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Changes of extreme precipitation and nonlinear influence of climate variables over monsoon region in China

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ABSTRACT

The El Niño-Southern Oscillation (ENSO), Indian Ocean Dipole (IOD), North Atlantic Oscillation (NAO), Atlantic Multidecadal Oscillation (AMO) and Pacific decadal oscillation (PDO) are well understood to be major drivers for the variability of precipitation extremes over monsoon regions in China (MRC). However, research on monsoon extremes in China and their associations with climate variables is limited. In this study, we examine the space-time variations of extreme precipitation across the MRC, and assess the time-varying influences of the climate drivers using Bayesian dynamic linear regression and their combined nonlinear effects through fitting generalized additive models. Results suggest that the central-east and south China is dominated by less frequent but more intense precipitation. Extreme rainfalls show significant positive trends, coupled with a significant decline of dry spells, indicating an increasing chance of occurrence of flood-induced disasters in the MRC during 1960–2014. Majority of the regional indices display some abrupt shifts during the 1990s. The influences of climate variables on monsoon extremes exhibit distinct interannual or interdecadal variations. IOD, ENSO and AMO have strong impacts on monsoon and extreme precipitation, especially during the 1990s, which is generally consistent with the abrupt shifts in precipitation regimes around this period. Moreover, ENSO mainly affects moderate rainfalls and dry spells, while IOD has a more significant impact on precipitation extremes. These findings could be helpful for improving the forecasting of monsoon extremes in China and the evaluations of climate models.

1. Introduction

Billions of people in China live in monsoon regions. Precipitation surplus or deficit, mainly characterized by floods and droughts, may have catastrophic consequences to people and property, and affect the social-economic sustainable development across the monsoon regions in China (MRC). One challenge in the current research is that East Asian summer monsoon (EASM) has been poorly simulated in most models owing to the complex climatic system and topography (e.g., Zhang and Zhou, 2015; Hsu, 2016; Gao and Xie, 2016). Therefore, studying the space-time variability of precipitation extremes in the MRC and their predictors has been the subject of many researches in recent decades. For example, Chen and Zhai (2013) reported that the majority of persistent extreme rainfall events occurred over central-east China in the context of precipitation pattern for southern flood and northern drought in China, and the heavy precipitation time series experienced inconsistent periods of abrupt changes among different geographical regions (Ding et al., 2008; Zhang and Zhou, 2015).

Previous studies on these issues have suggested that large-scale climate variables, including El Niño-Southern Oscillation (ENSO), Indian Ocean Dipole (IOD), North Atlantic Oscillation (NAO), Atlantic Multidecadal Oscillation (AMO) and Pacific decadal oscillation (PDO), etc., had substantial influences on the variability of precipitation over the MRC in a warming climate (Chan and Zhou, 2005; Linderholm et al., 2011; Wang et al., 2013; Zhang et al., 2014; Zhang et al., 2015; Gao et al., 2016; Xie et al., 2016; Huang et al., 2017; Xiao et al., 2017; Hao and He, 2017). Moreover, the relationships between rainfall and these climate variables possess significant interannual and interdecadal changes. Particularly, based on the entire-Indian monsoon precipitation, interdecadal variations for a weakening relation with ENSO since 1970s were found (e.g., Kumar et al., 1999; Krishnaswamy et al., 2015). The extensive researches related to intimate linkages between monsoon rainfall in China and large-scale climate variables or global sea surface temperature (SST) are mainly confined on a regional basis or on

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seasonal precipitation. However, the decadal variations of monsoon and their responses to internal feedback processes of climate often occur beyond regional scales (Wang et al., 2013). Thus far, the temporal variability of the relationships between all-monsoon anomalous rainfall in China and ocean-atmosphere phenomena is unclear, and research in this direction is crucial for monsoon rainfall forecasting and water resource management.

In addition, the nonlinear effect of SST on regional rainfall during the ENSO has been recognized by many studies. For instance, Hsieh et al. (2006) and Kajikawa et al. (2012) showed that the exact timing of Asian monsoon onset was difficult to be predicted based on the ENSO-monsoon linkage since this relationship was far from linear. The nonlinear relationship between precipitation and SST indicates that both very warm and cold SSTs may lead to regional precipitation extremes (Lu et al., 2015), and this has profound impacts on the predictability of monsoon extremes (Wang et al., 2013; Krishnaswamy et al., 2015). The objective of the present study is to investigate the space-time variations in extreme precipitation over the MRC, assess the non-stationary and nonlinear influences from ocean-atmosphere phenomena, and identify the dominating controls from the combined effects of climate variables. An understanding of these variability and relationships is of great importance for improving the prediction accuracy of monsoon rainfall and the infrastructure planning in China.

2. Data and methods

The daily station rainfall data (1960–2014) are obtained from China Meteorological Administration. Among 756 observing sites, we choose 495 stations that satisfy the following criteria: (1) are located over the MRC according to the definition from Wang and Ding (2008); (2) with the summer (May–September) minus winter (November–March) precipitation rate exceeding 2.0 mm/d; (3) with the local summer rainfall exceeding 55% of the annual total precipitation and (4) containing no consecutive missing data (Zhang et al., 2011); see Fig. 1 for detailed information. In this study, we consider 12 rainfall indices developed by Expert Team on Climate Change Detection and Indices (ETCCDI), and the boreal summer (June–August) total precipitation (referred to as monsoon thereafter); see Table 1 for variable descriptions. In addition, we consider five large-scale climate variables (Table S1) and regional precipitation indices computed by using the method from Powell and Keim (2015). To study the variability of the entire extreme precipitation in the MRC, we first standardize each precipitation index by subtracting the sample mean and dividing by the sample standard deviation of the time series of the index. Then we average each standardized index over the MRC in each year, producing an annual average regional precipitation index.

The Mann-Kendall (M-K) test is utilized to detect the regime shifts of regional precipitation indices over time. The Bayesian Dynamic Linear (BDL) model is fitted by using the R package dlm (Petris, 2010) to assess the time-varying linkages between the regional rainfall indices and climate variables. The BDL model can be described as

$$\begin{cases} y_t = \alpha_t + x_t\beta_t + v_t, & v_t \sim N(0, V_t) \\ \alpha_t = \alpha_{t-1} + \omega_{\alpha,t}, & \omega_{\alpha,t} \sim N(0, W_{\alpha,t}), \\ \beta_t = \beta_{t-1} + \omega_{\beta,t}, & \omega_{\beta,t} \sim N(0, W_{\beta,t}) \end{cases} \tag{1}$$

where y_t is the response variable (a rainfall index), x_t is the covariate (a climate variable), and α_t and β_t are the dynamic intercept and slope coefficients at time t. In contrast to the traditional regression method that models the regression coefficients as static, the BDL models them as dynamic and can capture the time-varying relationships between regional rainfall indices and climate variables. This approach can provide robust quantification as well as elegant visualization of the varying influences derived from coupled ocean-atmosphere phenomena.

In addition, we fit Generalized Additive Models (GAMs) to explore the combined nonlinear effects from different climate variables. The GAM is a nonparametric extension of generalized linear model (GLM); it models the mean of the response (or some transformation) as the sum of unknown smooth functions of the covariates and thus is more flexible than GLM to capture complex covariate effects (Hastie and Tibshirani, 1990). Specifically, we assume the following additive model

$$E(y_t \mid x_{1t},\ldots,x_{pt}) = f_0 + f_1(x_{1t}) + \cdots + f_p(x_{pt}), \tag{2}$$

where $x_{1t}, \ldots, x_{pt}$ are the p covariates at time t, and $f_j(\cdot)$ are unknown smooth functions such that $E[f_j(x_{jt})] = 0$, for $j = 1, \ldots, p$. The mean function in (2) is additive but each term can be nonlinear. We fit the model (2) by using the function gam in the R package gam with identity link, and assess the significance of each model term using the anova.gam function. Previous studies have suggested that GAMs were very flexible for accommodating a variety of nonlinear shapes and therefore were particularly suitable to explore teleconnections between coupled ocean-atmosphere phenomena and regional climate since those were complex and nonlinear (e.g., Hoerling et al., 1997).

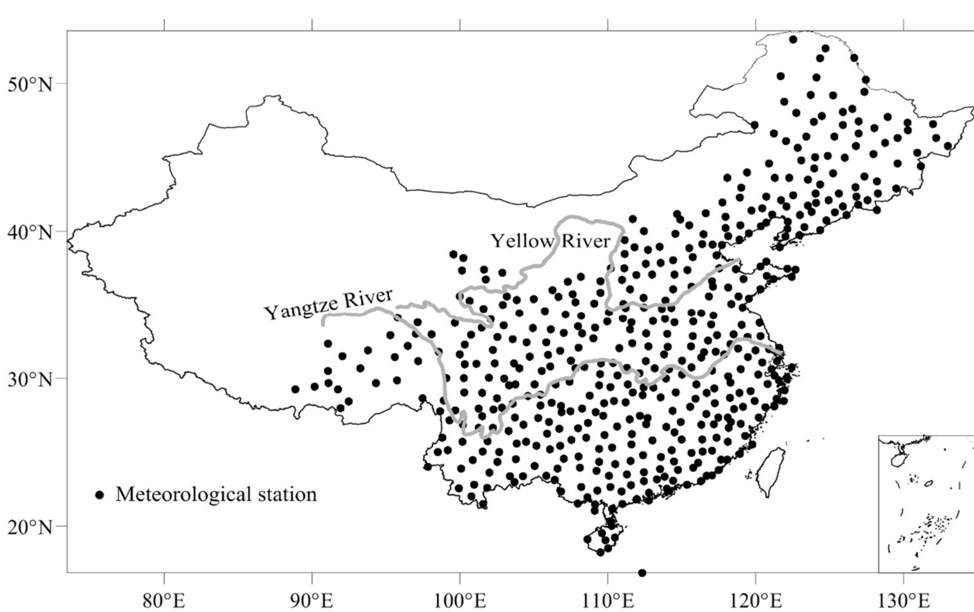

Fig. 1. Locations of the 495 meteorological stations over the monsoon regions in China (MRC).