Meteorological factors driving glacial till variation and the associated periglacial debris flows in Tianmo Valley, southeast Tibetan Plateau

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Abstract: Meteorological studies have indicated that high alpine environments are strongly affected by climate warming, and periglacial debris flows are frequent in deglaciated regions. The combination of rainfall and air temperature controls the initiation of periglacial debris flows, and the addition of meltwater due to higher air temperatures enhances the complexity of the triggering mechanism compared to that of storm-induced debris flows. On the southeastern Tibetan Plateau, where temperate glaciers are widely distributed, numerous periglacial debris flows have occurred over the past 100 years, but none occurred in the Tianmo watershed until 2007. In 2007 and 2010, three large-scale debris flows occurred in the Tianmo Valley. In this study, these three debris flow events were chosen to analyse the impacts of the annual meteorological conditions, including the antecedent air temperature and meteorological triggers. The remote sensing images and field measurements of the adjacent glacier suggested that sharp glacier retreats occurred in the one to two years preceding the events, which coincided with spikes in the mean annual air temperature. Glacial till changes providing enough active sediment driven by a prolonged increase in the air temperature are a prerequisite of periglacial debris flows. Different factors can trigger periglacial debris flows, and they may include high intensity rainfall, as in the first and third debris flows, or continuous, long-term increases in air temperature, as in the second debris flow event.

Key words: glacial till variation; meteorological factors; periglacial debris flows; southeast Tibetan Plateau

1. Introduction

Alpine environments are vulnerable to climate changes, and alpine glaciers and permafrost are the most sensitive to degradation (Harris et al., 2009; IPCC, 2013). Glacier and permafrost retreat can induce mass movements such as landslides, shallow slides, debris slides, moraine collapses, etc. (Cruden and Hu, 1993; Korup and Clague, 2009; McColl, 2012; Stoffel and Huggel, 2012; Fischer et al., 2012). These movements would bring the material out of the watersheds in the form of debris flows or sediment fluxes. Debris flows in alpine regions often bury residential areas, cut off main roads, block rivers (Shang et al., 2003; Cheng et al., 2005; Deng et al., 2013) and destroy basic facilities downstream; thus, they pose a considerable threat to the local economy and social development. In undeveloped alpine areas where the transportation system is particularly poor or limited, such as in southeastern Tibet, the negative effects produced by debris flows, such as cutting off main roads, can be serious (Cheng et al., 2005).

Periglacial debris flows occur in high alpine areas with large areas of glaciers, such as on the Tibetan Plateau in China (Shang et al., 2003; Ge et al., 2014), in the Alps in Europe (Sattler et al., 2011; Stoffel and Huggel, 2012), in the Caucasus Mountains in Russia (Evans et al., 2009) and in northern Canada (Lewkowicz and Harris, 2005). Periglacial debris flows can be initiated by rainfall (Stoffel et al., 2011; Schneuwly-Bollschweiler and Stoffel, 2012), glacial meltwater flow or ice particle ablation (Arenson and Springman, 2005; Decaulne et al., 2005) or outburst floods from glacier lakes (Chiarle et al., 2007) in different parts of the world; however, multiple triggers of a single event have rarely been studied. Because debris flows are commonly triggered by rainfall (Sassa and Wang, 2005; Decaulne et al., 2007; Kean et al., 2013; Takahashi, 2014), the rainfall threshold, intensity and duration have been widely used for debris flow monitoring and to provide event warnings in non-glacier areas (Guzzetti et al., 2008).

In deglaciated areas, the debris flow threshold can be more difficult to determine. Periglacial debris flows tend to occur in the summer when the thawing of glaciers and glacial tills predominates and meltwater penetrates the glacial tills at a constant and successive flow rate. The effect of meltwater is similar to that of antecedent rainfall (Rahardjo et al., 2008) and is variable in different periods, considering snow and glacier shrinkage and air temperature fluctuations. In the Swiss Alps, the meltwater volume is high in early summer, and debris flows can be initiated by low intensity rainfall. However, larger rainstorms are required to produce debris flows in late summer and early autumn when the meltwater volume is low (Stoffel et al., 2011; Schneuwly-Bollschweiler and Stoffel, 2012). On the southeastern Tibetan Plateau, the rainfall threshold given by Chen et al. (2011) is relatively wide (0.2~2.0 mm/10min, 0.6~6.3 mm/h or 3.0~19.4 mm/24h), the small rainfall threshold of which is likely affected by the air temperature. Moreover, periglacial debris flows induced by sudden releases of water from glacier lakes are closely related to increasing air temperature (Liu et al., 2014).

Air temperature fluctuations are likely important triggers of periglacial debris flows. Compared to storm-induced debris flows, the addition of meltwater due to increased air temperature can greatly enhance the complexity of the initiation mechanism of periglacial debris flows. It is difficult to simulate the triggering process via experiments or mathematical simulation; thus, case studies of natural debris flows must be explored. In this study, three debris flow events in the Tianmo watershed on the southeastern Tibetan Plateau are used as examples after a debris flow-free period of nearly 100 years as deglaciation continues. The annual meteorological conditions, antecedent air temperature and triggering conditions prior to debris flows are analysed to further understand the meteorological triggers and their roles in glacier retreat, glacial till variation and debris flow initiation.

2. Background

(1) Study area

Temperate glaciers on the Tibetan Plateau are primarily distributed in the Parlung Zangbo Basin, and they covered a total landmass of 2381.47 km^2 in 2010 based on TM images (taken by the No. 4 or 5 thematic mappers on the Landsat satellite with a spatial resolution of 30 m) (Liu, 2013). Historically, the movement of temperate glaciers has produced numerous moraines, the depth of which can reach 500 m locally (Yuan et al., 2012). In recent decades, a significant temperature increase has occurred, and the temperature at the Bomi meteorological station (central Parlung Zangbo Basin) increased by 0.23°C/10a from 1969 to 2007, resulting in remarkable glacial shrinkage (Yang et al., 2010).

Tianmo Valley, which is located in Bomi County and to the south of the Parlung

Zangbo River, covers an area of 17.76 km^2 (29°59’N/95°19’E; Figure 1). This valley has a northeast-southeast orientation and is surrounded by high mountains reaching 5590 m a.s.l. at the southernmost location and 2460 m a.s.l. at the fork in the Parlung Zangbo River. The TM image from 2013 illustrated the presence of a hanging glacier with an area of 1.42 km^2 in the upper concave area at an elevation of 4246 m to 4934 m. Bare rock, dipping at an angle of approximately 60°, emerges below and above the hanging glacier and is often covered by snow. Below 3800 m a.s.l., vegetation, including forest and shrubs, occupies most of the area (Table 1).

The river channel in the watershed is sheltered by shade and not directly affected by sunlight, resulting in less solar radiation and a location at which a small trough glacier can form. In the main channel, the trough glacier extended to 2966 m a.s.l. in 2006. The lower part of the trough glacier has been eroded by glacier meltwater flow, and an arch glacier that is vulnerable to high pressure was formed (Figure 2). The remnants of the landslide deposits are approximately 10 metres high can be observed on both sides of the channel. These deposits consist of low-stability sediment and can be easily entrained by debris flows.

Tianmo Valley is located on the north side of the bend in the Yarlung Zangbo River and is strongly affected by new tectonic movement. An inferred normal fault vertical to the channel cuts through the valley and is only 30 km from the Yarlung Zangbo fault. In 1950, a rather significant earthquake (Ms. 8.6) hit Zayu, which is only 200 km away, and local records reported that a large amount of rock collapsed and landslides were produced at that time. The whole valley is located in a strong ductile deformation zone and is dominated by gneissic lithology belonging to a Presinian System.

(2) Disaster history

According to our field interviews with local residents, there were no debris flows in the approximately 100 years prior to 2007 in Tianmo Valley. The channel was relatively narrow before 2007, and the local people could walk across via a wooden bridge to live and farm on the terrace on the west side. On the morning of September

4th, 2007, a rainfall even hit this area and it ceased around 7:00. On the evening of approximately 18:00, the local forest guard heard a loud noise coming from the upstream area and .rainfall later began in the upstream area at approximately 19:00. Then, debris flows occurred in the Tianmo Channel after the second rainfall event, and they subsequently blocked the Parlung Zangbo River. It is told by the local citizen that several debris flows occurred during that entire night while we cannot separate them according to the field measurements, and approximately 1,340,000 m^3 of sediment was transported during this event, resulting in 8 missing persons and deaths. This debris flow event is listed as DF1 in this paper, which contained the first debris flows and the following waves. Concurrently, debris flows occurred in the four adjacent 4 valleys (Table 2). According to the size classification proposed by Jakob (2005), which is based on the total volume, peak discharge and inundated area, the size classes of the debris flows in the five valleys are given in Table 2.

At 11:30 on July 25th, 2010, debris flows were again triggered in Tianmo Valley that traced the path of the preceding debris flow deposits and reached the other side of the Parlung Zangbo River. According to Ge et al. (2014), a solid sediment mass of approximately 500,000 m^3 was carried to (Table 1) and deposited in the channel and blocked the main river. A barrier lake was formed, and the rising water destroyed the roadbed of G318. Dozens of small-magnitude debris flows occurred in the following week. This debris flow event is listed as DF2 in this paper and it contained several waves.

Debris flows occurred again two months later on Sep. 6th (The Ministry of Land and Resources P. R. C., 2010), although we could not determine the exact time sequence of the events. According to speculation, the debris flows could have occurred in the early morning before dawn when the rainfall intensity reached its maximum (Figure 9). This theory agrees with the findings of Chen (1991), who found that periglacial debris flows historically occurred between 18:00~24:00 in this area. The debris barrier in the main river was consequently increased by an additional 450,000 m^3, and the barrier lake was enlarged to hold 9,000,000 m^3 of water. This debris flow event is listed as DF3 in this paper and waves of which cannot be determined.

A field investigation revealed that a high percentage of boulders in the downstream area and glacial tills above the trough glacier are loose and high porosity rocks (Figure 2); hence, they have low density and can be easily entrained. Our particle size tests of the glacial tills and debris flow deposits indicate a low clay (d<0.005 mm) content, whereas the debris flow deposits contain more fine particles that are smaller than 10 mm (Figure 4), suggesting that entrainment accounted for a considerable amount of fine particles.

(3) Meteorological data

The study area is located in a high alpine area where the economy is relatively undeveloped and few meteorological stations exist. Before 2011, the Bomi meteorological station (established in 1955) was the only station in the area. It is located 54 km from Tianmo Valley at an elevation of 2730 m, and other stations were located more than 200 km away.

The Tibetan Plateau is a massive terrace that obstructs the Indian monsoon, causing it to travel through the Yarlung Zangbo Canyon and its tributaries. As the Indian monsoon is transported to higher altitudes, a rainfall gradient emerges in the Parlung Zangbo Basin. However, according to the rainfall data from the area, rainfall often exhibits a similar intensity as that of the long-term rainfall process from Guxiang to Songzong, which suggests that a large rainfall gradient does not exist between Tianmo Valley and Bomi meteorological station; therefore, the rainfall data from Bomi meteorological station could be used in our study. To conduct additional studies, another meteorological station was built in 2011 near Tianmo Valley.

It has been established that the air temperature decreases with altitude; therefore, the air temperature in the source area of Tianmo Valley is lower than that in Bomi County. According to the research by Li and Xie (2006), the air temperature decreases at a rate of 0.46~0.69°C/100 m over the entire Tibetan Plateau, and the rate in the study area is 0.54°C/100 m. Because the glacier and permafrost in the source area have planar distributions, the air temperature at the geometric centre of the glacier and permafrost can be used to analyse the temperature process.

3. Analysis and results

(1) Air temperature and rainfall changes

The mean annual air temperature is generally used to reflect the trends of glacier change (Yang et al., 2015). We collected mean annual air temperature and annual rainfall data from 1970 to 2014 from the Bomi meteorological station (Figure 5). The records showed that the mean air temperature has increased by approximately 1.5 °C over the past 45 years at a rate of 0.033 °C/a. This air temperature increase was particularly rapid between 2005 and 2007 at approximately 0.7 °C/3a, which is 7 times the average value over the past 45 years. However, the annual rainfall from 2000 to 2010 was low and estimated as 828.2 mm per year. From 2000 to 2004, the rainfall during summer (July to September) accounted for approximately 50% of the total annual rainfall; however, only 32% of the rainfall occurred in the summer of 2005~2006, even though the annual rainfall exhibited a similar trend. In 2007, rainfall in the summer and the entire year returned to the mean rainfall state.

Figure 5 shows similar air temperature and rainfall trends before DF2 and DF3. The air temperature increased in 2009 and reached 10.2 °C which is the maximum of the past 45 years; however, the annual rainfall went down to only 65% of the average amount; and the summer rainfall reached a minimum value. In 2010, rainfall was abundant, and the annual rainfall increased to 1080.6 mm, which is approximately 30% more than the average value and close to the maximum.

The following common traits can be identified by comparing the annual meteorological conditions of DF1, DF2 and DF3: 1) one or two years before the debris flows, the mean annual temperature increased and the annual rainfall and summer rainfall decreased. Additionally, the climate was in a "hot-dry" state; 2) As the temperature gradually decreased, the annual rainfall returned to normal or increased, and a "hot-wet" climate state contributed to debris flow initiation (Lu and Li, 1989).

(2) Changing of glacier in Tianmo Valley

In our study, remote images were collected to analyse the glacier changes in the source area in recent years. To eliminate the effect of snow cover, images were taken in the thawing seasons when snow cover is limited, enabling easy detection of glaciers and snow. Moreover, an image taken on a bright, cloudless day is still needed to show the watershed clearly; however, a difficult case is encountered when the rainy season begins during the thawing season, as the atmosphere is often covered by thick clouds. Furthermore, to illustrate glacier retreat and its impact on debris flows properly, the images should be within similar time intervals, such as 3 years, before and after debris flow events. High-resolution images are rare, and we could only collect one SPOT image (taken by the Systeme Probatoired' Observation de la Terre satellite with a spatial resolution of 5 m) in 2008. To achieve image consistency, we collected 5 TM images taken on September 17th, 2000, July 24th, 2003, September 21st, 2006, September 24th, 2009 and August 4th, 2013.

Based on the 5 TM images, we classified the area as glacier, snow, bare land, gully deposit and vegetation in time series (Figure 6), and the area of each is given in Table 1. Figure 6 shows that deglaciation occurred in Tianmo Valley; notably, the eastern branch has experienced considerable deglaciation. To clearly show the rapid rate of glacial retreat in the entire basin and eastern branch, a graph of retreat was plotted, as shown in Figure 7.

Figure 7 shows that the glacier in Tianmo Valley shrank from 2000 to 2013, with variable rates of glacier retreat. In 2000~2003, 2003~2006, 2006~2009 and 2009~2013, the glacier retreat rates in Tianmo Valley were 0.02, 0.06, 0.027 and 0.0075 km^2/a, respectively, and those of the eastern branch were 0.0033, 0.01, 0.008 and 0.002 km^2/a, respectively. According to the figure, the largest glacier retreat rate was observed in 2003~2006, followed by that in 2006~2009. The glacier area at the beginning should be noted to assess the rate of change of the glacier. The glacier retreat rate can be normalized, and the relative glacier retreat rate can be calculated based on this change in area.

The relative glacier retreat rates were 11.30, 35.09, 17.43 and 5.17 $10^{-3}km^2/a/km^2$ in 2000~2003, 2003~2006, 2006~2009 and 2009~2013, respectively; and the corresponding values were 20.83, 66.67, 66.67 and 20.83 $10^{-3}km^2/a/km^2$ for the eastern branch. The relative glacier retreat rate of the eastern branch decreased sharply between 2000 ~2013.

In this study, TM images over 3-year intervals were applied to obtain the mean glacier retreat rate. As glacier retreat rate in the 3 three years could be either high or low, field measurements of the nearby glacier were used to show the glacier retreat condition before debris flows occurred. Yang et al. (2015) conducted field measurements of the No.94 Glacier in the Parlung Zangbo Basin since 2006, and the field measurements suggest it had a negative balance from 2006~2010 (Figure 7). The negative balance reached a maximum level in 2009, followed by 2008 and 2006, indicating rapid deglaciation in these three years.

When we combined the results of the TM image analysis and field measurements of the No. 94 Glacier, we observed that the glacier in Tianmo Valley experienced the most rapid deglaciation prior to debris flows in 2006, 2008 and 2009, which coincided with an increase in the mean annual air temperature (Figure 5). Moreover, the maximum glacier retreat in 2009 was potentially related to the decline in snowfall in the preceding winter and early spring.

(3) Antecedent air temperature and rainfall

The air temperature in the source area can be obtained based on a vertical rate of decline (0.54 °C/100 m). Based on this method, the air temperature in the source area was 9.8 °C lower than that at the Bomi meteorological station. We collected the lowest temperature, the mean temperature and daily rainfall from June to September in 2007 and 2010 (Figure 8).

Figure 8 shows that the lowest air temperature was below 0 at the end of June 2007. At the beginning of July, the air temperature started to rise quickly, which continued until early September when DF1 occurred. This trend suggests that the high air temperatures in July and August contributed to DF1.

Additionally, the air temperature was high from early July to late August, and another high air temperature period was observed in early September. When DF2 occurred in late July, the air temperature had reached the maximum for that year, which suggests that the air temperature in early and mid-July was responsible for DF2. After DF2 occurred, the air temperature in August varied towards the conditions that caused DF3.

Antecedent air temperature fluctuations include the air temperature and the duration of variations. The air temperatures and durations before debris flows are variable and difficult to evaluate. The accumulation of positive air temperature is often used to analyse the effect of air temperature on glacier melting (Rango and Martinec, 1995) and can be expressed as follows:

$$T_{PT} = \sum_{i=-n}^{0} T_i (T_i > 0) \qquad (1)$$

where T_{PT} is positive air temperature accumulation (°C) and T_i is the average daily air temperature (only $T_i > 0$ is included).

Because air temperature is successive, it is difficult to determine the beginning of positive air temperature accumulation. Glacial tills can decrease the heat that penetrates into them, and the low air temperature is only observed in the upper thin layer. Moreover, freeze-thaw cycles exist when the lowest air temperature is less than 0°C. From this perspective, the beginning of positive air temperature accumulation is defined as the time at which the lowest air temperature exceeds 0°C for two or three successive days or since the last debris flow.

Based on the above method, we can deduce that positive air temperature accumulation began when the lowest air temperature exceeded 0°C for several successive days beginning on June 28th, 2007, June 9th, 2010, and July 26th, 2010, which correspond to DF1, DF2 and DF3, respectively. The duration and T_{PT} were calculated for each debris flow event. The results were 69 days and 517.9 °C, 47 days and 332.1 °C and 42 days and 320.4 °C (Figure 8) for DF1, DF2 and DF3, respectively. The results showed that T_{PT} for DF1 was much larger than the other two T_{PT} values, which coincides with the fact that there were no debris flows in the past dozens of years, and extraordinary external forces such as large T_{PT} are required to disrupt the long-term balance.

(4) Triggering conditions

Rainfall in a short can trigger debris flows while it cannot be triggered by a sole abrupt increase in air temperature as the continuous and limited nature of air temperature, instead, air temperature of longer term should be included. In our analysis, the rainfall over the three days preceding a debris flow event is given in Figure 9.

Before DF1, the air temperature was high, which continued through July and August. Notably, the T_{PT} reached 517.9°C. According to the local forest guard, an isolated convective storm occurred prior to DF1, although no rainfall was recorded at the Bomi meteorological station or in the downstream area at that time. In Figure 9, as the rainfall right before DF1 occurred was not recorded by the Bomi metrological station, we added approximately 5 mm/h of rainfall intensity (according to the description provided by the forest guard) before DF1 to account for the storm, which might not reflect the real rainfall process. We can therefore conclude that this isolated convective storm initiated DF1, while the long-term high air temperature trend paved the way for DF1. Considering a large deglaciated area, several other periglacial debris flows simultaneously occurred near Tianmo Valley (Deng et al., 2013), which suggests the advantageous meteorological conditions for debris flow initiation.

DF2 occurred when the air temperature reached a peak in 2010. The thaw season began in the middle of June, and T_{PT} reached 332.1 °C. On July 24th, one day before DF2, the air temperature reached a maximum value for that year. No rainfall event hit this area preceding DF2 according to the record of Bomi meteorological station, and the local citizens also observed no rain. The trigger of DF2 was likely the continuous percolation of meltwater due to the long-term increase in air temperature.

According to field interviews, several debris flows of small magnitude occurred before DF3. The air temperature decreased in late August but increased to another high value before DF3, and the T_{PT} reached 320.4 °C. Rainfall began 2 days prior to DF3 and lasted the entire day before DF3. According to the rainfall trend at the Bomi meteorological station, the rapid increase in rainfall intensity started 4 hours before DF3 and reached 3.8 mm/h, which was responsible for the initiation of DF3.

4. Discussion

In this study, we found that the triggering factors of the three debris flows were high air temperature and rainfall for DF1, high air temperature for DF2 and storm for DF3, respectively. When we analysed the dates and triggers of these events, various questions should be settled first: 1) why did debris flows not occur in 2006 or 2009 when deglaciation reached its peak and more ice meltwater was present; 2) why did DF1 and DF3 occur in September when the air temperature and volume of ice meltwater were decreasing; and 3) why there were no large-scale debris flows triggered by previous heavy storms. Based on our results, we believe that the impact of the water source on the magnitude and frequency of debris flows is relatively small, or more debris flows would form during the early larger storm; instead, the sediment source, including the associated magnitude and activity, may be the predominant control, as reported by Jakob et al. (2005), who noted that channel recharge is a prerequisite for debris flows. However, in most situations, we cannot reach the source area to detect the soil source, and high-tech remote sensing can only distinguish the boundary of the soil source. In the periglacial area where glacial till is often covered by glacier or everlasting snow, a change in the soil source would be highly difficult to detect. In this study, we combine the meteorological conditions and literature reports to discuss the likely variations in glacial tills before debris flows.

(1) Annual variations in glacial till

Climate warming is a global trend (IPCC, 2013), and the Tibetan Plateau, as the third pole, is no exception to climate change. According to our statistics, the air temperature in Bomi County has increased by 1.5 °C over the past 45 years (1970~2014). Glacier retreat induced by climate warming has been widely accepted, and recent research suggests that the weaker Indian monsoon could be another reason for such retreat (Yao et al., 2012). Glaciers are always located in concave ground areas and cover large volumes of glacial tills. Glacial pressure can generate normal stress vertical to the slope, which can strengthen the slope stability. The effect of glaciers on slope stability is called glacial debuttressing (Cossart et al., 2008). As deglaciation continues, the result could lead to the exposure of the frozen glacial tills (Figure 10 A to B) and smaller glacial debuttressing.

The retreats of glaciers and glacial tills due to climate warming are quite different. The newly formed bare glacial till is frozen with a high ice content. The cohesion of the ice particles creates a bare glacial till with high shearing strength and stability. Deglaciation is accompanied by the melting of internal ice particles, which can greatly enhance the activity. This process first occurred at the surface layer of glacial till, followed the layers below, resulting in enlargement of active debris. As the debris obstruct heat fluxes from penetrating into the layer below, so the melting rate of internal ice particles is quite slower than that of glacial retreat (Takeuchi et al., 2000), result into a strong heat gradient at the surface while limited in deep layers, which means the activity of the debris decline with depth and long term high air temperature is required to enhance the activity in a deeper layer. As the ablation rates is quite low, only the surface layer is highly active and the sediment is relatively limited. Therefore, no debris flows of large magnitude could occurred in 2006 and 2009 when glacier retreat reached a maximum while the active glacial till is restricted to the surface layer.

(2) Variation in glacial till on antecedent days

After the long, cold winter, glacial tills become frozen. If a regressive glacier does not recover in the winter, glacial tills are covered by snow. As the air temperature increases again, the surface snow melts first, followed by the internal ice particles.

The thawing of internal ice particles induces a series of changes in the glacial till, which include the following: 1) the thawing will break the bonds of ice particles and increase the instability between ice cracks (Ryzhkin and Petrenko, 1997; Davies et al., 2001); 2) the sharp air temperature fluctuations in high alpine, mountainous areas induce a repeated cycle of expansion and contraction in the glacial till that can destroy the mass structure to some extent; 3) the seepage of ice meltwater can transport fine-grained sediments that were formerly frozen in the ice matrix (Rist, 2007); and 4) the ice meltwater can result in a higher water content and pore water pressure (Christian et al., 2012). These changes in glacial till can sharply decrease the soil strength, shifting to an active mass from an uncovered and frozen moraine (Figure 10B to C). Because heat conduction in glacial till is relatively slow, this process may last for a very long time and require a high antecedent air temperature.

Heat conduction via the percolation of rainfall and ice meltwater can amplify the depth of active glacial till (Gruber and Haeberli, 2007), whereas covering the surface glacial till can hinder a heat flux from penetrating into the deep layers(Noetzli et al., 2007). At a low air temperature, the heat flux should be constrained to the surface layer, and a large heat gradient due to a high air temperature would contribute much more to the heat flux and ice melt in the deep mass. Thus, the long-term effect of a high air temperature can amplify the active glacial till (Noetzli et al., 2007; Åkerman and Johansson, 2008), under which lies frozen glacial till with a high ice content. The activity of glacial till varies with depth from high at the surface to low in the deep layers, and landslide failure can take place on glacial till slopes in a retrogressive manner, coinciding with long-term air temperature fluctuations, as active glacial till is relatively limited in deglaciated areas.

(3) Failure of glacial till

Different factors can lead to glacial till failure. Active glacial till slopes with low strength are usually vulnerable, and their failure can occur when the air temperature is above 0 °C (Arenson and Springman, 2005). Rainfall or ice melt water induced by air temperature can trigger the failure (Figure 10 C to D). This type of event is called a shallow landslide, and the failure mechanism lies in the ablation of internal ice particles and the percolation of meltwater, which can initially decrease the soil strength (Arenson and Springman, 2005; Decaulne et al., 2005). Later, the subsequent rapid percolation of ice meltwater or heavy rainfall can saturate the debris, decrease soil suction and shearing strength, and form seepage flows that can trigger the shallow landslide failure (Springman et al., 2003; Decaulne and Sæmundsson, 2007; Chiarle et al.,2007). Whether the failure can induce debris flows is still dependent on its ability to entrain the debris layer as the flow moves through the channel.

Another type of failure might take place when peaked runoff flows over and entrains debris deposits in the charged channel and reach a critical discharge (Berti and Simoni, 2005; Gregoretti and Dalla Fontana, 2008; Kean et al., 2012, 2013; Takahashi, 2014; Rengers et al., 2016, Gregoretti et al., 2016), which is more determined by channel bed slope and grain size of debris (Tognaccaet al., 2000; Gregoretti, 2000; Theule et al., 2012; Hurlimann et al., 2014; Degetto et al., 2015). This type of channelized runoff could be a combination of three factors: rainfall, melting ice or the overflow that forms when a glacier collapses downward into a water pool. Mechanism of this process lies in the hydrodynamic forces exerted on the surface elements of debris layers and surpassing sediment resistance (Gregoretti and Dalla Fontana, 2008; Recking et al., 2009; Prancevic et al., 2014). FaThe concentration of runoff in the channel bottom causes the erosion of the debris surface layer forming a solid-liquid current at first, then extends to the layers below with whole or partial mobilization and debris flows was generated (Gregoretti and Dalla Fontana, 2008). Therefore, debris flows initiated by landslide failure caused by seepage flow or channelized runoff that entrain sediments in the periglacial area is similar with the mechanism of debris flows initiation in non-glacier areas (Iverson et al., 1997; Springman et al., 2003; Sassa and Wang, 2005; Gregoretti and Dalla Fontana, 2008; Kean et al., 2013), while the difference lies in the activity of debris and the source of water. In the European Alps, periglacial debris flows are mainly provoked by rainfall, which is also related to air temperature fluxes (Stoffel et al.,2011). Additionally, the values of rainfall and air temperature required to trigger debris flows could be inversely correlated. Air temperature increases can cause melting and water runoff; thus, the rainfall required to create percolation flows or critical discharge to trigger a debris flow would be much less. In addition, the intensity and duration of the required rainfall may require other preconditions, such as those associated with the distributions of glaciers and frozen glacial tills and the terrain of the source area, to enhance the debris flow (Lewkowicz and Harris, 2005).

The three debris flow events were associated with similar annual meteorological conditions, except that the positive air temperature accumulation prior to DF1 was the largest. DF1 occurred at the end of a prolonged period of high air temperature, prior to this, there were instances of small failures but no large-scale debris flows. On July 25th, 2007, the daily rainfall reached 20.7 mm, while no debris flows were generated because the active glacial till is restricted in the shallow surface layer after a short term of air temperature increase.

In 2010, the largest daily rainfall occurred on June 7th, accounting for 37.5 mm, at the beginning of an air temperature increase when the glacial till was frozen with low activity. The lack of glacial till with high activity was the likely cause of the absence of debris flows. The similar situation could be found on August 23rd when the daily rainfall was 20.3 mm and the positive air temperature accumulation is low since DF2, which had produced quite limited active glacial till. Besides, a low and positive air temperature was observed prior to September 6th when DF3 occurred, the boundary of active glacial till had been enlarged before; moreover, the high rainfall intensity could supplemented this lack of prolonged high air temperature and trigger debris flows.

5. Conclusion

Climate changes have serious effects in high mountainous areas, and the mass movement of sediments such as periglacial debris flows has become increasingly frequent. Prolonged increases in the mean annual air temperature are regarded as very favourable for periglacial debris flows. In particular, the annual “hot-dry” weather conditions one or two years prior were responsible for three debris flow events in

Tianmo Valley. Debris flows are generally not initiated in the year when the mean annual air temperature spikes, as the melting of internal ice particles lags behind the rate of glacial retreat resulting from a prolonged increase in air temperature.

Glacial till is unlimited in deglaciated areas, and its activity relies on glacial retreat and internal ice particle melting. Glacial till changes induced by increased air temperature are the first steps in forming periglacial debris flows compared to storm-induced debris flows in non-glacier areas. Glacial tills require a four-phase process prior to debris flow occurrence. In this process, the variation in air temperature drives the glacial till change, including causing glacier recession, producing bare glacial till and enhancing the glacial till activity. Debris flows can occur when a sufficient amount of active glacial till exists and rainfall-induced seepage or runoff is more likely to generate debris flows.

It is difficult to observe glacial till changes in source areas of debris flows, and the analysis of the phase conversion of glacial till in this study is based on the triggering conditions and other literature findings. Indeed, the meteorological conditions, such as the antecedent air temperature and meteorological triggers that drive the phase conversion, are partly coupled and difficult to distinguish.

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Table 1 Changes in glacier, snow, bare land, gully deposition and vegetation in Tianmo Valley

Year	Glacier (km^2)	Glacier(eastern branch) (km^2)	Snow (km^2)	Bare land (km^2)	Gully deposition (km^2)	Vegetation (km^2)
2000	1.77	0.16	2.13	2.80	0.44	10.46
2003	1.71	0.15	2.44	2.54	0.44	10.48
2006	1.53	0.12	2.68	2.44	0.44	10.55
2009	1.45	0.096	2.81	3.03	0.47	9.90
2013	1.42	0.088	1.74	3.83	0.51	10.17

Table 2 Basic information regarding the debris flows in Tianmo Valley and nearby valleys

No.	Name	Coordinates	Basin area (km^2)	Glacier area (in 2006) (km^2)	Date	Size class
1	Tianmo Valley	29°59'N 95°19'E	17.74	1.53	4th Sep. 2007 25th Jul. 2010 6th Sep. 2010	6 5 5
2	Kangbu Valley	30°16'N 94°48'E	48.7	1.06	4th Sep. 2007	3
3	Xuewa Valley	29°57'N 95°23'E	33.22	0.95	4th Sep. 2007	2
4	Baka Valley	29°53'N 95°33'E	22.15	2.46	7th Sep. 2007	3
5	Jiaqing Valley	30°16'N 94°49'E	15.51	1.12	9th Sep. 2007	3

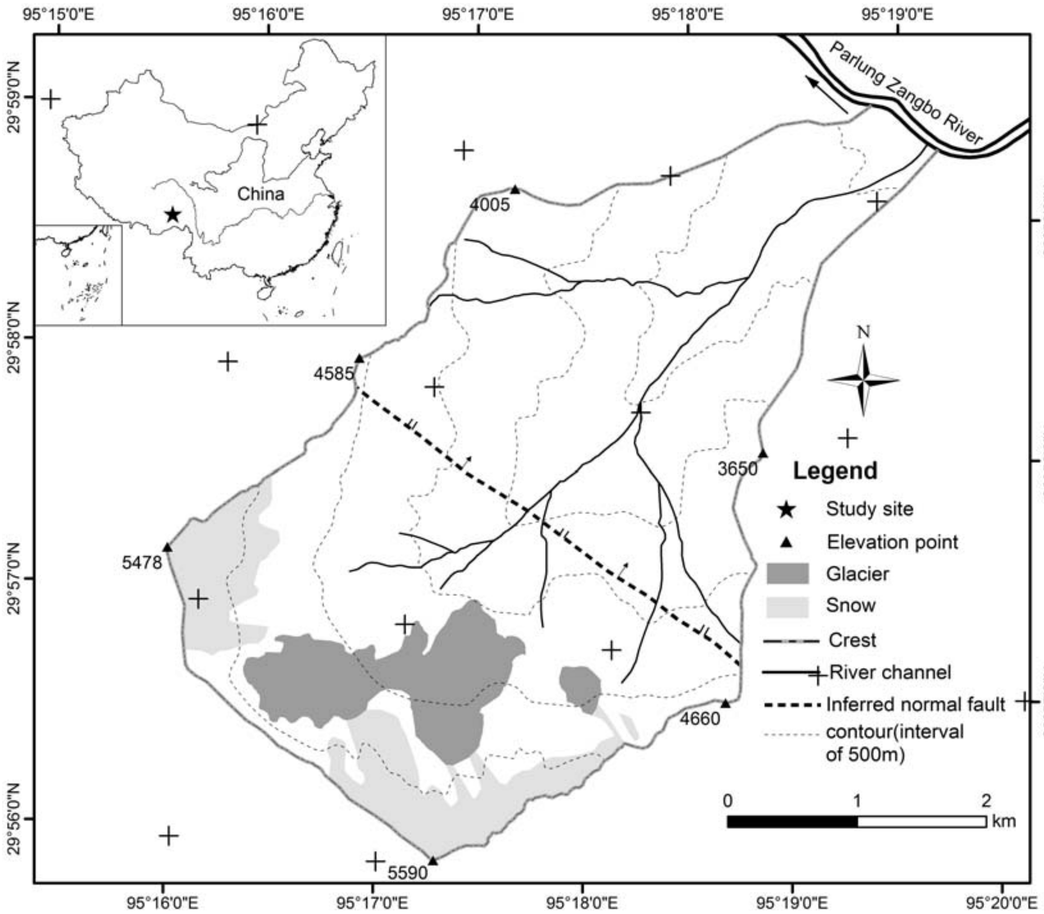

Figure 1 Location of Tianmo Valley and related information

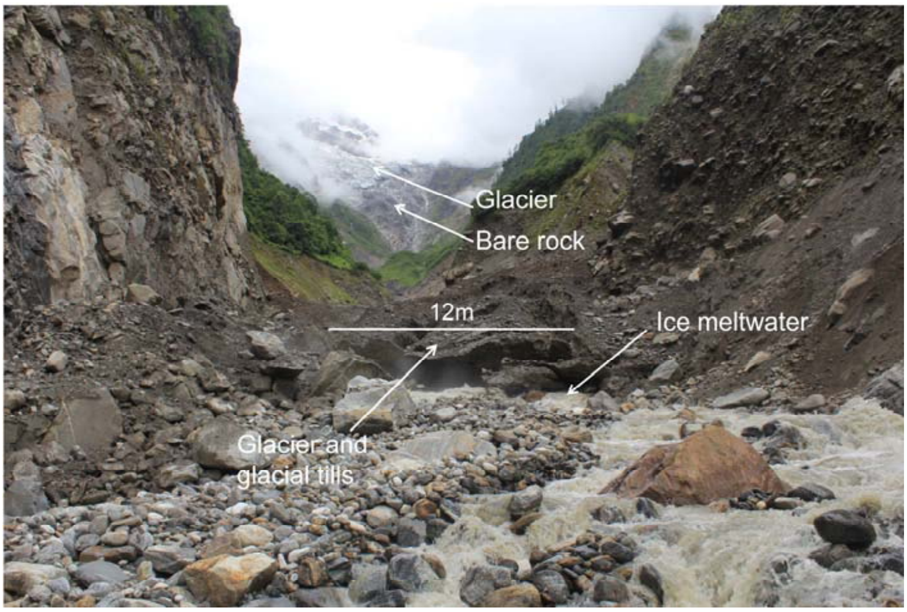

Figure 2 Overview of the valley from the channel(in 2014)

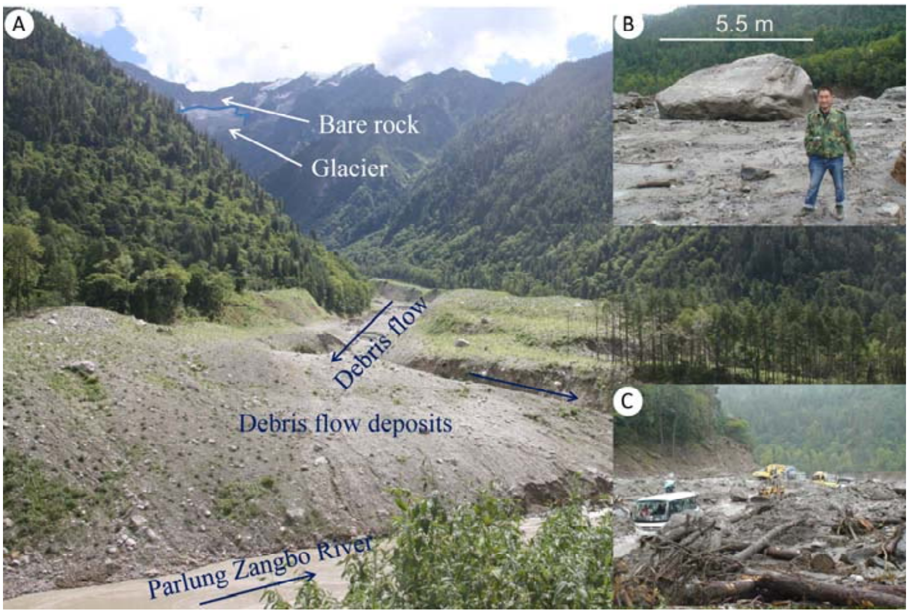

Figure 3 DF1 in 2007(A. Overview of the Tianmo debris flows from the downstream area; B& C. Boulder and debris flow deposits on the north side of the Parlung Zangbo River)

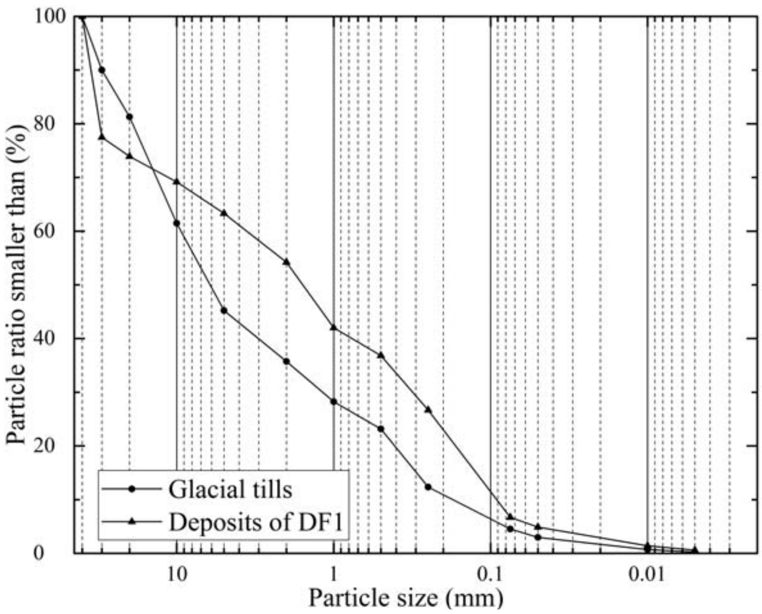

Figure 4 Particle size distributions of the glacial tills and debris flow deposits

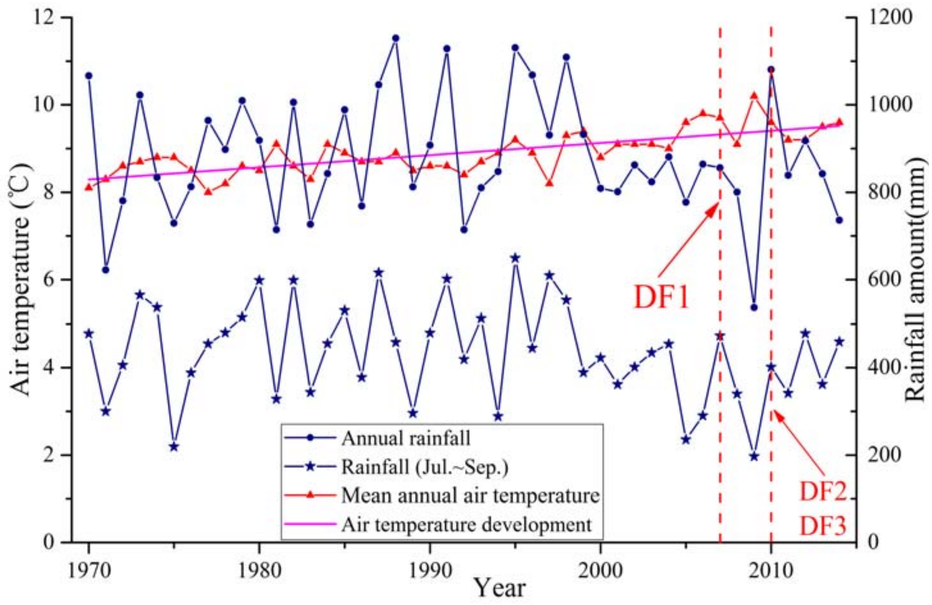

Figure 5 Variation in the mean annual air temperature and rainfall at Bomi from 1970 to 2014

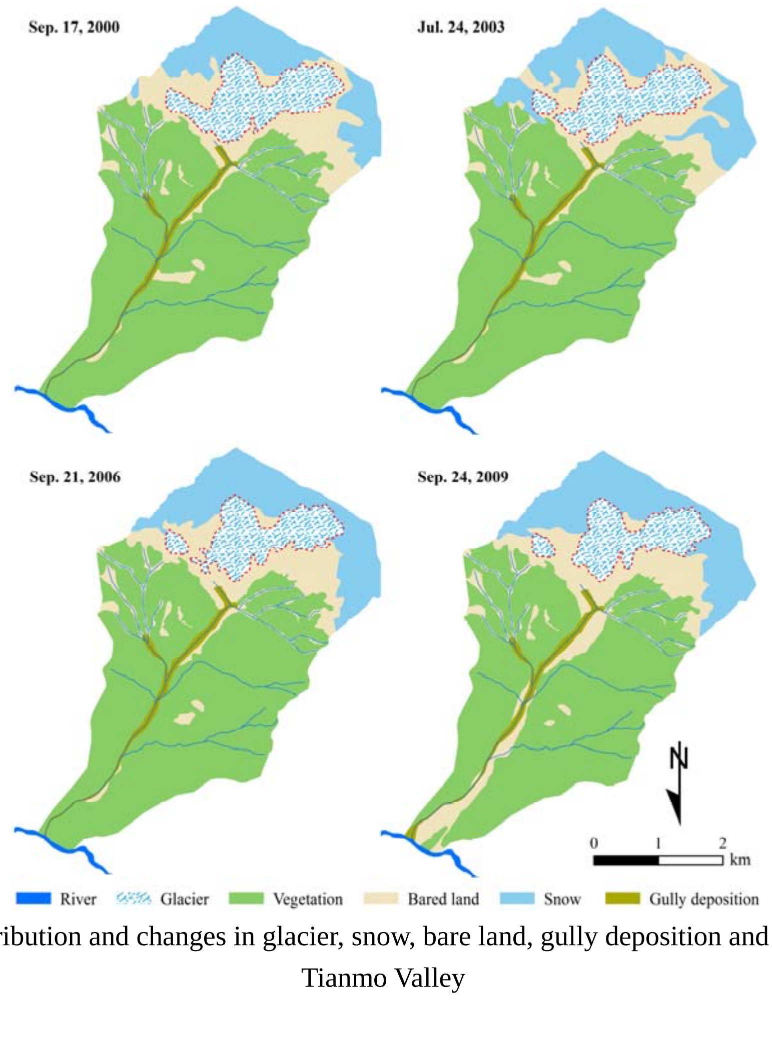

Figure 6 Distribution and changes in glacier, snow, bare land, gully deposition and vegetation in Tianmo Valley

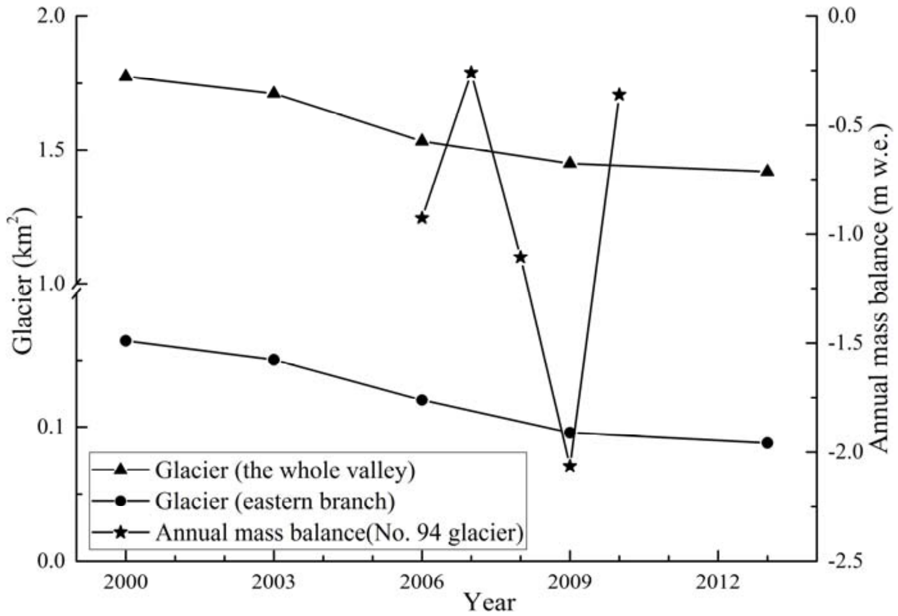

Figure 7 Changes in glacier over time and the measured annual mass balance of the Parlung No. 94 Glacier (mass balance was edited from Yang et al.(2015))

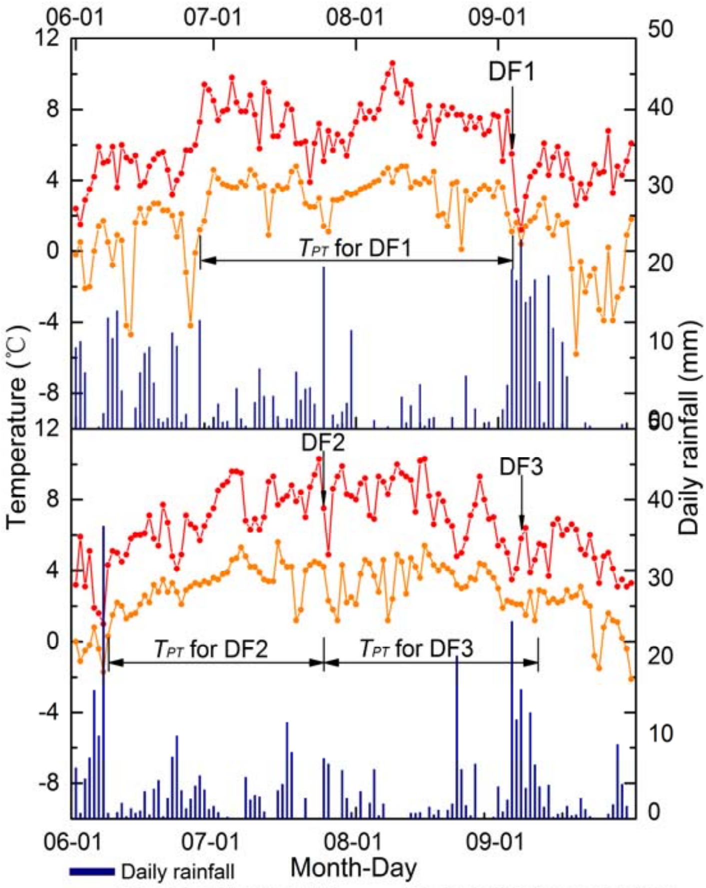

Figure 8 Air temperature and rainfall before and after DF1, DF2 and DF3

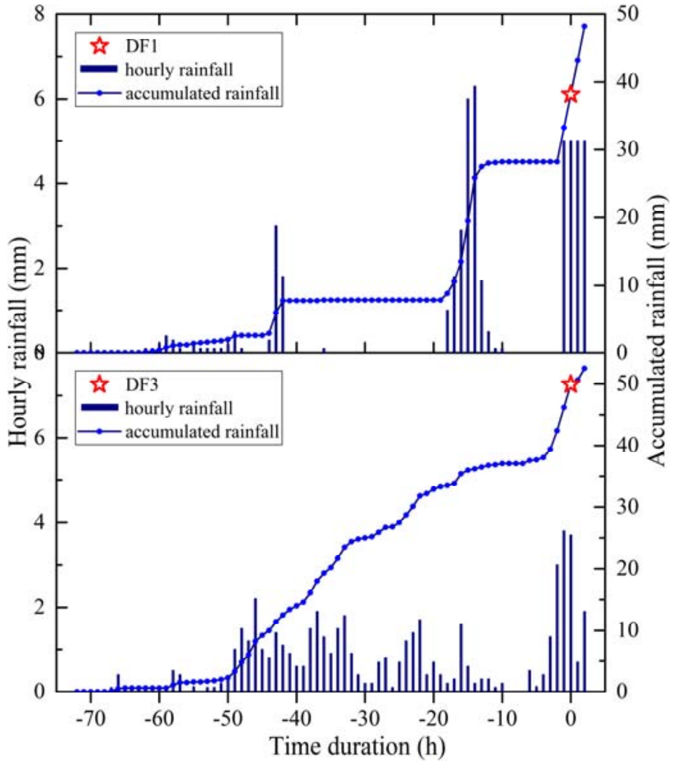

Figure 9 Variationsin rainfall accumulation prior to DF1 and DF3 (no rainfall before DF2)

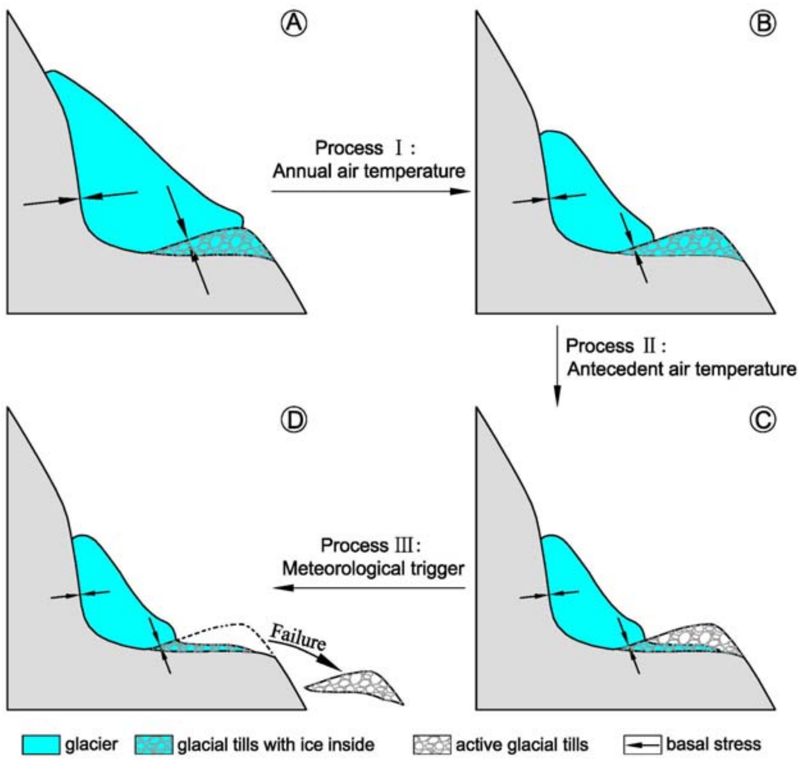

Figure 10 Changes in glacier and frozen glacial till before periglacial debris flow initiation(A: glacial-covered glacial tills; B: uncovered and frozen glacial tills; C: active glacial tills; D: failure of glacial tills)