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Contrasting impacts of two types of El Niño on the yields of early rice in Southern China

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Abstract

Rice (*Oryza sativa* L.) production in southern China (SC) is important to Chinese food security and sensitive to climate change. This study investigates the contrasting effects of eastern Pacific (EP) El Niño and central Pacific (CP) El Niño on early rice yields in SC during boreal early summer (May–June–July, or MJJ) for the first time. During EP El Niño events, early rice yields usually exhibit a moderate increase across the entire SC region, whereas during CP El Niño events the yields decrease in about two-thirds of the region. The increase and decrease of yields correspond to .86 and 1.54% of the mean total yield during the study period, respectively. The effects of EP and CP El Niño events on early rice yields are significantly different over nearly half of the harvested areas in SC. Their difference mainly derives from the variability in rainfall associated with the two types. During MJJ, EP events are accompanied by reduced rainfall across SC, which increases early rice yields. In contrast, CP events are accompanied by increased rainfall in northeastern SC, resulting in unfavorable growing conditions. Although temperature affects early rice yields in SC, it is not the major contributor to the yield differences. Our findings highlight the importance of investigating the impacts of both types of El Niño on crop yields separately; and provide a possible climatological mechanism, linking the different locations of sea surface temperature anomalies (SSTAs) with SC early rice yields differences, through atmospheric teleconnection effects on local climatic factors.

1 | INTRODUCTION

Rice (*Oryza sativa* L.) is the staple food for almost half of the global population (The World Bank Group, 2016). In 2016, Chinese rice production accounted for ~28.4% of the world's total (FAOSTAT, 2017). In major food-producing regions, even modest changes in yield have significant effects on global markets (Anderson, Seager, Baethgen, & Cane, 2017a, 2017b). Chinese rice production is therefore a key factor in global and regional food security (Xiong & Cai, 1999; Yao, Xu, Lin, Yokozawa, & Zhang, 2007). However, rice production is sensitive to meteorological variables such as rainfall and temperature during the reproductive growth period (Akram et al., 2018; Iizumi et al., 2014; Parry, Rosenzweig, Iglesias, Livermore, & Fischer, 2004; Shuai, Zhang, Tao, & Shi, 2016; Tao & Yokozawa, 2005; Tao et al., 2004; Tao, Yokozawa, Liu, & Zhang, 2008; Xiong, Yang, Wu, Huang,

Abbreviations: ASO, August–September–October; CNBS, Chinese National Bureau of Statistics; CP El Niño, central Pacific El Niño; DJF, December–January–February; EASM, east Asian summer monsoon; EMI, El Niño Modoki Index; ENSO, El Niño–Southern Oscillation; EP El Niño, eastern Pacific El Niño; HP filter, Hodrick–Prescott filter; JJA, June–July–August; MAM, March–April–May; MJJ, May–June–July; SC, southern China; SSTA, sea surface temperature anomaly; TAR, temperature accumulation that reduces yields.

& Cao, 2013; Ye et al., 2015; Zhang, Jin, & Turner, 2014; Zhang et al, 2014a, 2014b). Thus, it is important to study the factors that influence climate during the rice growing season, and ultimately, how these factors affect rice yields.

As the leading mode of global interannual climate variability, El Niño plays a dominant role in global and regional climates by affecting atmospheric circulation from seasonal to annual time scales (Huang & Xie, 2015; Li et al., 2015; Wang, Wu, & Fu, 2000; Webster & Yang, 1992; Zhao, Li, & Li, 2015; Wang, Deser, Yu, DiNezio, & Clement, 2017). Considering that crop yields are strongly dependent on the seasonal climate, many studies have investigated the relationship between El Niño–Southern Oscillation (ENSO) and yields of major crops in various regions or at the global scale (Cane, Eshel, & Buckland, 1994; Hammer, Nicholls, & Mitchell, 2000; Hansen, Hodges, & Jones, 1998; Iizumi et al., 2013, 2014; Kazmi & Rasul, 2012; Lobell & Field, 2007; Nnamchi & Ozor, 2009; Podestá et al., 2002; Selvaraju, 2003; Shuai et al., 2016; Shuai, Zhang, Sun, Tao, & Shi, 2013; Zhang, Feng, Shuai, & Shi, 2015). Iizumi et al. (2014) posited that El Niño had significant impacts on the yields of major crops worldwide and that these impacts vary across crop species and planting regions.

In Asia, where 90% of the world's rice is grown, El Niño results in significantly reduced rice yields. In Java (Indonesia), El Niño accounts for 40% of the interannual variance in rice production (Falcon, Naylor, Smith, Burke, & McCullough, 2004; Naylor, Falcon, Rochberg, & Wada, 2001; Naylor, Falcon, Wada, & Rochberg, 2002). A "Paddy Drought Impact Index" was defined to measure the increasing frequency of El Niño-induced drought, which is believed to be the main reason for planting delay and yields reduction in Indonesia (Bayong, Juaeni, Gernowo, & Baramantyono, 2006; Surmaini, Hadi, Subagyono, & Puspito, 2015). In India, El Niño events correspond to low rainfall and low yields (Webster et al., 1998), with rice production dropping by an average of 3.4 Tg (Selvaraju, 2003). Tao et al. (2004) and Shuai et al. (2013) investigated the impacts of El Niño and the East Asian summer monsoon (EASM) on the production of staple crops in China during the developing phase of ENSO years, respectively. Their results indicate that the variability in crop production is closely related to ENSO and EASM. However, over southern China (SC), which is the main planting region of early rice in China, the study covered only the area of cropland damaged by EASM-related flooding in Hunan Province. Deng et al. (2010) explored the relationship between ENSO and rice production in Jiangxi Province, and argued that ENSO has little impact on rice yields, because the strongest ENSO effects occur mostly in winter . Nevertheless, Iizumi et al. (2014) claimed that the reproductive growth period was the key interval determining crop yields. As the reproductive growth period of early rice in Jiangxi Province falls in MJJ, it would be rational to consider simultaneous sea surface temperature anomalies (SSTAs).

Core Ideas

- Eastern Pacific El Niño increases early rice yields by 0.86% across southern China.
- Central Pacific El Niño decreases early rice yields by 1.54% in ∼60% of southern China.
- Two types of El Niño have significantly different impacts on ∼30% of southern China.
- Different rainfall associates with two types of El Niño leads to different yields.
- An atmospheric teleconnection angled mechanism for different impact of two types.

The developing phase of ENSO also has direct impacts on local climate (Feng, Li, Zheng, Xie, & Sun, 2016) and the climatic effect of ENSO is only significant when SSTAs reach a certain threshold. Therefore, this effect may not be significant in terms of correlation coefficient between SSTAs and yield anomalies but can be revealed by composite analyses.

Iizumi et al. (2014) presented a global map of the impact of conventional El Niño events on rice yields, confirming previous results and further emphasizing that yields vary both regionally and for crops with different growing seasons. It is worth highlighting that SC in particular suffers from significant rice yield losses during El Niño events and is one of two areas worldwide that are most vulnerable to El Niño. However, the current understanding of the relationship between El Niño and crop meteorological yields lacks of the potential dynamic meteorological mechanisms.

The Earth has experienced a clear warming trend in recent decades, which has led to the structural transformation of El Niño. In addition to the conventional eastern Pacific (EP) El Niño event, in the 1980s researchers identified another type: the central Pacific (CP) El Niño (Ashok & Yamagata, 2009; Ashok, Behera, Rao, Weng, & Yamagata, 2007; Kao & Yu, 2009; Kug, Jin, & An, 2009; Li et al., 2017; Li et al., 2019; Yeh et al., 2009; Yu & Kao, 2007). Eastern Pacific El Niño exhibits maximum SSTAs over the eastern tropical Pacific Ocean, whereas CP El Niño is characterized by distinct warm SSTAs in the central Pacific. Consequently, the influences of these two types of El Niño on global climate are distinct due to the different atmospheric circulation responses. And the impacts of El Niño on the SC climate have been shown to vary with El Niño type and by season (Feng & Li, 2011, 2013; Karori, Li., & Jin, 2013; Zhang et al., 2014).

Although many researches have focused on the relationships between different types of El Niño and climate, little is known about the impacts of these two types of El Niño on crop yields, especially for rice. Early rice production in SC accounts for about 87% of the early rice production in

21st century China (CNBS, 2017). Given the importance of the SC region to early rice production in China and the world, the widely recognized impacts of climate change and El Niño on rice yields in SC, and the different effects of the two El Niño types on the climate of SC, it is vital to clarify the effects of EP and CP El Niño on early rice yields in SC and determine whether the effects differ between the two types. Most importantly, the mechanisms underlying any observed differences must be explained deeply, which will aid famine prevention efforts and contribute to agricultural and economic sustainability in China and the rest of the world.

2 | MATERIALS AND METHODS

2.1 | Study area, season, and period

Our study investigated the impacts of two types of El Niño event on early rice yields in five provinces of SC: Hunan, Jiangxi, Fujian, Guangdong, and Guangxi provinces. These provinces all share the same early rice growing season, similar rice cropping systems, and extensive rice production. The geographic location of SC is 104°28′–120°40′ E, 20°13′–30°08′ N. Southern China has a population of 317.6 million people and an area of 916,100 km^2 (91.61 million ha), 13.6 million ha of which is cultivated with rice. Climate in this region is mostly subtropical monsoon climate with hot summers and mild winters. The average annual precipitation is approximately 1200–2100 mm yr^{-1}. Benefiting from suitable climatic conditions, farms in SC employ a double rice-cropping system, including early rice and late rice, and single rice cropping system. The growing seasons of early and late rice and single rice are boreal early summer (MJJ), boreal early autumn (August–September–October, or ASO) and spring to autumn (April–October), respectively. The seasonality in this study is defined as follows: spring means March–April–May, or MAM; early summer means May–June–July, or MJJ, summer means June–July–August, or JJA; early autumn means August–September–October, or ASO; autumn means September–October–November, or SON; winter means December–January–February, or DJF.

Here, the reasons why we study the yields of early rice are listed as follows. The early rice grown in this region is mostly *Indica*, the production and yields of which directly influence national agricultural policy and the production of late rice. *Indica* is a standing grain with superior storage characteristics. It is the most important commodity grain in China and is vital to the material well being of local farmers. From the perspective of meteorology, the growing season of early rice falls within boreal early summer, and the impact of the two types of El Niño on the background atmospheric circulation in SC show seasonal variations. To analyze the atmospheric circulation, it is necessary to consider the seasonal climatic variables in isolation. Therefore, in this study we focus on the early rice yields in SC.

2.2 | Data

2.2.1 | Rice yields data

Two sets of data on the historical yields of SC early rice were applied to evaluate the consistency of our results. A provincial dataset covering the period 1979–2014 is on the China Planting Information website (http://202.127.42.157/moazzys/nongqing.aspx), the sources of which are the Ministry of Agriculture of China and the China Agricultural Statistics Yearbook. A grid-cell dataset covering the period 1982–2011 was obtained at a resolution of 1.125° × 1.125° from the satellite-statistics aligned global dataset (Iizumi et al., 2014; Iizumi & Ramankutty, 2016). We also compared these two yield datasets for the period 1982–2011, yielding a statistically significant correlation coefficient of .71 (figure not shown). Therefore, both datasets were used in this study. The study period was chosen for the following reasons. First, the two types of El Niño investigated here became more frequent after the late 1970s. Second, we sought to exclude the effects of important policy changes, including the "Great Leap Forward", which is an important political event when many statistics during the time were exaggerated just to achieve certain quota (Lin & Yang, 1998). Thirdly, the NCEP-2 reanalysis dataset utilized in this study starts from 1979 (Kalnay et al., 1996).

2.2.2 | Climate data

Sea surface temperature (SST) data were obtained from the U.S. National Oceanic and Atmospheric Administration (NOAA; Reynolds, Rayner, Smith, Stokes, & Wang, 2002). Rainfall, air temperature, downward shortwave radiation and total cloud cover reanalysis data at a resolution of 2.5° × 2.5° were obtained from the National Center for Environmental Prediction–National Center for Atmospheric Administration (NCEP/NCAR; Kalnay et al., 1996). The Global Precipitation Climatology Centre (GPCC) precipitation data (Rudolf & Schneider, 2005) were used to identify precipitation anomalies. According to Ashok et al. (2007), the El Niño Modoki Index is defined as

$$\mathrm{EMI} = [\mathrm{SSTA}]_{\mathrm{C}} - .5 \times [\mathrm{SSTA}]_{\mathrm{E}} - .5 \times [\mathrm{SSTA}]_{\mathrm{W}}, \quad (1)$$

where square brackets with a subscript represent the areal mean SSTAs over the central Pacific region (C: 10° S–10° N, 165° E–140° W), the eastern Pacific region (E: 15° S–5° N, 110° W–70° W), and the western Pacific region

TABLE 1 Two types of El Niño events and their corresponding southern China (SC) early rice yields anomalies for the period 1979–2014

EP[a] El Niño		CP[b] El Niño	
Years	△EP-Neutral($10^2 \times$ t ha^{-1})	Years	△CP-Neutral($10^2 \times$ t ha^{-1})
1982	10.19	1994	–22.86
1983	12.50	1995	–6.82
1987	–6.73	2002	–18.23
1991	3.39	2004	15.82
1992	11.35		
1993	.88		
1997	21.75		
1998	–25.25		
2009	12.15		
Average	4.47	Average	–8.02

[a]EP, eastern Pacific.
[b]CP, central Pacific.

(W: 10° S–20° N, 125° E–145° E). The index is available at http://www.jamstec.go.jp/frsgc/research/d1/iod/modoki_home.html.en. The Niño3 Index is the average of the SSTAs over the region (5° S–5° N, 150°–90° W). The EP and CP El Niño events are identified by using the Niño3 Index and the El Niño Modoki Index (EMI), respectively. The use of these indices has been validated by Weng, Ashok, Behera, Rao, & Yamagata (2007), Karori et al. (2013), and Feng et al. (2016). We used the larger of the average SSTAs values from the two indices for the growing season of early rice in the study region to distinguish the two types of El Niño. To evaluate the results of this classification, we also applied the MAM, SON, and DJF indices and obtained the same results as previous studies (Weng et al., 2007; Ashok et al., 2007; Feng & Li, 2011; Kao & Yu, 2009; Kim, Webster, & Curry, 2009; Yu & Kao, 2007). The EP and CP El Niño years were identified as years for which the MJJ mean SSTAs was at least 0.75 standard deviations above the mean for the period 1979–2014. Nine EP events (1982, 1983, 1987, 1991, 1992, 1993, 1997, 1998, and 2009) and four CP events (1994, 1995, 2002, and 2004) are selected, which are listed in Table 1.

2.3 | Analysis methods

2.3.1 | Rice yield anomalies during two types of El Niño event

According to previous studies (Iizumi et al., 2014; Lobell, 2003; Phillips, Rajagopalan, Cane, & Rosenzweig, 1999; Wang, 1991; Wang, Fang, & Xu, 2004; Zhang, Zhu, Yang, & Zhang, 2008) and the definition of China Meteorological Administration (2019), total crop yield comprises three parts: trending yield, also known as technological yield, meteorological yield and random disturbance. Among the three parts, technological yield continues to exhibit a growth trend due to anthropogenic factors such as variety renewal, change of planting mode, regulation of fertilizer and water, which primarily represent non-climatic factors. Conversely, our objective is meteorological yield which is mainly affected by meteorological factors.

The rice yields data were detrended using three validation methods: a Gaussian filter, a Hodrick–Prescott (HP) filter and a 5-yr-running mean method. The correlation coefficients between each pair of the three detrended results are statistically significant at the .01 level (figure not shown). We calculate $\bar{Y}_t$ as the meteorological yield, as follows:

$$\bar{Y}_t = Y_t - Y_t^*, \tag{2}$$

where the suffix t indicates the year, Y_t indicates total yield and Y_t^* indicates the technological yield. The yield anomaly was calculated as the deviation from the normal yield as follows:

$$Y_t' = \frac{Y_t - \bar{Y}_t}{\bar{Y}_t} \tag{3}$$

We used composite analysis to calculate the rice yield anomalies, rainfall anomalies and air temperature anomalies associated with the two types of El Niño event. Average percentage yield anomalies for EP and CP El Niño events were averaged over the period 1979–2014. The corresponding values for rainfall anomalies and air temperature anomalies were calculated in the same way. This method has been verified by Iizumi et al. (2014).

$$Y'_{EP-El\ Niño} = \frac{1}{n_{EP-El\ Niño}} \sum_{t=1980}^{2014} Y_t', \quad \text{if } t \text{ is an EP El Niño year} \tag{4}$$

$$Y'_{CP-El\ Niño} = \frac{1}{n_{CP-El\ Niño}} \sum_{t=1980}^{2014} Y'_t, \quad \text{if } t \text{ is a CP El Niño year} \tag{5}$$

$$Y'_{Neutral} = \frac{1}{n_{Neutral}} \sum_{t=1980}^{2014} Y'_t, \quad \text{if } t \text{ is in neither category} \tag{6}$$

Differences between the average percentage yield anomalies for EP (CP) El Niño events and neutral years were calculated as follows:

$$\Delta Y'_{EP-El\ Niño} = Y'_{EP-El\ Niño} - Y'_{Neutral} \tag{7}$$

$$\Delta Y'_{CP-El\ Niño} = Y'_{CP-El\ Niño} - Y'_{Neutral} \tag{8}$$

The sample size includes nine EP El Niño events, four CP El Niño events, and 19 neutral years. The bootstrap method was used with 10,000 iterations to test the significance of the impacts of both El Niño types on early rice yields. Correlation analysis was used to determine the strength of the relationships between precipitation/temperature parameters and early rice yield in SC. The statistical significance of values obtained from the composite and correlation analysis were then assessed by using the bootstrap method and the two-sided Student's t test.

2.4 | Temperature accumulation for yield reductions

The optimum temperature range for the phenological growing phases of early rice in SC is between 25 and 30°C (Sánchez & Porter, 2014). If the ambient temperature falls within this range, the growing speed of the crop reaches its maximum, otherwise the growth rate slows, resulting in a lower yield. Following the approach of Wang et al. (2014), we define the temperature accumulation that reduces yield (TAR) as follows:

$$TAR = \begin{cases} T_i - T_{opt}, & \text{if } T_i > T_{opt\ max} \\ 0, & \text{if } T_{opt\ max} > T_i > T_{opt\ min} \\ T_{opt} - T_i, & \text{if } T_i < T_{opt\ min} \end{cases} \tag{9}$$

where T_i is the actual monthly mean temperature, and $T_{opt\ min}$ and $T_{opt\ max}$ are the lower and upper limits of the optimum growing temperature range, respectively.

2.5 | Programming language and graphic software

All maps and plots were produced by NCL (NCAR Command Language), an interpreted language designed for scientific data analysis and visualization (The NCAR command language (Version 6.6.2, 2019). In this study we utilized the following functions: HP filter, Gaussian filter, interpolation, composite analysis, correlation analysis, bootstrap method and two-sided Student's t test in the 6.6.2 version.

3 | RESULTS

3.1 | Comparison of the impacts of eastern Pacific and central Pacific El Niño events on early rice yields in southern China

Figure 1 shows the composite spatial distribution of early rice yields in SC during EP (Figure 1a) and CP (Figure 1b) El Niño events, their differences (Figure 1c) from 1982–2011, and the time series of yield anomalies of early rice using the provincial yield data and MJJ SSTA indices from 1979–2014 (Figure 1d). During EP El Niño events, the early rice yield generally increases over the entire SC region (Figure 1a). The positive effect is significant in central SC. Results using data from the Ministry of Agriculture are consistent with those using the grid-cell data (Figure 1d). Compared with neutral years, seven of the nine EP El Niño events show a positive effect on SC early rice yields, which means that 78% of EP El Niño events are accompanied with yield increase. The maximum increase is 21.75 $10^2 \times$ t ha^{-1} in 1997, which is equivalent to 4.19% of the long-term mean total yield of SC early rice. The maximum negative association for the other two EP El Niño events that accompanied yield losses, 1987 and 1988, is –25.25 $10^2 \times$ t ha^{-1} and 4.86%. In June 1998, SC experienced the most severe flood in the past 150 yr, which caused severe agricultural damage in Jiangxi and Hunan provinces, both of which are included in our study area. Thus, it is unsurprising that SC early rice yields in 1998 declined dramatically. Despite this decrease, the overall effect of EP El Niño events on SC early rice yields was still positive, with an average yield anomaly of 4.47 $10^2 \times$ t ha^{-1}, which is 0.86% of the long-term mean. These results are consistent with those from grid-cell data. The positive association of the EP El Niño events is, to a certain degree, offset by the severe flood in 1998. Excluding 1998 as an outlier, the positive effect of the EP El Niño events reaches 1.57% of the long-term mean total yield. This suggests that the effect of the majority of El Niño events may be underestimated because of the influence of extreme events.

During CP El Niño events, in contrast to EP El Niño events, early rice yields in SC are negatively affected (Figure 1b). In harvested areas, early rice yields decrease in around

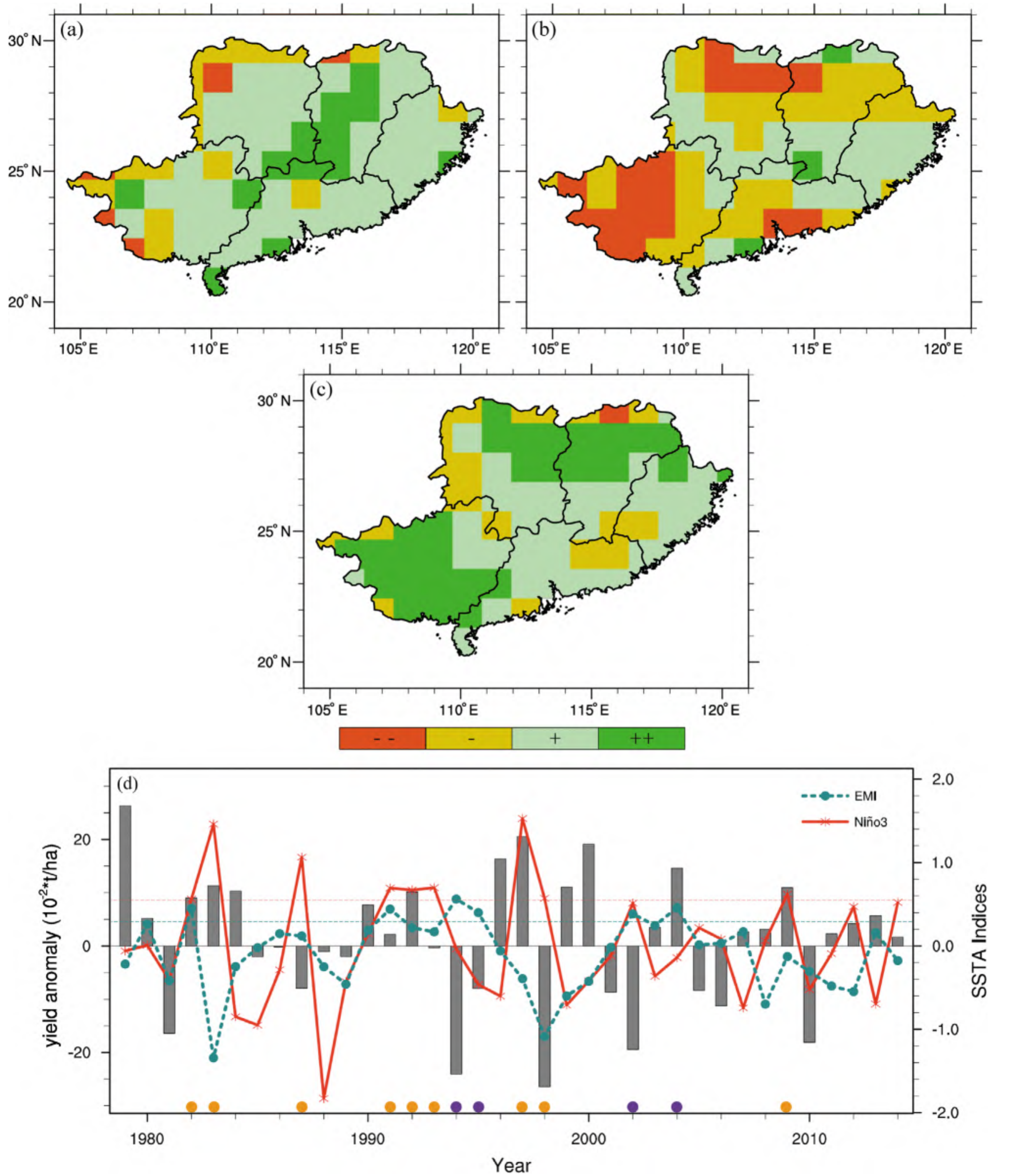

FIGURE 1 Composite spatial distribution of southern China (SC) early rice yields during (a) eastern Pacific (EP) El Niño events, (b) central Pacific (CP) El Niño events, and (c) the difference between EP and CP El Niño events, from 1982 to 2011. The *x* axis represents longitude 104–121° E; *y* axis represents latitude 19–31° N. Red (dark green) represents negative (positive) anomalies that are statistically significant at the .1 level. Yellow (light green) represents negative (positive) anomalies that are not significant. (d) Time series of MJJ Niño3 and EMI indices and early rice yields anomalies from 1979–2014. The red (green) line and the red (green) horizontal dashed line represent the Niño3 index (EMI) and its .75 standard deviation. Orange (purple) circles represent EP (CP) El Niño events

two-thirds of the study region (northern and western SC, specifically). The most distinct and significant yield decrease is observed in western Guangxi province, and suggests that during CP El Niño events farmers in western Guangxi province should take extra precautions to prevent yield losses. Results of data from the Ministry of Agriculture agree with those of grid-cell data (Figure 1d). During three of the four (75% of) CP El Niño events, SC early rice yields decrease. The maximum yield losses occurred in 1994, which was the strongest CP El Niño event in our study period. The yield reduction is –22.86 $10^2 \times$ t ha^{-1}, which is –4.40% of the long-term mean total yield of SC early rice. The overall effect of CP El Niño events on SC early rice yields is negative (–8.02 $10^2 \times$ t ha^{-1}, accounting for –1.54% of the long-term mean).

The yearly effects of EP and CP El Niño events are given in Table 1.

Compared with yield losses associated with CP events, yield growth associated with EP El Niño events was considerably smaller in terms of average amount (Table 1). With CP El Niño events predicted to occur more frequently in the future (Zhang et al., 2014), their negative effect on SC early rice warrants special investigation, and highlights the need to investigate the two types of El Niño and their effects separately.

To investigate differences in the impacts between the two types of El Niño on early rice yields in SC, the same analysis was performed to calculate the difference between EP and CP El Niño events (Figure 1c). In terms of harvested areas, the yield anomalies show significant differences between the two El Niño types across nearly half of the study area. The biggest differences exist mainly in southwestern and northern SC, which correspond to the area that is most affected by the CP El Niño events (Figure 1b). In these two subregions, the two types of El Niño have nearly opposite effects.

Together, these results indicate that the impact of EP and CP El Niño on early rice yields differ not only in spatial terms across various SC subregions, but also in amplitude and sign. Overall, EP El Niño events are accompanied with an increase in SC early rice yields, whereas CP El Niño events are accompanied with a yield decrease.

3.2 | Possible mechanism responsible for rice yields anomalies

3.2.1 | Relationship between rainfall and early rice yields

Previous studies have reported that rainfall temperature and solar radiation are the most critical and direct meteorological factors affecting the development of most crops (Sánchez, Rasmussen, & Porter, 2014; Xiong et al., 2013). To evaluate the relationships between these factors and early rice yields anomalies in SC, we considered the simultaneous correlations between early rice growing season rainfall, solar radiation, and temperature, as well as yield anomalies. In Figure 2a, the plot of rainfall against rice yields anomalies shows a significant negative correlation over almost all of SC ($P < .1$), except for a non-significant positive signal in the Northwest region. Figure 2b shows the time series of SC MJJ mean rainfall and annual early rice yields anomalies using the provincial yield data from the Ministry of Agriculture. The correlation coefficient is –.52 ($P < .01$). These results suggest that increases in rainfall reduce early rice yields in SC.

This negative correlation is consistent with the work of Shuai et al. (2013). However, in their research, they considered early rice and late rice together. It is likely that early rice and late rice experience different effects, as El Niño events gradually develop over time and thus might cause distinct climate effects in different seasons.

The analysis represented in Figure 2 reveals that rainfall during the growing season has a strong influence on early rice yields over the SC study region. Notably, the influence of EP El Niño events is the opposite to that of CP events. Thus, during EP El Niño events, MJJ rainfall deficits lead to a corresponding increase in early rice yields. In contrast, CP events are associated with rainfall increases, which retard the growth of early rice and are thus accompanied by yield decreases. Aside from providing the necessary water, another important role of rainfall is modifying radiation.

3.2.2 | Relationship between downward shortwave radiation, cloud cover, and early rice yields

Solar radiation is a key factor affecting rice yields through photosynthetic activity which is the major path that early rice accumulates grain weight. Solar radiation can be represented by downward shortwave radiation and cloud cover. Downward shortwave radiation and total cloud cover can reflect the strength of photosynthesis and the time that crop being exposed to sunshine. Here, we investigated the correlation between the two meteorological factors and early rice yields anomalies.

In Figure 3a, the plot of MJJ downward shortwave radiation against rice yields anomalies shows a significant positive correlation over the majority of SC ($P < .1$). In Figure 3b, the plot of MJJ total cloud cover against rice yields anomalies shows a significant negative correlation over almost all of SC ($P < .1$). The time series of both factors and early rice yields anomalies using the provincial yield data from the Ministry of Agriculture show consistent results. The correlation coefficients between both factors and early rice yields anomalies are .53 and –54, respectively (Figure 3c, 3d), both significant at the .01 level. The results are consistent with the expected biophysical responses to solar radiation which are more downward

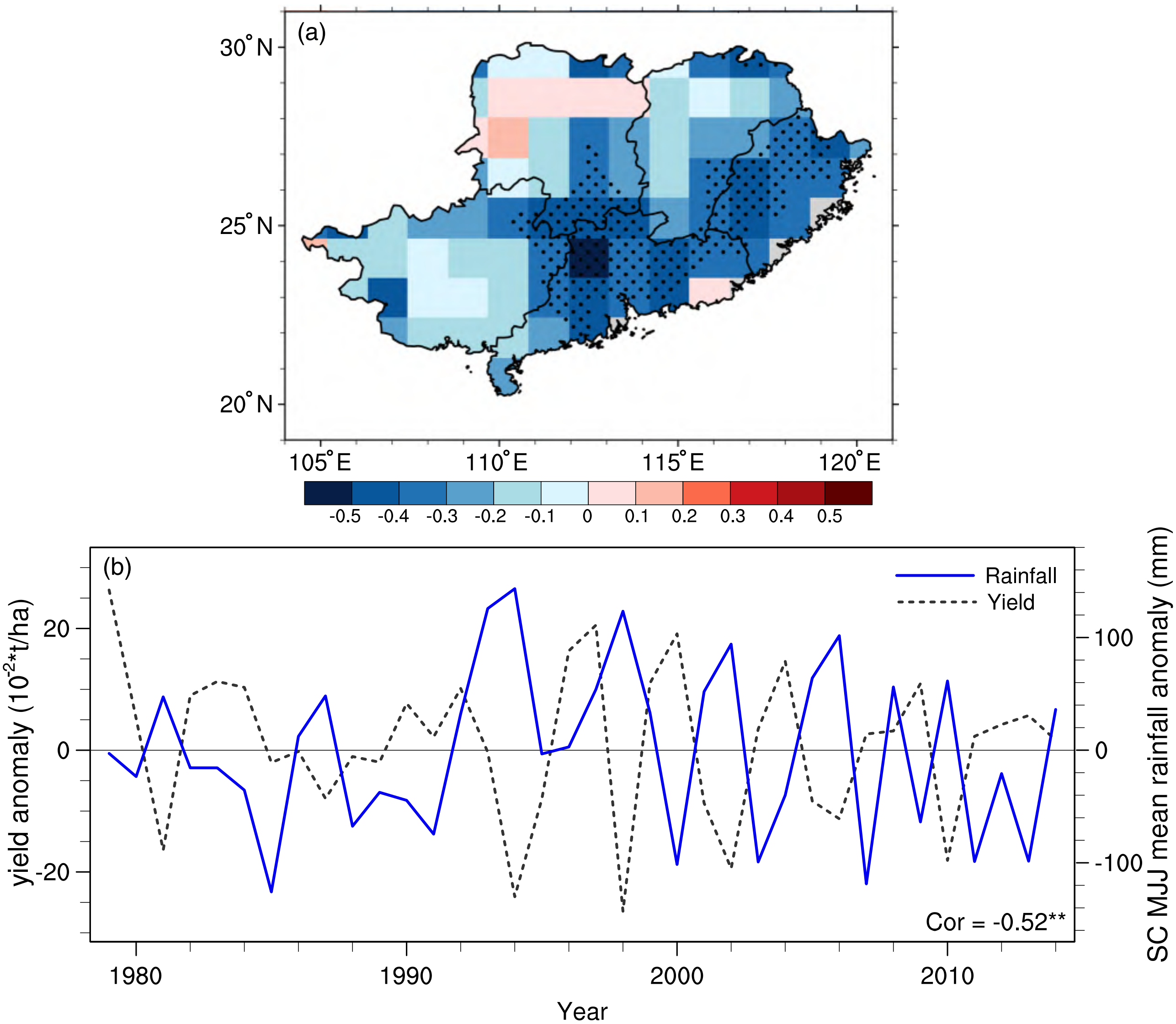

FIGURE 2 (a) Spatial distribution of correlation coefficients between growing season rainfall and early rice yields in southern China (SC) from 1982–2011. *x* axis represents longitude 104–121° E; *y* axis represents latitude 19–31° N. Shaded areas are statistically significant at the .1 level. (b) Time series of May–June–July (MJJ) rainfall (blue line) and early rice yields anomalies (black dash line) from 1979–2014. Correlation coefficients are statistically significant at the .01 level

shortwave radiation and less cloud cover during the growing season, and are accompanied by greater early rice yields in SC. These results also support the negative correlation between precipitation and early rice yields. More precipitation leads to less solar radiation and more cloud cover which hinder photosynthetic activity, thus resulting in yield decrease.

3.2.3 | Relationship between temperature and early rice yields

No significant relationships of monthly mean temperature, monthly maximum temperature (T_{max}), and monthly minimum temperature (T_{min}) during the early rice growing season with early rice yields were observed throughout the region (Figure 4a; T_{max} and T_{min} are not shown).

Using the method of Wang et al. (2014), we calculated the TAR for early rice associated with both types of El Niño. Results for both types are similar with differences of <1°, suggesting that it is not the difference in mean temperature (T_{max} or T_{min}) associated with the two types of El Niño that causes the difference in early rice yields. This also suggests that over the SC study region, rainfall during the early rice growing season is a more vital contributor to yield than is temperature. Moreover, rainfall might be the determining factor for early rice yields, and is the main feature of impact diversity between the two types of El Niño event. Based on this premise, it is therefore important to examine in more detail

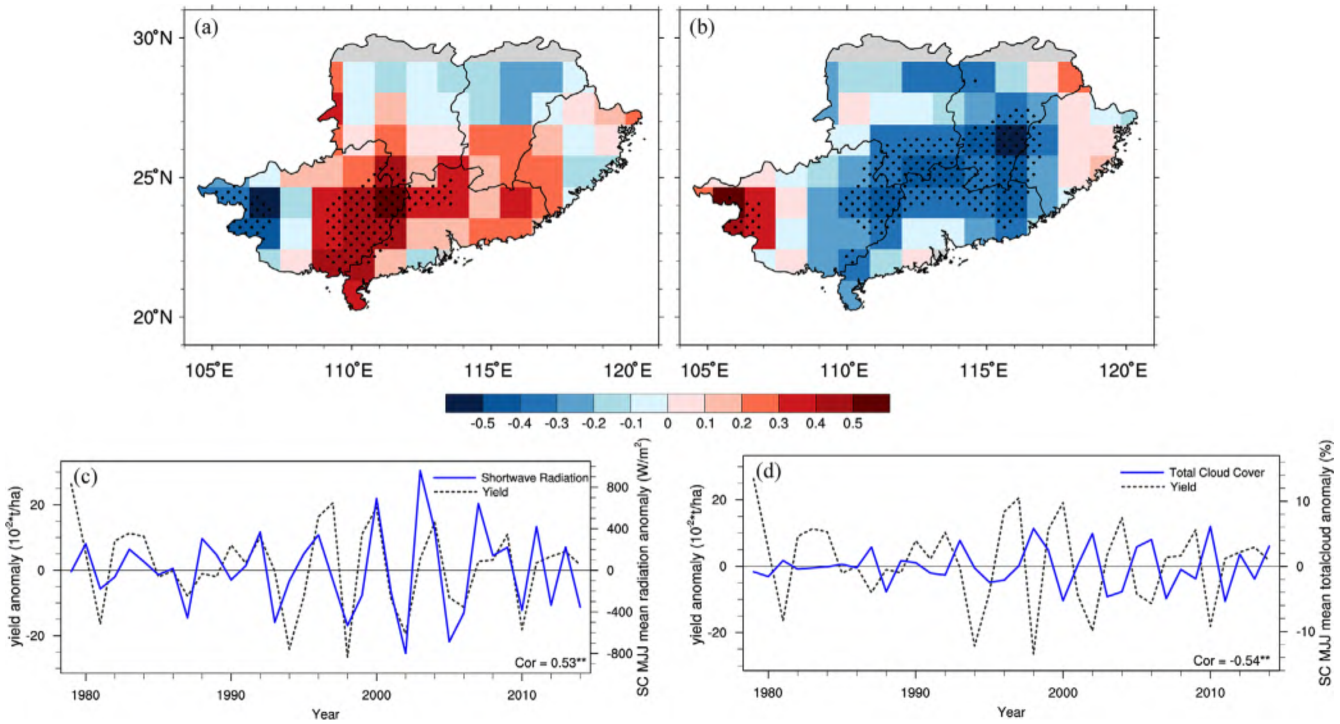

FIGURE 3 (a) Spatial distribution of correlation coefficients between May–June–July (MJJ) downward shortwave radiation and early rice yields in southern China (SC) from 1982–2011. *x* axis represents longitude 104–121° E; *y* axis represents latitude 19–31° N. Shaded areas are statistically significant at the .1 level. (b) Same as (a), but for MJJ total cloud cover. (c) Time series of MJJ downward shortwave radiation (blue line) and early rice yields anomaly (black dash line) for period 1979−2014. The correlation coefficient between the two series is .53, statistically significant at the .01 level. (d) Same as (c), but for MJJ total cloud cover and (blue line) and early rice yields anomaly (black dash line). The correlation coefficient between the two series is −.54, statistically significant at the .01 level

the rainfall anomalies associated with the different El Niño types.

3.2.4 | Rainfall anomalies associated with eastern Pacific and central Pacific El Niño events

The normal rainfall distribution for MJJ is shown in Figure 5a to illustrate the background setting and to reveal differences between EP and CP El Niño events. The MJJ rainfall decreases from South to North across SC, with maximum and minimum values of approximately 9 and 5 mm/day in the South and North of the region, respectively. Anomalous rainfall patterns associated with the two types of El Niño event are shown in Figure 5b and 5c. For EP El Niño, the dominant rainfall anomalies show a negative pattern throughout SC, with the most severe negative effect in eastern SC (Figure 5b), which is similar to the pattern of early rice yields. Compared with the climatology, rainfall is significantly decreased by up to 25% or more in eastern SC. In contrast, for CP El Niño events, rainfall anomalies are characterized mainly by a dipole pattern with enhancement in the west and a reduction in the East. The rainfall deficit in eastern SC during CP events is similar to that of EP events. However, western SC experiences much more rainfall during CP events with an anomalous uptake that accounts for ∼25% of the seasonal mean. The difference in rainfall in western SC between the two types of event can account for >25% of the seasonal mean and affects more than 60% of the SC harvested area.

The above analysis suggests that the impacts of EP and CP El Niño events on MJJ rainfall are in distinct contrast, concurring with findings from previous studies for summer rainfall in SC (Weng et al., 2007). As mentioned earlier, the mechanism that drives the differing impacts of the two types of El Niño event on SC summer rainfall was explained by Weng et al. (2007). Although the circulation processes and influences of El Niño on SC rainfall in early summer and summer are similar, several important differences exist. We therefore tested the El Niño impacts further and suggest a potential circulation process as a mechanism to validate our composite rainfall results.

Figure 6 shows the anomalous patterns during EP and CP El Niño events for SSTAs, velocity potential and divergent winds at 200 hPa, lower troposphere wind, geopotential height at 500 hPa and the stream function at 850 hPa. The composite SSTAs patterns for both El Niño types (Figures 6a

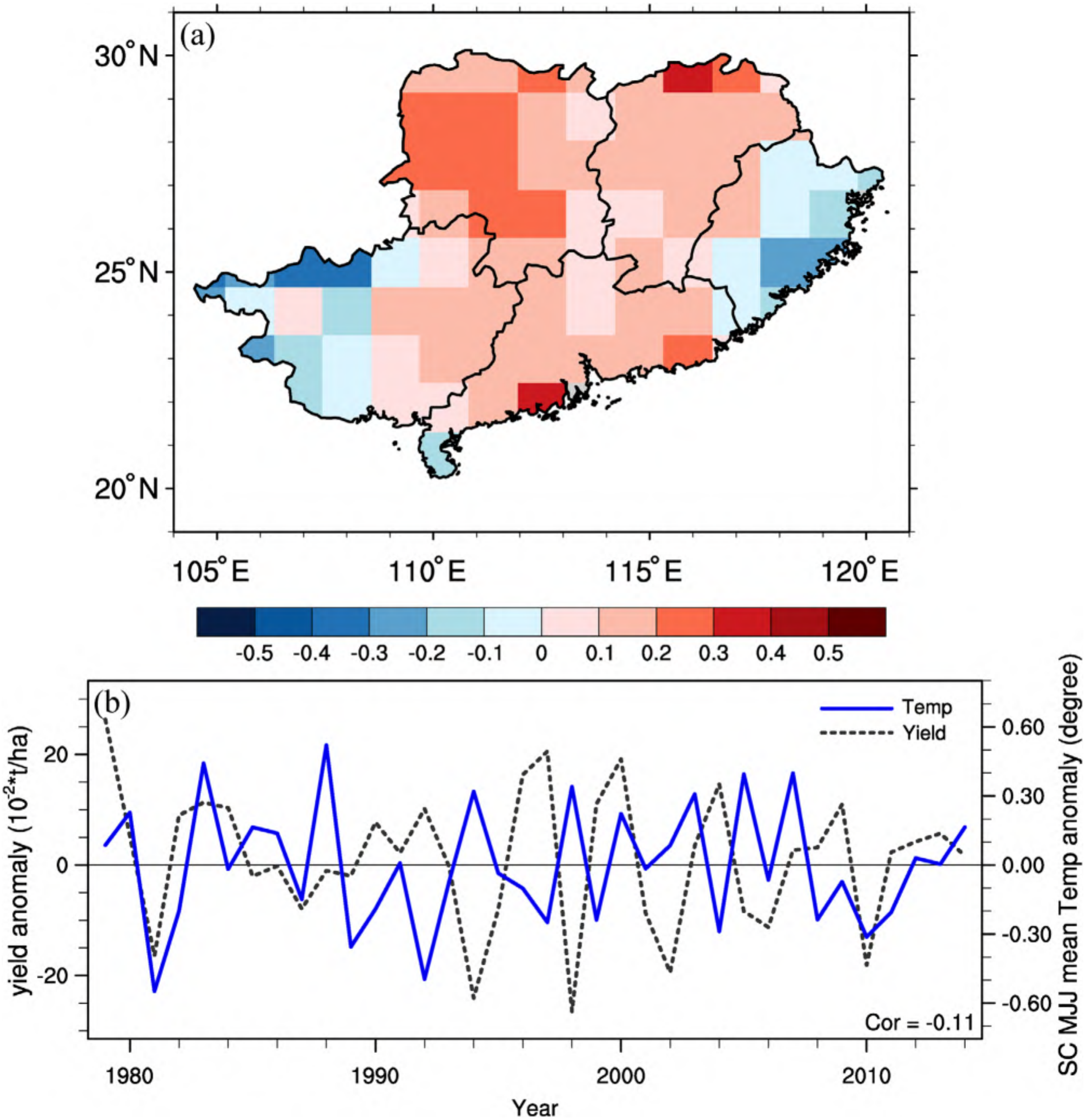

FIGURE 4 (a) Spatial distribution of correlation coefficients between growing season monthly mean temperature and early rice yields in southern China (SC) from 1982–2011. x axis represents longitude 104–121° E; *y* axis represents latitude 19–31° N. (b) Time series of May–June–July (MJJ) mean temperature anomalies (blue line) and early rice yield anomalies (black dashed line) from 1979–2014

and 6e) are consistent with typical SSTA conditions during DJF when El Niño events peak.

The 200 hPa velocity potential and divergent winds show how upper level air flows from mass sources to sinks, and also reveal the overall intensity of tropical circulations and low-level convergence and divergence (Tanaka, Ishizaki, & Kitoh, 2004). Figure 6b and 6f show the upper-level velocity potential and divergent winds associated with EP and CP El Niño events. For EP El Niño events, negative velocity potential anomalies over EP (Figure 6b) are derived from observations on the warming SSTAs in EP forming a negative–positive pattern from East to West. Thus, SC is affected by northerly divergent winds and anomalously positive velocity potential, which corresponds to an anomalous downward flow at lower levels in the region. The SC is affected by the anticyclone formed by this downward flow along with anomalously positive geopotential height (Figure 6c) and the stream function (Figure 6d). This indicates

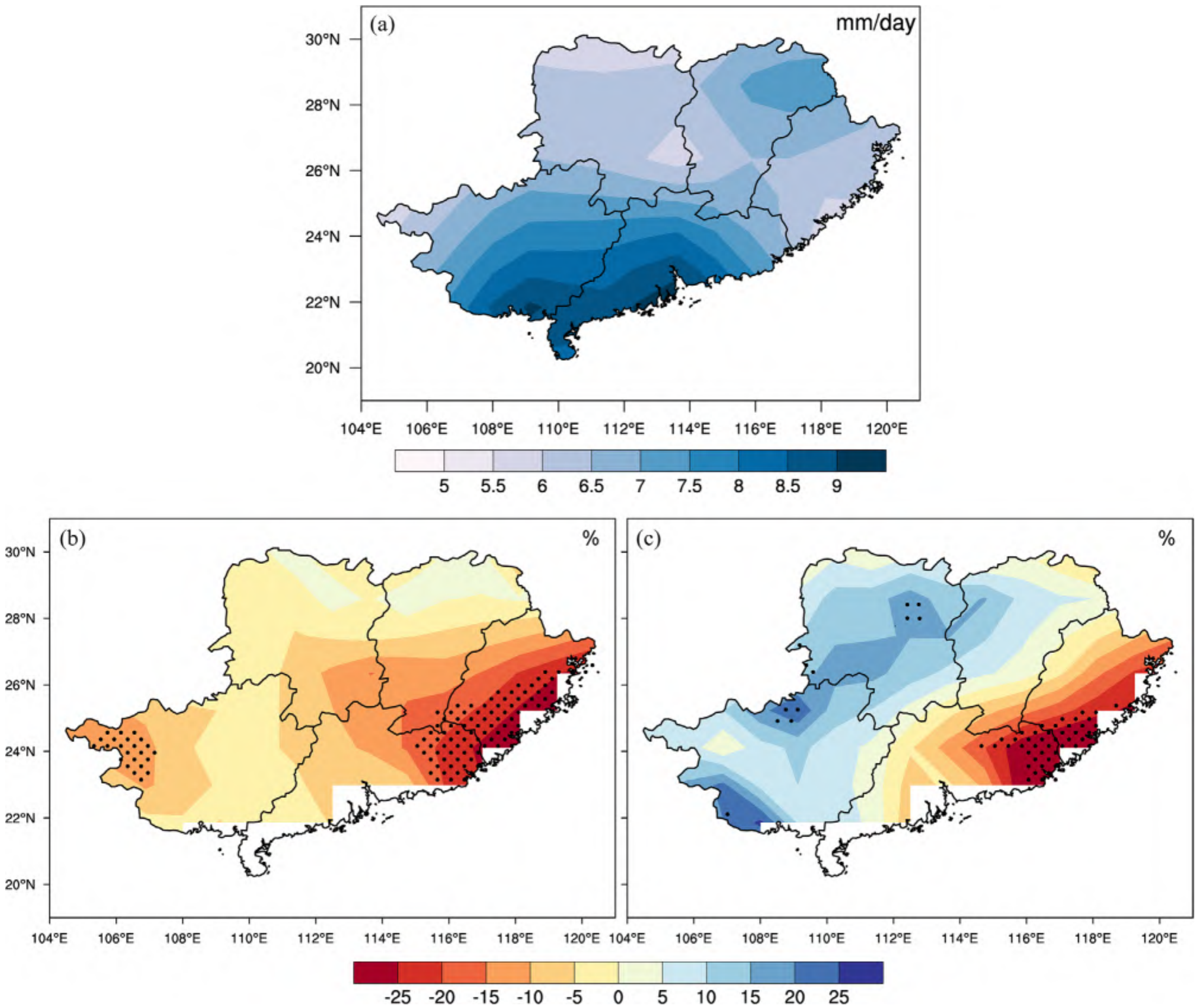

FIGURE 5 (a) May–June–July (MJJ) rainfall climatology over southern China (SC) for the period 1982–2011 (units: mm day^{-1}). (b) Composite spatial distribution of percentage rainfall anomaly (units: %) for eastern Pacific (EP) El Niño events, with respect to the MJJ climatological mean. x axis represents longitude 104–121° E; *y* axis represents latitude 19–31° N. Shaded areas are statistically significant at the .1 level. (c) Same as (b) but for central Pacific (CP) El Niño events

that during EP El Niño events, meteorological conditions are generally unfavorable for rainfall. Unlike during EP El Niño events, during CP El Niño events, both geopotential height (Figure 6g) and the stream function (Figure 6h) experience an anomalous drop over SC. The center of negative velocity potential and the warming center of SSTA during CP El Niño events shift westward in the CP (Figure 6e). Therefore, SC is under the control of anomalously negative velocity potential and southerly divergent winds (Figure 5f). The corresponding wind at lower levels over the study region is an anomalous cyclone, which indicates upward movement of the atmosphere. These circulation conditions are likely to reduce rainfall during the early rice growing season over SC during EP El Niño events, but to enhance rainfall during CP events.

4 | DISCUSSION

4.1 | The potential mechanism of the impacts of two types of El Niño on early rice yields

There is a significant difference in the SC rainfall caused by the two types of El Niño event, which is the main contributor to the differences in early rice yields. During the growing season of SC early rice, rainfall and yield have a significant negative relationship (Figure 2a, 2b).

During EP El Niño events, the dominant rainfall anomaly is negative (Figure 5b). During CP El Niño events, the rainfall anomaly forms a Northwest–Southeast positive–negative dipole (Figure 5c). According to Li, Yang, Ye, and Huang (2011) The Map of Chinese Agricultural Meteorological

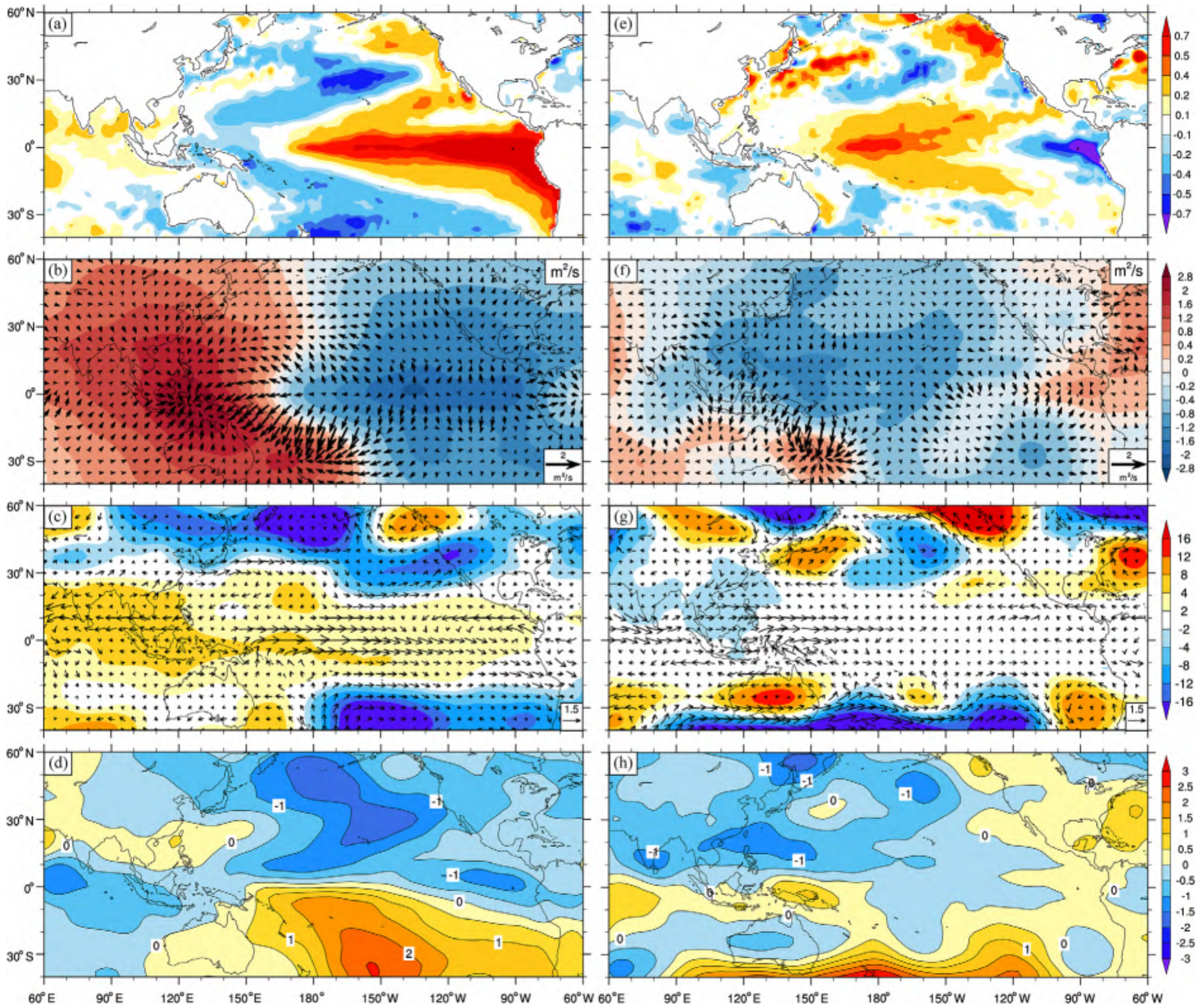

FIGURE 6 Anomalous patterns during eastern Pacific (EP) El Niño events for (a) sea surface temperature anomalies (SSTAs) (°C), (b) velocity potential (shading, units: $m^2\ s^{-1}$) and divergent winds (vectors, units: $m^2\ s^{-1}$) at 200 hPa, (c) wind (vectors, units: $m^2\ s^{-1}$) at 850 hPa, geopotential height (shading, unit: m) at 500 hPa, and (d) stream function at 850 hPa (units: $10^6\ m^{-2}\ s^{-1}$). Panels (e), (f), (g), and (h) are the same as (a), (b), (c), and (d), respectively, but for central Pacific (CP) El Niño events. *x* axis represents longitude 60° E, 60° W; *y* axis represents latitude 20° S, 60° N

Resources, the growing season climatology background of rainfall and solar radiation in SC are 200–300% and 30–40% of the amounts early rice needs in the entire growing season. This means that rainfall is adequate while solar radiation is not. In other words, too much rainfall might be disadvantageous for early rice yields, while increased solar radiation could benefit early rice yields through intensifying photosynthetic activity. During CP El Niño events, anomalously increased rainfall is accompanied with less shortwave radiation and more clouds, creating unfavorable growing conditions and then resulting in decreased rice yields, and vice versa. Therefore, EP El Niño events have a positive effect on SC early rice yields, whereas CP El Niño events have a negative effect on SC early rice yields.

We also adopt surface air temperature data to determine whether the two types of El Niño affect early rice yields via temperature. During the growing season, temperature is not well correlated with rice yields over the entire SC study area. Moreover, the two types of El Niño do not show significant differences with regard to temperature anomalies. Both El Niño types are comparable (differences within ±0.5°C) and result in a 0.5°C reduction in local temperature. Furthermore, based on the optimum growth–temperature range for early rice in SC (Sánchez, Rasmussen, & Porter, 2014), we followed the method of Wang et al. (2014) to provide a spatial distribution of temperature accumulation that reduces yield (TAR). Because of the small variances and identical patterns of temperature associated with both types of El Niño, the two corresponding TAR distributions are also similar (not shown). Therefore, rainfall variability is the main control factor on differences in rice yields between EP and CP El Niño events.

4.1.1 | Relationship between the occurrence of El Niño and southern China early rice yields anomalies

Two types of El Niño event both show significant impacts on SC early rice yields. We also calculated the correlation coefficients between MJJ mean SSTAs indices (Niño3 for EP events and EMI for CP events) and early rice yields anomalies in the period of 1979–2014, which were .06 and –.08. Though the correlation coefficients are not statistically significant, it does not mean there is no relationship between two types of El Niño event and early rice yields. In this study, seven of nine (78%) of EP El Niño events are associated with yield increase and three of four (75%) of CP El Niño events are accompanied by yield decrease. These indicate that there are correspondent relationships between the occurrence of both types of El Niño events and yields anomalies. It is reasonable to evaluate the relationship between El Niño events and SC early rice yields anomalies by using frequency instead of correlation.

Numerous studies have concluded that the impact of El Niño is observed when SSTAs reach a certain threshold (Wang & Picaut, 2013; Wang et al., 2017). In previous meteorological studies about ENSO, SSTAs threshold was the most commonly used criteria to diagnose ENSO events and evaluate the strength of ENSO. However, it does not mean that increasing numbers of SSTAs beyond the threshold results in greater impact of ENSO. For El Niño, the increase in SSTAs is not linearly correlated with the significance of the effect (Santoso, Mcphaden, & Cai, 2017). This may also partially explain why SC early rice yields decreased in 1987 and 1998 which are two EP events with SSTAs much higher than the threshold (.75 standard deviation of 1979−2011 Niño3 index) used to diagnose the occurrence of EP El Niño. Due to the asymmetry of ENSO, spatial structure and seasonal evolution of warm phase and cold phase are not necessarily opposite to each other, and neither are their climatic impacts. Compared with correlation, calculating composite difference between El Niño events and neutral years is more widely used in ENSO-related studies.

4.2 | Relationship between different phases of El Niño and SC early rice yields anomalies

There are some exceptional cases such as 1987, 1998 for EP events and 2004 for CP events. The early rice yields anomalies in these events are not consistent with the other events. We explain this issue from the viewpoint of developing and decaying phases of El Niño.

According to Iizumi et al. (2014), the reproductive growth period is the key interval that determines crop yield and is specified as a 3-mo interval commencing 3 mo before harvest and ending at harvest. For early rice in SC, the reproductive growth period is MJJ. Therefore, we use the SSTAs during MJJ to distinguish two types of El Niño. We also looked into the two SSTAs indices during our study period, Niño3 for EP events and EMI for CP events respectively to find out whether MJJ falls into the catalog of developing phase or decaying phase.

We defined the developing and decaying phases following three criteria. First, if an El Niño event occurred during the previous boreal winter and not during the following winter, then, MJJ is defined as a decaying phase. Second, if an El Niño event occurred during the following boreal winter and not during the previous winter, then, MJJ is defined as a developing phase. Third, if El Niño event occurred during both previous and following winters, we referred to prior studies to categorize these events. Following the previous criteria and studies on different phases of El Niño (Lin & Li, 2008; Wu, Zhou, & Li, 2009), we found that for nine EP events, there are six events characterized as developing phase of El Niño (1982, 1987, 1991, 1993, 1997, and 2009), while the other three are decaying phase (1983, 1992, and 1998). This categorization is the same with previous studies. Yields increase happens in five of six developing phase EP events (1982, 1991, 1993, 1997, and 2009), except for 1987. For the three decaying phase EP events, yields increase in 1983 and 1993, and decrease in 1998. For the two exceptional yields decrease EP events, 1987 is developing phase and 1998 is decaying phase. Also, for the four CP events, there are three developing phases (1994, 2002, and 2004) and one decaying phase (1995). The only yields increase case, 2004, is a developing phase CP event. The other two developing phase cases are accompanied by early rice yields decrease.

Therefore, the above results indicate that there is no consistent relationship between different phases of El Niño event and early rice yields in SC. So we suspect there might be other climate factors which would also affect yields of early rice in SC except for El Niño.

4.3 | Relationship between El Niño persistence and southern China early rice yields anomalies

El Niño usually develops in summer and autumn, peaks in winter and decays in spring, which exhibits persistence to some extent. According to previous studies, there is a significant decrease in the persistence of ENSO across the boreal spring, which is the well-known ENSO spring persistence barrier (McPhaden, 2003; Lopez & Kirtman, 2014). Possibly, there is not much signal of the previous winter left in the summer SSTAs. Also, Feng and Li (2011) suggested that EP El Niño events are accompanied with spring rainfall increase in SC, contradictory to CP events. These results of spring rainfall anomalies are the opposite of our results of early summer rainfall anomalies. This implies that MJJ SC rainfall is affected by the simultaneous SSTAs in tropical Pacific Ocean instead of spring SSTAs. Iizumi et al. (2014) also suggest that the SSTAs during the growing season have a direct impact on crop yields. The above discussion implies that the impact of ENSO persistence on SC early rice yields needs further investigation.

5 | CONCLUSIONS

Our findings suggest that EP and CP El Niño events have significantly different effects on the yield of early rice throughout SC. From composite analysis, the association with EP El Niño was found to be positive across the entire study region (Figure 1a). In contrast, the overall association with CP El Niño tends to be negative (Figure 1b). This difference between the impacts of the two types of El Niño event is significant in approximately one-third of the study area and is most pronounced in northern and western SC. In other words, compared with EP El Niño, CP El Niño significantly reduces the early rice yields (Figure 1c). This conclusion is supported by the results of both yield datasets considered here.

Our results illustrate how two types of El Niño have distinctive effects on early rice yields in SC. They also point towards a possible climatological mechanism from the perspective of linking the different locations of SSTAs with SC early rice yields differences through atmospheric teleconnection affects on local climatic factors. Our findings underscore the importance of taking into account both the respective influences and differences of the two El Niño types, and their relationships with major climatic factors, when investigating El Niño impacts on crop yield.

We note that additional assessment is needed of the impact of the two El Niño event types on other crops, besides rice, in adjacent regions. Further investigation is also warranted on the different types of La Niña events and their influences on rice crop yield.

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