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How do the multiple large-scale climate oscillations trigger extreme precipitation?

Pengfei Shi[a,b], Tao Yang[a,*], Chong-Yu Xu[a,c], Bin Yong[a,b], Quanxi Shao[d], Zhenya Li[a], Xiaoyan Wang[a], Xudong Zhou[a,e], Shu Li[f]

[a] State Key Laboratory of Hydrology-Water Resources and Hydraulic Engineering, Center for Global Change and Water Cycle, Hohai University, Nanjing 210098, China
[b] School of Earth Sciences and Engineering, Hohai University, Nanjing 210098, China
[c] Department of Geosciences, University of Oslo, P.O. Box 1047, Blindern, 0316 Oslo, Norway
[d] CSIRO Digital Productivity Flagship, Leeuwin Centre, 65 Brockway Road, Floreat, WA 6014, Australia
[e] Laboratorie des Sciences du Climat et de l'Environnement, Commissariat a L'Energie Atomique, 91191 Gif sur Yvette, France
[f] Yellow River Institute of Hydraulic Research, Yellow River Conservancy Commission, Zhengzhou 450003, China

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ABSTRACT

Identifying the links between variations in large-scale climate patterns and precipitation is of tremendous assistance in characterizing surplus or deficit of precipitation, which is especially important for evaluation of local water resources and ecosystems in semi-humid and semi-arid regions. Restricted by current limited knowledge on underlying mechanisms, statistical correlation methods are often used rather than physical based model to characterize the connections. Nevertheless, available correlation methods are generally unable to reveal the interactions among a wide range of climate oscillations and associated effects on precipitation, especially on extreme precipitation. In this work, a probabilistic analysis approach by means of a state-of-the-art Copula-based joint probability distribution is developed to characterize the aggregated behaviors for large-scale climate patterns and their connections to precipitation. This method is employed to identify the complex connections between climate patterns (Atlantic Multidecadal Oscillation (AMO), El Niño-Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO)) and seasonal precipitation over a typical semi-humid and semi-arid region, the Haihe River Basin in China. Results show that the interactions among multiple climate oscillations are non-uniform in most seasons and phases. Certain joint extreme phases can significantly trigger extreme precipitation (flood and drought) owing to the amplification effect among climate oscillations.

1. Introduction

A number of studies have confirmed that there are connections between the large-scale climate patterns and regional hydrological extremes like floods and droughts and water budget worldwide (e.g. Kim et al., 2006; Cayan et al., 1999; Ropelewski and Halpert, 1989). For example, the record-breaking high global temperature and devastating floods worldwide in 1998 could be partly attributed to El Niño (Lean and Rind, 2008; Foster and Rahmstorf, 2011), and the 2010 Pakistan flood was linked to a strong La Niña (Coumou and Rahmstorf, 2012). Precipitation is a principle component of hydrological cycle and water balance besides evapotranspiration and runoff (Thomas, 2000; Xu et al., 2006; Wang et al., 2013a; X. Wang et al., 2017; Y. Wang et al., 2017). The qualitative analysis and quantitative evaluation of the connections between large-scale climate patterns and precipitation could provide insights into the hazard prevention and mitigation, and contribute to improvements in regional water resources management strategy (Zhang et al., 2009; Wang et al., 2012).

Several oceanic-atmospheric indices have been widely used to explain the variability of precipitation in different regions. The El Niño-Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO) indices are commonly recognized as important tools for investigating hydrological process (Kim et al., 2006; Chiew et al., 1998; Liu et al., 1998; Gutiérrez and Dracup, 2001). ENSO is a naturally occurring phenomenon centered referring to the cycle of warm and cold sea surface temperatures in the equatorial Pacific arising from complex interactions between the atmosphere and ocean (McPhaden et al., 2006; Collins et al., 2010). El Niño is the warm phase of ENSO, and it is often followed by a cold phase called La Niña. La Niña usually has an opposite effect compared to El Niño. El Niño occurs irregularly, at different year intervals (sometimes every 2–7 years). In some areas, it brings heavy rainfall hereby causes floods, while in other regions it

* Corresponding author.
E-mail address: tao.yang@hhu.edu.cn (T. Yang).

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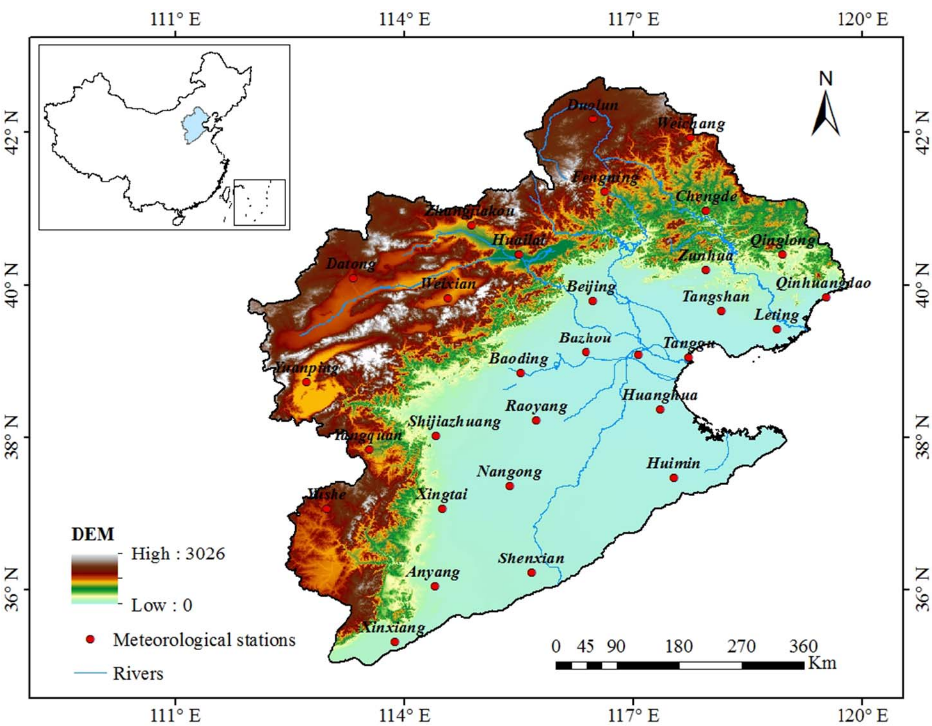

Fig. 1. Map of the Haihe River Basin (HRB) and major precipitation stations.

causes droughts. A number of studies have indicated that ENSO can drive substantial variability in rainfall (Ropelewski and Halpert, 1986; ABM and CSIRO, 2011; Power et al., 1999) in many regions around the world. The Pacific Decadal Oscillation (PDO) is a pattern of climate variability in the Pacific Ocean, north of 20° N, with a characteristic time scale of 20–30 years (Hare and Mantua, 2001). The PDO is detected as warm or cool surface waters in the North Pacific Ocean. The correspondence between PDO and extreme events was investigated by Hidalgo (2004) in the Colorado River Basin, showing that the PDO phase was correlated with the above-average and below-average precipitation. Other studies focused on the modulation of PDO cycle on the ENSO-precipitation signal (Brown and Comrie, 2004; Gutzler et al., 2009; Kurtzman and Scanlon, 2007). Brown and Comrie (2004) examined the relationships between the ENSO conditions and winter precipitation in the western U.S. within the context of decadal-scale variability, as presented by phasing of PDO, and identified the so-called 'dipole' signature. Goodrich (2007) investigated the influence of PDO on winter precipitation and droughts during years of neutral ENSO in the western United States, and found that the resulting winter precipitation patterns were spatially similar to those occur during years of La Niña-cold PDO and, to a lesser extent, years of El Niño-warm PDO. The Atlantic Multidecadal Oscillation (AMO) is a recent label for a climate oscillation in the North Atlantic with a period of 65–80 years (Kerr, 2000). It is defined as the detrended, regionally averaged, summer sea surface temperatures (SSTs) anomalies over the North Atlantic Ocean (Enfield et al., 2001). Previous studies have shown that the AMO could exert direct influences on the regional climate and drought (Sutton and Hodson, 2005; Knight et al., 2006; Mo et al., 2009). It has been reported that the warm-phase of AMO favors warmer winters in many regions of China, with enhanced precipitation in northern China, while reduced precipitation in the south, and vice versa (Lu et al., 2006; Li and Bates, 2007).

Generally, many studies have investigated the linkage between atmospheric circulation patterns and precipitation and the associated hazard effect, and these studies have detected generally consistent and systematic relationships more or less (Hu and Feng, 2001; Timm et al., 2005; Goodrich, 2007; Stevens and Ruscher, 2014). To the best of our knowledge, studies on identifying the interplay of multiple atmospheric oscillations and their associate effect on local precipitation are very limited now. Those atmospheric oscillations are non-independent and collectively affecting over some areas. Actually, the intricate interplay existing among the multiple large-scale climate oscillations and the regional hydrological process constitute a complex climate-land coupled system (Steinman et al., 2014). Multiple atmospheric oscillations collectively impose a more complex influence on local precipitation (Shi et al., 2016). Restricted by the current limited knowledge on underlying mechanisms, physical based methodologies generally fail to explain the complex interactions. Thus, statistical methods (e.g. correlation methods) are often used to discover and delineate these complex relationships. Unfortunately, the available statistical methodologies are generally unable to explain the interactions among a wide range of climate oscillations and associated effects on water cycle in some areas around the world (Xu et al., 2004). To date, identification of dimensional interactions among multiple large-scale circulations and associated hazardous impacts (flood and drought) is still a weak point in global change studies (Boers et al., 2014; Yang et al., 2011). It is urgent to clarify that how the multiple large-scale climate oscillations trigger extreme precipitation.

Therefore, this study strives to: (1) characterize the interactions among multiple large-scale climate oscillations by means of probabilistic approach; (2) construct a series of climate phases and a quantitative connection based on the phases; (3) address the potential impacts of multiple extreme phases on precipitation in the Haihe River Basin, a typical semi-humid and semi-arid basin in China.

2. Study area and datasets

2.1. Study area

Haihe River Basin (HRB) is located in the eastern part of northern China (112–120° E, 35–43° N). The northern, south-western and eastern boundaries are Mongolian Plateau, Yellow River and Bohai Sea, respectively (Fig. 1). The basin is characterized by a continental monsoon climate. The annual mean temperature is 9.6 °C, and annual precipitation is about 530 mm, which decreases from south-eastern coastal zone to north-western inland area (Wang et al., 2015; Xing et al., 2014).