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Recent changes in extreme precipitation and drought over the Songhua River Basin, China, during 1960–2013

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ABSTRACT

Based on ten indices of extreme precipitation and one drought index (composite index, CI), the trends in extreme events were investigated using a Mann–Kendall non-parametric method at 39 stations in the Songhua River Basin (SHB) during 1960–2013. The regionally averaged wet-day precipitation (PRCPTOT) increased at a rate of 1.65 mm/year ($R^2 = 0.28$, $P = 0.13$), in which 82% of the stations experienced increases, but only 4 stations showed significant positive trends. The annual R95 and R99 exhibited slight upward trends at rates of 1.37 ($R^2 = 0.21$, $P = 0.27$) and 1.28 mm/year ($R^2 = 0.23$, $P = 0.23$) over the last 54 years; however, there were not significant trends in R95 and R99 at the 0.05 level. PRCPTOT, R95 and R99 showed similar spatial trends, in which positive trends mainly occurred in the northern and southeastern basins. The trends in the maximum 1-day precipitation (RX1day) and maximum 5-day precipitation (RX5day) do not show a prevalent trend (approximately 50% of the stations have a positive trend and the remaining stations have a negative trend). The simple daily intensity index (SDII) significantly decreased at an annual rate of 0.02 mm/d during 1960–2013 ($R^2 = 0.66$, $P < 0.01$); spatially, 49% of the stations experienced statistically significant decreases at the 0.05 level based on the Mann–Kendall non-parametric test. The regionally averaged heavy (R10mm) and very heavy precipitation days (R20mm) and consecutive wet days (CWD) showed no significant trends during the past 54 years; however, several individual extreme precipitation events, such as the flood of 1998 in the SHB, were well detected by these indices. The regionally averaged consecutive dry days (CDD) significantly increased ($R^2 = 0.79$, $P < 0.01$) at a rate of 0.22 days/year from 1960 to 2013. All of the stations exhibited statistically significant increases in CDD, excluding the Tongyu station in the western basin. The monthly RX5day values were highest in summer, from June to August, in the SHB; a peak occurred in July (67.5 mm) in the SHB during 1960–2013. The CI peaked in July, with the highest value of 0.2 in the SHB during 1960–2013. However, the two lowest CI values occurred in spring and fall, with values of −0.56 and −0.41, respectively. During April and May, when most of the spring drought events occur, a prevalent trend does not exist; moreover, almost no stations have statistically significant CI increases. In August and September, respectively 79% and 97% of the stations exhibited a CI negative trend, but only 2 and 6 stations showed significant decreases at the 0.05 level. The increasing extreme climate events present a challenge for local water resources management.

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1. Introduction

Extreme precipitation events have been increasing since the late 20th century in the mid-latitude and high-latitude land

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areas of the Northern Hemisphere (IPCC, 2001; IPCC, 2007). Moreover, the changes in precipitation extremes are projected to continue into the future (Klein Tank et al., 2006). Climatic precipitation extremes aggravate the frequency, intensity, and duration of disasters, such as droughts and floods, and cause catastrophic damage to agriculture, ecology and life (Fu et al., 2013; Marengo et al., 2011; Penalba and Robledo, 2010; You et al., 2008). Extreme precipitation events have received worldwide attention due to their large-scale impacts (Alexander et al., 2006; Boccolari and Malmusi, 2013; Déqué, 2007; Douglas and Barros, 2003; Easterling et al., 2000; Fu et al., 2010; Fu et al., 2013; Goswami et al., 2006; Schmidli and Frei, 2005).

In China, trends in extreme precipitation have been documented in several studies, which showed that the occurrence of precipitation extremes increases at the national scale and exhibits apparent regional differences (Li et al., 2010; Liu et al., 2014; Liu et al., 2013; Qian et al., 2007; Su et al., 2008; Wan et al., 2013; Wang et al., 2013; Wang et al., 2008; Yang et al., 2008; You et al., 2008; Zhai et al., 1999; Zhang et al., 2011a). For example, Qian et al. (2007) found that the frequencies of extreme rain events increased in eastern China centered on the middle–lower reaches of the Yangtze River but decreased in North China and Southwest China. Zhai et al. (1999) examined observational data in China after 1950 and detected an increase well above the normal precipitation intensity and a statistically significant trend in the above-normal rain days. Zhang et al. (2011a) documented the maximum number of consecutive rainy days in China during 1960–2005 and concluded that the increasing fractional contribution of shorter consecutive rain days may imply intensifying precipitation. In addition, some researchers investigated extreme precipitation events in specific regions of China. Wang et al. (2008) investigated the variation in extreme precipitation in the Dongjiang River Basin in southern China and found that a slight change occurred in the annual extreme precipitation based on various indices. A general significant increase or decrease has occurred in extreme precipitation indices for the Yangtze River Basin based on historical recorded data during 1961–2010 (Guo et al., 2013). Extreme climate indices were spatially distributed with obvious gradients from the southeast to the northwest on the Loess Plateau of China during 1961–2007 (Li et al., 2010). Most precipitation indices exhibit increases in the southern and northern Tibetan Plateau and show decreases in the central Tibetan Plateau during 1961–2005 (You et al., 2008).

The Songhua River Basin (SHB), which is located in far northeastern China in the mid-high latitudes, is one of China's seven major river basins. Natural hazards (flash floods and droughts) have occurred frequently in the basin in recent years. For example, the Songhua River experienced extreme summer rainstorms in 1998 and 2013, while prolonged droughts occurred in the SHB in 2001 and 2003. Recently, investigations on long-term precipitation changes have become more important for developing management strategies that address the hazards in the SHB. Several studies have reported changes in precipitation in Northeast China (Li et al., 2014; Liang et al., 2011; Lu et al., 2012; Zhang et al., 2011b). For example, Li et al. (2014) assessed the spatio-temporal variability and trends in precipitation by utilizing 1960–2009 meteorological records in the SHB; their results showed that the annual precipitation greatly fluctuated and that a decadal decline has occurred since the 1980s. Liang et al. (2011) investigated the precipitation variability in Northeast China from 1961 to 2008, and their results indicate that a decrease in the precipitation occurred at 77 (annual) and 80 (summer) of the 98 meteorological stations over a 48-year period. Zhang et al. (2011b) documented the spatio-temporal changes in China's precipitation based on monthly precipitation data over 1960–2000; the authors detected decreasing precipitation in Northeast China. These studies provide insights into the annual and monthly precipitation through 2009 in the SHB. However, few studies have identified the characteristics of extreme precipitation events in the SHB. Extreme precipitation is somewhat more closely related to the safety of water systems than the mean precipitation. Furthermore, the monthly distribution of extreme precipitation events is more unevenly distributed than the monthly precipitation (Fu et al., 2013).

How has recent extreme precipitation events changed in the SHB? Given the above context, spatial and temporal variations in extreme precipitation events were examined on annual and monthly scales in the Songhua River Basin. Wet–day precipitation (PRCPTOT), maximum 1-day precipitation (RX1day), maximum 5-day precipitation (RX5day), very-wet-day precipitation (R95), extremely-wet-day precipitation (R99), a simple daily intensity index (SDII), number of heavy precipitation days (R10mm), number of very heavy precipitation days (R20mm), consecutive wet days (CWD), and consecutive dry days (CDD) were selected to investigate this topic.

In addition, precipitation and other meteorological variables associated with evapotranspiration (such as temperature and wind) affect drought events (Qian et al., 2007). Considering the influences of recent and accumulated precipitation and evapotranspiration, the composite drought index (CI) provided by the National Climate Center of China performs relatively better than other drought indices that are solely based on precipitation (Song et al., 2014). Therefore, the CI has been considered for drought monitoring and analysis (Zou et al., 2010). In this study, the CI was used to investigate the spatio-temporal variations in drought on a monthly scale during 1960–2013 in the Songhua River Basin.

The characteristics of extreme precipitation events across the Songhua River Basin were investigated by exploiting 11 extreme climate indices during the period of 1960–2013. Ten indices, which are on the list of recommended indices of the expert team on climate change detection and indices (ETCCDI), assess changes in precipitation intensities (PRCTOT, RX1day, RX5day, R95, R99, and SDII), the number of the days per year characterized by heavy ($\geq$10 mm/d, R10mm) or very heavy ($\geq$20 mm/d, R20mm) precipitation, and the duration of consecutive wet days (CWD) and consecutive dry days (CDD). In addition to these indices, the composite drought index (CI) was used to identify drought events at the monthly scale; this index is used for regional meteorological monitoring in China. The spring version (s-CI), developed using the CI index, was exploited to better identify dry periods during spring, when most droughts occur. The time series of the 11 indices were calculated and analyzed by using 39 daily precipitation datasets provided by the CMA. Furthermore, the Mann–Kendall trend test was applied to examine the temporal trends in extreme events at each ground station. This study is useful for flood and drought detection and monitoring and for exploring the

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