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ENSO, climate variability and crop yields in China

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ABSTRACT: The El Niño-Southern Oscillation (ENSO) is one of the most important contributors to global interannual climate variability, but the relationship between seasonal climate and crop yield variations associated with ENSO in China remains inconclusive. In this study, we investigated the impacts of ENSO on the yield of 3 staple crops (rice, wheat, and corn) at the provincial scale. We found that ENSO has significant impacts on wheat yields throughout China, and on rice and corn yields in major production areas. Specifically, more (less) rainfall during the wheat growing season in El Niño (La Niña) years leads to increases (decreases) in wheat yield, especially in southeastern China. Increases (decreases) in rice yield in northeastern China are due to warming (cooling) in El Niño (La Niña) years. In southern China, the variability of rainfall plays a more important role in rice yield than that in northern China. Corn yields in northern China are significantly affected by ENSO-induced changes in maximum temperature, solar radiation, and rainfall. Moreover, all of the staple crop yields are highly correlated with the ENSO index with a lead of at least 6 mo. For rice and corn in many provinces, the yields are typically most correlated with the index of the spring season during the ENSO developing years, suggesting that such yields can be predicted 1 yr before the growing season. The large variability in seasonal climate and agricultural production associated with ENSO warrants the application of ENSO information to food market management in China.

KEY WORDS: ENSO · Crop yields · Climate variability · China

1. INTRODUCTION

Global climate change may affect our food security, as agriculture output depends strongly on climate conditions (e.g. Lobell et al. 2011b). The recent suggestions that global change may cause stronger interannual climate variation have only strengthened this concern (Sun & Bryan 2010, IPCC 2012). Interannual climate variability directly impacts crop growth, development, and yield, and indirectly influences pest dynamics and fertilizer efficiency (Thompson 1986, IRRI 1975). Thus, a stronger interannual variability may increase the risk of production losses that farmers face (IRRI 1975, Thompson 1975, Phillips et al. 1999, Tao et al. 2008, Lobell et al. 2011b). To assess this increased risk, a better understanding of the effects of interannual climate variability on crop yield is necessary.

The El Niño-Southern Oscillation (ENSO), which refers to fluctuations in both sea-surface temperature (SST) in the tropical Pacific and sea-level pressure in the southern Pacific (the Southern Oscillation Index), is one of the most important contributors to global interannual climate variability (Rasmusson & Carpenter 1983, Nicholls 1989, Montecinos & Aceituno 2003). Climate variability in China is dominated by the East Asian monsoon system (Ding & Chan 2005), which is always significantly influenced by ENSO, including the winter temperature variations (Wu et al. 2010), the spring and summer total precipitation

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amount (Huang & Wu 1989, Chang et al. 2000), and summer precipitation extremes (Wang & Yan 2011). For example, Wu et al. (2003) found that more precipitation tends to occur in south and southeast China during the winter of El Niño years, and this anomaly continues until next spring. They also found that droughts are likely to appear in the Huai River watershed following the decaying stage of El Niño. A similar pattern has been substantiated by recent studies (e.g. Feng et al. 2010, 2011), suggesting the persistent influence of ENSO on precipitation in China. Actually, paleoclimatic evidence has shown that ENSO can continue to operate in very different background climate states regardless of glacial periods or glacial intervals (IPCC 2012). Moreover, in addition to global warming, the level of ENSO activity is also increasing (Liang et al. 2012), which indicates that ENSO will still be an important controlling factor in terms of climate variability in the changing future. Such a strong connection between ENSO and climate variability offers considerable opportunities for farmers to improve potential agricultural yields via an agricultural early warning system for meteorological disasters using ENSO information.

China provides about one-fifth of global grain production (Dawe 2009). Due to the large population and the relatively small cultivated land area in China, even small changes in food supply and demand could have large global impacts (Simelton 2011). Rice, wheat, and corn — 3 essential components of the diet for more than half of the world's population — are the most socially and economically important crops in China, contributing >90% of the national cereal yields (NBSC 2011). However, agriculture is very sensitive to variation in climate, and is vulnerable to natural hazards, such as flood and drought (Simelton 2011). Every year, an average of approximately 31.1% of cultivated areas is affected by meteorological disasters. Among these disasters, droughts (56.2%), floods (24.2%; since 1950), and frost (5.8%; since 1978), which all might be associated with ENSO, accounted for 86.2% of all events (Wang et al. 2007).

Studies assessing the impacts of ENSO on climate and crop yields have been conducted in many countries. For example, Cane et al. (1994) found that corn yields in Zimbabwe are more strongly associated with the ENSO index than climate variables such as rainfall, and concluded that the eastern equatorial SST can be used to predict national corn yields. Following them, extensive studies on the association between crop yields and ENSO have been performed for many regions of the world, such as Africa (Phillips & McIntyre 2000), North America (Phillips et al. 1999, Wu et al. 2011), South America (Meza & Wilks 2003, Meza et al. 2003), and Asia (Naylor et al. 2001, Bannayan et al. 2010). However, such studies in China are not extensive, and some results are inconsistent. For example, Tao et al. (2004) investigated the relationship between ENSO/EASM (East Asian Summer Monsoon) and 3 staple crop yields during developing ENSO years using data from 7 provinces, and found that there was large variability in production associated with EASM and ENSO. Other studies show strong connections between ENSO and crop yields in Yunnan (Tian et al. 2000), Sichuan (Xiao & Chen 1994), and mid-eastern China (Meng 2009). However, a study concerning rice yields in Jiangxi does not support the above statements (Deng et al. 2010), and instead implies that the relationship between ENSO and staple crop yields in China varies across crops and regions. Therefore, the effect of ENSO on main crop yields in China remains inconclusive. Investigation of the relationships between ENSO and crop yields in China was limited to some locations and crops. Identifying the mechanisms by which ENSO influences different crop yields at a provincial scale across the entire nation will be crucial for comprehensive assessment of the agricultural production risk.

In this study, we focus on the impact of ENSO on crop yields during the decaying stage of ENSO years, because the information on this stage allows much more time for governments and farmers to make decisions and preparations than that during the developing stage of ENSO years. The present study aims to investigate the: (1) variability in crop-growing seasonal climate associated with ENSO events at the provincial scale during decaying ENSO years; (2) impacts of the climate variations associated with ENSO on staple crop yield across China by province; and (3) applications of ENSO information to prevent agricultural disasters and to ensure food security.

2. DATA AND METHODS

2.1. ENSO index

The monthly SST anomalies in the region from 150 to 90° W and 4° N to 4° S, smoothed into 5 mo running means (ENSO index), are used to measure ENSO activity and define ENSO phases (El Niño, neutral, and La Niña). Our definition of ENSO phases follows that of the Center for Ocean-Atmospheric Prediction Studies (http://coaps.fsu.edu/jma.shtml). A year (October–September) is classified as El Niño (La

Niña) if SST anomalies are at least +0.5°C (≤−0.5°C for La Niña) for at least 6 consecutive months and if this 6-mo period starts before October and includes October–December. According to the classification, the study period from October 1962 to September 2008 includes 12 El Niño events in total (1963/64, 1965/66, 1969/70, 1972/73, 1976/77, 1982/83, 1986/87, 1987/88, 1991/92, 1997/98, 2002/03, and 2006/07) and 11 La Niña events (1964/65, 1967/68, 1970/71, 1971/72, 1973/74, 1974/75, 1975/76, 1988/89, 1998/99, 1999/00, and 2007/08).

2.2. Crops

The planting area of rice, wheat, and corn in mainland China is approximately 29, 28, and 22 million ha, respectively (Zhang & Huang 2013), and is distributed across a wide range of locations and climatic conditions. Nearly all provinces except Qinghai grow rice. However, in northern China, single-crop rice is common, while south of 30°N, double-crop rice (and triple-crop rice in some locations) dominates. Wheat occupies a high proportion of the area in the north, northeast, and northwest regions. Winter wheat is cultivated in most provinces of China, and spring wheat is mainly grown in the northeast and northwest regions. Corn is mainly cultivated in southwestern, northeastern, and northern provinces, and mostly in the summer. The growing seasons for rice, wheat, and corn are summarized in Table 1 (Sun & Huang 2011, Zhang & Huang 2013), and the distribution of provinces in China is shown in Fig. 1A.

Table 1. Growing seasons of rice, wheat, and corn in China. Provinces with continuous crop yield records are marked with 'Y' in the 'P' column. For the cropping system of double-crop rice, the growing season was defined to cover the growing period of both early and late rice. Chongqing was separated from Sichuan in 1997, but all statistics for Chongqing were included in Sichuan in our study

Province	Rice			Wheat			Corn		
	Sowing	Harvest	P	Sowing	Harvest	P	Sowing	Harvest	P
Anhui	May	Sep	Y	Oct	May	Y	Jun	Sep	Y
Beijing	May	Sep	Y	Oct	Jun	Y	Jun	Sep	Y
Fujian	Mar	Sep	Y	Nov	Apr	Y	Mar	Aug	–
Gansu	May	Sep	Y	Oct	Jun	Y	May	Sep	Y
Guangdong	Feb	Oct	Y	Nov	Mar	Y	Mar	Aug	–
Guangxi	Feb	Oct	Y	Nov	Mar	Y	Mar	Aug	Y
Guizhou	Apr	Aug	Y	Nov	Apr	Y	Jun	Sep	Y
Hebei	May	Sep	Y	Oct	Jun	Y	Jun	Sep	Y
Heilongjiang	Apr	Aug	Y	Apr	Jul	Y	May	Sep	Y
Henan	May	Sep	Y	Oct	Jun	Y	Jun	Sep	Y
Hubei	May	Sep	Y	Nov	May	Y	Jun	Sep	Y
Hunan	Mar	Sep	Y	Nov	May	Y	Jun	Sep	Y
Jiangsu	May	Sep	Y	Nov	May	Y	Jun	Sep	Y
Jiangxi	Mar	Oct	Y	Nov	May	Y	Jun	Sep	–
Jilin	Apr	Aug	Y	Apr	Jul	Y	May	Sep	Y
Liaoning	Aug	Aug	Y	Apr	Jul	Y	May	Sep	Y
Inner Mongolia	Apr	Sep	Y	Apr	Jul	Y	May	Sep	–
Ningxia	May	Sep	Y	Mar	Jul	Y	May	Sep	–
Qinghai	–	–	–	Mar	Jul	Y	May	Sep	–
Shaanxi	May	Sep	Y	Oct	Jun	Y	May	Sep	Y
Shandong	May	Sep	Y	Oct	Jun	Y	Jun	Sep	Y
Shanghai	Mar	Sep	Y	Nov	May	Y	Jun	Sep	–
Shanxi	May	Sep	Y	Oct	Jun	Y	May	Sep	Y
Sichuan	Apr	Aug	Y	Nov	Apr	Y	Jun	Sep	Y
Tianjin	May	Sep	Y	Oct	Jun	–	Jun	Sep	–
Xinjiang	Apr	Sep	Y	Oct	Jun	Y	May	Sep	Y
Xizang	–	–	–	–	–	–	–	–	–
Yunnan	Apr	Aug	Y	Nov	Apr	Y	Jun	Sep	Y
Chongqing	Apr	Aug	Y	Nov	Apr	Y	Jun	Sep	Y
Zhejiang	Mar	Sep	Y	Nov	May	Y	Jun	Sep	Y
Hainan	Feb	Oct	–	Nov	Mar	–	Mar	Aug	–

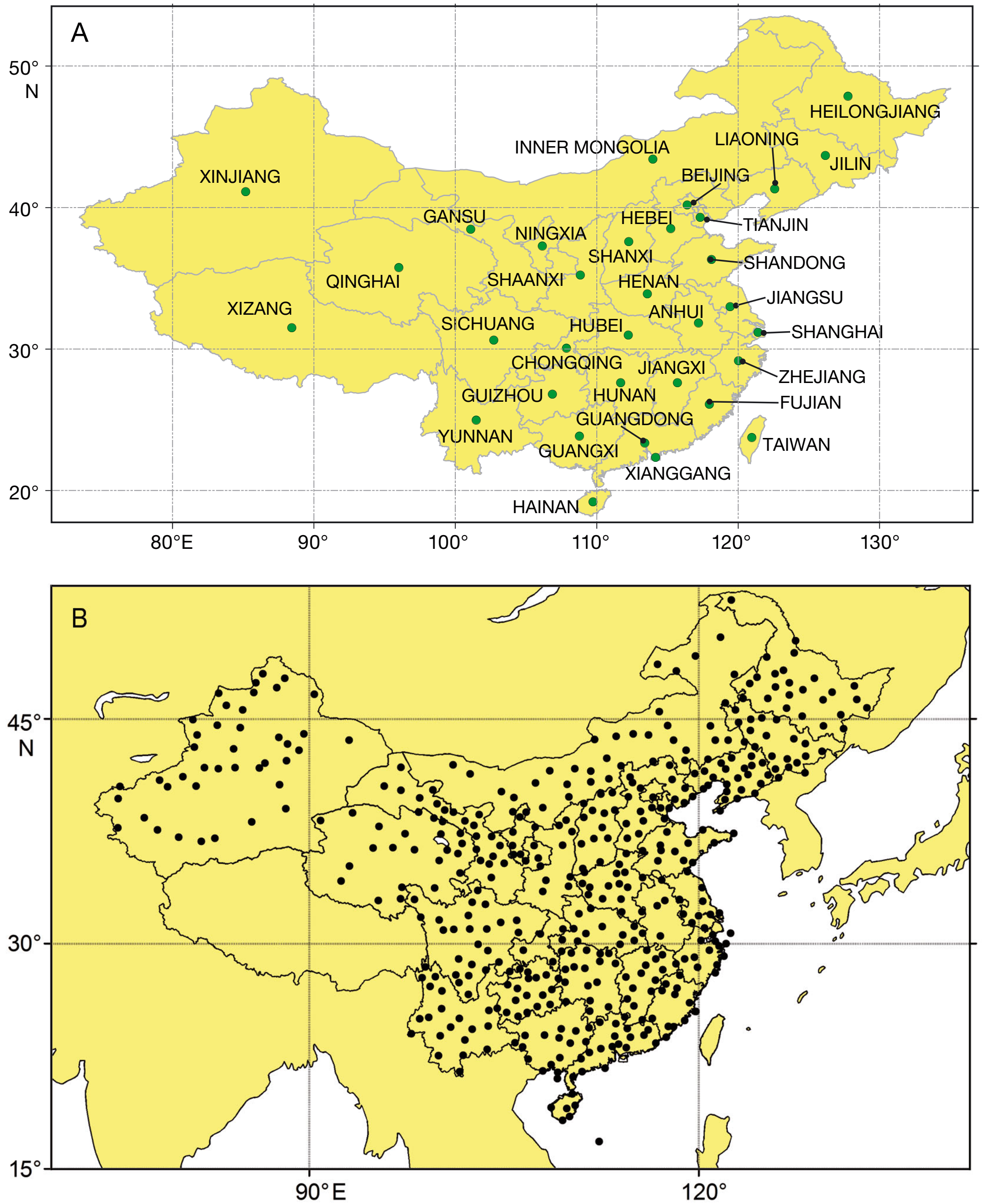

Fig. 1. (A) Provinces of China, covered in this study. (B) Distribution of weather stations used to calculate the province-averaged climate parameters. No stations in Xizang and Shanghai Provinces were used due to the lack of a continuous record

2.3. Data collection

National and provincial yield data of wheat and corn (1961–2010) were obtained from China Planting Information, sources of which are the China Agricultural Statistics Yearbook and China Statistic Yearbook (http://zzys.agri.gov.cn/nongqing.aspx). The data for rice from 1961 to 2010 were obtained from the world rice statistics of the International Rice Research Institute (www.irri.org/science/ricestat/index.asp). Provinces with continuous yield data during 1961–2010 are shown in Table 1.

Historical climate data in China were obtained from the China Meteorological Data Sharing Service System (http://cdc.cma.gov.cn/). Monthly maximum temperature (T_{max}), minimum temperature (T_{min}), precipitation (P), and sunshine duration (S) data are available from 458 weather stations that provide continuous records from October 1962 to present (Fig. 1B). Since solar radiation data are not available due to the cost, maintenance, and calibration requirements of the measuring equipment, here we use S as a substitute, as have many climate–yield relationship studies (e.g. Zhang et al. 2010, Shuai et al. 2013). The climate data are averaged over the growing season to derive average T_{max}, T_{min}, S, and total P during the growing season in each province/crop combination for each year. In order to alleviate the effects of inhomogeneous distributions of different climate variables on the analysis, all the climate data have been normalized (standardization to zero mean and unit variance). The 200 and 500 mb geopotential height data and 850 mb wind data were obtained from the National Center for Environmental Prediction–National Center for Atmospheric Research reanalysis (www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.derived.html).

2.4. Analysis

To investigate the ENSO–climate–yield relationships at the provincial scale, non-climatic influences such as improvement in crop management and technology should be removed. Previous studies have used some simple regression functions to remove the non-climate influences (e.g. Thompson 1986). However, crop management changes in response to price fluctuations and the availability of new technology are often difficult to fit to a simple regression function. Also, there is no theoretical basis for selecting one functional form over another (Hansen et al. 1998). Therefore, here we apply 5 yr running means to separate yield residuals from the low-frequency yield trend following Zhang et al. (2008):

$$y = \frac{x - \bar{x}}{\bar{x}} \times 100\% \tag{1}$$

where y is yield residuals (%), x is the actual yield (kg ha^{-1}), and $\bar{x}$ represents the expected yield smoothed into 5 yr running means (kg ha^{-1}).

First, the influences of ENSO on crop yield (for rice, wheat, and corn) and climate variables (T_{max}, T_{min}, P, and S) during each crop's growing season are examined. ANOVA is used to test the influence of ENSO phases on crop yield and climate variables. The significance ($p < 0.10$ or $p < 0.05$) of ENSO's effect on weather variables or crop yield is identified by the F-test. Then, we use Pearson's correlation to identify the crop–climate relationship for each crop at the provincial scale, and investigate the key provinces whose yield variability is highly related with ENSO. The significance is tested by a 2-tailed t-test. The Granger causality test (Granger 1969) is also used to examine the causal relationship between climate variables and crop yield. The significance is tested by the F-test. Finally, the leading time of the ENSO signal for crop yields in some key provinces is examined through Pearson's correlation between crop yields and 3 mo sliding ENSO index from the beginning of the developing year to the end of the decaying year, using a 2-tailed t-test to identify the significant correlation.

3. RESULTS

3.1. Variability in climate

3.1.1. El Niño

Most provinces in China show a decrease in T_{max}, T_{min}, and S, and an increase in P for the growing season of all 3 crops in El Niño years (Fig. 2). More rainfall appears in northwest China during the growing season of rice and corn, but for the wheat-growing season, more rainfall is found in southeast China (Fig. 2G–I). The spatial pattern of differences in S is similar to that of differences in P but with opposite sign (Fig. 2J,K,L). A reduction in S is observed in almost all provinces, with significant anomalies in Gansu and Ningxia Provinces ($p < 0.05$) in northern and northwestern China in the rice-growing season. As for temperature, especially T_{min}, such distributions look much more similar among the 3 crops. Temperature in northern China has a slightly negative difference between El Nino years and neutral years, while in south China shows a positive difference (Fig. 2A–F).

Additionally, the effect of El Niño on P is much more significant than that on T_{max} and T_{min} for all 3 crops. According to the F-test, there are significant changes ($p < 0.10$ and $p < 0.05$) in P in 5 provinces for rice and corn (Gansu, Shaanxi, Shanxi, Tianjin, and Xinjiang Provinces, mainly in northwest China), and 10 provinces for wheat (Fujian, Guangdong, Guizhou, Hubei, Hunan, Jiangsu, Jiangxi, Xinjiang, Yunnan, and Zhejiang Provinces, mainly in south and southeast China). Strong effects on temperature are found only in 2 provinces (Guangxi Province for T_{min} in the rice-growing season and Hainan Province for T_{max} in the corn-growing season).

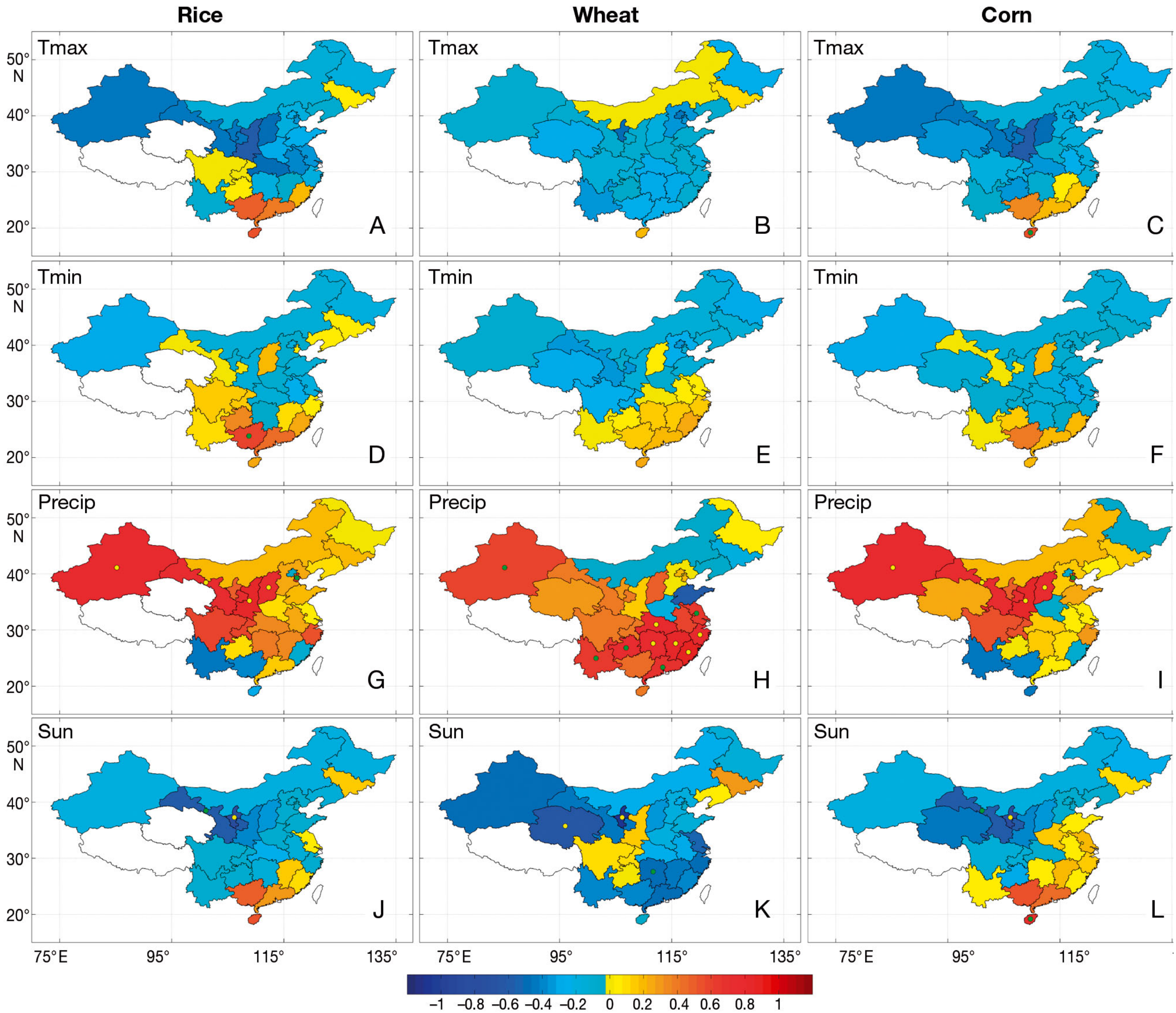

Fig. 2. Differences in climate variables during the growing season in El Niño years compared to neutral years: (A–C) maximum temperature, T_{max}; (D–F) minimum temperature, T_{min}; (G–I) precipitation; and (J–L) sunshine duration, S. Provinces where the differences in climate variables reached the 90 and 95% confidence levels are marked with green and yellow points, respectively. Color scale: difference after standardization of data to zero mean and unit variance

3.1.2. La Niña

La Niña leads to a decrease in T_{max}, T_{min}, and P, and an increase in S in most of the regions (Fig. 3). In La Niña years, the spatial distributions of these climate variables among the 3 crops are much more consistent than those during El Niño years, although there is a difference in the distribution of P under El Niño conditions. During the growing season of rice and corn, small increases in P are shown in both western and eastern China, while only western regions experience such increases for wheat. As for temperature, T_{max} increases slightly in northern China, while it decreases in southern China, especially for Sichuan, Guizhou ($p < 0.10$), and Yunnan Provinces ($p < 0.05$) in southwestern China for rice during La Niña years (Fig. 3A–C). With the exception of Shanxi Province for rice and corn, T_{min} decreases for all provinces in La Niña years, especially in southeastern regions (e.g. Jiangxi Province

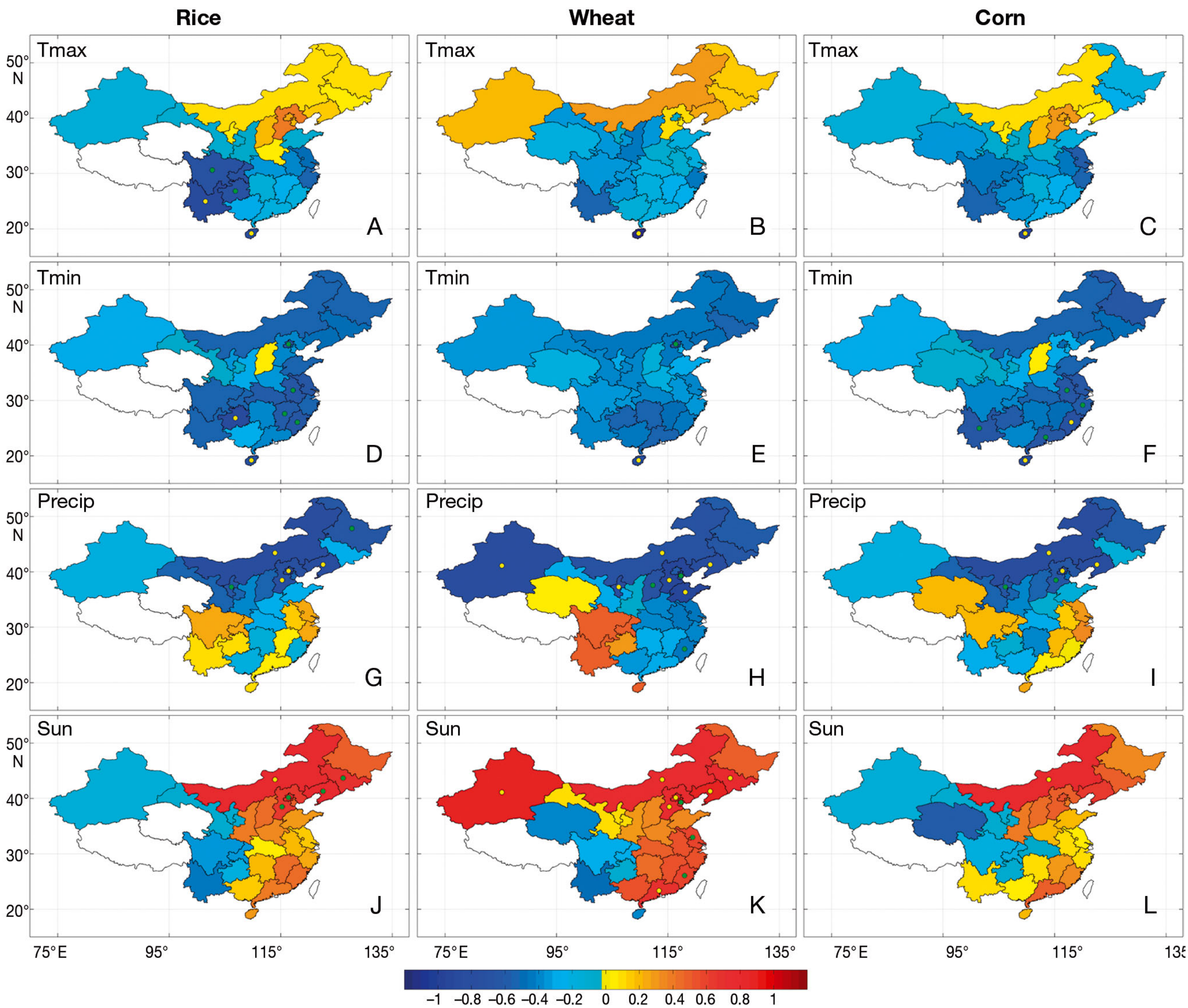

Fig. 3. Differences in climate variables during the growing season in La Niña years compared to neutral years: (A–C) maximum temperature, T_{max}; (D–F) minimum temperature, T_{min}; (G–I) precipitation; and (J–L) sunshine duration, S. Provinces where the differences reach the 90 and 95 % confidence levels are marked with green and yellow points, respectively. Color scale: difference after standardization of data to zero mean and unit variance

for rice, Anhui and Fujian Province for both rice and corn) and southwestern China (e.g. Guizhou for rice and Yunnan for corn; Fig. 3D,F). Meanwhile, La Niña events cause a decrease in sunshine in southwestern China but an increase in northeast, north, southeast, and south China, with significant anomalies in northeastern and northern provinces for all 3 crops (e.g. Jilin, Liaoning, and Hebei Provinces for rice and wheat, and Inner Mongolia for all crops) and eastern areas for wheat (e.g. Jiangsu and Fujian Provinces; Fig. 3J–L).

El Niño has stronger impact on P, while La Niña has a larger influence on temperature and S. Compared with the small increase of T_{max} and T_{min} mainly in southern China during El Niño years, La Niña causes strong decreases in temperature throughout China, especially in T_{min} during the rice and corn growing seasons, with 6 provinces showing strong responses. Additionally, the influences of El Niño and La Niña on P and S are almost opposite: P is enhanced and S is reduced in most provinces under the impacts of El Niño, while P is reduced and S is enhanced during La Niña years.

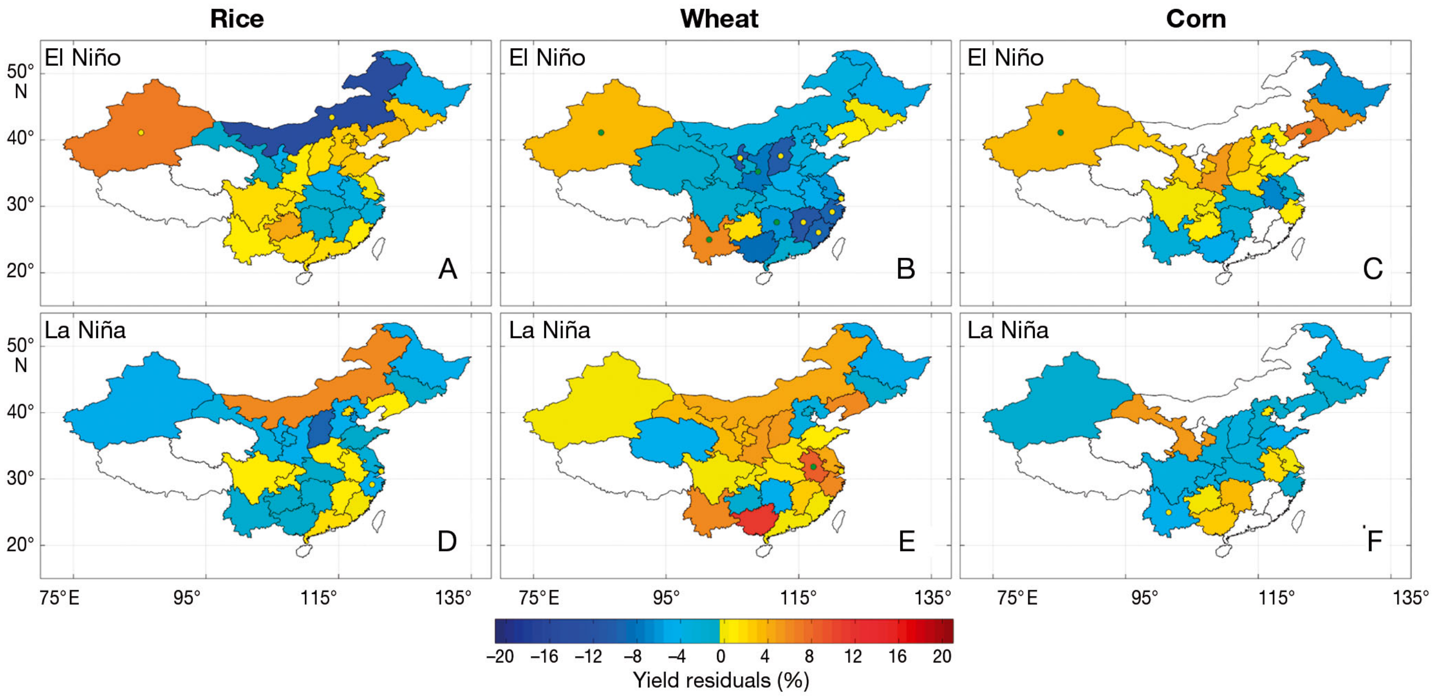

Fig. 4. Difference in yield residuals (%) for rice (A,D), wheat (B,E), and corn (C,F) in El Niño or La Niña years compared to neutral years). Provinces where the differences reach the 90 and 95% confidence levels are marked with green and yellow points, respectively

3.2. Variability in crop yields

Wheat is the only crop that experiences large areas of yield reduction as a result of El Niño events, with a remarkable decrease in northern (e.g. Shanxi) and southeastern China (e.g. Jiangxi); only 5 provinces benefit from El Niño (Fig. 4B).

In comparison with El Niño years, wheat yield benefits from La Niña in almost all provinces, especially in southern and southeastern China, although there still are slight reductions in 6 provinces, mainly in northeastern and southwestern China (Fig. 4E). For rice and corn, yields are reduced in most regions under the influence of La Niña (Fig. 4D,F).

3.3. Correlations between climate variables and crop yields

For rice (Fig. 5C,D), temperature (T_{max} and T_{min}) and P are the more important climate variables for most provinces. Increased temperature will result in increases in rice yields in north and northeast China, such as Ningxia and Jilin Provinces, but also leads to yields decreasing in Jiangxi in southeastern China. P affects rice yields mainly in southeastern, central, and southwest China. Increases in P reduce rice yields in a large number of provinces in these regions; however, it increases yields in northern and southwestern China. For S, only 4 provinces (Ningxia, Jiangsu, Guizhou and Guangdong) show a high correlation with rice yields. Among them, only Guizhou Province shows that S is a Granger cause for rice yield. Moreover, rice yields in some provinces (e.g. Yunnan) are simultaneously affected by 2 or more climate variables.

T_{max} has a high negative correlation with wheat yields in the north, northeast, and southwestern areas: an increase/decrease in T_{max} may reduce/enhance the yield. But only in Inner Mongolia does T_{max} Granger-cause changes in wheat yield. In southeast and northwest China, there is a strong correlation between wheat yields and P, but the coefficients are absolutely different from the east to the west: increases in wheat yields are associated with a higher P in western regions (e.g. Yunnan and Qinghai Provinces) while such yield increases are associated with a lower P in southeastern areas (e.g. Zhejiang and Fujian Provinces). Compared with the pattern of correlation between wheat yields and P, the pattern with S is similar but with opposite sign (Fig. 5K). With regard to T_{min}, only Guizhou shows a significant negative correlation with wheat yields.

Corn yields are mainly negatively correlated with T_{max} and S in most provinces in China, especially in the main production regions, i.e. northern and southwest China (Fig. 5C,L). The effects of P and T_{min} are much smaller compared with that of T_{max} and S, as the impacts of the former are only significant in a few provinces (Fig. 5F,I).

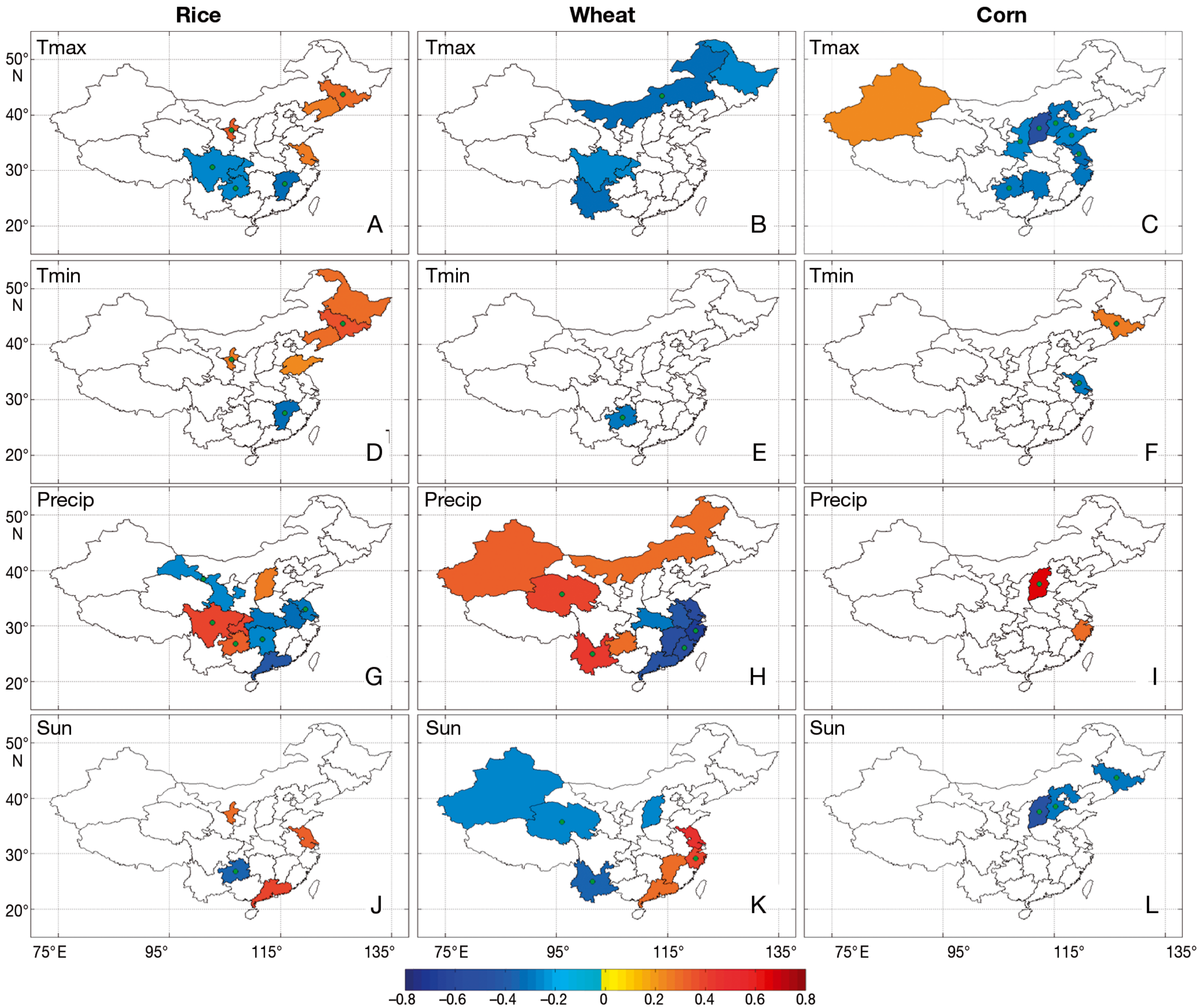

Fig. 5. Correlation between climate variables [(A–C) maximum temperature, T_{max}; (D–F) minimum temperature, T_{min}; (G–I) precipitation; and (J–L) sunshine duration, S] during the growing season and yield residuals. Only statistically significant ($p < 0.10$) correlations are shown. Provinces with a significant Granger causal relationship ($p < 0.10$) are marked with a green point. Color scale: value of correlations

4. DISCUSSION

4.1. Spatial patterns

Compared with rice and corn, wheat is the only crop that shows uniform and outstanding responses in yield to ENSO throughout China (Fig. 4), and the growing season Rainfall associated with ENSO plays a significant role in its variability, especially in south and southeast China. Wheat yields are negatively corrected with P in most provinces in south and southeast China (Table 2), because that climate is already humid, with annual precipitation generally >1000 mm, and the excess water promotes agricultural diseases such as rust and root rot (Tao et al. 2008). Because of the more westward position of the ridge of the sub-tropical high and the increased moisture brought by the western North Pacific anomalous anti-cyclone, southern China experiences much more rainfall and even flood disasters during winter and spring in the decaying phases of El Niño (Chang et al. 2000, Wang et al. 2000, Lin & Lu 2009, Feng et al. 2011). Moreover, in southeastern China, about 30–40% of the total annual precipitation occurs in spring, a value that is close to that in summer (Wu et al. 2003, Feng et al. 2011); at the same time, winter wheat is at the heading–flowering stage and is typically sensitive to precipitation variability (Bai et al. 1999). In El Niño years, much more rainfall occurs in Southeast China and results in significant yield losses, especially in Jiangxi, Zhejiang and Fujian.

North China also experiences striking decreases in wheat yields during El Niño years (Fig. 4), although the correlation between climate factors and wheat yields is not significant. In fact, from other assessments of climate–yield relationships at the county level in China (e.g. Tao et al. 2012, Zhang & Huang 2013), it is apparent that provinces in north China are in a transition area between water-stress-dominant regions in the northwest and water-abundant-dominant regions in the southeast. Although there are many counties showing high *P*–yield relationships in these provinces, the correlation becomes insignificant at the provincial level because the signals are not uniform within a single province. Thus, provin-

Table 2. Correlation between crop yields and climate variables, and effect of ENSO phases on growing season climate and agricultural production in China for 1962–2008. T_{min}: minimum temperature; T_{max}: maximum temperature; *S*: sunshine duration; *P*: precipitation. Data in the right 4 columns are differences in climate or yield residuals between ENSO phases. Asterisks: significantly different at the 90% (*) and 95% (**) confidence levels (ANOVA). All correlations listed reached the 90% confidence level under the 2-tailed t-test

Crop	Province	Variable	Coefficient	Climate El Niño	Climate La Niña	Yield residuals (%) El Niño	Yield residuals (%) La Niña
Rice	Heilongjiang	T_{min}	0.316	−0.163	−0.511	−3.435	−3.808
	Jilin	T_{max}	0.310[a]	0.072	0.028	2.392	−0.901
		T_{min}	0.352[a]	0.027	−0.457		
	Liaoning	T_{max}	0.265	−0.056	0.135	3.518	0.499
		T_{min}	0.296	0.054	−0.447		
	Jiangxi	T_{max}	−0.297[a]	−0.003	−0.208	−0.686	0.928
		T_{min}	−0.299[a]	0.080	−0.592*		
	Ningxia	T_{max}	0.327[a]	−0.435	0.067	−3.542	−3.284
		T_{min}	0.267[a]	−0.048	−0.299		
		S	0.291	−0.808**	−0.063		
	Sichuan	T_{max}	−0.255[a]	0.002	−0.676*	2.004	0.472
		P	0.389[a]	0.587	0.245		
	Shanxi	*P*	0.389	0.746**	−0.542	2.092	−9.536
	Guangdong	*P*	−0.433	0.152	0.055	1.646	1.444
		S	0.391	0.317	0.413		
Wheat	Anhui	*P*	−0.406	0.604	−0.418	−4.203	9.118*
	Fujian	*P*	−0.548[a]	0.876**	−0.438*	−9.477**	0.195
	Hubei	*P*	−0.295	0.788**	−0.389	−3.010	1.619
	Zhejiang	*P*	−0.684[a]	0.811**	−0.353	−8.961**	6.236
		S	0.411[a]	−0.489	0.536		
	Jiangsu	*P*	−0.576	0.670*	−0.436	−5.298	4.462
		S	0.463	−0.548	0.621*		
	Jiangxi	*P*	−0.539	0.828**	−0.275	−10.726**	3.046
		S	0.290	−0.426	0.556		
	Yunnan	T_{max}	−0.330	−0.315	−0.499	6.498*	6.184
		P	0.437[a]	0.661*	0.499		
		S	−0.357[a]	−0.353	−0.483		
	Guangdong	*P*	−0.436	0.716*	−0.260	−1.215	0.064
		S	0.306	−0.457	0.716**		
Corn	Hebei	T_{max}	−0.278[a]	−0.134	0.309	0.758	−0.547
		S	−0.286[a]	−0.050	0.500		
	Shandong	T_{max}	−0.258[a]	−0.150	−0.168	0.487	−3.202
	Shanxi	T_{max}	−0.502[a]	−0.445	0.178	3.698	−2.620
		P	0.675[a]	0.746**	−0.542		
		S	−0.456[a]	−0.318	0.452		
	Guizhou	T_{max}	−0.277[a]	−0.306	−0.351	1.224	0.013

[a]Granger-caused yield changes

cial data may be too coarse to capture significant climatic effects occurring within complicated transition regions.

Rice yields are more sensitive to temperature at high latitudes, while drought and flood disasters limit rice yields in western and southeastern regions. These relationships are consistent with previous climate–rice yield relationship assessments based on long-term field trials or statistical data and agro–meteorological disaster reports (Tao et al. 2008, Zhang et al. 2010, Chen et al. 2011). Moreover, T_{max} and T_{min} also influence yield in some southern areas (e.g. Jiangxi). In Sichuan Province, the changes in both temperature and precipitation associated with ENSO affect the rice yields (Table 2). However, according to the statistical results in our study, the impact of ENSO on temperature during the growing season of rice is even greater in south China compared with regions in north China, and the response of rainfall to ENSO is more significant in northwest China than in southeast China (Figs. 2, 3). Although many studies have emphasized the impact of ENSO on summer precipitation in southeast China (e.g. Huang & Wu 1989) and summer temperature in northeast China (e.g. Guan & Li 2008), the response of the decaying year precipitation in summer, the main rice-growing season, is weaker than that in winter and spring in China, especially in the north and northwest, where summer precipitation accounted for 50–70 % of the total annual rainfall (Wu et al. 2003). Also, some studies have suggested that the correlation between temperature and ENSO in northeast China is weakened or even changes sign after the 1980s (e.g. Wu et al. 2010). So, it is not surprising that there are weak impacts of ENSO on rice yields.

With regard to corn, the S associated with ENSO has a significant effect on yields, and appears to be the major climatic driver for yield fluctuations in northern China. The opposite correlation pattern of yield with S and P implies that the yields' vulnerability may be indirectly affected by solar-radiation-induced drought, which was also inferred by Tao et al. (2003). Simultaneously, in north China, the impacts of ENSO on S and P are opposite—a rise (decrease) in S but a decrease (rise) in P (Figs. 2, 3). Additionally, T_{max} is also an important factor affecting corn yields in many main production areas. Generally, T_{max} and solar radiation always have a positive relationship (Kaiser & Qian 2002), since the more solar radiation the surface absorbs, the higher the T_{max}. Many studies have shown that there are positive relationships in most areas in China (e.g. Zhang et al. 2010). This was also the case in our study: nearly all provinces showed positive correlations between T_{max} and S. So, one hypothesis is that S may be the major climatic driver for corn yield fluctuations, and the negative correlation between yield and T_{max} can be explained by the correlations between S and T_{max}, which were positive in most provinces.

4.2. Leading time of the ENSO signal

We examined the correlations between crop yields and the observed ENSO index at all leading or lag times in the ENSO year beginning at JFM (January to March) in the developing year to OND (October to December) in the decaying year, with a 3-mo moving window (Fig. 6). During the mature phase of ENSO,

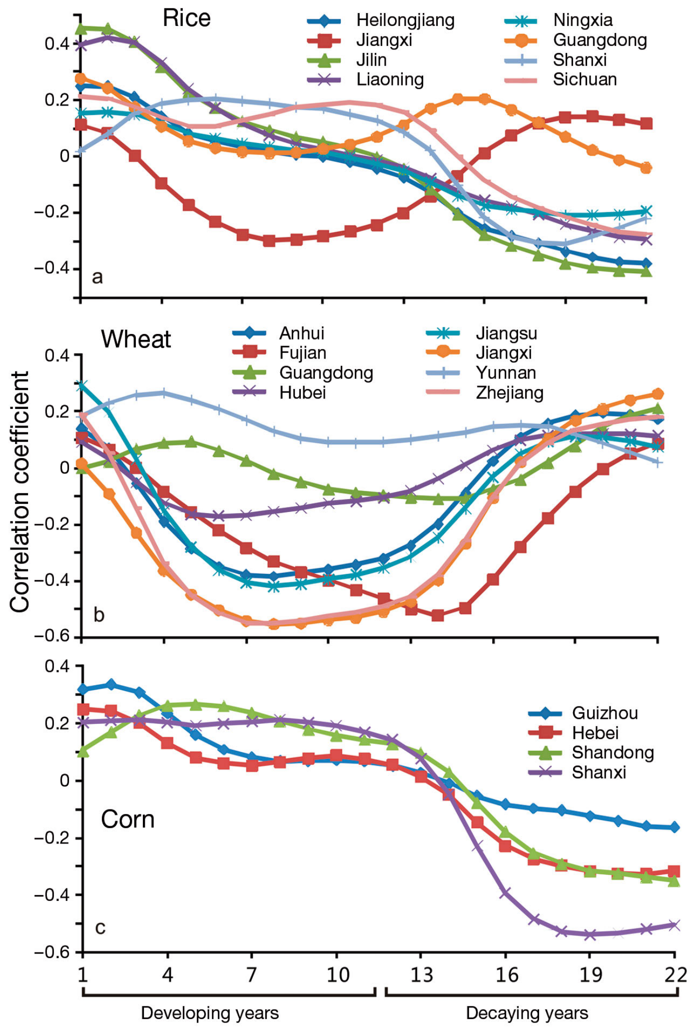

Fig. 6. Correlations between crop yield and the 3 mo sliding ENSO index from the beginning of the developing year to the end of the decaying year during 1962–2008

wheat yields in most provinces show significant negative correlations with ENSO index, while there are weak relationships between the index and yield for rice and corn in nearly all provinces except Jiangxi Province. Such results are consistent with the above analysis based on ENSO phases in that strong wheat yield responses are found in different ENSO phases while only weak responses can be seen in the rice and corn yields. As shown in Fig. 6B, it is apparent that the negative correlation for wheat starts becoming pronounced in early summer during the ENSO developing year, stays low until the next spring in the decaying year of ENSO, and then increases rapidly. It seems that wheat yield variability associated with

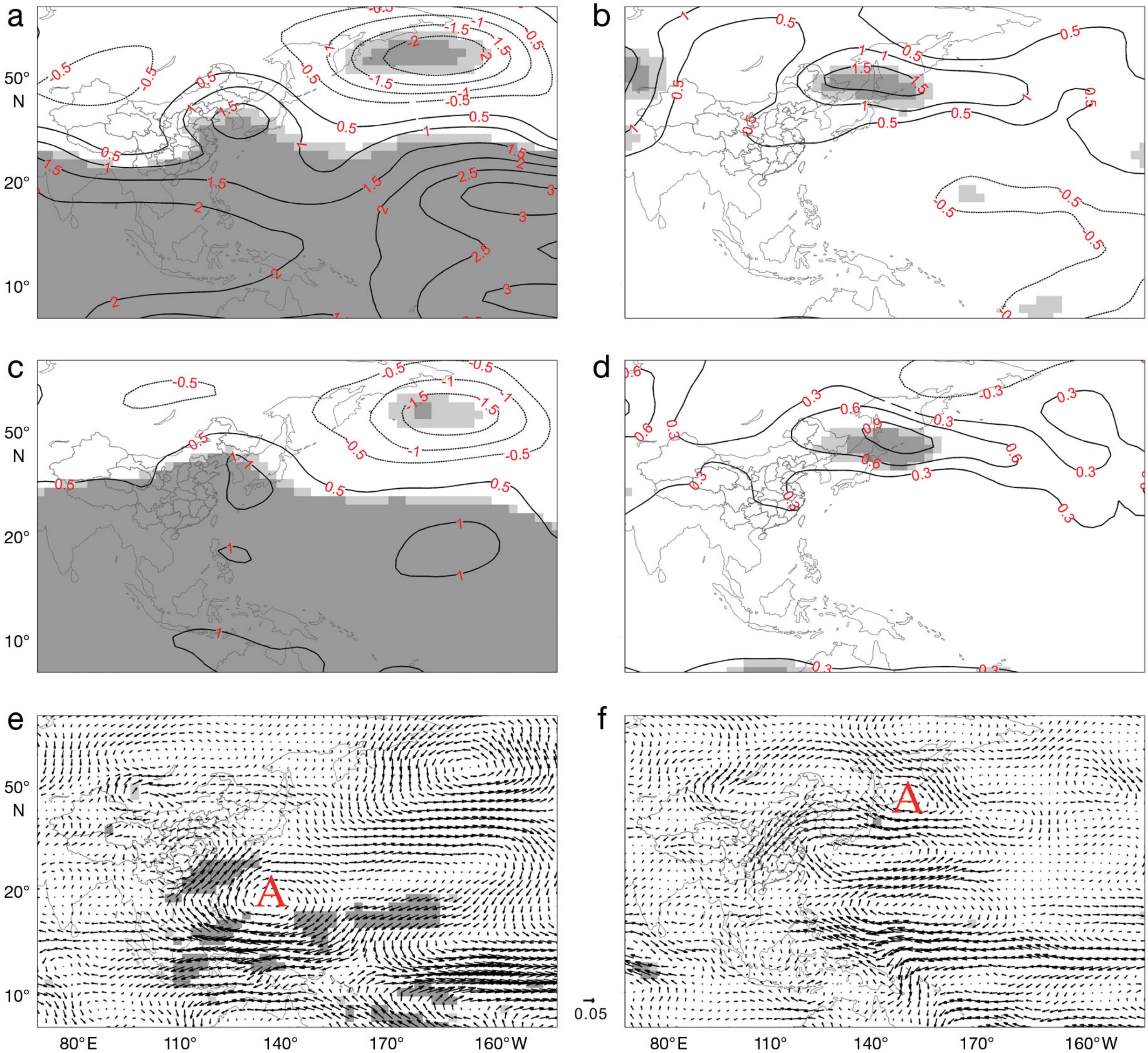

Fig. 7. Regression coefficient pattern of seasonal mean 200 mb geopotential height in (a) MAM(1) and (b) JJA(1), 500 mb geopotential height in (c) MAM(1) and (d) JJA(1), and 850 mb winds in (e) MAM(1) and (f) JJA(1) with respect to the ENSO index [left column: JJAS(0) SSTA; right column: JFMA(0) SSTA] for the period of 1962–2008. Light and dark shading indicate regions significant at the 95 and 99% confidence levels, respectively. Symbol 'A' indicates an anomalous anticyclone. Contour lines are regression coefficients

ENSO can be predicted the summer before its growing season. For rice and corn, although the mature ENSO shows little effect on yield variability, yield in some provinces (e.g. Heilongjiang, Liaoning and Hebei Provinces) responds strongly at the beginning of the ENSO developing year (Fig. 6A,C). The correlations in such provinces generally decrease from the beginning of an ENSO developing year to the end of an ENSO decaying year. This implies that it is possible to predict rice and corn yield variability during the spring of the previous year, much earlier than that for wheat.

Few studies have focused on the connection between the ENSO index in the developing year and climate in the decaying year in China, which may be more useful for farming preparations. As shown in Fig. 6, JJAS (early summer from June to September) in the developing ENSO year shows considerable leading signals for wheat yields, while rice and corn yields respond highly to JFMA (early spring from January to April). So, we derive 2 SST indexes, the JJAS index and the JFMA index, by summing and then normalizing the monthly ENSO index in the respective 4 months. By regressing the geopotential height (200 and 500 mb) and winds (850 mb) onto these 2 SST indices, we tried to investigate the possible mechanisms responsible for such leading signals. As shown in Fig. 7A,C,E, early summer SST already initiates mature ENSO-like geopotential height and wind anomalies in MAM(1), i.e. during the decaying years of ENSO. A significant positive height anomaly is shown in tropical regions, which could be extended to 30° N at both the 200 and 500 mb level. At 850 mb, there is already a clear anomalous anticyclone over the Philippines, which also could be induced by mature ENSO SST anomaly (Wang et al. 2000, Wang & Zhang 2002, Wu et al. 2003), so that sustained strong southeast winds bring moisture from the North Pacific Ocean to southeastern China. Such an anomalous pattern would cause a warmer and wet spring in southeast China, and further reduce wheat yields in El Niño years. With regard to the JFMA index (Fig. 7B,D,F), there is an obvious positive anomaly over Japan and Korea in JJA(1) at both 500 and 200 mb, suggesting that the high pressure ridge is strong and thus it would be warmer in northeast China. At 850 mb, there is an anticyclone over the Sea of Okhotsk, which would bring much warmer air to northeast China. At the same time, there are strong northeast wind anomalies over north China, which bring cold air from high-latitude areas at 850 mb. So, the higher the spring SST in the developing year, the warmer it is in northeastern and the colder it is in northern China.

4.3. Implications for agricultural disasters and food production

Armed with information on weather conditions in a particular growing season 6 mo or 1 yr earlier, farmers in ENSO-sensitive areas could adjust crop mixtures, planting areas, sowing times and other crop management plans to reduce the losses or increase the benefits associated with ENSO. For example, for wheat farmers in southeastern China, reducing the planting area or planting a waterlogging-tolerant wheat variety is an effective method of decreasing the losses caused by higher spring rainfall in El Niño years. Rice farmers in southwest China and corn farmers in north China could increase the amount of irrigation to complement the decrease in precipitation and increase in solar radiation during La Niña years. However, such ENSO leading signals are quite regional. At a national scale (Fig. 8), variations in the yield of rice and corn are not successfully predicted by ENSO signals. Only wheat yields can be predicted at such large

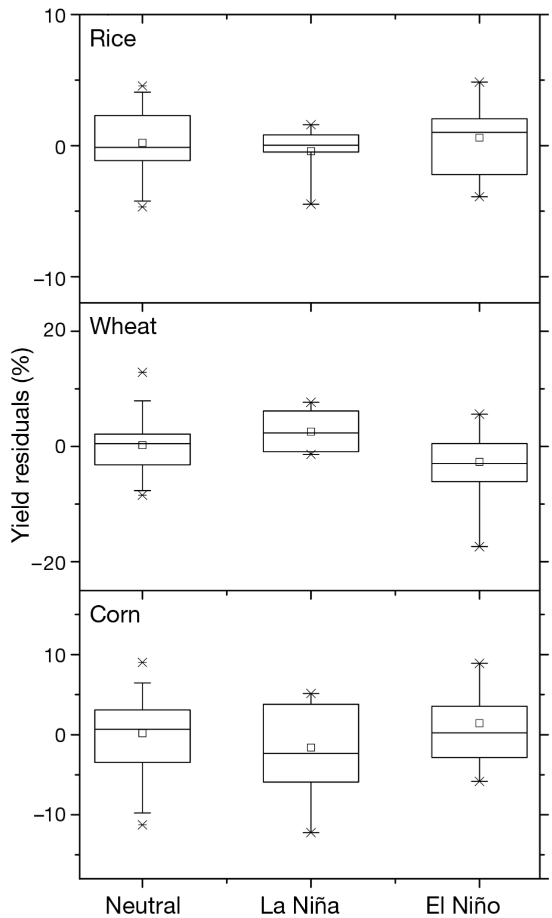

Fig. 8. Box plots showing 0, 25, 50, 75 and 100th percentiles and means (square) of national yield residuals with respect to ENSO phases in China, 1963–2008

scale. This is because the response of wheat yields is more uniform than that of rice and corn. Thus, crop farmers in different regions need to take different mitigation measures against the same ENSO phases, and a crop- and region-specific food security early warning system based on ENSO needs to be developed to improve planting and management decisions in China.

In addition, some studies indicate that the ENSO–yield relationship may be different before and after 1980 (Guan & Li 2008, Zhang et al. 2008, Wu et al. 2010). In order to examine this relationship, we split our samples into 2 segments: before 1980 (1963–1980) and after 1980 (1981–2008). As shown in Fig. 9, it is true that in some areas, especially in western China, crop yields reverse their sign of responses to ENSO phases. Yet the responses of crop yields in most regions in eastern China, also the main crop planting area (Tao et al. 2008), are rather robust over time. It is true that some agriculture facilities have been improved after 1980 in China. The different changes in eastern and western China suggest that the improve-

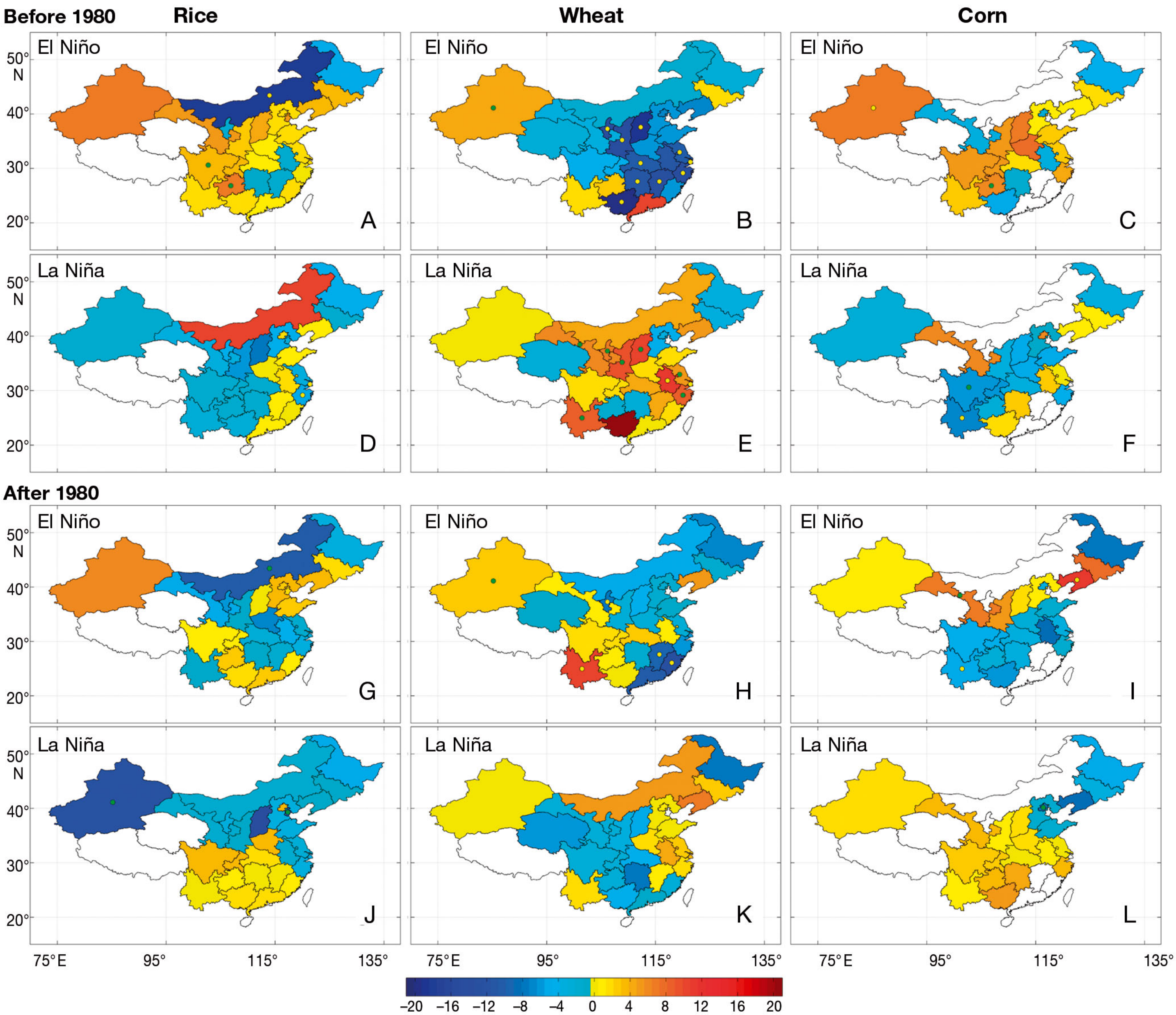

Fig. 9. Difference in yield residuals (%) in El Niño and La Niña years, compared to neutral years, for 1962–2008. Provinces where the differences reach the 90 and 95% confidence levels (ANOVA) are marked with green and yellow points, respectively. Color scale: difference in yield residuals (%)

ment of agriculture facilities contributes more to yield in western China, where the natural environment for crop growth is much poorer than eastern China. Also, eastern China had a more prosperous economy and better facilities than western China before 1980, and consequently has less demand for huge improvements in agricultural facilities.

There are some caveats: our results are based on regional statistical data, so they may not be suitable in certain crop fields. At the same time, some strong ENSO–yield relationships in specific crop fields cannot be detected using regional statistical data. Moreover, as some studies have suggested (Schlenker & Roberts 2009, Lobell et al. 2011a), the true climate–yield relationship could be nonlinear, which is impossible to detect using correlation. Further studies based on crop growth mechanisms need be carried out to detect more precise ENSO–yield relationships in China.

5. CONCLUSIONS

In this study, we investigated the impacts of ENSO on staple crop yields in China at the provincial scale during the decaying stage of ENSO years. Our results suggest that staple crop yields in China can be affected by the variability in growing season climate due to ENSO. The impact of ENSO on the yields has a clearly defined spatial pattern. During El Niño years, wheat yields in southeast China decrease significantly, mainly due to the increased precipitation. In contrast, rice yields increase due to the higher temperature in the northeast area during El Nino years, but decrease due to the higher rainfall connected with El Niño in central China. With regard to corn, the decreases in T_{max} and S and the increases in P jointly lead to yield increases in northern regions. We also found that crop yields of 3 staple crops in most provinces tend to show opposite responses in La Niña years, apparently due to the nearly opposite climate change from El Niño years. Although rice and corn yields in many provinces are less impacted by mature ENSO phases than the wheat yields, they can be predicted in the spring of ENSO developing year, a season earlier than the signal for wheat. Based on the impacts of ENSO on the staple crop yields in China, it is advisable to build an ENSO-based region-specific food security early warning system to improve planting and management decisions in China. However, some caution should be observed while applying the ENSO signals, as there still are uncertainties regarding the impact of ENSO on crop yields.

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