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Variation characteristics of extreme climate events in Southwest China from 1961 to 2017

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ABSTRACT

Climate change is increasing the intensity of *extreme* climate *events*. Significant impacts of extreme climate *events* on human society and ecosystem have occurred in many places of the world, for example, Southwest China (SWC). In this study, the daily temperature and precipitation data from 438 meteorological stations are used to analyze the variation characteristics of extreme climate events in the SWC from 1961 to 2017. The annual extreme warm events show a significant increasing trend at 99% confidence level at most stations, and a few stations with a decreasing trend are mainly located in the southern Sichuan Province, the northern Yunnan Province and the western Guizhou Province. Meanwhile, the annual extreme cold events show a significant decreasing trend at 99% confidence level at most stations, and a few stations with an increasing trend are mainly distributed in the Sichuan Basin. Both the annual extreme heavy precipitation indexes and rainstorm indexes show nonsignificant increasing trends, but they differ greatly in the spatial distribution. These indexes in the western Tibet, Chongqing and most parts of Guizhou show significant increasing trends at 95% confidence level, while those in the central Sichuan and southeastern Yunnan show significant decreasing trends. The percentage of extreme heavy precipitation shows a significant increasing trend at 99% confidence level, especially in the northeastern Sichuan, the central-eastern Guizhou and the central Yunnan. Overall, under the background of global warming, the extreme warm events in SWC increase significantly from 1961 to 2017, and the extreme cold events decrease significantly. The variation trends of extreme precipitation events differ greatly in different regions, and the percentage of extreme heavy precipitation increases significantly.

1. Introduction

Global warming can directly affect the variation of extreme temperature events. Many studies have found that the extreme warm events increase significantly while the extreme cold events decrease significantly [1], whether at the global scale [2] or the regional scale in Asia [3,4], Europe [5,6] and America [7–9]. The extreme precipitation events show great regional differences globally.

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Extreme precipitation events are increasing in some areas [5,10], while decreasing [11,12] or fluctuating periodically [13] in some other areas. In general, extreme climate events, such as torrential rainfall, drought and heatwaves, are increasing and strengthening, and their frequency will be higher under global warming [14–17]. Moreover, extreme climate events are more directly destructive than climate change, and human and ecosystem are more sensitive to the change of extreme climate events [18,19].

China is the region sensitive to and remarkably affected by the global climate change, and its warming rate is substantially higher than the global average [20]. The spatial difference of extreme precipitation events is large, with an increasing trend in Southwest China (SWC) and Northwest China, and a decreasing trend in North China and Northeast China [21–25].

The SWC is a globally important biodiversity hot spot and a climate change-sensitive region, owing to the geological, ecological and social backgrounds [26]. Studies have shown that the cold nights and cold days are decreasing in the Qinghai-Tibet Plateau, while the warm nights and warm days are increasing [27]. The temporal variation and spatial distribution of the extreme climate events in the Hengduan Mountains are very complex [28]. There are warming and drying trends in Yunnan Province, and the trend of changes in precipitation is more significant [29]. The number and frequency of extreme precipitation in the Sichuan Basin have a decreasing trend from 1961 to 2017 [30]. In recent years, extreme climate events have occurred frequently in the SWC. In 2006, the direct economic loss caused by heatwaves and drought in Sichuan and Chongqing exceeded 10 billion yuan [31]. In 2009–2010, the continuous drought in autumn, winter and spring in the SWC caused 9.65 million people to have difficulty in obtaining drinking water [32]. In August 2020, several rounds of heavy rainfall in the eastern SWC occurred, resulting in the direct economic loss of over 3.7 billion yuan in Chengdu alone [33]. Therefore, studying the variation characteristics of extreme climate events in the SWC has important scientific significance and application value for the prevention and mitigation of meteorological disaster and the climate change adaptation.

The remainder of this paper is organized as follows. Section 2 introduces the materials and method used in this study. In section 3, the main variation characteristics of extreme climate events in the SWC are analyzed. Section 4 gives the discussions and conclusions.

2. Materials and methods

2.1. Study area

SWC (21°N–36°N, 78.5°E−109.5°E) covers approximately 23.6×10^5 km^2 and includes three provinces, one municipality and one autonomous region: Sichuan Province, Yunnan Province, Guizhou Province, Chongqing City and Tibet Autonomous Region (see Fig. 1) [34]. The SWC is characterized by complex topography and geological environment, with deep canyons and hills over the Tibetan Plateau, Yunnan-Guizhou karst geomorphology and Sichuan Basin, which can remarkably affect regional climate and environment. The SWC is jointly controlled by monsoon systems, namely southwest monsoon, East Asian monsoon, Tibetan Plateau monsoon and westerlies. The climate varies with altitude from tropical to subtropical, temperate, alpine and frigid climate [35,36].

2.2. Data and methods

The daily average temperature, maximum temperature, minimum temperature and precipitation data of 438 meteorological stations in the SWC from 1961 to 2017 are provided by the National Meteorological Information Center of China Meteorological Administration.

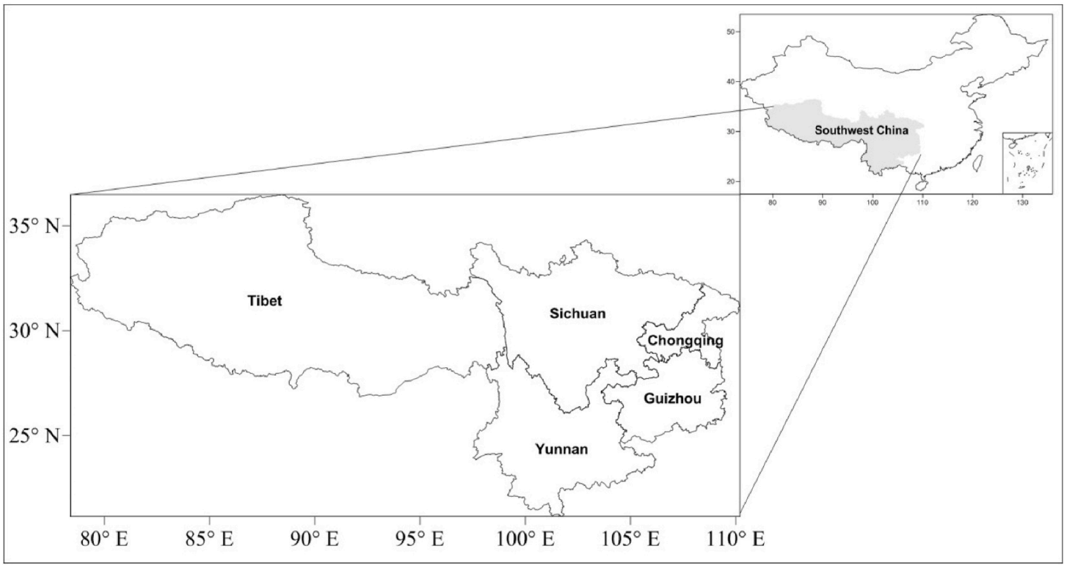

Fig. 1. Schematic of the study area.

Beniston et al. [37] summarized three kinds of criteria commonly used to define extreme climate events, which are low frequency of occurrence, relatively high or low intensity, and heavy social and economic losses, respectively. Usually, a specific extreme climate event cannot meet all the three criteria at the same time. From the perspective of probability, extreme climate events are the events with extremely low probability of occurrence (only 10% or less) [38]. In the studies of extreme climate events based on the climate indicators, the extreme climate indicators are commonly defined by relative thresholds (percentile thresholds) and fixed thresholds [39]. In this study, the extreme temperature index and extreme precipitation index [40] are defined by referring to the climate characteristics of SWC and the climate index defined by the Expert Team on Climate Change Detection and Indices (Tables 1 and 2).

The linear trend is used to represent the variation of each variable. The *t*-test is used to examine the significance at a confidence level of 95% or 99% for linear trend.

3. Results

3.1. Variations in extreme temperature events

3.1.1. Warm and cold events

From 1961 to 2017, the annual average number of cold nights(TN10p) and cold days(TX10p) in the SWC shows significant decreasing trends at 99% confidence level ($R^2 \geq 0.1$), with the decreasing rates of 7.4 days per decade and 2.3 days per decade, respectively (Fig. 2a, c). There are more cold nights from the 1960s to the 1980s, while less after entering into the 21st century (Fig. 2a). The decreasing rate of cold nights in the western SWC is higher than that in the eastern SWC. The decreasing rates in the western Tibet, western Yunnan and Ganzi State of Sichuan Province are more than 10 days per decade, and the decreasing rates in the eastern Sichuan and western Chongqing are less than 4.0 days per decade (Fig. 2b). There are more cold days from the 1960s to the 1990s, and less in the late 1990s (Fig. 2c). The spatial distribution characteristics of the variation trends of cold days are similar to those of cold nights, but the decreasing rate is much lower (Fig. 2d).

The annual average number of warm nights(TN90p) and warm days(TX90p) in the SWC shows significant increasing trends at 99% confidence level ($R^2 \geq 0.1$), with the rising rates of 6.5 and 5.6 days per decade, respectively. There are less warm nights and warm days from the 1960s to the mid-1990s, and there have been more since the late 1990s (Fig. 2e, g). The increasing rates of warm nights and warm days in the western SWC are higher than that in the eastern part. The increasing rates in most areas of Yunnan, the Ganzi State of Sichuan Province and the Tibet are more than 6–8 days per decade, and the increasing rates in most of Sichuan, Chongqing and Guizhou are less than 6 days per decade (Fig. 2f, h).

3.1.2. Extreme low temperature events

From 1961 to 2017, the annual average number of low temperature days (FD) in the SWC shows a significant decreasing trend at 99% confidence level ($R^2 \geq 0.1$), with a decreasing rate of 2.0 days per decade. The annual low temperature days from the 1960s to the middle 1980s are more than the average. After the middle 1980s, the annual number of low temperature day shows negative anomaly. Especially after 1997, the negative anomalies continue for 11 consecutive years (Fig. 3a). From 1961 to 2017, the annual number of low temperature days in most areas of the SWC shows decreasing trends, except for a few areas in the central-western Sichuan and the eastern Guizhou. In most areas, the decreasing rates are less than 5 days per decade. Among them, the annual number of low temperature days in the southwestern Sichuan, the central Tibet, the northwestern Yunnan, the northeastern Chongqing and the western Guizhou has the largest decreasing rate, which is more than 5.0 days per decade (Fig. 3b).

The annual extreme minimum temperature (TNn) in the SWC shows a significant increasing trend at 99% confidence level ($R^2 \geq 0.1$), with an increasing rate of 0.4 °C per decade. The annual extreme minimum temperature is lower from the 1960s to the early 1980s, and is higher after the middle 1980s (Fig. 4a). From 1961 to 2017, the annual extreme minimum temperature in most areas of SWC shows an increasing trend, except for the central-eastern Sichuan, western Chongqing and southern Yunnan. The increasing rates

Table 1
List of the extreme temperature indices.

Label	Description	Unit	Category	Indicator definitions
TN10p	Number of cold nights	day	Cold event	Number of days when daily minimum temperatures <10th percentile
TX10p	Number of cold days	day	Cold event	Number of days when daily maximum temperature <10th percentile
TN90p	Number of warm nights	day	Warm event	Number of days when daily minimum temperatures >90th percentile
TX90p	Number of warm days	day	Warm event	Number of days when daily maximum temperatures > 90th percentile
FD	Number of frost days	day	Cold event	Annual count of days when daily minimum temperature <0 °C
HD	Number of high temperature days	day	Warm event	Annual count of days when daily maximum temperature ≥35 °C
HW	High temperature and heat wave	day	Warm event	Three consecutive days where both daily maximum temperature ≥35 °C and daily minimum temperature ≥25 °C
TNn	Extreme minimum temperature	°C	Cold event	Annual minimum value of daily minimum temperature
TXx	Extreme maximum temperature	°C	Warm event	Annual maximum value of daily maximum temperature

Table 2
List of the extreme precipitation indices.

Label	Description	Unit	Indicator definitions
Rd95p	Number of extreme heavy precipitation days	day	Annual count of days when daily precipitation amount >95th percentile
Rp95p	Extreme heavy precipitation amount	mm	Annual total precipitation when daily precipitation amount >95th percentile
Ri95p	Extreme heavy precipitation intensity	mm/day	Extreme heavy precipitation amount/Number of extreme heavy precipitation days
PEHP	Percentage of extreme heavy precipitation	%	Percentage of annual total extreme heavy precipitation in annual total precipitation
RD	Number of rainstorm days	day	Annual count of days when daily precipitation amount ≥50 mm
RA	Rainstorm amount	mm	Annual total precipitation when daily precipitation amount ≥50 mm
RI	Rainstorm intensity	mm/day	Rainstorm amount/Number of rainstorm days

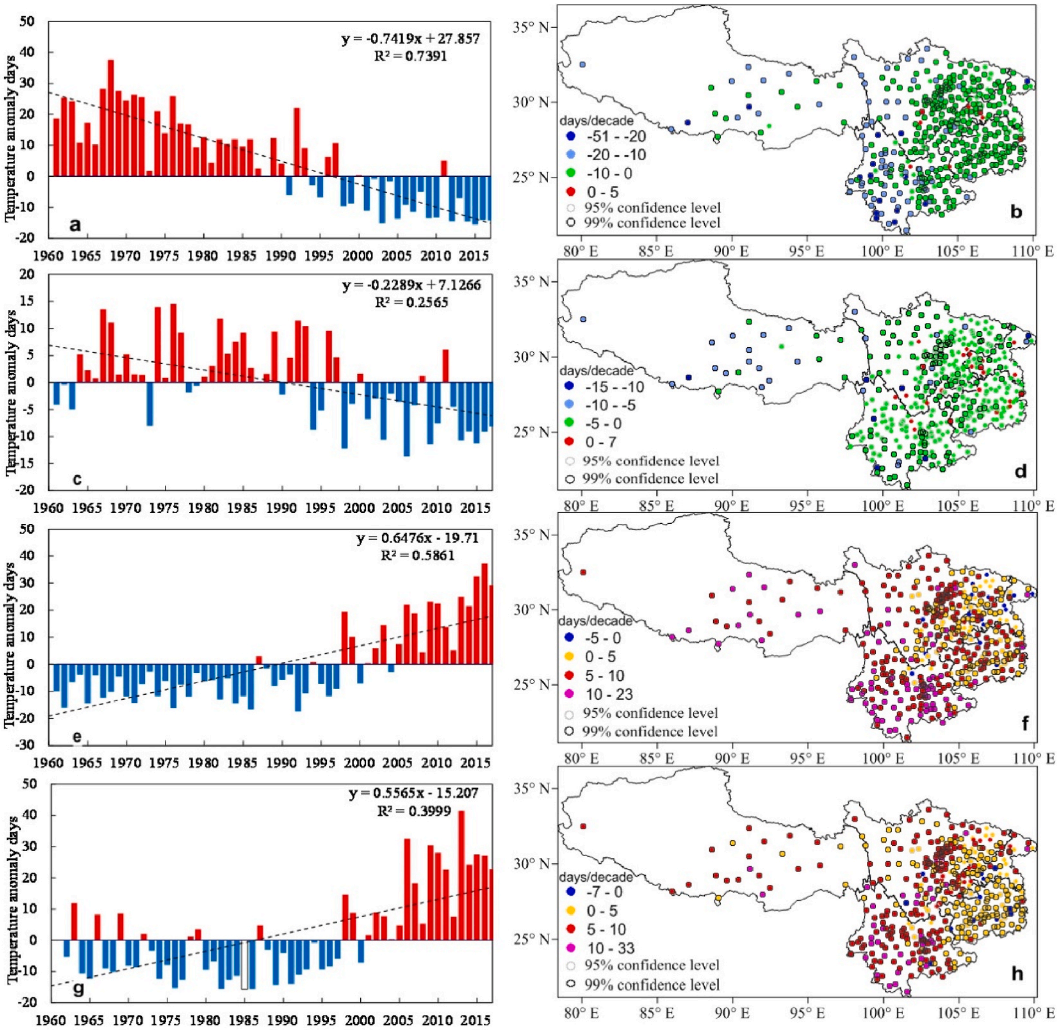

Fig. 2. Variation trends of the annual number of cold nights (a,b), cold days (c,d), warm nights (e,f) and warm days (g,h) from 1961 to 2017.

of annual extreme minimum temperature are below 0.5 °C per decade in the eastern Sichuan, most areas of Chongqing, the northwestern Guizhou and the western Yunnan, and above 0.5 °C per decade in most areas of the western Sichuan Plateau, the Tibet and the central-eastern Guizhou. The increasing rate in the central Tibet is as high as 1.0 °C per decade (Fig. 4b).

3.1.3. Extreme high temperature events

From 1961 to 2017, the annual average number of high temperature days (HD) in the SWC shows a significant increasing trend at 99% confidence level ($R^2 \geq 0.1$), with an increasing rate of 0.9 days per decade. The annual number of high temperature days fluctuates greatly from 1960s to the middle and late 1970s. It is lower from the late 1970s to the middle of 1990s, and is substantially higher after 2000 (Fig. 5a). The annual number of high temperature days from 1961 to 2017 in the Sichuan Basin, most areas of

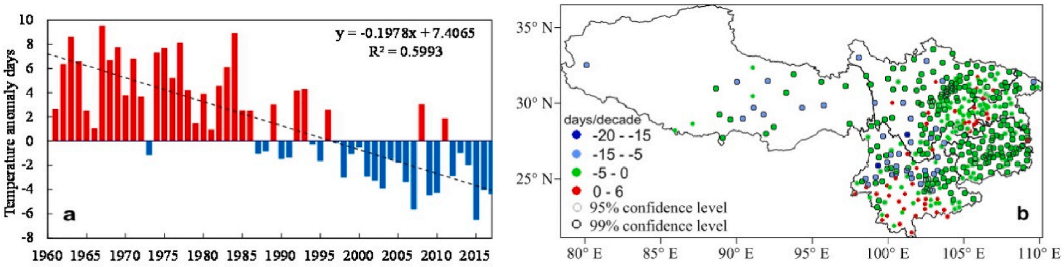

Fig. 3. Variation trends of the annual low temperature days in the SWC from 1961 to 2017.

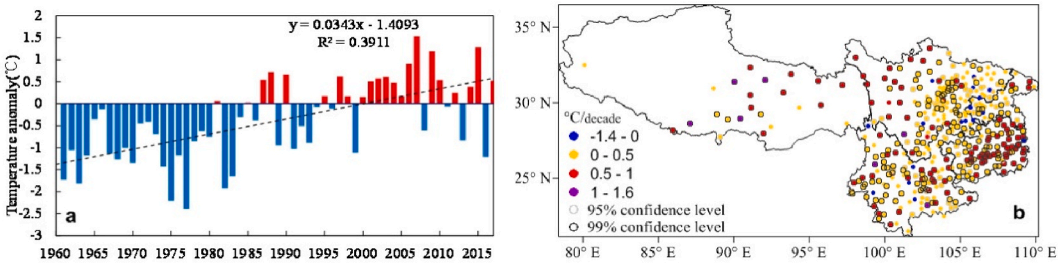

Fig. 4. Variation trends of the annual extreme minimum temperature in the SWC from 1961 to 2017.

Chongqing, the northeastern-southern Guizhou and the western-southern Yunnan shows increasing trends, with the increasing rates mostly within 2 days per decade. The increasing rates in the southwestern Sichuan Basin, the northeastern Chongqing and the southern Yunnan reach more than 3 days per decade, while the annual number of high temperature days in the eastern Yunnan, the western Guizhou and the southwestern Chongqing shows decreasing trends, with the decreasing rates mostly within 1 day per decade (Fig. 5b).

The annual average number of high temperature and heat wave days(HW) in the SWC shows a significant increasing trend at 99% confidence level ($R^2 \geq 0.1$), with an increasing rate of 0.3 days per decade. The annual number of high temperature and heat wave days fluctuates greatly from the 1960s to the late 1970s. It is lower from the late 1970s to the middle 1990s, and is substantially higher after 2000 (Fig. 6a). In terms of the spatial distribution, the high temperature and heat wave events mainly occur in the Sichuan Basin, Chongqing, Yunnan and parts of Guizhou. The annual number of high temperature and heat wave days in most areas of the Sichuan Basin, the northeastern Guizhou and the southern-central Yunnan shows an increasing trend, with a rate mostly below 2.0 days per decade, and exceeding 4 days per decade in some areas. However, the annual number of high temperature and heat wave days in a few stations of Chongqing shows decreasing trends (Fig. 6b).

From 1961 to 2017, the annual extreme maximum temperature (TXx) in the SWC shows a significant increasing trend at 99% confidence level ($R^2 \geq 0.1$), with an increasing rate of 0.2 °C per decade. The annual extreme maximum temperature fluctuates greatly from the beginning of 1960s to the early 1970s, maintaining lower value from the early 1970s to the middle 1990s, and is substantially higher after the middle 1990s (Fig. 7a). For the spatial distribution, the annual extreme maximum temperature in most areas of the SWC shows an increasing trend, except for some areas in Yunnan and Guizhou. The most remarkable regions of increasing temperature are eastern Tibet, the central part of the western Sichuan Plateau, and the transition zone between the plateau and the basin, with increasing rates of more than 0.4 °C per decade (Fig. 7b).

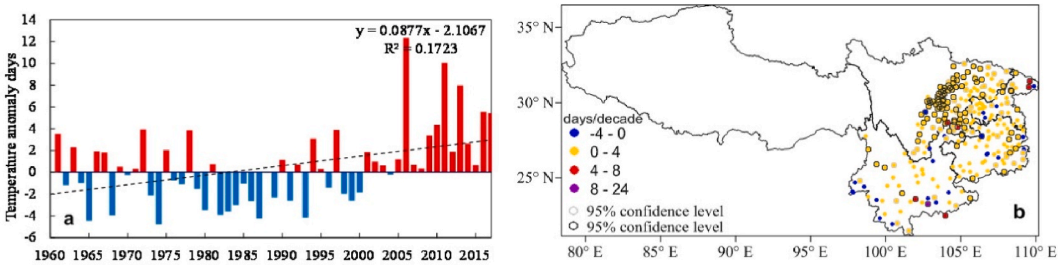

Fig. 5. Variation trends of the annual high temperature days in the SWC from 1961 to 2017.

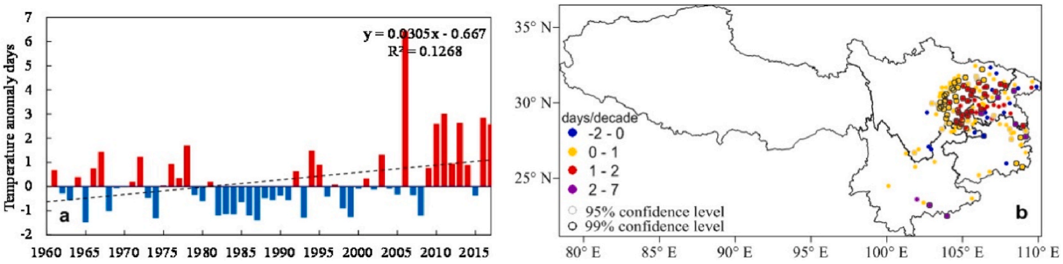

Fig. 6. Variation trends of annual high temperature and heat wave days in the SWC from 1961 to 2017.

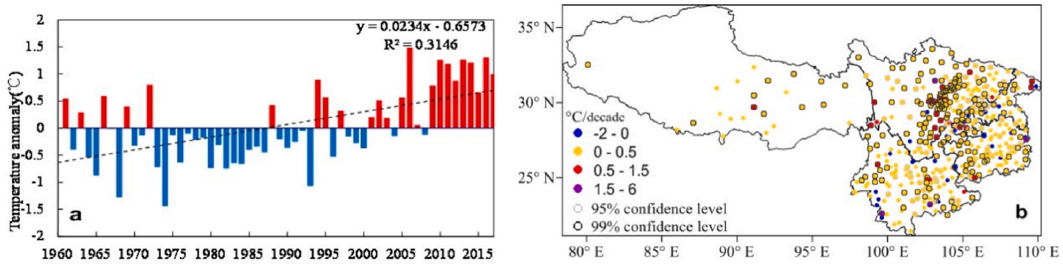

Fig. 7. Variation trends of the annual extreme maximum temperature in the SWC from 1961 to 2017.

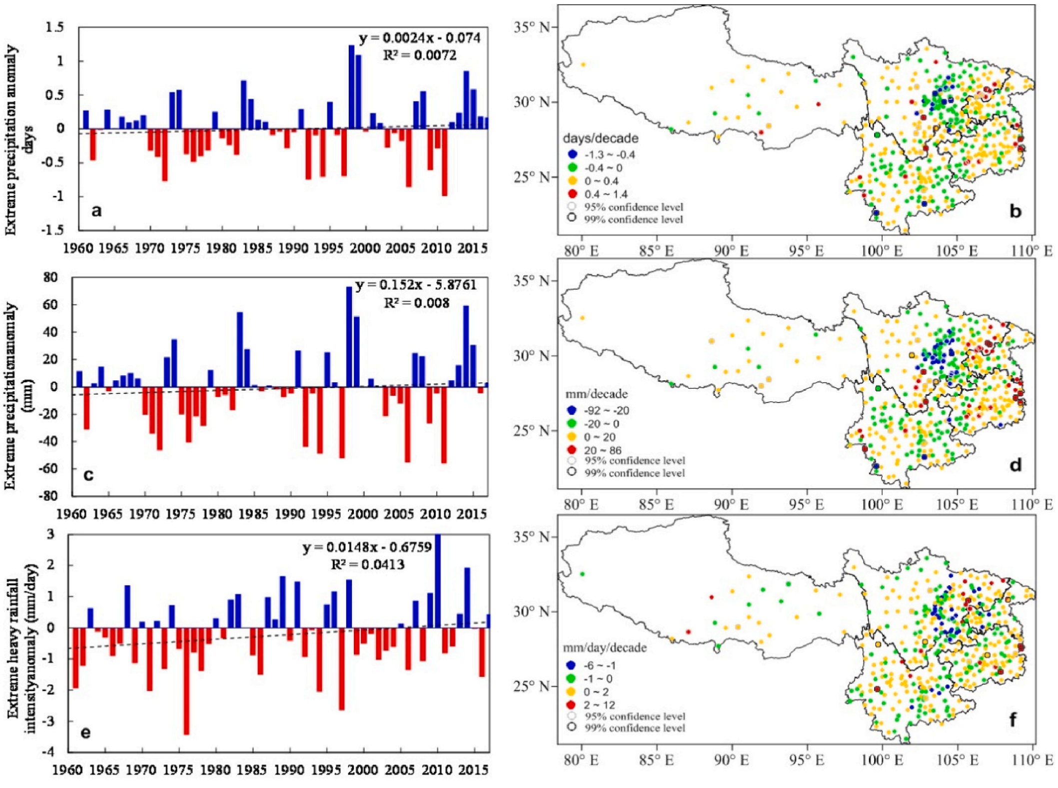

Fig. 8. Variation trends of the annual extreme heavy precipitation days (a,b), precipitation amount (c,d) and precipitation intensity (e,f) in the SWC from 1961 to 2017.

3.2. Variations in extreme precipitation events

3.2.1. Extreme heavy precipitation events

From 1961 to 2017, the annual average number of extreme heavy precipitation days (Rd95p) in the SWC shows a nonsignificant increasing trend with a rate of 0.02 days per decade. The annual extreme heavy precipitation events occur frequently before the mid-1970s, and less frequently from the mid-1970s to the mid-1990s. They occur most frequently from the end of 1990s to the beginning of the 21st century. From 2003 to 2011, the annual extreme heavy precipitation events obviously decrease, and become more frequent after 2012 (Fig. 8a). In terms of the spatial distribution, the annual number of extreme heavy precipitation days in the northeastern Tibet, the western and southern Sichuan Basin, the eastern Yunnan and the western Guizhou shows decreasing trends, of which the values in the western and southern Sichuan Basin decrease significantly with the decreasing rates at some stations exceeding 0.4 days per decade. The annual number of extreme heavy precipitation days in the Tibet, most areas of the western Sichuan Plateau, the central and western Yunnan, the northeastern Sichuan Basin, the western Chongqing, and parts of Guizhou is increasing, and the annual number at some stations significantly increases with the growth rate of more than 1.0 day per decade (Fig. 8b).

In 1961–2017, the variation characteristics of annual extreme heavy precipitation amount (Rp95p) in the SWC are similar to those of the annual extreme heavy precipitation days, and the overall increasing trend is nonsignificant. The annual extreme heavy precipitation amount is relatively large before the 1970s, and experiences great fluctuations from 1970s to the middle and late 1990s. From 1998 to 2002, most precipitation anomalies are positive. The annual extreme heavy precipitation amount shows a decreasing trend from 2003 to 2011 and an increasing trend after 2012 (Fig. 8c). For the spatial distribution, the annual extreme heavy precipitation amount in the western and southern Sichuan Basin, the eastern Yunnan and the western Guizhou shows decreasing trends, especially in the western and southern Sichuan Basin with decreasing rates over 40 mm per decade at some stations. However, the annual extreme heavy precipitation amount in the Tibet, Chongqing and most areas of the western Sichuan Plateau, the central-western Yunnan and the central-eastern Guizhou shows increasing trends, especially in the northeastern Sichuan Basin and the eastern Guizhou with increasing rates exceeding 30 mm per decade at some stations (Fig. 8d).

The annual extreme heavy precipitation intensity (Ri95p) in the SWC shows a nonsignificant increasing trend from 1961 to 2017. The intensity is lower from the 1960s to the 1970s and turns to be higher from the 1980s to the middle 1990s. It becomes lower again from the late 1990s to 2008, and turns to be higher after 2009 (Fig. 8e). For the spatial distribution, the intensity of annual extreme heavy precipitation in the western and southern Sichuan Basin, the southeastern Yunnan, and the central and eastern Tibet shows a decreasing trend, which fails to pass the 95% reliability test. The intensity is increasing in the central and southern parts of the western Sichuan Plateau, the northern Yunnan, Guizhou, the central-northern Sichuan Basin and the western Tibet. The annual extreme heavy precipitation intensity at some stations in the central Sichuan Basin and eastern Guizhou significantly increases, with an average increasing rate of 3–7 mm day^{-1} per decade (Fig. 8f).

3.2.2. Percentage of extreme heavy precipitation

From 1961 to 2017, the annual average percentage of extreme heavy precipitation(PEHP) to the total annual precipitation in the SWC shows a significant increasing trend at 99% confidence level ($R^2 \geq 0.1$), with a growth rate of 0.4% per decade. The percentages are smaller from the 1960s to the 1970s, and are larger in the 1980s. From the early to the middle 1990s, the annual percentage of extreme heavy precipitation becomes smaller again, and turns to obviously larger from the late 1990s to 2017 (Fig. 9a). For the spatial distribution, the annual percentages of extreme heavy precipitation in the central-eastern Sichuan, northwestern part of the western Sichuan Plateau and northeastern Tibet show decreasing trends, and some stations have a significant decreasing trend with a rate more than 2.0% per decade. The percentages in the southern part of the western Sichuan Plateau, the most areas of Yunnan, Guizhou and Chongqing, the northeastern Sichuan, and the western, central and southern Tibet show increasing trends, and some stations have a significant increasing trend with a growth rate more than 2.5% per decade (Fig. 9b).

3.2.3. Rainstorm

From 1961 to 2017, the annual average number of rainstorm days (RD) in the SWC shows a nonsignificant increasing trend, with an increasing rate of 0.02 days per decade. In the early and middle 1960s, the annual rainstorm days is mainly more than the average, and it turns to be less from the late 1960s to the early 1980s. From the middle 1980s to the early 1990s, the annual rainstorm days turns to be larger again. The inter-annual fluctuation of rainstorm days is obvious after the middle 1990s (Fig. 10a). For the spatial distribution,

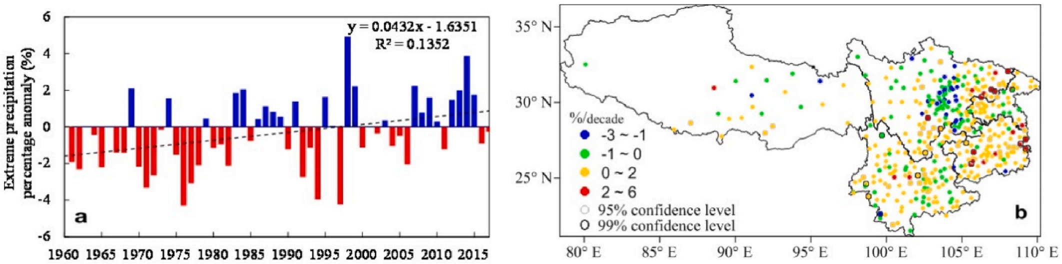

Fig. 9. Variation trends of the annual percentage of extreme heavy precipitation in the SWC from 1961 to 2017.

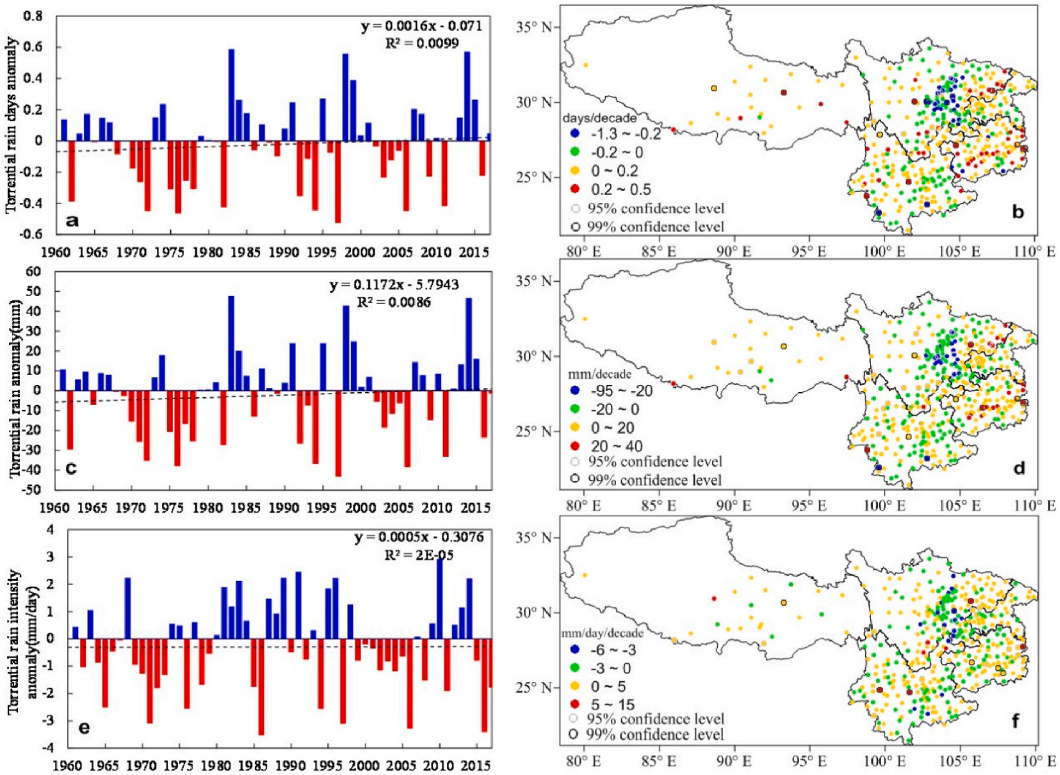

Fig. 10. Variation trends of the annual rainstorm days (a,b), and rainstorm amount (c,d) and rainstorm intensity (e,f) in the SWC from 1961 to 2017.
$R^2 \geq 0.07$ denotes the trend significant at $p < 0.05$ level, $R^2 \geq 0.1$ denotes the trend significant at $p < 0.01$ level.

the annual number of rainstorm days in the central Sichuan decreases significantly with a rate of 0.2–0.4 days per decade, while in other areas it increases with a rate of 0.2–0.5 days per decade. The stations with significant increasing trend are mainly in the northeastern Sichuan and the central Guizhou (Fig. 10b).

The annual average rainstorm amount (RP) in the SWC shows a nonsignificant increasing trend in 1961–2017, with an increasing rate of 11.7 mm per decade. The anomalies are positive in the middle and early 1960s, and turn to be negative from the late 1960s to the early 1980s. They become positive again from the middle 1980s to the late 1990s. Since the 21st century, the inter-annual fluctuation has been obvious (Fig. 10c). The spatial distribution of the variation trend of annual rainstorm amount is consistent with that of the number of annual rainstorm days (Fig. 10d).

The annual average rainstorm intensity (RI) in the SWC shows a nonsignificant increasing trend in 1961–2017. The annual rainstorm intensity is lower from the late 1960s to the late 1970s, and higher from the early 1980s to the middle 1990s. It has weakened again since the beginning of the 21st century, but it has staged-enhancement around 2010 (Fig. 10e). The spatial distribution of the annual rainstorm intensity variation trend in the SWC is also consistent with that of the number of annual rainstorm days and that of the annual rainstorm precipitation amount (Fig. 10f).

4. Discussions and conclusions

From 1961 to 2017, the average number of cold nights and cold days in the SWC shows significant decreasing trends. The number of cold nights decreases with a rate of 7.4 days per decade, which is three times of the decreasing rate of the number of cold days. For the spatial distribution, the western SWC shows a faster decreasing trend than the eastern SWC. On the contrary, the average number of warm nights and warm days in the SWC from 1961 to 2017 shows significant increasing trends, with an increasing rate of 5–6 days per decade, and the highest rate is in the Tibet, Sichuan and most areas of Yunnan. The distribution and degree of the increasing trend of the warm nights are similar to previous studies whose study time range is up to the beginning of the 21st century. However, the ranges of the decrease (increase) of cold nights and cold days (warm days) are wider, and the decreasing (increasing) trends are more obvious. In particular, the number of cold days (warm days) increases (decreases) in the central Yunnan in previous study [21], but decreases (increases) in our study.

The annual average number of low temperature days in the SWC shows a significant decreasing trend in 1961–2017, and the extreme minimum temperature shows a significant increasing trend. This result is similar to previous result whose study time range is up to the beginning of the 21st century [21]. From 1961 to 2017, the annual average number of high temperature days in the SWC shows an increasing trend. The annual average number of high temperature days is higher from the early 1960s to the middle and late 1970s, and lower from the late 1970s to the middle 1990s. Then, it gradually increases and reaches the maximum in 2006. This result is consistent with Gao et al. [41]. The number of high temperature days declines after 2006 but remains high. Ma et al. [42] pointed out that the annual number of high temperature and heat wave days in the SWC from 1961 to 2010 shows a nonsignificant increasing trend. However, it is found in our study that the number from 1961 to 2017 shows a significant increasing trend, with an increasing rate of 0.3 days per decade, and the increasing rate in the central-southern Yunnan even reaches 4 days per decade. From 1961 to 2017, the extreme maximum temperature of the SWC increases significantly at a rate of 0.2 °C per decade, and the increasing rate in the eastern Tibet, central Sichuan Plateau and the transition zone between plateau and basin can reach 0.4 °C per decade. Compared with previous results [21,42], the range with increased extreme maximum temperature has expanded remarkably.

In general, compared with previous studies, the decreasing trend of the extreme cold events in the SWC has slowed down in recent decade in this study, but the increasing trend of the extreme warm events has become more obvious. The variations of minimum (maximum) temperature directly reflects the variations of extreme cold (warm) events. As shown in this study, the changes of the lowest and highest temperatures in SWC from 1961 to 2000 are relatively consistent, showing the characteristics of first decreasing and then increasing. However, since 2001, the highest temperature exhibits a continuous increasing trend, while the lowest temperature shows a significant decreasing trend (Fig. 11). This may be the main reason for the decline of extreme cold events but the continuous increase of extreme warm events in recent decade. The slowdown of the decreasing trend of extreme cold events may be closely related to the reduction of Arctic sea ice caused by global warming. Studies have found that the reduction of Arctic sea ice can lead to more frequent blocking at the Ural Mountains, causing cold air to move south frequently, thus forming more cold events [43,44]. In addition, the reduction of Arctic sea ice is conducive to the emergence of the negative phase of the North Atlantic Oscillation, and cold waves tend to be stronger and last longer [45,46]. The increase of extreme warm events may be related to the effect of urbanization. The study found that urbanization has made a certain contribution to the increase of extreme warm events, and there is positive feedback between them [47–49]. In addition, the rapid increase of global ocean heat content after the 1990s is also closely related to the increase of extreme warm events in China in the same period [50,51].

From 1961 to 2017, the variation characteristics of extreme heavy precipitation days and extreme heavy precipitation amount are basically consistent, with nonsignificant variation trends on the whole. But the spatial differences are large. The decrease is the most significant in the western and southern Sichuan Basin, and the increase is the most significant in the eastern Guizhou and the western Chongqing. From 1961 to 2017, the extreme heavy rainfall intensity in the SWC tends to increase, with an increasing rate of 5 mm day^{-1} per decade in some areas in the middle of Sichuan Basin and the eastern Guizhou. The percentage of extreme heavy precipitation in the SWC shows a significant increasing trend, especially in the northeastern Sichuan, the central and eastern Guizhou, and the central Yunnan. The spatio–temporal distribution characteristics of rainstorm days, rainstorm amount and rainstorm intensity from 1961 to 2017 are similar to those of the extreme heavy precipitation index, mainly showing a significant decreasing trend in the western Sichuan Basin and a significant increasing trend in the eastern Sichuan Basin and the central-eastern Guizhou. The variation characteristics of extreme heavy precipitation and rainstorm are basically consistent with some previous research results [23,42,52], indicating that the extreme precipitation in the past decade has maintained the situation at the beginning of the 21st century.

The study shows that the increasing trend of extremely heavy precipitation in eastern Sichuan and Guizhou and the decreasing trend in the western Sichuan Basin may be caused by the difference in altitude [53]. In addiation, the difference may be related to the westward extension of the Western Pacific subtropical high and the eastward movement of the South Asian high from 1961 to 2017 (Fig. 12). When the Western Pacific subtropical high is located in the west, the warm and humid air from the western Pacific can transport more water vapor from the southwest of the subtropical high to the east of the southwest region, which is conducive to the generation of extremely heavy precipitation. When the South Asia High is located to the west, downdraft is more likely to occur in the central and western parts of Southwest China, which is not conducive to the generation of extreme precipitation.

The increasing trend of extremely heavy precipitation in the Hengduan Mountains may be closely related to the strong El Nino event [54]. The Arctic Oscillation may be a key factor in the increasing trend of extremely heavy precipitation in Tibet [55]. It is also pointed out that solar activity is the main influencing factor of the extreme precipitation change trend in southwest China [56]. The formation mechanism of extreme precipitation is very complex and is closely related to the change in the atmospheric circulation system [57]. It is not only regulated by the advance and retreat of the monsoon [58], but also affected by factors such as sea surface temperature and snow cover [59,60], and also directly related to the change of terrain height [61,62]. Therefore, the SWC extreme precipitation event does not show a large-scale consistent and significant change trend like the extreme temperature event. The number of the longest consecutive non-precipitation days in most parts of SWC shows an increasing trend, especially in most parts of Yunnan and southern Sichuan. Meanwhile, the frequency and intensity of extreme high temperature events increase while the precipitation amount decreases. This is closely related to the two extreme drought events in the SWC since 21st century [63].

In the past, there were many studies on extreme climate events in China, but few studies focused on the events in the SWC. Moreover, most studies only focused on the extreme temperature events or extreme precipitation events, and the study periods were only up to around 2010. In this study, the data from more meteorological observation stations and with longer time series were used, and more detailed variation characteristics of the extreme climate events in the SWC were obtained. Some results are consistent with previous studies, and some new findings are also made, which will help understand the variation characteristics of the extreme climate events in the SWC under the background of global warming. In addition, although this study is based on the observation data from more stations, there are still few meteorological observation stations in the plateau area of SWC. Therefore, how to supplement the data with high-resolution grid temperature and precipitation products and to reveal more accurate climate change laws is the key to the future studies. For example, Nie and Sun [64] compared and analyzed the applicability of multiple sets of grid precipitation products in the SWC, which can provide reference for future research.

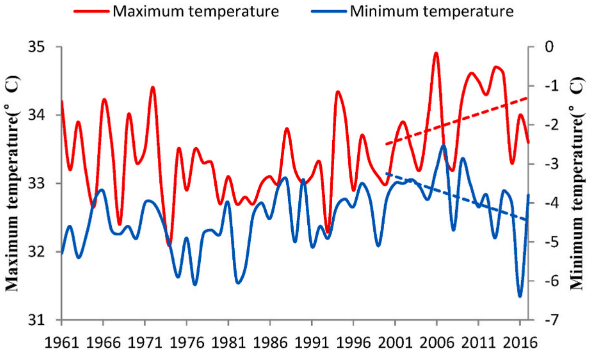

Fig. 11. Annual change of maximum and minimum temperatures in southwest China from 1961 to 2017.

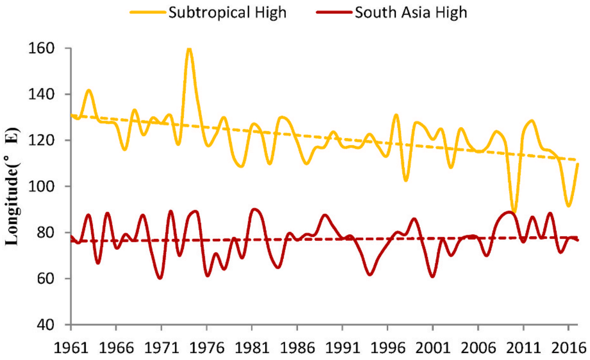

Fig. 12. The location change of the western extension ridge point of the Western Pacific subtropical high and the center of the South Asia high from 1961 to 2017.

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Data availability statement

Data will be made available on request.

Author contribution statement

Chunxue Wang: Performed the experiments; Analyzed and interpreted the data; Wrote the paper. Chao Chen: Conceived and designed the experiments; Analyzed and interpreted the data. Shunqian Zhang: Zhenfeng Ma: Yanmei Pang: Performed the experiments; Contributed reagents, materials, analysis tools or data.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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