Influences of the timing of extreme precipitation on floods in Poyang Lake, China

Xianghu Li, Qi Hu, Rong Wang, Dan Zhang and Qi Zhang

ABSTRACT

Changes in the timing of extreme precipitation have important ramifications for public safety and storm water management, but it has not received much attention in relation to flooding. This study analyzed the changes in the timing of extreme precipitation in the Poyang Lake basin and projected its future changes for the period 2020–2099. The study also quantified the influences of changes in the timing of peak flows on lake floods based on a hydrodynamic model. The results showed that peak rainfall in the Poyang Lake basin had occurred on later dates during the period 1960–2012, and it is this change that caused a delay in peak streamflows from five rivers in the lake basin. Moreover, the effects of these changes are expected to be more prominent during 2020–2099; for example, the rate of delay will be about 2.0 days per 10 years both for peak rainfall and for streamflow in the Poyang Lake basin. The hydrodynamic simulation further showed that a delay of peak streamflows from five rivers would significantly increase the flood level and outflow of the lake and also prolong the duration of floods. These results indicate that the risk of floods in Poyang Lake is likely to increase in the future, therefore making flood control in this region more challenging.

Key words | climate change, extreme precipitation, flood, Poyang Lake, timing change

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HIGHLIGHTS

- Peak rainfall in the Poyang Lake basin had occurred on later dates.
- This delay in peak rainfall, in turn, caused a delay in the peak runoff in the local basin and increased the chances of flooding.
- There is a delay in the timing of the projected future peak rainfall during the period 2020–2099.
- The delay in peak flows has further increased the highest lake level and the duration of floods.
- The risk of floods in Poyang Lake is likely to increase in the future.

INTRODUCTION

There is increasing evidence that global climate change is intensifying the hydrological cycle of the Earth (Allan & Soden 2008). Changes in the hydrological cycle are shown not only in the form of mean precipitation amounts (Held & Soden 2006; Trenberth 2011), but also in the form of precipitation distributions in space and time, and in terms of precipitation frequency, timing, and length of the peak precipitation period (Min *et al.* 2011; Chou & Lan 2012; Collins *et al.* 2013; Pal *et al.* 2013; Pascale *et al.* 2015). Understanding these changes in the hydrological cycle and their effects on the availability of water resources has become a

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matter of importance for governments, the public, and academic communities (Gao & Xie 2016). The Intergovernmental Panel on Climate Change (IPCC) released a special report in 2012 and summarized the influences of climate change on extreme and disastrous events including floods and droughts (Field 2012).

A warming climate could lead to frequent precipitation extremes, and will especially trigger more and heavy precipitation events and floods or droughts on both a regional and global scale (Groisman *et al.* 2005; Rahmstorf & Coumou 2011; Willems *et al.* 2012; Arnbjerg-Nielsen *et al.* 2013; Chen & Sun 2015; Duan *et al.* 2016a; Gao & Xie 2016). Since the mid-20th century, extreme precipitation events have been observed to become more intense and frequent in many areas (IPCC 2014) and are expected to intensify in the future (Rahmstorf & Coumou 2011; Kunkel *et al.* 2013; Villarini *et al.* 2013; Wuebbles *et al.* 2014; Asadieh & Krakauer 2015; Chen & Sun 2015; Mallakpour & Villarini 2015; Duan *et al.* 2019). On the other hand, mounting evidence is indicating that changes in the timing of extreme precipitation have important ramifications for public safety, storm water management infrastructure, and adaptation strategies for societies (Dhakal *et al.* 2015). Large-scale climate models predict increasing fluctuations in the timing of heavy precipitation that are likely to occur across the globe in a warmer environment (Meehl *et al.* 2000; Wu & Chau 2013). An understanding of the shift toward new extreme event seasons has significance for characterizing local hydroclimatic changes (Dhakal *et al.* 2015; Taormina & Chau 2015; Wang *et al.* 2017; Fotovatikhah *et al.* 2018; Shamshirband *et al.* 2020). For example, the current wet and dry seasons could shift in regions in future warmer climates (Chou & Lan 2012). Fu *et al.* (2013) indicated that the length of the dry season has extended in southern Amazonia since 1979. Zolina *et al.* (2010) found that the wet season has become longer over most of Europe by about 15–20% from the years 1950 to 2008. Ma & Zhou (2015) examined changes in precipitation variations in China and indicated that the timings of the wet and dry seasons have shifted considerably in recent decades. Meanwhile, shifts in the timings of the wet and dry seasons across the United States during 1930–2009 have been reported by Pal *et al.* (2013). Sahany *et al.* (2018) investigated the trends in the timing of peak rainfall over India and indicated later occurrence in the rainy season by 10–20 days per century, especially in southern Indo-Gangetic plains. Wilson *et al.* (2010) analyzed the trends in the timing of floods in Nordic countries (except Iceland) and found that more floods tend to occur earlier in spring. Hodgkins & Dudley (2006) also detected significantly earlier peak flows in eastern North America.

The timing of extreme precipitation events is closely related to the seasonal shifts of floods and droughts (Gu *et al.* 2017). In large river basins, tributaries may be distributed asymmetrically along main channels (He *et al.* 2007) and respond to rainfall events differently (Pattison *et al.* 2014), and any deviations in the precipitation pattern, time distribution, and intensity from the past will have significant influences on hydrographs at the confluent points of basins (Chen *et al.* 2012). JBA Consulting (2007) confirmed that the timing of the peak recharges from tributaries to main river channels determines the timing and magnitude of floods in downstream areas. Delaying the timing of peak flows from upstream tributaries can desynchronize downstream subwatersheds and reduce the chances of flood and its magnitude (Pattison *et al.* 2014). The Poyang Lake in China is a typical confluence zone of complex river systems with a complicated hydraulic connection and interaction. The lake receives water primarily from five rivers in the local basin and exchanges water with the Yangtze River through a channel in the northern extremity of the lake (Figure 1). The flood stage in the lake is influenced by both the inflows from five rivers and the discharge of the Yangtze River (Shankman *et al.* 2006; Hu *et al.* 2007). High water levels of the Yangtze River could block outflows from the Poyang Lake and even cause backflows from the river to the lake and raise the lake's water level (Yin *et al.* 2007; Wang *et al.* 2008; Nakayama & Shankman 2013). Therefore, a better understanding of variations in precipitation extremes in the context of climate change in the Poyang Lake basin is vital to improve flood prediction and mitigation in this area (Nie *et al.* 2012).

Warm season precipitation in the Poyang Lake basin is strongly influenced by the East Asian monsoon (EAM) (Liu & Liu 2002; Yu *et al.* 2009). The climate variations in recent decades have resulted in a significant increase in the variability of East Asian summer monsoon precipitation (Feng *et al.* 2011), a change leading to more frequent and intense extreme hydrological phenomena in this region

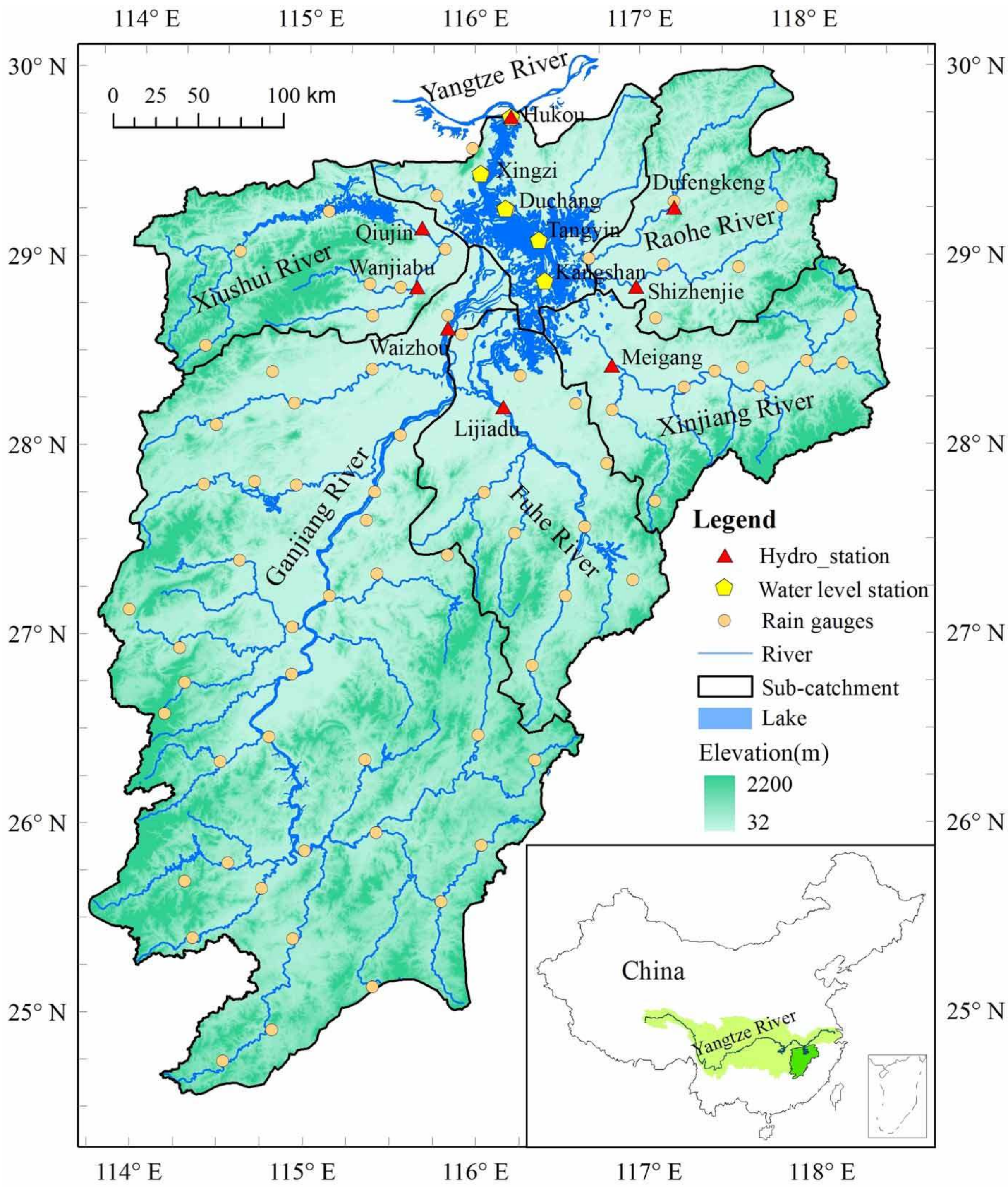

Figure 1 | The study area and the distribution of precipitation gauges. The inset map shows the Yangtze River basin and the location of the Poyang Lake basin.

(Groisman *et al.* 2005; Wang & Zhou 2005; Zhang *et al.* 2008; You *et al.* 2011). Many studies have investigated the occurrence characteristics of severe floods in the Poyang Lake basin and their causes in terms of climate variability and human activities in recent years (Yin & Li 2001; Piao *et al.* 2003; Shankman & Liang 2003; Zhao & Fang 2004; Zhao *et al.* 2005; Shankman *et al.* 2006, 2012; Nakayama & Watanabe 2008; Yu *et al.* 2009; Nakayama & Shankman 2013; Li *et al.* 2015a; Duan *et al.* 2016b). However, previous studies have focused more on extreme precipitation and have not paid enough attention to the impacts of changes in the timing of extreme precipitation events on floods (Gu *et al.* 2017) which is critical to flood disaster prevention and mitigation. Shankman *et al.* (2006) indicated that a great amount of runoff from the Poyang Lake basin at a later summer time than normal could easily trigger floods in the Poyang Lake. It is, thus, necessary to extend the previous studies and investigate the changes in the timing of extreme precipitation in the future years/decades and their impacts on peak flows and floods in the Poyang Lake.

The objectives of this study are to (1) identify changes in the timing of peak rainfall in the Poyang Lake basin and explore their relationships with the timings of peak flows and lake floods during the period 1960–2012, (2) project future changes in the timings of peak rainfall and peak flows for the future years from 2020 to 2099 under different Representative Concentration Pathway scenarios (RCP), and (3) quantify the influences of changes in the timing of peak flows on floods in Poyang Lake based on a hydrodynamic model MIKE 21. The outcomes of this study are expected to serve as useful references and provide valuable information for flood prediction, mitigation, and management in Poyang Lake.

STUDY AREA AND DATA

The Poyang Lake basin is located on the south bank of the middle and lower reaches of the Yangtze River (28°22′–29°45′N and 115°47′–116°45′E) in China (Figure 1). The lake basin consists of five sub-catchments: Xiushui, Ganjiang, Fuhe, Xinjiang, and Raohe, and has a total area of $1.62 \times 10^5\,\mathrm{km}^2$, accounting for 9% of the drainage area of the Yangtze River basin. The elevation of the basin varies from 2,200 m above sea level (asl) in mountainous regions to about 30 m asl in alluvial plains downstream of the major watercourses and around the lake (Ye *et al.* 2011). The basin area has a subtropical wet climate and is influenced by the EAM. The mean annual precipitation during 1960–2012 was 1,626 mm, of which more than 50% occurred during March–June. The annual mean temperature in the basin is 17.6 °C, with an average daily temperature of 27.3 °C in summer (June–August) and 7.1 °C in winter (December–February) (Zhang *et al.* 2014). The inflows from the five rivers vary considerably each year, ranging between 1.4×10^3 and $12.0 \times 10^3\,\mathrm{m}^3/\mathrm{s}$ during 1953–2010. On average, the peak flows of the five rivers occur during April–June, before the peak discharge of the Yangtze River in July and August (Guo *et al.* 2012). This particular time lag of the peak flows between the lake catchment and the Yangtze River has played a critical role in historical floods in the Poyang Lake (Hu *et al.* 2007; Guo *et al.* 2012).

The precipitation data used in this study are from observed daily rainfall data at 76 rainfall gauges in the Poyang Lake basin during the period 1960–2012, which are archived at the National Meteorological Information Center of China. Hydrological data are from observed daily streamflows from the five sub-tributaries and observed daily water levels of the Poyang Lake at five hydrological stations (i.e., Hukou, Xingzi, Duchang, Tangyin, and Kangshan). These data are made available from the Hydrology Bureau of Jiangxi Province, China. The streamflow was measured at seven hydrological stations: Qiujin, Wanjiabu, Waizhou, Lijiadu, Meigang, Shizhenjie, and Dufengkeng. The geographical locations of these rainfall gauges and hydrological stations are shown in Figure 1. The future climate data in the years 2020–2099 in the basin are extracted from the outputs of five widely used Global Climate Models (GCMs) in China, namely CanESM2, IPSL-CM5A-MR, MRI-CGCM3, CNRM-CM5, and GFDL-ESM2G in the Coupled Model Intercomparison Project (CMIP5) under three different emission scenarios (RCP2.6, RCP4.5, and RCP8.5).

METHODS

Hydrological model

The Water Flow Model for Lake Catchments (WATLAC) is a gridded spatially distributed hydrological model with effective computational techniques to simulate the complex spatial variability of surface and subsurface flows (Ye *et al.* 2011). The model is designed to simulate processes such as canopy interception, overland flow, stream flow routing, unsaturated soil water storage, soil lateral flow, soil water percolation to groundwater, and saturated groundwater flow (Zhang & Li 2009). The land surface (including river networks), unsaturated soil layer, and saturated groundwater aquifer are coupled in the model. Precipitation and potential evapotranspiration are the main driving forces in WATLAC. The WATLAC model has the capacity to meet the challenges of relatively sparse monitoring stations and multi-rivers in large catchments. It has been successfully applied to simulating daily hydrological processes in the Fuxian lake catchment (Zhang & Werner 2009), Xitiaoxi catchment (Zhang & Li 2009), and Poyang Lake basin (Liu *et al.* 2009). It has also been applied to quantify the effects of future climate change on catchment discharge and lake level (Ye *et al.* 2011). Based on the work of Ye *et al.* (2011), Li *et al.* (2014) have improved the model and calibrated and validated it to the Poyang Lake basin for the period 2000–2008. Their Nash–Sutcliffe efficiencies (E_{ns}) range from 0.71 to 0.84 for calibration and from 0.62 to 0.90 for validation, and the determination coefficients (R^2) range between 0.70 and 0.88 for calibration and between 0.70 and 0.90 for validation. These results support the WATLAC model as a robust and capable one for simulating daily discharges and its use in this study. The details of the WATLAC model structure are provided by Zhang & Li (2009) and Zhang & Werner (2009) and are, therefore, not repeated here.

Hydrodynamic model

Hydrodynamic models are powerful tools to address flow regime changes and hydraulic connections and interactions in complex river systems. Li *et al.* (2014) constructed a two-dimensional (2D) depth-averaged hydrodynamic model using the MIKE 21 Flow Model (Danish Hydraulic Institute (DHI) 2007) and used it to simulate the hydrodynamic processes of the Poyang Lake. The model covered an area of 3,124 km^2, which was discretized into 20,450 triangular elements according to the heterogeneity of lake bed topography (Li *et al.* 2014). The daily catchment inflows from the five rivers to the Poyang Lake were specified as the upstream boundary conditions at the outlets of the rivers in the model. The daily lake level at the Hukou station was used as the downstream boundary condition in the model (Li *et al.* 2014). The time step was 5 s for limiting the Courant–Friedrich–Levy (CFL) number (DHI 2007) to a stable solution. In the model, the hydraulic roughness (Manning number) was assumed to differ between flat regions and main channels, and the initial values in the range of 30–50 m^3/s were estimated from textbook values. A uniform value of 0.25 was assigned to the Smagorinsky factor (C_s) of eddy viscosity for the entire lake domain (Li *et al.* 2014). Li *et al.* (2018) calibrated and validated the model against the observed lake levels at four gauges in the lake and also the discharge at Hukou station for the period 2000–2008. The Nash–Sutcliffe efficiencies (E_{ns}) for lake level simulation ranged from 0.88 to 0.98, and the determination coefficients (R^2) ranged between 0.96 and 0.99. These results are considered satisfactory and indicate that the model has produced excellent agreement with observations. The model has the capability to reproduce the variations in lake level and discharge, and is, thus, used in this study to examine the influence of changes in the timing of peak flows from five rivers on the flood stage of the Poyang Lake.

The streamflow scenarios

On average, inflows from the five rivers in the Poyang Lake basin increase from March onward and reach their peak in June. The middle reach of the Yangtze River receives its annual peak precipitation from June to August. The peak flows in the five rivers occur one month earlier than that in the Yangtze River. This particular time lag has played a critical role in historical floods in Poyang Lake. In our simulations, four different scenarios are used to describe the different timings of the peak flows from the five rivers. Scenario S0 has average inflows from the five rivers in the Poyang Lake basin in the years when flood occurred in Poyang Lake (it happens when the lake level is $>$19.0 m at the Xingzi station). S0 is used as a reference case for comparison purposes. Scenarios S1, S2, S3, and S4 have the peak inflows from the five rivers delayed by 5, 10, 20, and 40 days, respectively, from that in S0, while the discharge from the Yangtze River remains the same.

In each scenario, the lake level at the Hukou station, which is the downstream boundary condition of the hydrodynamic model and must be specified as a known variable, is determined by the back-propagation neural network (BPNN) method. In a previous study of Li *et al.* (2015b), observed data from the period 1960 to 2000 were used to train the BPNN model, and data from 2001 to 2008 were used to validate the trained model's predictive capability. Their results showed that the observed highs and lows in lake levels were successfully simulated in both the training and testing periods, supporting the reliability of the BPNN model. Based on these tests, we use the same procedure in this study to estimate the lake level at the Hukou station for each hydrodynamic scenario modeling.

Trend analysis

A thirty-day moving average of daily rainfall is used to analyze temporal changes in order to smooth the fluctuations and reduce any potential errors. In addition, the timings of peak rainfall and peak flow are investigated by the Julian day number which is the continuous count of days from the beginning of a year. The trends of the timings of peak rainfall and peak flow are detected using the Mann–Kendall test (M-K), and the trend magnitude is estimated using the Sen's method. The evaluation is based on the Excel template application MAKESENS, developed by Salmi *et al.* (2002) for detecting trends in climatologic and hydrologic time series. The M-K test is a rank-based nonparametric method and has been widely used for detecting trends in climatologic and hydrologic time series (Novotny & Stefan 2007; Ye *et al.* 2013; Zhang *et al.* 2014). In the M-K test, a positive z-value indicates an increasing trend, and a negative value indicates a decreasing trend. The trend is statistically significant at the 0.1, 0.05, and 0.01 significance levels when $|z| > 1.645$, 1.96, and 2.576, respectively. The readers are referred to Novotny & Stefan (2007) and Ye *et al.* (2013) for additional details of the M-K test.

RESULTS

Relationships of changes in the timing of peak rainfall with runoff and lake flood stages

Variations in the timing of average peak daily rainfall (shown by Julian day numbers) in the Poyang Lake basin during 1960–2012 and the corresponding M-K test are shown in Figure 2. It is shown that the peak rainfall in the Poyang Lake basin occurred between 79 and 181 Julian day. The timing of peak rainfall shows a weak long-term upward trend in the study period with an M-K statistic of 0.07. A stronger trend of increase of peak rainfall is shown during 1978–2012. Figure 2 reveals that the annual peak precipitation in the Poyang Lake basin has occurred toward a later date during the study period. According to the mechanism delineated in Hu *et al.* (2007) and Guo *et al.* (2012), these changes are making the lake more vulnerable to flooding.

Figure 3 shows statistical relationships between the timings of peak rainfall, peak flows from the five rivers, and the lake level during 1960–2012. The scatter plot of the timings of peak rainfall and peak river flows (Figure 3(a)) shows a good linear relationship, with the determination coefficient

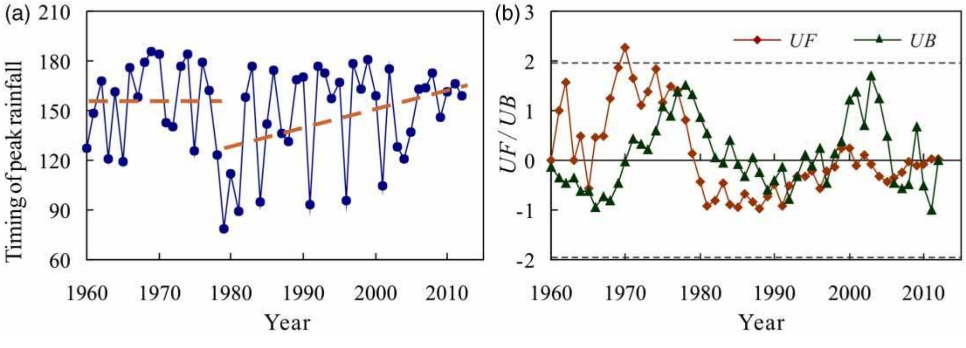

Figure 2 | Variation in the timing of average peak rainfall (a) in the Poyang Lake basin during 1960–2012 and its corresponding M-K test result (b).

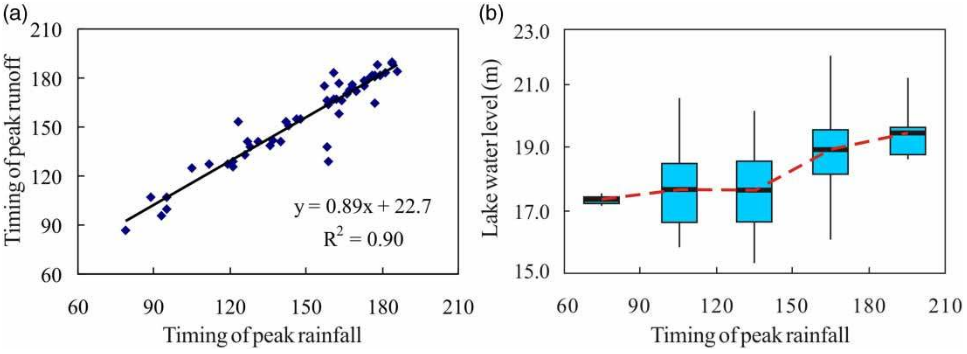

Figure 3 | Statistical relationship between the timing of peak rainfall, peak flows of the five rivers (a) and the peak lake level (b) during 1960–2012.

(R^2) of 0.90. This high R^2 indicates that the delay in the precipitation peak, in turn, causes a delay in the runoff peak in the five rivers. Because Poyang Lake receives inflows from the five rivers, changes in the timings of peak rainfall and runoff inflows affect the lake level. In Figure 3(b), the box plot reveals that the average lake level varies with the delay in precipitation, increasing from 17.41 m for early rainfall peak (peak rainfall occurring between 60 and 90 Julian day) to 19.59 m for late rainfall peak (peak rainfall occurring between 180 and 210 Julian day).

The delay of river inflows from the local catchment could further result in shortening the time between the peak flow from the five rivers and the Yangtze River, thus elevating the risk of floods in the lake. Figure 4 shows the statistical analysis of lake flood stage and the time lap between the peak flows from the five rivers and the Yangtze River. It is shown that the average lake level is as high as 19.18 m when the lap of the peak flows is less than 20 days, and the flood occurrence accounts for 38.5, 48.3, and 52.9% of the total flood events when the lake level is higher than 18.0 m (mild floods), 19.0 m (major floods), and 20.0 m (severe floods), respectively. Both the lake level and the flood frequency decrease with the increase of the lap time, and both reach their minimum when the lap time increases to 80–100 days. It is also important to note that the long time lap between the peak flow from the five rivers and the Yangtze River would mean that the flood peak from the five rivers comes much earlier than the peak discharge from the Yangtze River. Without blocking the latter, the river recharge is unlikely to cause floods in the lake.

Future changes in the timings of peak rainfall and runoff under different climate scenarios

Figure 5 shows the variation in the projected peak daily rainfall and the timing of its occurrence under different climate scenarios during 2020–2099. The projected peak daily rainfall from all five GCMs shows upward trends under RCP2.6, RCP4.5, and RCP8.5 emission scenarios (Figure 5(a)–5(c)) at the rates of 0.16–0.29, 0.28–0.59, and 0.74–1.55 mm per 10 years, respectively (Table 1). The trends are more significant in the RCP8.5 scenario. It is found from Figure 5(d)–5(f) that

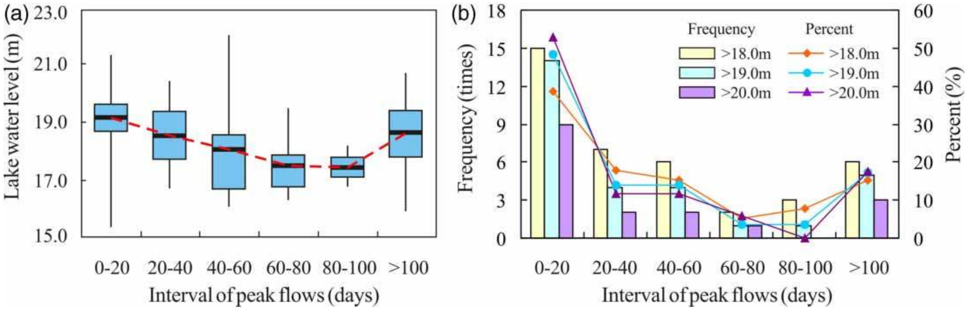

Figure 4 | Statistical relationship between lake flood stages (a), occurrence (b) and the time lap of peak flows from the five rivers and the Yangtze River.

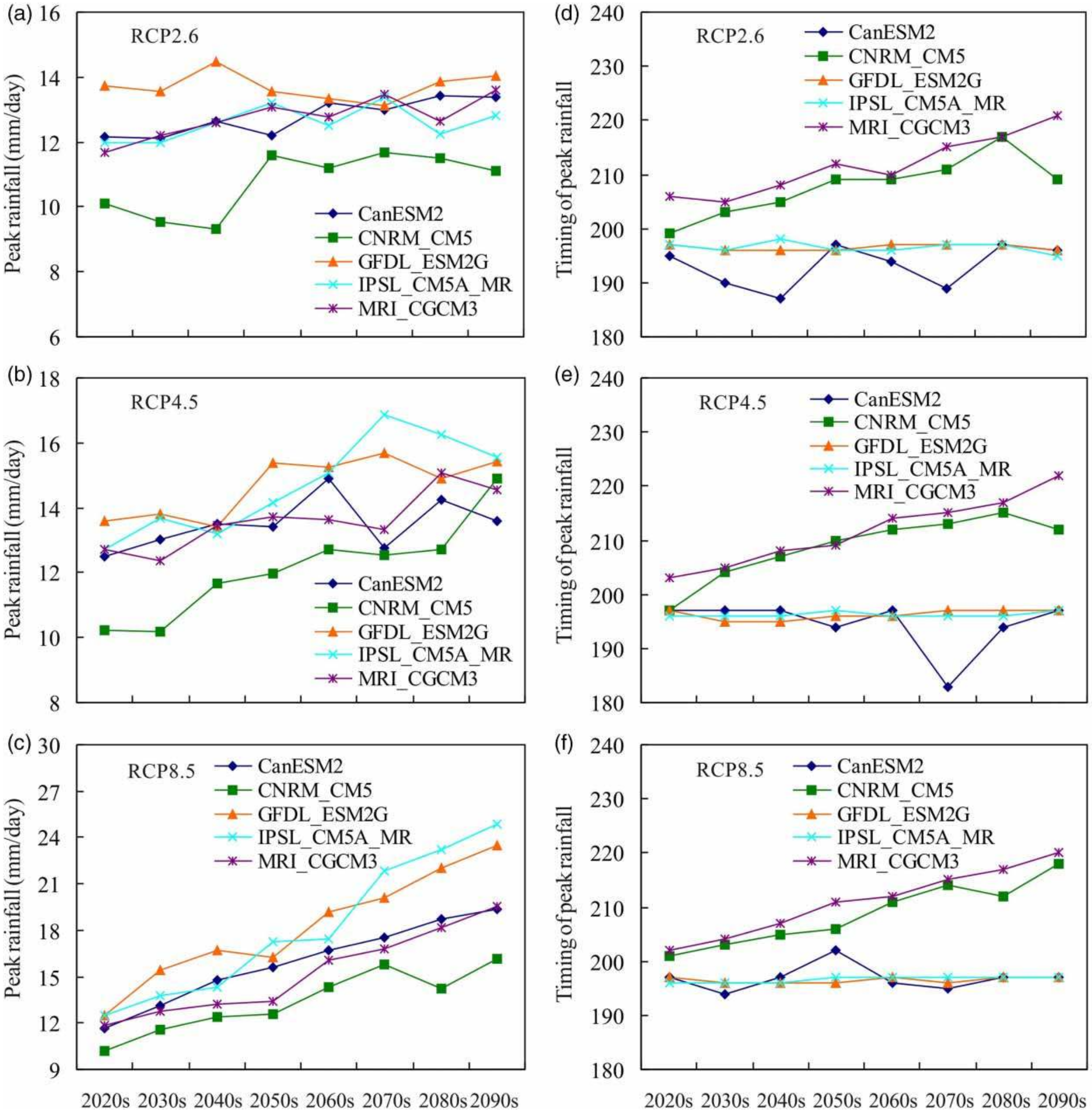

Figure 5 | Variations in the projected peak rainfall (a, b, c) and its timing of occurrence (d, e, f) under different climate scenarios during 2020–2099.

Table 1 | Change rates of peak rainfall and its timing under different climate scenarios during 2020–2099

	RCP2.6		**RCP4.5**		**RCP8.5**	
GCMs	**Rainfall (mm/10 years)**	**Peak timing (days/10 years)**	**Rainfall (mm/10 years)**	**Peak timing (days/10 years)**	**Rainfall (mm/10 years)**	**Peak timing (days/10 years)**
CanESM2	0.16	0.55	0.31	0.28	0.96	0.18
CNRM_CM5	0.29	2.25	0.59	2.25	0.74	2.12
GFDL_ESM2G	0.17	0.13	0.28	0.25	1.37	0.13
IPSL_CM5A_MR	0.18	0.38	0.52	0.13	1.55	0.13
MRI_CGCM3	0.24	2.0	0.33	2.37	0.96	2.25

the timing of peak rainfall also shows an upward trend. They indicate that peak rainfall in the Poyang Lake basin would occur at a later time in the future. We also note that the range of change in the timing projected from different GCMs differs. Specifically, the projected timing of peak rainfall from CNRM_CM5 and MRI_CGCM3 shows significant upward trends, with the rates of delay being 2.25 and 2.0 days per 10 years in RCP2.6, 2.25 and 2.37 days in RCP4.5, and 2.12 and 2.25 days in RCP8.5, respectively (Table 1). The changes projected from the other three models are small, with the rate of less than 1 day delay per 10 years under all emission scenarios (Table 1). Figure 5 and Table 1 indicate that the peak daily rainfall in the Poyang Lake basin may increase and its occurrence time may be delayed to a different extent in the future under the tested emission scenarios.

The projected future precipitation from the five GCMs under different emission scenarios during 2020–2099 is used to drive the WATLAC model to predict the runoff changes in the five rivers of the Poyang Lake basin. The variation in their peak discharges and occurrence timing under different climate scenarios is shown in Figure 6, and the rate

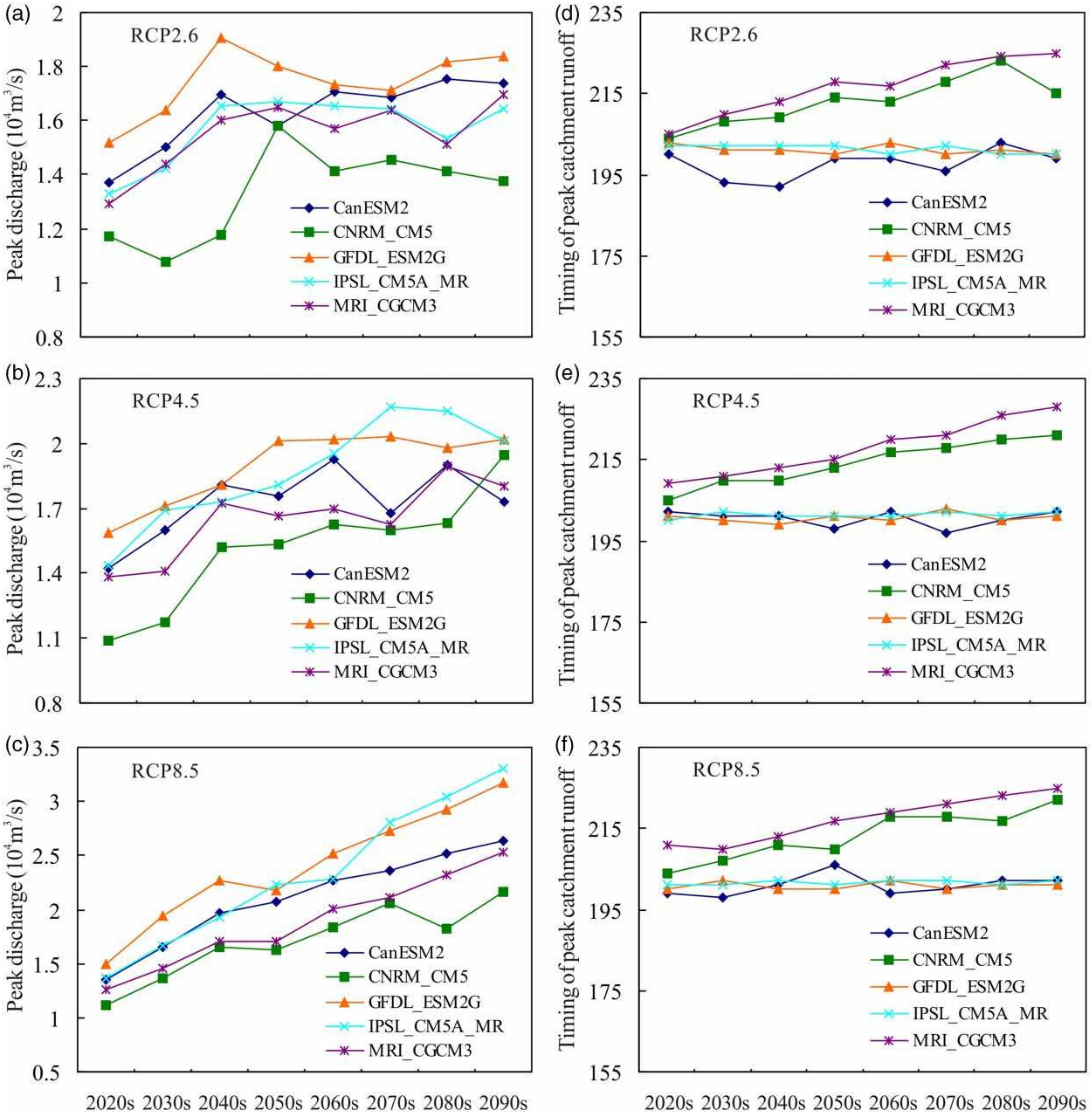

Figure 6 | Variations in peak discharge (a, b, c) and its timing of occurrence (d, e, f) under different climate scenarios during 2020–2099.

Table 2 | Change rates of peak discharge and timing under different climate scenarios during 2020–2099

	RCP2.6		**RCP4.5**		**RCP8.5**	
GCMs	**Discharge (m^3/s/10 years)**	**Peak timing (days/10 years)**	**Discharge (m^3/s/10 years)**	**Peak timing (days/10 years)**	**Discharge (m^3/s/10 years)**	**Peak timing (days/10 years)**
CanESM2	476	0.63	631	0.43	1,621	0.22
CNRM_CM5	629	2.38	1,077	2.0	1,305	2.25
GFDL_ESM2G	485	0.38	557	0.50	2,100	0.25
IPSL_CM5A_MR	425	0.25	919	0.25	2,412	0.13
MRI_CGCM3	510	2.50	638	2.38	1,590	1.88

of change is summarized in Table 2. As expected, the WATLAC simulated peak river discharge in the future shows strong upward trends under RCP2.6, RCP4.5, and RCP8.5 emission scenarios (Figure 6(a)–6(c)). The increase in trends is the largest in the RCP8.5 scenario. The rates of change of the peak discharge range from 425 to 629 m^3/s per 10 years in RCP2.6, 557 to 1,077 m^3/s per 10 years in RCP4.5, and 1,305 to 2,412 m^3/s per 10 years in RCP8.5 (Table 2). The simulated timing of peak river runoff also shows upward trends under the emission scenarios (Figure 6(d)–6(f)). However, the change rates of the timing of peak runoff calculated from different driving conditions of the five GCMs are different. Specifically, the timing of peak river runoff from CNRM_CM5 and MRI_CGCM3 shows significant upward trends, with the rates of delay being 2.38 and 2.50 days per 10 years in RCP2.6, 2.0 and 2.38 days in RCP4.5, and 2.25 and 1.88 days in RCP8.5, respectively (Table 2). The change rates in the other three models are small, with a rate of less than 1 day delay per 10 years under all three emission scenarios (Table 2). The results in Figure 6 and Table 2 show that the peak discharges of the five rivers in the Poyang Lake basin will increase, and the timing of peak flow may be delayed when the number of days is varied in the future under different emission scenarios.

Influences of changes in the timing of peak flows on floods

Hydrodynamic modeling is undertaken to provide quantitative interpretations of the influences of changes in the timing of peak flows from the five rivers on flood stages of the Poyang Lake. The hydrodynamic simulation shows that the highest lake level at the Xingzi station increases from 19.57 m in scenario S0 to 20.05 m in scenario S1, 20.21 m in scenario S2, and 20.63 m in scenario S3; similar lake level increases are also observed at the Duchang, Tangyin, and Kangshan stations (Figure 7(a)). These increases in the highest lake level with the delay of peak flows from the five rivers in the lake basin are mainly related to the rising of the Yangtze River water level and its blocking effect on the lake outflow. When the delay time of the peak flow from

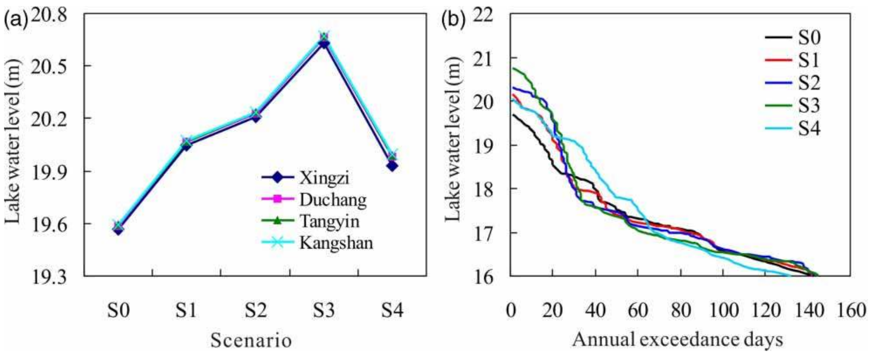

Figure 7 | Changes in the highest lake level (a) and the annual exceedance days (b) in different scenarios.

the five rivers is too long (i.e., 40 days as in scenario S4), the flood peak of the Yangtze River has passed, and in such cases, its blocking effect and the water level begin to drop. The annual exceedance days for different water levels in every scenario are shown in Figure 7(b). It shows that scenario S0 has fewer exceedance days (lake level at 18.3 m or higher) than the other scenarios. The duration of this high lake level extends when the peak flow from the five rivers into the lake is delayed. The increase in duration is the largest in scenario S4.

Figure 8 shows the changes in the average lake level during the flood period (June–August) and also the dry period (November–February) in different delay scenarios. The results show that the average lake level during the flood period increases with the delay of peak flows from the five rivers, i.e., the average lake level is 17.63–17.72 m in scenario S0 and increases to 17.72–17.80 m in S1, 17.78–17.86 m in S2, 17.86–17.94 m in S3, and 17.95–18.04 m in S4 (Figure 8(a)). During the dry period, the average lake level decreases slightly with the delay of peak flows from the five rivers (Figure 8(b)).

In addition, our hydrodynamic simulations show that the distribution of lake level change is also uneven in space. Figure 9 shows the spatial distribution of lake level changes in the flood season and the dry season. It is seen that there are small positive lake level changes in the northern part of the lake (channel area) in the flood season. The amplitude of changes increases toward the south. However, the lake surface becomes almost horizontal with very small gradients, such that the differences in water level changes in the different parts of the great lake area are insignificant in all scenarios (Figure 9(a)–9(d)). In the dry season, large negative lake level changes are seen in the northern part of the lake (channel area), and the rates of change decrease toward the south (Figure 9(e)–9(h)).

This study is also extended to investigate the changes in outflows from Poyang Lake to the Yangtze River at the Hukou outlet. Figure 10 shows the modeled average discharge at the Hukou station during the flood period and the dry period in different delay scenarios. The results show that the average discharge during the flood period increases with the delay of peak inflows from the five rivers. The average discharge is 6,294 m^3/s in scenario S0, and it increases to 6,537 m^3/s in S1, 6,987 m^3/s in S2, 7,472 m^3/s in S3, and 8,346 m^3/s in S4 (Figure 10). The average discharge during the dry period decreases slightly as anticipated, with different extents of reduction in different delay scenarios.

DISCUSSION

The results presented in the previous sections show that peak rainfall in the Poyang Lake basin has occurred on later dates during 1960–2012. Such change has caused a delay in the peak runoff from the five rivers in the lake basin and increased the chances of flooding in Poyang Lake. These results are in general agreement with those obtained in the previous studies. For example, Sahany *et al.* (2018) analyzed the timing of peak rainfall in India, and their result indicated a tendency for later occurrence of the wet season, with the largest delay by 10–20 days per century in the southern Indo-Gangetic plains. Pal *et al.* (2013) showed a delayed summer monsoon onset in the US

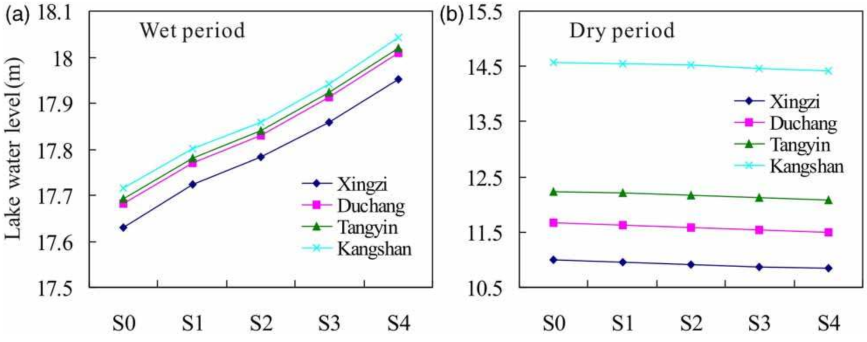

Figure 8 | Changes in the average lake level during the flood season (June–August) (a) and the dry season (November–February) (b) in different scenarios.

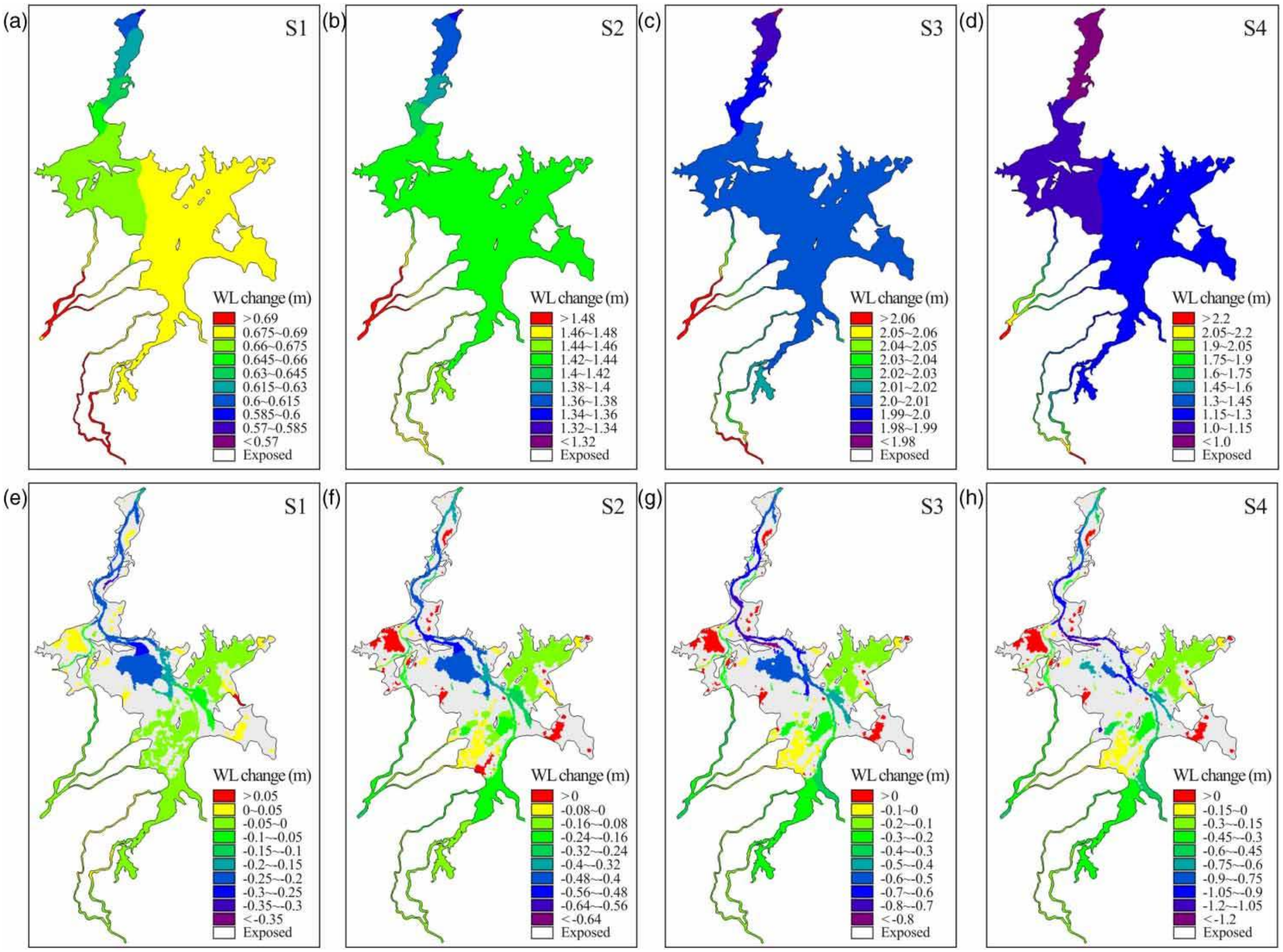

Figure 9 | Comparisons of the spatial distribution of lake level changes during the flood season (a, b, c, d) and the dry season (e, f, g, h) in different scenarios.

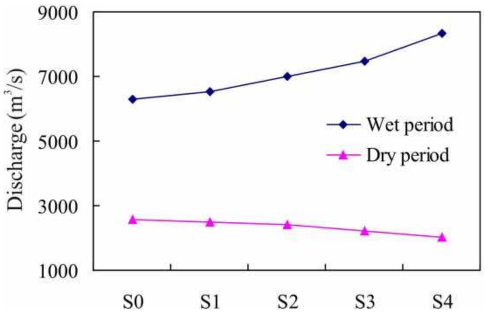

Figure 10 | Changes in average discharges at the Hukou station during the flood period and the dry period in different scenarios.

Southwest, and Cook & Seager (2013) also delineated a delayed wet season in that region. In China, Gu *et al.* (2017) found that although the timing of annual maximum (AM) based extreme precipitation does not exhibit significant trends at most stations in China, more stations are showing trends of increase or a significant increase in the timing of Peak-Over-Threshold (POT)-based extreme precipitation in central and south China. Their results suggest increasingly late occurrence of extreme precipitation in central and south China. Ma & Zhou (2015) showed that the timings of the wet and dry seasons have shifted significantly in the middle and lower Yangtze River basin in China. The onset of the wet season is delayed at a rate of 1 month per 50 years.

In addition to the projected significant future increase in the peak rainfall in the Poyang Lake basin, based on five CMIP5 GCMs, the timing of peak rainfall is found to be delayed with time from 2020 to 2099 under RCP2.6, RCP4.5, and RCP8.5 emission scenarios. The late peak rainfall will cause a delay in the runoff peak from the five rivers in the Poyang Lake basin and shorten the time lapse between the peak flow from the five rivers and the Yangtze River. Previous studies have shown that this particular time lapse has played a critical role in determining the severity of floods in Poyang Lake (Shankman *et al.* 2006; Hu *et al.* 2007; Guo *et al.* 2012). A shorter time lapse between the two is likely to result in a higher lake flood stage and a longer duration for floods (Li *et al.* 2017). Accordingly, these results would suggest that Poyang Lake will face a higher risk of flooding in the future. Similar results have also been obtained in the study of Ye *et al.* (2011), who pointed out that climate change impacts on Poyang Lake are expected to be manifested with more severe floods during the wet season and more extreme droughts during the dry season in the future.

A potentially strong factor influencing these changes in the timings of peak rainfall and wet/dry season in the Poyang Lake basin could be the weakening of EAM circulation (Ma & Zhou 2015). Many studies have identified the impacts of EAM on precipitation changes in eastern China (Ding *et al.* 2008; Ren *et al.* 2013; Xiao *et al.* 2015; Zhang *et al.* 2016). Sahany *et al.* (2018) suggested that shifts in the timing of peak rainfall in India are linked to the El Niño–Southern Oscillation (ENSO) and Indian Ocean sea surface temperatures (SSTs) through a regime shift in the tropical Pacific SSTs. In addition, global climate change will undoubtedly reshape precipitation patterns and temporal variations (Qian *et al.* 2009; Song *et al.* 2014; Li & Hu 2019; Homsi *et al.* 2020). On a regional scale, many studies have indicated that human activities, such as changing land use patterns, irrigation, and urbanization, also add complications to changes in the timing of peak rainfall (Kunkel *et al.* 2007; Stone *et al.* 2009; Stott *et al.* 2010; Cook & Seager 2013; Higgins & Kousky 2013; Pal *et al.* 2013; Ma & Zhou 2015).

CONCLUSIONS

This work analyzed the changes in the timing of extreme precipitation in the Poyang Lake basin and projected their future changes during 2020–2099 under different emission scenarios (RCP2.6, RCP4.5, and RCP8.5). The study also provided quantitative influences of changes in the timing of peak flows on Poyang Lake flood stages based on a hydrodynamic model, MIKE 21, in Poyang Lake. The results of the study show that peak rainfall in the Poyang Lake basin has occurred between 79 and 181 Julian day on later dates during 1960–2012. This change has caused a delay in the runoff peak from the five rivers in the lake basin and has further increased the chances of flooding in the lake. There is also a delay in the timing of the projected future peak annual rainfall during 2020–2099 from the five GCMs under RCP2.6, RCP4.5, and RCP8.5 emission scenarios. The average rate of the delay is by 2.0–2.37 days per 10 years. The hydrodynamic simulations further show that this delay in the peak flows from the five rivers will contribute to an increase in the highest lake level from the current 19.57 to 20.63 m during the flood period in the lake. There is the possibility that this high lake level and floods will extend when the peak flow from the five rivers to the lake occurs at a later time. These results indicate that flood risk in Poyang Lake is likely to be elevated in the future, thus making flood control in this region even more challenging.

Finally, it is also important to recognize that the outcomes of this study will help in providing valuable information on flood prediction, mitigation, and management in Poyang Lake. However, the above conclusions are derived only on the basis of the outputs of the given five GCMs, and, therefore, it is wise to apply the conclusions drawn in this study to other regions with caution. Some areas for making further improvements to this study would include the use of ensemble predictions of the GCMs with a spread of precipitation distribution to quantify the variance of the results and their level of uncertainty. Additionally, it is necessary to investigate the hydrodynamic processes and mechanism of potential floods in Poyang Lake resulting from the shift of the timing of extreme precipitation.

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DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

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