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# Characteristics of dry-wet abrupt alternation events in the middle and lower reaches of the Yangtze River Basin and the relationship with ENSO

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**Abstract:** During recent decades, more frequent flood-drought alternations have been seen in China as a result of global climate change and intensive human activities, which have significant implications on water and food security. To better identify the characteristics of flood-drought alternations, we proposed a modified dry-wet abrupt alternation index (DWAAI) and applied the new method in the middle and lower reaches of the Yangtze River Basin (YRB-ML) to analyze the long-term spatio-temporal characteristics of dry-wet abrupt alternation (DWAA) events based on the daily precipitation observations at 75 rainfall stations in summer from 1960 to 2015. We found that the DWAA events have been spreading in the study area with higher frequency and intensity since 1960. In particular, the DWAA events mainly occurred in May and June in the northwest of the YRB-ML, including Hanjiang River Basin, the middle reaches of the YRB, north of Dongting Lake and northwest of Poyang Lake. In addition, we also analyzed the impact of El Niño Southern Oscillation (ENSO) on DWAA events in the YRB-ML. The results showed that around 41.04% of DWAA events occurred during the declining stages of La Niña or within the subsequent 8 months after La Niña, which implies that La Niña events could be predictive signals of DWAA events. Besides, significant negative correlations have been found between the modified DWAAI values of all the rainfall stations and the sea surface temperature anomalies in the Nino3.4 region within the 6 months prior to the DWAA events, particularly for the Poyang Lake watershed and the middle reaches

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of the YRB. This study has significant implications on the flood and drought control and water resources management in the YRB-ML under the challenge of future climate change.

**Keywords: dry-wet abrupt alternation; the middle and lower reaches of the Yangtze River Basin; spatio-temporal characteristics; La Niña**

## 1 Introduction

Global climate change and excessive human activities have induced more intense and frequent summer drought and flood anomalies throughout the world during past decades (Dai *et al*., 1998; Frich *et al*., 2002; May, 2004; Djebou *et al*., 2014; Li *et al*., 2015; Song *et al*., 2016). In particular, the alternations between wet spells and dry spells over a short period of time, namely dry-wet abrupt alternation (DWAA) events have frequently occurred in China since the 1990s, especially in the middle and lower reaches of the Yangtze River Basin (YRB-ML) as well as in the south and southwest of China (Wang *et al*., 2009; Feng *et al*., 2012; She *et al*., 2013; He and Lu, 2014; He *et al*., 2016). As a new feature and trend of summer drought/flood anomalies, the DWAA events have significant impact on the water and food security in China, for example, the grain yields of those croplands with less tolerance to flood and drought will be largely decreased (Dickin and Wright, 2008; Yu *et al*., 2012; Akhtar and Nazir, 2013). In order to solve the environmental problems induced by drought/flood anomalies, numerous researches have been done to identify the long-term characteristics of precipitation and to analyze the relationship between precipitation anomalies and large-scale ocean-atmospheric features (Wu *et al*., 2006a; Tang *et al*., 2007; Sun *et al*., 2012; Turner and Annamalai, 2012; Agnese *et al*., 2013; Gitau *et al*., 2013; Luo *et al*., 2013; Yang *et al*., 2013; Langousis and Kaleris, 2014; Huang, 2015). Specifically, for the YRB-ML region, the summer drought and flood events are found to have an increasing trend and are usually accompanied by high Southern Hemisphere annual mode, anomalously intraseasonal oscillation of West Pacific subtropical high, cross-equatorial wind anomalies, cyclones over East Asia, Asia Polar Vortex, Asia Meridional Circulation, as well as sea surface temperature anomalies due to El Niño (Wu *et al*., 2006b; Yang *et al*., 2013; Ji and Shan, 2015). As a result of the large-scale climate impact, the increasing frequency and intensity of extreme flood/drought events could lead to more DWAA events (Tang *et al*., 2007).

To better identify and quantify DWAA events, numerous quantification methods have been proposed. Wu *et al*. (2006b) defined a long-cycle drought-flood abrupt alternation index (LDFAI) by considering the differences between May-June and July-August precipitation and analyzed the correlation between the DWAA events in the YRB-ML and large-scale atmospheric circulation anomalies. Zhang *et al*. (2008) analyzed the characteristics of DWAA events of a city in the YRB-ML by calculating the percentages of anomalous ten-day precipitation events. The limitations of these methods include coarse time scale (seasonal or ten-day), fixed drought-flood alternation time point and lack of consideration of drought-flood alternation duration, which could lead to inaccurate identification of DWAA events. To overcome these limitations, in this paper we modified the LDFAI proposed by Wu *et al*. (2006b) and proposed a new daily-scale dry-wet abrupt alternation index (DWAAI) by considering prior and posterior dry/wet conditions as well as drought-flood alternation duration to better study the spatio-temporal characteristics of DWAA events in the YRB-ML.

In addition, we also studied the impact of large-scale climatic dynamics, specifically the El Niño Southern Oscillation (ENSO) on DWAA events in the YRB-ML. The ENSO is one of the strongest interannual variability signals in the coupled global ocean-atmosphere system and has significant impact on sea surface temperature (SST). Previous researchers mainly focused on the impact of ENSO on summer precipitation patterns and found that warmer winter SST of equatorial eastern Pacific Ocean, warmer summer SST of equatorial Indian Ocean, SST anomalies of East Australian Current and South China Sea as well as West Pacific warm pool can lead to abnormal increase of summer precipitation in the YRB-ML (Luo *et al*., 1985; Sun and Ma, 2003; Gong and He, 2006; Hartmann *et al*., 2008; Liu *et al*., 2008; Li *et al*., 2009; Li, 2013; Dong, 2016). Recent years have seen a few researchers' attempts on analyzing the impact of ENSO on DWAA events (Li *et al*., 2014; Ma *et al*., 2014; Wang *et al*., 2014). For example, Feng *et al*. (2012) found that a DWAA event in the YRB-ML in the early summer of 2011 mainly owed to the La Niña event from July 2010 to April 2011 and the corresponding anomalously cold SST in the Indian Ocean. Li *et al*. (2013) found that the persistent dry condition before a DWAA event in spring 2011 are induced by the eastward deflection of cold stream and subtropical high in the Northwestern Pacific Ocean as a result of the La Niña event in January-May, 2011, while the subsequent wet conditions after the DWAA event owed to the enhanced decay of La Niña in June by the increased sensible heat flux over the Tibetan Plateau. However, these studies are limited to a single DWAA event without a comprehensive statistical analysis on long-term historical DWAA events.

In this study, we will analyze the spatio-temporal characteristics of long-term historical DWAA events in the YRB-ML during the summer monsoon period (May-August) from 1960 to 2015 and assess the impact of ENSO on DWAA events on a long-term basis. The precipitation data in the study area (YRB-ML) and the methodology of new daily-scale DWAAI method are described in section 2, followed by the validation of the new DWAAI method in section 3. The spatio-temporal characteristics of DWAA events, the spatial distribution of Pacific SST anomalies and the statistics of El Niño/La Niña prior to DWAA events as well as the correlation between DWAAI and SST anomalies in the Nino3.4 region are discussed in section 4 and 5. The results of this study could give some important clues for the prediction of DWAA events in the YRB-ML in the future and provide significant guidance for drought and flood control and management in the YRB-ML.

## 2 Data and methods

### 2.1 Data

The middle and lower reaches of the Yangtze River Basin (YRB-ML) (106°54′–124°25′E, 24°30′–35°45′N) is located in the East Asian monsoon region with a drainage area of 800,000 km$^2$. Strongly influenced by the monsoon features, the YRB-ML has significant nonuniform seasonal precipitation distribution patterns, as more than 50% of the annual precipitation comes from the monsoon season (May-August) every year. The climatic conditions in this area can easily lead to DWAA events, which means the time period with a precedent dry spell due to rainfall shortage in spring and a subsequent wet spell induced by summer monsoons and enhanced warm-cold air mixing in summer. Therefore, the YRB-ML has suffered some of the most severe DWAA disasters in China (Shen *et al*., 2012). However, the spatial distribution of DWAA events in the YRB-ML has substantial variations because of the wide geographic scope (Shan *et al*., 2015). If the characteristics of DWAA events in the YRB-ML are analyzed based on average precipitation of the whole basin, the spatial heterogenous signals of the DWAA events may be smoothed out. To overcome this limitation, the YRB-ML was divided into six sub-basins as the secondary partitions in this article, including the Hanjiang River watershed, the middle reaches of the Yangtze River, Dongting Lake watershed, Poyang Lake watershed, the lower reaches of the Yangtze River and the delta plains (Cheng *et al*., 2012). The location of the YRB-ML is shown in Figure 1. The daily precipitation dataset of 75 representative meteorological stations from 1960–2015 were obtained from the National Meteorological Information Center of China. Moreover, corresponding monthly SST data were generated from the National Oceanic and Atmospheric Administration (NOAA) – Extended Reconstructed Sea Surface Temperature (ERSST) dataset with 2°×2° latitude-longitude resolution.

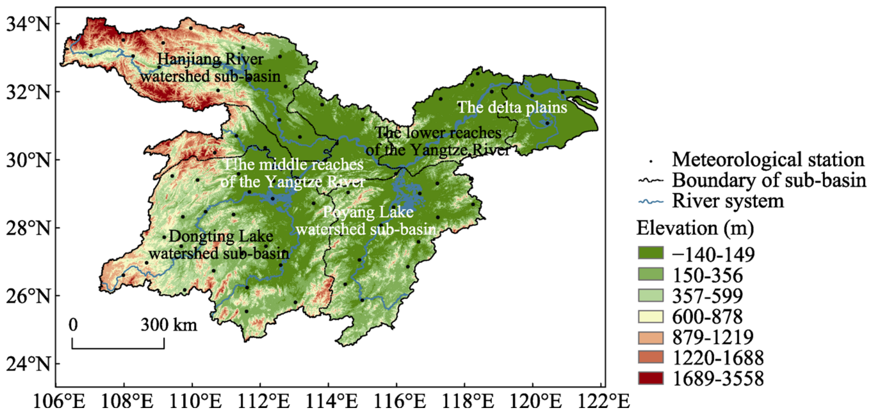



**Figure 1** The location of the middle and lower reaches of the Yangtze River Basin in China. The black dots denote the meteorological stations. Boundaries of sub-basins (black lines) and first-order streams in the basin (in blue) are shown.

## 2.2 Methodology

To describe the DWAA phenomena quantitatively and qualitatively, a long-cycle drought-flood abrupt alternation index (LDFAI) was defined by Wu *et al*. (2006b) as follows:

$$LDFAI = (R_{78} - R_{56}) \cdot (|R_{56}| + |R_{78}|) \cdot 1.8^{-|R_{56}+R_{78}|} \quad (1)$$

where $R_{56}$ and $R_{78}$ refer to the normalized May-June and July-August precipitation, respectively. ($R_{78}$–$R_{56}$) represents the DWAA intensity term, ($|R_{56}|$+$|R_{78}|$) represents the dry-wet intensity, and $1.8^{-|R_{56}+R_{78}|}$ is the weighting coefficient, which enhances the weights of DWAA events and reduces the weights of persistent dry-wet phenomena.

The long-cycle droughts-floods abrupt alternation index (LDFAI) is the first index used to identify DWAA events, and can be easily calculated without artificial selection. Therefore, the definition of the LDFAI establishes the foundation for analyzing the characteristics and physical mechanisms of DWAA events. However, there are some limitations about this index. Firstly, the magnitude of the LDFAI was defined within 4 months, including 2 months for the dry spell and 2 months for the wet spell. Therefore, the turning point from the dry spell to the wet spell was fixed at the end of June or the beginning of July. However, DWAA events may occur at any time, and if the event occurred during the period from May to June, the antecedent precipitation could be considered as normal due to the average effect of the precipitation in the dry spell and wet spell, which would inevitably lead to the omission of some DWAA events. Secondly, the LDFAI only reflected the difference between mean precipitation in the two stages without explicitly considering the alternation duration from a dry spell to a wet spell, therefore cannot differentiate the two DWAA events from identical mean precipitation values during dry-wet spells but with different temporal distributions of precipitation in each spell.

To overcome these limitations of the LDFAI method, we modified the original LDFAI and proposed a new DWAAI as follows:

$$DWAAI = \left[ K + \left( SPA_{post} - SPA_{pre} \right) \cdot (| SPA_{post} | + | SPA_{pre} |) \right] \cdot \alpha^{-|SPA_{pre} + SPA_{post}|} \tag{2}$$

$$K = \sum_{i=1}^{n} \left( \frac{SAPI_i - SAPI_0}{i} \right) \tag{3}$$

where $SPA_{pre}$ and $SPA_{post}$ refer to the standardized precipitation anomalies (SPAs) of the pre-phase and post-phase of an event, respectively; $SAPI_i$ and $SAPI_0$ represent the standardized antecedent precipitation index anomalies of the $i$th day in the post-phase and the last day in the pre-phase, respectively. In particular, standardized antecedent precipitation index anomalies are calculated by standardizing the antecedent precipitation index (McQuigg, 1954). $n$ is the number of days prior to a precipitation event. A DWAA event in this paper is regarded as only an event that rapidly alternates from dry to wet, i.e., with a precedent dry spell and a subsequent wet spell. As the response times of dry-wet events are different, the durations of dry and wet spells should be considered independently. Lu (2009) noted that the antecedent and current precipitation contributed to the extents of floods and droughts, while the contribution from the antecedent precipitation decayed exponentially with time, and the influence of precipitation would decline to 1‰ after 44 days. Therefore, a dry spell is considered to be 44 days in this study. In addition, a wet spell is defined as 10 days. In brief, the duration of a DWAA event is the time period from 44 days before the abrupt alternation date to 10 days after that date.

In Equation (2), the term $K \cdot \alpha^{-|SPA_{pre} + SPA_{post}|}$ is defined as the "urgency" degree, the term $(SPA_{post} - SPA_{pre}) \cdot (| SPA_{post} | + | SPA_{pre} |) \cdot \alpha^{-|SPA_{pre} + SPA_{post}|}$ is defined as the "alternation" degree from dry spell to wet spell, where $\alpha^{-|SPA_{pre} + SPA_{post}|}$ is the weighting coefficient.

To better understand the physical meaning of parameter $a$, the "alternation" degrees of DWAA events with different SPAs before and after DWAA events were analyzed (see Table 1). We selected 8 events for comparison, including 6 DWAA events (No.1–6) with different intensities and 2 non-DWAA events, i.e. a complete drought event (No.7) and a complete flood event (No. 8). The known order of the "alternation" degree of No.1–6 is as follows: No.3> No.2> No.1, No.6> No.5> No.4, No.1–6 > No.7–8. From Table 1, we can see that when parameter $a$ is less than 1, the "alternation" degree of No.8 will be greater than that of No.1; when parameter $a$ is larger than 1.4, the "alternation" degree of No.6 will be smaller than that of No.5. Both cases are unreasonable based on the known conditions of the orders. Therefore, we consider the range from 1.0 to 1.4 as the reasonable domain for parameter $a$, in particular, we set the value of parameter $a$ in this article as 1.3.

**Table 1** The "transition" degree of events that alter from dry to wet according to different values of parameter *a*

| No. | SPA | | "Transition" degree | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Pre-phase | Post-phase | $a$=0.8 | $a$=1.0 | $a$=1.2 | $a$=1.3 | $a$=1.4 | $a$=1.6 | $a$=1.8 | $a$=2.0 | $a$=2.5 | $a$=3.0 |
| 1 | –1 | 1 | 4.00 | 4.00 | 4.00 | 4.00 | 4.00 | 4.00 | 4.00 | 4.00 | 4.00 | 4.00 |
| 2 | –1 | 2 | 11.25 | 9.00 | 7.50 | 6.92 | 6.43 | 5.63 | 5.00 | 4.50 | 3.60 | 3.00 |
| 3 | –1 | 3 | 25.00 | 16.00 | 11.11 | 9.47 | 8.16 | 6.25 | 4.94 | 4.00 | 2.56 | 1.78 |
| 4 | –2 | 1 | 11.25 | 9.00 | 7.50 | 6.92 | 6.43 | 5.63 | 5.00 | 4.50 | 3.60 | 3.00 |
| 5 | –2 | 2 | 16.00 | 16.00 | 16.00 | 16.00 | 16.00 | 16.00 | 16.00 | 16.00 | 16.00 | 16.00 |
| 6 | –2 | 3 | 31.25 | 25.00 | 20.83 | 19.23 | 17.86 | 15.63 | 13.89 | 12.50 | 10.00 | 8.33 |
| 7 | –2 | –3 | –15.26 | –5.00 | –2.01 | –1.35 | –0.93 | –0.48 | –0.26 | –0.16 | –0.05 | –0.02 |
| 8 | 2 | 3 | 15.26 | 5.00 | 2.01 | 1.35 | 0.93 | 0.48 | 0.26 | 0.16 | 0.05 | 0.02 |

## 3 Validation of the DWAAI method

In this section, we selected Wuhan station as test case to compare the LDFAI and DWAAI from 1960–2015 and discuss whether the modified DWAAI can better identify the occurrence of DWAA events in the YRB-ML. For each year, we selected the day with maximum DWAAI between May and August as the most "urgent" day or the most severe abrupt alternation day, and selected the period from 44 days before the "urgent" day and 10 days after the "urgent" day as the most severe DWAA event. The topmost 10 severe DWAA events in 10 different years with the maximum DWAAI or LDFAI are listed in Table 2, along with the distribution of SPA in the dry/wet periods shown in Table 3. Among the identified 10 severe

**Table 2** Years and comparison of normalized precipitation values for the 10 highest LDFAI values

| Year | LDFAI | May-June | July-August | Year | LDFAI | May-June | July-August |
|---|---|---|---|---|---|---|---|
| 1963 | 5.06 | –2.31 | 1.00 | 2010 | 1.74 | –0.56 | 0.91 |
| 1969 | 3.77 | –0.75 | 2.43 | 2006 | 1.45 | –1.11 | 0.38 |
| 1998 | 2.77 | –0.57 | 1.83 | 2003 | 1.26 | –0.54 | 0.61 |
| 1994 | 2.33 | –1.88 | 0.45 | 1962 | 1.18 | 0.00 | 1.91 |
| 1997 | 1.85 | –1.86 | 0.30 | 1991 | 0.93 | 0.40 | 1.99 |

**Table 3** Years and comparison of SPA values for the 10 highest DWAAI values

| Year | Abrupt alternation date | Pre-phase SPA | Post-phase SPA | "Urgency" degree | "Alternation" degree | DWAAI |
|---|---|---|---|---|---|---|
| 2000 | May 24 | –1.93 | 2.21 | 6.69 | 15.99 | 22.68 |
| 1988 | May 6 | –1.79 | 3.19 | 4.99 | 17.19 | 22.18 |
| 2008 | May 3 | –1.50 | 3.61 | 5.75 | 15.02 | 20.77 |
| 2011 | June 10 | –1.66 | 4.96 | 1.74 | 18.41 | 20.15 |
| 1961 | June 7 | –1.29 | 3.49 | 5.33 | 12.82 | 18.15 |
| 2007 | May 24 | –1.64 | 2.88 | 2.60 | 14.70 | 17.30 |
| 1984 | June 7 | –1.49 | 2.69 | 2.97 | 12.73 | 15.70 |
| 1982 | June 19 | –0.76 | 3.76 | 4.74 | 9.29 | 14.03 |
| 1998 | July 17 | –0.78 | 5.81 | 1.77 | 11.60 | 13.37 |
| 1994 | July 12 | –1.26 | 2.22 | 3.90 | 9.39 | 13.29 |

years with the 10 highest LDFAI and DWAAI values, only two years (i.e. 1994 and 1998) coincide with each other. However, other DWAA events like the severe DWAA event in June 2011 can only be identified by DWAAI method. This is mainly because the DWAAI method is more flexible in the selection of dry-wet alternation point while the LDFAI method has fixed alternation point between period 1 (May-June) and period 2 (July-August). Specifically, the alternation time points identified by DWAAI method occasionally fall in the fixed time period between May-June and July-August of LDFAI method for the years 1994 and 1998, while fall out of the fixed time period of LDFAI method for other years.

From Table 3, we can see that the pre-phase SPA values are less than –1 for 8 high-DWAAI years, among which 5 years have SPA values less than –0.5, which indicates median and severe drought conditions (dry spells). The post-phase SPA values are greater than 2 for all the 10 years, among which 5 years have SPA values larger than 3, which indicates median and severe flood conditions (wet spells). It can also be seen from Table 3 that the high DWAAI values corresponding to high absolute SPA values capture the occurrence of DWAA events with high accuracy. To better clarify the physical meaning of DWAAI, the precipitation processes of events with high DWAAI values are shown in Figure 2, from which significant differences can be seen during and between dry spells and wet spells. For example, by comparing the precipitation process in Figures 2a and Figure 2c, the precipitation difference between wet spell and dry spell in 2011 was 54.1% higher than that in 1984, indicating that the DWAA event in 2011 was more severe than that in 1984. The same conclusion can be made by comparing the DWAAI vales of the two years since the DWAAI in

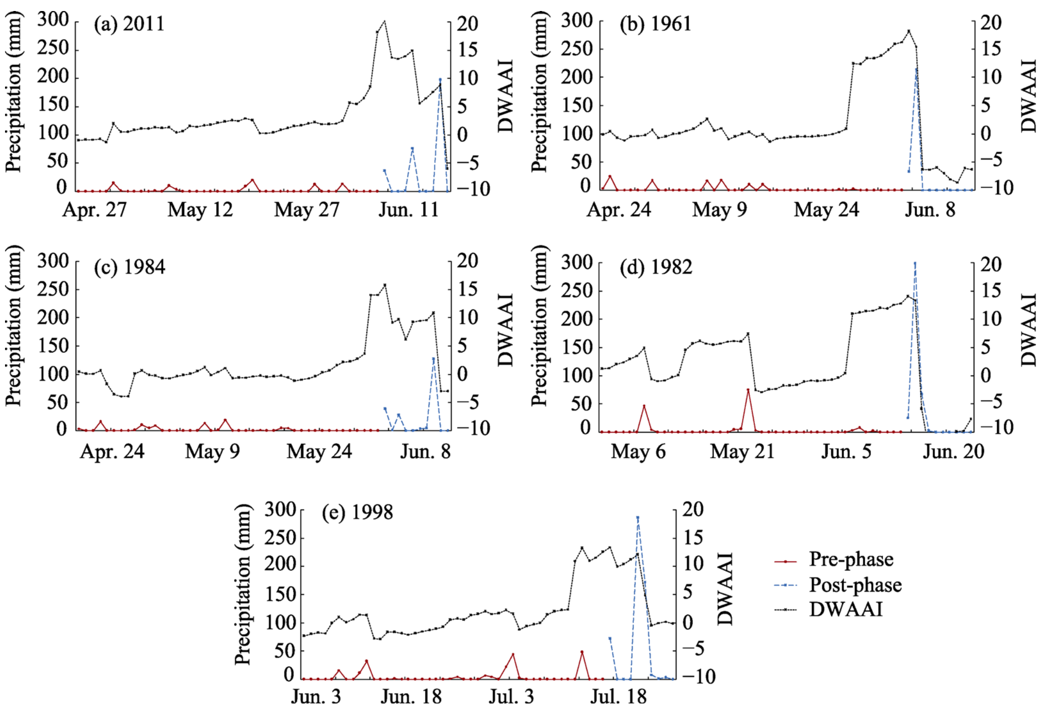



**Figure 2** Precipitation and DWAAI sequences of DWAA events in the high DWAAI years (i.e., (a) 2011, (b) 1961, (c) 1984, (d) 1982 and (e) 1998). Red lines and blue dashed lines represent the precipitation during periods of the pre-phase and post-phase, respectively. Black dotted lines represent the calculated DWAAI values during the whole event.

2011 (20.15) is higher than the DWAAI in 1984 (15.70). This proves that the DWAAI can reasonably represent the intensity of DWAA event, i.e., the “alternation” degree from a dry spell to a wet spell. In addition, by comparing the precipitation process in Figures 2b and 2c, we can see that the transition durations between dry spell and wet spell are similar for both year 1961 and year 1984, meaning similar “alternation” degrees of the DWAA events. However, since the first 5-day average of precipitation amount during the wet spell in 1961 is 35.66 mm greater than that in 1984, the DWAA event in 1961 is considered as more urgent and serious. This phenomenon is also reflected in the DWAAI values since the DWAAI value in 1961 (18.15) is greater than the value in 1984 (15.70).

On the other hand, the “alternation” degree of the DWAA event in 1982 (Figure 2d) is considered low since the difference between the daily mean precipitation of the dry spell (3.72 mm) and the precipitation at the beginning of the wet spell (26.2 mm) is small. Besides, the “urgency” degree of the DWAA event in 1998 (Figure 2e) is considered low since the precipitation amount in the initial stage of wet spell is low with only 72.3 mm at the first day and 0 mm for the following 3 days. The low “alternation” degree and low “urgency” degree of the DWAA event in 1982 and 1998 respectively can also be reflected by the low values of DWAAI of both events (14.03 for the year 1982 and 13.37 for the year 1998).

All the above examples about DWAA events show that the DWAAI is an effective index to represent both the “alternation” degree and the “urgency” degree of DWAA events. Specifically, the events with DWAAI values over 15 are defined as DWAA events, and the larger the DWAAI, the more serious the DWAA event. Events with the DWAAI values between 20 and 23 are defined as moderate DWAA events, while those under 20 and over 23 are defined as mild and severe DWAA events, respectively. Moderate and severe DWAA events with DWAAI larger than 20 are considered as high-intensity DWAA events.

To validate the effectiveness of the modified DWAAI method, we identified all the DWAA events for six representative rainfall stations in six sub-basins of YRB-ML based on both the LDFAI values and DWAAI values (Table 4). It was found that only a few events occurred at the end of June or early July were selected by both indices. On the other hand, 76.47% DWAA events that occurred in May and June can only be identified by DWAAI method. In particular, for a known severe DWAA event recorded in most of the YRB-ML during spring to early summer in 2011, the DWAAI method identified DWAA events at 28 stations within the basin, which were concentrated in the southeast of Hubei Province, central-north Hunan Province and central-north Jiangxi Province, which are identical to the actual conditions. However, during this 2011 DWAA event, only 5 stations located in the northwest of the Hanjiang River basin and the delta plains were identified by the LDFAI, which does not conform to the real case. In addition, many DWAA events identified by the LDFAI are not realistic. Two typical examples of wrong identification by the LDFAI include the 1963 event at Tianmen station and the 1993 event at Shimen station. For the Tianmen station, the average precipitation values of dry and wet spells were 2.23 mm and 6.30 mm respectively on the selected “alternation” date, i.e., July 30, 1963 event. For the Shimen station, the average precipitation values of the dry and wet spells were 4.90 mm and 21.66 mm, respectively for the July 30 of 1993 event. However, in reality, both events cannot be regarded as DWAA events since the difference of mean precipitation between dry spell and wet spell is relatively small with less precipitation in the wet spell and more precipitation in the dry spell. From the above test cases, we can see that the DWAAI method can identify the DWAA events in the YRB-ML region with more accuracy in the occurrence time as well as "alternation" and "urgency" degrees than the LDFAI method.

**Table 4** Comparison of DWAA events selected by the LDFAI and DWAAI

| Stations | Sub-basins | DWAA events selected by LDFAI | DWAA events (abrupt alternation date) selected by DWAAI |
|---|---|---|---|
| Tianmen | Hanjiang River watershed sub-basin | 1963, **1968** | 1961 (June 8), **1968 (July 14)**, 1969 (June 9), 1982 (May 12). 1997 (June 6), 2000 (May 24) |
| Jingzhou | The middle reaches of the Yangtze River | **1968**, **1991**, 2007 | **1968 (July 13)**, 1981 (May 27), **1991 (July 1)**, 2000 (May 24), 2011 (June 13) |
| Shimen | Dongting Lake watershed sub-basin | **1991**, 1993, 2007, 2008, 2014 | 1982 (May 26), 1986(June 4), 1988 (May 5), **1991 (July 1)**, 1996 (May 31), 2006 (May 5), 2011 (June 10) |
| Zhangshu | Poyang Lake watershed sub-basin | _ | 1982 (June 14), 1985 (June 4), 1988 (May 9), 2011 (June 3) |
| Huang-shan | The lower reaches of the Yangtze River | 1965, 1987, 1997, **2009** | 1992 (August 26), 1994 (June 8), 1996 (June 3), 2000 (May 25), 2008 (June 8), **2009 (July 24)**, 2011 (June 4) |
| Nantong | Delta plains | 1965, 1980, 1982, 1987, 1997, **2003**, 2006, 2007, **2010**, 2014 | 1971 (May 17), 1974 (May 4), 1981 (June 24), **2003 (June 29)**, **2010 (July 3)** |

Boldface and underlined font indicate that the events that occurred in the same year were identified by both indices

# 4 Spatio-temporal characteristics of DWAA events in the YRB-ML

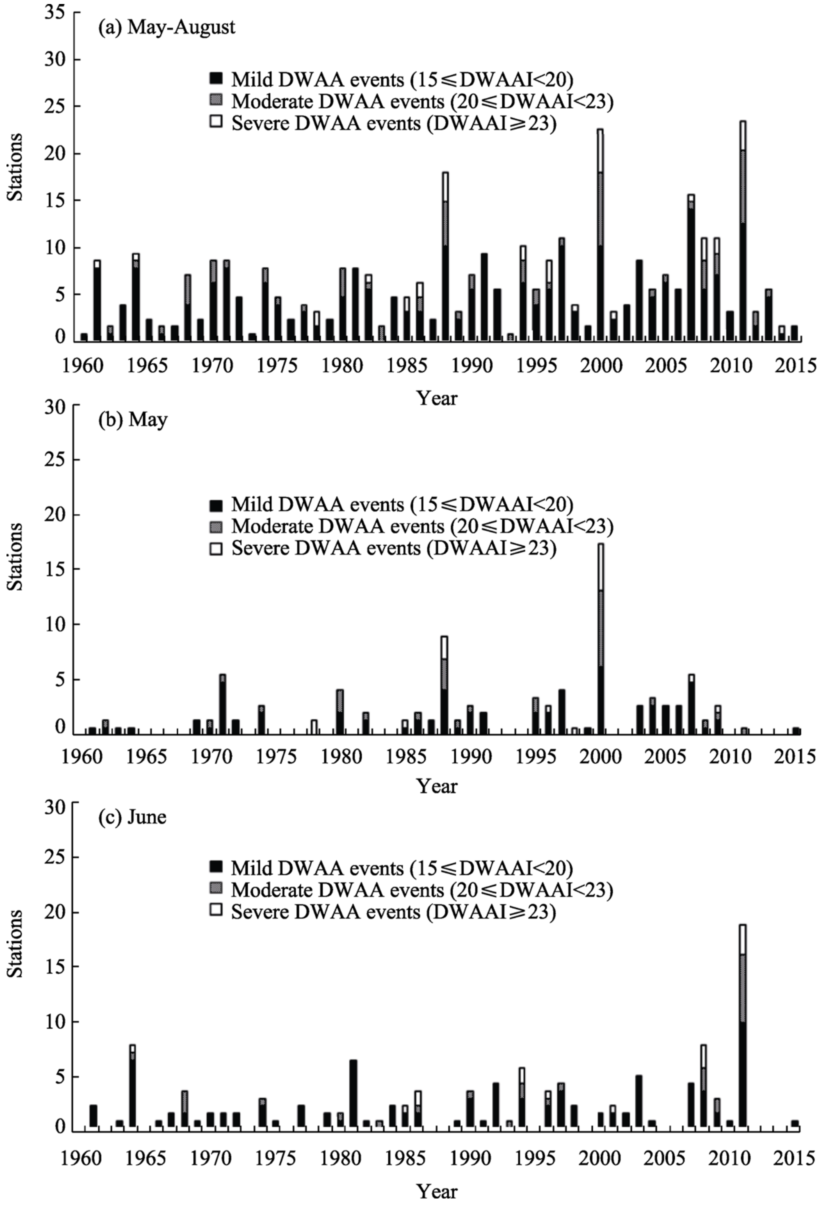
## 4.1 Temporal evolution characteristics of DWAA events

Based on the daily precipitation data at 75 rainfall stations from 1960 to 2015 in the YRB-ML, the characteristics of the temporal distribution of DWAA events during summer were analyzed by calculating the DWAAI. The statistics of the stations where different levels of events occurred in each year of the basin are shown in Figure 3. It can be seen that DWAA events occurred throughout the years in the YRB-ML with significant interannual differences between different rainfall stations, especially after the year 1986 (Figure 3a). Generally, the DWAA events are increasing in the YRB-ML with enhanced frequency and intensity since 1986, especially for moderate and severe DWAA events. The 3 most severe years after 1986 were 1988, 2000 and 2011 when there were relatively more stations with DWAA events. In addition, the mean DWAAI values of these 3 years were greater than 19, and the stations with high-intensity events accounted for 43.48%, 55.17% and 44.83% of the total stations with DWAA events in 1988, 2000 and 2011, respectively, which indicates that these years had higher incidences of high-intensity DWAA events.

In particular, during the summer monsoon season (May-August), most of the DWAA events with enhanced frequency and intensity occurred in May and June, which accounted for 31.29% and 37.41% of the total events, respectively (Figures 3b and 3c). The number of stations with DWAA events in May and June exhibited a comparatively large interannual difference, especially during 1988–2015. On the other hand, there were fewer stations with DWAA events in July and August than in May and June. Moreover, the DWAA events in July (Figure 3d) features non-significant interannaual change of station numbers and decreased intensity throughout the years, while a significant increasing trend of enhanced DWAA events has been found in August (Figure 3e).

## 4.2 Spatial distribution characteristics of DWAA events

The spatial distribution and interdecadal variability of the frequency of DWAA events in the YRB-ML are shown in Figure 4. DWAA events tend to occur more frequently in the Hanjiang River Basin, the middle reaches of the Yangtze River, the north region of the Dongting Lake watershed and the northwest region of the Poyang Lake watershed (Figure 4a). Among these events, the high-intensity DWAA events are concentrated in the central region of the Hanjiang River watershed sub-basin and the middle reaches of the Yangtze River with



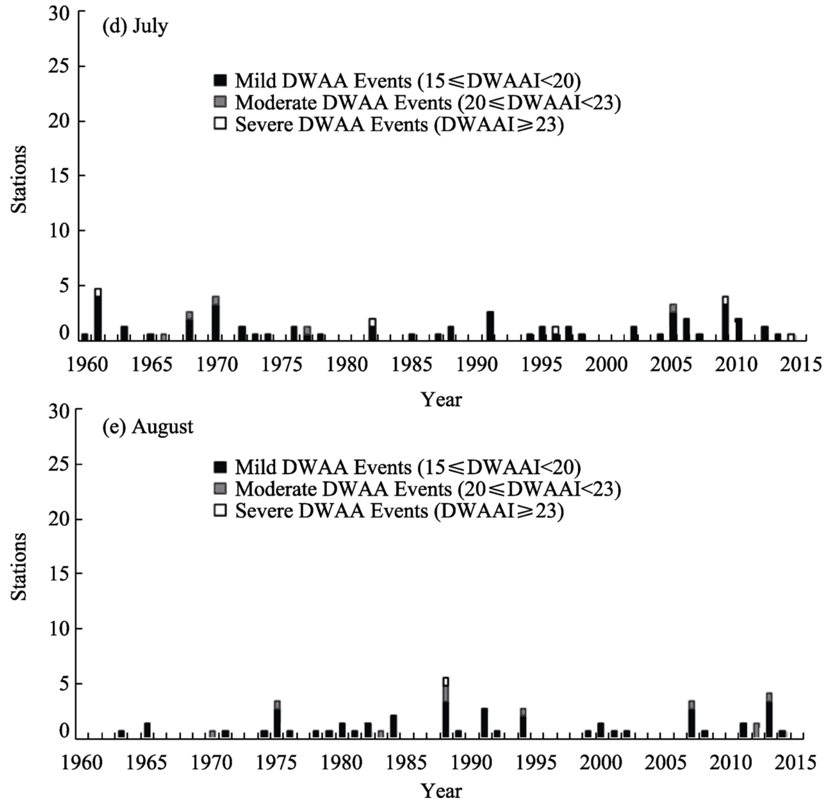



**Figure 3** Statistics of stations where summer DWAA events occurred in the YRB-ML. White, reticular and black rectangles represent the number of stations with severe, moderate and mild DWAA events, respectively

high frequency of once per six years, while the low-intensity DWAA events usually occurred in the southern part of the Dongting Lake watershed sub-basin, the southern part of the Poyang Lake watershed sub-basin and the delta plains with low frequency of once per 12 years.

Figures 4b–4g show the spatial distribution of summer DWAA events in the 1960s, 1970s, 1980s, 1990s, 2000s and 2010s respectively. Based on the comparison of these figures, the main characteristics of each decade can be summarized as follows. In the 1960s and the 1970s, there are less DWAA events with low intensities. Specifically, DWAA events mainly occurred in the middle reaches of the Yangtze River and northern region of the basin in the 1960s and occurred in the Hanjiang River watershed sub-basin and the southeast of the Dongting Lake watershed sub-basin in the 1970s. In the 1980s, DWAA events occurred throughout the northwest of the YRB-ML with higher frequencies and intensities, especially for the middle reaches of the Hanjiang River Basin, the northwest of Dongting Lake watershed and the middle reaches of the Yangtze River. In the 1990s, the DWAA events have lower frequencies and intensities with shifted coverage mainly in the middle reaches of the Hanjiang River Basin, the west of the Dongting Lake watershed, the northeast of Poyang Lake watershed and the lower reaches of the Yangtze River. In the 2000s, DWAA events occurred throughout the YRB-ML with significantly enhanced intensities. In addition, high-intensity DWAA events occurred in most areas in the first six years of the 2010s. In general, from 1960 to the present, DWAA events have been spreading out in the whole YRB-ML with increasing trends of frequencies and intensities.

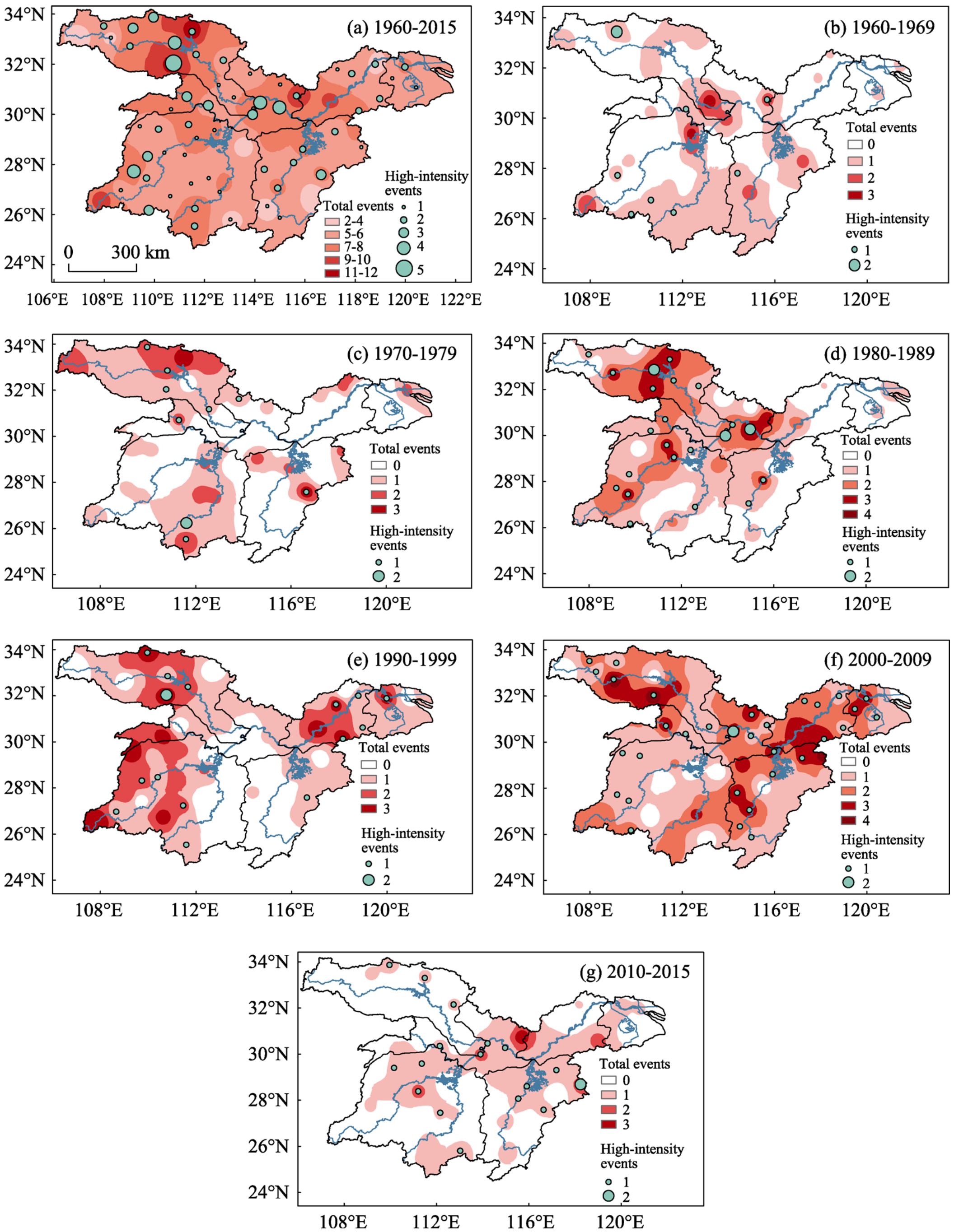



**Figure 4** Spatial distributions of the interdecadal frequencies of summer DWAA events in the YRB-ML. All of the stations with DWAA events are shaded, and stations with high-intensity DWAA events are marked by green dots.

# 5 Impact of ENSO on DWAA events in the YRB-ML

## 5.1 Distribution of Pacific SST anomalies before DWAA events

To investigate the impact of ENSO on DWAA events in the YRB-ML, we analyzed the abnormalities of Pacific SST in the precedent year before each DWAA event. The spatial distributions of Pacific SST abnormalities are shown in Figures 5–7. The results show that 6 months before a DWAA event, the SST of the West Pacific starts to become abnormally high while the SST of the eastern equatorial Pacific (with the anomaly center point located in the range of 5°N–5°S, and 150°W–130°W or more specifically in the Nino3.4 region) starts to be abnormally low and then gradually becomes higher after the coldest time (i.e., two months before the DWAA event). In the meanwhile, the center point of eastern equatorial Pacific SST anomaly center will be shifted eastward from the region lying between 5°N–5°S and 150°W–130°W to that of 5°N–5°S and 110°W. It is noteworthy that the higher the intensity of the event, the more severe the cold SST anomaly in the eastern equatorial Pacific will be. Specifically, the SST anomalies during the period from 4 months before the occurrence of a severe event to the occurrent month of the event are continuously less than –0.4°C, which coincides with a La Niña event.

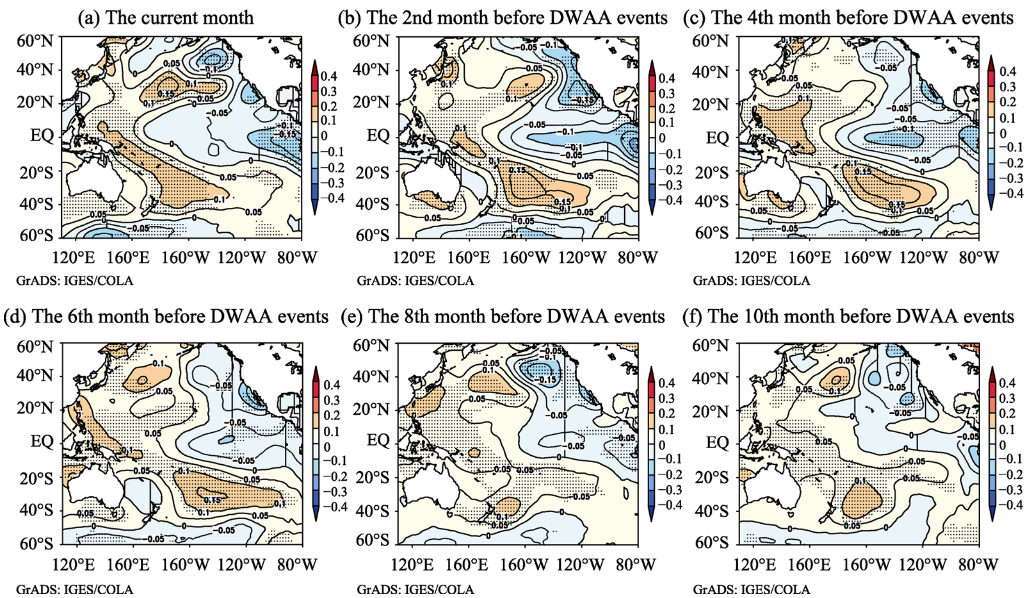



**Figure 5** Spatial distributions of Pacific SST anomalies before mild DWAA events. The dotted regions indicate values that are significant at the 0.1 level

In addition, we also analyzed the SST distributions in the South China Sea, since the South China Sea is the closest part of the West Pacific to China and is within the upstream of monsoon currents that will directly affect the precipitation patterns in the YRB-ML. We found that the SSTs of the South China Sea are abnormally high with a continuous high anomaly of 0.4°C during the period from 4 to 6 months before the occurrence of DWAA events, especially for high-intensity DWAA events. The anomalously high SST in the South China Sea could also be contributed to the occurrence of La Niña based on Tan *et al*. (1995). Thus, we assume that there could be some correlation between SST anomalies led by La

Niña and the occurrence of DWAA events in the YRB-ML and will test our assumptions with more details in the following context.

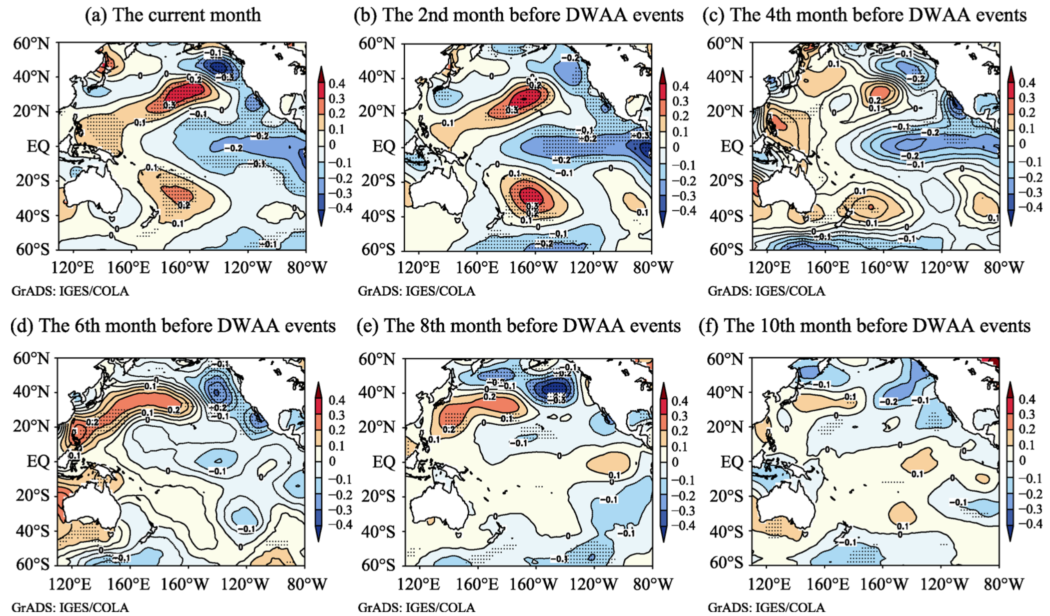



**Figure 6** Spatial distributions of Pacific SST anomalies before moderate DWAA events. The dotted regions indicate values that are significant at the 0.1 level

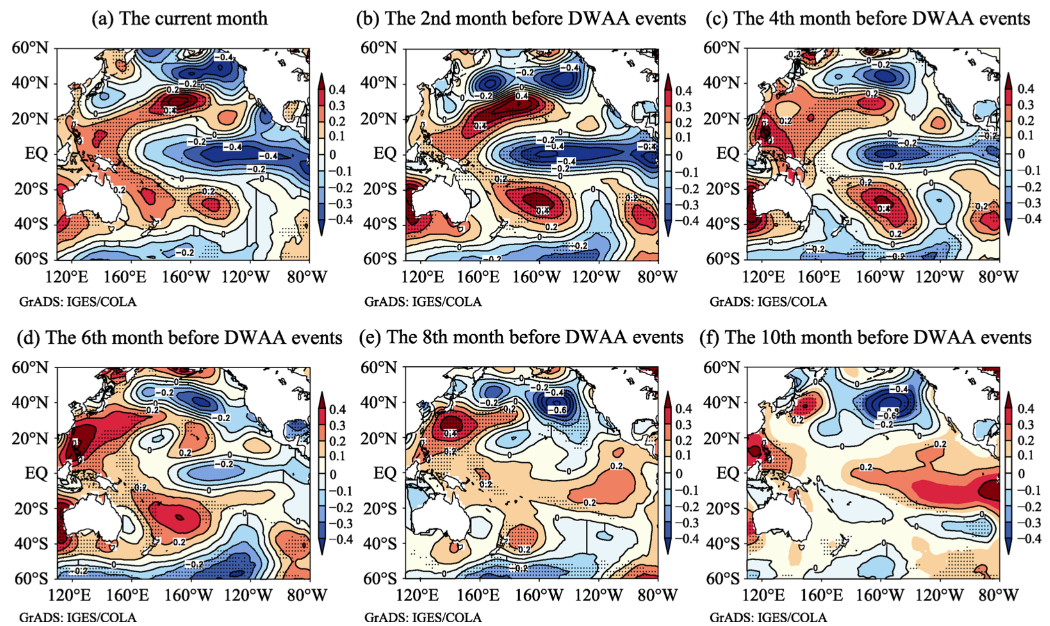



**Figure 7** Spatial distributions of Pacific SST anomalies before severe DWAA events. The dotted regions indicate values that are significant at the 0.1 level

To better understand the distributions of SST anomalies prior to DWAA events in the YRB-ML, we have done statistical analysis for the SST in the Nino3.4 area within one year before the occurrence of all DWAA events (Figure 5). Based on the national standard *Identi-*

*fication Standard for El Niño/La Niña Events*, an El Niño event is defined as a phenomenon in the equatorial Pacific Ocean with a 3-monthly moving average of SST anomaly greater than or equal to 0.5°C for at least 5 consecutive months; while a La Niña event is defined as a phenomenon in the equatorial Pacific Ocean with a 3-monthly moving average of SST anomaly less than or equal to 0.5°C for at least 5 consecutive months. We found that more than 52% of the DWAA events occurred after the phenomena of persistently low SST in the Nino3.4 region (such as La Niña events or a year of negative SST anomalies), and 22.22% of the DWAA events occurred with the phenomena of consistently high SST anomalies in the Nino3.4 region. It indicates that the DWAA events in the YRB-ML have more tendency to occur when the SST in the Nino3.4 region is anomalously lower for a continuous period of time, which is consistent with the conclusions from Figures 5–7.

**Table 5** Abnormal conditions of SST in the Nino3.4 region within 1 year before DWAA events

| SST abnormal conditions | Occurrence frequency | Percentage (%) |
|---|---|---|
| La Niña | 181 | 41.04 |
| SST anomalies persistently less than 0 (La Niña has not formed yet) | 52 | 11.79 |
| El Niño | 62 | 14.06 |
| SST anomalies persistently larger than 0 (El Niño has not formed yet) | 36 | 8.16 |
| Other | 110 | 24.95 |

### 5.2 Statistics of El Niño/La Niña events that occurred before DWAA events

To analyze the impact of La Niña events on DWAA events, we selected 3 severe DWAA events in 3 La Niña years, including the years 1988, 2000 and 2011 (see Figure 3a) and did statistical analysis based on the concurrent La Niña– DWAA events. The statistics of mild, moderate and severe DWAA events that occurred during the declining stages of La Niña events or within the first 8 months after the end of La Niña events are presented in Table 6. The corresponding spatial distributions of Pacific SST anomalies in the Nino3.4 region before mild, moderate and severe DWAA events are shown in Figures 5–7, respectively. It can be seen from Table 6 that 181 DWAA events occurred during the declining stages of La Niña or within the first 8 months after La Niña ended, accounting for approximately 41.04% of all events. Specifically, 120 of those events occurred 4 to 6 months after the month with the coldest SST. In addition, there are more high-intensity DWAA events occurred within the first 8 months after La Niña, and with the lowest SST in the 4th to 6th month before the DWAA event. The higher the intensity of the event, the larger the proportions of events that occurred within the first 8 months after La Niña ended and occurred 4 to 6 months after the month with the coldest SST. Moreover, we found that there are 62 events that were preceded by El Niño events within 1 year, including 54 mild DWAA events, 6 moderate DWAA events and 2 severe DWAA events, among which the proportion of severe events is small. These results indicate that La Niña events could be predictive signals for the occurrence of DWAA events, and the higher the intensity of the DWAA events, the higher the probability that these events will occur after La Niña.

### 5.3 Correlation between DWAAI and SST anomaly values before DWAA events

To better quantify the impact of SST anomaly on DWAA events, we calculated the correlation

**Table 6** Statistics of DWAA events that occurred during the declining stages of La Niña events or within the first 8 months after La Niña events ended

| Intensity of events | Occurrence frequency | Months with the coldest SST in the Nino3.4 region before DWAA events occurred | | | | | | | | | Percentage (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1st month | 2nd month | 3rd month | 4th month | 5th month | 6th month | 7th month | 8th month and above | Total number of times | |
| Mild | 330 | 4 | 4 | 1 | 19 | 32 | 20 | 18 | 18 | 116 | 35.15 |
| Moder-ate | 74 | 2 | 1 | 0 | 16 | 14 | 2 | 2 | 6 | 43 | 58.11 |
| Severe | 37 | 1 | 0 | 0 | 6 | 8 | 3 | 1 | 3 | 22 | 59.46 |
| Total | 441 | 7 | 5 | 1 | 41 | 54 | 25 | 21 | 27 | 181 | 41.04 |

coefficients between the DWAAI values in different sub-basins and the SST anomalies in the Nino3.4 region before DWAA events. Temporally, there is a general significantly negative correlation at the 0.05 significance level between the DWAAI values of all stations in the YRB-ML and the SST anomalies during the first six months before DWAA events with the strongest negative correlation in the 3 months prior to DWAA events. Spatially, the strongest negative correlation between DWAAI values and SST anomalies occurred in the Poyang Lake watershed since the correlations from the 2nd month to the 6th month before the DWAA events occurred are all significant at the 0.01 level with the largest absolute correlation coefficient of 0.39 in the 3rd month before the DWAA event. The second strongest negative correlations between the DWAAI values and SST anomalies occurred in the middle reaches of the Yangtze River for the first 3 months before DWAA events with the largest absolute correlation coefficient of 0.44 in the first month before the DWAA event. On the other hand, the correlation coefficients in the lower reaches of the Yangtze River and the delta plains range from 0.26 to –0.19, which are not statistically significant at the 0.05 level. In addition, the correlations in the Hanjiang River Basin and Dongting Lake watershed are the weakest with absolute correlation coefficients less than 0.1. Based on the above results, we can see that there are significant negative correlations between the DWAAI values and the SST anomalies in the Nino3.4 region in the precedent 3 months of the DWAA events for the Poyang Lake watershed and the middle reaches of the Yangtze River.

**Table 7** Correlations between DWAAI values and SST anomalies in the Nino3.4 region before DWAA events

| Sub-basins | Occur. fre-quency | Months before DWAA events occurred | | | | | |
|---|---|---|---|---|---|---|---|
| | | 1st month | 2nd month | 3rd month | 4th month | 5th month | 6th month |
| Hanjiang River watershed | 103 | 0.06 | 0.09 | 0.03 | 0.00 | 0.00 | 0.00 |
| Dongting Lake watershed | 144 | –0.06 | –0.04 | –0.06 | –0.05 | –0.07 | –0.06 |
| Poyang Lake watershed | 80 | **<u>–0.23</u>** | **<u>–0.31</u>** | **<u>–0.39</u>** | **<u>–0.38</u>** | **<u>–0.37</u>** | **<u>–0.34</u>** |
| Middle reaches of the Yangtze River | 47 | **<u>–0.44</u>** | **<u>–0.42</u>** | **<u>–0.36</u>** | –0.23 | –0.20 | –0.18 |
| Lower reaches of the Yangtze River | 47 | –0.21 | –0.20 | –0.24 | –0.26 | –0.22 | –0.20 |
| Delta plains | 20 | –0.19 | –0.20 | –0.26 | –0.24 | –0.22 | –0.25 |
| Total basin | 441 | **<u>–0.12</u>** | **<u>–0.12</u>** | **<u>–0.15</u>** | **<u>–0.14</u>** | **<u>–0.14</u>** | **<u>–0.12</u>** |

Boldface and underline font indicate the correlations that are significant at the 0.05 level.

It is also noteworthy that different types of El Niño/La Niña events have different developing features of SST anomalies and could result in completely different summer precipitation patterns in China for the following year (Yuan *et al*., 2012). The East Pacific type of El

Niño/La Niña index ($I_{EP}$) and Central Pacific type of El Niño/La Niña index ($I_{CP}$) were also calculated in this paper according to the *Identification Standard for El Niño/La Niña Events*. The DWAAI~$I_{EP}$ and DWAAI~$I_{CP}$ correlations for the 6 months before an event occurring in different sub-basins are shown in Table 8. It can be found that the DWAAIs have weak correlations with pre-phase $I_{EP}$, but strong correlations with pre-phase $I_{CP}$. More specifically, the DWAAI values of all stations in the YRB-ML have significantly negative correlation with $I_{CP}$ at the 0.05 significance level during the first five months before DWAA events with the largest correlation coefficients at the 2nd month before the DWAA event. In addition, by comparing Table 8 with Table 7, we can see that although the general trends of correlation between the DWAAI and different large-scale climatic symbols (SST anomaly, $I_{EP}$ or $I_{CP}$) are similar for each sub-basin, the significance of correlation between DWAAI and climatic symbols are different. For example, the correlations between the DWAAI and the SST anomalies in the lower reaches of the Yangtze River and the delta plains are not significant at the 0.05 level, as shown in Table 7. However, the correlation between the DWAAI values and $I_{CP}$ in the second month before the DWAA events are significant at the 0.05 level with correlation coefficients of –0.30 and –0.43 respectively for the lower reaches of YRB and the delta plains. The results give us some important hints that we can use more climatic symbols including but not limited to SST anomaly, $I_{EP}$ and $I_{CP}$ to better investigate the impact of ENSO or global climate change on DWAA events.

**Table 8** Correlations between DWAAI values and $I_{EP}$/$I_{CP}$ before DWAA events

| Sub-basins | Occur. fre-quency | Indices | Months before DWAA events occurred | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | 1st month | 2nd month | 3rd month | 4th month | 5th month | 6th month |
| Hanjiang River watershed | 103 | $I_{EP}$ | 0.13 | 0.12 | 0.03 | 0.04 | 0.05 | 0.05 |
| | | $I_{CP}$ | 0.02 | 0.02 | 0.03 | –0.02 | –0.04 | –0.04 |
| Dongting Lake watershed | 144 | $I_{EP}$ | 0.03 | 0.10 | 0.04 | 0.09 | 0.02 | 0.01 |
| | | $I_{CP}$ | –0.11 | –0.13 | –0.08 | –0.15 | –0.16 | –0.14 |
| Poyang Lake watershed | 80 | $I_{EP}$ | –0.05 | –0.05 | –0.12 | **–0.26** | **–0.33** | **–0.28** |
| | | $I_{CP}$ | **–0.29** | **–0.41** | **–0.39** | **–0.40** | **–0.22** | –0.20 |
| The middle reaches of the Yangtze River | 47 | $I_{EP}$ | –0.19 | –0.25 | **–0.39** | –0.26 | –0.23 | –0.27 |
| | | $I_{CP}$ | –0.24 | **–0.30** | –0.25 | –0.11 | –0.08 | –0.00 |
| The lower reaches of the Yangtze River | 47 | $I_{EP}$ | –0.01 | –0.06 | –0.13 | **–0.32** | **–0.30** | –0.25 |
| | | $I_{CP}$ | –0.25 | –0.23 | –0.19 | –0.06 | –0.07 | –0.06 |
| Delta plains | 20 | $I_{EP}$ | 0.23 | 0.20 | –0.03 | –0.25 | –0.23 | –0.29 |
| | | $I_{CP}$ | –0.37 | **–0.43** | –0.36 | –0.12 | –0.14 | –0.13 |
| Total basin | 441 | $I_{EP}$ | 0.01 | 0.02 | –0.05 | –0.07 | **–0.10** | –0.09 |
| | | $I_{CP}$ | **–0.15** | **–0.18** | **–0.14** | **–0.12** | **–0.10** | –0.09 |

Boldface and underline font indicate the correlations that are significant at the 0.05 level

## 6 Conclusions

In this study, we modified a seasonal-scale LDFAI method and proposed a new daily-scale DWAAI method and applied the new method to analyze the spatio-temporal characteristics of DWAA events in summer periods (May-August) from 1960 to 2015 over the YRB-ML region in China. The new DWAAI method is found to be more accurate and effective than the original LDFAI method in identifying the summer DWAA events in the YRB-ML, since it considers finer time scale, extra prior and posterior dry/wet conditions of DWAA events as well as drought-flood alternation duration. Based on the new DWAAI method, we found that the frequency and intensity of DWAA events are more significantly increased in May, June, less significantly increased in August and slightly decreased in July throughout the years. Besides, we found that although the occurrence frequency of DWAA events is increasing throughout the YRB-ML, the spatial distribution of DWAA events in the YRB-ML is uneven. Specifically, it is found that DWAA events mainly occur in the northwestern part of the YRB-ML, including Hanjiang River Basin, the middle reaches of the YRB, north of Dongting Lake watershed and northwest of Poyang Lake watershed.

In addition, we also analyzed the impact of large-scale climatic dynamics (i.e., ENSO) on the DWAA events in the YRB-ML by establishing the correlation between DWAAI and SST in the Nino3.4 region prior to DWAA events. It is found that the continuously low SST in the Nino3.4 region has profound impact on the occurrence of DWAA events in the YRB-ML. In particular, 41.04% of DWAA events occurred during declining stages of La Niña, within the subsequent 8 months after a La Niña, or in the subsequent 4th-6th months after the coldest month in the Nino3.4 region, implying that La Niña is a key predictive signal of DWAA events in terms of occurrence time. On the other hand, significant negative correlations were found between the DWAAI at all stations and the SST anomalies in the Nino3.4 region prior to DWAA events, especially for the Poyang Lake watershed and the middle reaches of the Yangtze River.

In order to predict the occurrence time and intensity of DWAA events more accurately in the future, we can try to establish the correlations between DWAA events with more climatic symbols (including not only SST anomaly but also other climatic indices like $I_{EP}$ and $I_{CP}$) as well as use land cover change characteristics under climate change and rapid urbanization in the fast-developing China (Song and Wang, 2016). In addition, we need to have a better understanding on the physical mechanisms of atmospheric dynamics at local, regional and global scale as well as land-atmospheric interactions (Song and Wang, 2015) before, during and after DWAA events. And then DWAA events can be simulated and predicted eventually by using climate models, which can be able to capture the genesis, intensification of depressions and their track (Stowasser *et al*., 2009; Turner and Annamalai, 2012). These mechanisms and predictability need further investigations and will be researched in other papers.

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