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Future joint probability behaviors of precipitation extremes across China: Spatiotemporal patterns and implications for flood and drought hazards

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ABSTRACT

Observed daily precipitation from 527 meteorology stations in China during 1960–2005, and simulated daily precipitation from five Earth System Models (ESMs) under historical, RCP2.6 and RCP8.5 scenarios from Coupled Model Intercomparison Project Phase 5 (CMIP5) datasets are analyzed to investigate joint probability behaviors of precipitation extremes in China during 2021–2050 and 2071–2100. Five joint return periods based on six extreme precipitation indices are defined. These joint return periods consider co-occurrence of extreme heavy and weak precipitation, as well as joint extreme heavy precipitation events in terms of different combinations of extreme precipitation amount, intensity, fractional contribution to annual precipitation days, and consecutive wet periods. Weather Generator Model (WGEN) is used to downscale the outputs of ESMs, and Copula is applied to construct joint probability distributions. The variations of joint return periods with 5-year marginal values (marginal values larger than their 5-year return period values respectively) and 20-year marginal values are discussed to represent changes in joint probability behaviors. Results show that: (1) during 1960–2005, spatial distributions of joint return periods with 5-year marginal values are similar to those with 20-year marginal values; (2) changes in marginal distributions and bivariate relationships between extreme indices may be the causes of joint probability distribution shift; (3) in general, during 2021–2050 and 2071–2100, there is less co-occurrence of consecutive wet and dry days, and more joint extreme heavy precipitation events with various aspects, implying less risk of co-occurrence of floods and droughts in the same year but higher risk of floods in China. But north China may face higher risk of co-occurrence of severe floods and droughts in the same year; and (4) changes in joint return periods under RCP8.5 are more remarkable than under RCP2.6. Even under RCP2.6, a scenario 2 °C global average warming target is met, the changes in joint return periods are still considerable.

1. Introduction

Change in climatic extremes is one important aspect of global climate change (Easterling et al., 2000; IPCC, 2007; Min et al., 2011). Climatic extremes are one of the crucial drivers of meteorological and hydrological hazards, such as floods and droughts (Zhang et al., 2008). Hence, the change in climatic extremes, especially precipitation extreme, may alter the occurrence, duration, and intensity of floods and droughts (Ely et al., 1993; Mirza, 2002). The increasing catastrophic losses as a result of natural hazards arouse the public awareness of extreme events in recent years (e.g. Beniston and Stephenson, 2004; Zolina et al., 2004). By 2100, the mean annual global surface temperature increases by 1.4–5.8 °C, and future climatic extremes tend to increase and intensify correspondingly (Houghton et al., 2001; Beniston et al., 2007; IPCC, 2007). Therefore, it is of great merits to investigate future variations of precipitation extremes to provide scientific insight into probable changes in floods and droughts, and similar studies could be practically helpful for water resource management.

The regional responses of precipitation extremes to climate changes are diverse. Sillmann et al. (2013) used the Coupled Model Intercomparison Project Phase 5 (CMIP5) multimodel ensembles to analyze changes in extreme precipitation indices over the 21st century relative to the period of 1981–2000, and found out that extreme precipitation generally increases in most regions, except for Australia, Central America, South Africa and the Mediterranean region. Kothavala (1997)

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found out that more wet and dry spells would occur and the frequency of extreme precipitation would increase in the Midwest USA under enhanced greenhouse conditions based on an atmospheric Global Circulation Model (GCM). Frei et al. (2006) used six European Regional Climate Models to analyze the precipitation extremes under A2 scenario, indicating that winter precipitation extremes increase in the north to about 45°N, and those to the south decrease or change insignificantly.

Recently, with the release of the CMIP5 datasets, some GCMs are coupled to biogeochemical components, i.e. vegetation and atmospheric chemistry, and the ocean and land carbon cycle (Moss et al., 2010; Taylor et al., 2012). These GCMs are called Earth System Models (ESMs) (Collins et al., 2011). ESMs consider more components of the real physical world, but they are with simplified equations and coarser spatial resolutions compared to GCMs (Moss et al., 2010). Meanwhile, a new type of scenario called "Representative Concentration Pathway" (RCP) is also proposed by CMIP5. One of advantages of RCP is that it takes into account the policy interventions to achieve certain emission targets (Moss et al., 2010). Such improvements in CMIP5 provide a more robust and detailed picture about the future climate conditions.

Many previous literatures investigate probabilistic behaviors of precipitation (e.g. Groisman et al., 1999; Frei and Schär, 2001; Palmer and Räisänen, 2002). Recently, increasing concerns have been drawn to the joint behaviors of precipitation extremes. Hashino (1985) studied the joint distributions of precipitation intensity and maximum storm surge in Osaka Bay, Japan, via the Freund bivariate exponential distribution. Yue (2001) used the bivariate extreme value distribution with Gumbel marginal to investigate the joint probability distribution of the annual maximum rainfall intensity and amount. However, these studies are basically based on one of these assumptions: precipitation variables each have the same type of marginal distribution; or variables are assumed to follow or can be transformed to the normal distribution (Zhang and Singh, 2007). Copula is considered as a flexible and important tool in bivariate analysis of precipitation extreme, and no assumption is needed (Salvadori and De Michele, 2004; Zhang and Singh, 2007; Leonard et al., 2008). Zhang and Singh (2007) employed the Archimedean Copulas to estimate joint return periods of precipitation and this application was tested using the precipitation data from the Amite River basin in Louisiana, United States. Zhang et al. (2013a) investigated spatiotemporal patterns of historical precipitation extremes in China during 1960–2005 based on Copula. Wang et al. (2010) applied weighted likelihood Copula to construct joint return periods of extreme precipitation in the state of Connecticut.

China is a developing country with high exposure to the threats of floods and droughts, and it's heavily relying on agriculture, which makes China more vulnerable to these threats (Zhang et al., 2012). Changing properties of historical precipitation extremes and corresponding joint probability behaviors, and future possible changes in univariate precipitation extremes in China are analyzed in previous studies (Li et al., 2013a, 2013b; Zhang et al., 2013a). A study about future joint probability behaviors of precipitation extremes in China is important for better understanding of the regional responses of precipitation extremes to climate change and for reference to the water resource management and also for flood and drought control. In this case, this paper aims to investigate the possible spatiotemporal patterns of changes in joint probability behaviors of precipitation extremes in China during 2021–2050 and 2071–2100 based on Copula and ESMs from CMIP5. In this study, firstly, a case study is discussed to present how to estimate the observed and future joint distributions and joint return periods by using Copula and downscaling technique. Then spatial patterns of joint return periods of precipitation extremes in China during 1960–2005 are investigated to give the historical picture of joint return periods of precipitation extremes in China. Finally, possible changes in joint return periods of precipitation extremes during 2021–2050 and 2071–2100 are presented.

2. Data

The gridded daily precipitation data from five ESMs under historical, RCP2.6 and RCP8.5 scenarios provided by the World Climate Research Program's (WCRP's) CMIP5 multi-model dataset are applied (Table 1) (Taylor et al., 2012). The RCP2.6 and RCP8.5 scenarios are future RCP scenarios. The RCP2.6, a scenario where the 2 °C global average warming target is met, assumes that the radiative forcing increases to a peak at approximately 3 W/m^2 before 2100 and then decline to 2.6 W/m^2 by the end of the 21st century (van Vuuren et al., 2011). In RCP8.5, the radiative forcing is assumed to increase in a high rate and reach 8.5 W/m^2 by the end of the 21st century (Riahi et al., 2011). ESMs are adopted based on the availabilities of their outputs under considered scenarios and their institutions. Multimodel ensemble is used in this study. One of the most important assumptions of establishing the multimodel ensemble is that the error of each model may be canceled if models are independent (Tebaldi and Knutti, 2007), so the multimodel ensemble is usually expected to be more robust and less uncertain than individual model (Sillmann et al., 2013). Some institutions release more than one ESMs. These ESMs usually have lots of similarities, which offend the above assumption to some extent. Therefore only one ESM is chosen from an institution. Furthermore, it should be noted that most ESMs use a 365-day calendar, in which the leap days are excluded, so no leap day in ESM outputs is considered in this study (Griffies et al., 2004).

Observed daily precipitation during 1960–2005 from 527 meteorology stations in China provided by the National Climate Center of China Meteorological Administration is used (Fig. 1). A station with total observed precipitation amount ranking 75th percentile among 527 considered stations during 1960–2005 is chosen to carry out the case study. This station is called the 75th station. Observed daily precipitation and the outputs of ESMs under historical scenario during 1960–2005 are used to develop the downscaling relationship, and then based on this relationship, the outputs of ESMs under RCP2.6 and RCP8.5 during 2021–2050 and 2071–2100 are downscaled to the site scale.

Six extreme precipitation indices, including consecutive wet days (CWD), consecutive dry days (CDD), number of extreme heavy precipitation days (D90), the total amount of extreme heavy precipitation (P90), the intensity of extreme heavy precipitation (I90), and annual precipitation fraction due to extreme heavy precipitation (RT90) are defined to represent precipitation extremes in different aspects (Table 2). Some of these indices were proposed by Frich et al. (2002) and are widely used by IPCC and international academic communities (IPCC, 2007; Sillmann and Roeckner, 2008). The other indices were used in previous studies (e.g. Zhang et al., 2013a).

In this study, the joint probability behaviors of five combinations of above indices are studied, including {CWD, CDD}, {CWD, D90}, {P90, RT90}, {D90, P90}, and {P90, I90}. The {CWD, CDD} denotes the cooccurrence of extreme heavy and weak precipitation within the same year in terms of consecutive wet and dry days, implying the cooccurrence of floods and droughts in the same year; the {CWD, D90} represents a joint extreme heavy precipitation event in terms of consecutive wet days and number of extreme heavy precipitation; the {P90, RT90} denotes a joint extreme heavy precipitation event in terms of precipitation amount and contribution to annual precipitation of the extreme heavy precipitation; the {D90, P90} represents a joint extreme

Table 1
Details of ESMs from CMIP5.

ESM	Modeling center	Resolution (Lon × Lat)	Data duration		
			Historical	RCP2.6	RCP8.5
CanESM2	CCCma	128 × 64	1850–2005	2006–2300	2006–2100
GFDL-ESM2G	GFDL	144 × 90	1861–2005	2006–2100	2006–2100
MIROC-ESM-CHEM	MIROC	128 × 64	1850–2005	2006–2100	2006–2100
MPI-ESM-MR	MPI-M	192 × 96	1850–2005	2006–2100	2006–2100
NorESM1-M	NCC	144 × 96	1850–2005	2006–2100	2006–2100