Synchronous Characteristics of Precipitation Extremes in the Yangtze and Murray–Darling River Basins and the Role of ENSO

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ABSTRACT

The floods caused by the extreme precipitation in the Yangtze River basin (YRB) and Murray–Darling River basin (MDRB), the largest basins in China and Australia, have significant impacts on the society and regional economies. Based on the spatial–temporal analysis of the daily precipitation extremes (DPEs) during 1982–2016, we found that for both basins, the whole-basin-type DPEs have the highest proportion and a synchronous DPE interannual variation characteristic exists in the two basins, with the 3-yr running correlation coefficient of the annual DPE days (DPEDs) reaching almost 0.7 (significant at the 0.01 level). The El Niño–Southern Oscillation (ENSO), which is one of the most significant climate disturbance factors in the world, plays an important role in modulating the variability of the DPEs in the two basins. Singular value decomposition (SVD) analysis revealed that both the YRB and the MDRB’s whole-basin-type DPEs are closely coupled with the procedure that the preceding winter eastern Pacific (EP)-type El Niño faded to a central Pacific (CP)-type La Niña. This means that the DPEs in the YRB and MDRB may synchronously occur more frequently when the above process occurs. Owing to the atmosphere–ocean interaction from the east–west dipole sea surface temperature (SST) anomaly pattern, the atmospheric circulation disturbance exhibits a pattern in which the equatorial eastern Pacific region is a mass source anomaly with a higher pressure, drier air, and weaker convection, while the equatorial western Pacific region is a mass sink anomaly with a lower pressure, wetter air, and stronger convection. Moreover, two wave trains that originated from the tropical western Pacific were found to extend to the YRB and MDRB. The interaction between the wave train’s interphase dynamics and water vapor transport disturbance results in the ascent conditions and enhanced water vapor transport, which leads to the synchronous occurrence of DPEs in the YRB and MDRB on an interannual scale.

Key words: precipitation extreme, El Niño–Southern Oscillation (ENSO), Yangtze River basin (YRB), Murray–Darling River basin (MDRB)

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1. Introduction

Floods are severe natural disasters that are characterized by the widest impact range and the greatest economic losses (Kundzewicz et al., 2010, 2014; Liu et al., 2014; Fang et al., 2015; Tanoue et al., 2016). During 1998–2017, flood events accounted for 43.4% of the total number of natural disasters globally, and the population af-
fected and direct economic losses caused by these floods accounted for 45% and 23% of the totals for all natural disasters (Wallemacq and House, 2018). Owing to climate change and socioeconomic development, the losses caused by floods have been increasing yearly (Wallemacq and House, 2018). Many previous studies have found that precipitation extremes are increasing in many regions, including some dry regions, under the warming background caused by climate change, and this is an important cause of flood (Rajeevan et al., 2008; Wang and Fu, 2013; Donat et al., 2016; Chisanga et al., 2017).

The interannual variability in precipitation and its underlying mechanisms are very complex. As the most significant interannual disturbance globally (Ward et al., 2014; Fan et al., 2019), the El Niño–Southern Oscillation (ENSO) system affects the precipitation in most parts of the world through significant atmosphere–ocean interactions (Alexander et al., 2002; Yeh et al., 2009; Yang et al., 2018). Ward et al. (2014) found that ENSO has a wide and strong impact on floods, and there are significant anomalies involving flooding of nearly half of the earth’s land surface (44%) during an El Niño or La Niña year. In Australia, New Zealand, South America, central America, and East Asia, a strong teleconnection between ENSO and river flow has been detected with remarkable regional consistency (Chiew and McMahon, 2002; Jiang et al., 2006). In recent years, the conventional eastern Pacific (EP) ENSO with sea surface temperature (SST) anomalies centered in the eastern equatorial Pacific and central Pacific (CP) or on the international dateline and the Modoki ENSO with an SST anomaly centered in the central equatorial Pacific have been frequently discussed (Larkin and Harrison, 2005; Ashok et al., 2007; Capotondi et al., 2015). Because of the different SST structures and deep convection characteristics in the equatorial Pacific, the EP and CP types usually correspond to a unique Walker circulation pattern (Ashok et al., 2007; Weng et al., 2007, 2009). Thus, they have different impacts on temperature, precipitation, and large-scale circulation in the Pan-Pacific region, including East Asia, North America, and Australia (Larkin and Harrison, 2005; Weng et al., 2007, 2009; Zhang et al., 2014).

The Yangtze River basin (YRB) and Murray–Darling River basin (MDRB) are important economic zones in China and Australia, respectively. The precipitation in the two basins has strong interannual variability, and it often results in the occurrence of floods and severe economic losses. Previous studies have found that the ENSO can affect the climate disturbances in both East Asia and Australia (Cai and Cowan, 2009; Hsu et al., 2014; Wu, 2016; Kundzewicz et al., 2019). The ENSO may stimulate the East Asia–Pacific (EAP) wave train by influencing the convective activity near the Philippines, which further modulates the summer rainfall in China (Huang and Li, 1987; Kurihara and Tsuyuki, 1987; Nitta, 1987; Huang and Lu, 1989). Moreover, the different types of ENSO have various effects on the summer precipitation in China. When the El Niño event is in the development (attenuation) stage, the summer precipitation in the Jiang–Huai River basin will be above (under) average (Jin and Tao, 1999; Huang and Chen, 2002). During the El Niño attenuation period, abnormal anticyclones are triggered over the tropical northwestern Pacific Ocean, which can enhance the transport of water vapor by the summer monsoon and increase the frontal precipitation in eastern China (Wang et al., 2000, 2003). Similarly, the climate variance in Australia is also very sensitive to the ENSO (Power et al., 1999; Wang and Hendon, 2007; Chand et al., 2013). Studies have found that the different types and onset timings of the ENSO have diverse impacts on the interannual variations in the precipitation in the different regions of Australia (Brown et al., 2009; Fan et al., 2019).

Since many previous studies have shown that the interannual variability in the precipitation in the two basins is significantly modulated by the ENSO, it is important to determine whether there is any correlation between the precipitation extremes in the two basins. The type or phase of ENSO drives this correlation feature and the mechanism behind this phenomenon has not been determined. Determining this information is of great significance to disaster prevention and mitigation in China and Australia, which are two major economies in the world. In this study, the spatial–temporal analysis of the precipitation extremes in the two river basins was conducted to explore their correlation. The coupled patterns between the precipitation extremes and equatorial Pacific SST were identified to investigate the role of ENSO. Moreover, the SST anomaly related atmospheric disturbance was analyzed to explain the mechanism that causes the coupling between the precipitation extremes in the two basins.

2. Study area, data, and methods

2.1 Study area

The Yangtze River originates from the Qinghai–Tibetan Plateau and flows into the East China Sea. The YRB is located at 25°–35°N, 91°–122°E, and is dominated by a subtropical monsoon climate with an annual
mean temperature of 11.6°C and an annual precipitation of 1040 mm (Fig. 1). The total basin area is about $1.8 \times 10^6 \text{ km}^2$, and the annual runoff is about $9.0 \times 10^{11} \text{ m}^3$ at the outlet (Dai and Yang, 2006). Corresponding to the uneven distribution of precipitation, 60%–80% of the runoff is concentrated in the flood season.

The Murray–Darling River is the only well-developed water system in Australia. It is composed of a confluence of the Murray and Darling rivers, and it is the most important river with the largest flow in Oceania. It originates from southeastern Australia and flows into Incont Bay (i.e., the Indian Ocean). Located at 24°–37°S, 138°–153°E, the MDRB covers an area of about $1.06 \times 10^6 \text{ km}^2$, with an annual runoff of $2.4 \times 10^{10} \text{ m}^3$ (Prasad, 2008; Fig. 1). The MDRB mainly has a subtropical arid to semi-arid climate, with an annual mean temperature of 17.6°C and an annual precipitation of 479 mm.

2.2 Data

The Global Precipitation Climatology Centre’s (GPCC) full data daily product v.2018 (https://opendata.dwd.de/climate-environment/gpcc) was used to identify the precipitation extremes in the studied river basins. This dataset is based on observations from 116,000 rainfall stations around the world, and it is generated with a horizontal resolution of $1° \times 1°$ over a time range of 1982–2016 (Ziese et al., 2018).

The ERA-Interim daily reanalysis data from the ECMWF (https://apps.ecmwf.int/datasets/data/interim-full-daily) was used to analyze the SST anomalies in the equatorial Pacific region and their effects on the atmospheric circulation anomalies. This dataset includes the geopotential height, total column water vapor, vertical integral of the eastward and westward water vapor flux, $u$ component of the wind, $v$ component of the wind, vertical velocity, total cloud cover, mean sea level pressure, and SST for 1979–2019.

The monthly El Niño Modoki index (EMI) defined for the monitored ENSO Modoki events and the monthly NiñoEP index used to monitor EP Pattern-type El Niño events were obtain from the Japan Agency for Marine Earth Science and Technology (JASMTEC; http://www.jamstec.go.jp/aplinfo/sintexf/e/elnmodoki/about_elnm.html) and the National Climate Center of the China Meteorological Administration (https://cmdp.ncc-cma.net/Monitoring/cn_nino_index.php?product=cn_nino_index_nino), respectively, and these datasets were used to ana-

![Fig. 1. The location of the Yangtze River basin (YRB) and Murray–Darling River basin (MDRB).](image-url)
lyze the correlation between the interannual variations in the DPEs and the different types of ENSO.

### 2.3 Methods

Daily precipitation extremes (DPEs) are defined by arranging the areal-averaged daily precipitation in ascending order based on the daily rainfall of greater than 1 mm, and the 99% percentile is used as the threshold (Guan et al., 2011; Jin et al., 2015; Li et al., 2016; Chen et al., 2019).

To classify the spatial types of the DPEs, empirical orthogonal function (EOF) decomposition analysis was conducted by using the standardized daily precipitation at each grid during the DPE days (DSEDs) as the input:

\[
S(x) = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (x_{i} - r)^2},
\]

where \(x\) is each grid’s daily precipitation field during the DPE; \(x_i\) is each year’s daily precipitation field in a period corresponding to the DPE; \(r\) is the multiyear averaged daily precipitation during the DPE; and \(N\) is the total number of years.

As for the temporal variation features of the DPEs, the intraannual and interannual variance were statistically analyzed. The correlation between the interannual change variations of the DSEDs of the two river basins was calculated using a 3-yr sliding and significance level and the Student’s \(t\)-test method.

To investigate the effect of the ENSO on the variations in the DPEs, the coupled patterns between the precipitation anomalies during the DSEDs and the equatorial Pacific SST anomalies were explored for the period of 1979–2019. The standardized deviation of the precipitation during the DSEDs and the contemporaneous 2–8-month preceding SST anomalies in the equatorial Pacific were input as the left and right fields of the singular value decomposition (SVD) analysis (Ming and Sun, 2019). The correlation coefficient between the right field time series of the SVD leading mode (SVD1) and the standardized deviation values of the atmospheric parameters, including the total column water vapor, vertical integrated eastward and westward water vapor flux, \(u\) component of the wind, \(v\) component of the wind, vertical velocity, total cloud cover, and the mean sea level pressure, were calculated to analyze the atmospheric circulation’s response to the SST anomalies.

To further study the seasonal effects of the ENSO, the correlation coefficients between the monthly EMI and NiñoEP and the interannual variations in the DSEDs during the flood season in the two basins were calculated. The flood season each year is from June to October for the YRB and is from March to December for the MDRB.

### 3. Results

#### 3.1 Spatial–temporal characteristics of the DPEs

The EOF analysis based on the GPCC data for 1982–2016 shows that the types of DPEs are similar in the YRB and MDRB (Fig. 2). The main two DPE types in the YRB are the whole-basin type and the northwest–southeast dipole type, accounting for 43.9% and 10.2% of the total DPE types, respectively. The whole-basin-type DPEs also accounts for the largest portion (68.8%) in the MDRB, while the north–south dipole type accounts for 9.6%.

The intraannual variation in the DSEDs in the YRB exhibits significant seasonal variability (Fig. 3a). The DPEs mainly occur from May to October and are rare in other months. The interannual variation in the DPEs is also significant, with the maximum frequency of the DPEs appearing in the years 1981–1982, 1989–1991, 1998–1999, 2010–2011, and 2016. For the MDRB (Fig. 3b), the DPEs may appear in any month, but the austral summer months (DJF) are more vulnerable than the other seasons. Although the two basins are in the Northern and Southern Hemispheres, respectively, and they have significantly different geographical and climatic characteristics, the interannual variations of the DSEDs of the MDRB are very similar to those of the YRB. The occurrences of the DPEs in the two basins are significantly related to each other on the interannual scale, with the value of the 3-yr sliding correlation coefficient between the two basins’ annual DSEDs being 0.7 (significant at the 0.01 level; Figs. 3a–c).

#### 3.2 Relationship between the basins’ DPEs and the equatorial Pacific SST

The coupled patterns between the equatorial Pacific SST and precipitation anomalies during the DPEs reveal that for the whole-basin-type DPEs in the two river basins, the associated contemporaneous SST anomaly patterns all confome to CP-type ENSO features (Larkin and Harrison, 2005; Ashok et al., 2007; Figs. 4a, f). On the interdecadal scale, the increase in the contemporaneous CP-type ENSO makes the correlation between the precipitation variances in eastern China and Australia stronger (Ming and Sun, 2019).

If coupled with the SST anomaly that occurred eight months earlier (Figs. 4e, j), the leading SST anomaly patterns associated with the whole-basin-type DPEs in the YRB and MDRB is the EP ENSO (Ashok et al., 2007; Taschetto and England, 2009). In terms of the overall
temporal evolution from eight months in advance to the same month, the equatorial SST anomaly patterns related to the DPEs in the two river basins change from the EP ENSO positive phase to the CP ENSO negative phase as time progresses (Fig. 4). That is, when the EP El Niño event appears and weakens to a CP-type La Niña event about eight months in advance, precipitation extremes may occur in both the YRB and MDRB on an interannual scale.

Since the effect of ENSO on the occurrence of DPEs can be different within an annual cycle, the correlation coefficients among the monthly EMI, NiñoEP, and interannual variation in the sub annually accumulated DPEDs were calculated. The analysis shows that, for the MDRB’s DPEDs sub annually accumulated period ranging from March to December, its correlation coefficients with NiñoEP and EMI reach 0.64 in the preceding December (significant at the 0.01 level) and −0.54 in July of the same year. This indicates that the interannual variations in the DPEs in the two basins are significantly related to the transition from the EP El Niño to the CP La Niña.

3.3 Atmospheric circulation anomaly related to the equatorial Pacific SST and DPE

To investigate the process through which the equatorial SST perturbation affects the variations in the DPEs in the two river basins, correlation analysis between the right field of the dominant mode of the time series from the SVD analysis and the variations in the atmospheric parameters was conducted.

3.3.1 Circulation anomaly in the equatorial area

The perturbations in the low-level air directly correspond to the SST anomaly. As for the mean sea level pressure and the 10-m wind, when whole-basin-type DPEs occur in both the basins, the equatorial low-level air is
significantly disturbed by the SST anomalies. In the western equatorial Pacific Ocean, there is a negative sea level pressure anomaly over the Maritime Continent, and in the eastern Pacific Ocean, there is a positive anomaly. The established east–west dipole pattern results in a westward pressure gradient force. Thus, a significant easterly wind anomaly emerges along the equator in the low-level air (Figs. 6a, b).

It was also found that the distribution patterns of the water vapor related atmospheric element anomalies are also roughly the same for the YRB and MDRB (Figs. 6c, d). When whole-basin-type DPEs frequently occur in the two basins, there is a significant water vapor transport anomaly from east to west in the equatorial region. The water vapor of the total column is abnormally low in the eastern equatorial Pacific and is abnormally high in the western equatorial Pacific Ocean, forming a significant positive water vapor anomaly. In addition, the equator can be seen as the dividing line, since the water vapor is transported towards higher latitude areas in the north and south for the two basins. An anticyclonic water vapor transport belt is formed in the area of the Philippines and South China Sea, and it points toward the YRB. As a result, significant positive water vapor anomalies appear in the YRB, providing favorable water vapor conditions for the frequent occurrence of DPEs (Fig. 6d). The structure of the anticyclone is slightly different from that of the anticyclone in the northwestern Pacific Ocean (Li, 1988; Huang and Wu, 1989; Zhang et al., 1996, 1999), with the former’s scale being slightly smaller and its location farther to the west. Similarly, an anticyclone anomaly was also found in the sea area to the east of Australia, which transports lower latitude water vapor to the MDRB, resulting in more water vapor anomalies in the basin (Fig. 6c).

The analysis of the total cloud cover and vertical velocity of the air movement revealed that the perturbation
pattern of 500-hPa vertical air motion and the total cloud cover are related to the fact that the whole-basin-type DPEs in the two basins are basically the same, i.e., both have east–west dipole distribution patterns. The total cloud cover in the eastern equatorial Pacific is abnormally low (Figs. 6e, f) and the vertical air movement forms a sinking anomaly (Figs. 6g, h), indicating that the convection in this region is weaker than normal. In contrast, the atmospheric upwelling and total cloud cover are abnormally high in the western equatorial Pacific Ocean, indicating that the convective activity is stronger than usual.

The above results reveal that, due to the atmosphere–ocean interaction caused by the east–west dipole SST anomaly pattern, the atmospheric circulation disturbance exhibits a pattern in which the equatorial east Pacific region is a mass source anomaly with a higher pressure, drier air, and weaker convection, while the equatorial western Pacific region is a mass sink anomaly with a lower pressure, wetter air, and stronger convection.

3.3.2 Atmospheric linkage between the river basins and equatorial region

Previous studies have shown that a free Rossby wave train, i.e., the Pacific–Japan (PJ) pattern, can be excited by convective activity near the Philippines (Huang and Li, 1987; Kurihara and Tsuyuki, 1987; Nitta, 1987), which links eastern China with the equatorial area. In this study, wave trains that originate in the tropical area where convection is abnormally intense were also found. The analysis revealed that the abnormal patterns of the 850-hPa vertical velocity (Figs. 7a, d), total column wa-
ter vapor (Figs. 7b, e), and 850-hPa vorticity (Figs. 7c, f) are all in the form of wave trains originating in the equatorial region and moving toward higher latitudes.

Influenced by the wave train’s positive phase, the air flow in the lower layer forms an anticyclonic anomaly in the eastern part of the MDRB. The easterly wave trough (Holland et al., 1987; Hopkins and Holland, 1997) generated by the easterly wind on the northern side of the anticyclone creates a synoptic uplift effect in the basin. In addition, the water vapor from the Tasman Sea on the east side is input into the basin by the easterly wind, which makes the water vapor throughout the entire basin adequate (Fig. 7b). When these anomalous ascents and water vapor conditions are superimposed, the DPEs in the MDRB can be frequent. Similarly, on the southern and northern flanks of the YRB, the anomalous wave train, which originates in the western equatorial Pacific, is in the positive phase, while in the YRB, it is in the negative phase. The strong anticyclone circulation in the positive phase region on the southern side of the basin continuously transports water vapor into the YRB, causing the water vapor to be abnormally high throughout the entire basin (Fig. 7c). In addition, accompanied by the input of cold air from another anticyclone on the north side of the YRB (Figs. 7d–f), which is also a part of the wave train, the enhanced ascents and water vapor conditions superimpose and result in frequent occurrence of DPEs. However, it should be noted that the position of this wave train is different from that of the classical PJ wave train (Huang and Li, 1987; Kurihara and Tsuyuki, 1987; Nitta, 1987), which is more west and south than the PJ wave train and links the convection anomalies over the western equatorial Pacific with the YRB and MDRB.

Therefore, through the wave trains, which originated in the stronger convection anomaly area, the water vapor and ascent conditions over the YRB and MDRB are linked to the atmospheric perturbations in the tropical western Pacific region, and subsequently, they are linked to the variation in the ENSO.

4. Discussion and conclusions

Floods cause losses at the level of tens of billions of dollars and thousands of casualties around the world every year. Studies of the spatial–temporal distribution of precipitation extremes, which is an important factor driving flood hazards and the mechanism behind them, are of
Fig. 6. Correlation coefficients of the SVD1’s SST time series with the (a, b) standardized mean sea level pressure (shading; hPa) and 10-m wind (vector; m s$^{-1}$), (c, d) total column water vapor (shading; mm) and vertical integral water vapor flux (vector; kg m$^{-1}$s$^{-1}$), (e, f) total cloud cover (shading; %), and (g, h) 500-hPa vertical velocity (shading; Pa) for the (a, c, e, g) MDRB and (b, d, f, h) YRB. The range within the green dashed line represents the 0.05 significance level, and the vectors all pass the 0.1 significance test. The blue and yellow areas indicate negative and positive anomalies, respectively.
great significance for disaster prevention and mitigation. The YRB and MDRB are the largest basins in China and Australia, respectively. Although they are in the Northern and Southern Hemispheres and in completely different climate zones, previous studies have suggested that the climates over the Asian and Australian monsoon regions have a close relationship (e.g., Gregory, 1991; Joseph et al., 1991; Meehl, 1997; Wu, 2008; Zhu, 2012; He, 2015). In this study, it was found that the spatial–temporal variation of DPEs in the two basins are significantly correlated. Spatially, the whole-basin-type DPEs account for the highest proportion of extremes in the both the YRB and MDRB, accounting for 43.9% and 68.8%, respectively. Temporally, the 3-yr running correlation coefficient between the interannual variations of the DPEDs in the two basins is nearly 0.7 (significant at the 0.01 level), which means that there is a significant possibility of flood concurrence on the interannual scale. As the hinterlands of the most important industrial and agricultural economic production in China and Australia, the simultaneous outbreak of floods in these two regions have huge impacts on the regional economies and sus-

Fig. 7. Correlation coefficients of the SVD1’s SST time series with the (a, d) standardized 850-hPa vertical velocity (shading; Pa), (b, e) total column water vapor (shading; mm), (c, f) 850-hPa relative vorticity (shading; \(10^{-5}\text{ s}^{-1}\)), and (a–f) 850-hPa wind (vector; m s\(^{-1}\)) for the (a–c) MDRB and (d–f) YRB. The range within the green dashed line corresponds to the 0.05 significance level, and the vectors all pass the 0.1 significance test. The blue and red ellipses indicate the negative and positive phase ranges of the wave train, respectively. The blue areas indicate negative 850-hPa vertical velocity, total column water vapor, and 850-hPa relative vorticity anomalies, while the yellow areas indicate positive anomalies.
tainable development.

By analyzing the coupled patterns between the precipitation anomalies of the DPEs and the corresponding SST anomalies in the equatorial Pacific Ocean, it was found that the whole-basin-type DPEs of both the YRB and MDRB are closely coupled when in the preceding winter, the EP-type El Niño fades to a CP-type La Niña, indicating that the DPEs in the YRB and the MDRB may synchronously occur more frequently when the above process occurs. Moreover, analysis of the SST anomaly related to atmospheric disturbances revealed that, due to the atmosphere–ocean interactions caused by the east–west dipole SST anomaly pattern, the atmospheric circulation disturbance shows a pattern that the equatorial eastern Pacific region acts as a mass source anomaly with a higher pressure, drier air, and weaker convection, while the equatorial western Pacific region acts as a mass sink anomaly with a lower pressure, wetter air, and stronger convection. The pressure disturbance induced by the atmosphere–ocean interactions in the low-level air is greater in the eastern equatorial Pacific Ocean and is lower in the western equatorial Pacific Ocean, resulting in the emergence of an easterly wind anomaly along the equator, the enhancement of water vapor transport toward the west along the equatorial region, and strengthening the convective activity in the western Pacific Ocean. Thus, the two abnormal wave trains in the low-level air originate in the tropical western Pacific region with anomalously stronger convective activity, and they extend towards the YRB and MDRB. Compared with the classical PJ wave train (Huang and Li, 1987; Kurihara and Tsusuyki, 1987; Nitta, 1987), the wave trains found in this study are farther to the west and south. As a result, the equatorial ocean region is linked to the two basins. Under the influence of the interphase anomalous ascents and water vapor transport disturbances of the wave trains, favorable precipitation conditions are superimposed over the YRB and MDRB, which may lead to the occurrence of synchronous precipitation extremes on an interannual scale.

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