is spatially less consistent, the growing season tends to be wet in El Niño years and dry in La Niña years. Temperature and the distribution of rainfall during the growing season influence plant growth. Maize needs moisture during the flowering phase for the pollen to stick to the tassels and, later, for filling the grains (Cane et al. 1994).

Evidence has been growing that ENSO influences crop production through its influence on weather patterns in some regions. El Niño events were associated with low grain yields in south Asia and Australia and with high grain yields in the North American prairies (Garnett and Khandekar 1992; Hansen et al. 1998). We tested two extreme cases in this study, namely plentiful water (through irrigation) and scarcity of water (precipitation as the sole source of water), to assess the extent to which lower yields due to the variability of weather can be attributed to limited availability of water (Fig. 4a–l).

Hansen et al. (1998) attributed the effect of ENSO on maize yield in La Niña years primarily to enhanced precipitation in June, a period that coincides with tasselling, the stage at which maize is most susceptible to water stress in southern Georgia. Correlations between ENSO and crop yields in China have been recognized, but research that focuses on causes continues to be inadequate.

Acknowledgments This work was supported by the Ministry of Science and Technology of China ('973' project, Grant No. 2010CB951502), National Key Technology R&D Program (NO. 2012BAD20B04), the Department of Agriculture (No. 200903003), Basic Scientific Research Foundation of National non-Profit Scientific Institute of China (No. BSRF201102) and also by the CSIRO-Chinese Ministry of Education (MOE) PhD Research Fellowship Program.

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