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The Impact of Climate Change on Glacial Lake Outburst Floods

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Abstract: Glacial lake outburst floods (GLOF) hazards in alpine areas are increasing. The effects of climate change on GLOF hazards are unclear. This study examined 37 glacial lakes and climate data from 15 meteorological stations and explored the correlation between climate variations at different temporal scales. The results indicate that 19 GLOFs hazards occurred in El Niño (warm) years, 8 GLOFs hazards occurred in La Niña (cold) years, 3 GLOFs hazards occurred in cold/warm or warm/cold transition years, and 7 GLOFs hazards occurred in normal years. The higher the fluctuations, the higher the probability of GLOF hazards. Climatic conditions can be divided into three categories: extreme temperature and precipitation, as represented by the Guangxie Co GLOF; extreme precipitation, as represented by the Poge Co GLOF; and extreme temperature, as represented by the Tsho Ga GLOF.

Keywords: climate index; El Niño; La Niña; GLOF hazards; threshold value; Tibetan Plateau

1. Introduction

Glacial lakes are rapidly growing in response to climate change and glacial retreat [1]. According to data from meteorological stations, the average temperature over the Tibetan Plateau increased by 1.4 °C from 1961 to 2019, a rate of 0.28 °C/10a. In the same period, precipitation increased at a rate of 4.1 mm/10a [2]. As a result of global warming, glacial lakes are increasing in number and size [3,4], and the risk of glacier-related hazards in high mountain regions has increased [5–9]. Glacial lake outburst floods (GLOFs) are glacier-related hazards. The frequency of GLOFs has risen. Moreover, GLOFs receive widespread attention. GLOFs occur in the eastern Himalayas (China), the Ganga Basin, the Alps, the Central Caucasus, and in Alaska [10–14].

GLOF hazards can be triggered by both internal and external factors. Temperature and precipitation variations, which are external factors, affect snow accumulation and the melting of ice that feeds glacial lakes; additionally, ice/snow/rock falls, landslides, overtopping erosion, piping, and other factors trigger glacial lake outbursts, thereby influencing the magnitude and frequency of GLOF hazards [15–21]. Analysis of high-resolution satellite imagery and geomorphological evidence has revealed that approximately 100 GLOF hazards have occurred in the Third Pole since the 1930s [22]. Moreover, studies have shown that climate change is an important trigger for GLOF hazards [23–26]. For instance, Cui et al. [27], Chen et al. [28], and Zhao et al. [29] have noted that GLOFs are likely to occur during warm, humid periods or climatic abrupt change years (cold-to-warm transition). Moreover, Chen et al. [26] found that as a result of increasing temperatures, the frequency of GLOFs in the Yarkant region of Karakoram almost doubled from an average of 0.4 annually in 1959–1986 to 0.7 annually in 1997–2006. Additionally, Liu et al. [30] documented the associations of temperature and precipitation fluctuations with GLOFs in the Tibet Autonomous Region of China.

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The factors that lead to GLOF hazards are complex, and the relationship between GLOF hazards and climate change remains unclear [31,32]. Air temperature is the most critical factor for GLOF hazards because it affects radiation balance, turbulent heat exchange, and the solid–liquid precipitation ratio [33]. High temperatures mainly affect the melting of ice and snow and increase the amount of water in a lake. GLOF hazards are increasing, particularly in southern Tibet [21,26,34]. Despite the attention given to the effects of climate warming on GLOF disasters, the mechanisms by which climate warming affects alpine and cold regions remain unclear, thereby hindering the effectiveness of disaster prevention and mitigation efforts. Therefore, in this study, 40 GLOF events were examined to assess the relationship between these events and the hazards and effects of climate change. The main objectives of this research were to (i) assess the climatic conditions before each GLOF hazard, (ii) analyze the associations of temperature and precipitation with GLOF hazards, and (iii) identify the climate threshold for GLOF hazards.

2. Study Area, Data, and Methods

2.1. Study Area

The Tibetan Plateau (TP) region has one of the highest concentrations of glacial lakes in the world (Figure 1). The region contains more than 36,000 glaciers, which cover an area of approximately 49,000 km^2 [35]. TP has unique topographic and landscape features and is strongly influenced by the Asian monsoon. The climate in the TP has changed substantially since the 20th century. For instance, data from meteorological stations shows that from 1961 to 2019, the average temperature in the TP increased by 0.37 °C per decade, and precipitation increased at a rate of 4.1 mm per decade. Several studies have shown that glacial retreat in this region is exacerbated by climate warming and that the area and number of glacial lakes have increased [36]. According to the second Chinese glacier inventory data set, a glacial retreat of >20% has occurred in Gangdise, Nyainqentanglha, and the Western Himalayas [37]. Increased temperatures and glacial retreat in the TP and its surrounding regions have led to increasingly frequent disasters and GLOFs [10].

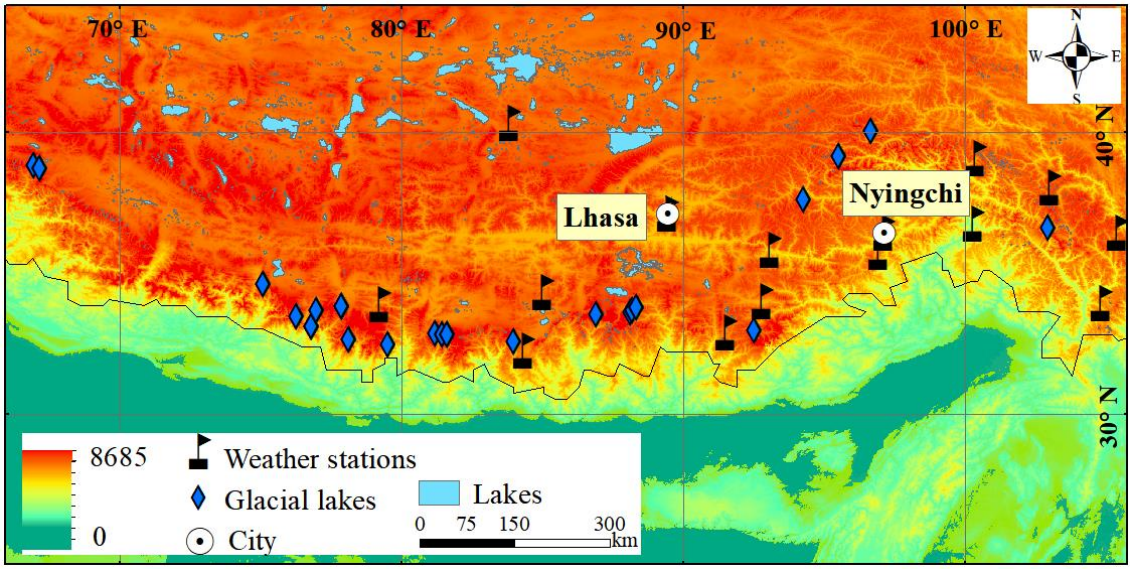


Figure 1. Study area.

2.2. Data

Since the 1950s, 37 GLOFs have occurred on the TP. These data were obtained from a literature review [38–41] and a field investigation. A brief description of each event is provided in Table 1.

Table 1. Meteorological characteristics of burst glacial lakes.

ID	Name	County	Date of Glacial Lake Outburst	Causes of Glacial Lake Outburst	Glacial Lake Outburst Year					Glacial Lake Outburst Month				
					Percentage of Precipitation Anomaly	Temperature Anomaly	Max-T	Min-T	Mean Wind Speed	Percentage of Precipitation Anomaly	Temperature Anomaly	Max-T	Min-T	Mean Wind Speed
1	Sangwang Co	Kangmar	1954.7	glacier surging	-	-	-	-	-	-	-	-	-	-
2	Lure Co	Lhozhag	1950s	avalanche	-	-	-	-	-	-	-	-	-	-
3	Cirenma Co	Nyalam	1964	avalanche	-	-	-	-	-	-	-	-	-	-
4	Longda Co	Gyirong	1964.8	avalanche	-	-	-	-	-	-	-	-	-	-
5	Jilai Co	Dinggyê	1964.9	glacial landslide	-	-	-	-	-	-	-	-	-	-
6	Damenhai Co	Gongbo′gyamda	1964.9	avalanche	-	-	-	-	-	-	-	-	-	-
7	Aya Co	Tingri	1965.8	glacial landslide	-	-	-	-	-	-	-	-	-	-
8	Aya Co	Tingri	1968.8	glacial landslide	-	-	-	-	-	-	-	-	-	-
9	Aya Co	Tingri	1969.8	glacial landslide	-	-	-	-	-	-	-	-	-	-
10	Aya Co	Tingri	1970.8	glacial landslide	-	-	-	-	-	-	-	-	-	-
11	Bange Co	Sog	1972.7	glacial landslide	−36.5	0.7	24.3	−26	-	−20.4	1	24.3	0.2	-
12	Boge Co	Dênqên	1974.7	avalanche	23.5	0.2	22.6	−21	-	9.7	−0.1	22.6	2.8	-
13	Zhari Co	Lhozhag	1981.6	avalanche	−16.6	−0.5	13.7	−33	-	−39.9	−0.4	13.7	−1.9	-
14	Cirenma Co	Nyalam	1981.7	avalanche	6.7	−0.7	16.8	−16	-	−10.5	0.2	16.8	4.1	-
15	Yindapu Co	Dinggyê	1982.8	avalanche	−64	−1	23.7	−20		−64.4	0.6	21.9	3.9	
16	Cirenma Co	Nyalam	1983.7	avalanche	34.9	3	22.4	−17	-	8.4	−0.2	22.4	3.8	-
17	Guangxie Co	Bomi	1988.7	avalanche/glacial landslide	37.5	0.1	30.1	−10	-	29.8	−0.5	30.1	6.4	-
18	Upper Gebuma Co	Baxoi	1991.6	glaciers retreat	24.2	−0.5	27.6	−9.9		221.9	−1.3	27.6	7.4	
19	Gebuma Co	Baxoi	1991.6	Upstream flood	24.2	−0.5	27.6	−9.9		221.9	−1.3	27.6	7.4	
20	Bange Co	Sog	1991.6	glacier surging	−19.2	0	21.3	−27	-	−12.7	0.2	17	−1.8	-
21	Remu Co	Yadong	1992.6	avalanche	−42	−0.8	21	−22.5		−90.5	−2.3	21.1	−4	
22	Xiaga Co	Naidong	1995.5	avalanche/glacial landslide	−38.3	0.4	27.6	−13	-	−51.1	0.9	27.6	2.8	-

Table 1. *Cont.*

ID	Name	County	Date of Glacial Lake Outburst	Causes of Glacial Lake Outburst	Glacial Lake Outburst Year					Glacial Lake Outburst Month				
					Percentage of Precipitation Anomaly	Temperature Anomaly	Max-T	Min-T	Mean Wind Speed	Percentage of Precipitation Anomaly	Temperature Anomaly	Max-T	Min-T	Mean Wind Speed
23	Zana Co	Gyirong	1995.5	glacial landslide	7.1	−0.7	17.4	−19	-	−53.2	1.8	17.4	0.7	-
24	Longjiu Co	Kangmar	2000.8	avalanche	38.3	−0.4	22.7	−19	-	6.7	−0.5	21.3	4.3	-
25	Zangla Tsho	Gyirong	1995–1998	avalanche	-	-	-	-	-	-	-	-	-	
26	Jialong Co	Nyalam	2002.5	avalanche	32.9	0.3	19.4	−16	-	29.7	0.4	19.4	−7	-
27	Jialong Co	Nyalam	2002.6	avalanche	27.3	0.2	19.4	−16	-	−6.2	0.1	15	3.1	-
28	Dega Co	Lhozhag	2002.9	glacial landslide/avalanche	7.5	0	17.2	−24	-	19.8	−1.1	15.2	−0.4	-
29	Ouguchong Co	Nyingchi	2003–2004	avalanche	-	-	-	-						
30	Lang Co	Cona	2007.8	heavy precipitation	8.9	0.8	17.5	−32	3.4	84.5	0.4	16.1	1.8	3.2
31	Zhemai Co	Cona	2009.7	glacial melt water	−2.2	−0.4	15.2	−23	3.5	−38	0.8	15.2	1.6	4
32	Tsho Ga	Banbar	2009.7	glacial melt water	−34.9	1.7	28.9	−16	2.1	−3.2	2.5	28.9	8.4	1.9
33	Geiqu	Dinggyê	2010	heavy precipitation	-	-	-	-						
34	Ranzeria Co	Lhari	2013.7	avalanche	−15.8	1	21	−25	1.8	−14.2	1.4	21	−2.4	1.7
35	Nalong Zangbu branch Co	Bomi	2014.6	glacial mud-rock flow	−18.1	0.8	30.5	−2.7	1.7	0.4	1	28.6	6.5	1.6
36	Unknown	Banbar	2015.7	glacial landslide	16.5	0.8	25.7	−18	2.6	−17.6	1.2	25.7	4.4	2.8
37	Gongbashatong Tsho	Nyalam	2016.7	glacial mud-rock flow	−25.3	0.5	20	−13	24.4	12.2	0.7	17.4	7.2	4.3

Daily temperatures (mean, maximum, and minimum) from 15 meteorological stations were collected from the Tibet Meteorological Bureau. The data cover the 1980–2018 period. Because the altitude of the glacial lakes was higher than that of the meteorological stations, the data were adjusted using the vertical decline rate to obtain the temperatures of the glacial lakes. The precipitation data are based on the observed data from the nearest meteorological station. These precipitation data have not been interpolated.

2.3. Methodology

Due to the lack of relevant meteorological data in some glacial lake outburst areas, we conducted a climate background analysis for 25 glacial lakes.

The amount of precipitation and air temperature variation relative to the average for the year and month of each outburst event was calculated. The highest and lowest temperatures for the year and month of each outburst event and their respective rankings compared with historical data were computed. The outburst year refers to the period from 1 January of the outburst year to the outburst date. The outburst month is 30 days before the outburst date.

To assess the amount of heat gained by glacier ablation during GLOFs, an accumulated temperature index was developed [42]. The 5-day moving average method was applied to determine the start date with a mean daily temperature of $\geq$0 °C.

First, we examined the extreme climatic characteristics at various time scales, which are represented by 13 extreme climatic indexes, including the maximum temperature, minimum temperature, number of cold nights, number of cold days, number of warm days, number of growing days, annual precipitation, precipitation intensity, number of consecutive days without rain, number of consecutive days with rain, number of days with heavy rain, number of days with moderate rain, and maximum daily precipitation. The weight of each index was calculated using the method outlined in another study [39].

We used weights and extreme values to construct a comprehensive climate index to describe climate change characteristics.

$$\text{Precipitation composite index} = \sum_{1}^{14} \text{weight} \times \text{annual precipitation extreme index}$$

$$\text{Temperature composite index} = \sum_{1}^{14} \text{weight} \times \text{annual temperature extreme index}$$

Additionally, this study incorporated the El Niño and La Niña indices. El Niño typically denotes a climate phenomenon characterized by persistently high sea temperatures in the equatorial central and western Pacific Ocean, leading to abnormal atmospheric circulation. During El Niño events, there is an unusual increase in rainfall across most regions of the TP. La Niña refers to extensive regions of abnormally cold sea surface temperatures in the equatorial central and eastern Pacific Ocean, which contrasts with El Niño and is often termed the anti-El Niño phenomenon. The La Niña phenomenon is associated with frequent precipitation and temperature fluctuations within the Tibetan region.

3. Results

3.1. Circulation Background

We collected data on the dates of GLOFs in Tibet and analyzed the spatiotemporal correlation between GLOF hazards and El Niño and La Niña events. From 1950 to 2020, 19 GLOFs (51%) occurred in El Niño (warm) years, 8 GLOFs (22%) occurred in La Niña (cold) years, 3 GLOFs (8%) occurred in El Niño–La Niña transition years, and 7 GLOFs occurred in normal years (Table 2). From the perspective of interdecadal changes, the outbreak frequency of glacial lake outburst disasters in Tibet has increased significantly since the 1950s. These disasters occurred frequently during the La Nina years in the 1950s and 1960s. However, since the 1970s, the frequency of glacial lake outburst disasters in El Nino years has been increasing. Generally, the frequency of glacial lake outburst disasters in El Nino years is higher than that in La Nina years.

Table 2. Correlation between GLOFs in the Tibet and El Niño and La Niña events.

El Niño/La Niñaevents	Year	Frequence
El Niño events	1951, 1952, 1953, 1958, 1963, 1965, 1969, 1972, 1976, 1978, 1980, 1983, 1987, 1992, 1994, 1997, 2002, 2004, 2006, 2009, 2015, 2020	16
La Niña events	1950, 1955, 1956, 1964, 1968, 1971, 1973, 1975, 1985, 1988, 1995, 1999, 2000, 2008, 2010, 2011	14
El Niño and La Niña transition years	1968, 1984, 1995, 1996, 1998, 2008	10

Fewer GLOFs occurred before 1960 than after 1960 (Figure 2). GLOFs occurred only 3 times in 1970–1980, the period with the fewest GLOFs. In 1960–1970 and 1980–1990, seven and five GLOFs occurred, respectively. A large number of GLOFs occurred in 2000–2020. In 2000–2010, 9 GLOFs occurred. Before 1980, GLOFs mainly occurred in La Niña years. After 1980, GLOFs mainly occurred in El Niño years. From the changes in each year (Tables 1 and 2), glacial lake outbursts occurred twice in 1981, three times in 1991, two times in 1995, three times in 2002, two times in 2009, and one time in other years. Notably, 1981, 1991, 2002, and 2009 are El Nino years, while 1995 is an El Nino/La Nina event transition year.

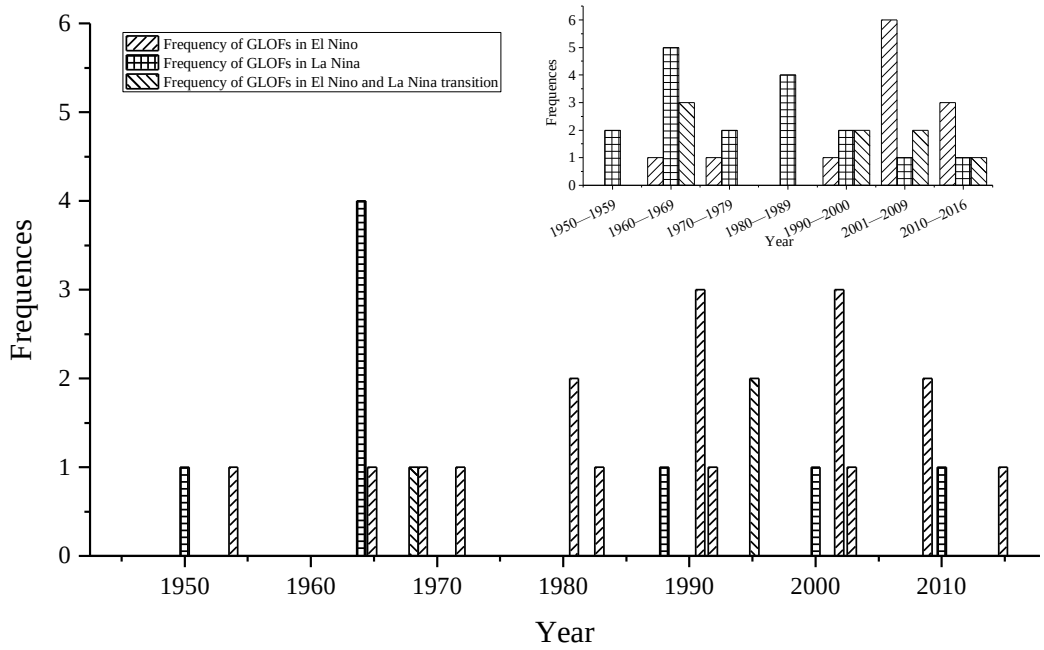


Figure 2. Temporal frequency of GLOFs in El Niño and La Niña events in TP.

We collected data on annual mean precipitation and annual mean temperature at each GLOF location. The annual mean precipitation for the 30-year period from 1981 to 2010 was calculated for each region where a GLOF hazard occurred. Data on precipitation and temperature in El Niño, La Niña, and transition years were compared with those in normal years. Annual precipitation was slightly higher than average in El Niño years and fluctuated substantially. Additionally, annual precipitation was significantly higher than average in La Niña years. Furthermore, annual precipitation in El Niño–La Niña transition years was generally higher than average. Furthermore, annual precipitation was generally higher during El Niño and La Niña years. As precipitation increases, the likelihood of a GLOF hazard increases.

3.2. Climatic Conditions

Annual precipitation levels were 20–30% higher than average in 8 of the years in which GLOF hazards occurred (Table 1). Furthermore, the temperature in these 8 years was slightly higher than average. Moreover, in 1983 (the year in which a GLOF occurred at Cirenma Co glacier lake), the temperature was 3 °C higher than average. Moreover, annual precipitation levels were 0.2–30% lower than average in 11 of the years in which GLOFs occurred. Further, the temperature in these 11 years was 0.1–1.7 °C higher than average. Additionally, precipitation levels were higher than average and the temperature was lower than average in the 3 years in which GLOF hazards occurred. Moreover, precipitation levels and temperatures were lower than average in the 4 years in which GLOF hazards occurred. Precipitation levels in 11 outburst months were lower than in the associated outburst years. Furthermore, temperatures in these 11 outburst months were 0.2–2.5 °C higher than in the associated outburst years. In the Tsho Ga Glacier, the temperature in the outburst month was 2.5 °C higher than in the associated outburst year. Moreover, in seven outburst months, precipitation levels were higher than average and temperatures were lower than average. Additionally, in four outburst months, precipitation levels and temperatures were higher than in the associated outburst years. According to the above findings, climatic conditions during the outburst years and outburst months are not consistent. For example, in the glacial lake of Zhemai Co during outburst years, precipitation levels were 20% lower than average and temperatures were 0.4 °C lower than average but 0.8 °C higher than those in outburst months. The gradual temperature rise appears to lead to an increase in glacial meltwater, resulting in a GLOF.

The highest temperature recorded was 22.4 °C. This temperature was recorded at Cirenma Co (a glacier lake) in 1983. The lowest outburst monthly temperature was 8.4 °C. Studies have shown that GLOFs are often preceded by higher-than-average temperatures and humidity. These climatic conditions were present in 1983, the year of the GLOF at Cirenma Co. Furthermore, high temperatures result in increased levels of meltwater in the upper reaches of a lake.

Associations of temperature and precipitation with GLOF hazards are clear in 24 GLOFs. A total of 24 GLOFs occurred between May and September (Table 1). GLOF hazards occurred nine times in July, three times in June, three times in May, two times in August, and once in September. Moreover, precipitation levels and temperatures were highest in July and August. Heavy precipitation sharply increases glacial lake levels, and high temperatures increase glacier activity. Zakwan et al. [43] reported that the waterbodies in the Himalaya region receive heavy rainfall during July-August, and the glacial melt is high due to summer temperatures, leading to an increase in the risk factor of glaciers. A favorable combination of precipitation and temperature conditions resulted in a disproportionately high number of GLOF hazards in July and August. Furthermore, a total of 61% of all GLOF hazards occurred between these months.

We have re-analyzed the correlation between extreme temperatures and the effective accumulated temperature before glacial lake outbursts and the correlation between average annual temperatures and the effective accumulated temperature before glacial lake outbursts. It can be seen from the following table that cumulative temperature and rainfall reached their maximum in the July 1988 outburst (Table 3) in Guangxie Co. Furthermore, the correlation between annual temperature and the accumulated temperature was high (0.63), while the correlation between extreme temperature and the accumulated temperature was low (0.32) (Figure 3a,b). This outcome indicates that the accumulation of heat and the increase in rainfall have a significant influence on the outburst of glacial lakes. The accumulated temperature value and the number of cumulative temperature days for Tsho Ga in the outburst year reached the maximum values observed in past years, while the rainfall in the current year was not the maximum observed in past years (Table 4). Therefore, heat accumulation in the early stages had a significant impact on the outburst of Tsho Ga (Figure 3c,d).

Table 3. Changes in accumulated temperature and rainfall before the outburst of Guangxie Co.

Year	Annual Total Accumulated Temperature Days	Annual Accumulated Temperature Days	Accumulated Temperature Value before the Outburst Day	Accumulated Temperature Days before the Outburst Day	Total Rainfall before the Outburst Day
1979	6912.26	207	3113.8	104	589
1980	6932.46	203	3170.62	101	606.4
1981	7145.48	204	3123.46	98	451.6
1982	7182.62	215	3058.7	104	672.4
1983	7205.76	187	2908.22	80	494.8
1984	7317.0	209	3134.78	93	575.5
1985	7223.56	217	3138.42	110	735.3
1986	7169.98	198	3143.52	95	451.5
1987	6995.82	219	3109.06	112	517.6
1988	7256.8	204	3204.34	101	758.4

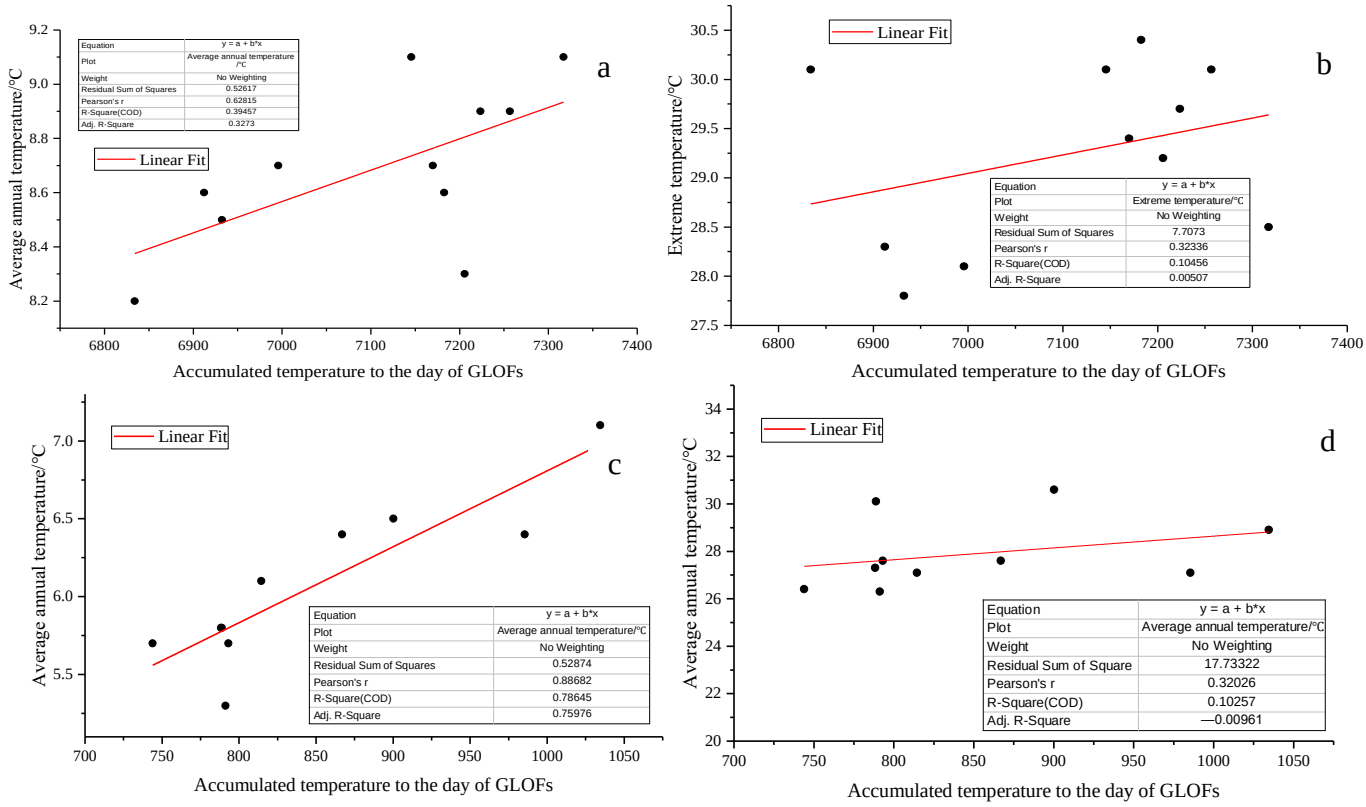


Figure 3. Correlation between annual temperature and extreme temperature and accumulated temperature before a glacial lake outburst. ((**a**,**b**): represent the correlation between the annual average temperature, extreme temperature, and accumulated temperature before the glacial lake outburst in Guangxie Co; (**c**,**d**): represent the correlation between the average annual temperature, extreme temperature, and accumulated temperature before the glacial lake outburst in Tsho Ga).

Table 4. Changes in accumulated temperature and rainfall before the outburst of Tsho Ga.

Year	Annual Total Accumulated Temperature Days	Annual Accumulated Temperature Days	Accumulated Temperature Value before the Outburst Day	Accumulated Temperature Days before the Outburst Day	Total Rainfall before the Outburst Day
2000	791.24	161	463.68	83	282
2001	788.86	156	383.40	78	270
2002	793.17	144	439.03	76	228.4
2003	814.51	158	360.37	75	239
2004	743.98	151	365.81	81	369.5
2005	866.87	143	435.41	73	154.4
2006	900.19	141	462.96	73	299.6
2007	985.54	170	490.37	87	247.2
2008	788.31	155	425.44	86	234.1
2009	1034.48	180	594.25	97	151.5

3.3. Clusters of Climate Extreme Index

Climatic conditions during GLOF hazards can be divided into three categories (Figure 4) based on the type of comprehensive extreme temperature and precipitation index, as represented by Guangxie Co; the type of extreme precipitation index, as represented by Poge Co; and the types of extreme temperature index, as represented by Tsho Ga.

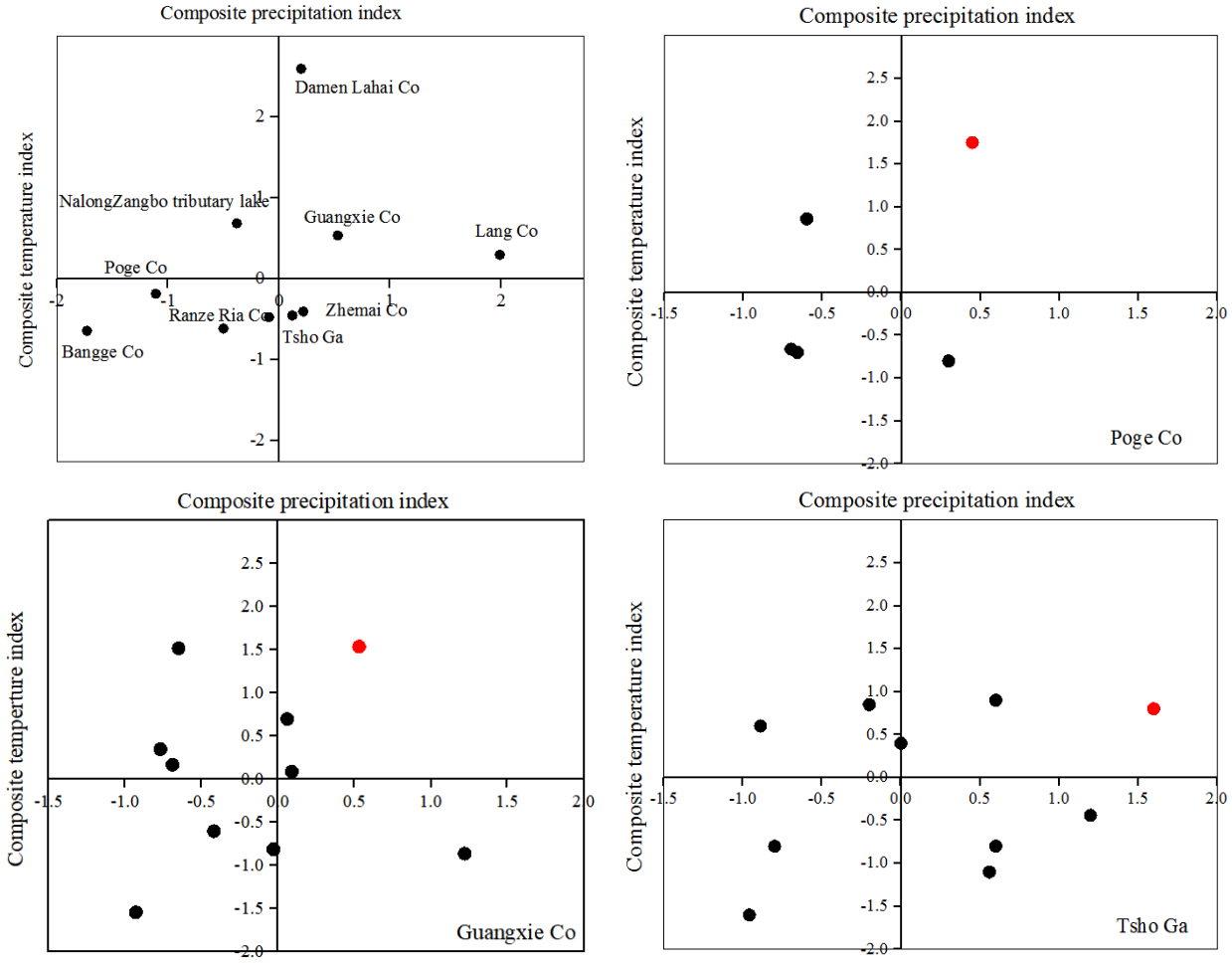


Figure 4. Three categories of extreme climate in GLOF years (red dots represents the composite index).

Among the 10 GLOF hazards in southeastern Tibet, 7 (70%) were of the comprehensive extreme temperature and precipitation index type. We further compared and analyzed the climatic conditions at Damenla Co, Lang Co, and Guangxie Co in outburst years and 9 years before the GLOFs (meteorological data earlier than 3 years before the GLOF at the Poge Co was unavailable). In the outburst year of Guangxie Co, the temperature deviated from the annual average by 1.3 °C, and the precipitation level was 20% higher than average. The degree of deviation in the extreme temperature index and extreme precipitation index was 0.78, indicating that the conditions exceeded those of the extreme temperature and extreme precipitation in 85% of previous years. The degrees of deviation in the extreme temperature index and extreme precipitation index of Damenla Co and Lang Co were 0.3 and 0.5, respectively. The GLOF hazards at the Bange Co, Ranzerea Co, and Nalong Zangbu branch Co occurred during climatic conditions that fit the composite temperature and precipitation index; however, the extreme temperature and extreme precipitation index of the three lakes deviated from those recorded when the GLOF hazards occurred. Furthermore, Zhemai Co and Tsho Ga are affected by temperature and belong to a category that accounts for 20% of total glaciers. The outburst year temperatures at Zhemai Co and Tsho Ga were 0.8 °C and 1.4 °C higher than average, respectively.

The climatic conditions of outburst months are more predictive of GLOF hazards than are those of outburst years [39]. We used the same method to analyze the extreme climate conditions in each region in outburst months (i.e., 30 days before the GLOF hazards). Conditions were again divided into three categories (Figure 5). The outburst at Bange Co was caused by changes in temperature and precipitation; the outburst at Guangxie Co was mainly caused by temperature; and the outburst at Damenla Co was mainly caused by precipitation.

The conditions in the outburst months at Bange Co, Damenla Co, Ranzeria Co, Poge Co, Lang Co, and Tsho Ga glaciers fall under the category of combined temperature and precipitation and account for 70% of the total GLOF events. The degree of deviation in the extreme temperature index and extreme precipitation index in the outburst months of the GLOF hazards at these 6 locations was 0.86, indicating that the extreme climate anomaly level exceeded 65% of the climate conditions in the same month. Conditions at the Nalong Zangbu branch fall under the category of extreme precipitation, indicating that the extreme precipitation in the outburst year was higher than that in 83% of previous years. A comparison of climatic conditions in each month did not reveal any clear patterns of extreme precipitation; however, this outcome could be due to an increase in extreme precipitation events in outburst months compared with previous periods. The extreme precipitation deviated from the mean climate conditions by 0.89 in the outburst months, suggesting that the disaster site was strongly impacted by short-term extreme weather.

The climatic conditions in the Bange Co and Guangxie Co outburst months were analyzed. The temperature and precipitation levels in the Bange Co outburst month were higher than in the 9 years before the GLOF hazards. Additionally, the temperature deviation degree was 0.77 in the Bange Co outburst month, and the precipitation deviation degree was 0.67 in the outburst month. Furthermore, the combined effects of temperature and precipitation were the main factors leading to the GLOF hazards.

The precipitation conditions in the outburst month were unclear, but the temperature was higher than in the 9 years before the GLOF hazards, with a deviation degree of 0.83, suggesting that the persistently high temperature led to an increase in the instability of the glacier, thus leading to GLOF hazards.

We also analyzed the correlation between the extreme temperature index and annual accumulated temperature and the extreme precipitation index and annual precipitation in Guangxie Co and Tsho Ga. It may be seen that there is a positive correlation between the extreme temperature index and average annual heat and between the extreme precipitation index and precipitation in the region in Guangxie Co (Figure 6a,b). The extreme temperature index is positively correlated with the annual mean accumulated temperature, while the extreme precipitation index is negatively correlated with the total precipitation before the

glacial lake outburst in Tsho Ga (Figure 6c,d). This outcome indicates that heat accumulation in the early stage has a great effect on the outburst of Tsho Ga, while the precipitation factor has a low effect.

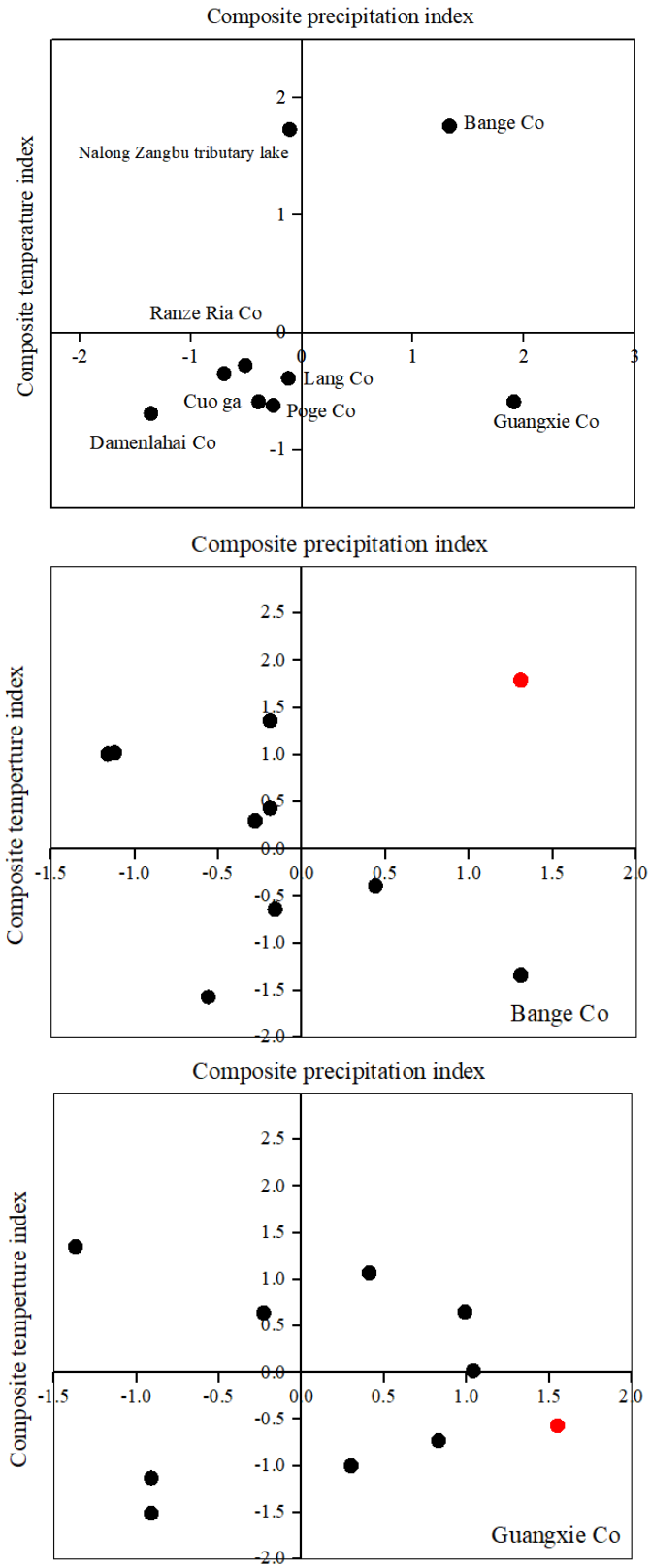


Figure 5. Three categories of climate conditions in outburst months (red dots represents the composite index).

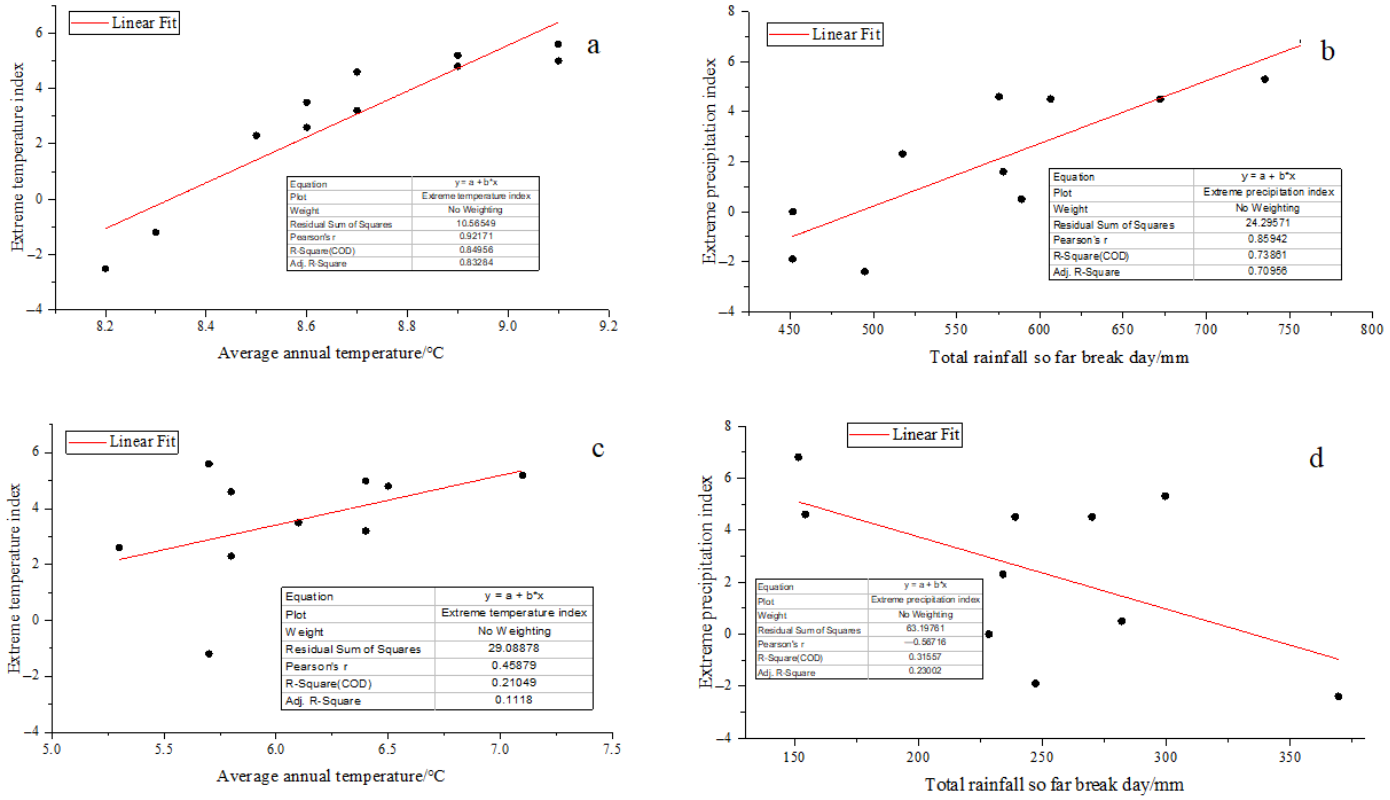


Figure 6. Correlation between the extreme temperature index and annual accumulated temperature and the extreme precipitation index and annual precipitation. ((**a**,**b**): represent the extreme temperature index and annual accumulated temperature and the extreme precipitation index and annual precipitation in Guangxie Co; (**c**,**d**): represent the extreme temperature index and annual accumulated temperature and the extreme precipitation index and annual precipitation in Tsho Ga).

4. Discussion

Several factors can influence GLOF hazards, including the glacial lake accumulation area, the thickness of a glacier, the size and capacity of the glacial lake, the structure and stability of lake levees, temperature, and precipitation. Among them, temperature and precipitation change the most and are some of the excitation factors behind glacial lake outbursts [44].

Meteorological conditions that lead to a GLOF hazard usually manifest from either slow accumulation or rapid excitation. The slow accumulation process is mainly affected by persistently high temperatures and precipitation levels and can be divided into two categories: (1) High temperatures, which melt ice and snow, and high precipitation levels, which mean enhanced water from rainfall, elevate the amount of glacial lake water and consequently increase dam pressure, possibly damaging a dam or causing an overflow. (2) High temperatures increase the ablation of buried ice inside a moraine, which leads to dam seepage and possible pipe failure. The other manifestation, namely rapid excitation, occurs as a result of extreme temperature and precipitation events. When temperatures are extremely high, large amounts of ice and snow melt, causing concentrated meltwater to form on the glacier tongue. This meltwater seeps down through cracks and lubricates the bottom bed. When the viscosity of the glacier tongue has sufficiently decreased (i.e., the friction between the glacier, the bottom bed, and the ice wall is reduced to less than the shear downward stress of the glacier tongue), the glacier tongue is thrown into a lake, rapidly increasing the water level of the lake. The resulting swells and shockwaves can damage the terminal moraine, resulting in a GLOF hazard [39].

Because of its monsoon climate, the Tibet Plateau has higher summer temperatures and more rainfall than other regions. From 1960 to 2019, the annual mean precipitation in

southeastern Tibet was 629.28 mm, approximately 20% higher than in the Qinghai–Tibet Plateau and the Three-River Headwaters Region and 3 times higher than in the western Qiangtang region, which is the driest in the plateau [45]. Increased temperatures in summer lead to enhanced volumes of meltwater, which increase glacial lake water levels and can result in an overflow. Therefore, heavy precipitation in summer is a leading cause of elevated glacial lake water levels.

Researchers have long recognized that the hydrothermal combination of climate change plays a key role in GLOF hazards [46]. In the third section, we demonstrated that GLOF hazards at the Guangxe Co glacier (in 1988) and at the Tsho Ga glacier were caused by persistently high temperatures and latent early-stage erosion of the glacier as meltwater. Moreover, the GLOF hazards at the Nalong Zangbu branch glacier were caused by early, persistent precipitation. Several researchers have noted that the mean daily temperature during GLOF hazards in Tibet is higher than 0 °C and that the higher the elevation of the GLOF hazards, the later the outburst time [28,47].

Global climate change has a direct influence on GLOF hazards. A wet and cold climate is conducive to the accumulation and advancement of glaciers, whereas a hot and dry climate causes the melting, thinning, and shrinking of glaciers, often leading to an increase in the number and size of glacial lakes [48]. In the early 1960s, especially 1960–1963, the emergence of La Niña events changed the circulation of cyclones at 700 hPa over the Indochina Peninsula, causing updrafts, increased humidity, and increased precipitation in Tibet and reduced temperatures compared with the same period in previous years [49]. During this period, several glaciers on the TP accumulated and advanced. After the 1980s, with the increasing number of El Niño events, the climate shifted from wet and cold to wet and hot or dry and hot. When summer El Niño events began to occur, precipitation levels in parts of the northern front and southern edge of Tibet were close to or slightly higher than the annual mean. Higher temperatures and levels of precipitation increase meltwater from ice and snow and enhance glacier activity, which increases the likelihood of GLOF hazards. In the 1980s, 7 GLOFs occurred in northern Tibet and the upper Himalayas, accounting for 60% of total GLOFs (Tables 1 and 2). Therefore, the occurrence of GLOF hazards is associated with abrupt climatic fluctuations.

GLOF hazards are less common than climatic fluctuations. Nevertheless, a critical threshold risk of a GLOF can be determined. The threshold can be devised by taking one or more temperature and rainfall indexes as variables, even though a certain temperature and rainfall index value may not necessarily predict a GLOF. A GLOF warning model based on climatic conditions may be developed in future studies.

It is noteworthy that temperature and precipitation are considered motivating factors rather than definitive direct causes of GLOFs. Glacial lakes across various regions may exhibit distinct outburst risk profiles, influenced by regional attributes including geographical positioning, topography, and climatic conditions. Hence, a singular predictive model may not be universally adaptable across all regions.

Future research should not only consider meteorological factors but also other elements, such as environmental factors, to establish a comprehensive evaluation index. Additionally, the development and refinement of climate models could be pursued to improve the simulation of small-scale and localized climatic conditions, thereby enhancing the predictive capabilities of the risks associated with glacial lake outbursts.

5. Conclusions

Glacial lake outbursts not only have a significant impact on downstream areas, especially on major engineering facilities, but can also cause a sharp rise in river levels downstream, leading to flooding and damage to residential areas, farmland, and infrastructure along the river. Simultaneously, a large amount of sediment and gravel carried by the flood may accumulate in a reservoir, affecting the normal operation of a hydropower station and reducing power generation efficiency.

A total of 37 GLOF hazards were analyzed. Among these, 19 (51%) occurred in El Niño (warm) years, 8 (22%) occurred in La Niña (cold) years, and 3 (8%) occurred in cold/warm or warm/cold transition years. The numbers of GLOF hazards in 1960–1970, 1980–1990, and 2000–2020 were higher than average.

A total of 25 GLOFs occurred between May and September. The climatic conditions in outburst months are more apparent than those in outburst years. Further, precipitation levels in the outburst months in which 11 GLOFs occurred were lower than in outburst years, and temperatures were 0.2–2.5 °C higher than in outburst years. Precipitation levels in the outburst months in which 7 GLOFs occurred were higher than average, whereas temperatures were lower than average. Precipitation levels in the outburst months of four GLOF hazards were higher than in the outburst years, and temperatures were higher than in the outburst years.

Climatic conditions during GLOF hazards can be divided into three categories: extreme temperature and precipitation, as represented by the Guangxie Co glacier; extreme precipitation, as represented by the Poge Co glacier; and extreme temperature, as represented by the Tsho Ga glacier.

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