

# Spatio-temporal analysis of meteorological disasters affecting rice, using multi-indices, in Jiangsu province, Southeast China

Jin Huang<sup>1</sup> · Yadong Lei<sup>2</sup> · Fangmin Zhang<sup>3</sup> · Zhenghua Hu<sup>3</sup> 

Received: 26 September 2016 / Accepted: 9 May 2017 / Published online: 19 June 2017  
© Springer Science+Business Media Dordrecht and International Society for Plant Pathology 2017

**Abstract** With the increasing risk of people and economies being subject to meteorological disasters, it is of great importance to analyse the spatio-temporal variation of these disasters. In this paper, the possible impacts of meteorological disasters on rice yields in Jiangsu Province, southeast China was studied. A total of 17 rice meteorological disaster indices (RMDI) during 1961–2012 was calculated and analyzed. The spatial distribution of RMDI indicated that south Jiangsu should be classified as a high-intensity zone for heat stress, while north Jiangsu should be classified as a high-intensity zone for precipitation extremes and chilling injury. Changing trends of RMDI were detected by the Mann-Kendall test. Precipitation extremes and heat stress indices presented increasing trends, while the chilling injury indices showed decreasing trends. Correlation analysis between rice yield and RMDI with the first difference method and climate-induced yield method showed that precipitation

extremes had more dramatic negative effects than the other two types of meteorological disaster. Principal components analysis provided additional information about the regional differences of changes in meteorological disasters. Jiangsu could be divided into three regions (south, middle, and north) with different and changing patterns for RMDI. Also the Western Pacific Subtropical High Intensity Index and the Pacific Decadal Oscillation had significant influences on these changes. These findings could provide a scientific basis for the prevention or reduction of rice meteorological disasters in Jiangsu Province.

**Keywords** Rice meteorological disasters · Jiangsu, China

## Introduction

Agro-meteorological disasters are generally referred to as meteorological hazards (e.g., storm rainfall, heat stress, chilling injury, and typhoon) that negatively affect crop growth, development, and production (Zhang et al. 2014). China is a populous, agricultural country that has suffered severely from agro-meteorological disasters in recent decades and global warming has contributed to the increasing risk of their occurrence (Liu et al. 2015; Sun et al. 2015). Against this background, understanding the spatio-temporal variability of agro-meteorological disasters and their effect on main grain crops has become an increasingly important research topic in China. Shi and Tao (2014a) pointed out that drought significantly affected wheat yields in most of the regions with drier conditions during 1983–2008 in major wheat producing regions. The comparison for occurrence frequency of major rice disasters between 2000 and 2009 and 1991–2000 indicated that floods occurred more frequently at earlier growth stages, while chilling damage occurred more frequently at later

✉ Zhenghua Hu  
nuistecology@163.com

<sup>1</sup> Jiangsu Collaborative Innovation Center of Atmospheric Environment and Equipment Technology (CICAEET), Jiangsu Key Laboratory of Agricultural Meteorology, Nanjing University of Information Science & Technology, Nanjing 210044, China

<sup>2</sup> Key Laboratory of Meteorological Disaster of Ministry of Education, Collaborative Innovation Center on Forecast and Evaluation of Meteorological Disasters, Nanjing University of Information Science & Technology, Nanjing 210044, China

<sup>3</sup> Collaborative Innovation Center on Forecast and Evaluation of Meteorological Disasters, Jiangsu Key Laboratory of Agricultural Meteorology, Nanjing University of Information Science & Technology, Nanjing 210044, China

growth stages in southwestern China during the twenty-first century (Tao et al. 2013a, b). Spatial patterns of major disaster frequency for maize were region-specific, with cold stress in northeastern China, drought in northern and western China, and rainstorms in southwestern China (Zhang et al. 2014).

Rice is one of the most important food sources for more than half the world's population, and China is the largest rice producing country in the world (Wang et al. 2014). The mid-lower reaches of the Yangtze River are the main rice producing areas in China, and the disasters, which include heat stress, chilling injury and precipitation extremes, often bring about inter-annual fluctuations of rice yields. Thus, using meteorological indices to discuss the spatio-temporal changes of rice yields has always been a concern of Chinese scholars. Previous studies have constructed several common indicators for evaluating the effects of high and low temperature stress on rice. Frequency of high-temperature events (with daily mean temperatures of  $\geq 30$  °C continuously for 3 or more days during July–August) was often used to describe the effect of heat stress on rice (Tao et al. 2013a). Similarly, the number of continuous days with daily mean temperature  $< 20$  °C during August–September was often used to describe chilling injury on single-cropped rice (Yin et al. 2016). Although precipitation extremes occurring in July–August were reported to have detrimental impacts on rice yields, there is no unified meteorological index for measuring precipitation-induced rice disasters (Shen 2015).

Located in the mid-lower Yangtze River basin of China, Jiangsu's rice production was ranked in the top five of all provinces, and the province is an important net exporter of grain (Huang et al. 2016a). In view of this, extreme temperature stress in Jiangsu has always been a concern (Ren et al. 2010; Bao et al. 2012; Yin et al. 2016). However, the possible impact of precipitation extremes on rice yields in Jiangsu has rarely been investigated. Additionally, the applicability and validity of existing meteorological indices for agro-meteorological disasters have not been evaluated in depth. To solve some of these problems, the objectives of this study were to: (1) investigate spatial and temporal variability of rice meteorological disasters using multiple indices; (2) test the applicability of the meteorological indices used in describing rice agro-meteorological disasters; and (3) discuss the atmospheric circulation underlying the changes in rice meteorological disasters. Such a study may provide help for the management and planning of rice production under global warming in this province.

## Study area and data

### Study region

Jiangsu province lies in southeast China along the southern bank of the mid-lower Yangtze River Basin at latitudes between 113°

E and 119° E and longitudes between 24° N and 31° N. The province is situated in a transition belt from a subtropical to a temperate zone and has a typical monsoon climate. Average annual temperature is 17 °C and there are 240–330 frost-free days. Annual precipitation is between 1200 and 1900 mm. In this province, single season cropping is the main planting pattern for rice.

### Climate data and rice yield data

Daily precipitation and daily mean temperatures of 52 meteorological stations in Jiangsu province (Fig. 1), recorded from 1961 to 2012, were provided by the Meteorological Bureau of the Province. Climate data in each station passed the homogeneity test using the RHtestsV4 software package developed by Wang and Feng (2013). Additionally, data records of single-cropping rice yield from 1961 to 2012 in 52 producing counties corresponding to the meteorological stations in Fig. 1 were collected from the Statistical Bureau of Jiangsu Province.

### Circulation indices

Several large-scale anticyclonic circulations were also used in this study. The North Atlantic Oscillation (NAO), Southern Oscillation Index (SOI), Multivariate ENSO Index (MEI), Pacific Decadal Oscillation (PDO), Northern Oscillation Index (NOI), North Pacific pattern (NP) and Antarctic Oscillation (AO) were downloaded from the National Oceanic and Atmospheric Administration of the U.S.<sup>1</sup>, but the West Pacific Subtropical High Intensity Index (WPSHII) was downloaded from the National Climate Center of China.<sup>2</sup>

## Method

### Rice meteorological disaster indices

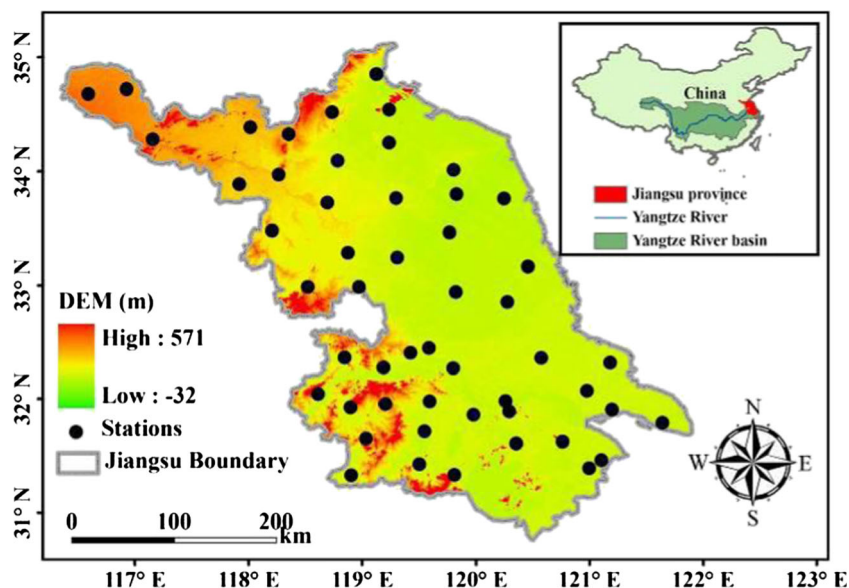
A total of 17 rice meteorological disaster indices (RMDI; Table 1) were constructed in this study based on the thresholds of extreme temperature stress and the definition of the extreme precipitation index recommended by the joint World Meteorological Organization CCL/CLIVAR/JCOMM Expert Team on Climate Change Detection and Indices (ETCCDI).<sup>3</sup>

<sup>1</sup> <http://www.esrl.noaa.gov/psd/data/climateindices/list/>. (August 1, 2016)

<sup>2</sup> <http://ncc.cma.gov.cn/Website/index.php?ChannelID=43&WCHID=5>. (August 1, 2016)

<sup>3</sup> [http://etccdi.pacificclimate.org/indices\\_def.shtml](http://etccdi.pacificclimate.org/indices_def.shtml). (August 1, 2016)

**Fig. 1** Meteorological stations used in this study and location of Jiangsu province, China. The Digital Elevation Model (DEM) with a spatial resolution of 90 m is available at <http://srtm.csi.cgiar.org/>



**Response of rice yields to meteorological disasters**

Before estimating the effects of meteorological disasters on rice yields, the influence of possible confounding non-climatic factors

should first be removed (Yang et al. 2015). Usually, the first difference method and climate-induced yield method were used for detrending the time series of actual crop yield (Lobell 2007; Revadekar and Preethi 2012; Shi and Tao 2014b).

**Table 1** Definition of rice disaster meteorological indices (RMDI) used in this study

Types of rice meteorological disasters	Meteorological index	Definition	units
Precipitation extremes occurring during July–August	PI1	days when daily precipitation $\geq 50$ mm	days
	PI2	days when daily precipitation $\geq 100$ mm	days
	PI3	maximum 1-day precipitation	mm
	PI4	maximum 7-days precipitation	mm
	PI5	maximum number of consecutive days with daily precipitation $\geq 1$ mm	days
Heat stress occurring during July–August	HTI1	number of high temperature days	days
	HTI2	accumulated temperatures of high temperature days	$^{\circ}\text{C}$
	HTI3	number of short continuous high temperature events (duration is 2 to 4 days)	events
	HTI4	number of moderate continuous high temperature events (duration is 5 to 7 days)	events
	HTI5	number of long continuous high temperature events (duration is $>7$ days)	events
	HTI6	duration of extreme continuous high temperature event	days
	HTI7	accumulated temperatures of extreme continuous high temperature event	$^{\circ}\text{C}$
Chilling injury occurring during August–September	LT11	number of low temperature days	days
	LT12	number of short continuous low temperature events (duration is 2 to 4 days)	events
	LT13	number of moderate continuous low temperature events (duration is 5 to 7 days)	events
	LT14	number of long continuous low temperature events (duration is $>7$ days)	events
	LT15	duration of extreme continuous low temperature event	days

The daily mean temperature  $\geq 30$   $^{\circ}\text{C}$  in July–August is taken as the threshold for high temperature days, and the daily mean temperature  $\leq 20$   $^{\circ}\text{C}$  in August–September is taken as the threshold for low temperature days. The continuous high/low temperature events are usually regarded as the period with consecutive high/low temperature days, and the extremes should be defined as the continuous high/low temperature events with longest duration

### First difference method

In the first difference method, the equation to calculate the first difference value of a time series of rice yield/RMDI ( $\Delta y$ ) can be written as:

$$\Delta y = y_i - y_{i-1}$$

where  $i$  is the  $i$ th year in the time series of rice yield/MDI,  $y_i$  is rice yield for the  $i$ th year, and the first value in each time series was omitted (Yang et al. 2015). The correlation between first difference value series of rice yield and RMDI should be calculated for understanding the response of rice yields to meteorological disasters.

### Climate-induced yield method

In the climate-induced yield method, the actual crop yield is the equivalent of the sum of the management-induced yield and the climate-induced yield (EI-Maayar and Lange 2013). The management-induced yield is the fitted results for the annual series of actual yields using mathematical methods (including linear regression, moving average, logistic curve, quadratic curve) (Huang et al. 2016b), and the correlation between climate-induced yield of rice and RMDI should be used to describe the possible impacts of meteorological disasters on rice yield. In Jiangsu, the 5-year moving average function has proved to be best for simulating the management-induced yield of rice in the province (Huang et al. 2016a).

### Principal components analysis

Principal components analysis (PCA) is an important dimensionality reduction method. According to a different input matrix of time, variables, stations, PCA has six different modes (Gocic and Trajkovic 2014). The more common is to identify the stations with variables (i.e. columns in the data matrix) and time observations with the individual realizations (rows) (Huth 1996). Using PCA with such an input matrix is usually referred to as S-mode PCA, which isolates groups of stations varying similarly in time (Casado et al. 2009). This method is often used to identify the sub-regions with similar temporal evolution in a single index. To achieve more stable spatial patterns, a rotation of the principal components with the Varimax procedure was applied (Raziei et al. 2008). In general, the Varimax rotation is a linear transformation of the modes that attempts to find a new location for the coordinate axes, such that projections of the variable onto those axes simplify the spatial or temporal structure of the modes (Mestas-Nuñez 2000).

### M-K trends test

In this study, the non-parametric Mann–Kendall (M-K) trend test, which is often used for climatological time series (Sun et al. 2013; Liu et al. 2016), was applied to test the significance of trends on the time series of RMDI. Given the possible interference by serial correlation in the time series, the effective sample size method developed by Yue and Wang (2004) was applied for optimizing the output of the M-K test. If the absolute value of  $Z$  calculated from the M-K test is larger than 1.96, a trend is considered to be statistically significant at the 5% level.

## Results

### Spatial and temporal variability of RMDI

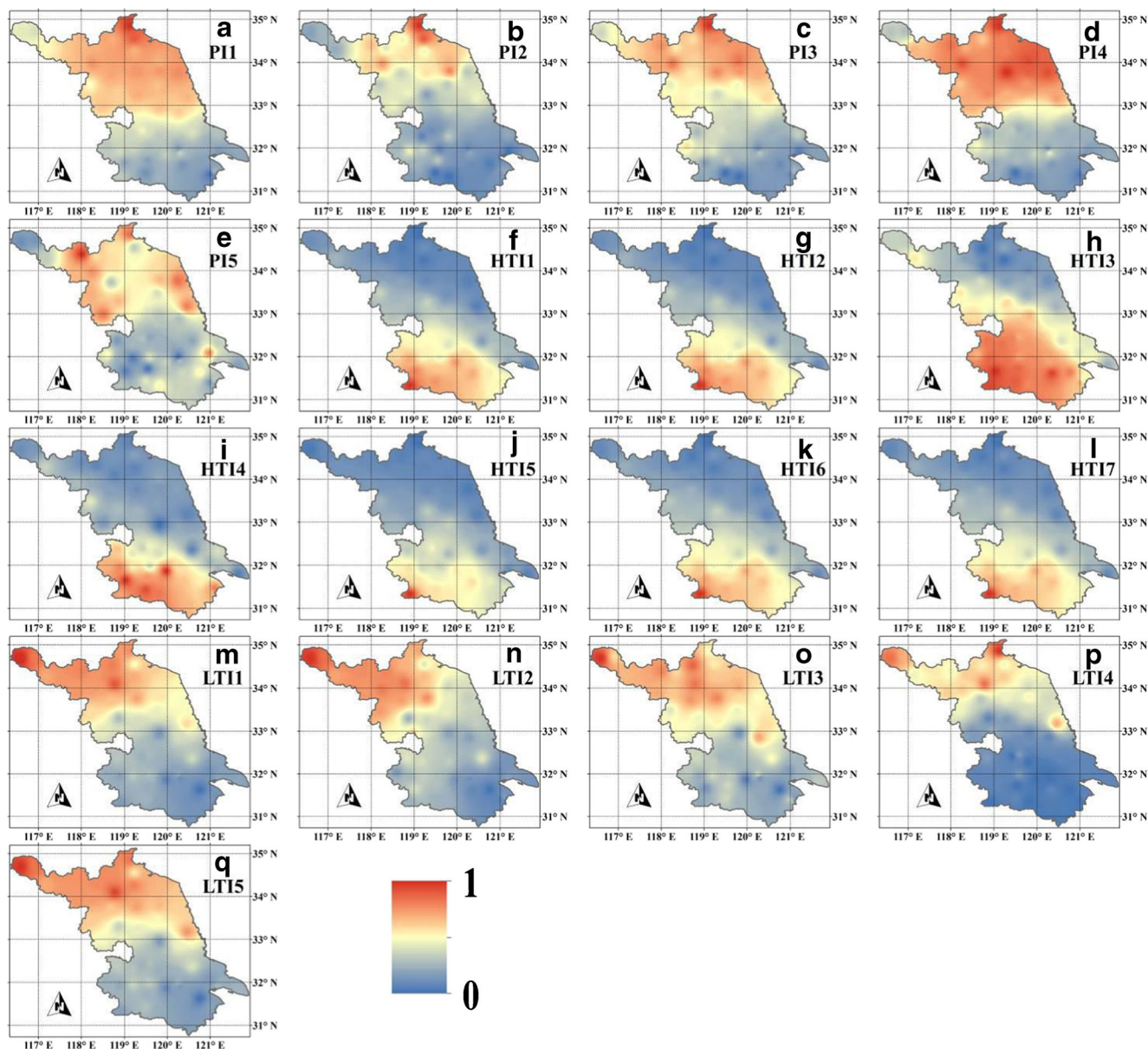
#### Spatial distribution of RMDI

At first, the normalized value of the multiannual average of RMDI in each station was spatially interpolated in two. The higher values of high-temperature indices (Fig. 2f-l) were found in south Jiangsu, while the higher values of precipitation indices (Fig. 2a-e) and low-temperature indices (Fig. 2m-q) were observed in north Jiangsu. Thus the greater harmfulness for heat stress was detected in the southern areas, while the greater harmfulness for precipitation extremes and chilling injury was found in the northern areas. Jiangsu takes the Huai River Irrigation Line as the approximate demarcation between the south, which has a subtropical monsoon climate and the north, which has a warm moist monsoon climate. These different may be the cause of the obvious spatial distribution of RMDI.

#### Trends of RMDI

The M-K test was applied to the time series of the 17 RMDI. Positive trends were detected for all the precipitation extremes indices and heat stress indices over Jiangsu (Fig. 3a). On the contrary, the chilling injury indices in all-Jiangsu showed negative trends. Among the 17 indices, the PII (days when daily precipitation  $\geq 50$  mm) and HTI4 (number of moderate continuous high temperature events) had significant upward trends, while the LTI1 (number of low temperature days), LTI2 (number of short continuous low temperature events) and LTI5 (duration of extreme, continuous low temperature events) had significant downward trends. All these indicated that the harmfulness of precipitation extremes and heat stress had increased, while the harmfulness for chilling injury had declined. At the station scale, the changes in PI4 (maximum 7-days precipitation), HTI2 (accumulated temperatures of high temperature days), and LTI1 were more obvious (Fig. 3b). From the spatial perspective, the 10 stations with significant positive trends for PI4 (maximum 7-days precipitation) were





**Fig. 2** Spatial distribution for normalized value of multiannual average of RMDI across Jiangsu

mainly located in south Jiangsu (Fig. 4a). Similarly, the 15 stations with significant positive trends for HTI2 (accumulated temperatures of high temperature days) were mainly found in south Jiangsu (Fig. 4b). As for LTI1 (number of low temperature days), most of the 29 stations with significant negative trends were also distributed in south Jiangsu (Fig. 4c). Overall, the chilling injury indices in Jiangsu showed more obvious changes compared to precipitation extremes and heat stress indices.

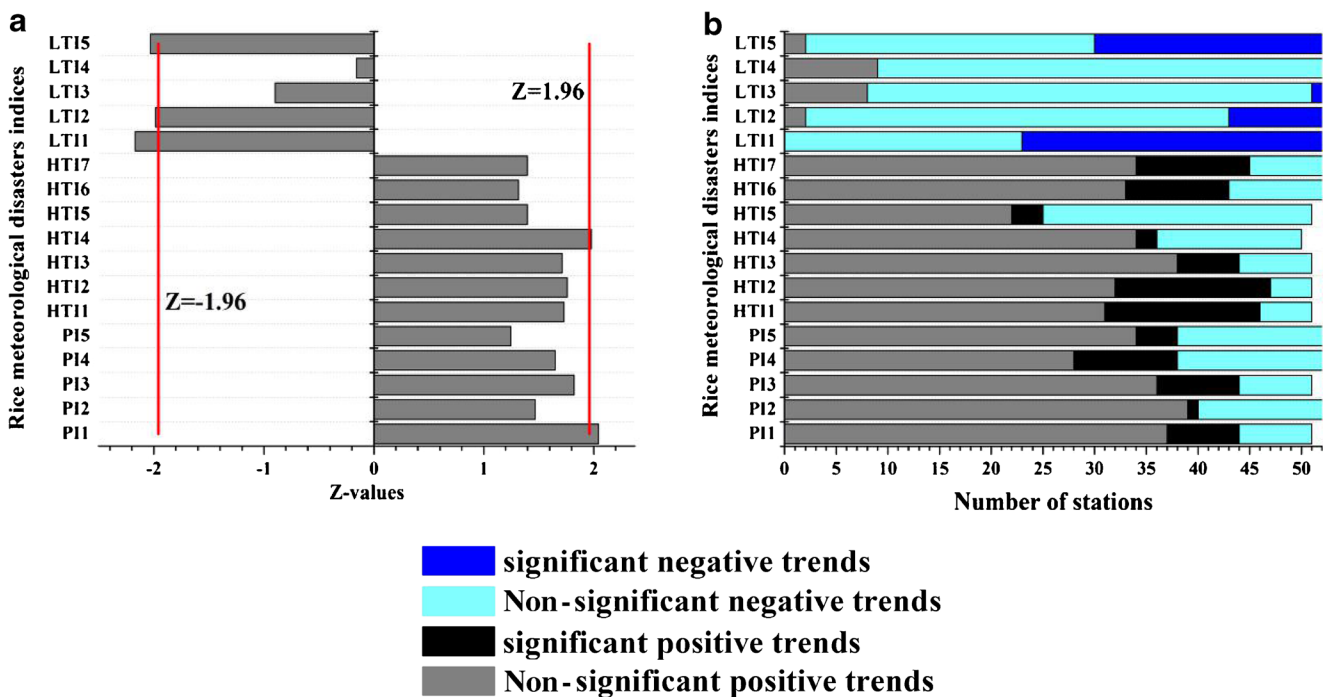
**Relationship between rice yield and RMDI**

To investigate the possible impact of meteorological disasters on rice yield, the correlation analysis between rice yield and

the 17 disaster indices in each station were computed using the first difference method and the climate-induced yield method. It can be seen from Fig. 5 that the results calculated using the first-different method were consistent with those derived from the climate-induced yield method. In terms of the number of stations with significant correlation in Fig. 5, the negative impacts of meteorological disasters on rice yield by using the first difference method were more obvious.

*Relationship between rice yield and precipitation-related indices*

It is important to note that 17 disaster indices had various correlations with rice yield. For the three main types of rice



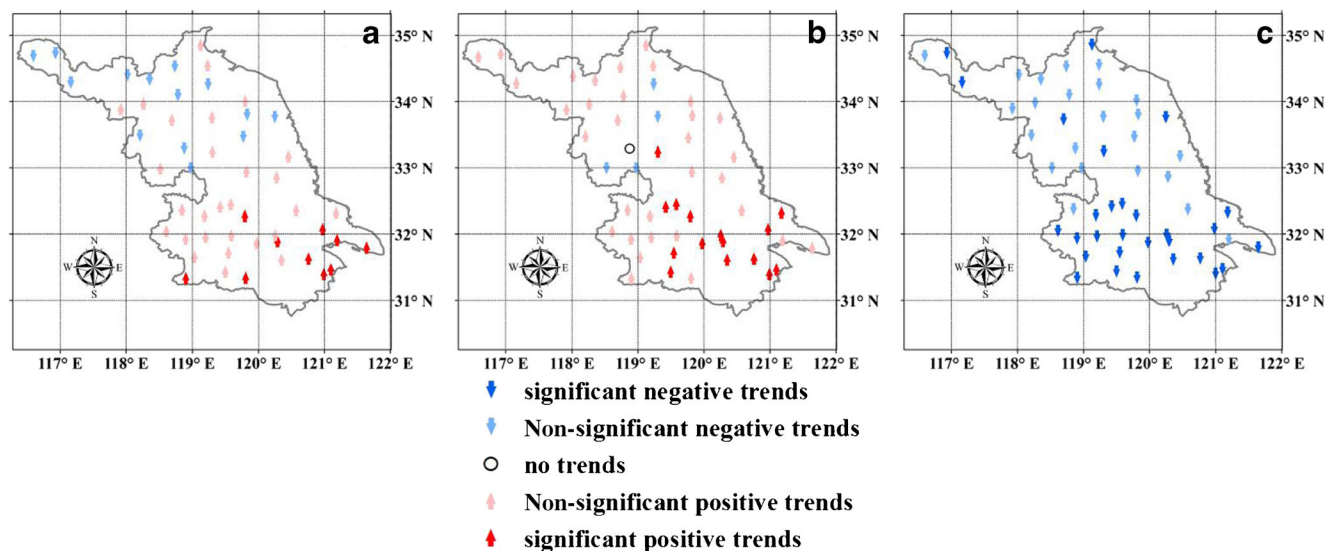
**Fig. 3** M-K trend test for RMDI at scales of entire province and individual stations (a: trends of RMDI in all-Jiangsu; b: number of stations with different trends for RMDI). The definitions of RMDI (LT11–5, HT11–7 and PI1–5) are listed in Table 1

meteorological disasters, the negative impact of extreme precipitation events on rice yield were more obvious. In more than 40 stations, all the precipitation-related indices had negative correlations with rice yield. As shown in Fig. 5, the number of stations with significant negative correlations between rice yield and precipitation-related indices was always more than 10. Especially for the relationship between rice yield and PI4 (maximum 7-days precipitation), the number of stations with significant negative correlations shown in Fig. 5a and b was 19 and 17, respectively, which ranks first among all the disaster indices. This may indicate that PI4 has

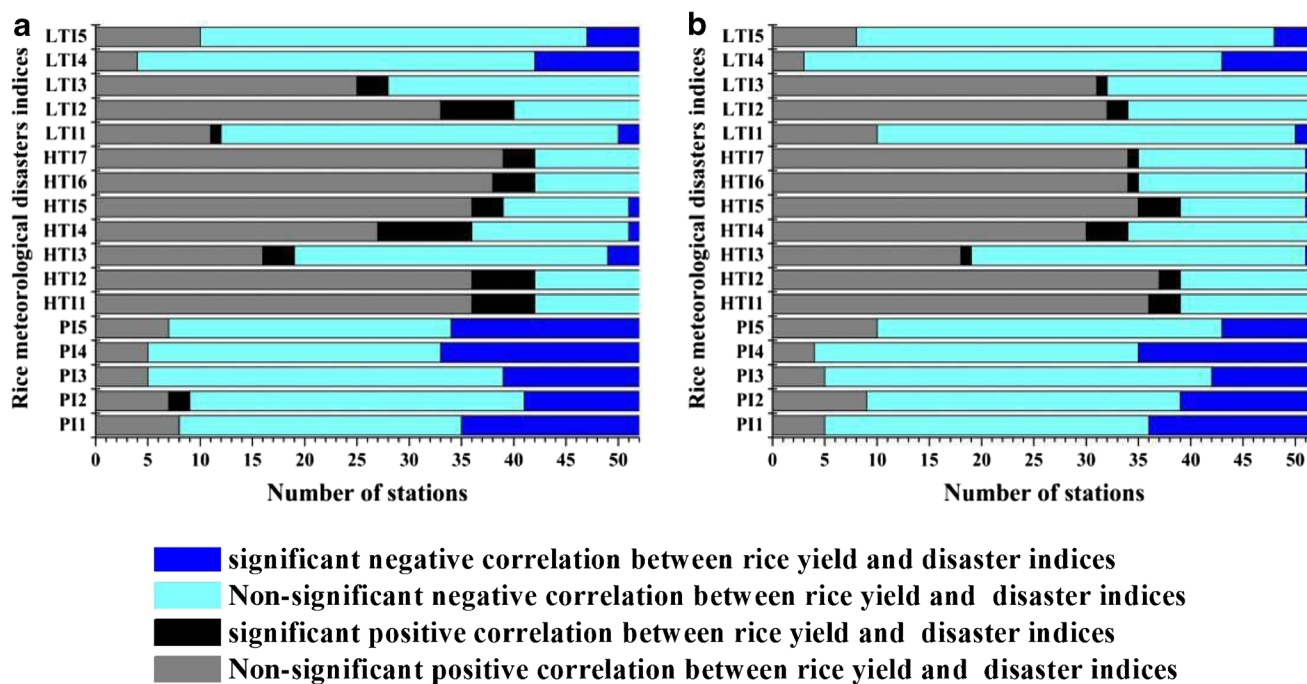
better applicability for depicting the adverse effects of precipitation extremes on rice, and could be regarded as a strong indicator of the fluctuation in rice yields across Jiangsu.

*Relationship between rice yield and temperature-related indices*

Low temperature indices showed a certain degree of adaptability for characterizing rice chilling injury in Jiangsu. In more than 40 stations, the LT11 (number of low temperature days), LT14 (number of long continuous low temperature



**Fig. 4** Spatial distribution of trends for PI4 (a), HTI2 (b), and LTI1 (c) across Jiangsu



**Fig. 5** Summary results for the correlation between rice yield and 17 RMDI in all stations a correlation computed using first-different method; b: correlation computed using climate-induced yield method)

events), and LTI5 (duration of extreme, continuous low temperature events) had negative correlations with rice yield. Among the three indices, the LTI4 may be more suited to depicting the adverse effects of chilling injury in this study area, as this index had the largest number of stations with significant negative correlations. In contrast, the performance of high temperature indices was not satisfactory. It can be seen from Fig. 5 that rice yield had positive correlations with most of the high temperature indices in more than 70% of the stations. The HTI3 (number of short continuous high temperature events) was the only high temperature index that had negative correlations with rice yield in most stations. This indicates that the rice yield in Jiangsu was less sensitive to the negative impacts of heat stress, than precipitation and chilling stress.

#### *Spatial distribution of correlations between rice yield and three key indices*

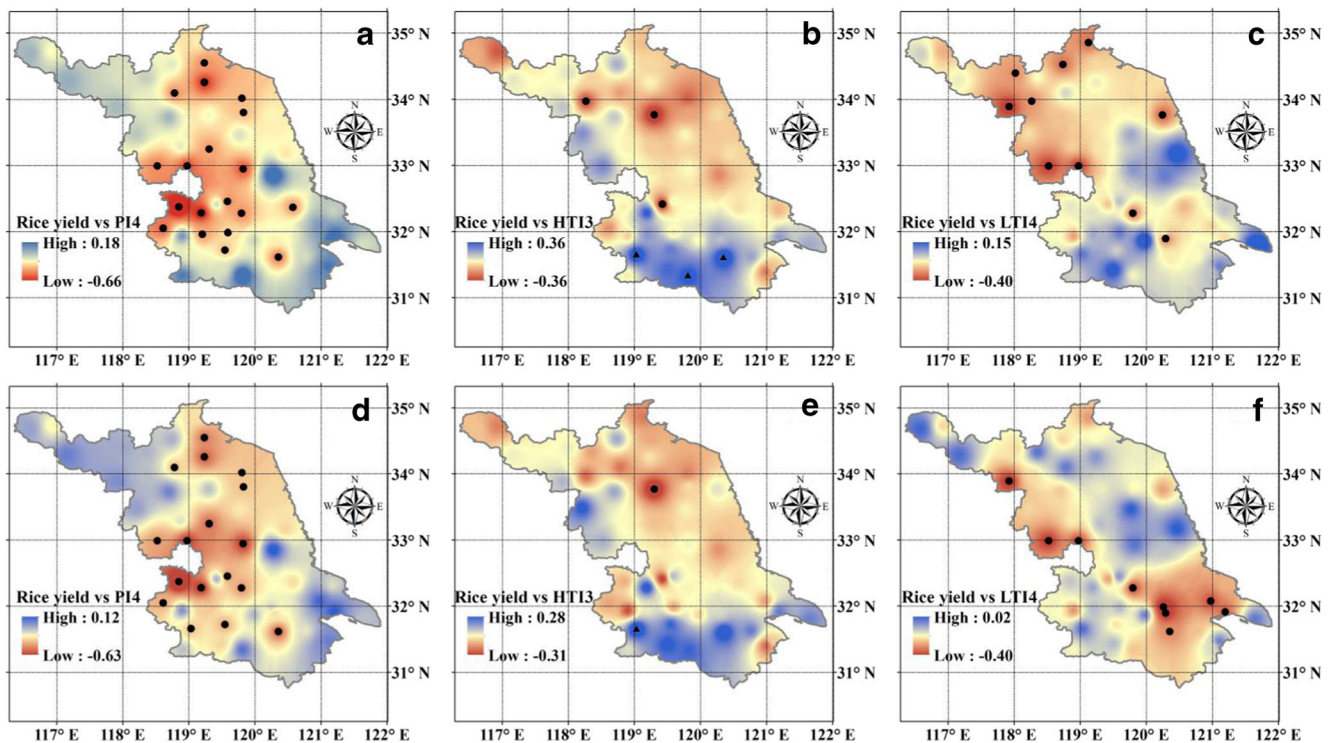
In summary, the PI4, HTI3, and LTI4 should be used as the key indices for characterizing rice meteorological disasters covering precipitation extremes, heat stress, and chilling injury. On the basis of the first difference method and climate-induced yield method, the correlation coefficients between rice yield and the three meteorological disasters indices in all stations were spatially interpolated (Fig. 6). Overall, the spatial distribution for correlation coefficients derived from the two methods were basically the same. As displayed in Fig. 6a and d, the northeastern and mid-western areas in Jiangsu

should be classified as the sensitive regions for precipitation extremes. For rice heat stress, the sensitive region was mainly located in the northern areas in Jiangsu (Fig. 6b and e). As for rice chilling injury, the sensitive region was mainly observed in the northwestern and southeastern areas in Jiangsu (Fig. 6c and f).

#### **Regional changes of key RMDI**

S-mode PCA was applied to the annual series of PI4, HTI3, and LTI4 from 52 stations distributed across the study area. Taking into account the variance explained by each principal component (PC), three main space-time modes (PC1, PC2, and PC3) were identified for each disaster index. These three modes explain about 74% of the total variance in the original PI4 series, and about 77% for the HTI3 and about 79% for the LTI4 (Fig. 7). The spatial patterns of loading represent the correlation between the original data and the corresponding principal component scores (PCS) time series, which were used for aggregation of climate sub-regions that experienced similar conditions during the study period (Raziei et al. 2015). The loading displayed in Fig. 7a, b, and c seemed to localize in space three distinct sub-regions, the southern area, northern area and middle area of Jiangsu, that were characterized by different temporal variability of PI4. Similar regionalization was also observed for HTI3 (Fig. 7d–f) and LTI4 (Fig. 7g–i) according to the spatial distribution of loading. The PCS time series corresponding to each mode is shown in Fig. 8, which illustrates the different changing behaviors of meteorological





**Fig. 6** Spatial distribution of correlation between rice yield and three key RMDI across Jiangsu (**a, b, c**: correlation computed using first-different method; **d, e, f**: correlation computed using climate-induced yield

method; the black circle denote significant negative correlation, while the black triangle significant positive correlation)

disaster indices in different sub-regions. As displayed in Fig. 8a, b, and c, the temporal variability of PCS indicated that PI4 had a weak increasing tendency in south and middle Jiangsu. For rice heat stress, all Jiangsu was dominated by the weak increasing tendency of HTL3 (Fig. 8d, e, and f). As for Fig. 8g, h, and i, the tendency of PCS for LHT4 was almost negligible in each sub-region.

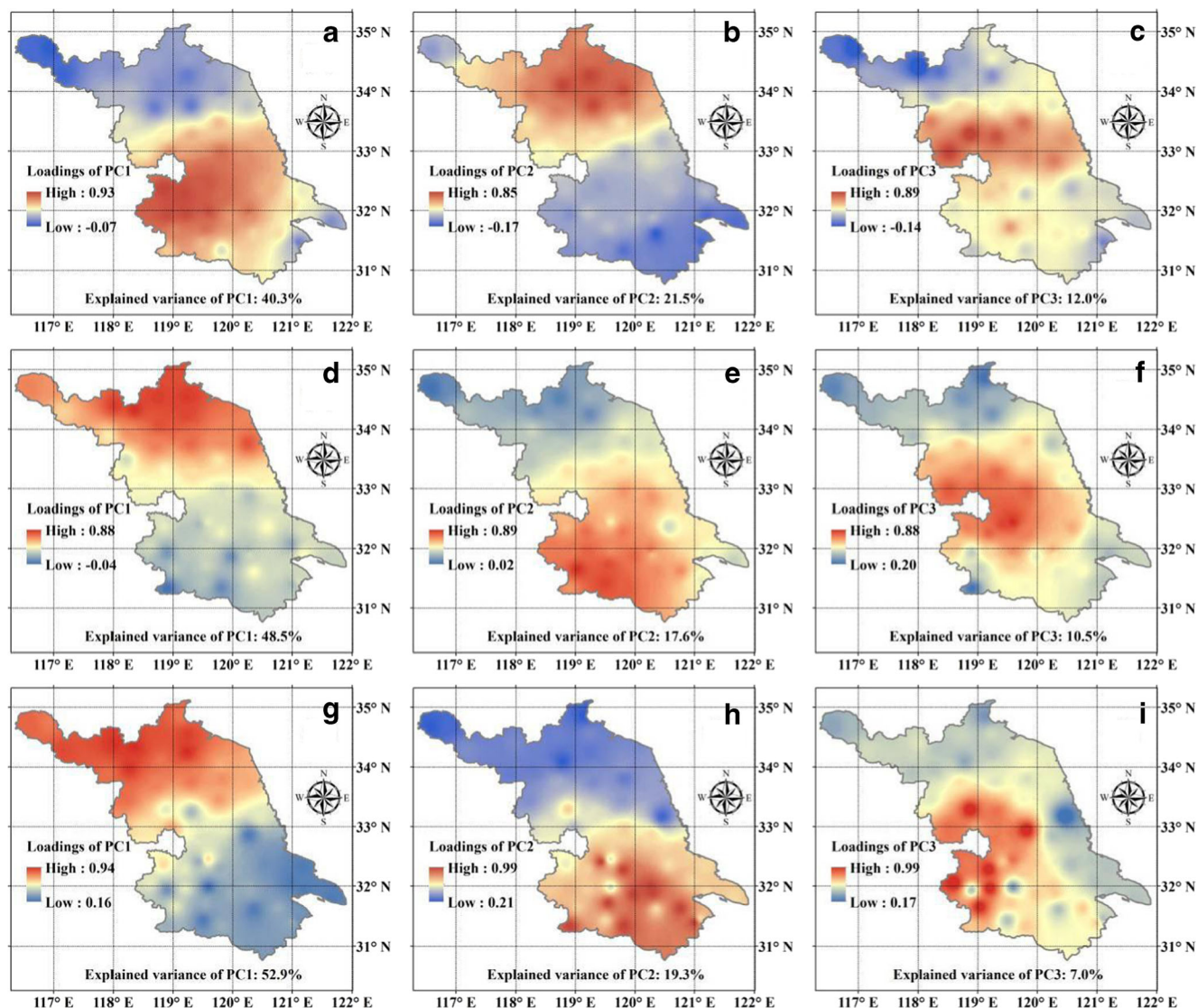
## Discussion

In this study, rice yield was positively correlated with most of the heat stress indices in the majority of stations across Jiangsu, which agreed with the positive correlation between rice yield and August average temperature found in the studies by Shuai et al. (2013). All this may mean that the adverse affects of high temperature events on rice are not obvious in Jiangsu. Previous studies indicated that the rainfall condition and irrigation availability play key roles in determining the correlation between rice yield and temperature in China, and the negative correlations between yields and high temperature were particularly obvious in the rainfed regions (Lobell 2007; Zhang et al. 2010). In Jiangsu, the abundant rainfall and complete irrigation system for rice growing may cause the weak response of yield to heat stress. In contrast to heat stress, obvious negative impacts of precipitation extremes on rice yield were found. Similarly, the climate-yield relationships

established in the studies by Tao et al. (2012) showed that rice yield in southeast China will likely decrease owing to the increase of precipitation during the growing period. In southeast China, low daily solar radiation (SRD) is unfavorable for single rice cropping, and continuous heavy precipitation events usually causes decreases in SRD, increases in pests and diseases, and reduces crop yield indirectly (Tao et al. 2008; Tao et al. 2013b). Additionally, the waterlogging and even flooding caused by continuous heavy precipitation events could directly decrease rice yields in southeast China. Thus, PI4 has been the key indicator for precipitation-induced rice meteorological disasters in this province.

Western Pacific Subtropical High (WPSH) is a crucial component of the East Asian summer monsoon (EASM) system and has significant influences on the East Asian summer climate (Lee et al. 2013; Huang et al. 2014). In Table 2, the strong positive correlations between the PCS of PI4 and Western Pacific Subtropical High Intensity index (WPSHII) were detected in south and middle Jiangsu. Besides, the WPSHII has a significant influence on the PCS of HTI3 in north Jiangsu (Table 2). All these confirmed the dominant influence of WPSH on the summer climate extremes in the mid-lower Yangtze River Basin. During the past three decades, the WPSH has been enlarging, strengthening, and extending westward (Huang et al. 2014; Matsumura et al. 2015), which may be the main cause of the increases of PI4 and HTI3 detected in most of Jiangsu. Moreover, the Pacific Decadal





**Fig. 7** First three loading patterns of principal components of three key RMDI in Jiangsu (a, b, c: results calculated from applying S-mode PCA to PI4; d, e, f: results calculated from applying S-mode PCA to HTI3; g, h, i: results calculated from applying S-mode PCA to LTI4)

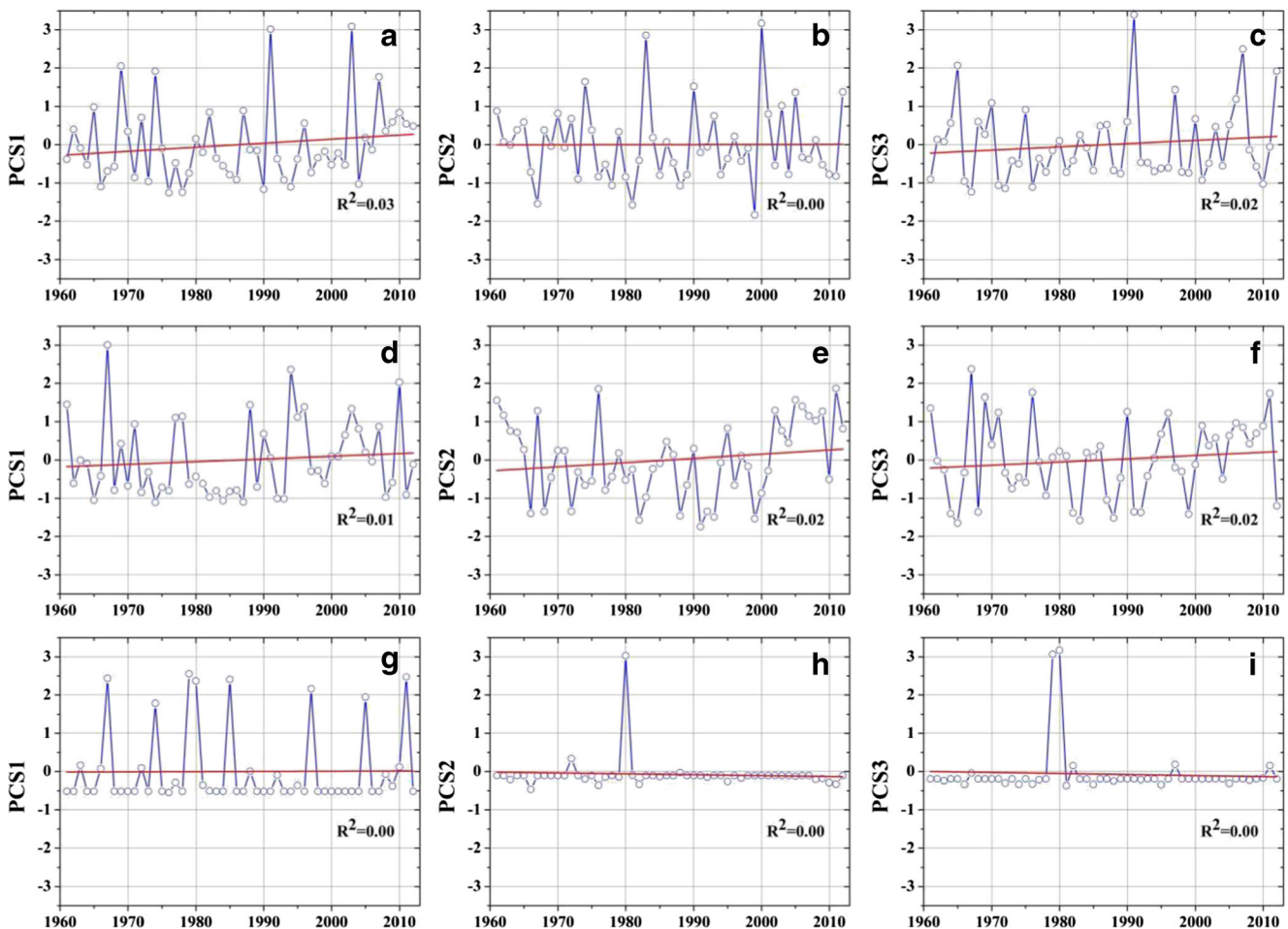
Oscillation index (PDO) was significantly correlated with the PCS of HTI3 in north and middle Jiangsu (Table 2). PDO can modulate the frequency and strength of El Niño and Southern Oscillation (ENSO) phases and is closely interrelated with the interdecadal climate variability in South China (Wang and Liu 2016). However, different from PI4 and HTI3, the relationship between LTI4 and circulation indices was not obvious (Table 2). On the basis of the above results, applying large-scale atmospheric circulation information to forecast rice meteorological disasters in Jiangsu should be feasible.

## Conclusions

In this study, a total of 17 meteorological indices were constructed to explore the spatial-temporal variation of rice

meteorological disasters including precipitation extremes, heat stress, and chilling injury in Jiangsu province. The main conclusions are as follows:

- (1) On the basis of the multiannual average values of 17 indices of whole stations, the spatial distribution of rice meteorological disasters across Jiangsu was explored. Overall, the higher values of heat stress indices were found in south Jiangsu, while the higher values of precipitation extremes and chilling injury were observed in north Jiangsu.
- (2) At both the provincial and station scales, the summary results of trends in 17 indices, using the MK-test, indicated that the precipitation extremes and heat stress indices in Jiangsu had increasing trends, while the chilling injury indices had decreasing trends. Among these



**Fig. 8** Time series of principal components scores (PCS) corresponding to the loadings presented in Fig. 7 (a, b, c: PCS of PI4; d, e, f: PCS of HTI3; g, h, i: PCS of LTI4)

indices, the LTI1 presented the greatest changes, which were detected in more than half of the stations.

(3) According to the correlation analysis between rice yield and meteorological disaster indices in each station, the

**Table 2** Correlation coefficients between the principal components of three key RMDI and large-scale atmospheric circulation indices during the corresponding periods

RMDI.	PCS	Corresponding sub-region	Circulation Indices							
			NAO	SOI	MEI	PDO	NOI	NP	AO	WPSHII
PI4	PCS1	South Jiangsu	-0.134	-0.024	0.099	-0.065	-0.068	0.07	0.052	<b>0.325**</b>
	PCS2	North Jiangsu	-0.069	-0.077	0.122	0.091	0.027	-0.092	-0.046	-0.089
	PCS3	Middle Jiangsu	-0.011	-0.166	0.216	0.101	-0.125	-0.113	-0.100	<b>0.322**</b>
HTI3	PCS1	North Jiangsu	0.156	0.127	-0.208	<b>-0.257*</b>	-0.021	-0.01	0.069	<b>0.333**</b>
	PCS2	South Jiangsu	-0.053	-0.064	-0.031	-0.230	0.101	-0.077	-0.108	0.200
	PCS3	Middle Jiangsu	0.06	0.034	-0.158	<b>-0.252*</b>	0.05	-0.034	-0.03	0.178
LTI4	PCS1	South Jiangsu	0.225	0.058	0.057	0.107	-0.185	-0.194	0.147	0.044
	PCS2	North Jiangsu	0.072	-0.087	0.035	0.031	-0.077	0.093	0.064	-0.011
	PCS3	Middle Jiangsu	0.181	-0.064	0.117	0.135	-0.16	-0.085	0.066	-0.009

\*Significant at the 5% level; \*\*Significant at the 1% level

NAO North Atlantic Oscillation, SOI Southern Oscillation Index, MEI Multivariate ENSO Index, PDO Pacific Decadal Oscillation, NOI Northern Oscillation Index, NP North Pacific pattern, AO Antarctic Oscillation, WPSHII West Pacific Subtropical High Intensity Index

negative impacts of precipitation extremes on rice yield were the most prominent, and the chilling injury also showed some degree of negative impacts on yield. However, the adverse effects of heat stress on rice yield were not obvious. From the spatial perspective, the rice-growing areas in northeast and mid-west Jiangsu should be classified as the sensitive regions for precipitation extremes.

- (4) Regional changing patterns of rice meteorological disasters in Jiangsu were assessed by applying S-mode PCA to the time series of three key indices (PI4, HTI3, and LTI4). As a result, it is suggested that this province should be divided into three regions (south Jiangsu, middle Jiangsu and north Jiangsu) with different temporal variability for rice meteorological disasters. Furthermore, the large-scale atmospheric circulation systems such as WPSH and PDO had significant influence on the regional changes in disaster indices.

**Acknowledgments** This paper was mainly supported by the China Special Fund for Meteorological Research in the Public Interest (Major projects) (Grant NO. GYHY201506001-6), Natural Science Foundation for Higher Education Institutions in Jiangsu Province, China (Grant NO. 16KJB170008), National Natural Science Foundation of China (Grant NOs. 41375006, 31300420 and 41605042), Natural Science Foundation of Jiangsu Province, China (Grant NO. BK20130987, BK20151525), Public welfare projects “key technology and demonstration for the vegetation recovery and reconstruction in open-pit mines” (NO. 201504406).

#### Compliance with ethical standards

**Conflict of interest statement** The authors declared that they have no conflict of interest.

## References

- Bao, Y., Liu, W., Gao, P., & Shen, S. (2012). Study on characteristics of rice heat damages in Jiangsu province under the background of climate warming and its influence on rice yield. *Chinese Journal of Agrometeorology*, *33*, 289–296 (in Chinese with English abstract).
- Casado, M. J., Pastor, M. A., & Doblas-Reyes, F. J. (2009). Euro-Atlantic circulation types and modes of variability in winter. *Theoretical and Applied Climatology*, *96*(1–2), 17–29.
- EI-Maayar, M., & Lange, M. A. (2013). A methodology to infer crop yield response to climate variability and change using long-term observations. *Atmosphere*, *4*, 365–382.
- Gocic, M., & Trajkovic, S. (2014). Spatio-temporal patterns of precipitation in Serbia. *Theoretical and Applied Climatology*, *117*(3–4), 419–431.
- Huang, Y. Y., Wang, H. J., Fan, K., et al. (2014). The western Pacific subtropical high after the 1970s: Westward or eastward shift? *Climate Dynamics*, *44*(7–8), 2035–2047.
- Huang, J., Zhan, F., Xue, Y., & Li, Q. (2016a). Recent changes of extreme dryness/wetness pattern and its possible impact on rice productivity in Jiangsu Province, southeast China. *Natural Hazards*. doi:10.1007/s11069-016-2529-0.
- Huang, J., Chen, X., Zhou, L., et al. (2016b). Statistical analysis of the relationship between climate-induced maize yield and rainy-season precipitation across Inner Mongolia. *North China. Theoretical and Applied Climatology*. doi:10.1007/s00704-016-1839-1.
- Huth, R. (1996). Properties of the circulation classification scheme based on the rotated principal component analysis. *Meteorology and Atmospheric Physics*, *59*(3–4), 217–233.
- Lee, S. S., Seo, Y. W., Ha, K. J., & Jhun, J. G. (2013). Impact of the western North Pacific subtropical high on the East Asian monsoon precipitation and the Indian Ocean precipitation in the boreal summertime. *Asia-Pacific Journal of Atmospheric Sciences*, *49*(2), 171–182.
- Liu, L., Xu, X., & Chen, X. (2015). Assessing the impact of urban expansion on potential crop yield in China during 1990–2010. *Food Security*, *7*(1), 33–43.
- Liu, Y., Xiao, J., Ju, W., et al. (2016). Recent trends in vegetation greenness in China significantly altered annual evapotranspiration and water yield. *Environmental Research Letters*, *11*(9), 094010.
- Lobell, D. B. (2007). Changes in diurnal temperature range and national cereal yields. *Agric. Forest Meteorol*, *145*, 229–238.
- Matsumura, S., Sugimoto, S., & Sato, T. (2015). Recent intensification of the western Pacific subtropical high associated with the East Asian summer monsoon. *Journal of Climate*, *28*(7), 2873–2883.
- Mestas-Núñez, A. M. (2000). Orthogonality properties of rotated empirical modes. *International Journal of Climatology*, *20*, 1509–1516.
- Raziei, T., Bordi, I., & Pereira, L. S. (2008). A precipitation-based regionalization for western Iran and regional drought variability. *Hydrology and Earth System Sciences*, *12*(6), 1309–1321.
- Raziei, T., Martins, D. S., Bordi, I., et al. (2015). SPI modes of drought spatial and temporal variability in Portugal: Comparing observations, PT02 and GPCC gridded datasets. *Water Resources Management*, *29*(2), 487–504.
- Ren, Y. F., Gao, P., & Wang, C. Y. (2010). Impacts of high temperature stress on rice and the causes in Jiangsu province. *J Nat Disaster*, *19*, 101–107 (in Chinese with English abstract).
- Revadekar, J. V., & Preethi, B. (2012). Statistical analysis of the relationship between summer monsoon precipitation extremes and foodgrain yield over India. *International Journal of Climatology*, *32*(3), 419–429.
- Shen, C. H. (2015). Meteorological effects on rice yields in Jiangsu Province. *Acta Ecologica Sinica*, *35*(12), 4155–4167 (in Chinese with English abstract).
- Shi, W., & Tao, F. (2014a). Spatio-temporal distributions of climate disasters and the response of wheat yields in China from 1983 to 2008. *Natural Hazards*, *74*(2), 569–583.
- Shi, W., & Tao, F. (2014b). Vulnerability of African maize yield to climate change and variability during 1961–2010. *Food Security*, *6*(4), 471–481.
- Shuai, J., Zhang, Z., Liu, X., Chen, Y., Wang, P., & Shi, P. (2013). Increasing concentrations of aerosols offset the benefits of climate warming on rice yields during 1980–2008 in Jiangsu Province, China. *Regional Environmental Change*, *13*(2), 287–297.
- Sun, S., Chen, H., Ju, W., et al. (2013). Effects of climate change on annual streamflow using climate elasticity in Poyang Lake Basin, China. *Theoretical and Applied Climatology*, *112*(1–2), 169–183.
- Sun, S. L., Sun, G., Caldwell, P., McNulty, S., Cohen, E., Xiao, J. F., & Zhang, Y. (2015). Drought impacts on ecosystem functions of the U.S. National Forests and grasslands: Part II assessment results and management implications. *Forest Ecology and Management*, *353*, 269–279.
- Tao, F., Yokozawa, M., Liu, J., & Zhang, Z. (2008). Climate–crop yield relationships at province scale in China and the impacts of recent climate trends. *Climate Research*, *38*, 83–94.
- Tao, F., Zhang, Z., Zhang, S., Zhu, Z., & Shi, W. (2012). Response of crop yields to climate trends since 1980 in China. *Climate Research*, *54*(3), 233–247.



- Tao, F., Zhang, S., & Zhang, Z. (2013a). Changes in rice disasters across China in recent decades and the meteorological and agronomic causes. *Regional Environmental Change*, 13(4), 743–759.
- Tao, F., Zhang, Z., Shi, W., et al. (2013b). Single rice growth period was prolonged by cultivars shifts, but yield was damaged by climate change during 1981–2009 in China, and late rice was just opposite. *Global Change Biology*, 19(10), 3200–3209.
- Wang, X. L., & Feng, Y. (2013). *RHtestsV4 user manual*. ASTD: Climate Research Division.
- Wang, X., & Liu, H. (2016). PDO modulation of ENSO effect on tropical cyclone rapid intensification in the western North Pacific. *Climate Dynamics*, 46(1–2), 15–28.
- Wang, P., Zhang, Z., Song, X., et al. (2014). Temperature variations and rice yields in China: Historical contributions and future trends. *Climatic Change*, 124(4), 777–789.
- Yang, L., Qin, Z., & Tu, L. (2015). Responses of rice yields in different rice-cropping systems to climate variables in the middle and lower reaches of the Yangtze River, China. *Food Security*, 7(5), 951–963.
- Yin, S. H., Xu, J. L., & Xu, L. Q. (2016). Temporal and Spatial Variation of Chilling Injury at Rice Heading- Filling Stage and Its Influence on Rice Yield in Jiangsu Province in Recent 30 Years. *Acta Agricultrae Jiangxi*, 28(5), 7–13 (in Chinese with English abstract).
- Yue, S., & Wang, C. Y. (2004). The Mann–Kendall test modified by effective sample size to detect trend in serially correlated hydrological series. *Water Resources Management*, 18, 201–218.
- Zhang, T., Zhu, J., & Wassmann, R. (2010). Responses of rice yields to recent climate change in China: An empirical assessment based on long-term observations at different spatial scales (1981–2005). *Agricultural and Forest Meteorology*, 150(7), 1128–1137.
- Zhang, Z., Chen, Y., Wang, P., Zhang, S., Tao, F., & Liu, X. (2014). Spatial and temporal changes of agro-meteorological disasters affecting maize production in China since 1990. *Natural Hazards*, 71(3), 2087–2100.



**Jin Huang** is a geographer specializing in ecology, climate extremes, agro-meteorological disaster, soil and geographic information science and technology. He is a lecturer at Nanjing University of Information Science & Technology.



**Yadong Lei** is a geographer specializing in climate change, agriculture, soil and geographic information science and technology. He is a Masters candidate at Nanjing University of Information Science & Technology.



**Fangmin Zhang** is a geographer specializing in land use change, climate change, agriculture, soil and geographic information science and technology. She is an Associate Professor of Nanjing University of Information Science & Technology.



**Zhenghua Hu** is a geographer specializing in land use change, climate change, agriculture, soil and geographic information science and technology. He is the director of Nanjing University of Information Science & Technology.