Centennial Annual Rainfall Pattern Changes Show an Increasing Trend with Higher Variation over Northern Australia

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ABSTRACT: Global warming and anthropogenic activities have imposed noticeable impacts on rainfall pattern changes at both spatial and temporal scales in recent decades. Systematic diagnosis of rainfall pattern changes is urgently needed at spatiotemporal scales for a deeper understanding of how climate change produces variations in rainfall patterns. The objective of this study was to identify rainfall pattern changes systematically under climate change at a subcontinental scale along a rainfall gradient ranging from 1800 to 200 mm yr^{-1} by analyzing centennial rainfall data covering 230 sites from 1910 to 2017 in the Northern Territory of Australia. Rainfall pattern changes were characterized by considering aspects of trends and periodicity of annual rainfall, abrupt changes, rainfall distribution, and extreme rainfall events. Our results illustrated that rainfall patterns in northern Australia have changed significantly compared with the early period of the twentieth century. Specifically, 1) a significant increasing trend in annual precipitation associated with greater variation in recent decades was observed over the entire study area, 2) temporal variations represented a mean rainfall periodicity of 27 years over wet to dry regions, 3) an abrupt change of annual rainfall amount occurred consistently in both humid and arid regions during the 1966–75 period, and 4) partitioned long-term time series of rainfall demonstrated a wetter rainfall distribution trend across coastal to inland areas that was associated with more frequent extreme rainfall events in recent decades. The findings of this study could facilitate further studies on the mechanisms of climate change that influence rainfall pattern changes.

SIGNIFICANCE STATEMENT: Characterizing long-term rainfall pattern changes under different rainfall conditions is important to understand the impacts of climate change. We conducted diagnosis of centennial rainfall pattern changes across wet to dry regions in northern Australia and found that rainfall patterns have noticeably changed in recent decades. The entire region has a consistent increasing trend of annual rainfall with higher variation. Meanwhile, the main shifting period of rainfall pattern was during 1966–75. Although annual rainfall seems to become wetter with an increasing trend, more frequent extreme rainfall events should also be noticed for assessing the impacts of climate changes. The findings support further study to understand long-term rainfall pattern changes under climate change.

KEYWORDS: Australia; Climate change; Rainfall

1. Introduction

Rainfall patterns have been influenced by global climate change due to increasing temperatures and elevated CO_2 concentrations (Allan and Soden 2008; Ma et al. 2016; Ukkola et al. 2015). The major impacts of global warming include the acceleration of the hydrological cycle, more hydroclimatic extremes, and high variability in the water balance at both spatial and temporal scales (Guerreiro et al. 2018; Wasko and Sharma 2015). Rainfall is the most sensitive hydrological process responding to natural climate changes and anthropogenic influences. As such, there is an ongoing interest in characterizing abrupt climatic changes and shifts. Climatic systems have major impacts on rainfall intensity and timing (Chen et al. 2013; Cook and Heerdegen 2001; Fu et al. 2010; Huang et al. 2013; Piechota and Dracup 1996; Ranatunge et al. 2003; Yilmaz et al. 2014). Meanwhile, rainfall influences ecosystems, agriculture, society, and human activities (Guan et al. 2014, 2018; Heisler-White et al. 2009; Huxman et al. 2004; Kanniah et al. 2011; Ponce-Campos et al. 2013; J. Shen et al. 2018). The diagnosis of rainfall variations is fundamental and crucial for identifying and quantifying climate influences considering the interactions among the water cycle, the carbon cycle, and the global energy balance. Hence, the diagnosis and characterization of changes in rainfall patterns, variability, and distribution in space and time can provide insights into the functioning of climatic systems and the degree of their impact over multiple space and time scales.

Currently, a great deal of rainfall pattern research based on reliable observations and model projections has concluded

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that extreme rainfall intensity has increased in many regions (Kulmatiski and Beard 2013; Wasko and Sharma 2017; Zhang and Cong 2014). A prevalent finding is that climate change has intensified the water cycle, thereby causing wet regions to become wetter, and leading to more imbalanced distributions of rainfall (Feng and Zhang 2015; Oki and Kanae 2006). However, those previous studies mainly interpreted rainfall variations or features by adopting the isolated and limited methods. As a result, only some features of rainfall patterns were analyzed and the connections between different aspects of variations have not been explored further. Therefore, a deeper analytical and comprehensive understanding of rainfall patterns and behaviors is needed to analyze the quantitative and spatiotemporal changes in long-term rainfall patterns and their connections for exploring the modes of rainfall pattern change in response to climate change.

Numerous studies have characterized rainfall pattern changes by analyzing variations in observations and model scenario simulations. Generally, trend analysis is a widely used and straightforward method to present variations of rainfall amount over time (Haylock et al. 2006; Makuei et al. 2013; Suppiah and Hennessy 1998; Syafrina et al. 2015). In addition, temporal rainfall analysis builds the linkage between variations in magnitude and timing of rainfall (Fu et al. 2010; Montazerolghaem et al. 2016a; Panagos et al. 2017). Rainfall patterns have also been characterized by climatic indices that represent the fluctuation of rainfall and extremes by extracting the features of rainfall variability (Haylock and Nicholls 2000; Montazerolghaem et al. 2016b; Rouillard et al. 2015). Furthermore, rainfall modeling provides an approach for analyzing rainfall pattern changes under different scenarios and environments (Chadwick et al. 2015; Raut et al. 2017; Wang and Chen 2014).

The findings of these studies have demonstrated changes on rainfall patterns. However, only some specific characteristics among the many features of rainfall patterns have been identified and derived insights and knowledge have been limited. The main reasons leading to a lack of comprehensive understanding of climatic impacts include limited approaches, restricted regional representation, and the lack of integrated analysis. According to the characteristics of time series, the components, including trend, period, and abrupt changes, are all strongly related to quantitative and temporal variations. Meanwhile, those changes in multiple dimensions or aspects could also have influences and interactions on each other. If we merely concentrate on quantitative changes and ignore temporal variations, and vice versa, we may recognize the impacts of climate changes on rainfall incompletely. By contrast, we intend to obtain a comprehensive view on rainfall variations by integrating both variations from quantitative and temporal analysis. Hence, a systematic diagnostic framework of rainfall patterns is required to analyze aspects of trends and periodicity of rainfall, abrupt rainfall changes considering the features of time series, and extreme rainfall events observed in long-term rainfall records. In this way, we could establish an integrated perspective on long-term rainfall variations for further understanding the impacts of climate changes.

Many studies have addressed the issue of rainfall pattern variations and changes in Australia by methods ranging from rain gauge data analysis to monitoring hydroclimatic extremes via remote sensing (Haylock and Nicholls 2000; Spessa et al. 2005; Suppiah and Hennessy 1998; Xie et al. 2016a,b). Vegetation in Australia is more sensitive to rainfall conditions compared to temperature and radiation (Seddon et al. 2016). Rainfall patterns show high interannual variability driven by multiple complex climatic systems (Forootan et al. 2016; Risbey et al. 2009; Wang and Hendon 2007). Specifically, climatic variability in Australia is mainly influenced by El Niño–Southern Oscillation (ENSO), the Indian Ocean dipole (IOD), and the southern annular mode (SAM) that have been shown to have a strong and complex effect on rainfall variations due to the synchronization of three climate modes (Suppiah 2004; Cleverly et al. 2016; Xie et al. 2019). Due to the extensive scope of the continent and the different degree of climatic impacts on rainfall, interannual precipitation variability is large and rainfall conditions vary across Australia from coastal areas to central areas. These conditions have created interest in rainfall pattern analysis in Australia under different wetness conditions. Although many studies have attempted to characterize rainfall variation and establish the relationship between climate change and rainfall patterns in Australia, a comprehensive understanding of rainfall pattern changes has not yet been established. Meanwhile, Australia is an ideal natural laboratory for rainfall analysis to reveal various aspects of climatic influences and the driving mechanism of rainfall pattern changes (Hutley et al. 2011).

In this study, we analyzed long-term rain site data from 1910 to 2017 at a subcontinental scale in the Northern Territory of Australia. This region is well known as a north–south rainfall gradient transect varying from wet to dry rainfall conditions (Hutley et al. 2011). We used analytical methods to systematically and comprehensively identify rainfall pattern changes, including rainfall trend, periodicity, abrupt change timing, rainfall probability density changes, and extreme rainfall events. The objectives of this study were to 1) identify rainfall pattern changes under climate change along the rainfall gradient, 2) characterize rainfall variations quantitatively at both spatial and temporal scales over the subcontinental region, and 3) assess the impacts of climate changes on extreme rainfall. Results from this study will be useful in illustrating climate change impacts on rainfall patterns according to long-term historical records. The results will also improve understanding of interactions between hydrological dynamics and climate variation, resulting in the capacity to design strategies for adapting to and mitigating the negative impacts of climate change.

2. Data and methods

a. Study area

In this study, we aimed to comprehensively detect long-term rainfall pattern changes under different rainfall conditions. The Northern Territory of Australia (ranging from 128° to 138°E and from 11° to 26°S) was selected as the study region (Fig. 1) because of its north–south rainfall gradient acting as a well-known natural laboratory (Hutley et al. 2011). The entire area can be divided into two climatic zones according

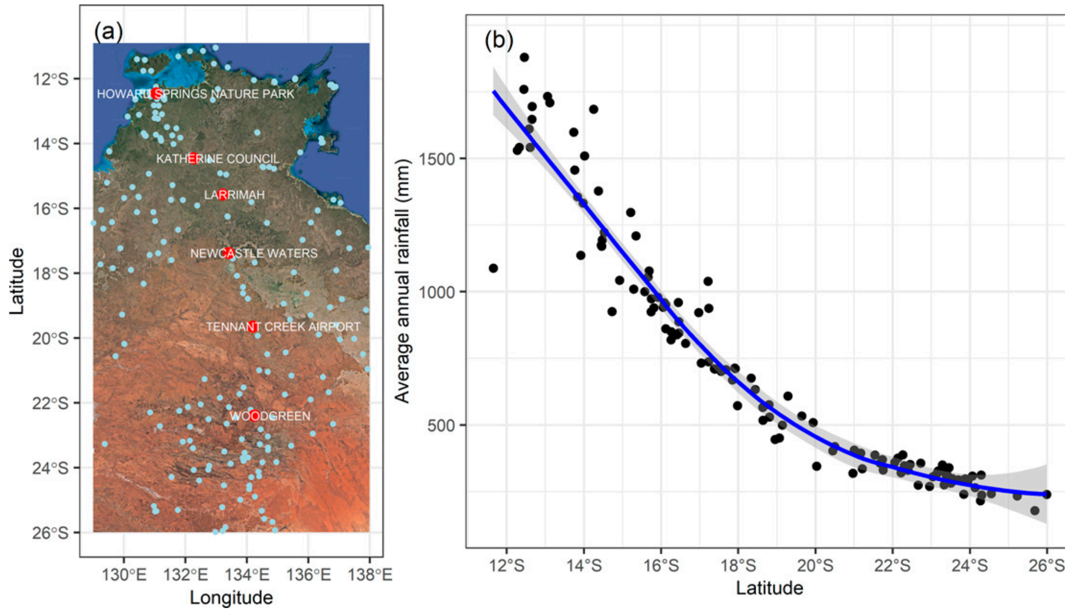

FIG. 1. Study area and the spatial distribution of weather stations in the Northern Territory, Australia. (a) Satellite image and weather sites; (b) rainfall gradient along latitudinal position. Six sites [red dots in (a)] were selected as representative of different rainfall conditions.

to two distinctive climatic conditions that influences the structures and distribution of vegetation biomes: 1) the coastal wet region and 2) the hinterland dry region. In the northern coastal region, two seasons are seen in the monthly rainfall distribution, namely, the wet season from October to April and the dry season from May to September. This seasonal precipitation pattern is also associated with tropical cyclones and monsoonal activity (Williams et al. 1996). Average annual rainfall decreases at a rate of about 1 mm per 1 km from the northern coast (1800 mm yr^{-1}) to the inland area (200 mm yr^{-1}). Hence, the central hinterland region is semiarid or desert with the lowest water supply, and the driest region receives annual rainfall of less than 200 mm yr^{-1} Additionally, the interannual variability of rainfall in this region is large, with the difference in rainfall amount between wet years and dry years reaching up to 1000 mm. In terms of rainfall gradient associated with rainfall variability, the Northern Territory is a suitable area for accomplishing the research aims of this study (Koch et al. 1995).

b. *Rainfall data*

In the Northern Territory of Australia, annual rainfall varies from the coastal regions to the central inland. To analyze long-term rainfall variations at this subcontinental scale, high-quality meteorological data were obtained from the Scientific Information for Land Owners (SILO) database that included gauge-based daily rainfall data from 1910 to 2017 with quality assurance controlled by the Australian Bureau of Meteorology (https://www.longpa ddock.qld.gov.au/silo/point-data/). A total of 230 sites were located in our study area. The spatial distribution of those sites covered regions evenly from the coastal wet rainfall condition to the central dry rainfall condition in the Northern Territory of Australia, except for the western mountainous region between 20° and 22°S that had few established observation sites (Fig. 1). We desired to analyze the long-term variations of rainfall patterns with the longest qualified records. However, because rainfall records prior to 1910 were not quality-checked (Lavery et al. 1992), we only used the rainfall records from 1910 to 2017. To further analyze rainfall pattern changes, we deliberately selected six representative sites across wet to dry regions (Table 1). The selection of six sites was mainly based on two criteria, namely, representative for different rainfall conditions along rainfall gradient and higher data quality compared with adjacent sites. The annual rainfall at each site was derived from daily rainfall amounts. A single rainfall event was defined as the period of consecutive rainy days from the beginning to the end of a rain period in order to analyze variations in rainfall magnitude.

The long-term rainfall series were analyzed based on the fundamental components of time series and the comparison of changes among different periods. The illustrative workflow figure was presented, and the detail and processes were introduced as follows (Fig. 2).

c. *Trend analysis*

Trend analysis is one of the most prevalent methods used to identify the overall changes of time series data (Longobardi and Villani 2010; Partal and Kahya 2006). In this study, we used linear regression to examine long-term rainfall variations and to identify the long-term trend of annual rainfall in the Northern Territory of Australia. Rainfall data from a total of 230 sites were used from 1910 to 2017 (108 years). Additionally, six representative sites (shown as red dots in Fig. 1 and listed in Table 1) were selected to represent long-term rainfall trends under different rainfall conditions. The spatial pattern

TABLE 1. Representative rainfall sites in the Northern Territory, Australia.

Sites	Lon (°)	Lat (°)	Rainfall (mm)	Temperature (°C)	Biomes	Observed rate (overall/after 1960)
Howard Springs Nature Park	131.05	−12.46	1700	27.58	Tree open	34.5%/76.6%
Katherine Council	132.25	−14.46	1000	27.32	Tree open	94.8%/89.2%
Larrimah	132.21	−15.57	797	26.83	Tree sparse	49.2%/98.5%
Newcastle Waters	133.41	−17.38	515	26.72	Tussock grasses closed	92%/94.6%
Tennant Creek Airport	134.18	−19.64	396	25.78	Shrubs and grasses sparse scattered	37.6%/83.5%
Woodgreen	134.23	−22.40	287	22.39	Shrubs and grasses sparse scattered	55.3%/99.8%

of long-term rainfall trends was produced by spatial interpolation of trends at all sites.

d. Periodicity analysis

The periodicity of a hydrological phenomenon refers to its periodic variations over time. Due to the influence of meteorological factors, rainfall presents the regularity of alternating periods of wet and dry states. In this study, wavelet analysis was employed to analyze rainfall periodicity. This method has been widely applied to analyze periods for stationary and nonstationary features of time series in meteorology (Beecham and Chowdhury 2010; Nakken 1999; Rashid et al. 2015).

Wavelet transform is a local time–frequency domain transform that can effectively extract information from signals and perform multiscale analysis on signals through operations including scaling and translation. Unlike Fourier transform only being able to transfer time series from time scale to frequency scale with a fixed frequency, wavelet transform analysis inherits and develops the idea of localization of Fourier transform and overcomes the shortcomings of window size not changing with frequency. Therefore, wavelet transform analysis can provide a "time–frequency" window that varies with frequency, leading to an ideal tool for stationary and nonstationary signal time–frequency analysis (Addison 2002; Torrence and Compo 1998).

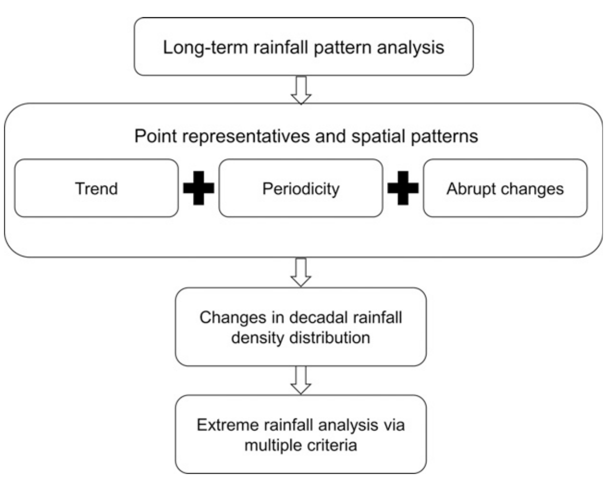

FIG. 2. The workflow of the study.

Hence, we adopted wavelet transform to determine the long-term period of rainfall and its time–frequency variations. The continuous wavelet transform is expressed as

$$W(a, b) = \frac{1}{\sqrt{a}}\int_{-\infty}^{\infty} f(t)\psi_{a,b}\left(\frac{t-b}{a}\right)dt, \tag{1}$$

where W is the wavelet transform coefficient with a as the scale parameter and b as the time position parameter. The term $1/\sqrt{a}$ is used to normalized wavelet energy, $f(t)$ is time series or signals to be analyzed, and $\psi(t)$ is the mother wavelet complex conjugate. In this study, the Morlet wavelet was selected as the mother wavelet function for rainfall period analysis and has been widely applied in hydrological and meteorological time series analysis (Moreira et al. 2019; Nakken 1999). The expression of the Morlet wavelet is presented as

$$\psi(t) = \pi^{-1/4}\exp(i\omega_0 t)\exp\left(-\frac{1}{2}t^2\right)\int_{-\infty}^{\infty} f(t)\psi_{a,b}\left(\frac{t-b}{a}\right)dt, \tag{2}$$

where ω_0 is frequency and t is time. When considering periodical analysis, setting ω_0 as 6 is an appropriate choice to balance time and frequency.

In this study, we first calculated wavelet coefficients for the six representative sites from the coastal area to the central region in the Northern Territory, and then plotted the wavelet power spectrum of annual rainfall at the time–frequency domain for detecting periodicity and temporal variances. Afterward, the Morlet wavelet method was applied to all 230 sites located in the study area and the major long-term period (>10 years) at each site was diagnosed by detecting peak value of global power spectrum derived by integrating power spectrum over time scale to get an overall mean value of period for rainfall periodicity analysis. Here, wavelet analysis processes were completed via the WaveletComp package in R programming developed by Roesch and Schmidbauer (2014).

e. Abrupt change analysis

In this study, the Mann–Kendall test (Kendall 1948; Mann 1945) was applied to diagnose abrupt changes in rainfall patterns and to identify the timing of abrupt rainfall changes. This method has been extensively used in meteorology and hydrology for diagnosis of abrupt changes (Douglas et al. 2000; D. Shen et al. 2018). We used the Mann–Kendall test at the six representative sites to first identify the timing of rainfall patterns shifting under different water conditions, and then to summarize the major times of abrupt changes in regional rainfall patterns by analyzing statistical values at all 230 sites. To conduct the Mann–Kendall test for abrupt change analysis, the annual rainfall time series were processed by the following steps.

The statistical rank series S_k is constructed as

$$S_k = \sum_{i=1}^{k} r_i,\ k = 2, 3, \ldots, n, \tag{3}$$

where

$$r_i = \begin{cases} 1, & X_i > X_j \\ 0, & X_i \le X_j \end{cases} \ 1 \le j \le i. \tag{4}$$

The statistical series is defined as

$$\mathrm{UF}_k = \frac{S_k - E(S_k)}{\sqrt{\mathrm{var}(S_k)}},\ k = 2, 3, \ldots, n, \tag{5}$$

where $\mathrm{UF}_k = 0$ is given, $E(S_k)$ and $\mathrm{var}(S_k)$ are the mean and variance of the rank series, respectively, and can be calculated as

$$E(S_k) = \frac{k(k-1)}{4}, \tag{6}$$

$$\mathrm{var}(S_k) = \frac{k(k-1)(2k+5)}{72}. \tag{7}$$

Then the original time series, $X_1, X_2, \ldots, X_n$, is reversed and the above steps repeated to calculate UF_i. Following this, the process shown below was used to obtain the rank series UB_k:

$$\mathrm{UF}_1 = 0, \tag{8}$$

$$\mathrm{UB}_k = -\mathrm{UF}_i,\ i = n,\ n-1, \ldots, 1. \tag{9}$$

The abrupt changepoint was determined as the intersection point of the UF_k and UB_k sequences. If the intersection point existed and was also located within the confidence interval [−1.96, 1.96], then we could identify the specific year of the occurrence of the abrupt change in rainfall via its corresponding time of rank series intersection.

f. Probability density distribution

To explore rainfall pattern changes through time, we analyzed the changes in annual rainfall probability density distribution. The six representative sites were used to illustrate rainfall pattern changes under different rainfall conditions. To validate that rainfall patterns had changed distinctively, we divided the time series into four periods, namely, 1910–35, 1936–62, 1963–89, and 1990–2016. These partitioning times were determined by association with the results of the mean major period to determine the length of the partitioning time (described in section 3b) and the abrupt change times to determine the cutting point of partitioning time (described in section 3c). Then the annual rainfall probability density distribution for each 27-yr period was derived from the smoothed histogram over via kernel density estimate, and then overlayed together for comparison. Annual rainfall amounts greater than the 95th percentile were considered to be extremely wet years (Haylock and Nicholls 2000; Shahid 2011) and were presented as a threshold in analysis. Furthermore, mean precipitation, standard deviation values, and coefficient of variation for each period at each of the six sites were also calculated for illustration and comparison.

g. Extreme rainfall event analysis

In addition to annual rainfall amounts, the rainfall amount of each individual rainfall event is also a critical element for analyzing the impacts of climate change on rainfall patterns (Boers et al. 2013; Jung et al. 2011). In this study, the total rainfall amount of consecutive rainy days was considered to be the rainfall amount of one single rainfall event. We defined an extreme rainfall event as one that exceeded the 95th percentile from the historical record at the six sites. The frequency of extreme rainfall events was counted for every 10-yr interval. The influence of climate change was assessed from the trends of extreme rainfall events. The rainfall events were ordered from smallest to largest values, and then the percentile formula was used to identify the extreme rainfall event threshold as

$$R = \frac{P}{100} \times (N + 1), \tag{10}$$

where R is the rank for the specific percentile, P is the desired percentile ($P = 95$ in this analysis), and N is the number of total rainfall events.

To further investigate the changes in extreme rainfall, we selected multiple criteria to evaluate extreme rainfall, including maximum 1-day rainfall (Rx1day), maximum 5-day rainfall (Rx5day), consecutive wet days (CWD), consecutive dry days (CDD), number of rainy days with rainfall > 10 mm day^{-1} (R10mm), and simple daily intensity (SDII). The above indices were calculated each year across six representative sites, and mean values of each index during the partitioned period were used for comparison and analyzing changes in extreme rainfall.

In addition, all of above analyzing diagnosis of rainfall pattern were conducted by using R programming.

3. Results

a. Trends of long-term annual rainfall

The long-term annual rainfall time series showed both noticeable decadal trends and interannual variability at all six selected sites from the wet coastal region to the dry central region in the Northern Territory (Fig. 3). We found that all six representative sites exhibited a significant increasing trend ($p < 0.05$) from 1910 to 2017 across the regional rainfall gradient. The coastal site (Howard Springs Nature Park) was the wettest site with mean annual rainfall around 1700 mm yr^{-1}. At this location, annual rainfall increased at a rate of 4.36 mm yr^{-1}.

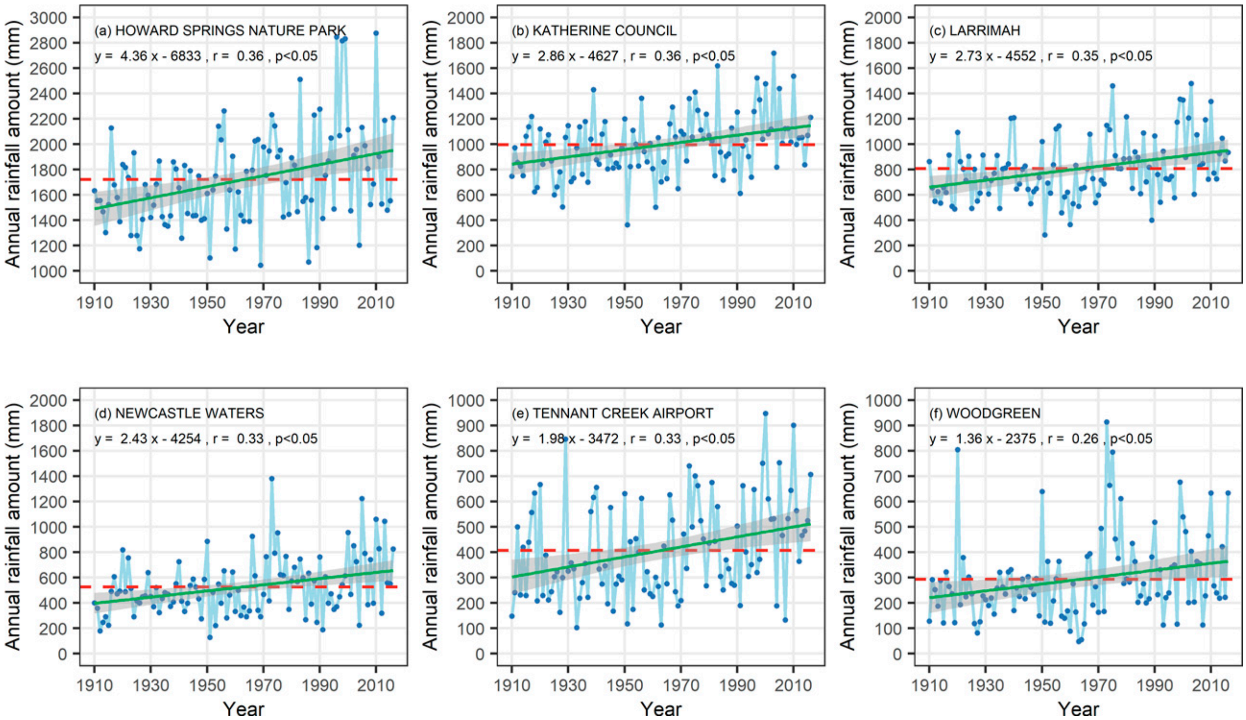

FIG. 3. Long-term annual rainfall trends at six selected sites in the Northern Territory, Australia, from wet coastal regions to dry central regions. The red dashed lines show the average annual rainfall for each site. The green line indicates the linear regression, and the gray areas denote the 95% confidence intervals.

Mean annual rainfall declined as distance from the coast increased toward the central areas. The rate of rainfall increases over time declined to 1.36 mm yr^{-1} ($p < 0.05$) at the driest site (Woodgreen) where mean annual rainfall was around 300 mm yr^{-1}. Although a consistent increasing rainfall trend was observed under the different annual rainfall conditions at the six sites, a striking finding was that the annual rainfall amount increased with higher rainfall variation in recent decades. Starting with the 1970–90 period, the fluctuations of annual rainfall became larger than observed in previous decades at all six selected sites. The wettest representative site showed rainfall amounts varying from around 1000 mm yr^{-1} to as much as 2800 mm yr^{-1}, and even the driest site had an annual rainfall observation reaching as high as 900 mm yr^{-1} after 1970 (triple the mean annual rainfall amount). The detectable rainfall pattern changes could be characterized not only as consistently increasing trends, but also as having higher rainfall variability since 1970 according to the rainfall data at the six sites.

The spatial pattern of annual rainfall trend in the study area (Fig. 4) was determined by Kriging interpolation of data from the 230 weather sites. The rainfall trend across the region was in line with the consistent increasing trend at the six selected sites. On average, precipitation for the coastal region increased at a rate of 45–65 mm per 10 years, whereas precipitation in the central region increased at a rate of only 5 mm per 10 years. However, the incremental proportion of annual rainfall was 50% in central dry region, which was twice than that in coastal wet region. As latitude increased toward the central hinterland, annual rainfall amount decreased following the rainfall gradient. However, an increasing trend of annual rainfall over time was seen over the entire Northern Territory of Australia.

b. *Periodicity of long-term rainfall patterns*

The decadal periods of rainfall pattern were diagnosed via Morlet wavelet analysis for the six representative sites using the annual rainfall time series from 1910 to 2017. The results shown in Fig. 5 are wavelet power spectra in the time–frequency domain. When focusing on long-term decadal periods greater than 10 years, a striking finding was that six selected sites presented a consistent period mainly concentrated within a 27–30-yr interval, indicating temporal variations in rainfall patterns that represented a corresponding 27–30-yr interval for rainfall cycle or shift from one rainfall state to another rainfall state. As for time domain, the distinct long-term main periods became significant after 1970 across wet sites to dry sites represented by black dashed lines in Fig. 5, indicating the consistent timing of periodical variations.

The peaks of the average wavelet spectra across period scale indicated the main period for time series. After removing short-term period disruptions and illustrating the long-term periods (>10 years) for the 230 sites in our study area, the results revealed that 27 years was the mean long-term period for the entire study area. This result indicated that a noticeable rainfall pattern shift could be part of the reason

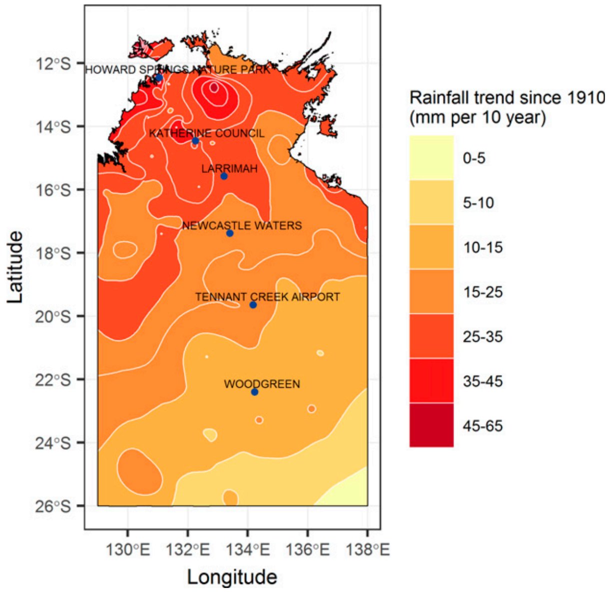

FIG. 4. The spatial pattern of annual rainfall trend in the Northern Territory, Australia, via kriging interpolation.

attributed to a periodical cycle of about every 27 years (Fig. 6). Those period changes were relatively consistent, and the value of the main period became less variable (with a temporal interval of 26–30 years) in the drier regions where annual rainfall was below 600 mm yr^{-1}. In addition to the main period of 27 years, a second period at the spatial scale was found at 20 years and was found at some specific sites from wet regions to dry regions.

c. Abrupt changes in long-term rainfall patterns

The observation of an abrupt change in the rainfall pattern (i.e., rainfall amount increasing steeply or decreasing dramatically) indicates the time of a major change in rainfall pattern and may also be associated with greater rainfall variation. In this study, the abrupt changes in the annual rainfall time series retrieved from the six selected sites located from wet coastal regions to dry hinterland regions were detected by the Mann–Kendall test. This test identifies the year of the abrupt change by testing whether the intersection point of Mann–Kendall statistical sequences from the original time series and reversed time series is within the 95% confidence interval. Figure 7 shows that all six selected sites identified the abrupt change in precipitation to occur in the period between 1965 and 1975 (see the point at which the blue and red lines intersect in Fig. 7), except at Tennant Creek Airport, where the intersection point occurred in 1989. We found the times of the abrupt change in rainfall pattern at different rainfall levels (from wet to dry) across the region pointed out a relatively distinct and temporally consistent shift. The annual rainfall time series shown in Fig. 3 clearly shows an increase after the 1970s. Furthermore, the detected time of abrupt rainfall change was also consistent with the timing of wavelet power spectra for most sites that showed apparent higher values within the 95% confidence contour after the 1970s (Fig. 5). The time of change in rainfall pattern was not distinctly different for the six selected representative sites across the rainfall gradient, and the changes of rainfall pattern remained relatively uniform at the temporal scale irrespective of rainfall conditions.

The times corresponding to the abrupt change in rainfall for the 230 sites over the entire study area were divided into four groups according to average annual rainfall amounts (Fig. 8). We found two apparent timing points for abrupt changes in rainfall (i.e., 1970 and 1990), indicating that the rainfall pattern shifted dramatically primarily during the periods of 1966–75 and 1986–95. Most of the sites classified as wet (humid and semi humid) or dry (arid) rainfall conditions were found to have the abrupt rainfall change occurring in 1970. However, sites classified as medium dry (semiarid) were found to have the highest frequency of time of abrupt rainfall change close to 1990, and this was the second peak timing of abrupt changes throughout the 230 sites. Overall, 73% of the sites presented the time of abrupt rainfall change after 1965, demonstrating that the regional rainfall pattern had an apparent shift in recent decades.

d. Density distribution of rainfall patterns and extreme rainfall events

We compared the density distribution curves of rainfall patterns at the six selected sites (Fig. 9) by analyzing annual rainfall time series from 1910 to 2016. Each time series was divided into four periods according to the 27-yr mean cycle period and two abrupt timing points, 1970 and 1990, to guide our selection of the four time intervals to be used for analysis. Following this, the changes in rainfall pattern were determined for four periods, namely, 1910–35, 1936–62, 1963–89, and 1990–2016. The distributions clearly showed that the mean values of annual rainfall had continuously increased over time across the wet regions to the dry regions. As for the Howard Springs Nature Park site (representing the wettest rainfall condition), mean annual rainfall increased 390 mm from the earliest 1910–35 period to the latest 1990–2016 period. Although mean annual rainfall at the Woodgreen site (representing the driest rainfall condition) was not different between the period from 1990 to 2016 and the period from 1963 to 1989, mean annual rainfall was almost 100 mm greater after 1963 than before 1963. The significant increasing rainfall trend over time was observed at the other sites toward the central hinterland, but the increases over time became less as annual rainfall declined.

Although all six representative sites presented an increasing trend in rainfall over time, we noticed that the timing of a larger increment shift coincided with the timing of the abrupt change in rainfall amount described above. Furthermore, not only did rainfall pattern change (increasing values of mean annual rainfall), but the variation of annual rainfall also became larger throughout the study area. The standard deviation of annual rainfall at the wettest location increased by 240 mm from 227 to 467 mm and increased by about 30 mm for the two driest sites. While the coefficient of variation (CV)

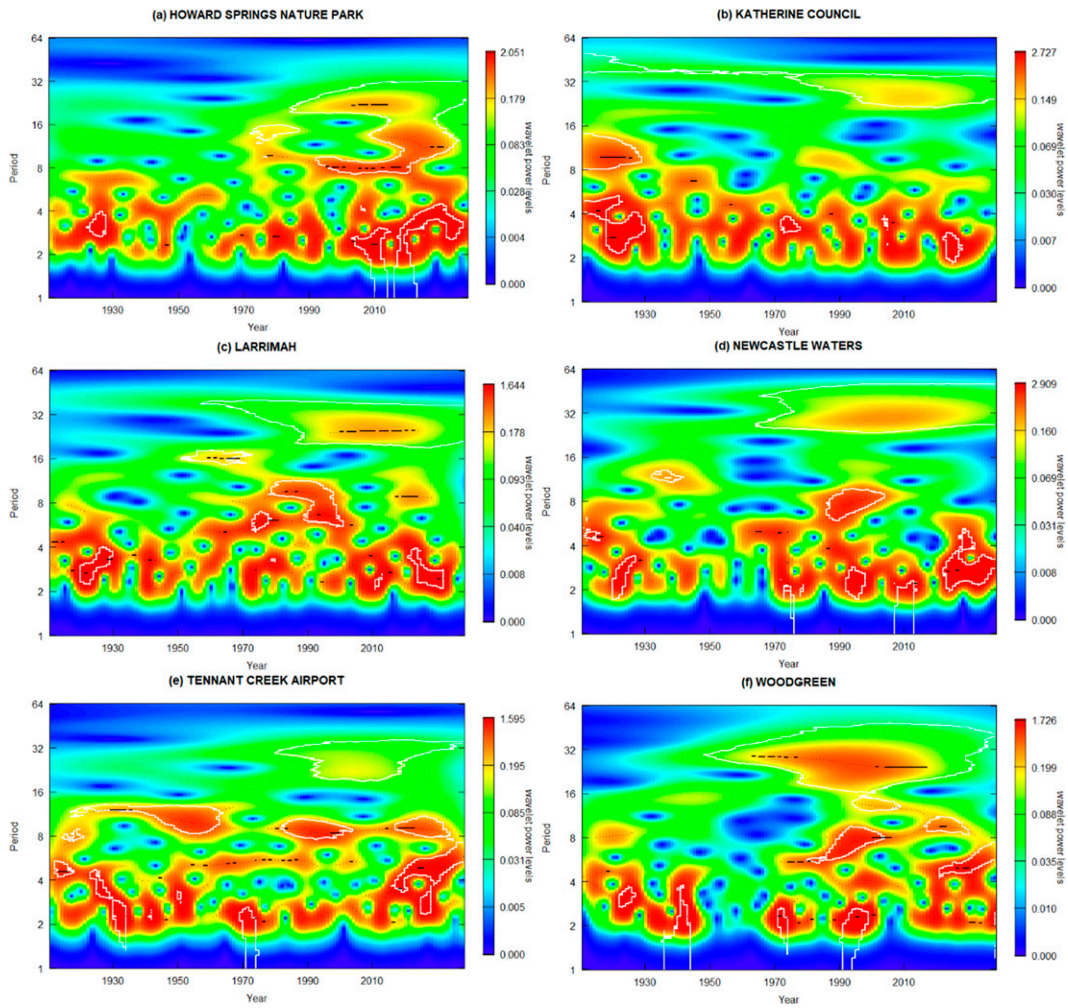

FIG. 5. Wavelet power spectra using Morlet wavelet analysis for six representative sites in the Northern Territory, Australia. The area within the thick white contours indicates that wavelet power spectra were statistically significant at the 95% confidence level, and black dashed lines denote the main detected periods of rainfall pattern in the frequency domain.

denoted a higher rainfall variability in drier regions by showing higher CV values along rainfall gradient from wet to dry at spatial scale. Meanwhile, the density distribution curves appeared to become flatter over time as a result of the higher variability with temporal comparison. The black dashed lines in Fig. 9 are the 95th percentile values of annual rainfall that were used as the threshold values to represent the extreme annual rainfall condition at the six sites. We found that all six sites showed that the highest density of extreme annual rainfall occurred after 1990, indicating that rainfall patterns had changed to be wetter along with greater probabilities of extreme wet year in recent decades.

In addition to the increase in annual rainfall amount over time, we also observed that the frequency of extreme rainfall events increased with time to demonstrate rainfall pattern changes in wetter tendency with higher variations (Fig. 10). We counted the number of times that rainfall events occurred with accumulated rain amount greater than the 95th percentile of the long-term historical values at each site and found all six sites exhibited an increasing trend of the frequency of extreme rainfall events throughout the entire rainfall gradient region. Meanwhile, the sites located under medium rainfall conditions, such as Larrimah and Newcastle Waters, presented a higher variation of the frequency of extreme rainfall events than observed at the other sites. The changes in rainfall pattern, therefore, exhibited not only increasing amounts of rainfall over time, but also had more extreme rainfall events and larger variation in rainfall over the entire study region from wet to dry rainfall conditions.

To further explore variations of rainfall pattern changes, we selected six indices to characterize the frequency and intensity of extreme rainfall. The comparison of mean values of six indices among the four partitioned periods covering 1910–2016 was used to analyze changes in extreme rainfall (Fig. 11). Rx1day and Rx5day characterized the extreme of short intense rainfall event over the year. Both indices presented

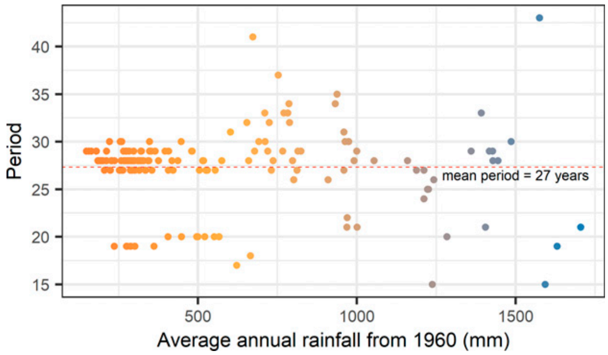

FIG. 6. Diagnosis of the major long-term period for all rainfall sites in the Northern Territory, Australia. The major period was extracted from the wavelet power average across the time of a single time series at each site. The dashed line denotes the mean value for all sites (27 years). The symbol colors indicate different rainfall conditions from dry to wet.

a consistent increase from wet sites to dry sites in recent decades. Particularly, sites in humid and arid regions (i.e., Howard Springs Nature Park and Woodgreen) presented a higher changed proportion than other sites in semihumid and semiarid regions. CWD and CDD expressed the consecutive rainy days and the length of drought. According to our results, sites in humid and arid regions (i.e., Howard Springs Nature Park, Katherine Council, and Woodgreen) have clear shortened consecutive rainy days and a corresponding longer length of period with no rain, which means the intensity and variability of rainfall could increase further in those sites by indicating more rainfall events within shorter rainy season. R10mm and SDII indicate overall changes in wetness by showing more effective rainy days and average rainfall intensity over the rainy days. Our results of those two indices confirm that the entire region from wet to dry was becoming wetter.

4. Discussion

a. Significant rainfall pattern changes over a subcontinental region

Our study confirmed that rainfall patterns had already changed under climate change with respect to the aspects of trend, periodicity of annual rainfall, and abrupt changes of long-term rainfall observations. The analytic results, derived from rainfall observations at 230 sites covering an extensive subcontinental region from 1910 to 2017, revealed distinct rainfall pattern changes in recent decades, presenting an increasing trend of rainfall amount associated with higher variations across wet to dry rainfall conditions. With measurable global warming (Chou et al. 2013, 2009; Held and Soden 2006; IPCC 2013), hydrological processes have been accelerated, and the intensification is expected to follow the law of thermodynamics at a rate of 6.5% $°C^{-1}$ according to the Clausius–Clapeyron rate (Allan and Soden 2008), resulting in greater

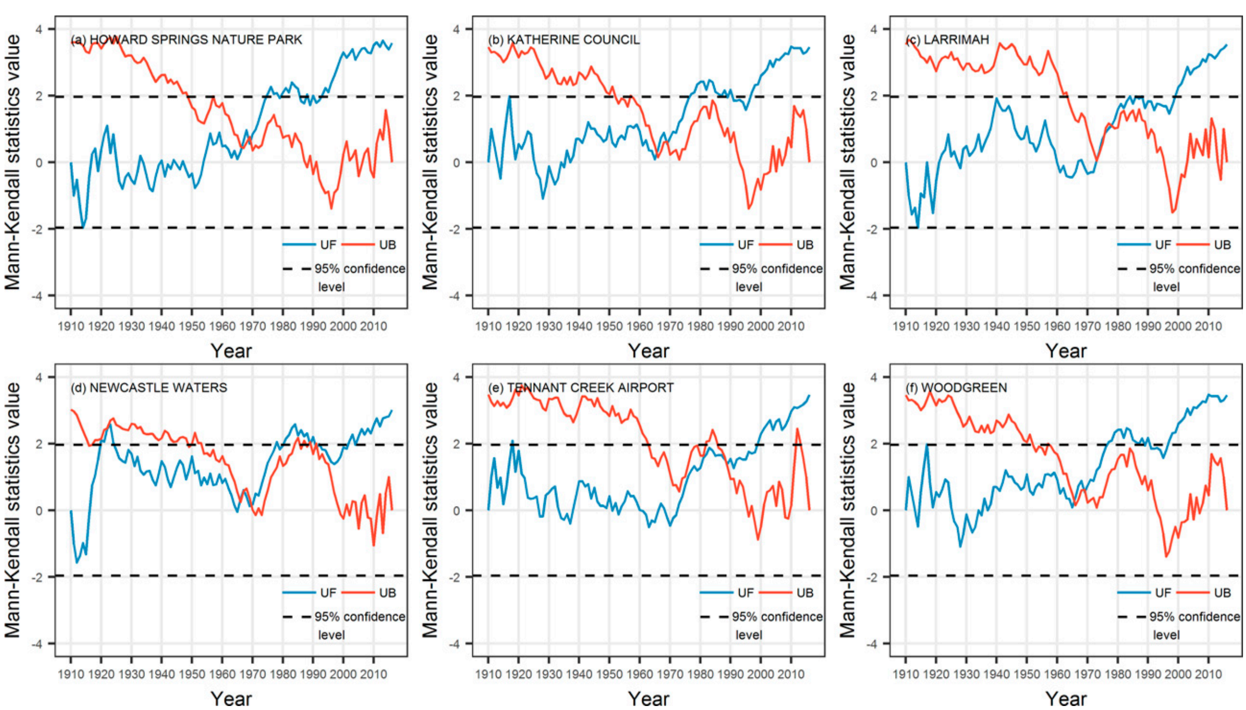

FIG. 7. Diagnosis of the time of abrupt change in annual rainfall for six representative sites in the Northern Territory, Australia as determined by the Mann–Kendall test. The blue line (UF) denotes the statistical series from the original time series, and the red line (UB) denotes the statistical series from the reversed time series. The corresponding time of intersection point within the 95% confidence interval (dashed lines) indicates the specific year of the abrupt change in rainfall.

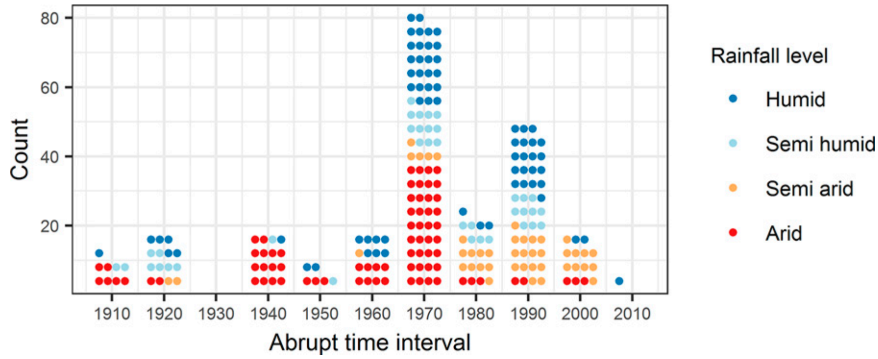

FIG. 8. The statistical frequency of the year of abrupt change in rainfall for 230 sites across the Northern Territory, Australia. Each single dot represents the corresponding time of abrupt change within the 10-yr interval for one site (e.g., 1970 representing 1966–75). The colors denote the mean annual rainfall (i.e., dark blue: >1200 mm yr^{-1}; light blue: 800–1200 mm yr^{-1}, orange: 400–800 mm yr^{-1}; red: <400 mm yr^{-1}).

atmospheric moisture and more frequent rainfall events. Our findings also confirmed that climate change had a distinctive climatic impact on increasing tendency of annual rainfall amount, which is in line with results of previous studies (Haylock and Nicholls 2000; Suppiah 2004).

Our study showed the rainfall pattern not only changed in terms of quantitative variation, but also presented a temporal shift in rainfall. Northern Australia has seen a relatively stable increasing trend in rainfall amount over time, with noticeable fluctuations or oscillations in rainfall. However, in latter decades,

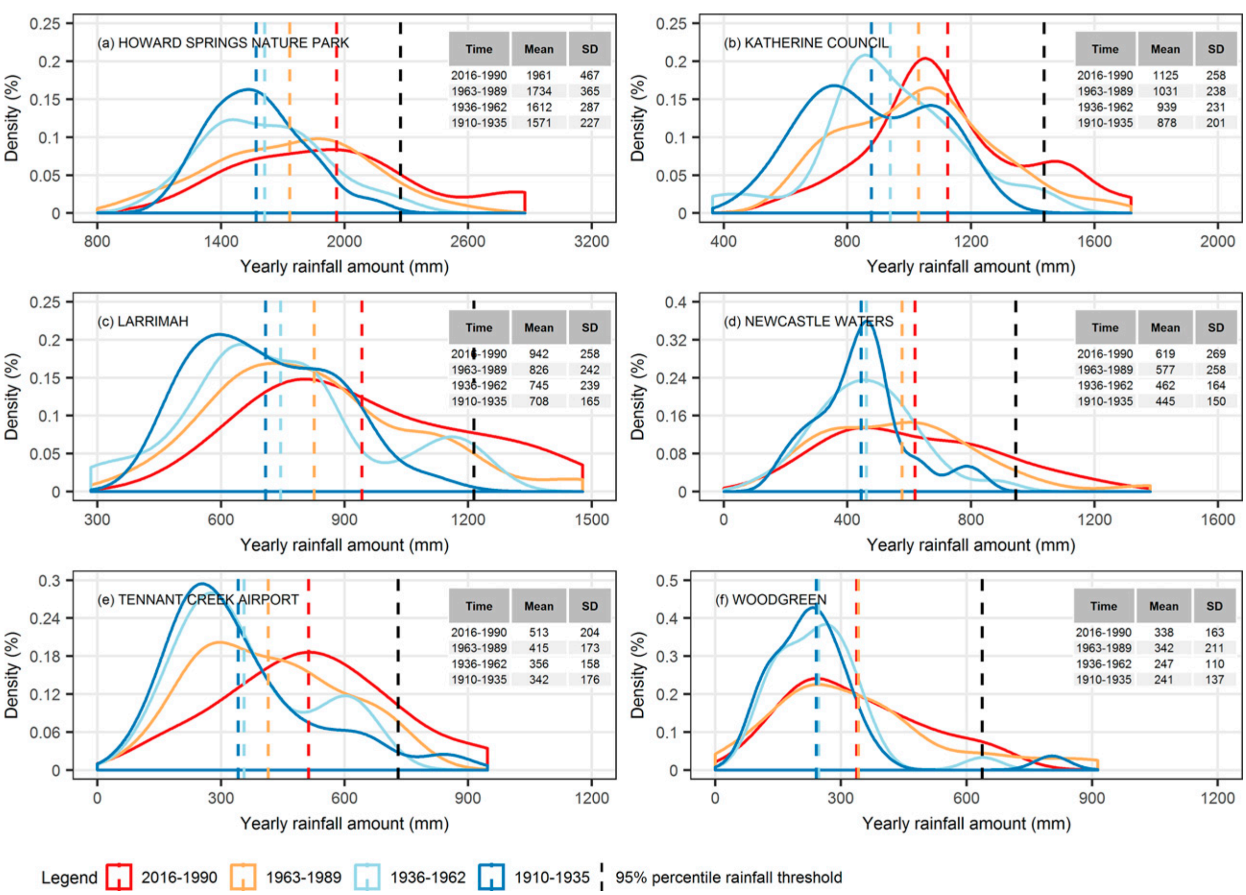

FIG. 9. Changes in the probability density of rainfall for six locations in the Northern Territory, Australia. Each time series was divided into four periods for comparison. The mean value for each period was shown with the corresponding dashed color line. The dashed black line denotes the 95th percentile (i.e., rainfall amounts greater than this line were considered as extreme rainfall amounts).

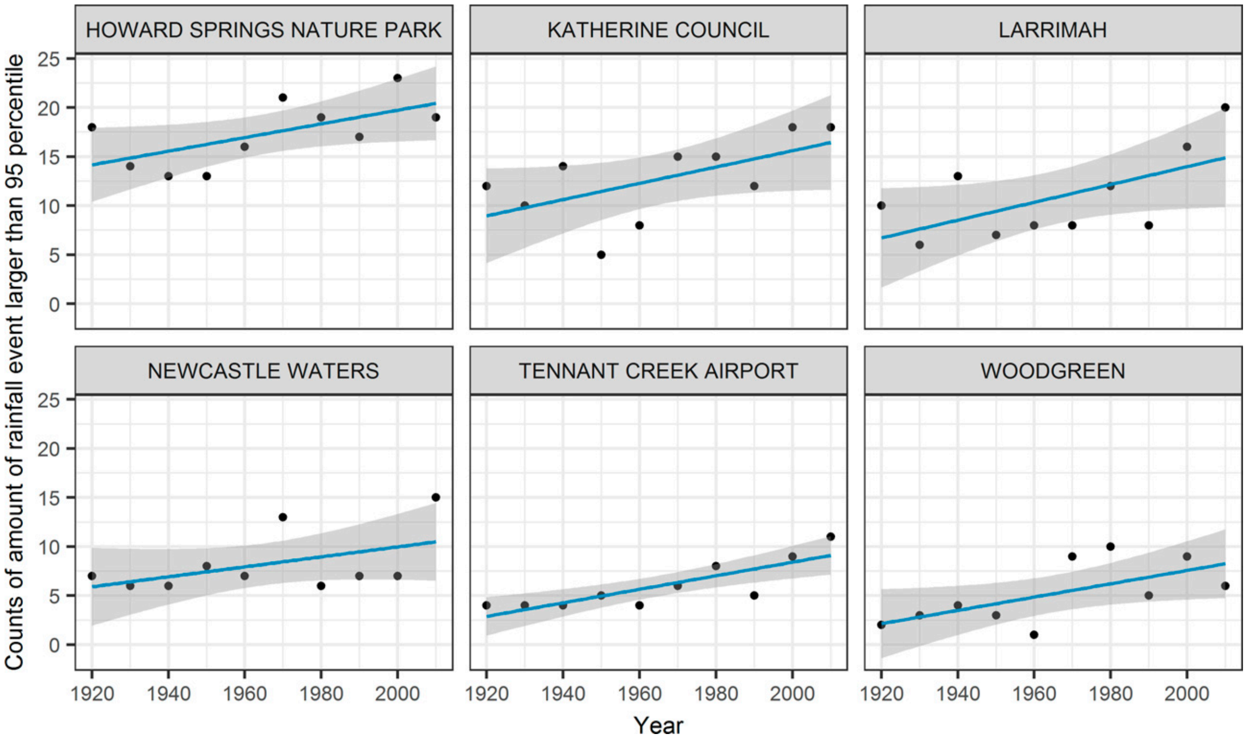

FIG. 10. The tendency of extreme rainfall events at six representative sites in the Northern Territory, Australia. The blue lines are linear regressions applied to the data points. The blue shaded area represents the 95% confidence interval of the regression.

the rainfall pattern shifted from a stable but small increasing state to a state of larger rainfall increase over time with higher variability. We characterized the timing of rainfall pattern shift over the subcontinental region in the aspects of trend, periodicity of annual rainfall, and abrupt change in annual rainfall. It is worth noting that the rainfall pattern shift appeared to happen within a specific period around 1970. We not only detected the convergence of the timing of the abrupt change in rainfall amount at 1970 or so via the Mann–Kendall test, but also found that annual rainfall amount showed a dramatically increasing trend since 1970. The wavelet power spectrum that indicated temporal variations was observed to increase since 1970 as well. Those shifts and changes were all consistent at the temporal scale. Hence, the interactions and changes in rainfall patterns help to explain some of the pressure felt from changing climatic factors that had occurred since 1970. Much research has observed and reported the rainfall pattern changes in the 1970s and related the rainfall anomalies to modes of ENSO (Cook and Heerdegen 2001; Forootan et al. 2016; Grimm and Tedeschi 2009; Watterson 2009). This research pointed out that frequent strong El Niño events occurred around 1970 (Yu and Zou 2013) and coincided with the time of observed rainfall pattern changes in our study. These findings supported the potential climatic drivers of rainfall pattern changes (King et al. 2014; Risbey et al. 2009).

According to a systematic diagnosis of rainfall pattern, we obtained a further understanding of how climatic factors influenced rainfall pattern behaviors. Meanwhile, we cannot ignore that anthropogenic activities have intervened in natural processes in recent decades and have been a potential factor affecting rainfall. Further discussion on the connections between those natural and anthropogenic factors is beyond the scope of this study. However, we realize that rainfall patterns had distinctive changes over the study area in both annual amount and variability around 1970, and this period provides a diagnosing window to investigate the influences of changing rainfall patterns on society and dependent ecosystems.

b. *The modes of rainfall pattern changes*

We also found the mode of rainfall pattern changes responding to climate change in consideration of trend, periodicity, abrupt change, and extreme events did not present a distinct difference between wet regions and dry regions. Although the quantitative changes in long-term rainfall pattern varied from coastal wet regions to central dry regions, the changes of rainfall pattern in the temporal aspect or shifting state kept consistent at the majority of sites over the study area. Annual rainfall maintained a continuously increasing trend over the entire Northern Territory from the early period of record to the most recent period, irrespective of the different rainfall conditions across the region. According to the long-term observations, the entire region was getting wetter under climate change. Additionally, the entire region showed a relatively consistent time regarding the shifting of rainfall amount. The highest frequency of the time in which rainfall amount was shifting was around 1970, and then in 1990 for both humid and arid areas. Hence, although rainfall

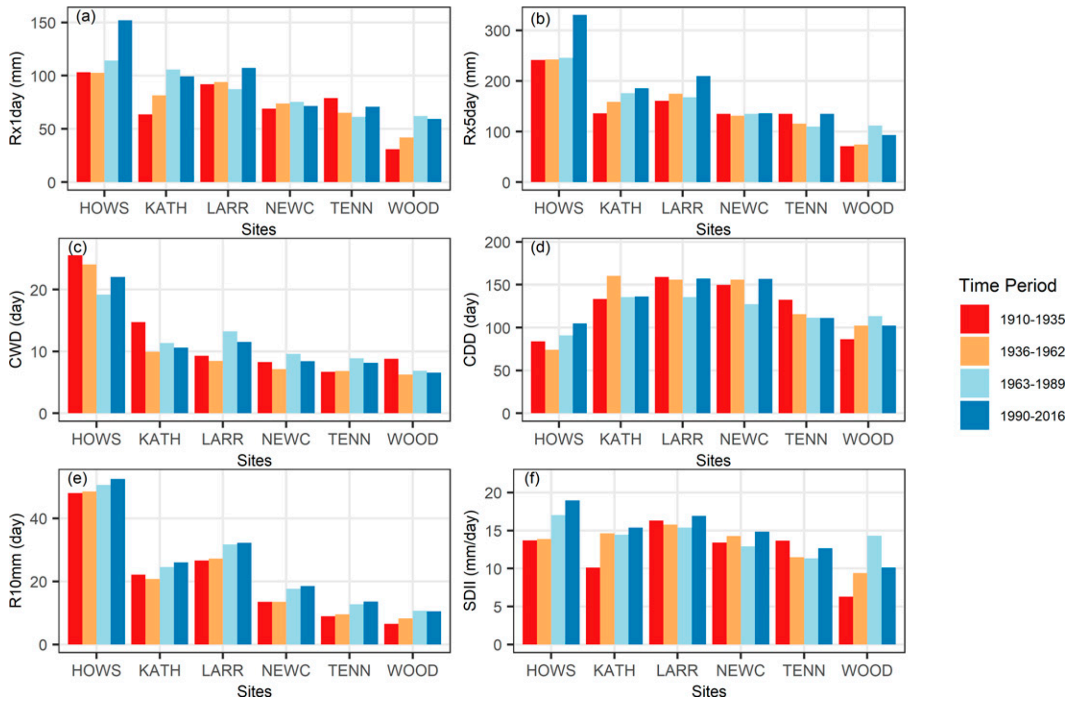

FIG. 11. The mean values of extreme indices in six representative sites across four time periods. The sites were ordered according to annual rainfall levels and names were shortened for clarity.

amounts were clearly different along the regional rainfall gradient from wet to dry, the abrupt change in rainfall amount mainly occurred around 1970 over the entire area. Also, this shift was monotonic for most sites, rather than a decadal oscillation. This means only one single abrupt changepoint was determined for the majority of sites by using the Mann–Kendall test. Meanwhile, the quantitative change in annual rainfall was also in line with abrupt changes. The rate of increasing trend became steeper after 1970 and showed higher variability. Furthermore, the time of this abrupt change was also captured by using wavelet analysis to extract time–frequency variations. We found the stable long-term cycle also appeared around 1970 for all of the sites (wet to dry) by using Morlet wavelet analysis, and this time period also corresponded to the time of an abrupt change. The impacts of climate change on rainfall pattern have increased since 1970, and the intensity of these impacts has covered the extensive subcontinental area from coastal regions to hinterland in the Northern Territory.

Although the entire region presented a consistent shift of rainfall pattern from a stable state to a complex and variable state under climate change, the degree of impacts was different along the rainfall gradient. Mean annual rainfall amount increased by 25% at the coastal site. In contrast, mean annual rainfall increased by as much as 50% at inland locations. The standard deviation of annual rainfall amount also revealed the higher variability of rainfall observed in drier regions. The changes in rainfall patterns were more intense in water-limited regions. Water is not a major restriction to vegetation or ecosystems in wet regions, so the impacts of rainfall fluctuations in such regions are limited. However, intense fluctuation of rainfall patterns is strongly linked to water availability and water distribution in arid or semiarid regions, and the higher variability can influence vulnerable ecosystems (Thornton et al. 2014). Therefore, rainfall pattern changes should be considered as a more sensitive and influential factor for adaptation and mitigation of climate change in dry regions than in wet regions.

c. *The challenge of rainfall pattern changes with frequent extreme events*

Apart from the findings of rainfall pattern changes with regard to trend, periodicity, and abrupt changes, we also noticed that more extreme rainfall appeared in forms of both frequency and intensity of rainfall events. Considered over the 1910–2017 historical rainfall record, annual rainfall exhibited an apparent increasing trend, as did extreme annual rainfall, defined as annual precipitation greater than the 95th percentile in the historical rainfall record (shown in Fig. 9), and a higher probability of occurring across the entire region from wet to dry sites were detected in the most recent 30 years. However, this did not simply indicate water availability increased with regions getting wetter, because the rainfall variability also became higher in the entire regions from wet to dry by showing more extreme rainfall events. The frequency of extreme rainfall events (larger than 95th percentile in history) were all showing an increasing trend in six representative sites, and the intensity of rainfall events also became stronger across six sites by comparing the multiple criteria of rainfall extremes (Fig. 11). Rx1day and Rx5day, presenting the short-term rainfall intensity in sites, were almost consistently increasing across the six sites. Meanwhile, R10mm and SDII, indicating the average wetness level in a certain period, also demonstrated the study area became wetter in average across all six sites. However, it is noteworthy that CWD became shorter in coastal wet representative sites (Howard Springs Natural Park and Katherine Council) and in dry inland sites (Woodgreen). Meanwhile, the CDD became longer as well in the wet site (Howard Springs Natural Park) and dry site (Woodgreen). Those changes implied the shift of long-term rainfall patten was not a stationary process by simply showing more rainfall amount accumulated within shorter rainy period. Therefore, the intensity and the variability of rainfall pattern were becoming higher, especially in wet and dry regions than in the middle study area with semihumid and semiarid rainfall conditions.

The rainfall events became more frequent during wet years, while frequent extreme rainfall events possibly resulted in a series of responses of hydrological processes, including soil water content, evapotranspiration, and runoff generation (Fay et al. 2008; Mpelasoka and Chiew 2009; Wei et al. 2009). More frequent heavy rainfall can cause a series of undesirable consequences, including soil erosion, flooding, and negative impacts on water availability (Fay et al. 2003; Johnson et al. 2016; Knapp et al. 2002; Zhu et al. 2019) that can ultimately result in more uncertainty and risks to ecosystems (Knapp et al. 2008). To be specific in our tropics savanna study area, changes in rainfall pattern and higher variations could directly influence water availability for ecosystems. The abundance and distribution of ever green and rain green biomes are strongly related to rainfall in this study area (Spessa et al. 2005). The evergreen biomes are more related annual rainfall, such as closed forest, open forest, closed woodland, and open woodland, distributing in humid regions and semihumid regions. By contrast, the growth and distribution of rain green biomes are closely related to interannual rainfall and its seasonality. The length of rainy season and water distribution in that period would determine water availability directly for vegetation growth. Hence, the increase of variations with more extreme rainfall also resulted in the uncertainty of ecosystems instead of keeping beneficial as becoming wetter.

Among multiple influential climatic mode of variability, ENSO has been examined to reveal a strong relationship between variations of temperature and hydrological extremes (Risbey et al. 2009). In our study, the finding that the long-term rainfall pattern shifted mainly after 1970 was consistent with the temporal pattern of ENSO events (Suppiah 2004). The Bureau of Meteorology (2012) also reported a strong relationship between La Niña events and frequent extreme rainfall events. Furthermore, combined with the impacts of global warming, extreme rainfall events are expected to become more frequent with accelerated hydrological cycle impacts (Huang and Xie 2015). Rainfall, as one of the most sensitive climatic factors, also reflects climate changes rapidly at both spatial and temporal scales. We also noticed that the annual temperature in Australia also presented a steeper increasing trend after 1970, which coincided with abrupt changes time of rainfall pattern. Therefore, increasing temperature could be another factor to contribute to the frequency and intensity of extreme rainfall events by accelerating water cycle.

In this study, we found that although the magnitude of rainfall events was not uniform over different rainfall conditions, the increasing trends of extreme rainfall events were consistent under the current climatic environment. The impacts of climate change were considered to produce extremes in both coastal and central areas in northern Australia. The increasing trend in annual rainfall amount appeared to be continuous since 1970 rather than fluctuating. Our results confirmed the changes in rainfall pattern across the rainfall gradient region in the northern Australia at both quantitative and temporal scales. Irrespective of rainfall conditions, changes in rainfall patterns and extremes have been detected. However, the impacts of rainfall pattern changes and higher variability would be larger in water-limited inland. We must acknowledge the prospect that extreme rainfall events will happen more frequently if global warming is not alleviated. Frequent extreme rainfall events also play a critical role in climatic systems by influencing water distribution at spatial and temporal scales, further threatening biospheres, vulnerable ecosystems, and our society (Barron et al. 2012; Greenville et al. 2012; Heisler-White et al. 2009; Vörösmarty et al. 2013; Wilhelmi and Morss 2013). Hence, our research serves a supporting role in assessing the impacts of climate change in future scenarios.

d. *The reliability of results regarding to data quality*

In this study, we combined the results based on observations in representative sites and regional statistical results derived from 230 sites over the whole study area to diagnose rainfall pattern changes under climate change. Actually, based on the quality of the SILO dataset, we have to face the issue that the detected changes in rainfall pattern could be caused not only by climate change but also by data quality and artifacts, including relocation or upgrading instruments. However, according to the consistency of findings and comparison to the analyzed results based on high-quality sites, we have confidence to infer that the changes in long-term rainfall pattern are mainly caused by climate change rather than artificial factors. First, the detected changes in rainfall pattern were consistent among different rainfall features, including trend, periodicity, and abrupt timing point, which were shown a clear shifting time around 1970. This timing point also coincided with the shifting time of ENSO and temperature (Suppiah 2004; Bureau of Meteorology 2012). Second, the temporal variations were also captured via multiple decomposed rainfall components, and the findings were consistent or convergent along rainfall gradient from wet to dry. Those changes were more likely caused by climate changes at a large subcontinent scale rather than upgrading instruments at a closed period. Third, the analyzed results based on representative sites were also consistent with the majority of other common sites. For instance, two representative sites (i.e., Katherine Council and Newcastle Waters) were listed in high-quality datasets recommended by Lavery et al. (1997) and the Australian Bureau of Meteorology, which have a relative completeness of recording and examination of relocation of instruments for climate detection. Therefore, the results from high-quality datasets could be treated as a benchmark for comparison when considering the reliability of statistical results. Besides, the other 12 high-quality sites within the Northern Territory of Australia were also adopted to examine consistency in statistics for comparison with the adjacent sites. Finally, the majority of sites were maintained well for recoding rainfall variable since 1957, and the missing values were checked and reconstructed by temporal and spatial interpolation (Jeffrey et al. 2001). In summary, it is a balance to take both high-quality representative sites and overall common sites into account to achieve the reliability of datasets and also guarantee the availability of sample size for climate detection at a large spatial scale. According to the abovementioned, our findings in northern Australia were reliable to support the analysis in the effects of climate change.

5. Conclusions

Hydrological diagnosis of rainfall variations is urgently needed to investigate the impacts of climate change on the hydrological cycle and hydroclimatic extremes. Our study established a framework to assess rainfall variations under climate change by analyzing long-term rainfall time series along a rainfall gradient in the Northern Territory of Australia. The findings resulting from diagnosing rainfall variations from the aspects of trend, periodicity, time of abrupt changes in rainfall amount, rainfall probability density distribution, and extremes of rainfall events supported the conclusion that rainfall patterns have changed significantly and were associated with higher variability at an entire subcontinent scale. Annual rainfall amounts across the study area were seen to consistently increase over time, and a dramatic shift of rainfall pattern has occurred over the subcontinental region in recent decades (since about 1970). Due to the analytical findings derived over a rainfall gradient varying from 1800 to 200 mm yr^{-1}, the magnitude and variation of rainfall pattern changes showed distinct differences from wet to dry environments. However, the modes and shifting time of rainfall pattern changes were shown to be consistent across different annual rainfall conditions and were more distinct in drier regions. We also confirmed that the frequency of extreme rainfall events had increased significantly across all sites in this subcontinental-scale region. The study characterized the rainfall variations and analyzed shifting modes by considering the factors of space–time and magnitude, thereby improving our understanding of rainfall pattern changes and providing opportunities to mitigate negative impacts of climate change.

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