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Analysis of Change in Summer Extreme Precipitation in Southwest China and Human Adaptation

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Abstract: This study analyzed the change in and mechanisms of summer extreme precipitation in Southwest China (SWC) during 1979–2021. The trend in summer extreme precipitation showed an evident interdecadal mutation in the late 1990s; it decreased during 1979–1996 (P1) and increased during 1997–2021 (P2). It is observed that the moisture flux in SWC is more abundant in P2 than in P1. The South Asian high (SAH) and western Pacific subtropical high (WPSH) contributed to the change in extreme precipitation in SWC. Both the SAH and WPSH weakened in 1979–1996 and enhanced in 1997–2021. The enhanced SAH and WPSH are conducive to forming updrafts in SWC and transporting moisture from the Bay of Bengal (BOB) and South China Sea (SCS) into SWC. Further research found that the causes for the interdecadal variation of the SAH and WPSH are the anomalies of sensible heat flux (SSH) over the Tibetan Plateau (TP) and sea surface temperature (SST) in the tropical western Pacific–Indian Oceans. The SSH is the main energy source of troposphere air and an essential component of the surface heat balance because it can maintain the intensity and influence range of the SAH. The increasing SST stimulated strong upward motion and thus maintained the strength of the WPSH, which also made the WPSH extend westward into mainland China. This study also summarized local human adaptation to climate change. The use of advanced science and technology to improve monitoring and forecasting ability is an important measure for human society to adapt to climate change. At the same time, increasing the participation of individuals and social organizations is also an indispensable way to increase human resilience to climate change.

Keywords: extreme precipitation; climate change; South Asian high; western Pacific subtropical high; sensible heat flux; sea surface temperature; human adaptation



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1. Introduction

In recent years, frequent extreme precipitation events under the background of global warming have caused great impacts on the economy and ecological environment systems [1]. In order to make the forecast more accurate and reduce the losses from disasters, more and more studies on extreme precipitation have been conducted. Zhu et al. [2] pointed out that extreme precipitation is increasing in many parts of the world, especially China. More and more extreme precipitation events have resulted in increasing amounts of precipitation. By calculating the temporal and spatial characteristics of daily precipitation at 272 meteorological stations in China from 1960 to 2000, Liu et al. [3] found that the amount of precipitation increased by 2%; however, the frequency of precipitation events decreased by 10%. The increase in the amount of precipitation and decrease in frequency would make extreme precipitation events occur more frequently, and the increase in the frequency of heavy precipitation events would contribute to 95% of the increase in the amount of total precipitation. Based on the observational data and numerical experiments, many scholars made conclusions that extreme precipitation events in most regions of China had increasing trends; in particular, in the southeast coastal region, the middle and lower

reaches of the Yangtze River (MLRYR), and northern China, there would be more extreme precipitation events in the future [4,5].

The rainy seasons in Southwest China (SWC) are from late spring to early autumn, and the extreme precipitation events mainly occur in summer. The SWC region mainly includes the Sichuan Basin, the Yunnan–Guizhou Plateau, and the Hengduan Mountains, which are a mountainous region with complex terrain, drastically varying altitudes, and fragile ecosystems [1,6–8]. Therefore, geological disasters related to extreme precipitation during rainy seasons occur more frequently in SWC than in most other regions of China, and cause larger losses of human life and losses within the economy [9–11]. The purpose of our research on extreme precipitation in SWC was to find out the associated physical mechanism, which can help us improve the ability to prevent disasters. Summer precipitation in SWC is affected by many atmospheric circulation systems [5,12,13]. From June to August, the South Asian summer monsoon (SASM) and East Asian summer monsoon (EASM) jointly influence the precipitation in SWC [7,14–16]. When the SASM and the EASM strengthen simultaneously, sufficient moisture from the Bay of Bengal (BOB) and the South China Sea (SCS) is transported into SWC; therefore, precipitation in this region increases. Conversely, the precipitation decreases when the two weaken simultaneously [17–19]. Therefore, the SCS and BOB have become crucial moisture source regions for summer precipitation in SWC [12,20]. The interdecadal change in the EASM and SASM in the late 1990s probably led to the abrupt change in extreme precipitation in SWC. Many scholars have attempted to explain this phenomenon from multiple perspectives, such as interdecadal variations in tropical sea surface temperature (SST), anomalies of surface sensible heat (SSH) over the Tibetan Plateau (TP), and the climate effects of greenhouse gasses and aerosols [21–24].

The thermal effect of the TP can affect atmospheric circulation and precipitation in SWC [25–29]. Spring sensible heat flux (SSH) over the TP has a significant influence on the intensity variations in the South Asian high (SAH) and western Pacific subtropical high (WPSH). An abnormally strong SSH over the TP in spring leads to an abnormally strong SAH and WPSH. At this moment, SWC is controlled by cyclonic circulation and moisture convergence, which are conducive to the generation of extreme precipitation in summer [4,29–33]. The SAH also usually couples with the WPSH to affect summer precipitation in SWC. Sea surface temperature anomaly (SSTA) is another critical factor affecting rainy season precipitation in SWC [34–36]. The tropical Pacific Ocean (PO) and Indian Ocean (IO) SSTA significantly affect summer precipitation in SWC by influencing the Walker Circulation and the local Hadley Circulation [14,15,33,37]. Similarly, the North Atlantic SSTA, such as the tripolar SSTA mode, affect precipitation in SWC by the downstream Rossby wave train [37–40].

Summer extreme precipitation has had evident interannual variations and long-term trend changes. For example, in the late 1990s, because of the interdecadal variation of the EASM, summer extreme precipitation in eastern China and SWC both experienced interdecadal mutations. Two questions are raised as follows: (1) Did the trend of summer extreme precipitation in SWC change in sync with the EASM? (2) Which physical mechanisms affected the increase or decrease in the trend of summer extreme precipitation in SWC? (3) How can local humans adapt to the risks and challenges brought by climate change? In the following sections of this paper, we will answer these questions in order to deepen the understanding of the variation regularity of the summer extreme precipitation in SWC and provide a reference for disaster warnings and loss reduction.

The remainder of this paper is structured as follows. The methods and datasets used in this paper are described in Section 2. Section 3 presents the spatiotemporal features of extreme precipitation in SWC and analyzes the evolution of atmospheric circulation patterns and SSTA associated with SWC's extreme precipitation. Section 3 also includes the specific practices and methods adopted by local humans in order to respond to climate change. The discussion and conclusions are presented in Sections 4 and 5.

2. Materials and Methods

2.1. Datasets

In this paper, daily precipitation data with the resolution of $0.5^\circ \times 0.5^\circ$ for the period 1979 to 2021 are obtained from the National Oceanic and Atmospheric Administration (NOAA) Climate Prediction Center (CPC). The CPC morphing technique dataset (CMORPH) by NOAA has been created using precipitation estimates derived from low orbiter satellite microwave observations exclusively. Then, geostationary IR data are used as a means to transport the microwave-derived precipitation features during periods when microwave data are not available at a location. This study focuses on the area of SWC (97° – 109° E, 21° – 34.3° N). Atmospheric variables, including geopotential height, omega, wind, vertical velocity, and specific humidity are obtained from the National Centers for Environmental Prediction (NCEP) and National Center for Atmospheric Research (NCAR) reanalysis dataset using a global dataset with $2.5^\circ \times 2.5^\circ$ spatial resolution [41]. The COBE SST dataset at a $1^\circ \times 1^\circ$ spatial resolution is provided by the NOAA Climate Diagnostic Center (CDC) [42]. The average condition from 1981 to 2010 is considered as the climate average state.

2.2. Definition of Extreme Precipitation and Regional Extreme Precipitation Events

In this study, extreme precipitation and regional extreme precipitation events (REPEs) in SWC are selected using the percentile threshold method [1,43,44]. The 95th percentile of observed precipitation on rainy days (with precipitation ≥ 0.1 mm) based on the rain gauge during June to August from 1979 to 2021 is defined as the daily extreme precipitation threshold of that gauge. Then, the number of gauges with extreme precipitation events in the region on each day is counted. A gauge with extreme precipitation refers to a gauge with observed daily precipitation greater than its daily extreme precipitation threshold. Furthermore, a regional extreme precipitation day is defined when the number of gauges with extreme precipitation on that day is greater than the 95th percentile from June to August. An REPE is defined as a period containing one or more consecutive regional extreme precipitation days. For one-day REPEs, the onset day of REPE is marked as day 0.

2.3. Analysis Methods

In order to analyze the circulation anomalies when the REPEs occur, we apply a composite analysis on day 0 of the REPEs for daily variable anomalies. Daily variable anomalies are obtained by removing the climatological and seasonal cycles that occurs on each calendar day between 1981 and 2010 [1,29].

The methods of moving t test and Yamamoto test are used to determine the mutation of extreme precipitation in this study [29].

3. Results

3.1. Extreme Precipitation in SWC in the Past 40 Years

The results of moving t test and Yamamoto methods show the characteristics of consistency, exhibiting abrupt trend changes in summer extreme precipitation and precipitation in SWC in 1997 (Figure 1). The abrupt change in the extreme precipitation trend in 1997 divides the study period into two subperiods: a decreasing period (1979–1996, P1) and an increasing period (1997–2021, P2).

From 1979 to the mid-late 1990s, there are downward trends in the amount of summer precipitation and extreme precipitation. After the mid-late 1990s, both of them increase (Figure 2). The annual variation rate of summer precipitation amount in SWC is $-10.33 \text{ mm}\cdot\text{yr}^{-1}$ during 1979–1996 and $3.47 \text{ mm}\cdot\text{yr}^{-1}$ during 1997–2021. However, the summer precipitation days show a consistent downward trend rather than a sudden change, the annual variation rate is $-0.45 \text{ day}\cdot\text{yr}^{-1}$ during 1979–1996 and $-0.25 \text{ day}\cdot\text{yr}^{-1}$ during 1997–2021. The annual variation of extreme precipitation days in SWC is $-0.15 \text{ day}\cdot\text{yr}^{-1}$ during 1979–1996 and $0.09 \text{ day}\cdot\text{yr}^{-1}$ during 1997–2021.

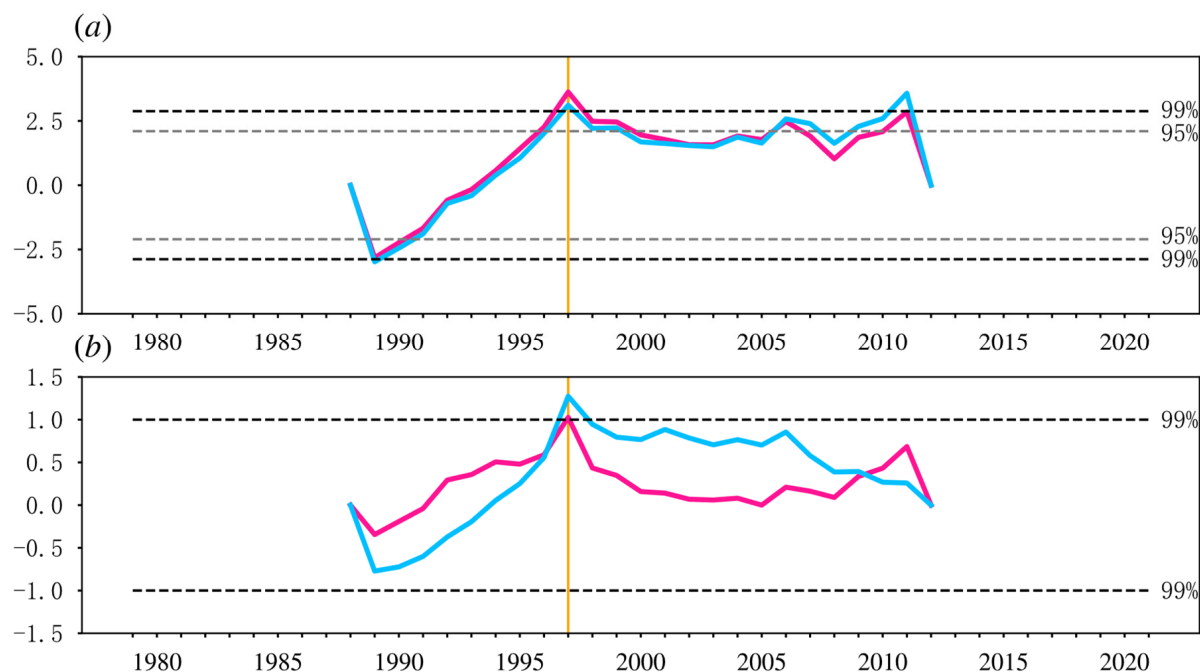


Figure 1. Moving t test (a) and Yamamoto test (b) for extreme precipitation amount (red lines) and its frequency (blue lines). The black and gray dashed lines indicate the 99% and 95% significance level, respectively. The orange line represents the year (1997) in which the trend mutation occurs.

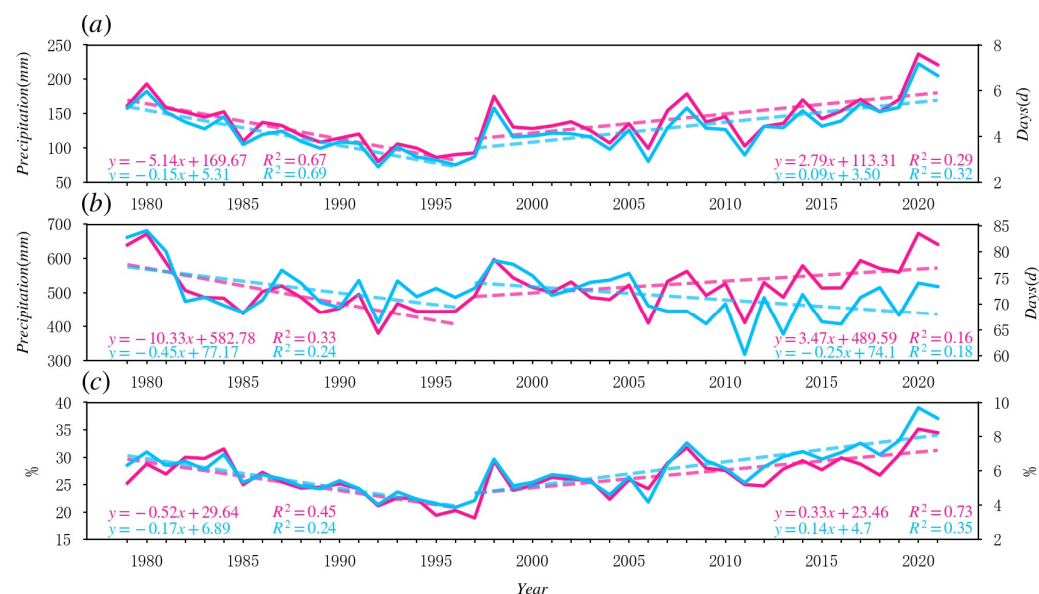


Figure 2. Summer extreme precipitation amount ((a); red lines; unit: mm) and its frequency ((a); blue lines; unit: day) in SWC. Summer total precipitation amount ((b); red lines; unit: mm) and the number of rainy days ((b); blue lines; unit: day) in SWC. Percentage of extreme precipitation to summer total precipitation ((c); red lines; unit: %) and ratio of extreme precipitation frequency to rainy days ((c); blue lines; unit: %). Dotted lines indicate linear trends during P1 and P2. Regression function and variance contribution during P1 and P2 are shown in the left or right corners of each panel.

The annual variation trend in extreme precipitation amount (Figure 2a) in SWC is similar to that of the summer precipitation amount. The correlation coefficient between these two values is 0.92. The annual variation rate of the extreme precipitation amount in SWC is $-5.14 \text{ mm} \cdot \text{yr}^{-1}$ during 1979–1996 and $2.79 \text{ mm} \cdot \text{yr}^{-1}$ during 1997–2021. Figure 2c shows the percentage of extreme precipitation to summer precipitation as well as the

extreme precipitation days to precipitation days in SWC during 1979 to 2021. Both the ratios are consistent with the trend in extreme precipitation amount and show trend mutations in the mid-to-late 1990s. That is, during 1979–1996, the percentage of summer extreme precipitation in total precipitation in SWC generally shows a downward trend, but an upward trend is observed during 1997–2021.

The distribution of the extreme precipitation amount and frequency is spatially inhomogeneous. It can be seen from the spatial distribution of extreme precipitation that the mean (Figure 2a) and frequency values (Figure 2b) are highest in the eastern and southern SWC. The proportion of extreme precipitation to total precipitation reflects the risk of flood disasters in this region [45]. This proportion is higher in the eastern portion and lower in the western portion of SWC. The linear trends of this proportion in P1 and P2 are shown in Figure 3. In the central and northern parts of SWC and western Yunnan Province, this proportion decreased in P1 and increased in P2. The result is consistent with the decadal variation of the extreme precipitation trend, as shown in Figure 2.

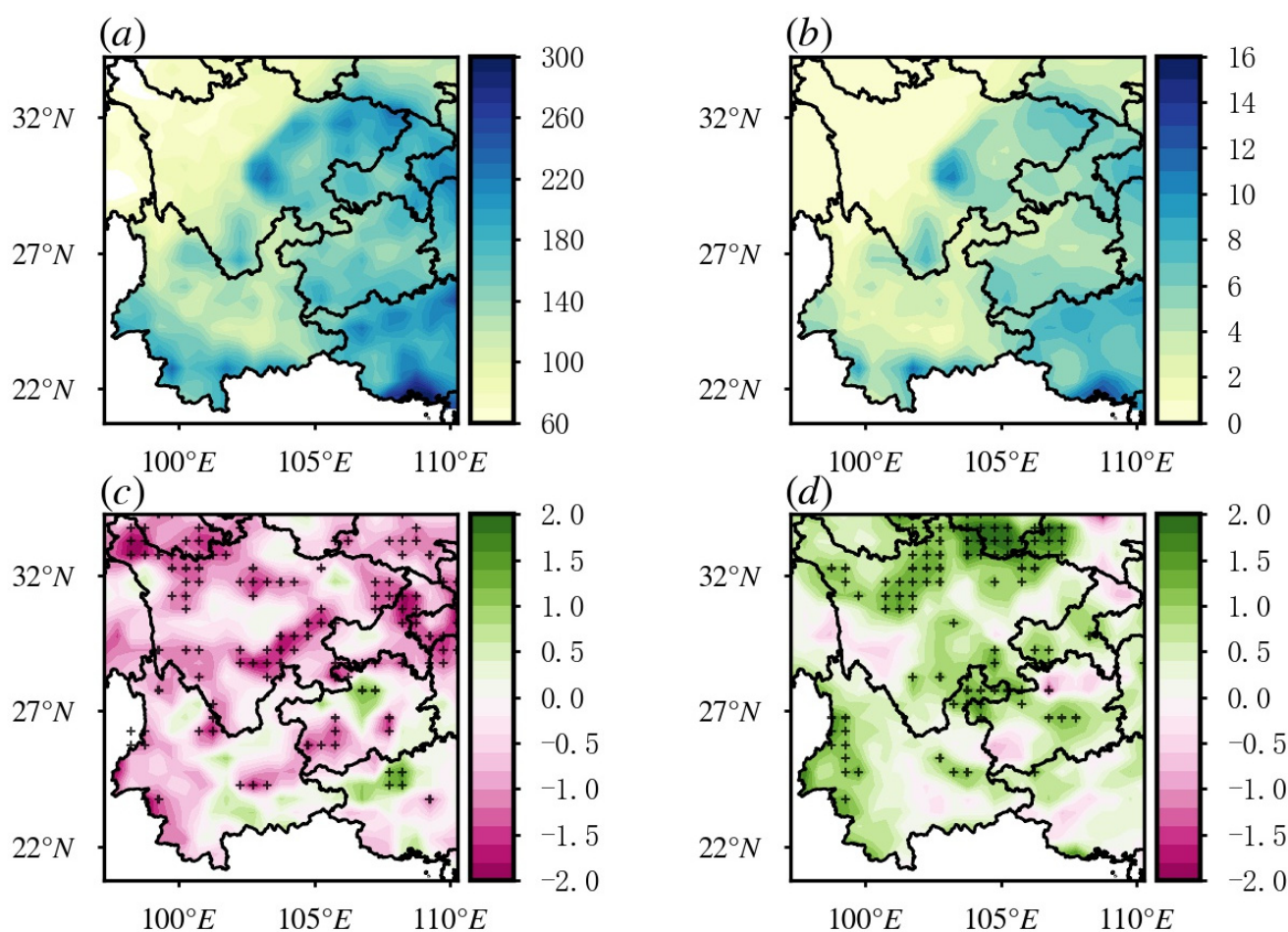


Figure 3. Climatology of summer extreme precipitation amount ((a); unit: mm) and frequency ((b); unit: day) during 1979–2021. Distribution of the linear trend in the percentage ratio of extreme precipitation to summer total precipitation (unit: $\% \cdot \text{yr}^{-1}$) during 1979–1996 (c) and 1997–2021 (d). + denote the linear trend significant at the 95% confidence level.

During P1 and P2, extreme precipitation shows overall decreasing and increasing trends, respectively, in SWC (Figure 4). The extreme precipitation amount and the frequency in most regions of SWC show a linear decrease in P1, except for northwestern Guangxi, southern Yunnan, and central Guizhou Provinces (Figure 4a,b). In contrast, in P2, the amount and frequency of summer extreme precipitation in most regions of SWC shows a

linear increase, particularly in southwestern Yunnan Province and the central and eastern Sichuan–Chongqing regions (Figure 4c,d).

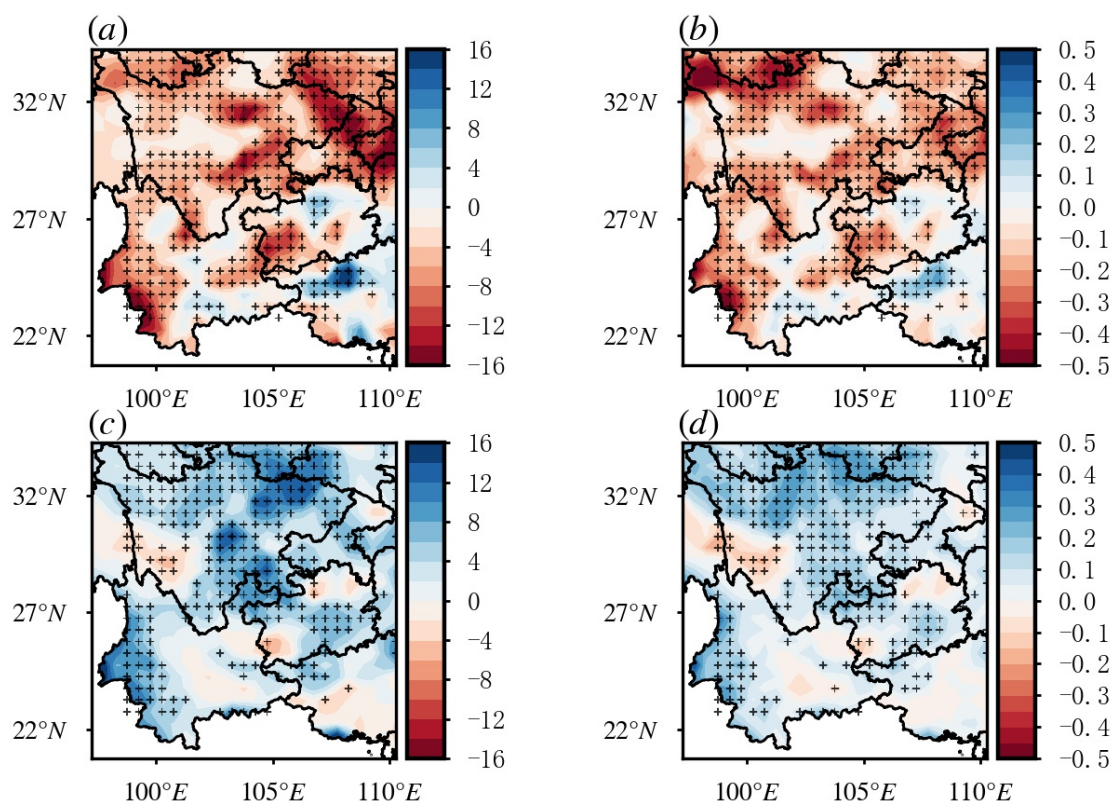


Figure 4. Distribution of the extreme precipitation amount linear trend (shaded; unit: $\text{mm}\cdot\text{yr}^{-1}$) during 1979–1996 (a) and 1997–2021 (c). Distribution of the extreme precipitation frequency linear trend (shaded; unit: $\text{day}\cdot\text{yr}^{-1}$) during 1979–1996 (b) and 1997–2021 (d). + denote the linear trend significant at the 95% confidence level.

The impact of extreme precipitation on sustainability is multifaceted, and with the intensification of global climate change, this impact is becoming increasingly significant. First, heavy rains and floods caused by extreme precipitation events often lead to damage to infrastructure and result in huge direct economic losses. According to the assessment results of the National Climate Center of China, the economic losses caused by extreme weather and climate events in China have been increasing in recent years, and the direct economic losses caused by rainstorms and floods account for the largest proportion. Second, extreme precipitation may cause crop damage, affect food production and quality, and thus threaten food security. Floods may scour the soil, leading to a decline in soil fertility and long-term impact on agricultural productivity. Third, extreme precipitation events can disrupt transportation and logistics networks, lead to disruptions in the supply of raw materials, and affect enterprise production and market supply. This kind of supply chain disruption not only affects the economic efficiency of enterprises, but also may trigger a chain reaction such as rising prices.

Summer is the main period of agricultural production in SWC. The main cash crop in SWC is rice. Frequent summer extreme precipitation events can cause rice plants to fall over, making it difficult for farmers to harvest the fallen rice plants. Besides, a large number of rice particles fall to the paddy fields via heavy rain. Therefore, in the rice harvest season, extreme precipitation will directly decrease grain production. Agricultural production is essential to achieve human sustainability, and food security is an important component of national security. Therefore, only with a full understanding of the formation mechanism of

extreme precipitation can we formulate specific strategies for human adaptation to climate change and achieve sustainability.

3.2. Anomalous Atmospheric Patterns Associated with the Abrupt Change in Extreme Precipitation Trend

To investigate the background atmospheric circulations responsible for the abrupt change in extreme precipitation trend in SWC, we analyze simultaneous atmospheric circulation anomalies at 200 hPa, 500 hPa, and 850 hPa. At 200 hPa, there is an anomalous cyclonic circulation over East Asia (20° – 40° N, 80° – 120° E), indicating that the influence and intensity of SAH tend to weaken during P1 (Figure 5a). At 500 hPa, the geopotential height over Northwest Pacific (20° – 40° N, 150° – 170° E) shows a decreasing trend, and the horizontal wind field shows a cyclonic circulation, indicating that WPSH has a weakening trend during P1 (Figure 5b). The decrease in its influence range and the weakening of its intensity are not conducive to guiding the moisture flux into SWC (Figure 5a,b). At 850 hPa, the geopotential height over SWC tends to increase, which corresponds to the enhancement of the near-surface downward motion. Warm and wet moisture from SCS and BOB enters southeastern China, but does not enter SWC (Figure 5c).

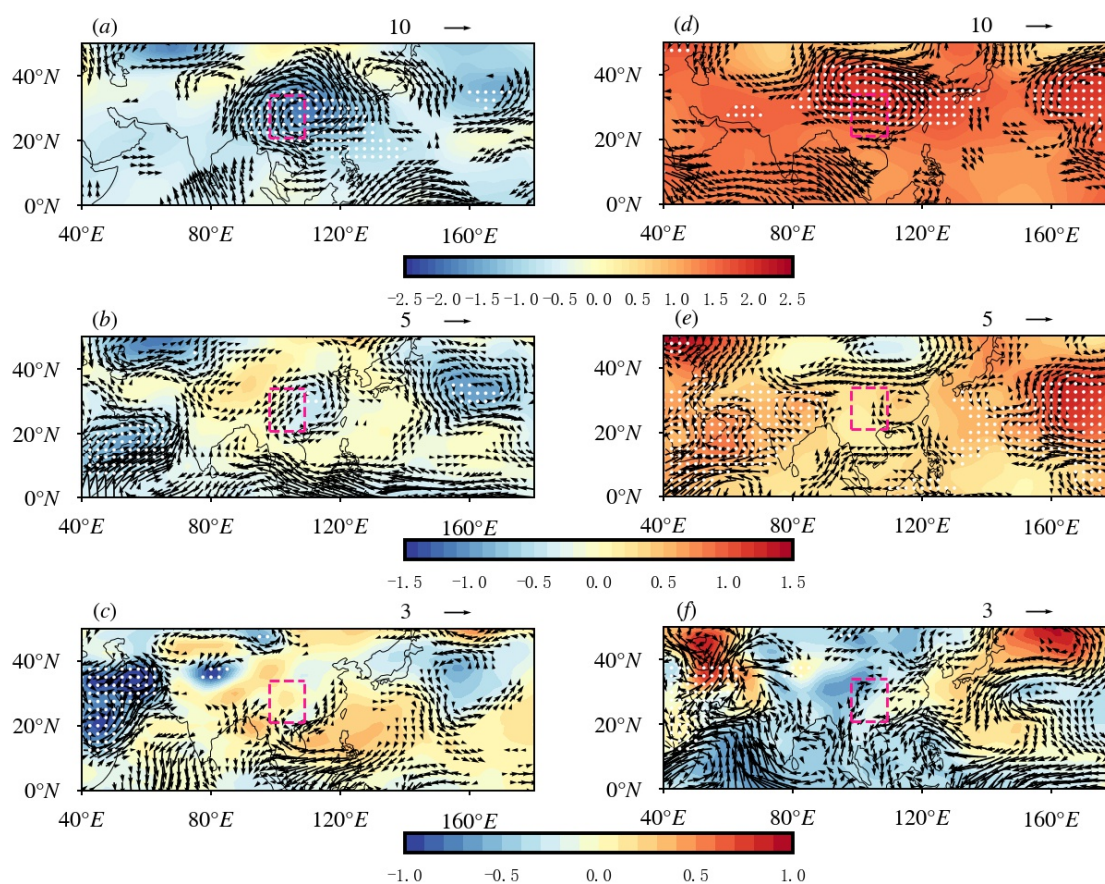


Figure 5. Distribution of the linear trend in geopotential height (unit: gpm·yr⁻¹) and horizontal wind velocity (unit: m·s⁻¹·yr⁻¹) during 1979–1996 at 200 hPa (a), 500 hPa (b), and 850 hPa (c). Distribution of the linear trend in geopotential height (unit: gpm·yr⁻¹) and horizontal wind velocity (unit: m·s⁻¹·yr⁻¹) during 1997–2021 at 200 hPa (d), 500 hPa (e), and 850 hPa (f). Wind vector arrows exceeding the 95% confidence level are displayed. Dots denote the linear trends significant at the 95% confidence level. Areas bounded by pink rectangles denote SWC.

There is an anomalous anticyclone over East Asia (20° – 40° N, 80° – 120° E) during P2 at 200 hPa, indicating that the influence range and intensity of the SAH are increasing. At 500 hPa, strong anticyclonic circulation dominates the Northwest Pacific (20° – 40° N, 150° – 170° E), indicating that the intensity of the WPSH strengthens. The enhanced influ-

ence range and intensity are conducive to guiding the southerly warm and wet moisture into SWC and they promote convective activity over SWC (Figure 5d,e). At 850 hPa, the geopotential height over SWC tends to decrease, which corresponds to the strengthening of the near-surface upward motion. In addition, the southwest wind from BOB and southeast wind from Northwest Pacific tend to increase, and these are conducive to the transport of moisture flux from BOB and SCS into SWC to trigger the extreme precipitation (Figure 5f).

Sufficient moisture flux and strong upward movements are necessary conditions for extreme precipitation [46,47]. Figure 6 shows the spatial distribution of the linear trends in moisture flux and its divergence in P1 and P2. The southward moisture flux transport is enhanced, and the moisture flux from BOB and SCS is relatively weakened in P1. In addition, the divergence trend in this region is enhanced (Figure 6a). In P2, moisture flux from BOB and SCS is enhanced, as is the convergence in this region (Figure 6b). The moisture flux over SWC primarily originates from BOB and SCS. These moisture fluxes enter SWC under the transportation of SASM, EASM, as well as mid-upper westerly winds, and then constitute the main moisture sources for summer extreme precipitation in SWC [12,20]. In P1 (P2), the moisture flux reaching SWC via BOB and SCS exhibits a decreasing (increasing) trend. Figure 6c,d show the linear trends in vertical velocity at 500 hPa in P1 and P2, respectively. The enhanced upward movement in P2 provides favorable dynamic conditions for the occurrence and development of extreme precipitation, and cooperates with sufficient moisture, making the amount and frequency of extreme precipitation tend to increase.

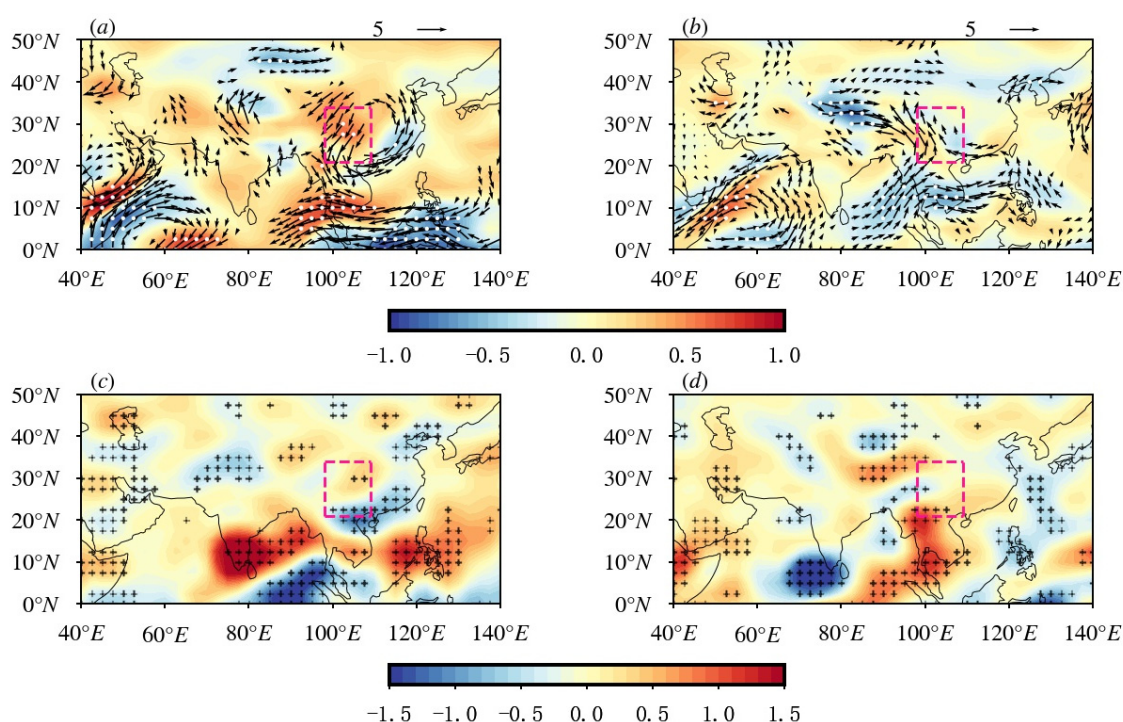


Figure 6. Distribution of the moisture flux (unit: $\text{kg} \cdot \text{m}^{-1} \cdot \text{s}^{-1} \cdot \text{yr}^{-1}$) and divergence (unit: $\text{s}^{-1} \cdot \text{yr}^{-1}$) linear trend during 1979–1996 (a) and 1997–2021 (b). Distribution of the 500 hPa omega linear trend (unit: $\text{pa} \cdot \text{s}^{-1} \cdot \text{yr}^{-1}$) during 1979–1997 (c) and 1997–2021 (d). Moisture flux arrows exceeding the 95% confidence level are displayed. Dots and + denote linear trends in divergence and omega significance at the 95% confidence level, respectively. Areas bounded by pink rectangles denote SWC.

The SAH and WPSH indices decrease in P1; however, these indices increase in P2 (Figure 7a,b). This result is consistent with the summer extreme precipitation in SWC (Figure 1). As SAH and WPSH enhance and extend, there is abnormal upward movement and moisture convergence over SWC. Warm and wet moisture from SCS and BOB enters

SWC along the edge of WPSH (Figure 5e), leading to water moisture convergence in SWC (Figure 6b).

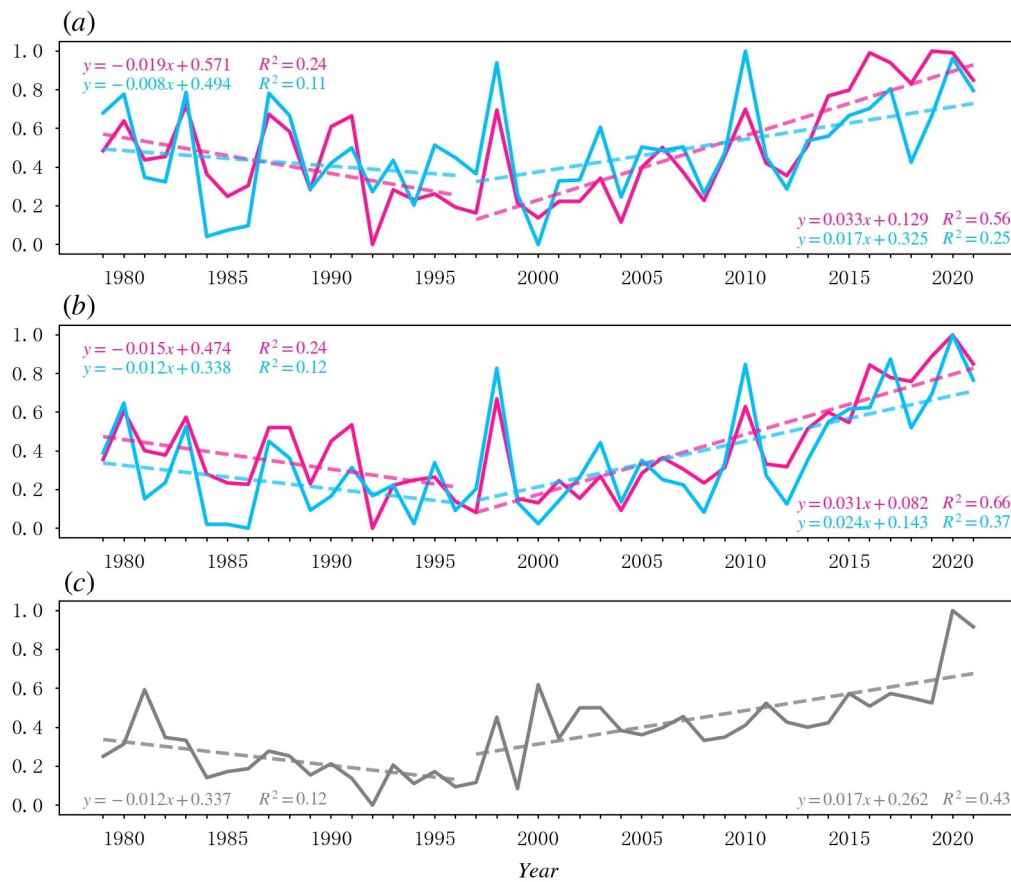


Figure 7. Standardized area index of SAH ((a); red line) and WPSH ((a); blue line). Standardized intensity index of SAH ((b); red line) and WPSH ((b); blue line). Regional average spring standardized SSH over TP (c). The dotted lines indicate linear trends during P1 and P2. Regression functions and variance contributions during P1 and P2 are marked in the left or right bottom corners of each panel.

Table 1 lists the correlation coefficients between SAH (WPSH) indices and summer extreme precipitation in SWC. The SAH intensity index, area index, and eastern extension index are significantly correlated with the summer extreme precipitation in SWC, indicating that when the intensity of SAH increases and its coverage extends eastward, the summer extreme precipitation in SWC increases. The WPSH indices also have a significant correlation with the extreme precipitation in SWC; almost all of indices show correlation with the extreme precipitation at a confidence level greater than 95%.

Table 1. Matrix of correlation coefficients between SAH and WPSH indices and extreme precipitation indices.

	Index Name	Precipitation	Intensity	Frequency
SAH	Intensity index	0.722 **	0.526 **	0.729 **
	Area index	0.660 **	0.530 **	0.665 **
	Eastern extension index	0.596 **	0.581 **	0.611 **
WPSH	Intensity index	0.652 **	0.501 **	0.649 **
	Area index	0.504 **	0.371 *	0.488 **
	Western extension index	−0.620 **	−0.585 **	−0.584 **
	Ridge index	0.599 **	0.568 **	0.512 **

* Values are statistically significant at the 95% confidence level. ** Values are statistically significant at the 99% confidence level.

Figure 7c shows the standardized values of the average spring SSH over TP. The spring SSH over TP shows a downward trend from the early 1980s to the late 1990s and then an upward trend. This trend is consistent with the trend in extreme precipitation in SWC and subtropical high indices. The SSH can increase the heat of the lower troposphere air and moisture content in the air, thus, the SSH is related to the occurrence and development of extreme precipitation.

In addition, the spring SSH over TP is the key factor for maintaining the intensity of the SAH [48,49]. SSH is the main energy source of lower troposphere air and an essential component of the surface heat balance. The uneven spatial distribution and interannual variation in SSH inevitably lead to differences in the surface heating of the lower-troposphere air, affecting local weather and climate. Table 2 shows the correlation between the spring SSH over TP and subtropical high indices. The spring SSH over TP has a high positive correlation with the SAH indices. The SSH over central TP (85° E– 95° E) has the highest correlation with the SAH intensity, indicating that it is a main factor that maintained the intensity of the SAH.

Table 2. Matrix of correlation between SSH and SAH (WPSH) indexes.

Index Name		TP	Western TP	Central TP	Eastern TP
SAH	Intensity index	0.640 **	0.560 **	0.694 **	0.496 **
	Area index	0.585 **	0.523 **	0.636 **	0.446 **
	Eastern extension index	0.486 **	0.479 **	0.534 **	0.343 *
WPSH	Intensity index	0.621 **	0.490 **	0.659 **	0.523 **
	Area index	0.453 **	0.378 *	0.507 **	0.351 *
	Western extension index	−0.374 *	−0.442 **	−0.407 *	−0.227 *

* Values are statistically significant at the 95% confidence level. ** Values are statistically significant at the 99% confidence level.

Figure 8 shows the spatial distribution characteristics of the linear trend in spring SSH over TP in P1 (Figure 8a) and P2 (Figure 8b). In P1, except for a small part of TP, the linear trend in spring SSH is negative, indicating that SSH presents a relatively consistent decreasing trend over the entire region. In P2, the linear trend in spring SSH over TP is positive, except for some regions in the southern part of TP, indicating that SSH presents a relatively consistent increasing trend over the entire region. The linear trend of SSH over TP is consistent with the time series of SSH shown in Figure 7b.

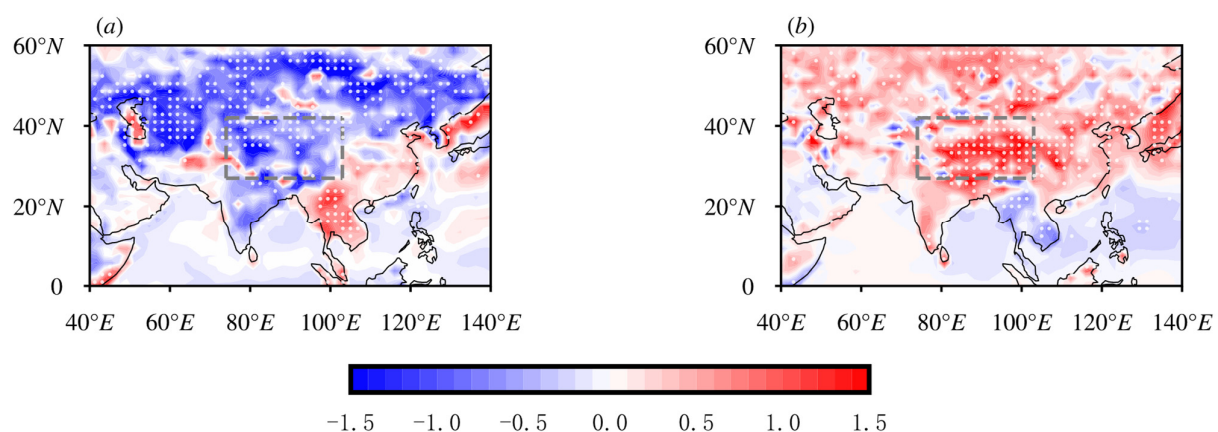


Figure 8. Distribution of SSH linear trend (unit: $\text{W}\cdot\text{m}^{-2}\cdot\text{yr}^{-1}$) during 1979–1996 (a) and 1997–2021 (b). Areas bounded by dashed gray rectangles denote TP. Dots denote the linear trend of SSH significance at the 95% confidence level.

Based on the aforementioned discussion, the spring SSH over TP cools in P1 and heats in P2 (Figure 7), resulting in SAH weakening in P1 and strengthening in P2 (Figure 5a,d). The extended and strengthened SAH couples with enhanced WPSH (Figure 5b,e), causing

the weather and climate background over SWC in the mid-to-late 1990s to become more conducive to the occurrence and development of extreme precipitation events.

3.3. Evolution of Atmospheric Circulation Patterns Associated with Extreme Precipitation

Although the linear trend in summer extreme precipitation and the evolution characteristics of atmospheric circulation over SWC are observed by dividing the research period into two subperiods (P1 and P2), we also desire to further analyze the differences in circulation patterns that lead to the different characteristics of REPEs in the two periods more completely and clearly. In order to achieve this goal, we select REPEs from 1992 to 1996 and from 2017 to 2021, then perform a composite analysis on them. The REPEs of 1992–1996 and 2017–2021 are used because the REPEs that occur during these two periods are the most representative cases, which can reflect the characteristics of the atmospheric circulation patterns that trigger REPEs to the greatest extent. Table 3 lists selected cases of REPEs.

Table 3. Extreme precipitation event cases.

Period	Year	Date
Sub-P1	1992	20 June, 15 July
	1993	11 June, 24 June, 21 July, 23 August
	1994	7 June, 26 July
	1995	8 June, 1 July
	1996	20 June, 31 July
Sub-P2	2017	4 June, 15 June, 24 June, 3 July, 6 July, 8 July, 7 August, 25 August, 29 August
	2018	5 June, 12 June, 26 June, 4 July, 8 July, 11 July, 4 August, 31 August
	2019	12 June, 5 July, 9 July, 13 July, 24 July, 3 August, 5 August, 23 August
	2020	3 June, 16 June, 18 June, 27 June, 2 July, 12 July, 21 July, 27 July, 12 August, 19 August, 25 August, 27 August, 31 August
	2021	9 June, 29 June, 12 August, 22 August, 25 August

In the subtropics, the extreme precipitation in SWC is influenced by low latitude and middle-to-high latitude atmospheric circulation systems [1,50,51]. Figure 9 shows the spatial distribution of the geopotential height and horizontal wind anomalies at different altitudes on the days on which REPEs occur (day 0) in Sub-P1 (Figure 9a–c) and Sub-P2 (Figure 9d–f). On day 0 of Sub-P1, the Eurasian continent is controlled by a strong anomalous anticyclone and a strong anomalous cyclone at 200 hPa. SWC is on the southwest side of the anomalous cyclone and controlled by the north wind. The main range of the SAH is over TP, and its influence range is slightly smaller than the climate average state with the eastern extension point locating at 20° N, 120° E (Figure 9a). At 500 hPa, a cyclone anomaly extends from the eastern China to SWC. The western extension point of the WPSH is located at 20° N, 120° E. Although its influence range is larger than the climate average state, its influence range does not extend into SWC and has no significant influence on SWC (Figure 9b). At 850 hPa, SWC is controlled by the northerly airflow, and neither the moisture flux from BOB nor SCS could reach SWC (Figure 9c). In conclusion, the attenuated (inconspicuously enhanced) influence range and intensity of the SAH (WPSH) lead to weak upward movement over SWC and insufficient moisture supply (Figure 10a). Therefore, the REPEs during this period exhibits characteristics of low frequency and weak intensity.

On day 0 in Sub-P2, an anomalous anticyclone dominates the Eurasian continent at 200 hPa, indicating that the SAH extends into SWC. Its influence range is greater than the climate average state with the eastern extension point located at 28° N, 124° E (Figure 9d). At 500 hPa, SWC is controlled by the southwest wind. The geopotential height over the Northwest Pacific is a positive anomaly and the western extension point of WPSH is located at 22° N, 112° E, indicating that the WPSH is stronger than the climate average state and affects SWC (Figure 9e). At 850 hPa, SWC is controlled by southerly airflow, and moisture flux from BOB and SCS is transported into SWC (Figure 9f). During this period,

the influence range and intensity of SAH and WPSH are enhanced, and the moisture is sufficient. The eastward extension of SAH and westward extension of WPSH lead to a strong upward movement over SWC (Figure 10b). Therefore, the REPEs in this period show characteristics of high frequency and strong intensity.

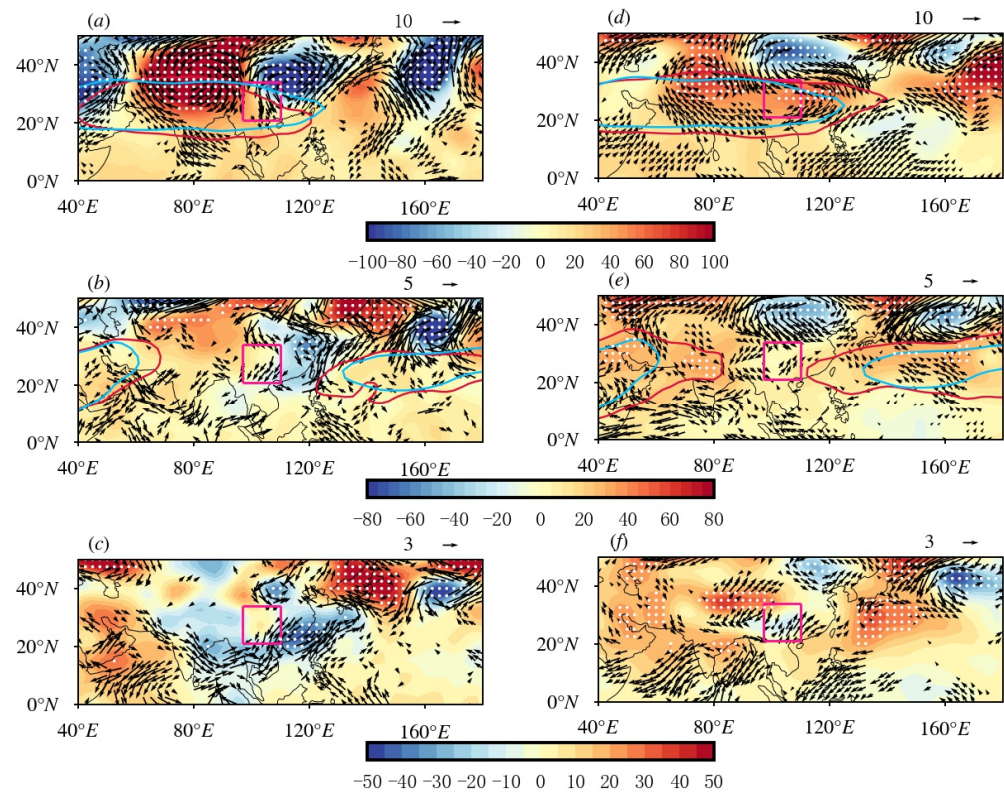


Figure 9. Composite geopotential height anomalies (shaded; unit: gpm) and horizontal wind anomalies (vectors; unit: $\text{m}\cdot\text{s}^{-1}$) at 200 hPa (a,d), 500 hPa (b,e), and 850 hPa (c,f) on day 0 of extreme precipitation events in SWC during Sub-P1 (left column) and Sub-P2 (right column). The region bounded by pink rectangles denotes SWC. Wind vector arrows exceeding the 95% confidence level are displayed. Dots denote the anomalies significant at the 95% confidence level. The blue and red lines represent 588 gpm (12,500 gpm) when the climate average state and extreme precipitation events occur, respectively.

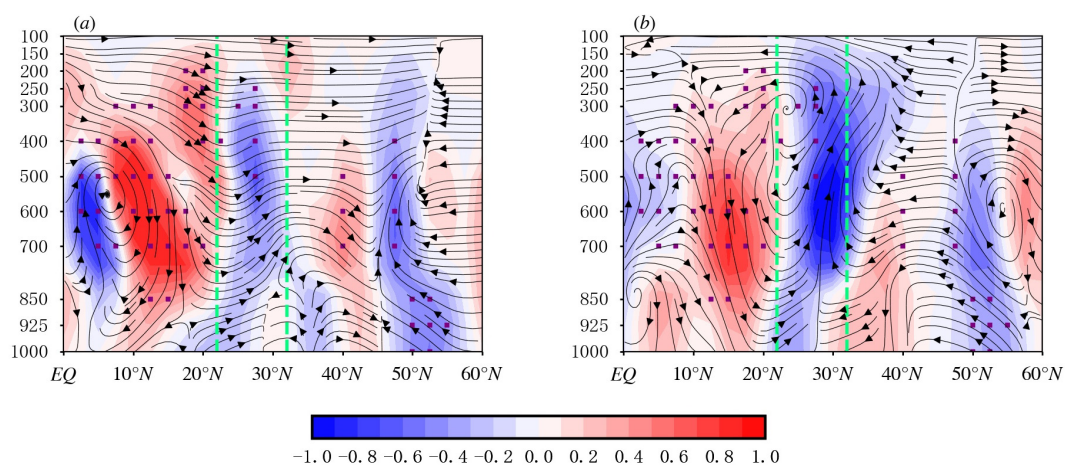


Figure 10. Latitude pressure (left vertical coordinate) cross-section of composite meridional wind (unit: $\text{m}\cdot\text{s}^{-1}$) and vertical motion (unit: $10^{-2} \text{ Pa}\cdot\text{s}^{-1}$) vectors anomalies averaged over 97.5°–110° E on day 0 of REPEs during Sub-P1 (a) and Sub-P2 (b). The area within the green dashed lines denotes SWC. Dots denote anomalies significant at the 95% confidence level.

Figure 11 shows the spatial distribution of the moisture flux and its divergence and the SSH anomalies on day 0 in Sub-P1 (Figure 11a,b) and Sub-P2 (Figure 11c,d). On day 0 in Sub-P1, there is an evident divergence of moisture flux over SWC (Figure 11a), and the SSH over TP does not show a consistent positive anomaly (Figure 11b). On day 0 in Sub-P2, there is an evident convergence of moisture flux over SWC (Figure 11c) and moisture flux primarily originates from BOB (Figure 11c). In addition, the SSH over TP shows a consistent positive anomaly (Figure 11d), which is indicative of the enhanced strength and influence range of the SAH.

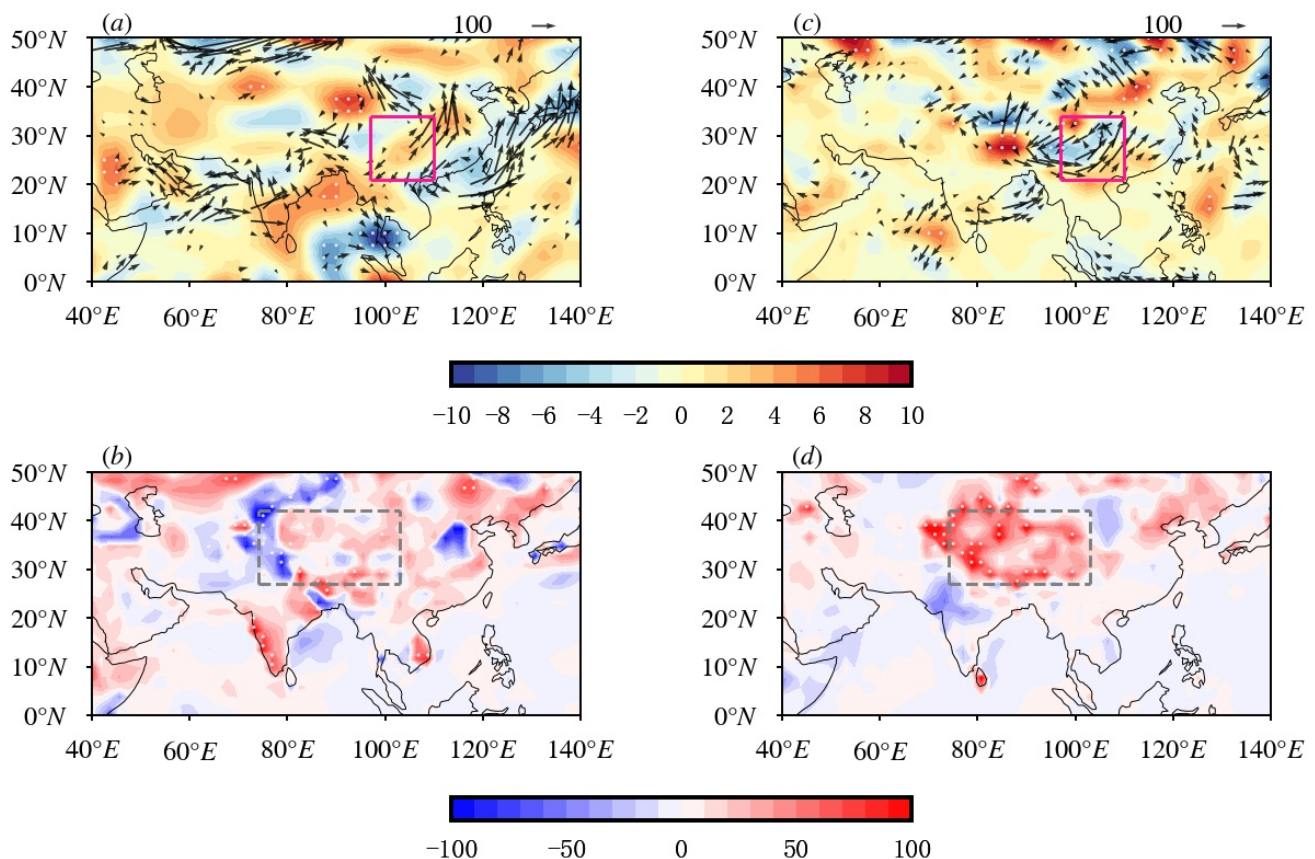


Figure 11. Composite moisture flux anomalies (vectors; unit: $\text{kg} \cdot \text{m}^{-1} \cdot \text{s}^{-1}$) and divergence anomalies (shaded; unit: s^{-1}) at 850–500 hPa averaged on day 0 of REPEs in SWC during sub-P1 (a) and sub-P2 (c). Composite SSH anomalies (shaded; unit: $\text{W} \cdot \text{m}^{-2}$) on day 0 of REPEs over SWC during sub-P1 (b) and sub-P2 (d). The regions bounded by pink rectangles denote SWC. The areas bounded by gray rectangles denote TP. Moisture flux arrows exceeding the 95% confidence level are displayed. Dots denote anomalies significant at the 95% confidence level.

The atmospheric circulation patterns on day 0 in Sub-P1 and Sub-P2 differ. When REPEs occur in Sub-P1, the attenuated (inconspicuously enhanced) influence range and intensity of SAH (WPSH) lead to weak upward movement and insufficient moisture supply over SWC. Moreover, the SSH over TP does not show a consistent positive anomaly. Therefore, the thermo-dynamic conditions are not conducive to the occurrence and development of REPEs in Sub-P1. However, in Sub-P2, thermo-dynamic conditions are conducive to the occurrence and development of REPEs. The composite analysis of the selected REPEs demonstrates that the different atmospheric circulation patterns in P1 and P2 have different impacts on REPEs.

3.4. SST Anomalies Associated with REPEs

The SST, a relevant extrinsic forcing factor of the atmospheric circulation system, of PO and IO have a significant influence on precipitation [14,15]. From winter to summer,

SST in BOB and Northwest PO have high positive correlations with the summer extreme precipitation in SWC (Figure 12a–c). The spatial distributions of linear SST trends in winter (Figure 12d,g), spring (Figure 12e,h), and summer (Figure 12f,i) are calculated. In winter and spring in P1, SST in BOB and Northwest PO show a decreasing trend, and in P2, SST in BOB and Northwest PO increase significantly. In summer, although the SST in BOB and Northwest PO do not cool in P1, the increasing trend in SST in these two regions in P2 is much greater than in P1. The BOB is the main moisture source for the extreme summer precipitation in SWC, and moisture in this region is transported into SWC via SASM. As the difference between SST and land surface temperature is an essential factor affecting monsoon intensity, increasing SST might increase the moisture content over the sea surface. Therefore, the decrease in moisture flux from BOB into SWC and attenuated southwest wind during P1 could be attributed to the decrease in SST in BOB; conversely, increase in moisture flux and enhanced southwest wind during P2 is due to the increase in the SST of BOB.

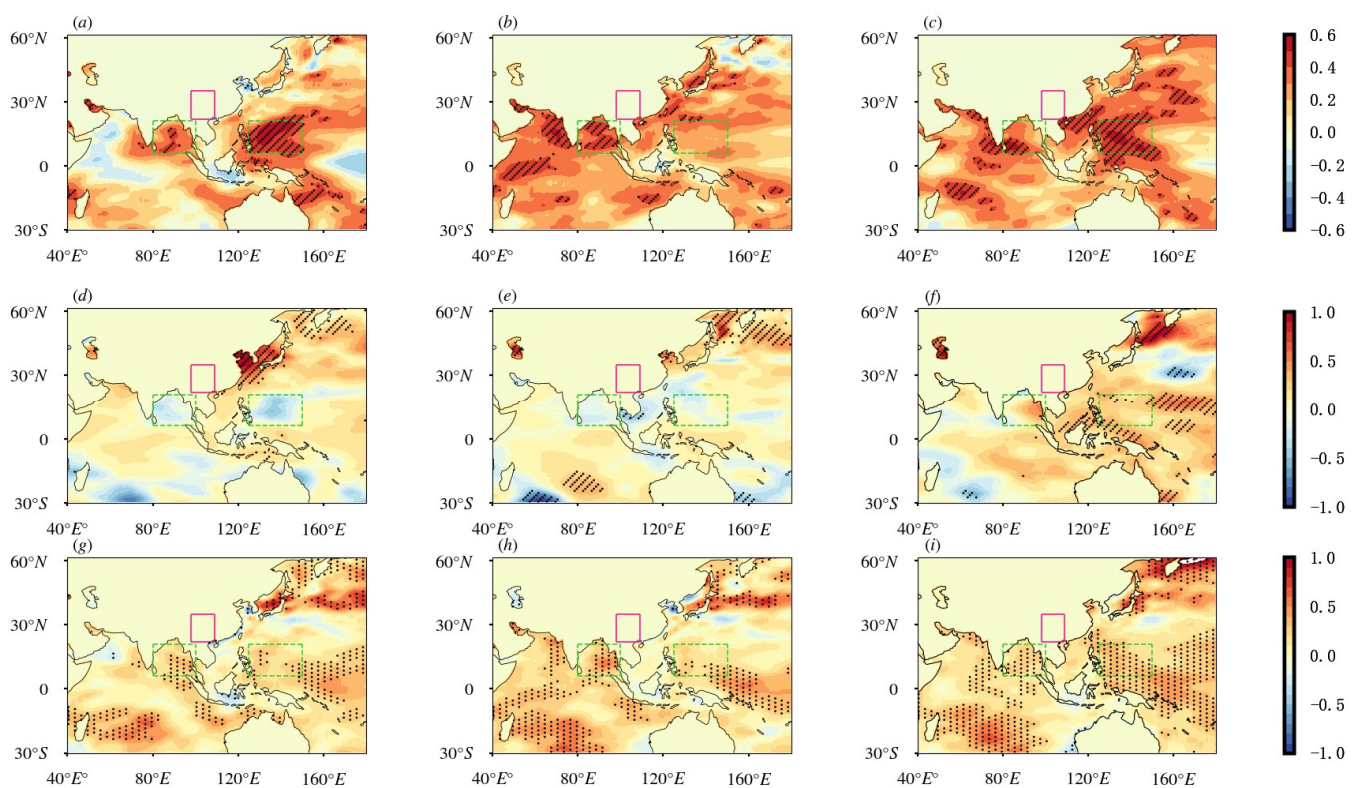


Figure 12. Correlation coefficients between SST in winter ((a); December–February), spring ((b); March–May), and summer ((c); June–August) and extreme precipitation in SWC. Areas bounded by pink rectangles denote SWC. Areas bounded by green rectangles denote the key regions used to define the significant impact on extreme precipitation. Distribution of the SST (DJF, MAM, and JJA) linear trend (unit: $^{\circ}\text{C}\cdot\text{decade}^{-1}$) during 1979–1996 (d–f) and 1997–2021 (g–i). Dots denote the linear trend significant at the 95% confidence level.

The Western Pacific warm pool (WPWP) is a crucial thermal factor for maintaining and strengthening the intensity of WPSH [52]. Cooling (Figure 12d,e) and insignificant heating (Figure 12f) of WPWP are the direct causes of the attenuated influence range and intensity of WPSH in P1 (Figure 5b). The evident heating of WPWP (Figure 12g–i) leads to the intensification of WPSH in P2 and its westward extension into mainland China (Figure 5e). Under the control of southeasterly winds (Figure 5e), moisture flux from SCS is transported into SWC (Figure 6b). In conclusion, under the influence of thermo-dynamic effects, the SST of BOB and Western PO can lead to an increase or decrease in REPEs in SWC by influencing the moisture supply.

The interdecadal differences in the Hadley (Figure 13a) and Walker circulations (Figure 13b) are driven by the land–sea thermal differences (Figure 12). Large interdecadal differences are observed in the Walker circulation (P2–P1): after 1997, driven by the heating SST in BOB and western PO, the Walker circulation during P2 is significantly stronger than in P1 [29]. The two ascending branches of the Walker circulation are at 80°–100° E and 120°–160° E, respectively. The descending branch is located at 100°–120° E. The ascending branch of the Walker circulation in the equatorial western Pacific leads to the formation of meridional Hadley circulation on the northern side (Figure 13a). Hadley circulation links the wind fields in low and middle-to-high latitudes, playing a crucial role in the exchange of heat, momentum, and moisture among the latitudes. In P2, the local Hadley circulation in East Asia is abnormally strong, with upward movements at approximately 20°–30° N and downward movements at approximately 0°–18° N. The descending branch near 10° N tilts to the north near the ground, further strengthening the southerly winds over SWC. This result is conducive to the transportation of moisture from SCS and strengthens the upward movement in SWC. Our analysis reveals that the joint impacts of latitudinal and longitudinal circulations driven by land–sea thermal differences promote the occurrence and development of REPEs in SWC in summer.

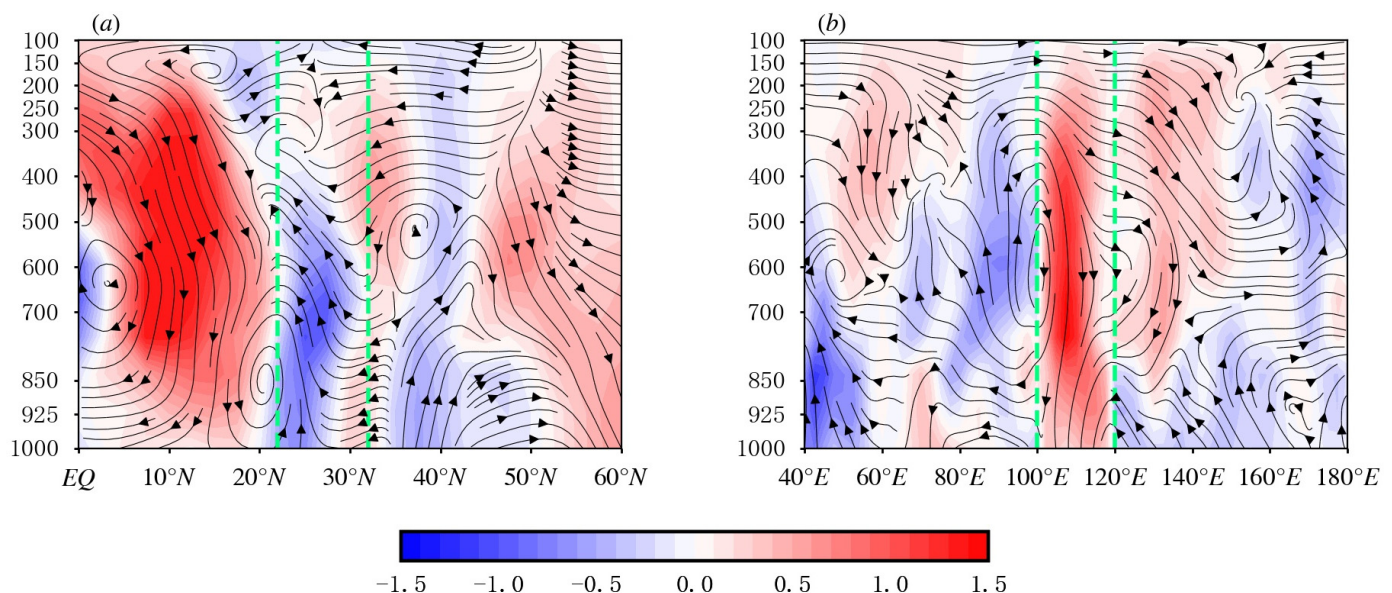


Figure 13. (a) Decadal difference in Hadley circulation (P2 minus P1) averaged over 97.5°–110° E. (b) Decadal difference in Walker circulation (P2 minus P1) averaged over 0°–20° N. The area within green dashed lines denotes SWC. The arrows represent the direction of air flow. The regions bounded by green rectangles denote SWC.

3.5. Local Human Adaption to Climate Change

Natural disasters caused by climate change have posed great threats and challenges to human society; however, the development and progress of science and technology have provided new methods and paths for human to solve these threats and challenges. Emerging technologies, such as artificial intelligence and satellite remote sensing, have the capabilities of powerful processing and situational awareness. Combined with traditional climate disaster management models, they can effectively improve the adaptability of human society to climate change. At the same time, social factors are also indispensable conditions for adapting to climate change. Human society is the sum of the relationships between people and organizations. Therefore, any form of resilience is ultimately human resilience. Considering that natural disasters caused by climate change have regional and seasonal characteristics, specific measures to deal with climate change with regional characteristics are crucial for local human adaptation to climate change.

Strengthening dynamic monitoring in climate-sensitive areas is the basis and prerequisite for addressing climate change risks and challenges. Considering the geographical environment and rainy climate state of Guizhou Province, it is necessary to improve the mountain ecological meteorological monitoring and evaluation system. Guizhou Province pays special attention to the investigation and monitoring of mountain floods, severe convective weather, freezing rain, and rocky desertification caused by meteorological drought. Sichuan Province is a vast region with abundant geographical features, and traditional climate monitoring methods cannot adapt to the new challenges presented by climate change. Therefore, Sichuan Province spares no effort with regard to the transformation and application of emerging technology achievements, and proposes to optimize the layout of natural disaster monitoring station network with the aim of building a natural disaster risk perception network based on satellites, radar, and artificial intelligence.

Strengthening the prediction and early warning ability of severe weather and climate events is an important measure for coping with the risks and challenges of climate change. It is considered that the resolution of the current meteorological disaster-warning technology is too rough, and cannot effectively predict the small-scale catastrophic weather events. Therefore, Sichuan Province has developed high-resolution regional numerical prediction technology in SWC to explore the forecast technology of local severe weather events. On this basis, Sichuan Province hopes to establish accurate and efficient forecast models of regional rainstorms, heat waves and cold waves. Combining deep learning and other technologies, Sichuan Province aims to build an intelligent severe weather forecasting and early warning system to improve the accuracy, precision, and advancement of extreme weather and climate events and their resulting floods and forest fires.

Addressing climate change requires not only the advancement of science and technology, but also the extensive participation of local members of society. Yunnan Province not only focuses on improving the technical level, but also attaches great importance to mobilizing social factors to enhance the region's resilience to climate change. Yunnan Province proposes to improve the mechanism for releasing and re-disseminating natural disaster early warning information and promotes the deep integration of early warning information into the public information release system such as the Internet, radio, television and short messages. At the same time, Yunnan encourages professional social organizations to participate in disaster rescue and post-disaster reconstruction. Sichuan Province raises people's attention to climate change through social training and enhances the ability to actively adapt to climate change risks through the construction of resilient cities.

4. Discussion

Under the background of global warming, extreme weather and climate events have become increasingly frequent. They often result in substantial losses to society because of events such as mountain floods caused by extreme precipitation, urban waterlogging, and debris flows [10]. Thus, developing warning and prediction methods for extreme weather and climate events is urgent. For example, accurate earthquake prediction would save thousands of lives. Therefore, after REPEs have been classified according to certain standards, further research and analysis of the precursor factors of each type of REPE will be critical to improving disaster warning and prediction abilities. In addition, after 1997, summer sea ice in the Arctic shows shock and rapid melting, and the melting area covers almost the entire Arctic Ocean [50,51]. The summer sea ice index in most areas shows a significant negative correlation with the REPEs in SWC, indicating that when the summer Arctic ice melts, the amount of summer extreme precipitation in SWC tends to increase. Although the relationship between Arctic ice and extreme precipitation in SWC has not been systematically and comprehensively investigated in this study, the melting of Arctic ice (an important result of global warming) has a substantial feedback effect on the global weather and climate system.

Land use can also directly impact the climate by altering the character of the land surface. Land use changes energy fluxes and their partitioning and this can amplify or

suppress meteorologically driven extremes [53,54]. The mechanism of land use influence on precipitation is a complex process, involving changes in surface albedo, evaporation and evapotranspiration, greenhouse gas concentration, and so on. Anthropogenic land use has significant impacts on the earth's climate, carbon cycle, and water balance [55]. Typically, land use alters the biophysical properties of the land cover, such as albedo, evapotranspiration, and roughness, which in turn affects land–atmosphere energy and water exchange. Land use can also affect the carbon cycle between the land and atmosphere through biogeochemical emissions and uptake [56]. Hong et al. [57] uses ten Earth system models participating in future land use policy sensitivity experiments in Land Use Model Intercomparison Project (LUMIP) to assess the impact of two different land use scenarios (SSP1-2.6 and SSP3-7.0) on extreme climate. The results demonstrate that the use of different land use change scenarios has a substantial effect on the projections of regional climate extreme changes. However, there are great uncertainties in modeling the effects of land use on extreme precipitation. Therefore, observation-based studies on reducing models' uncertainties are needed to obtain more robust future projections of regional climate change. Golroudbary et al. [58] uses observation-based factors to assess the influences of urban land use on extreme precipitation patterns in Netherlands. The possible effects of land use on extreme precipitation are assessed by quantifying the differences between urban and rural rain gauge stations according to the spatial gridding method. And the conclusion is that urban areas receive more intense extreme precipitation than rural areas because of land use.

The world is currently undergoing climate change, which is predominantly characterized by heat waves and extreme precipitation [59]. Global climate change poses a significant threat to the sustainability of human society, highlighting the critical importance of developing effective adaptation strategies in response to climate-related disasters [60]. Addressing climate change is not only a technical issue, but also a social issue. The efforts and wisdom of scientists alone cannot solve the challenges and threats climate change poses to all mankind. First, the government should establish sound laws and regulations and coping mechanisms. Secondly, social organizations and institutions actively assume social responsibilities and mobilize social resources to promote sustainability. Third, urban residents should also be more resilient to climate change, as increased risk awareness and professional skills are critical to tackling climate change. In addition, it is worth noting that while climate change is a global problem, the response to climate change should have local characteristics. Strategies will only work if they fit the realities on the ground [61,62]. Therefore, in the next phase of research, we will continue to focus on the strategies and measures of human local climate adaptation.

5. Conclusions

This study analyzes the change in REPEs in SWC in the mid-to-late 1990s and explores the effect of thermo-dynamic conditions on REPEs in SWC, as well as local human adaptation to climate change. We find that after 1997, the summer extreme precipitation in SWC began to increase. The enhanced WSPH and SAH contribute to this change. The main conclusions are given as follows.

The trend in summer extreme precipitation shows an obvious interdecadal mutation in the late 1990s, as it decreased during 1979–1996 and increased during 1997–2021. The distributions of the extreme precipitation amount and frequency are spatially inhomogeneous, and are highest in the eastern and southern SWC and lowest in the western SWC.

The SAH and WSPH contribute to the abrupt change in the extreme precipitation trend in SWC. The intensity of WSPH and SAH was enhanced and their range extended during 1997–2021, which was conducive to forming updrafts over SWC and transporting moisture from BOB and SCS into SWC.

SSH plays a crucial role in the occurrence of REPEs and is important for maintaining the intensity of SAH. The spring SSH over TP showed a downward trend from the early 1980s to the late 1990s and then an upward trend. The SSH can increase the heat of the

lower troposphere air and the moisture content in the air, resulting in increases in extreme precipitation. In addition, SSH is the main energy source of lower troposphere air and an essential component of the surface heat balance.

The WPWP plays a crucial role in maintaining and strengthening the intensity and influence range of WPSH. The WPWP has a cooling or slight heating effect in P1 and a significant heating effect in P2, resulting in the intensity and influence range of WPSH weakening in P1 and strengthening in P2. The strengthening of WPSH increases the moisture supply from SCS and BOB into SWC and finally leads to an increase in REPEs.

Because the difference between SST and land surface temperature is a notable factor affecting monsoon intensity, increasing SST might increase the moisture content over the sea surface. Therefore, the cooling (heating) of SST in BOB in P1 (P2) is the cause of the decrease (increase) in the moisture flux into SWC and the attenuated (enhanced) southwest wind in P1 (P2). Under the influence of thermo-dynamic effects, the joint impacts of latitudinal and longitudinal circulations driven by land–sea thermal differences promote the occurrence and development of REPEs in SWC in summer.

Provinces in SWC have taken local measures to improve resilience to climate change. Guizhou Province pays attention to the establishment of mountain ecological meteorological monitoring and evaluation systems, while Sichuan Province spares no effort with regard to the transformation and application of emerging technological achievements, such as artificial intelligence and satellite remote sensing. In addition to the use of science and technology, Yunnan Province also emphasizes the important role of social factors in improving human society's resilience to climate change.

Despite the above conclusions, this study has several limitations. First, we do not use machine learning or multiple regression analysis to determine the importance of independent variables. Second, we also do not use models to predict future trends in extreme precipitation. In future research, we will use machine learning and multiple regression analysis to study the impact of land use on extreme precipitation and try to predict the future trend.

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