



# Article Changes of Extreme Temperature and Its Influencing Factors in Shiyang River Basin, Northwest China

# Junju Zhou<sup>1</sup>, Jumei Huang<sup>1,\*</sup>, Xi Zhao<sup>1</sup>, Li Lei<sup>2</sup>, Wei Shi<sup>1</sup>, Lanying Wang<sup>3</sup>, Wei Wei<sup>1</sup>, Chunfang Liu<sup>4,5</sup>, Guofeng Zhu<sup>1,\*</sup> and Xuemei Yang<sup>6</sup>

- <sup>1</sup> College of Geography and Environment Science, Northwest Normal University, Lanzhou 730070, China; zhoujj2019@testmail.nwnu.edu.cn (J.Z.); 201875110134@nwnu.edu.cn (X.Z.); shiwei@nwnu.edu.cn (W.S.); weiweigis2006@126.com (W.W.)
- <sup>2</sup> Wuwei Occupational College, Wuwei 733000, China; leili0426@163.com
- <sup>3</sup> The Administrative Center for China's Agenda 21, Beijing 100038, China; wanglanyingbj@163.com
- <sup>4</sup> Gansu Engineering Research Center of Land Use and Comprehension Consolidation, Lanzhou 730070, China; liuchunfang@nwnu.edu.cn
- <sup>5</sup> College of Social Development and Public Administration, Northwest Normal University, Lanzhou 730070, China
- <sup>6</sup> State Key Laboratory Breeding Base of Desertification and Aeolian Sand Disaster Combating, Gansu Desert Control Research Institute, Lanzhou 730073, China; yxm9693@163.com
- \* Correspondence: HuangJumei@nwnu.edu.cn (J.H.); zhugf@nwnu.edu.cn (G.Z.); Tel.: +86-1840-931-1340 (J.H.)

Received: 12 October 2020; Accepted: 26 October 2020; Published: 29 October 2020



Abstract: The increase in the frequency and intensity of extreme weather events around the world has led to the frequent occurrence of global disasters, which have had serious impacts on the society, economic and ecological environment, especially fragile arid areas. Based on the daily maximum temperature and daily minimum temperature data of four meteorological stations in Shiyang River Basin (SRB) from 1960 to 2015, the spatio-temporal variation characteristics of extreme temperature indices were analyzed by means of univariate linear regression analysis, Mann-Kendall test and correlation analysis. The results showed that the extreme temperatures warming indices and the minimum of daily maximum temperature (TXn) and the minimum of daily minimum temperature (TNn) of cold indices showed an increasing trend from 1960 to 2016, especially since the 1990s, where the growth rate was fast and the response to global warming was sensitive. Except TXn and TNn, other cold indices showed a decreasing trend, especially Diurnal temperature (DTR) range, which decreased rapidly, indicating that the increasing speed of daily min-temperature were greater than of daily max-temperature in SRB. In space, the change tendency rate of the warm index basically showed an obvious altitude gradient effect that decreased with the altitude, which was consistent with Frost day (FD0) and Cool nights (TN10p) in the cold index, while Ice days (ID0) and Cool days (TX10p) are opposite. The mutation of the cold indices occurred earlier than the warm indices, illustrating that the cold indices in SRB were more sensitive to global warming. The change in extreme temperatures that would have a significant impact on the vegetation and glacier permafrost in the basin was the result of the combined function of different atmospheric circulation systems, which included the Arctic polar vortex, Western Pacific subtropical high and Qinghai-tibet Plateau circulation.

Keywords: extreme temperatures; arid region; Shiyang River Basin; atmospheric circulation anomalies

#### 1. Introduction

The Fifth Assessment Report of IPCC indicated that the surface temperature showed a change tendency rate of increase from 1880 to 2012, with an increase of 0.85 °C. The surface temperature in the last 30 years has been higher than any other decade since 1850 [1]. In the Northern Hemisphere, the period 1983–2012 was very likely the warmest 30-years period of the last 1400 yars [2]. Global warming has led to increased frequency of extreme climate events [3,4]. The fact that global, and most local, mean temperatures are increasing does not by itself determine the frequency of extreme events [5,6]. For many purposes, including production and human life, extreme temperatures may be more critical than mean temperature and changes in local extreme temperature may be more critical than global mean changes [5,7,8]. Therefore, extreme climate change has attracted extensive attention from domestic and foreign scholars [3,9]. In the global scope, the highest trend of the lowest temperature indices, the increase in the extreme temperatures indices and the decrease in the cold extreme value all show the obvious warming trend from the 20th century to the beginning of the 21st century [3,10]. Since 1950, the number of cold days and nights has decreased on a global scale, while the number of warm days and nights has increased [1]. The areas affected by extreme temperatures in the northern hemisphere are increasing, but their impact is relatively small compared with extreme precipitation [11]. In most extreme temperatures indices in Asia, the variation range in a high latitude is larger than that in a low latitude [3,12], the number of warm days and nights is increasing, and the increasing speed of the latter is significantly higher than that of the former [13]. The frequency of heat waves has also increased in most parts of Asia, Europe and Australia [1]. In the past 30 years, the extreme temperatures values in Central Asia and North America have shown an increasing trend year, but the growth rate of the highest temperature (TMAX) is faster than that of the lowest temperature (TMIN), resulting in the overall increase in the diurnal temperature range (DTR) [14,15]. In Asia, in the context of global warming, India is basically consistent with the observation and prediction in other parts of the world, with the frequency and intensity of extreme warming indices increasing [16]. In the past 60 years, the rise rate of the lowest temperature in Iran is twice that of the highest temperature. Therefore, the frequency of extreme high temperature increases and the frequency of extreme low temperature decreases [17,18]. In the study of extreme temperatures in China, an increase in warm extremes and a decrease in cold extremes have also been observed [19]. The daily average temperature in January and the extremely low value of the daily minimum temperature both show an upward trend, while the daily average temperature and the extremely high values of the daily maximum temperature in July also show a decrease from northeast China to central China [7].

Domestic and foreign scholars have relatively mature researches on the spatio-temporal changes and characteristics of extreme temperatures, and there are also more researches on the spatio-temporal changes of extreme temperatures in China and arid regions in northwest China [9,19,20]. Research showed that in the past 50 years, the temperature in arid areas of northwest China has shown an increasing trend as a whole, with more extreme high-temperature events and less extreme low-temperature events [21–23], the climate is changing from "warm and dry" to "warm and wet" [24], but the climate change trends and laws in different regions are different, and the large-scale integrated characteristic cannot fully represent the change characteristics of extreme temperatures in small regions or basins.

Shiyang River Basin (SRB) is located in the arid region of northwest China, the intersection of Qinghai-Tibet Plateau, Inner Mongolia Plateau and Loess Plateau, and the edge of monsoon region. It is affected by atmospheric circulation systems such as westerly belt, plateau monsoon and southeast monsoon. Its ecological environment is fragile and sensitive to global climate change. In the context of global change, the annual average temperature in SRB is increasing at a rate of 0.45 °C/10 years from 1960 to 2016. The annual average temperature is much higher than the national average (0.25 °C/10 years) [25,26]. Moreover, under the background of future climate warming, the temperature in SRB will further increase, extreme cold events will further decrease, extreme warming events will further increase, and extreme climate events will have greater impact on society and ecosystem

than the average climate state [27], and the climate risk will further increase. Therefore, it is urgent and necessary to strengthen the in-depth study of extreme weather events in SRB [28]. This paper refers to a set of unified extreme indices [9,29,30] defined by WMO Climate Change Monitoring and Indicators Expert Group (ETCCDI), selects 14 extreme temperatures indexes in combination with the specific climate characteristics of the study area, and systematically analyzes the changes in extreme temperatures in SRB based on refined observation data. The main objectives were to: (1) Analyze the temporal variation and spatial heterogeneity of extreme temperatures in SRB in recent 56 years; (2) Study the influencing factors of extreme temperatures change in the basin; (3) Analyze the impact of temperature changes in the basin. The results of this study would provide a solid basis for the formulation of regional adaptive strategy of the inland river basin in arid areas.

### 2. Data and Methods

#### 2.1. Study Area

SRB is located in the arid region of northwest China (101°41'~104°16' E,36°29'~39°27' N), the northeast edge of Qinghai-Tibet Plateau, the transition zone between a monsoon region and non-monsoon region, and the atmospheric circulation system is complex (Figure 1). It is the most sensitive zone for global climate change response. The basin covers an area of about  $4.16 \times 108$  km<sup>2</sup>, and its upstream originates from the northern slope of the eastern Qilian Mountain, with an altitude of 2000–5000 m. The annual precipitation amount is 300–600 mm, annual evaporation is 700~1200 mm, drought index (the ratio of annual evaporation capacity to annual precipitation) is 1~4, average temperature in January is –11.6 °C, average temperature in July is 11.7 °C. The main vegetation types are arbor forest and shrub forest, with obvious vertical zonal distribution characteristics. A large number of glaciers are distributed above 4500 m. Glacier melt water is one of the sources of mountain runoff. The middle reaches corridor plain and the lower reaches Tail oasis are surrounded by Badain Jaran Desert and Tengger Desert, and is the dissipation area of runoff with arid climate. Among them, the middle reaches corridor plain is a warm and cool arid area with an altitude of 1500–2000 m, annual precipitation of 150-300 mm, annual evaporation of 1300-2000 mm, drought index of 4-15, average temperature of –8.6 °C in January and average temperature of 20.4 °C in July. The northern warm arid region has an altitude of 1300–1500 m and an annual precipitation of less than 150 mm. The northern Minqin region is close to the edge of the Tengger Desert with an annual precipitation of 50 mm, an annual evaporation of 2000–2600 mm, a drought index of 15–25, and an average temperature of -8.6 °C in January and 23.6 °C in July. The middle and lower reaches of the basin are irrigated and cultivated areas, as well as windy and sandy areas.

# 2.2. Materials and Methods

#### 2.2.1. Data Sources and Quality Controls

#### Meteorological Data

The daily maximum temperature, daily minimum temperature and daily precipitation data of Wushaoling, Yongchang, Wuwei and Minqin weather stations (Table 1) from 1 January 1960 to 31 December 2015 were all from China Meteorological Data website (http://data.cma.cn/). The four weather stations have not migrated in recent 59 years, so the data integrity and continuity are good, and the data have a high credibility [31]. Before the data analysis, this paper used RHtests software [32] to strictly control and screen the data quality. The RHtests software was developed by Wang and Feng [33] at the Climate Research Branch of Meteorological Service of Canada (http://etccdi.pacificclimate.org/software.shtml).The data needed to meet the following three conditions: the daily maximum temperature was higher than the minimum temperature, the daily precipitation was higher than 0, and the deviation value was eliminated (the value exceeding three times the standard deviation was defined as the limit value), so as to ensure the reliability of the data. The daily

value data with trace amount of daily precipitation was uniformly treated as the precipitation was 0. The daily precipitation was tested to see if it deviated seriously from the actual situation of the local precipitation. This paper kept reasonable precipitation values, and treated the unreasonable values, i.e., deviation values, as the missing measured values (–99.9).



Figure 1. Study area and distribution of meteorological stations.

Table 1. Basic information of meteorological stations in Shiyang River Basin(SRB).

Watershed	Station Name	tation Name Longitude (E)		Elevations (m)	Start	End
upstream	Wushaoling	37°12′	102°52′	3045.1	1960	2015
midstream	Wuwei	37°55′	102°40′	1531.5	1960	2015
	Yongchang	38°14′	101°58′	1976.9	1960	2015
downstream	Minqin	38°38′	103°05′	1367.5	1960	2015

#### Amospheric Circulation Indices

To examine the influence of the main atmospheric circulation types on climate extremes in the SRB, a Pearson's correlation analysis was performed between atmosphere circulation indices and the climate extreme indices, based on the potential factors affecting the climate in China [34–36]. The selected amospheric circulation indices all come from the National Oceanic and Atmospheric Administration (https://www.esrl.noaa.gov/psd/data/climateindices/list/), which include Arctic Oscillation (AO), North Atlantic Oscillation (NAO), Pacific Decadal Oscillation (PDO). Other atmospheric circulation indices all come from the national climate center's climate system monitoring, diagnosis, prediction and evaluation system (https://cmdp.ncc-cma.net/cn/download.htm), which include Western Pacific (WP), Tibet Plateau Region 2 Index (TPR2I), the Northern Hemisphere Polar Vortex Area Index (NHPVAI), the Northern Hemisphere Polar Vortex Intensity Index (APVII), the Asia Polar Vortex Area Index (APVAI), the Western Pacific Subtropical Sigh Intensity Index (WPSHII), the Northern Subtropical High Intensity Index (NHSHII) and East Asian Trough Intensity Index (EATII).

#### 2.2.2. Extreme Temperatures Indices

The definition of extreme temperatures index adopts the climate change detection index determined by the World Meteorological Organization (WMO) Climate Committee (CCI), Global Climate Research Program (WCRP) and Predictability Program (CLIVAR) Climate Change Detection, Monitoring and Indicators Expert Group (ETCCDMI,). At present, these indices have been widely used in extreme temperatures research [11,29], 14 extreme temperatures indices are selected in this paper, including six warm indices, six cold indices and two other indices (Table 2). Extreme temperatures indices were calculated from daily meteorological records using the computer program RClimDex, which was developed and maintained at the Climate Research Branch of the Meteorological Service of Canada (http://etccdi.pacificclimate.org/software.shtml) [36].

	Name	Indicator Index	Definition	Units					
	TX10p TN10p	Cool days Cool nights	Percentage of days when TX <10th percentile Percentage of days when TN <10th percentile	Days Days					
	TXn	Minimum Tmax	nimum Tmax Annual minimum value of daily maximum temperature						
cold extreme indices	TNn	Minimum Tmin	Annual minimum value of daily minimum temperature	°C					
	ID0	Ice days	Annual count when TN (daily maximum temperature) <0 °C	Days					
	FD0	Frost days	Annual count when TN (daily minimum temperature) <0 °C	Days					
	SU25	Summer days	days Annual count when TX (daily maximutemperature) >25 °C						
	TR15	Tropical nights	Annual count when TN (daily minimum temperature) >15 °C	Days					
Warm extreme indices	TXx	Maximum Tmax	Annual maximum value of daily maximum temperature	°C					
	TNx	Maximum Tmin	Annual maximum value of daily minimum temperature	°C					
	TX90p TN90p	Warm days Warm nights	Percentage of days when TX >90th percentile Percentage of days when TN >90th percentile	Days Days					
Others extreme indice	GSL	Growing season length	Annual count between first span of at least 6 days with TG>5 °C and first span after 1 July of 6 days with TG <5 °C, where TG is daily mean temperature (TX + TN)/2	Days					
	DTR	Diurnal temperature range	Annual mean difference between TX and TN	°C					

**Table 2.** Definition of extreme temperatures indices [11,29] (TN: daily minimum temperature; TX: daily maximum temperature).

# 2.2.3. Method

### Climate Tendency Rate

Climate tendency rate is generally described by unary linear regression equation, assuming a time series with sample size n,  $x_i$  as a variable, the time corresponding to  $x_i$  is expressed by  $t_i$ , and the expression of unary linear regression equation between  $x_i$  and  $t_i$  is as follows [26]

$$x_i = a + bt_i, i = 1, 2, ..., n$$

where *a* is a regression constant and *b* is a regression coefficient.  $b \times 10$  is usually called climate tendency rate, and its unit is days/10 years or °C/10 years.

#### Weighted Average Method

Due to the difference in watershed topography and uneven spatial distribution of meteorological stations, the arithmetical average method cannot be used to directly calculate the temperature of the watershed. Therefore, the area weighting method was adopted in this study [37]

$$\mathbf{T} = (\mathbf{A}_1\mathbf{T}_1 + \mathbf{A}_2\mathbf{T}_2 + \dots + \mathbf{A}_n\mathbf{T}_n)/\mathbf{A}$$

6 of 19

T is the average temperature of the basin (°C), A is basin area (km<sup>2</sup>). A<sub>1</sub>, A<sub>2</sub> and A<sub>n</sub> are area controlled by each meteorological station (km<sup>2</sup>). P<sub>1</sub>, P<sub>2</sub> and P<sub>n</sub> are temperature at each meteorological station (°C).

### Other Methods

The trend rate of extreme temperatures indices in river basin and each station was calculated by using the univariate linear regression analysis [30,38]. Using DPS software to do M-K mutation test [16,39], and use sliding *t* test to verify the authenticity of mutation points, increasing the credibility of mutation analysis results. Finally, Pearson correlation analysis is made between the extreme temperatures indices and the atmospheric circulation indices [13].

### 3. Results

### 3.1. Temporal Variation Characteristics of Extreme Temperatures Indices

3.1.1. Variation Characteristics of Interannual and Interdecadal Warm Indices

The interannual tendency rate of each extreme temperatures index was calculated by using the method of one-dimensional linear regression analysis, and its significance was tested (Table 3).

Table 3.	The change	tendency	rate of temp	perature	extremes	in SRB	from	1960 tc	2015.
----------	------------	----------	--------------	----------	----------	--------	------	---------	-------

Warm Extreme Indices	Climate Inclination Rate	Cold Extreme Indices	Climate Inclination Rate	Others Extreme Indice	Climate Inclination Rate
TX90p (days/10 years)	1.38 *	1.38 * TX10p (days/10 years)		DTR (°C/10 years)	-0.18 **
TN90p (days/10 years)	3.3 *	TN10p (days/10 years)	-2.13 *	GSL (days/10 years)	3.56
TXx (°C/10 years)	0.3 **	TXn (°C/10 years)	0.34 *		
TNx (°C/10 years)	0.33 **	TNn (°C/10 years)	0.45 *		
SU25 (days/10 years)	2.74	FD0 (days/10 years)	-3.8		
TR15 (days/10 years)	2.44 **	ID0 (days/10 years)	-2.81		
	4 01 10			. 1 1	

\* Significant at the 0.05 level, \*\* Significant at the 0.01 level.

In terms of time scale, the extreme temperatures warm indices showed an upward trend from 1960 to 2015. The change tendency rates of TX90p, TN90p, TXx, TNx, SU25, TR15 were 1.38 days/10 years, 3.3 days/10 years, 0.3 °C/10 years 0.33 °C/10 years, 2.74 days/10 years, 2.44 days/10 years (Figure 2 and Table 2), respectively, indicating that the extreme temperature warm indices increased significantly and were sensitive to global warming response. Among them, the increase rate of TXx and TNx from 1960 to 2015 was relatively small, while the increase rate of other indices was relatively larger, especially the increase rate of TN90p, which was the fastest, whose interannual variation tendency rate reached 3.3 days/10 years (Table 3). As can be seen from Figure 2, except SU25, the rest of the warm indices showed a downward trend from the early 1970s to the 1980s, indicating that there may be a cooling event during this period. TX90p changed smoothly before the 1980s and rose at a higher rate after the end of the 1980s (Figure 2a). TN90p changed smoothly before the early 1990s and then showed a rapidly upward trend (Figure 2b). TNx and TXx had relatively small changes before the end of the 1990s, showing a downward and upward trend, respectively, and thereafter both had large fluctuations and showed an upward trend (Figure 2a,b). SU25 dropped significantly before the early 1990s, rising at a faster rate from the early 1990s to the early 21st century, and then declining slightly (Figure 2e). TR15 showed a downward trend before 1993, but the change was relatively stable, then the fluctuation rose and finally entered a stable period (Figure 2f). Based on the above analysis, the extreme temperatures warm indices in SRB showed an overall increasing trend in the past 56 years. Among them, there was a decreasing trend in different degrees from the 1970s to the 1990s. Since the 1990s, the warm indices showed a rapidly increasing trend and was sensitive to global warming response.



**Figure 2.** Interannual variation of warm of extreme indices in SRB from 1960 to 2015 ((**a**–**f**) represent TX90p, TN90p, TXx, TNx, SU25, and TR15, respectively).

From the 1960s to the beginning of the 21st century, the extreme temperatures warm indices generally showed an increasing trend (Table 4). From the 1960s to 1970s, except TXx, the other warming indices showed a decreasing trend with a large range. From the 1970s to 1980s, except TN90p, the other warm indexes also showed a slight decreasing trend. From the 1980s to 1990s, except for the slight decrease in TN90p, the other warming indices showed an increasing trend. From the 1980s to the beginning of the 21st century, the extreme gas warmth index showed an increasing trend, and the range was relatively large. Based on the above analysis, the interdecadal change in extreme temperatures warm indices in SRB showed an upward trend, with a slight downward trend before 1990s and an upward trend from the 1990s to the 2000s.

Table 4. Interdecadal variation of extreme temperature indices in SRB from 1960 to 2015.

	Year	1960s	1970s	1980s	1990s	2000s
	TX90p (days)	8.615	8.42	7.463	8.166	13.307
	TN90p (days)	6.723	5.81	6.356667	6.296556	17.121
Marine automatic dia a	TXx (°C)	30.99	31.155	31.0575	31.0675	32.1675
warm extreme indices	TNx (°C)	16.805	16.5725	16.0875	16.48833	17.8325
	SU25 (days)	45.4	39.9	38.6	41.3	54.4
	TR15 (days)	4.7	4.4	3.6	4.233333	11.9
	TX10p (days)	11.805	11.999	10.595	11.46633	8.373
	TN10p (days)	14.346	13.506	11.121	12.991	4.997
Cald automa indiana	TXn (°C)	-12.185	-12.345	-11.2825	-11.9375	-11.46
Cold extreme indices	TNn (°C)	-23.1975	-23.275	-22.0975	-22.8567	-22.185
	FD0 (days)	183.6	183.3	181.2	182.7	169.5
	ID0 (days)	59.2	57.6	57	57.93333	47.5
	DTR (°C)	13.443	13.251	13.029	13.241	12.734
Other extreme indices	GSL (days)	194	198.5	200	197.5	210.4

#### 3.1.2. Variation Characteristics of Interannual and Interdecadal Cold Indices

The extreme temperatures cold indices TX10p, TN10p, ID0 and FD0 all showed a downward trend (Table 3), and their change tendency rates were -0.85 days/10 years, -2.13 days/10 years,

-2.81 days/10 years, and -3.8 days/10 years, respectively. This shows that these four indices had a significant downward trend, of which the TN10p had the largest decrease and the ID0 had the smallest decrease, which was also a positive response to global warming. TNn and TXn both showed an upward trend in fluctuation, with the variation ranges of 0.34 °C/10 years and 0.45 °C/10 years, respectively, which indicated that, with global warming, the minimum values of daily minimum and daily maximum temperature both showed an increasing trend. As can be seen from Figure 3, TX10p fluctuated and changed significantly before 1998, increased significantly from 1998 to 2011 and then declined significantly (Figure 3a). TN10p showed a fluctuating downward trend from 1960 to 2015 (Figure 3b). TXn showed an upward trend before the middle and late 1990s, decreased suddenly at the beginning of the 21st century, and then showed an obvious upward trend (Figure 3c). TNn showed a fluctuating upward trend from 1960 to 2015, indicating that, with global warming, the minimum value of daily minimum temperature showed an upward trend (Figure 3d). ID0 increased significantly before the 1970s, then decreased significantly, and showed an upward trend after the late 1990s (Figure 3e). FD0 declined slowly before the mid-1990s, and showed a significant downward trend since then (Figure 3f). Based on the above analysis, the fluctuation trend of extreme temperatures cold indices in SRB in the past 56 years showed that FD0, ID0, TN10p, and TX10p all showed a decreasing trend, especially FD0, ID0, TN10p, which showed the fastest decreasing speed. The daily maximum temperature's extremely low value (TXn) and the daily minimum temperature's extremely low value (TNn) both showed an increasing trend.



**Figure 3.** Interannual variation in cold of extreme indices in SRB from 1960 to 2015 ((**a**–**f**) represent TX10p, TN10p, TXn, TNn, FD0, and ID0, respectively).

3.1.3. Variation Characteristics of Interannual and Interdecadal Other Indices

In terms of time scale, the extreme temperatures index DTR of SRB from 1960 to 2015 showed a fluctuating process of decline-steady rise-rapid decline, but showed a decreasing trend as a whole (Table 2 and Figure 4). Bennett [14] and Feng [15] studies showed that DTR in Asia was on the increase, which indicated that the large-scale study of holistic characteristics cannot fully represent the changing

characteristics at local scale. Among them, although there was a fluctuating upward trend from the 1960s to the end of the 1990s; the change was relatively stable, belonging to a stable period, and entered a rapid decline stage at the end of the 1990s (Figure 4), indicating that the increase rate of daily maximum temperature in SRB was less than the increase rate of daily minimum temperature in the past 56 years. GSL showed an overall upward trend from 1960 to 2015, but fluctuated greatly (Figure 4).



Figure 4. Interannual variation of other extreme indices in SRB from 1960 to 2015.

From the 1960s to the beginning of the 21st century, GSL generally showed a downward trend; from the 1960s to 1980s, it showed a downward trend; from the 1980s to 1990s, it showed an upward trend; from the 1990s to 21st century, except for a downward trend, DTR showed an opposite trend to GSL (Table 4).

#### 3.2. Spatial Variation Analysis of Extreme Temperatures Indices

Meteorological data are the basic basis of extreme temperature analysis. This paper selected the data of four meteorological stations in SRB to analyze the spatial variability of extreme temperature. Due to the small number of stations and uneven spatial distribution of stations, the spatial variation analysis of extreme temperature was limited to some extent. However, the four meteorological stations are located in the upstream, middle reaches and downstream (Table 1), respectively, which is a good representative of the SRB.

#### 3.2.1. Analysis of Spatial Change of Warm Indices

The change tendency rates of extreme temperatures warm indices at four stations in SRB were greater than 0 (Figure 5a), indicating that the warm indices at each station were on the rise.

According to Figure 5a, the change tendency rate of each warm index was different at each station, in which the change speed of TX90p at each station was basically the same, ranging from 1.14 to 1.53 days/10 years, and the increase speed in Wuwei and Yongchang was larger, the increase speed in Wushaoling was the smallest, and the Minqin was in between. The increase rate of TN90p in all stations was relatively high, with the highest value of 3.2 days/10 years in Wuwei, followed by Yongchang and Minqin. The change tendency rate of SU25 was the smallest in the upstream and the largest in the midstream, with 2.57 days/10 years and 3.14 days/10 years, respectively, and the smallest in Wushaoling, with 2.11 days/10 years. The climate tendency rate of TR15 changed the most in the downstream, the second in the middle, the least in the upstream, which may be related to the higher altitude of Wushaoling. In addition, vegetation coverage was high and human activities were small in the upstream high altitude area, so the climatic tendency rate of TR15 was smaller, while desert was widespread and human activities were relatively strong in the downstream area, so its change was larger. Despite global warming, its lowest temperature is still relatively low. Compared with other

warm indices, the change tendency rates of TNx and TXx at each station were smaller, and Wushaoling has the slowest growth rate. In sum, except SU25, the change tendency rates of other warm indices basically showed an obvious altitude gradient effect, i.e., the higher the altitude, the smaller the growth rate.



**Figure 5.** Trends of extreme temperatures indices of four stations in SRB from 1960 to 2015 ((**a**) represents warm and other extreme indices, (**b**) represents cold extreme indices).

# 3.2.2. Analysis of Spatial Change of Cold Indices

The change tendency rates of extreme temperatures cold indices FD0, ID0, TN10p and TX10p at the four meteorological stations in SRB were all less than 0, while the change tendency rates of TNn and TXn were all greater than 0, showing a slight increasing trend at each station (Figure 5b). The change in speed of TX10p at the four stations was different, but the difference was small and it was the largest in Wushaoling, at -0.96 days/10 years, followed by Wuwei and Yongchang, and Minqin was the smallest (-0.69 d/a). The decrease speed of TN10p was the largest in Minqin (-3 days/10 years), followed by Wuwei, Yongchang and Wushaoling, which indicated that there was a negative correlation between the decrease rate of TN10p and altitude. FD0 had a large change speed at all stations, of which the decrease speed was the largest in Minqin, which was -5.43d/a, followed by Wuwei (-3.7 days/10 years), Wushaoling (-3.19 days/10 years) and Yongchang (-3.04 days/10 years), respectively. The fastest decrease speed of ID0 was -4.38 days/10 years in Wushaoling, and the change speeds of ID0 were about the same, with a range from -2.41 to 2.48 days/10 years.

The change speed of ID0 was less than FD0 in all stations except Wushaoling. The change tendency rate of TNn and TXn in the lower reaches of Minqin was slightly higher than that in the middle and upper reaches.

Based on this, it can be inferred that, except that the change tendency rates of TXn and TNn were not significantly different at each station, the reduction rates of FD0 and TN10p were larger in the downstream Minqin and smallest in the upstream area, while the reduction rates of ID0 and TX10p were fastest in the upstream area and slower in the middle and lower reaches, i.e., with the increase in altitude, the reduction rates of FD0, ID0 and TN10p decreased and the reduction rate of TX10p increased.

#### 3.2.3. Analysis of Spatial Change of Other Indices

From the perspective of spatial scale, the change tendency rate of GSL was relatively large at all stations, with the largest change rate in Wushaoling, and it was relatively smaller in the middle and lower reaches. The change rate of DTR at each station was smaller than that of other indices,

and the decrease trend was not obvious (Figure 5a), with the smallest change rate in Wushaoling  $(-0.04 \degree C/10 \text{ years})$ , followed by Yongchang  $(-0.09 \degree C/10 \text{ years})$  and Wuwei  $(-0.19 \degree C/10 \text{ years})$ , and the largest change rate was in Minqin  $(-0.38 \degree C/10 \text{ years})$ . The variation in DTR also shows significant elevation gradient effect.

#### 3.3. Mutation Analysis of Extreme Temperatures Indices

Using DPS software, the M-K mutation test was carried out for each extreme temperature index, and the mutation year was determined by combining the sliding *t* test method (Table 5).

Warm Extreme Indices	Year of Abrupt Change	Year of Abrupt Cold Extreme Change Indices		Others Extreme Indice	Year of Abrupt Change
TX90p	2001 **	TX10p	1989 **	GSL	1997 **
TN90p	2002 **	TN10p	1997 **	DTR	1997 **
TXx	-	TXn	1981 **		
TXn	2003 **	TNn	1991 *		
SU25	2000 **	FD0	2005 **		
TR15	2001 **	ID0	1992 *		

Table 5. Extreme temperatures index mutations.

- indicates that no mutation has occurred; \* Significant at the 0.05 level; \*\* Significant at the 0.01 level.

From Table 5, it can be seen that TXx did not mutate, the other mutation points of warm index occurred at the beginning of 21st century, while the mutation points of cold index were relatively early, the mutation points of TX10p, TN10p, TXn, TNn and ID0 occurred in 1989, 1997, 1981, 1991 and 1992, respectively, and the mutation point of FD0 appeared later in 2005. The mutation points of other indexes (GSL and DTR) were all in 1997, and the mutation points of all extreme temperature indexes passed the 0.05 significance test. To sum up, except FD0, the mutation points of cold index was more sensitive to global warming. On the other hand, the daily minimum temperature changed faster than the daily maximum temperature. A major issue is the possible urbanization effect on the series of extreme temperature indices [40]. In China, the urbanization effect exacerbated the trends of extreme temperatures indices related to daily minimum temperature. However, the urbanization effects of extreme temperature indices associated with daily maximum temperatures were usually mild [40–42].

#### 4. Discussion

#### 4.1. Comparison with Other Regions

In recent years, extreme weather events have attracted worldwide attention due to the great impact of extreme climate changes on nature and human production and life [3,26]. In order to understand how extreme climate affects society and ecosystem, it is very important to analyze the temporal and spatial change trend of extreme climate. In this paper, we analyzed the temporal and spatial changes in extreme temperatures in arid inland river basins in China in the past 56 years (1960–2015). The results showed that in the past 56 years, the temperature warm indices in SRB showed an overall increasing trend. Except TXn and TNn showed a slight increasing trend in cold indices, other indices showed a decreasing trend. The extreme temperatures events in SRB are strongly consistent with other similar studies in many regions, and are positive responses to global warming. Many scholars, both domestic and abroad, have also studied extreme temperature events (Table 6).

	Period	TX10p (Days/10 Years)	TN10p (Days/10 Years)	TXn (°C/10 Years)	TNn (°C/10 Years)	ID0 (Days/10 Years)	FD0 (Days/10 Years)	SU25 (Days/10 Years)	TXx (°C/10 Years)	TNx (°C/10 Years)	TX90p (Days/10 Years)	TN90p (Days/10 Years)	GSL (Days/10 Years)	DTR (°C/10 Years)	Source
This paper	1960-2015	-0.85 *	-2.13 *	0.34	0.45	-2.81 **	-3.8 *	2.74 **	0.3 **	0.33 *	1.38 **	3.3 *	3.56 **	-0.18 *	
Shule river basin	1959–2011	-1.15 **	-1.44 **	-	0.16	-	2.7 **	3 *	0.32 *	-	1.96 *	1.89 *	-	-	[43]
Hexi Corridor	1986–2011	-0.32	-1.31	-1.11	-0.64	0.47	-6.61	-	0.59	0.86	3.32	4.93	6.5	0.19	[44]
Loess Plateau	1960–2013	-2.71 *	-4.31 *	-	-	-2.11 *	-3.22 *	2.76 *	-	-	2.6 *	3.14 *	3.16 *	-0.06	[34]
Northeast China Region	1960–2011	-0.86 *	-1.8 *	0.39	0.82 *	-1.74 *	-3.36 *	2.3 *	0.11	0.23 *	0.97 *	2.27 *	2.62 *	-0.24 *	[45]
The monsoon region	1961–2016	-2.1 **	4.08 **	0.29 *	0.54 **	-2.23 **	-	-	0.23 **	0.34 *	2.81 **	4.04 **	-	-0.19 **	[46]
TCZ	1956-2015	-0.79 **	-1.36 **	0.4 **	0.55 **	-	-	-	0.16 *	0.22 **	0.99 **	2.04 **	-	-	[47]
TMZ		-0.72 **	-1.47 **	0.35 **	0.63 **	-	-	-	0.12	0.18 **	0.68 **	2.06 **	-	-	
MPZ		-0.89 **	-1.59 *	0.36 **	0.58 *	-	-	-	0.23 *	0.27 *	1.38 *	2.29 *	-	-	-
SMZ		-0.36 **	-1.27 **	0.22 *	0.41 **	-	-	-	0.1 **	0.17 **	1.13 **	2.08 **	-	-	-
China		-0.7 **	-1.44 **	0.35 **	0.55 **	-	-	-	0.15 **	0.22 **	1 **	2.12 **	-	-	-
Asia-Pacific Network rregion		-3.3	-6.4	-	-	-1.3	-2.1	1.9	-	-	3.9	5.4	3	-1	-

**Table 6.** Comparison between this paper and other studies.

\* Significant at the 0.05 level, \*\* Significant at the 0.01 level.

Compared with domestic researches, the results showed that the change speeds of TX10p, SU25, TXx and TX90p in Shule River Basin were larger, and the change speeds of TN10p, TNn and TN90p were lower than that of SRB. FD0 showed a downward trend in SRB, while it showed an upward trend in Shule River Basin. In the Hexi Corridor, except for TX10p and TN10p change speeds, which were lower than that of SRB, other indices' change speeds were all greater than that of SRB. Except TX10p, TX10P and TX90p, the change speeds of other indices in the Loess Plateau were smaller than that of SRB. In non-monsoon region, except the change speeds of TXn, ID0 and TXx, which were smaller, the change speeds of other indices were all larger than that of SRB. In Northeast China, the change speeds of TX10p, TXn, TNn, TXx and DTR were higher, and the change speeds of other indices were lower than that of SRB. In the temperate continental zone (TCZ), the change speeds of TXn and TNn were all larger, and the change speeds of other indices were all smaller than those of SRB. Except TNn, the change speeds of other indexes in temperate monsoon zone (TMZ) were all smaller than those in SRB. In mountain plateau zone (MPZ), the change speeds of TX10p and TNn were larger, and the change speeds of other indexes were smaller than those in SRB. In the Tropical Monsoon Zone (SMZ), the change speeds of all extreme temperature indexes were all smaller than that of SRB. As for China as a whole, the change speeds of all indexes of Shiyang River were higher than the national average, except TXn. Based on the above analysis, it can be concluded that the warming rate of SRB was faster not only than that of China's temperate continental zone, temperate monsoon zone, mountainous plateau region and tropical monsoon zone, but also faster than the national average speed. Compared to the Asia-Pacific Network region, except for ID0, FD0 and GSL, the change speeds of other indexes were larger than that of SRB.

#### 4.2. Analysis of Influencing Factors

North Atlantic Oscillation (NAO), Arctic Oscillation (AO) and Polar Vortex are all mid-high-latitude circulation systems, which are closely related. Polar vortex and subtropical high are the two most important atmospheric circulation entities that affect the weather system and climate change in China [48]. The results show that AO and Northern Hemisphere Polar Vortex Area Index (NHPVAI) have significant effects on the temperature in the middle and high latitudes of the Northern Hemisphere. In the past 50 years, the correlation between NHPVAI and temperature had an inverse distribution pattern. The contraction trend of polar vortex area in the northern hemisphere was closely related to global warming, especially polar warming. In addition, when the East Asian trough weakened, the temperature in most parts of China rose [49]. AO has a significant impact on geopotential height and temperature in the mid-high latitudes of the northern hemisphere, which also has a remarkable impact on regional temperature in Northeast Asia and China [50–52]. However, some studies also show that AO is more significantly related to temperature in polar regions, northern Middle East, North Africa and North Atlantic [53]. At the same time, the polar vortex and subtropical high are the two most important atmospheric circulation entities that affect the weather system and climate change in China [48]. The North Atlantic Oscillation (NAO) and the Pacific Interdecadal Oscillation (PDO) have remarkable impacts on the atmospheric circulation in East Asia and the weather and climate in China [54]. In the years of strong NAO and PDO, the subtropical high is stronger and northerly, and the temperature is higher in most parts of China [55]. Therefore, on the basis of the existing research, in order to further explore the influencing factors of extreme temperatures changes in SRB, some indexes representing atmospheric circulation are selected and used to analyze the relationship between these indexes and the extreme temperatures index, which include Arctic Oscillation (AO), North Atlantic Oscillation (NAO), Pacific Interdecadal Oscillation (PDO), Western Pacific Index (WP), Tibetan Plateau-2 Index (TPR2I), Northern Hemisphere Polar Vortex Area Index (NHPV), Northern Hemisphere Polar Vortex Intensity Index (NHPV VII), Asian Polar Vortex Intensity Index (APVII), Asian Polar Vortex Area Index (APVAI), Western Pacific Subtropical High Intensity Index (WPSHII), Northern Hemisphere Subtropical High Intensity Index (NHSHII) and East Asian Trough Intensity Index (EATII). The correlation analysis shows (Figure 6) that the correlation between AO, NAO,

PDO and WP and most extreme temperatures indexes (except TXn) is not significant, indicating that the changes in these circulation systems have little influence on the extreme temperatures changes in SRB. NHPVAI, NHPVII, APVII and APVAI are significantly positively correlated with most extreme temperatures cold indexes (except TNn and TXn) and DTR, while they are significantly negatively correlated with most extreme temperatures warm indexes (except TXx and TR20) and GSL. At the same time, WPSHII, NHSHII, TPR2I and EATII have significant negative correlation with most extreme temperatures cold indexes (except TNn and TXn) and DTR, while they have a significant positive correlation with most extreme temperatures warm indexes and GSL.



General circulation of atmosphere

**Figure 6.** Heatmap of relationships between atmospheric circulation indices and extreme temperatures indices during 1960–2015. \* Significant at the 0.05 level, \*\* Significant at the 0.01 level.

NHPVAI, NHPVII, APVII and APVAI are all indicators that reflect large-scale cold air conditions in polar regions of the northern hemisphere. When the intensity and area of polar vortices in the northern hemisphere and Asia are weakened, the influence of cold air on the surrounding areas will be weakened. At this time, the zonal circulation in the mid-latitude region of Asia will be strengthened, further limiting the southward invasion of cold air. At the same time, the subtropical circulation is strengthened, and warm and humid air is active in the lower latitudes, resulting in high temperatures in most parts of Asia. The weakening of southward invasion cold air and the strengthening of warm and humid air flow have an impact on the temperature in SRB located at the edge of monsoon, resulting in a continuous increase in extreme temperatures warm indexes and a continuous decrease in cold indexes. Besides, the increase in the East Asian trough intensity index means that the influence of cold air from the north on northeast and north China will be strengthened, while the influence on SRB located in the northwest will be weakened to a certain extent. Compared with the surrounding atmosphere, the original surface of the Qinghai-Tibet plateau is a heat source in summer and a source of cold in winter. The increase in the Qinghai-Tibet plateau-2 index (TPR2I) means that the heat exchange between the surface of the Qinghai-Tibet plateau and the atmosphere above it, and the surrounding atmosphere is strengthened, which has an impact on the temperature of SRB located at the northeast

edge of the Qinghai-Tibet plateau, mainly reflected in its impact on the temperature rise in summer. In sum, the change in extreme temperatures in SRB was the result of the combined function of different atmospheric circulation systems, which included the Arctic polar vortex, Western Pacific subtropical high, East Asian trough and local circulation in Qinghai-Tibet Plateau.

#### 4.3. Possible Impact-Influence on Vegetation and Glacier Frozen Soil in Basin

The temperature in SRB increased, the frost days continued to decrease and the growth season length increased, which made the crops in the basin respond to this change. Warming increased the yield of cotton and maize, decreased the yield of spring wheat, raised the upper limit of crop planting and expanded the planting area [56]. The sowing date of maize was 2.2 days earlier and that of spring wheat was 0.6 days earlier for every 1 °C rise in temperature in Wuwe [57]. The temperature of growth season length (GSL) increased, the growth period of limited growth habit crops spring wheat and maize was shortened, and the growth period of unlimited growth habit crops cotton was prolonged. At the same time, climate was also the main factor that affects the vegetation change in Qilian mountain area in the upper reaches of SRB. The increase in extreme temperatures indices, especially the warming of cold indices, elevates the upper limit of vegetation growth in the upper reaches of SRB, increased the area of high density arbor, and decreased the area of grassland [58]. The rise of extreme temperatures in SRB had a profound impact on the changes of snow cover glacier and frozen soil in Qilian Mountain upstream. According to the calculations by the Institute of Environment and Engineering in Cold and Arid Regions of the Chinese Academy of Sciences [59]: since 1956, the glacier area and ice reserves in the Hexi Inland River Basin decreased by 12.6% and 11.5%, respectively, the glacier thickness decreased by 5–20 m, and the snow line rose by 100–140 m. In addition, the snow cover area in the upper reaches of SRB decreased most obviously, and the "solid reservoir" function of glacier snow gradually disappeared. In SRB, the annual maximum frozen soil depth, frozen soil days and frozen soil distribution range showed a decreasing trend. In terms of mutation time, the extreme temperature indexes changed abruptly from the 1990s to the beginning of the 21st century, and the decreasing rate of frozen soil distribution also showed a jump growth in the same period [56].

#### 5. Conclusions

In recent years, extreme weather events have attracted worldwide attention due to the great impact of extreme climate changes on nature and human production and life [3,26]. In order to understand how extreme climate changes affect societies and ecosystems, it is very important to analyze the temporal and spatial change trend of temperature extremes. The change in temperature is more uncontrollable than precipitation. In this paper, we analyzed the temporal and spatial changes of extreme temperatures in arid inland river basins in China in the past 56 years (1960–2015). The results showed that the temperature warm indices in SRB was on the increase in the past 56 years, especially after the 1990s. Except TXn and TNn in cold indexes, which showed a slight increasing trend, the other indexes showed a decreasing trend. DTR showed a downward trend as a whole, indicating that the increase rate of daily maximum temperature in SRB in the last 56 years was less than that of daily minimum temperature. This proves that SRB in China's arid inland river basin is continuously developing towards a warmer direction, which is a positive response to global warming.

The extreme temperature indices showed obvious altitude gradient effect on the spatial scale, in which the change rate of the warm index SU25 (summer days) was the largest in the middle reaches, while the change rate of other warm indexes was the largest in the upper reaches and the smallest in the lower reaches, elevation gradient effect was obvious. The decreasing speed of cold indexes FD0, ID0 and TN10p decreased with the increase in altitude, while the decreasing speed of TX10p increased with the increase in altitude. GLS increased at the highest rate in the upper reaches, then in the middle reaches, and finally in the lower reaches. The change speed of DTR at each station was less than that of other indexes, whose change tendency rate was the smallest in the upstream and the decrease speed was larger in the downstream. Based on the comprehensive analysis of the extreme temperature

indexes in SRB, the change speed is the largest in the lower reaches, followed by the middle reaches and finally the upper reaches, showing an altitude gradient effect.

The intensity weakening and area contraction of Arctic polar vortex, the continuous strengthening of the northern subtropical High, the western Pacific subtropical high, the East Asian trough and the local circulation in the Qinghai-Tibet Plateau all have an impact on the changes in temperature and extreme temperatures in SRB, located at the eastern edge of the Qinghai-Tibet Plateau and the edge of the East Asian monsoon.

The increase in the warm indices and the decrease in the cold indices have already affected the glacier, frozen soil and the succession of vegetation in the upper reaches of the basin, and the oasis agricultural production in the middle and lower reaches of the basin. With the rise in temperature and the increase in extreme weather events predicted in the future, there will be more profound effects. Therefore, in order to ensure the sustainable development of the basin, governments at all levels must scientifically take sufficient countermeasures according to the characteristics of climate change and continuously improve their ability to cope with climate change and extreme climate events.

**Author Contributions:** Conceptualization, J.Z. and J.H.; methodology, J.Z. and J.H; software, J.H.; validation, G.Z., C.L. and X.Y.; formal analysis, W.W.; investigation, L.W.; resources, W.S.; data curation, J.H.; writing—original draft preparation, J.H.; writing—review and editing, J.Z. and X.Z.; visualization, L.L.; supervision, G.Z.; project administration, J.Z., W.W. and C.L.; funding acquisition, J.Z., W.W., G.Z. and X.Y. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by the National Natural Science Foundation of China (Grant No. 41761047, 41661005, 31760241, 41861040), and Gansu Engineering Research Center of Land Use and Comprehension Consolidation.

Conflicts of Interest: The authors declare no conflict of interest.

#### References

- 1. IPCC. Intergovernmental Panel on Climate Change (IPCC), 1st ed.; Elsevier Inc.: Amsterdam, The Netherlands, 2013; Volume 1–3, ISBN 9780123750679.
- IPCC. 2014: Climate Change 2014: Synthesis Report. Contribution of Working Groups 1, Il and Ill to the Fifth Assessment Report of theIntergovernmental Panel on Climate Change; Core Writing Team, Pachauri, R.K., Meyer, L.A., Eds.; IPCC: Geneva, Switzerla, 2013; ISBN 9789291695386.
- 3. Weaver, S.J.; Kumar, A.; Chen, M. Recent increases in extreme temperature occurrence over land. *Geophys. Res. Lett.* 2014, 41, 4669–4675. [CrossRef]
- 4. Liu, Y.; Geng, X.; Hao, Z.; Zheng, J. Changes in Climate Extremes in Central Asia under 1.5 and 2 °C Global Warming and their Impacts on Agricultural Productions. *Atmosphere* **2020**, *10*, 1076. [CrossRef]
- 5. Finkel, J.M.; Katz, J.I. Changing world extreme temperature statistics. *Int. J. Climatol.* 2018, 38, 2613–2617. [CrossRef]
- 6. Gleixner, S.; Demissie, T.; Diro, G.T. Did ERA5 Improve Temperature and Precipitation Reanalysis over East Africa? *Atmosphere (Basel)* **2020**, *11*, 996. [CrossRef]
- 7. Gao, M.; Franzke, C.L.E. Quantile regression-based spatiotemporal analysis of extreme temperature change in China. *J. Clim.* **2017**, *30*, 9897–9914. [CrossRef]
- Katz, R.W.; Brown, B.G. Extreme events in a changing climate: Variability is more important than averages. *Clim. Chang.* 1992, 21, 289–302. [CrossRef]
- 9. Chen, H.; Sun, J. Changes in climate extreme events in China associated with warming. *Int. J. Climatol.* 2015, 35, 2735–2751. [CrossRef]
- Alexander, L.V.; Zhang, X.; Peterson, T.C.; Caesar, J.; Gleason, B.; Klein Tank, A.M.G.; Haylock, M.; Collins, D.; Trewin, B.; Rahimzadeh, F.; et al. Global observed changes in daily climate extremes of temperature and precipitation. *J. Geophys. Res. Atmos.* 2006, *111*, 1–22. [CrossRef]

- 11. Dittus, A.J.; Karoly, D.J.; Lewis, S.C.; Alexander, L.V. A multiregion assessment of observed changes in the areal extent of temperature and precipitation extremes. *J. Clim.* **2015**, *28*, 9206–9220. [CrossRef]
- 12. Dong, S.; Sun, Y.; Aguilar, E.; Zhang, X.; Peterson, T.C.; Song, L.; Zhang, Y. Observed changes in temperature extremes over Asia and their attribution. *Clim. Dyn.* **2018**, *51*, 339–353. [CrossRef]
- Cheong, W.K.; Timbal, B.; Golding, N.; Sirabaha, S.; Kwan, K.F.; Cinco, T.A.; Archevarahuprok, B.; Vo, V.H.; Gunawan, D.; Han, S. Observed and modelled temperature and precipitation extremes over Southeast Asia from 1972 to 2010. *Int. J. Climatol.* 2018, *38*, 3013–3027. [CrossRef]
- 14. Bennett, K.E.; Walsh, J.E. Spatial and temporal changes in indices of extreme precipitation and temperature for Alaska. *Int. J. Climatol.* **2015**, *35*, 1434–1452. [CrossRef]
- 15. Feng, R.; Yu, R.; Zheng, H.; Gan, M. Spatial and temporal variations in extreme temperature in Central Asia. *Int. J. Climatol.* **2018**, *38*, e388–e400. [CrossRef]
- 16. Panda, D.K.; Mishra, A.; Kumar, A.; Mandal, K.G.; Thakur, A.K.; Srivastava, R.C. Spatiotemporal patterns in the mean and extreme temperature indices of India, 1971–2005. *Int. J. Climatol.* **2014**, *34*, 3585–3603. [CrossRef]
- Alizadeh-Choobari, O.; Najafi, M.S. Extreme weather events in Iran under a changing climate. *Clim. Dyn.* 2018, 50, 249–260. [CrossRef]
- 18. Rahimi, M.; Hejabi, S. Spatial and temporal analysis of trends in extreme temperature indices in Iran over the period 1960–2014. *Int. J. Climatol.* **2018**, *38*, 272–282. [CrossRef]
- 19. Li, L.; Zhang, Y.; Liu, Q.; Ding, M.; Mondal, P.P. Regional differences in shifts of temperature trends across China between 1980 and 2017. *Int. J. Climatol.* **2019**, *39*, 1157–1165. [CrossRef]
- Fang, S.; Qi, Y.; Yu, W.; Liang, H.; Han, G.; Li, Q.; Shen, S.; Zhou, G.; Shi, G. Change in temperature extremes and its correlation with mean temperature in mainland China from 1960 to 2015. *Int. J. Climatol.* 2017, 37, 3910–3918. [CrossRef]
- 21. Deng, H.; Chen, Y.; Shi, X.; Li, W.; Wang, H.; Zhang, S.; Fang, G. Dynamics of temperature and precipitation extremes and their spatial variation in the arid region of northwest China. *Atmos. Res.* **2014**, *138*, 346–355. [CrossRef]
- 22. Qi, Y.; Chen, H.; Fang, S.; Yu, W. Variation Characteristics of Extreme Climate Events in Northwest China During 1961–2010. *J. Arid Meteorol.* **2015**, *33*, 963–969.
- 23. Wang, B.; Zhang, M.; Wei, J.; Wang, S. Variation characteristics of extreme events of temperature and precipitation in the northwest region of nearly 50a. *J. Nat. Resour.* **2012**, *27*, 1720–1733. [CrossRef]
- 24. Shi, Y.; Shen, Y.; Li, D. The characteristics and trend of climate transition from warm and dry to warm and wet in northwest China. *Quat. Sci.* **2003**, *3*, 1–5. [CrossRef]
- 25. Li, B.; Chen, Y.; Shi, X. Why does the temperature rise faster in the arid region of northwest China? *J. Geophys. Res. Atmos.* **2012**, *117*, 1–7. [CrossRef]
- 26. Li, B.; Chen, Y.; Shi, X.; Chen, Z.; Li, W. Temperature and precipitation changes in different environments in the arid region of northwest China. *Theor. Appl. Climatol.* **2013**, *112*, 589–596. [CrossRef]
- Wang, Y. Study on Climate Change and Adaptation of Typical Watersheds in Arid Areas of Northwest China. 2017. Available online: http://cdmd.cnki.com.cn/Article/CDMD-10284-1018151328.htm (accessed on 10 May 2020).
- 28. Wang, Y.; Qin, D. A review on the effects of climate change and human activities on water resources in arid areas of northwest China. *Clim. Chang. Res.* **2017**, *13*. [CrossRef]
- Brown, P.J.; Bradley, R.S.; Keimig, F.T. Changes in extreme climate indices for the Northeastern United States, 1870-2005. J. Clim. 2010, 23, 6555–6572. [CrossRef]
- Donat, M.G.; Peterson, T.C.; Brunet, M.; King, A.D.; Almazroui, M.; Kolli, R.K.; Boucherf, D.; Al-Mulla, A.Y.; Nour, A.Y.; Aly, A.A.; et al. Changes in extreme temperature and precipitation in the Arab region: Long-term trends and variability related to ENSO and NAO. *Int. J. Climatol.* 2014, 34, 581–592. [CrossRef]
- 31. Wang, J.; Fei, X.; Wei, F. Further Study of Temperature Change in Northwest China in Recent 50 Years. *J. Desert Res.* **2008**, *28*, 128–236.
- 32. Mou, L.T.; Ibrahim, A.L.; Cracknell, A.P.; Yusop, Z. Changes in precipitation extremes over the Kelantan River Basin, Malaysia. *Int. J. Climatol.* **2017**, 37. [CrossRef]
- Wang, X.L.; Feng, Y. RHtestsV4 User Manual; Climate Research Division Atmospheric Science and Technology Directorate Science and Technology Branch, Environment Canada: Toronto, ON, Canada, 2013.

- 34. Sun, W.; Mu, X.; Song, X.; Wu, D.; Cheng, A.; Qiu, B. Changes in extreme temperature and precipitation events in the Loess Plateau (China) during 1960–2013 under global warming. *Atmos. Res.* **2016**, *168*, 33–48. [CrossRef]
- 35. You, Q.; Ren, G.; Fraedrich, K.; Kang, S.; Ren, Y.; Wang, P. Winter temperature extremes in China and their possible causes. *Int. J. Climatol.* **2013**, *33*, 1444–1455. [CrossRef]
- 36. He, S.; Richards, K.; Zhao, Z. Climate extremes in the Kobresia meadow area of the Qinghai-Tibetan Plateau, 1961–2008. *Environ. Earth Sci.* **2016**, *75*, 1–15. [CrossRef]
- 37. Zhang, J.; Ma, L.; Tijiu, C. Hydrology and Water Resources; China Forestry Press: Beijing, China, 2016; pp. 40-41.
- 38. Donat, M.G.; Alexander, L.V.; Yang, H.; Durre, I.; Vose, R.; Caesar, J. Global land-based datasets for monitoring climatic extremes. *Bull. Am. Meteorol. Soc.* **2013**, *94*, 997–1006. [CrossRef]
- 39. Gallant, A.J.E.; Karoly, D.J. A combined climate extremes index for the Australian region. *J. Clim.* **2010**, 23, 6153–6165. [CrossRef]
- 40. Zhou, Y.; Ren, G. Change in extreme temperature event frequency over mainland China, 1961–2008. *Clim. Res.* **2011**, *50*, 125–139. [CrossRef]
- 41. Yaqing, Z.; Guoyu, R. The Effect of Urbanization on Maximum, Minimum Temperatures and Daily Temperature Range in North China. *Plateau Meteorol. Meteorol.* **2009**, *28*, 1158–1166.
- 42. Duan, C.; Miu, Q.; Cao, W.; Ma, D. Effect of Urbanization on Variation Trends of Air Temperatures Based on Mountain Stations. *Atmos. Sci.* **2012**, *35*, 811–812. [CrossRef]
- 43. Chen, Y. Response of Extreme Hydrological Events to Extreme Climate in the Shule River Basin. *Plateau Meteorol.* **2019**, *38*, 583–592.
- 44. Feng, Q.; Li, Z.; Liu, W.; Li, J.; Guo, X.; Wang, T. Relationship between large scale atmospheric circulation, temperature and precipitation in the Extensive Hexi region, China, 1960–2011. *Quat. Int.* **2016**, 392, 187–196. [CrossRef]
- 45. Yu, Z.; Li, X. Recent trends in daily temperature extremes over northeastern China (1960–2011). *Quat. Int.* **2015**, *380–381*, 35–48. [CrossRef]
- 46. Wang, Y.; Ding, Z.; Ma, Y. Spatial and temporal analysis of changes in temperature extremes in the non-monsoon region of China from 1961 to 2016. *Theor. Appl. Climatol.* **2019**, *137*, 2697–2713. [CrossRef]
- 47. Zheng, J.; Fan, J.; Zhang, F. Spatiotemporal trends of temperature and precipitation extremes across contrasting climatic zones of China during 1956–2015. *Theor. Appl. Climatol.* **2019**, *138*, 1877–1897. [CrossRef]
- 48. Zhang, H.; Gao, S.; Liu, Y. Advances in polar vortex research. Plateau Meteorol. 2008, 30, 2.
- 49. Gu, S.; Yang, X. The variation of polar vortex in the northern hemisphere and its relationship with climate anomaly in China. *Meteorol. Sci.* **2006**, *26*, 135–142.
- 50. Thompson, D.W.J.; Wallace, J.M. The Arctic oscillation signature in the wintertime geopotential height and temperature fields. *Geophys. Res. Lett.* **1998**, 25, 1297–1300. [CrossRef]
- 51. Gong, D. Prediction of summer precipitation in east Asia by Arctic Qscillation. *Meteorol. Mon.* 2003, 29, 3–6. [CrossRef]
- 52. Wu, B.; Jia, W. Possible impacts of winter Arctic Oscillation on Siberian high, the East Asian winter monsoon and sea-ice extent. *Adv. Atmos. Sci.* 2002, *19*, 297–320. [CrossRef]
- 53. Shen, B.; Lian, Y.; Zhang, S.; Li, S. The influence of arctic oscillation and polar vortex activity anomalies on the winter temperature of Eurasia in the northern hemisphere. *Progress. Inquisitiones Mutat. Clim.* **2012**, *8*, 434–439. [CrossRef]
- 54. Liang, S.; Ding, Y.; Zhao, N.; Sun, Y. Study on interdecadal variation of winter temperature and regional circulation in mainland China in recent 50 years. *Chin. J. Atmos. Sci.* **2014**, *38*, 974–992. [CrossRef]
- 55. Wang, Y.; Shi, N. The relationship between summer north Atlantic oscillation and weather and climate in China. *J. Meteorol. Sci.* 2001, *21*, 271–278. [CrossRef]
- 56. Yang, X.; Ma, Z.; MA, Y.; Wang, R. The Spatial-Temporal Distribution State of Seasonal Frozen Soil and Responses to Temperature Change in the Shiyang River Basin. *Resour. Sci.* **2013**, *35*, 2104–2111.
- 57. Wang, T. Spatial-Temporal Characteristics and Influencing Factors of Climate Growth Period of Chimonophilous Crop in North China from 1960 to 2016. Master's Thesis, Northwest Normal Univercity, Lanzhou, Gansu, China, 2018.

- 58. Gui, J.; Wang, X.; Li, Z.; Zou, H.; Li, A. Research on the response of vegetation change to human activities in typical cryosphere areas: Taking the Qilian Mountains as an example. *J. Glaciol. Geocryol.* **2019**, *41*, 1235–1243. [CrossRef]
- 59. Meng, J.; Zhang, S.; Zhang, Y. The Temporal and Spatial Change of Temperature and Precipitation in Hexi Corridor in Recent 57 Years. *Acta Geogr. Sin.* **2012**, *67*, 1482–1492. [CrossRef]

**Publisher's Note:** MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.



© 2020 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).