Vol. 61: 123–131, 2014
doi: 10.3354/cr01247

CLIMATE RESEARCH
Clim Res

Published September 23

Changing structure of wet periods across southwest China during 1961–2012

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ABSTRACT: Using homogenized daily precipitation observations during 1961 to 2012, changes in duration-based structure of precipitation over southwest China under drought conditions were investigated. The results reveal a distinct regrouping of wet periods of different length. Wet days and precipitation related to long wet periods (>3 d) decreased significantly. Such decreases resulted in significantly fewer fractional contributions of long wet periods to total wet days and annual precipitation totals. In contrast, contributions from short wet periods (<3 d) showed significant ascending trends. Substantial decreases in precipitation of long wet periods after 2000 accounted for most reductions in annual precipitation totals and resultant drought tendency. A more specific analysis on seasonal timescales highlights the significance of changes in autumn precipitation structure in causing the drying tendency across southwest China.

KEY WORDS: Changing precipitation structure · Duration · Wet periods

1. INTRODUCTION

Southwest China, including southern Sichuan, Chongqing, Yunnan, Guangxi, and Guizhou (see Fig. 1), is characterized by abundant precipitation and is a major water resource for the country (Qiu 2010, Barriopedro et al. 2012). However, this region has witnessed frequent severe droughts during the last decade, such as exceptional droughts in spring in 2005, during summer–autumn in 2006, and during autumn–spring in 2009–2010 (Wang et al. 2011, Barriopedro et al. 2012, Yun et al. 2012). Local agriculture and hydroelectric production are largely influenced by these recurrent droughts. The recent prolonged drought in 2009–2010 threatened over 21 million people and 11 million livestock with shortages of drinking water, and led to economic losses of nearly US$30 billion (Lu et al. 2011, Yang et al. 2012). The fact that southwest China is becoming dryer has been noted and validated by many recent studies (Zou et al. 2005, Dai 2011, Lei & Duan 2011, Zhang et al. 2013a, Yu et al. 2014). Subsequently, quite a few studies have focused on the mechanism of severe droughts and/or drying trends over southwest China under global warming from the perspective of large-scale circulation anomalies. It is believed that a reduction in water vapor transport caused by weaker southwesterlies, enhanced evaporation due to warmer temperatures, and reduced summertime precipitation related to coverage by the westward-extended western Pacific subtropical high combined to contribute to frequent occurrences of severe droughts and the drying tendency over southwest China (e.g. Lu et al. 2011, Barriopedro et al. 2012, Yang et al. 2012). From the perspective of precipitation itself, wet periods, WP (also known as wet spells) are important in determining annual precipitation totals and their variation may be linked to local drying and wetting tendencies (Bai et al. 2007). For studies on WPs, very general discussions on variations in frequency, mean duration and resultant precipitation have been published extensively in literature (e.g. Tolika & Maheras 2005, Bai et al. 2007, Ratan & Venugopal 2013). Little attention has been paid to variations between WPs of different length.

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Such variations actually indicate changes in precipitation structure. Further, changes in precipitation structure itself corresponding to the drying trend over southwest China have hitherto been rarely reported. This study therefore aims to reveal possible changing precipitation structure that may be related to the drought tendency across southwest China. The changing precipitation structure in this study refers in particular to variations of duration-based WPs, i.e. precipitation persistence, rather than widely discussed temporal-spatial structure of sub-regions whose boundaries are based on the spatial coherence and similar temporal evolution of precipitation (e.g. Qian & Qin 2008, Yang et al. 2010).

2. DATA AND METHODS

2.1. Data preparation

Daily rain gauge observations in southwest China (22°–32° N, 100°–110° E; Fig. 1) during 1961–2012 are selected from a daily precipitation dataset of 2480 stations across China that is provided by the National Meteorological Information Center (NMIC), China Meteorological Administration (CMA). This dataset has been subjected to rigorous quality control procedures by the NMIC, including completing some missing observations, rectifying suspect/wrong observations, and reconciling temporal and spatial inconsistencies possibly caused by new instrumentation and site displacement. The stations are retained when they meet the following criteria: (1) the station is located in the domain of 22°–32°N, 100°–110°E (Fig. 1); (2) it contains no missing values in the annual records of any year during 1961–2012; (3) the horizontal and vertical displacements are less than 20 km and 50 m, respectively, during the whole study period. The first criterion aims to select the stations located in southwest China; the second one ensures data continuity, which is important for the following trend analyses. The third criterion aims to further minimize uncertainties caused by possible site relocations by requiring sufficiently small relocation distance, though this dataset has been through homogenized procedures performed by the NMIC. After these procedures, 144 stations in southwest China were finally retained.

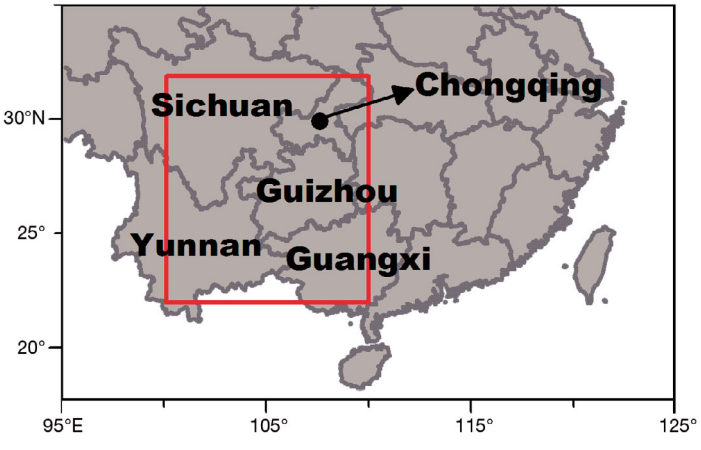

Fig. 1. Study region (red rectangle): southwest China (22°–32° N, 100°–110° E)

2.2. Methods

The wet days (WDs) are defined as the days with significant precipitation (≥1 mm d^{-1}). This definition excludes very light precipitation, and takes the limitation in accuracy of rain gauges into consideration simultaneously (Klein Tank & Können 2003, Zolina et al. 2010). The WPs are subsequently defined as the periods with consecutive WDs. The WPs are classified into 15 categories based on their durations at 1 d interval (1–14, and >14 d). The changing structure of precipitation is presented based on this duration-based classification.

The Kendall's tau slope estimator (Sen 1968) was employed to evaluate linear trends in different parameters of precipitation. This nonparametric method does not assume any distributional forms for the original data, and is sufficiently insensitive to outliers (Zhai et al. 2005).

3. RESULTS

Occurrences of WPs decrease exponentially with duration (blue bars in Fig. 2a). More than 50% of WP events are a 1 d event. Little contribution (<1%) to total events comes from WPs lasting >1 wk. The WDs from isolated (1 d) and 2 d WPs account for ~50% of the total number of WDs (Fig. 2a, red bars). The WDs from WPs of 3 to 7 d occupy ~40%, and the remaining longer WPs contribute ~10% to total WDs. Fig. 2b presents the temporal evolution of the fractional contribution from different WPs to the total WDs, smoothed with a 5 yr running mean as described by Zolina et al. (2010). The structure of negative anomalies in short durations (≤3 d) and positive anomalies in long durations (>3 d) before 1978 gradually evolves into the pattern of positive anomalies in short durations and negative anomalies in long durations

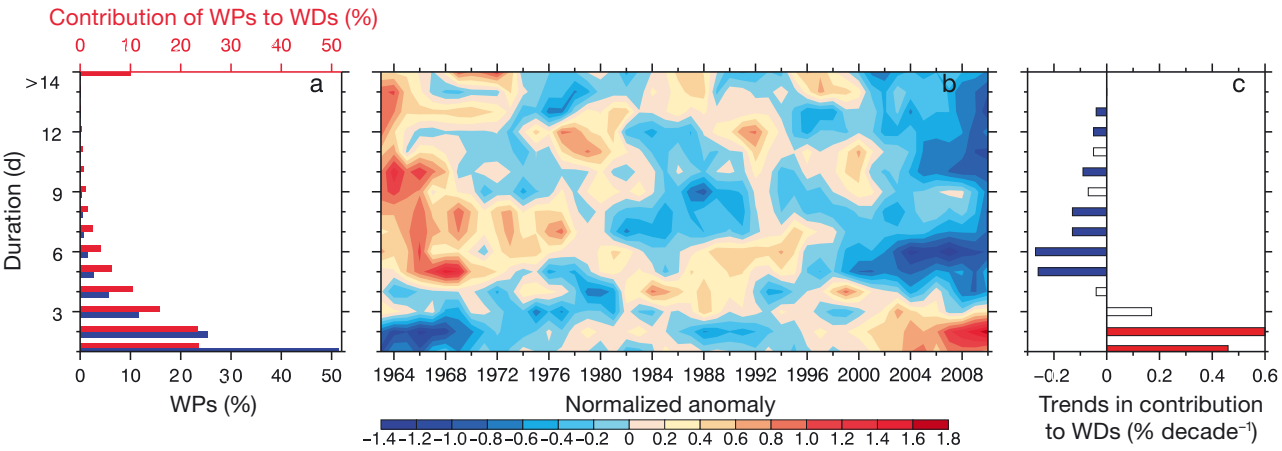

Fig. 2. (a) Occurrence (in %) of wet periods (WPs; blue bars, bottom axis) according to duration (15 classes), and their fractional contribution to the total number of wet days (WDs; red bars, top axis). (b) Temporal evolution of the normalized anomalies in fractional contribution of the WP classes to total number of WDs across southwest China, smoothed with a 5 yr running mean. (c) Linear trends in the fractional contribution of the WPs to WDs, where shaded bars (red = positive, blue = negative) indicate $p < 0.05$

after 2000. The reversal between patterns before 1978 and after 2000 indicate that the contribution of long WPs to the total number of WDs decreases with time, while the contribution of short WPs increases. Such regrouping in the fractional contributions from WPs of different durations is further markedly delineated by their linear trends (Fig. 2c). Generally, increases in fraction contributions are detected in short WPs, while consistent decreases are found in long WPs. The contributions from isolated and 2 d WPs experienced respective significant increases of 0.47 and 0.6 % decade^{-1}, while the contributions from WPs of duration ranging from 5 to 8 d decreased significantly. Regionally speaking, the number of long WPs significantly decreased at a rate of −0.3 ± 0.1 occurrences decade^{-1} (±0.1 represents the 95 % confidence interval), leading to a significant reduction in WDs of −1.8 ± 0.7 d decade^{-1}. While an insignificant positive trend was detected in the number of short WPs, resulting in a slight increase in WDs of 0.2 ± 0.5 d decade^{-1}. Significant decreases in long WPs and insignificant increases in short WPs jointly led to a sharp WD decrease of −1.6 ± 1.1 d decade^{-1}, significant at the 0.01 level. Compared with values before 1978, the number of long WPs decreased by 18.5 % during the last decade, while the number of short WPs increased by only 1.3 %. The sharp decrease of long WPs led to a manifest decrease in total WDs of about 7 % during the last decade compared with those before 1978. Corresponding to such regrouping between long and short WPs, the mean duration of WPs across southwest China shortened with a negative trend of −0.03 ± 0.01 d decade^{-1} over the past 52 yr, significant at the 0.01 level. Additionally, the fractional contribution of short WPs to the total number of WDs increased with a significant positive trend of 1.3 ± 0.4 % decade^{-1}, increasing from about 67 % in the 1960s to 73 % after 2000; Correspondingly, the contribution from long WPs decreased by a total percentage of 6.5 ± 2.5 %, reducing from 33 % to roughly 27 %.

Spatially, the number of total WDs has decreased significantly across southwest China (Fig. 3a). Especially in eastern Sichuan, southern Guizhou, eastern Yunnan and northwestern Guangxi, obvious decreases in WDs of 3 d decade^{-1} were recorded during the past 52 yr (the most rapid decrease of −6.7 d decade^{-1} was detected in southeastern Sichuan). Basically, increases in WDs contributed by short WPs are of larger magnitude in the northern part of southwest China (Fig. 3b). Particularly, significant negative trends can be identified in the southeastern corner (Guangxi Province). In contrast, sharp decreases of WDs related to long WPs constitute a general pan-southwest China pattern (Fig. 3c). The comparison among Fig. 3a and Fig. 3b–c clearly indicates that the decreases in total WDs mainly resulted from the significant decreases in WDs contributed by long WPs. The spatial distribution of trends in WDs from short WPs (Fig. 3b) is not as consistent as the distribution of trends in WDs from long WPs (Fig. 3c). In Fig. 3b, the ratio of stations with positive trends to those with negative trends is around 1.56. Most stations with significant negative trends in Fig. 3b are located in eastern Sichuan and northwestern Guangxi, where they experienced the most serious reduction in total WDs. Concurrent reductions in WDs from both long and short WPs that cause such substantial reductions in total WDs in these two areas. In other regions, decreases in total WDs can be merely attributed to

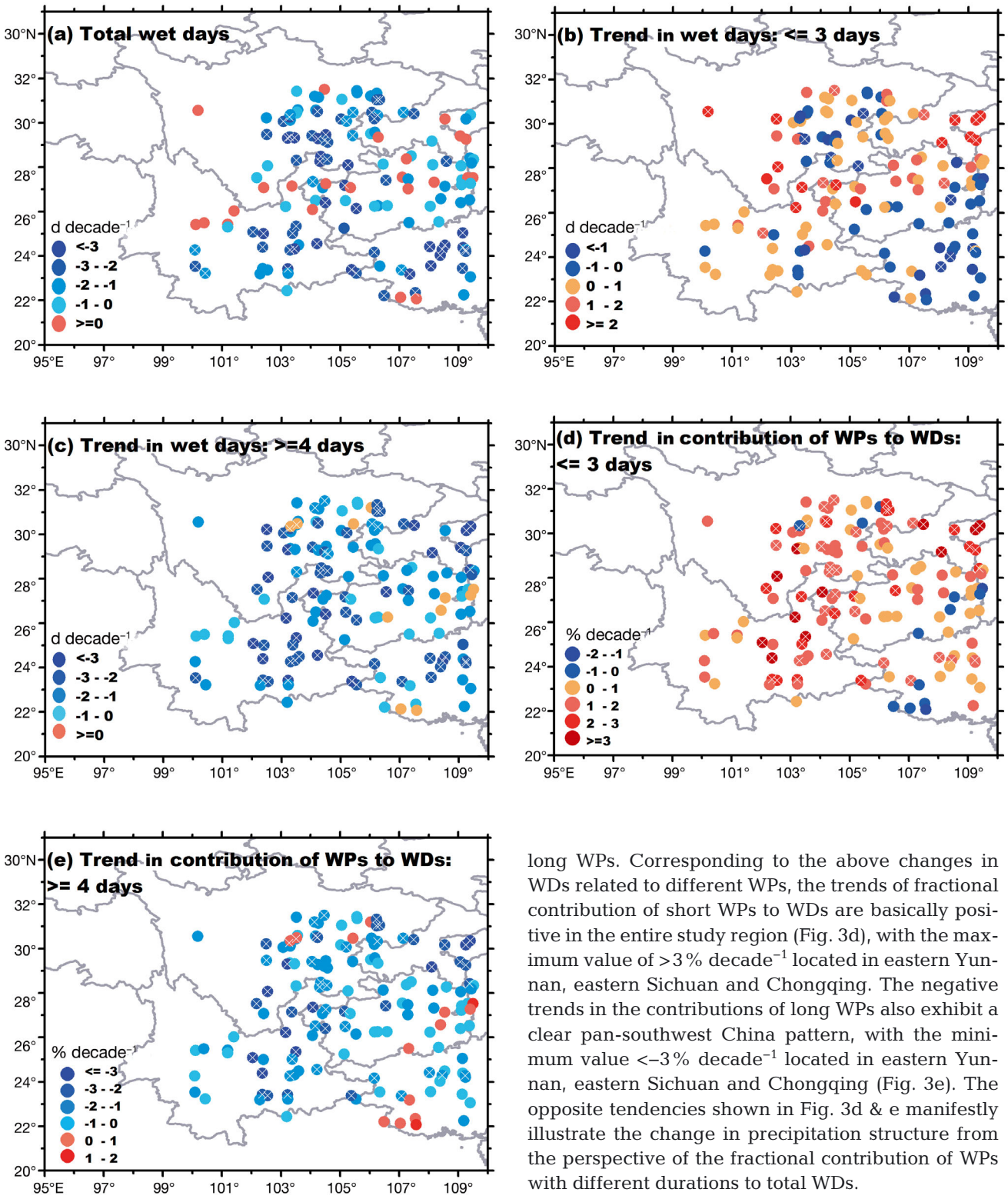

Fig. 3. Trends in (a) total wet days (WDs), (b) WDs from short wet periods (WPs), and (c) WDs from long WPs. Trends in the fractional contribution from (d) short WPs and (e) long WPs to total WDs. Dots: negative (blue) and positive (red) trends; Crosses: $p < 0.05$

long WPs. Corresponding to the above changes in WDs related to different WPs, the trends of fractional contribution of short WPs to WDs are basically positive in the entire study region (Fig. 3d), with the maximum value of >3% decade^{-1} located in eastern Yunnan, eastern Sichuan and Chongqing. The negative trends in the contributions of long WPs also exhibit a clear pan-southwest China pattern, with the minimum value <–3% decade^{-1} located in eastern Yunnan, eastern Sichuan and Chongqing (Fig. 3e). The opposite tendencies shown in Fig. 3d & e manifestly illustrate the change in precipitation structure from the perspective of the fractional contribution of WPs with different durations to total WDs.

A dramatic reduction in precipitation amount is a major factor in causing severe droughts. Hence, changes in precipitation amount in response to the above regrouping in WPs of different durations need to be investigated as well. On average, 2 d precipita-

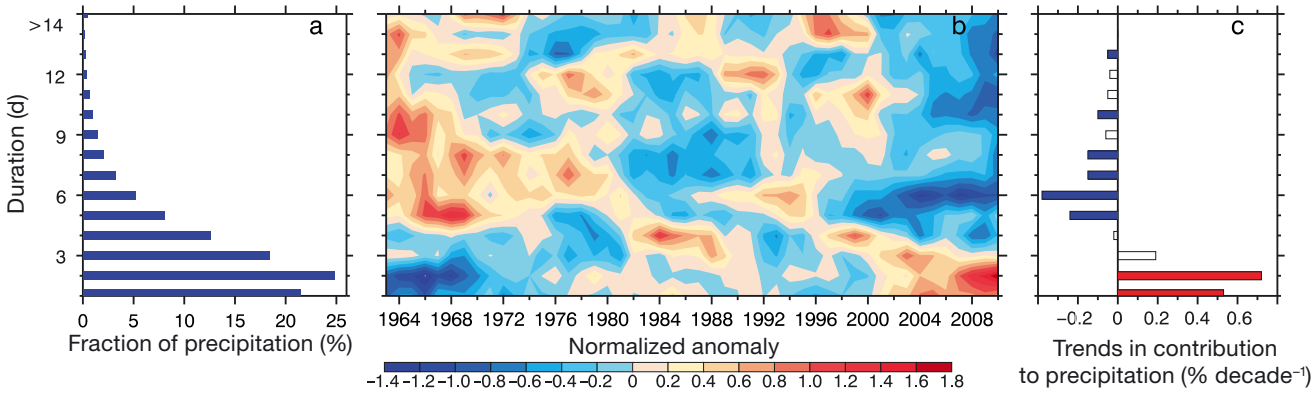

Fig. 4. (a) Percentage of precipitation contributed by wet periods (WPs) of different duration (15 classes), (b) temporal evolution of the normalized fractional contribution anomalies in precipitation for each WPs class smoothed with a 5 yr running mean, and (c) linear trends in the fractional contribution of precipitation for each WPs class to annual precipitation amount, where shaded bars (red = positive, blue = negative) indicate $p < 0.05$

tion contributes the most (>25%) to total precipitation amount in southwest China (Fig. 4a). Similar to the characteristics presented in Fig. 2b, Fig. 4b shows a clear evolution in the contributions of WPs of different length to annual precipitation totals. After 1978, the positive anomalies of short duration replaced previous negative ones. The anomalies of long duration however showed the opposite tendencies. Such changing in precipitation components of different lengths is further confirmed by trend analyses shown in Fig. 4c. The contributions of short WPs to the annual precipitation totals across southwest China showed a significantly positive trend of 1.5 ± 0.6% decade^{-1}, increasing from 61% in the 1960s to 69% after 2000, while the contributions from long WPs decreased by 7.5 ± 3.0% in total during the past 5 decades, from 39% in the 1960s to roughly 31% after 2000.

Specifically, the most obvious decreases in precipitation amount were observed in eastern Sichuan and eastern Yunnan, with negative trends of −60 to −40 mm decade^{-1} (Fig. 5a). These negative trends primarily resulted from the significant decreases in precipitation amount of long WPs (Fig. 5b–c). For eastern Sichuan, in addition to sharp decreases in precipitation amount of long WPs, precipitation amount from short WPs also decreased significantly (Fig. 5b). For all stations combined, the ratio of trends (positive:negative) in fractional contribution of precipitation related to short WPs was 2.45, with most stations that had negative trends located in eastern Sichuan. Of particular note is that the northwest–southeast contrasting pattern of WDs from short WPs as revealed in Fig. 3b is not observed in the pattern of short-WPs inducing precipitation. Instead, slightly increasing precipitation amount is observed in the southeastern part (Fig. 5b), which corresponds well to significantly decreasing WDs (Guangxi Province, Fig. 3b). This phenomenon may imply the increasing intensity of short-lasting precipitation in Guangxi Province. The fractional contributions of short WPs to annual precipitation totals showed prominently positive trends across southwest China, with the maximum trend more than 3% decade^{-1}. Correspondingly, the negative trends in the contributions from long WPs were detected across the entire southwest China. These opposite variations further justify the changing structure from the perspective of the fractional contributions of different WPs to annual precipitation totals. Corresponding to such changes in duration-based structure of precipitation, negative precipitation anomalies of long WPs appeared almost in every year since 1980 (red bars in Fig. 6e), accounting for most of the negative anomalies of annual precipitation totals. Especially after 2000, substantial decreases in the precipitation amount of long WPs frequently caused remarkable deficiency in annual precipitation totals (1 to 2 SD below normal), which further triggered extremely severe droughts across southwest China during the last decade. Precipitation amount related to long WPs decreased in total by 10.0 ± 4.1% (110.5 ± 45.0 mm) during the past 5 decades, significant at the 0.01 level. This dramatic decrease in the precipitation amount is coincident with the obvious changes in precipitation structure after 2000 revealed by Figs. 2b & 4b.

More specific changes in the duration-based precipitation structure across southwest China during individual seasons are presented in Fig. 6a–d, and corresponding trend estimates are listed in Table 1.

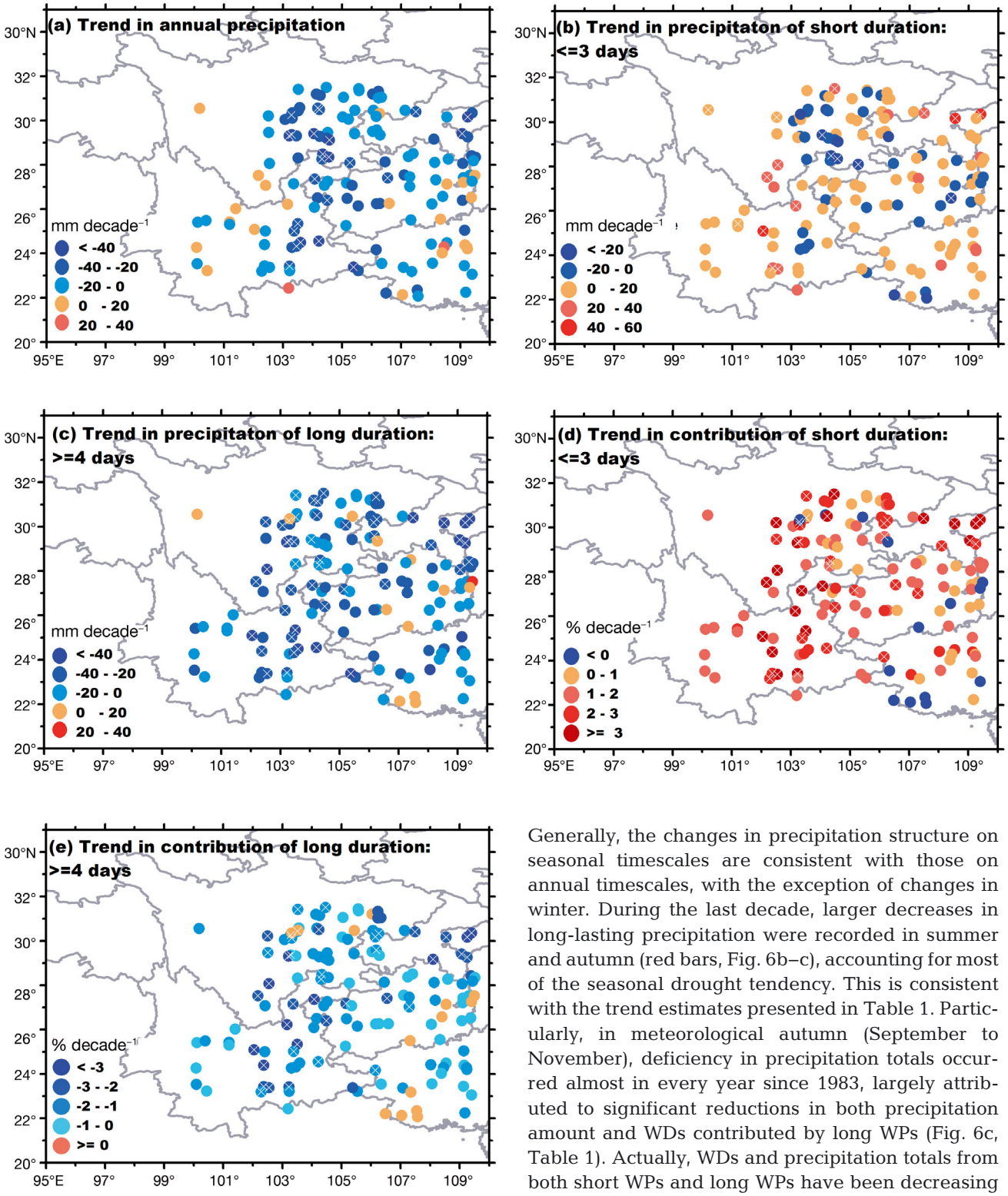

Fig. 5. Trends in (a) annual precipitation, (b) precipitation from short wet periods (WPs), and (c) precipitation from long WPs. Trends in the fractional contribution of precipitation related to (d) short WPs and (e) long WPs to annual precipitation. Dots: negative (blue) and positive (red) trends; crosses: $p < 0.05$

Generally, the changes in precipitation structure on seasonal timescales are consistent with those on annual timescales, with the exception of changes in winter. During the last decade, larger decreases in long-lasting precipitation were recorded in summer and autumn (red bars, Fig. 6b–c), accounting for most of the seasonal drought tendency. This is consistent with the trend estimates presented in Table 1. Particularly, in meteorological autumn (September to November), deficiency in precipitation totals occurred almost in every year since 1983, largely attributed to significant reductions in both precipitation amount and WDs contributed by long WPs (Fig. 6c, Table 1). Actually, WDs and precipitation totals from both short WPs and long WPs have been decreasing markedly during autumn (Table 1). Different from variations during spring–autumn, winter WDs and precipitation amount contributed by both short and long WPs showed slightly ascending trends (Fig. 6d, Table 1). During the last decade, anomalies of winter-

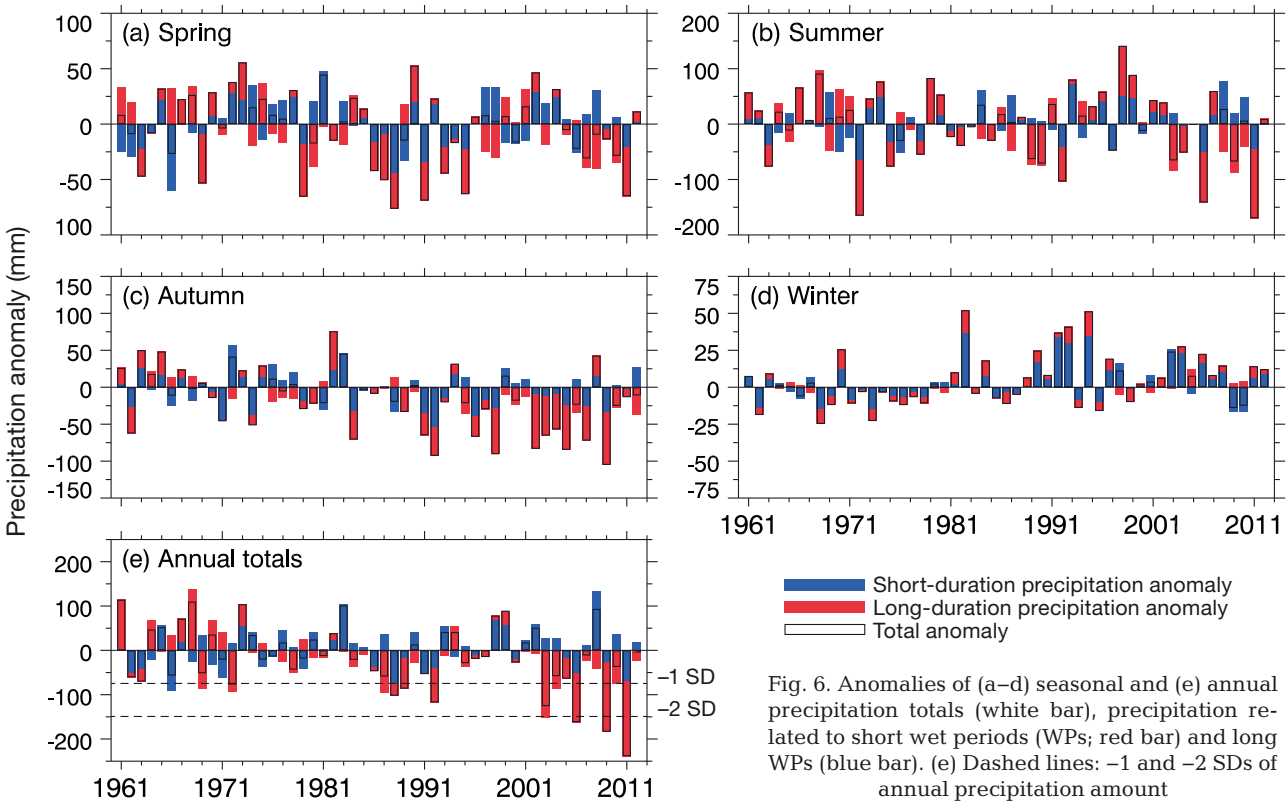

Fig. 6. Anomalies of (a–d) seasonal and (e) annual precipitation totals (white bar), precipitation related to short wet periods (WPs; red bar) and long WPs (blue bar). (e) Dashed lines: –1 and –2 SDs of annual precipitation amount

time precipitation are of much smaller magnitude compared with those in the other 3 seasons. Hence, it is the consecutive precipitation reductions persisting from spring to autumn that lead to severe precipitation deficiencies (Fig. 6e). In addition, it is also implied that decreases in the famous 'autumn rain' phenomena in west China noted by Zhai et al. (2005) are mainly attributed to the reductions in long WPs (Table 1). Of particular note is that some WPs may span 2 consecutive seasons, such as lasting from late summer to early autumn. Some caution therefore needs to be paid to relevant conclusions on seasonal timescales, especially for the periods at the beginning and/or ending of a certain season.

Table 1. Trends in precipitation amount (mm decade^{-1}) and in wet days (d decade^{-1}) related to different wet spells (WPs) in different seasons. Spring: Mar–May, summer: Jun–Aug, autumn: Sep–Nov, winter: Dec–Feb. *p < 0.05

Season	Precipitation amount			Wet days		
	Total	Short WPs	Long WPs	Total	Short WPs	Long WPs
Spring	–5.2	0.5	–5.9*	–0.3	0.0	–0.3
Summer	–4.4	4.8	–10.3*	–0.5	0.1	–0.7*
Autumn	–13.9*	–2.4	–11.1*	–1.4*	–0.3	–1.0*
Winter	4.4*	2.7	1.6*	0.4	0.3	0.1

4. CONCLUSIONS AND DISCUSSIONS

This study investigates the changes in precipitation structure over southwest China in the context of frequent droughts. The precipitation components of different durations have regrouped, with more wet days (WDs) and more precipitation amount contributed by short wet periods (WPs) (≤3 d). In contrast, the contribution of long WPs (>3 d) to total WDs decreased by 6.5 ± 2.5% (from 33% in the 1960s to 27% after 2000) and the contribution of related precipitation amount decreased by 7.5 ± 3.0% (from 39 to 31%) during the past 5 decades. It is these decreases in the long WPs-related WDs and precipitation amount that led to significant reductions in annual precipitation totals across southwest China, especially after 2000. Further specific analyses on seasonal timescales indicate that the largest decreases in WD and precipitation amount tend to occur in autumn. These substantial decreases in autumn are also mainly modulated by long WPs.

In contrast to the decreases in long WPs and related precipitation across southwest China, Zolina et al. (2010)

reported that during the last 60 yr, wet periods became longer over most of Europe, bringing more abundant precipitation to the continent. Other studies concerning WPs have also pointed out that climate trends in durations and related precipitation differed in other regions in the world (Kunkel et al. 1999, Kunkel 2003, Schmidli & Frei 2005, Brommer et al. 2007). For example, recurrent long WPs affected Singapore during the last decade, while shorter WPs have been frequently witnessed by most parts of India (Singh & Ranade 2010, Chatterjea 2011). Also in different parts of China, diverse regional variations in WPs were observed. Shortening WPs were also observed in North and Central China. In contrast, significant lengthening of WPs has been detected in the eastern Tibetan Plateau and lower Yangtze River Basin (Bai et al. 2007, Zhao et al. 2009). These differences in changes of WPs may imply distinctive regional responses to ongoing global climate change.

As for the reason for this change in precipitation structure and associated long-term drying tendency, El Niño-like sea surface temperatures (SSTs) may play a key role by modulating the circulation anomalies over East Asia (Dai 2011, 2013, Zhang et al. 2013b). Moreover, frequent occurrences of negative phases of Arctic Oscillation (AO) in the last decade led to recurrent cyclonic anomalies over the Arabian Sea, which obstructed normally persistent moisture transport toward southwest China by southwesterlies, which are a major cause of long WPs (Barriopedro et al. 2012, Yang et al. 2012). Additionally, local soil moisture–atmosphere interaction may be another factor accounting for sharp decreases in long WPs (Jaeger & Seneviratne 2011, Wang et al. 2011, Liu et al. 2014). Dry soil may reduce subsequent precipitation amount and precipitation days, and reduce the liklihood of long consecutive precipitation periods. In turn, decreases in precipitation amount and precipitation days will further exacerbate the existing drying condition. An in-depth understanding of the changing structure of WPs related to the drying trend in southwest China can provide scientific advice for drought mitigation and prevention. Whether this changing precipitation structure and related drying trend will continue or not needs to be investigated by climate models. Pertinent results from model outputs may shed light on future changes in the hydrological cycle across southwest China.

Acknowledgements. This study was jointly funded by the National Key Basic Research Program of China (Grant No. 2012CB417205), the National Natural Science Foundation of China (Grant No. 41175080), and the Major Research and Operational Services Program of Southwest regional Meteorological Center (Grant No. 2014-1), and was also supported by Jiangsu 2011 Program (Collaborative Innovation Center of Climate Change). The authors are grateful to the editors and 4 anonymous reviewers for their invaluable and constructive suggestions and comments that helped improve the manuscript.

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Editorial responsibility: Gouyu Ren, Beijing, China

Submitted: January 16, 2014; Accepted: May 30, 2014
Proofs received from author(s): September 2, 2014