Increasingly dry/wet abrupt alternation events in a warmer world: Observed evidence from China during 1980–2019

Yu Qiao, Wei Xu, Chenna Meng, Xinli Liao, Lianjie Qin

1Key Laboratory of Environmental Change and Natural Disaster of Ministry of Education, Faculty of Geographical Science, Beijing Normal University, Beijing, China
2State Key Laboratory of Earth Surface Processes and Resource Ecology, Beijing Normal University, Beijing, China
3Academy of Disaster Reduction and Emergency Management, Ministry of Emergency Management and Ministry of Education, Beijing Normal University, Beijing, China

Abstract
The evolution of the frequency of dry/wet spells is a hot topic in global climate change research. The synergistic effects of dry/wet spells make their consequences far more significant than a single disaster, having considerable impacts on hydrology, ecology, and economies, especially in the context of global warming. In this study, the standardized precipitation evapotranspiration index (SPEI)-based identification of dry/wet spells was used to explore the evolution of the frequency of dry/wet abrupt alternation (DWAA) events in the past four decades in China, makes up for the lack of research on the evolution of such compound disasters. China has been affected by dry/wet spells in many areas for a long time. Studies found that high-frequency DWAA areas are concentrated in densely populated areas, China’s essential food bases and core areas for economic development. Dry-to-wet (D–W) events and wet-to-dry (W–D) events basically increased or decreased at the same pace in this period. We innovatively find DWAA events (D–W events and W–D events) are projected to occur increasingly in a wider region of China. The frequency of D–W events across China has increased from 2.35 in the 1980s to 3.56 in the last decade, a 50% increase. On the other hand, W–D events increased from 2.6 to 3.23, increasing 24%. The three regions with the most remarkable changes in the past four decades are Inner Mongolia, northwest China, and north China, where D–W events increased by 121, 61, and 58%, respectively, and W–D events increased by 71, 57, and 61%, respectively. Hereby, it is vital to implement effective prevention against DWAA events in the area which has been neglected in the past decades because of lower frequency. These results may help policymakers develop suitable disaster mitigation plans for reducing the potential risks of extreme compound natural events.

KEYWORDS
China, DWAA events, increasing trend, regional mutation, SPEI
1 | INTRODUCTION

Global warming and the associated increase in extreme weather events substantially increase the chance of concurrent dry spells and wet spells. Changes in the frequency and destructiveness of dry spells and wet spells in a warmer climate have necessitated understanding the evolution of these compound disasters (Dai, 2013; Chen et al., 2020a). Both of them are a hot issue in climate change research and their understanding is an essential aspect of disaster prevention and mitigation (UNDRR, 2019; World Economic Forum, 2019). Previous studies usually regarded dry spells and wet spells as separate natural disasters because of their differences in duration, mechanism, and spatial distribution (Dai and Trenberth, 1998). However, the occurrence of these two natural disasters is closely related to abnormal precipitation. Recent studies found that some drought and flood events show inherent “seesaw” effects in land surface model simulations (He and Sheffield, 2020). Dry/wet abrupt alternation (DWAA) is a combination of two extreme natural disasters: dry spells and wet spells. It refers to the phenomenon that the local area suddenly changes from one powerful state to another powerful state due to a sudden precipitation change in a short time, including dry-to-wet events and wet-to-dry events. The combined impact of the two disasters on society, ecology (Lesk et al., 2016), agriculture, and economy (Wang et al., 2019) is far greater than that of single-hazard disasters (Yoon et al., 2017).

Understanding the local dry and wet state is a crucial aspect of regional water resources and related disaster risk management. Global climate change has led to the redistribution of global water resources, which will further cause changes in the temporal and spatial patterns of global dry and wet events. These changes are manifested in the spatial distribution, intensity, and frequency of disasters (PreventionWeb, 2020). More frequent, longer lasting, and stronger wet spells are projected in wet regions, and the same are projected for dry spells in dry regions (Martin, 2018). Exploring the law of dry spells and wet spells under the background of climate change is an essential prerequisite for comprehensive risk assessments of regional wet spells and dry spells. The impact of the changes in the frequency and intensity of meteorological and hydrological disasters on social production, the ecological environment, and the economy has been increasing each year, necessitating the exploration of their laws a hot research topic.

Deducing the evolution law of extreme disaster events through long-term climate resource analysis on a regional or even global scale is a relatively common and popular climate analysis method. However, prior research only focused on analysing DWAA on a regional scale in a specific area with a higher frequency of occurrence (Li and Ye, 2015; Case, 2016). The lack of evolutionary laws on global or national scales creates challenges for researchers trying to accurately and quickly capture the changes in extreme events that accompany climate change. Research on national and global scales has focused more on the evolutionary law of a single disaster rather than compound disasters (Singh et al., 2014). Due to its large area, diverse climate, and complex terrain, China is one of the countries that are most severely affected by dry spells and wet spells. The combination of topography and climate has increased the extreme weather events occurring in China, and dry spells and wet spells events will be even more severe in the future (Chen et al., 2020b). Studies showed that DWAA appears to be more frequent in China’s lower reaches of the Yangtze River.

Dry spells and wet spells have frequently occurred in the Huaihe River Basin and the Guangdong and Guangxi regions in China since 1990, having significant impacts and producing severe losses because of their long durations and lack of understanding at that time. Many studies have since been conducted of their occurrence and development mechanisms, the quantitative analysis of intensity changes, and the quantitative discussion of influence. An overview of the severe weather in China showed that the dry spells that occurred in the early summer of south China from April to May and the heavy rainfall that began in June caused the sudden change in dry spells and wet spells, which seriously affected farmland, factories, transportation, and communications in the region (Tang and Han, 1994). In the past 15 years, quantitative indicators of DWAA have begun to emerge, including the long-cycle drought–flood abrupt alternation index (LDFAI) (Wu et al., 2006b), the short-cycle drought–flood abrupt alternation index (SDFAI) (Sun et al., 2012), and the daily-scale drought and flood rapid transition index (DWAAI) (Shan et al., 2018). Based on these indexes, analyses have been conducted of the DWAA in multiple hotspot regions such as the middle and lower reaches of the Yangtze River (Yang et al., 2013), the Huaihe River basin (Wang et al., 2009), and south China (He et al., 2016), and their possible causes. The occurrence of sudden dry spells and wet spells is closely related to atmospheric circulation index anomalies, atmospheric intraseasonal oscillations (ISO) (Yang et al., 2013), and El Niño–Southern Oscillation (ENSO) (Shan et al., 2018). Based on these index anomalies, dry spells and wet spells can also be predicted and warned at early stage.

Studies of how drought and flood changes are distributed, when they occur, and their relationship with climate factors are vital to agricultural production and socioeconomic development. Understanding the evolution of DWAA is thus imperative to helping decision-makers and relevant officials develop effective measures...
for reducing the potential risks of extreme natural events. To ensure robustness and ease of use, we used the standardized precipitation evapotranspiration index (SPEI) to identify dry/wet spells. SPEI has been widely used in many countries and regions to characterize dry spells and wet spells and comprehensively consider the coupling effect of multiple meteorological factors. We calculated the station-based frequency of dry/wet abrupt alternation (DWAA) events in China from 1980 to 2019. We aimed (a) to investigate the time-series trends of DWAA at both the climate zone (CZ) level and in China overall, (b) to quantify the frequency of DWAA in different decades, and (c) to identify the hotspot regions of different DWAA cases (dry-to-wet and wet-to-dry). We find DWAA events are projected to occur increasingly in a wider region of China. The three regions with the most remarkable changes in the past four decades are Inner Mongolia, northwest China, and north China, where D–W events increased by 121, 61, and 58%, respectively, and W–D events increased by 71, 57, and 61%, respectively.

2 | DATA AND METHODOLOGY

2.1 | Study region and dataset

China has a vast territory and a large range of latitude and longitude. Significant differences exist in the climatic conditions in different climate intervals. For example, the East Asian summer monsoon (EASM) climate dominates the middle and lower reaches of the Yangtze River and most parts of south China, with high-frequency abnormal weather and extreme climate, while the arid climate dominates the western region. (Zhao, 1983) divides China into seven regions (Figure 1), and we employ shapefile data for this partition digitized by Yao et al. (2018) in this paper. Monthly meteorological factors including precipitation (P), relative humidity (RH), minimum (Tmin), and maximum temperatures (Tmax), wind speed (U10), sunshine hour (n) were calculated based on meteorological stations’ daily datasets from 1980 to 2019 from the China Meteorological Administration (CMA), excluding stations in Hong Kong, Macao, and Taiwan. Data control are based on the following procedures: Stations with more than 3% missing data of a single meteorological element and migration distance of more than 10 km were rejected. Accordingly, a subset of 609 stations were selected in our analysis. To make up the gaps, we use the linear interpolation method for the missing data of less than five consecutive days, except for the precipitation data. For data missing for more than five consecutive days, the average of the remaining years is used to make up the difference. The gaps of the precipitation data were replaced from the nearest meteorological station data on the same day.

2.2 | Methods

2.2.1 | Standardized precipitation evapotranspiration index

The precipitation, seasonality, and precipitation patterns vary from region to region, and differences in the climate zones and regions. The standardization approach accounts for these differences by normalizing the observed precipitation deviations from a long-term (30 to 60 years) mean. The SPEI is calculated on a monthly basis using the following formula:

$$\text{SPEI} = \left( \frac{\text{P}}{\text{P}_{\text{norm}}} - 1 \right) \times 100$$

where P is the observed precipitation, and Pnorm is the long-term mean precipitation. The SPEI is a dimensionless index that ranges from -2 to 2, with values closer to 0 indicating average conditions, positive values indicating dry conditions, and negative values indicating wet conditions.

The SPEI has been widely used to study climate extremes and their impacts on hydrological and ecological systems. It has also been used to study the coupling effect of multiple meteorological factors and to quantify the frequency of dry/wet abrupt alternation events. The SPEI has been shown to be a useful tool for monitoring and predicting drought conditions and for assessing the risks associated with extreme natural events.
judgement of drought based on multiple calculation methods often affect the results. SPEI expresses the regional dry and wet conditions according to which the difference between precipitation and evapotranspiration deviates from the average. SPEI has the advantage of being spatially comparable at multiple scales (i.e., 1, 2, 3 months, etc.), easy to calculate (Vicente-Serrano et al., 2012, 2013) and even in drought forecasting (Yao et al., 2020) based on the difference between precipitation and PET. Therefore, considering the combined effect of water balance and the simplicity of calculation, SPEI has the irreplaceable advantage under the climate change context. According to the Penman–Monteith formula, the reference evapotranspiration calculated based on the energy balance and water vapour diffusion theory (Equation (1)) can comprehensively consider meteorological elements such as temperature, pressure, and wind, and is suitable for application in both arid and humid regions. Equation (1) shows the reference evapotranspiration calculation,

\[ ET_0 = \frac{0.408 \Delta (R_n - G) + \gamma \frac{900}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma (1 + 0.34 u_2)}, \]

where \( ET_0 \) is the potential evapotranspiration (mm), \( R_n \) is the net radiation at the crop surface (MJ/(m²·day⁻¹)), \( G \) is the soil heat flux density (MJ/(m²·day⁻¹)), \( T \) is the air temperature at the height of 2 m (°C), \( u_2 \) is the wind speed at the height of 2 m (m·s⁻¹), \( e_s \) is the vapour pressure of the air at saturation (kPa), \( e_a \) is the actual vapour pressure (kPa), \( \Delta \) is the slope of the vapour pressure curve (kPa·°C⁻¹), and \( \gamma \) is the psychrometric constant (kPa·°C⁻¹). The calculation of each element is based on the methodology provided in Allen et al. (1998).

### 2.2.2 Dry/wet abrupt alteration

The standardized precipitation evapotranspiration index (SPEI), which is calculated based on meteorological elements such as precipitation, temperature, wind speed, and so on, has been widely used to assess and quantify dry spells and wet spells and can be used to monitor DWAA. In this study, the dry spell was defined by an SPEI value less than −1, whereas the wet spell was defined by an SPEI value greater than 1 (Chen, 2013). The abrupt alternation between dry spell and wet spell in adjacent months was defined as a DWAA event using the SPEI-1. There are two types of DWAA: abrupt alternation from dry-to-wet (D–W) and wet-to-dry (W–D) conditions (Figure 2). If a W–D event occurs immediately after the D–W event, it is regarded as two events.

![Figure 2](image)

**Figure 2** Schematic diagram of DWAA. (a) Wet-to-dry (W–D) events are defined by SPEI ≥ 1 in the \( i \)th month and the SPEI, value ≤−1 in the \( i + 1 \) month, which is represented inside the brown rectangle; (b) dry-to-wet (D–W) events are defined by SPEI, ≤−1 in the \( i \)th month and the SPEI, value ≥1 in the \( i + 1 \) month, which is represented inside the blue rectangle; and successive D–W and W–D events were judged to be two separate events [Colour figure can be viewed at wileyonlinelibrary.com]

### 2.2.3 Detection of trends and test

We evaluated the DWAA characteristics in each region based on its frequency and the average frequency per station. The Mann–Kendall mutation test was used to reveal how the DWAA events evolved.

1. **Average frequency of D–W/W–D (Si).** The range of DWAA within a certain period of time in a region can be characterized by the proportion of stations that have experienced DWAA as a percentage of the total number of stations. The calculation formula is as follows:

\[ S_i = \frac{m}{M}, \]

where \( m \) is the number of stations where DWAA occurs, and \( M \) is the total number of stations in the area.

2. **Mann–Kendall mutation test.** The M–K mutation test is a commonly used nonparametric statistical test (Mann, 1945; Kendall, 1975), widely used to analyse the time series changes in climate data series (Goossens and Berger, 1986). The sample does not need to follow a certain distribution and is not affected by a few outliers (Zhao et al., 2019). In this study, the M–K was conducted on the time series of DWAA frequency in each region, and the occurrence of mutations in different regions was obtained.
3 | RESULTS

3.1 | Spatial variations

The spatial distribution of DWAA showed noticeable spatial differences; as a whole, the occurrence was more frequent in the east, followed by the central region, then the west (Figure 3). The overall frequency of D–W events was higher than that of W–D and more widely distributed. D–W events mainly occurred in the four climatic regions of the eastern monsoon region. Temperate and Warm Temperate Northwestern China Desert and Qinghai–Tibetan Plateau have the lowest frequency during the study period. W–D events were more concentrated in the middle and lower reaches of the Yangtze River, southern China in the eastern monsoon region, south parts of north China, and the east part of northeast China. The highest frequency per station in the different regions shows an evolution path (Table 1). The maximum frequency gradually moved northward from southern China over time. Most areas have experienced their highest-frequency DWAA in the past 10 years. Throughout China, the D–W frequency (per station) gradually increased from 2.35 to 3.56, and similarly, dynamically increasing from 2.60 to 3.23 is also found of the W–D frequency.

In terms of the frequency distribution in different years, D–W events showed a gradual spatial expansion trend (Figure 4). In the 1980s, they concentrated in the humid subtropical area of southern China in the eastern monsoon region, expanded to the north in the 1990s, and covered central China. In most humid subtropical areas in south China, the areas with more D–W events became more scattered in the early twentieth century due to the overall increase in frequency. Except for the eastern part of northeast China and the southeast coast of the humid subtropical area of south China, the overall disaster frequency was relatively low. In the 2010s, they were widely distributed in five regions in the east, and their overall frequency increased significantly. The spatial distribution of W–D events was similar to D–W events, gradually expanding to the entire eastern monsoon region over time. Notably, high numbers of W–D events were only distributed in the southeast of northeast China in the 1990s. The general event-prone areas are the humid tropics of south China in the eastern monsoon region, the humid subtropical regions of south China, and the humid and semi-humid warm temperate regions of north China.

Compared with previous studies, our determination of the region of high value of DWAA events is basically consistent, for example, subtropical humid central and southern China. However, in this paper we depicted the events in several previously neglected regions such as Temperate and Warm Temperate Northwestern China Desert, temperate grassland of Inner Mongolia. Therefore, comparisons remain difficult because of insufficient attention to such events in the past.

The increase in DWAA events may be related to changes in the frequency and intensity of extreme events in the context of climate change. We should be aware that the DWAA index are closely related to the precipitation change and highly related to temperature, wind speed, radiation, and so on. Changes in climate factors caused by human activities have to be considered. Land use change (Gao et al., 2007), greenhouse gas emission (Chiang et al., 2021), and urban sprawl (Emadodin et al., 2016) are all illustrated to be

---

**FIGURE 3** Distribution of DWAA frequency during the past 40 years in China: (a) D–W events and (b) W–D events [Colour figure can be viewed at wileyonlinelibrary.com]
impactful to the climate are hereby imperative to further investigate the possible function mechanism. These elements mentioned above are important environmental factors that may contribute to regional or global climate change.

It is noteworthy that the reasons that trigger changes in the frequency of such events may differ in different regions. In north China, the poleward shift of typhoons generated in the northwest Pacific Ocean may be the most influential factor in recent years. In the middle and lower reaches of the Yangtze River, which are subject to such events year-round, current analyses of the causes include Pacific Decadal Oscillation (PDO), ENSO. At the same time, the changes may be related to changes in evapotranspiration due to temperature increases in the northeast. Meanwhile, precipitation anomalies in northwest China and Inner Mongolia in recent years have also triggered extensive discussions, which may be caused by the increased impact in arid and semi-arid regions in the context of climate change. Possible physical mechanisms include:

1. Dry and wet changes due to the alternating control of cyclone and anticyclone pairs.
2. The influence of warm-core structures left in the mid-troposphere after the transit of strong typhoons (McTaggart-Cowan et al., 2007).
3. The increased frequency of heavy precipitation events and the increased time interval between precipitation events in the context of climate change (Dai et al., 2020).

### 3.2 Seasonal cycle (seasonal differences)

From the perspective of different seasons, D–W events are more concentrated in winter (Figure 5). Northeast China and the middle and lower reaches of the Yangtze River are the areas where dry spells and wet spells frequently occur in spring. In the humid subtropical regions of southern China, D–W events are concentrated and more frequent in summer. This discovery allows policymakers to focus on the previously studied hot spots: the middle and lower reaches of the Yangtze River and pay more attention to the disaster events in the spring in the northeast China. The ecology and economy impact of spring occurred D–W events should also be taken seriously.

The frequency of W–D events is relatively low. Still, we found that W–D events only focus in the humid subtropical area of southern China and are more frequent in summer. In different regions, the changes in W–D events show obvious regional differences, even though they are in the same climate zone. Such a difference may be caused by the combined effect of atmospheric circulation characteristics and topography, and it is also a problem worthy of in-depth study. The middle and lower reaches of the Yangtze River are areas with high incidence of two kinds of DWAA events, that we need to value.

### 3.3 Trend of DWAA

The spatial distribution and sequence test of the frequency of DWAA showed that the events frequently occurred in the past 10–20 years. Hence, it is of important to quantify the frequency changes in DWAA and their regional characteristics. Overall, there is no apparent linear trend in the frequency of dry spells and wet spells, but the interdecadal pattern is clear (Figure 6). The DWAA in the 1980s to 1990s was significantly lower than in the most recent two decades. The frequency of dry spells to wet spells was lower than that of wet spells to dry spells, whereas in the past two decades, the frequency

| Subregion | DWAA frequency (per station) | W–D frequency (per station) |
|-----------|-------------------------------|-----------------------------|
| Subregion | D–W 1980s 1990s 2000s 2010s 1980–2019 | W–D 1980s 1990s 2000s 2010s 1980–2019 |
| I | 2.49 2.65 4.25 3.29 12.68 | 2.29 2.72 3.13 2.67 10.81 |
| II | 1.74 2.64 2.74 3.85 10.97 | 1.43 2.19 2.13 2.45 8.2 |
| III | 2.33 2.94 2.69 3.75 11.71 | 2.19 2.97 1.92 3.44 10.52 |
| IV | 2.52 3.42 3.10 3.72 12.76 | 3.08 3.17 2.96 3.63 12.84 |
| V | 2.65 2.47 2.89 3.91 11.92 | 3.80 2.67 3.15 3.93 13.55 |
| VI | 1.44 1.82 2.08 2.28 7.62 | 1.31 1.33 2.18 1.85 6.67 |
| VII | 2.38 2.41 2.64 3.14 10.57 | 2.54 2.21 2.18 2.93 9.86 |
| China | 2.35 2.90 3.01 3.56 11.82 | 2.60 2.75 2.63 3.23 11.21 |
of dry spells to wet spells was higher than that of wet spells to dry spells. The time variability also increased significantly (the standard deviation increased).

In the past 10 years (2010–2019), the frequency of DWAA events at a single station in most regions was the highest. Except for the humid and semihumid temperate regions in northeast China, the changes occurred earlier, and the maximum frequency occurred in 2000–2009. This transformation was also found through M–K analyses (Figure S1, Supporting Information). The eastern monsoon region is a sensitive area for DWAA. The interdecadal frequency of different regions fluctuated wildly, with obvious high-value DWAA years in different regions. The DWAA events in the Mongolian grassland increased significantly. Such a large interdecadal variation maybe related with the changes in Intraseasonal Oscillation (Yang et al., 2013), ENSO events (Shan et al., 2018), and so on.
4 | DISCUSSION AND CONCLUSIONS

4.1 | The important role of anthropogenic activities

The frequency of dry spells and wet spells has changed significantly, and the areas with a high incidence of DWAA events are concentrated in densely populated areas. Existing research indicates that global warming and wetting have occurred in the past 50 years and thus are likely to be part of a much longer-term trend (Alexander et al., 2006). The persistence and large-scale climate anomalies in a warmer climate also affect the trends and change point in precipitation (Tan et al., 2017). As mentioned before, the DWAA index is not only closely related to the precipitation change, also highly related with temperature, wind speed,
radiation, and so on. The observed climate trends can be related to anthropological activities such as urban sprawl, industrial development, and increasing population density. Thus, the role of human activities in the changes in the frequency of dry spells and wet spells is worth discussing. Also, (Chen and Sun, 2021) studied the possible impacts of anthropologies based on different forcing simulation of CMIP6 (Coupled Model Intercomparison Project) models in China indicate that humans have increased probabilities of historical hot and wet extremes, including in more than 75 and 56% of the areas, respectively. Although there is no uniformity in the criteria for determining disaster events, there is a consensus to value and quantify the role of human activities. The possible impacts and mechanisms of land use change, greenhouse gas emission, urban sprawl on DWAA events require more targeted research.

FIGURE 6  (a–h) Time series of DWAA Frequency (times/station) in China and seven subregions. The orange and blue solid lines indicate D–W and W–D events, respectively. The blue and orange dashed lines indicate the average decadal frequency [Colour figure can be viewed at wileyonlinelibrary.com]
4.2  The new type of DWAA

In the context of climate change, dry spell and wet spell disasters are not only changing in frequency and intensity: new types of dry spell and wet spell events are also occurring occasionally, including dry–wet–dry events and wet–dry–wet events, which are more complex. A compound disaster occurred near the coastal zone (Chen et al., 2020a). For such novel disaster events that have two alternations, identifying whether they will occur and how to calculate their intensity and duration will be a new challenge.

4.3  Unification of criteria for identifying DWAA

Additionally, there is currently no unified verification for the DWAA. Researchers have used multiple indices such as the standardized precipitation index (SPI), LDFAI, and SDFAI to quantify the occurrence of dry spells and wet spells. We need to identify and unify the law of DWAA evolution and to verify the results in the natural disaster records. Studies showed that future changes on dry spells and floods in the most part of China are sharing stronger intensity and longer duration than present (Chen, 2013). The increasing risk of compound natural disasters is the challenge of our time; whether global warming or the coming novel disasters, these are shared challenges.

Studies on DWAA began in the middle and lower reaches of the Yangtze River, which has always been a frequent area for such events, although the judging criteria varies (Wu et al., 2006a; Shan et al., 2018). There are no specific studies on the frequency change of DWAA events throughout China in historical periods, so it is tough to compare other regions. In addition, because previous studies on DWAA events have used precipitation only as a criterion, in this paper, water balance is used to determine the results, so there may some differences need to detect nationally. It is still challenging to figure out and unify the law of its evolution and verify the results with the natural disaster records. In this study, we used the more commonly used SPEI index to identify. However, when it comes to smaller area studies, perhaps the nonstationary drought index will have an improvement in a specific region if the researchers are able to choose appropriate covariates (Cammalleri et al., 2021). At present, it is quite challenging to comprehensively consider the nonstationary change of meteorology factors and human activities in large-scale research.

4.4  Conclusions

To analyse the spatiotemporal evolution of the long-term climate sequence of DWAA events throughout China. We employed SPEI to identify DWAA events in different subregions around China. This study investigated the evolution of DWAA events during the past 40 years from 1980 to 2019 and the seasonal characteristics in different subregions. The main findings are as follows:

DWAA events (D–W events and W–D events) are projected to occur increasingly in a wider region of China. Results show that the frequency of D–W events across China has increased from 2.35 in the 1980s to 3.56 in the last decade, a 50% increase. On the other hand, W–D events increased from 2.6 to 3.23, increasing 24%. The three regions with the most remarkable changes in the past four decades are temperate grassland of Inner Mongolia, temperate and warm temperate Northwestern China desert, and warm temperate humid and subhumid northern China.

From the evolution of seasonal DWAA events identified in this study, it can be seen that DWAA events, especially D–W events, show noticeable seasonal and regional differences. Previous studies on DWAA events only focused more on the monsoon season in monsoon-affected regions. According to our study, the D–W events in the spring in the northeastern region and the winter of middle and lower reaches of the Yangtze River are worthy of more attention.

Notably, except for the humid and semi-humid temperate zone in the northeast, other regions experienced single-station maximums of D–W and W–D events in the past 10 years (2010–2019). According to the Mann–Kendall test results, the changes first occurred in the humid and semi-humid temperate zones of the northeast around 2000. These abrupt changes have impacted the ecology of the agricultural and pastoral transition zone, arid and semi-arid areas, and the Qinghai–Tibet Plateau. The results of this study also provide a basis for the assessment of the vulnerability and resilience of the ecological environment of China's wet and dry disasters.

ACKNOWLEDGEMENTS

This work was supported by the National Key Research & Development Program of China (2018YFC1508802) and the Program of Introducing Talent to Universities (111 Project, Grant No. BP0820003). The observed meteorological data, precipitation, maximum temperature, minimum temperature, and wind speed are available from the National Meteorological Information Center, China Meteorological Administration (CMA; http://data.cma.cn/en/?r%20=data/detail&dataCode%20=A.0029.0001, Climate Daily Data From Surface Meteorological Stations
In China V3.0). We thank the anonymous reviewers who gave us very constructive suggestions for improving the paper.

AUTHOR CONTRIBUTIONS
Yu Qiao: Methodology; software; formal analysis; investigation; visualization; writing – original draft preparation. Wei Xu: Writing – review and editing; supervision; funding acquisition; project administration. Chenna Meng and Xinli Liao: Data curation; software. Lianjie Qin: Writing; formal analysis.

CONFLICTS OF INTEREST
The authors declare no potential conflict of interest.

ORCID
Yu Qiao https://orcid.org/0000-0002-2276-4509
Wei Xu https://orcid.org/0000-0002-6912-9000
Chenna Meng https://orcid.org/0000-0002-2379-2843
Xinli Liao https://orcid.org/0000-0001-6686-044X
Lianjie Qin https://orcid.org/0000-0002-3581-3752

REFERENCES
Alexander, L.V., Zhang, X., Peterson, T.C., Caesar, J., Gleason, B., Klein Tank, A.M.G., Haylock, M., Collins, D., Trewin, B., Rahimzadeh, F., Tagipour, A., Rupa Kumar, K., Revadekar, J., Griffiths, G., Vincent, L., Stephenson, D.B., Burn, J., Aguilar, E., Brunet, M., Taylor, M., New, M., Zhai, P., Rusticucci, M. and VAZQUEZ-Aguirre, J.L. (2006) Global observed changes in daily climate extremes of temperature and precipitation. Journal of Geophysical Research, 111(D5), D05109.
Allen, R.G., Pereira, L.S., Raes, D., and Smith, M. (1998). Crop Evapotranspiration: Guidelines. Rome: Food and Agriculture Organization.
Cammlerli, C., Spinoni, J., Barbosa, P., Toreti, A., and Vogt, J.V. (2021) The effects of non-stationarity on SPI for operational drought monitoring in Europe. International Journal of Climatology, 1–13. https://doi.org/10.1002/joc.7424
Case, J.L. (2016) From drought to flooding in less than a week over South Carolina. Results in Physics, 6, 1183–1184.
Chen, H. and Sun, J. (2021) Anthropogenic influence has increased climate extreme occurrence over China. Science Bulletin, 66(8), 749–752.
Chen, H., Wang, S., and Wang, Y. (2020a) Exploring abrupt alternations between wet and dry conditions on the basis of historical observations and convection-permitting climate model simulations. Journal of Geophysical Research: Atmospheres, 125(9), 1–17. https://doi.org/10.1029/2019jd031982
Chen, H., Wang, S., Zhu, J., and Zhang, B. (2020b) Projected changes in abrupt shifts between dry and wet extremes over china through an ensemble of regional climate model simulations. Journal of Geophysical Research: Atmospheres, 125(23), 1–20. https://doi.org/10.1029/2020jd033894
Chen, H.S.J.C. (2013) Future changes of drought and flood events in China under a global warming scenario. Atmospheric and Oceanic Science Letters, 6(1), 8–13.
Chiang, F., Mazdiyasni, O. and Aghakouchak, A. (2021) Evidence of anthropogenic impacts on global drought frequency, duration, and intensity. Nature Communications, 12(1), 2754.
Dai, A. (2013) Increasing drought under global warming in observations and models. Nature Climate Change, 3(1), 52–58.
Dai, A., Rasmussen, R.M., Liu, C., Ikeda, K. and Prein, A.F. (2020) A new mechanism for warm-season precipitation response to globalwarming based on convection-permitting simulations. Climate Dynamics, 55(1–2), 343–368.
Dai, A. and Trenberth, K.E. (1998) Global variations in droughts and wet spells. Geophysical Research Letters, 25, 3367–3370.
Emadolin, I., Taravat, A. and Rajaei, M. (2016) Effects of urban sprawl on local climate: A case study, north central Iran. Urban Climate, 17, 230–247.
Gao, X., Zhang, D., Chen, Z., Pal, J.S. and Giorgi, F. (2007) Land use effects on climate in China as simulated by a regional climate model. Science in China Series D: Earth Sciences, 50(4), 620–628.
Goossens, C.H. and Berger, A. (1986) Annual and seasonal climatic variations over the Northern Hemisphere and Europe during the last century. Annals of Geophysics, 4, 385–400.
He, H., Liao, X., Lu, H. and Chen, S. (2016) Features of long-cycle drought-flood abrupt alternation in south China during summer in 1961–2014. Acta Geographica Sinica (in Chinese), 71(01), 130–141.
He, X. and Sheffield, J. (2020) Lagged compound occurrence of droughts and pluvials globally over the past seven decades. Geophysical Research Letters, 47(14), e2020GL087924.
Kendall, M.G. (1975) Rank Correlation Methods. London: Griffin.
Lesk, C., Rowhani, P. and Ramankutty, N. (2016) Influence of extreme weather disasters on global crop production. Nature, 529(7584), 84–87.
Li, X. and Ye, X. (2015) Spatiotemporal characteristics of dry-wet abrupt transition based on precipitation in Poyang Lake Basin, China. Water, 7(12), 1943–1958.
Mann, H.B. (1945) Nonparametric tests against trend. Econometrica, 13, 245–259.
Martin, E.R. (2018) Future projections of global pluvial and drought event characteristics. Geophysical Research Letters, 45(21), 11913–11920.
McTaggart-Cowan, R., Bosart, L.F., Gyrakum, J.R. and Atallah, E.H. (2007) Hurricane Katrina (2005). Part II: evolution and hemispheric impacts of a diabatically generated warm pool. Monthly Weather Review, 135(12), 3927–3949.
PreventionWeb. (2020). 2019 global natural disaster assessment. https://www.preventionweb.net/files/73363_2019globalnaturaldisasterassessment.pdf
Shan, L., Zhang, L., Song, J., Zhang, Y., She, D. and Xia, J. (2018) Characteristics of dry-wet abrupt alternation events in the middle and lower reaches of the Yangtze River basin and the relationship with ENSO. Journal of Geographical Sciences, 28(8), 1039–1058.
Singh, D., Tsang, M., Rajaratnam, B. and Diffenbaugh, N.S. (2014) Observed changes in extreme wet and dry spells during the South Asian summer monsoon season. Nature Climate Change, 4(6), 456–461.
Sun, P., Liu, C. and Zhang, Q. (2012) Spatio-temporal variations of drought-flood abrupt alternation during main flood season in east river basin. *Pearl River* (in Chinese), 33(5), 29–34.

Tan, X., Gan, T.Y. and Shao, D. (2017) Effects of persistence and large-scale climate anomalies on trends and change points in extreme precipitation of Canada. *Journal of Hydrology*, 550, 453–465.

Tang, H. and Han, J. (1994) An overview of China’s disastrous weather in the summer of 1994. *Disaster Reduction in China* (in Chinese), 4, 6–8.

UNDRR. (2019) *Global Assessment Report on Disaster Risk Reduction 2019*. Geneva, Switzerland: United Nations Office for Disaster Risk Reduction (UNDRR).

Vicente-Serrano, S.M., Begueria, S., Lorenzo-Lacruz, J., Camarero, J.J., Lopez-Moreno, J.I., Azorin-Molina, C., Revuelto, J., Moran-Tejeda, E. and Sanchez-Lorenzo, A. (2012) Performance of drought indices for ecological, agricultural, and hydrological applications. *Earth Interact.*, 16, 1–27.

Vicente-Serrano, S.M., Gouveia, C., Camarero, J.J., Bequeria, S., Trigo, R., Lopez-Moreno, J.I., Azorin-Molina, C., Pasho, E., Lorenzo-Lacruz, J., Revuelto, J., Moran-Tejeda, E. and Sanchez-Lorenzo, A. (2013) Response of vegetation to drought time-scales across global land biomes. *Proceedings of the National Academy of Sciences of the United States America*, 110, 52–57.

Wang, M., Bi, W., Weng, B., Yu, Z. and Xu, T. (2019) Review on impact from drought-flood abrupt alternation on crop growth and yield. *Water Resources and Hydropower Engineering*, 50, 189–196 (in Chinese).

Wang, S., Tian, H., Ding, X., Xie, W. and Tao, Y. (2009) Climatic characteristics of precipitation and phenomenon of drought flood abrupt alternation during main flood season in huaihe river basin. *Chinese Journal of Agrometeorology*, 30, 31–34 (in Chinese).

World Economic Forum. (2019) *The Global Risks Report 2019*. Geneva: World Economic Forum.

Wu, Z., Li, J., He, J. and Jiang, Z. (2006a) Occurrence of droughts and floods during the normal summer monsoons in the mid- and lower reaches of the Yangtze River. *Geophysical Research Letters*, 33, L05813.

Wu, Z., Li, J., He, J. and Jiang, Z. (2006b) Anomalies of large-scale atmospheric circulation and the abrupt change of long-period drought and flood in summer in the middle and lower reaches of the Yangtze River. *Scientific Bulletin* (in Chinese), 14, 1717–1724.

Yang, S., Wu, B., Zhang, R. and Zhou, S. (2013) Relationship between an abrupt drought-flood transition over mid-low reaches of the Yangtze River in 2011 and the intra-seasonal oscillation over mid-high latitudes of East Asia. *Acta Meteorologica Sinica*, 2, 129–143.

Yao, N., Li, L., Feng, P., Feng, H., Li Liu, D., Liu, Y., Jiang, K., Hu, X., and Li, Y. (2020) Projections of drought characteristics in China based on a standardized precipitation and evapotranspiration index and multiple GCMs. *Science of The Total Environment*, 704, 135245. [https://doi.org/10.1016/j.scitotenv.2019.135245](https://doi.org/10.1016/j.scitotenv.2019.135245)

Yoon, J., Wang, S.S., Lo, M. and Wu, W. (2017) Concurrent increases in wet and dry extremes projected in Texas and combined effects on groundwater. *Environmental Research Letters*, 13(5), 54002.

Zhao, H., Pan, X., Wang, Z., Jiang, S., Liang, L., Wang, X. and Wang, X. (2019) What were the changing trends of the seasonal and annual aridity indexes in northwestern China during 1961–2015? *Atmospheric Research*, 222, 154–162.

Zhao, S. (1983) A new scheme for comprehensive physical regionalization in China. *Acta Geographica Sinica*, 38, 1–10 (in Chinese with English abstract).

**SUPPORTING INFORMATION**

Additional supporting information may be found in the online version of the article at the publisher’s website.

**How to cite this article:** Qiao, Y., Xu, W., Meng, C., Liao, X., & Qin, L. (2022). Increasingly dry/wet abrupt alternation events in a warmer world: Observed evidence from China during 1980–2019. *International Journal of Climatology*, 42(12), 6429–6440. [https://doi.org/10.1002/joc.7598](https://doi.org/10.1002/joc.7598)