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

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Abstract: Meteorological studies have indicated that high a~~A~~lpine environments~~s~~ are strongly affected by climate warming, and ~~.~~p~~P~~eriglacial 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 melt~~-~~water due to higher air temperatures enhances the complexity of the triggering mechanism compared to that of storm-induced debris flows. ~~In~~ On the south~~-~~eastern Tibetan Plateau, where temperate glaciers are widely distributed, numerous periglacial debris flows have occurred ~~in~~ over the past 100 years, but none ~~had happened~~occurred in the Tianmo watershed until 2007. In 2007 and 2010, three large-scale debris flows occurred in the Tianmo~~watershed~~Valley. In this ~~research~~study, these three debris flow events were chosen to ~~analyze~~ analyse the impacts of the annual meteorological conditions, including~~:~~ the antecedent air temperature and meteorological triggers. TM images and field measurements of thenearby glacier suggested that ~~a~~ sharp glacier retreats ~~had existed~~occurred in the ~~previous~~ one ~~or~~ to two years preceding the events, which coincided with ~~the~~ spikes in~~dm~~the mean annual air temperature~~.~~ ~~Besides,~~. Moreover, ~~changing of~~ glacial till changes~~s~~ driven by a prolonged increase in the air temperature ~~is~~ are ~~the~~ a prerequisite of periglacial debris flows. Different factors can trigger ~~The tTriggers of~~ periglacial debris flows ~~are multiplied often coupled~~, and they ~~could be~~may include high intensity rainfall, as in the first ~~debris flows~~ and ~~the~~ third debris flows, or continuous, long-term ~~rising~~ increases in air temperature,~~s~~ as in the second debris flow events.

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

1. Introduction

~~The~~ Alpine~~alpine~~ environments are ~~strongly~~ vulnerable to climate changes,~~of which the~~and alpine glaciers and permafrost are the most sensitive ~~in the form of glacier and permafrost~~to degradation (Harris et al., 2009; IPCC, 2013). Glacier and

批注 [A1]: Answer to reviewer #2: the three debris flows is of large magnitude while debris flows with small magnitude occurred followed each of the three debris flows; while debris flow with small magnitude is hard to be determined compared with the larger ones.

批注 [A2]: Answer to reviewer #2: Line 18 spikedm?? What is it?

批注 [A3]: Answer to reviewer #2: Triggers of periglacial debris flows are multiplied….What does it mean?

批注 [A4]: Answer to reviewer #2: as in the first and third debris flow is better than as in the first debris flows and third debris flows

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permafrost retreat can induce mass movements~~,~~ such as landslides, shallow slides, debris slides, moraine collapses, etc. (Cruden and Hu, 1993; Korup and Clague~~Korup~~, 2009; McColl, 2012; Stoffel and Huggel, 2012; Fischer et al., 2012). These movements~~,that will be expelled out of the~~ would bring the material out of the ~~expel material from~~ watersheds in the form of debris flows or sediment fluxes. ~~The D~~debris flowsin alpine ~~areas~~ regions ~~can~~ often bury residential areas, cut off main roads, ~~and~~ block rivers (Shang et al., 2003; Cheng et al., 2005; Deng et al., 2013) and destroy basic facilities ~~located in~~ downstream; thus, they ~~,posing a great~~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 ~~the~~ south-eastern Tibet, ~~where the transportation system is particularly poor or limited,~~ the negative effects produced by debris flows, such as cutting off main roads, ~~such as cutting off main roads are~~can be serious (Cheng et al., 2005).

Periglacial debris flows occur~~s~~ in~~the~~ high alpine areas ~~where there is~~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~~1~~ and Harris, 2005). Periglacial debris flows ~~were reported to be~~can be initiated by rainfall (Stoffel et al., 2011; Schneuwly-Bollschweiler and Stoffel, 2012), glacial melt-water flow ~~of glacier~~ 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, ~~, while the~~ multiple ~~-~~triggers of a single event have rarely been studied~~s for the case is rarely to be read~~. 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 ~~has~~ have been widely used for debris flow monitoring and ~~giving~~ to provide event warnings in non-glacier areas (Guzzetti et al., 2008).

In deglaciated~~ion~~ 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 melt-water penetrates ~~into~~ the glacial tills at

批注 **[A5]:** Answer to reviewer #2: that will be expelled out... what does it mean?

批注 **[A6]:** Answer to reviewer #2: occurs without s

批注 **[A7]:** Answer to reviewer #2: for the case is rarely to be read. What does it mean?

a constant and successive flow rate. The effect of melt-water ~~appears~~ 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 melt-water volume is high in early summer, ~~;~~ and ~~as~~ debris flows can be initiated by low ~~total~~ intensity ~~rainstorm~~rainfall. However, ~~,whereas higher total~~larger rainstorms are required to produce debris flows in late summer ~~or~~ and early autumn when the melt-water volume is low (Stoffel et al., 2011; Schneuwly-Bollschweiler and Stoffel, 2012). ~~In~~ On the south-eastern Tibetan Plateau, the rainfall threshold given by Chen et al.~~,~~ (2011) is ~~quite~~ relatively wide (0.2~2.0 mm/10min, 0.6~6.3 mm/h or 3.0~19.4 mm/24h), ~~and~~ the small rainfall threshold of which ~~in particular~~ is likely ~~to contain the effect of~~affected by the air temperature. Moreover, periglacial debris flows induced by ~~a~~ sudden releases of water from glacier lakes~~have a close relationship with~~are closely related~~the rising~~to increasing air temperature (Liu et al., 2014).

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

批注 **[A8]:** Answer to reviewer #2: the small rainfall threshold which is the reference of this?

批注 **[A9]:** Answer to reviewer #2: Lines 69-71 Confused text

2. Background

(1) Study area

~~The~~ T~~t~~emperate glaciers~~in~~ on the Tibetan Plateau ~~is~~ 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 mapperson the Landsatsatellite with a spatial resolution of 30 m) (Liu, 2013). Historically, the movement of temperate glaciers has produced ~~a large amount of~~numerous moraines, the depth of which can reach ~~up to~~ 500 m locally (Yuan et al., 2012). In recent decades, ~~there has been~~ a ~~dynamic~~ significant ~~increase in~~ temperature increase has occurred,and ~~according to statistics~~ the temperature at the Bomi meteorological station (~~midstream~~ central ~~in the~~ Parlung Zangbo Basin) ~~has rose~~ increased by 0.23°C/10a from 1969 to 2007, resulting in remarkable glacial shrinkage ~~of the glacier~~(Yang et al., 2010).

Tianmo Valley, which is located in Bomi County and to the south of the ParlungZangbo 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 ~~site~~ location and 2460 m a.s.l. at the ~~junction of~~fork in the ParlungZangbo River. The TM image ~~in~~ from 2013 ~~showed~~ illustrated the presence of a hanging glacier with an area of 1.42 km^2 in the upper concave area at an ~~altitude~~ elevation of 4246 m to 4934 m. Bare~~d~~ rock, dipping at an angle of ~~around 6~~approximately 60°, emerges~~ed~~ below and above the hanging glacier and is often covered by ~~everlasting~~ snow. Below 38~~0~~00~~m~~ 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 melt~~-~~water flow, and an arch glacier that is vulnerable to high pressure was formed (Figure 2). The remnants of the landslide deposits are approximately 10~~-meter~~ metres high can be observed on both sides of the channel. These deposits ~~,which~~ consist of low-stability sediment and can be easily entrained by debris flows~~, can be observed in both sides of the channel~~.

Tianmo Valley is located on the north side of the bend in the YarlungZangbo River and is strongly affected by ~~the~~ new tectonic movement. An inferred normal fault vertical to the channel cuts through the valley and is only 30 km ~~away~~ 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 ~~quite~~ 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~~th~~, 2007, after ~~the~~ a rainfall ~~which~~ even that did not hit the downstream area ceased, the local forest guard heard a loud noise coming from the upstream area at approximately 18:00.~~;with~~ R~~r~~ainfall ~~which~~ later began in the upstream area at approximately 19:00. Then,~~,following this rainfall was~~ debris flows ~~which rushed out of~~began to occur in the Tianmo Channel, and they subsequently blocked the Parlung Zangbo River. This debris flow event is listed as DF1 in this paper. It is told by the local citizen that several debris flows occurred during that entire night~~—and lasted,lasting the entire night~~ while we cannot separate them~~.~~ According to the field measurements, approximately 1,340,000 m^3 of sediment was transported during this event, resulting in 8 missing persons and deaths.~~.~~ Concurrently~~ within this same time~~, debris flows occurred in the four nearby 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 s~~S~~ize classes of the debris flows in the five valleys

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批注 [A10]: Answer to reviewer #2: Line 125-128 Sentence a bit confused.

批注 [A11]: Answer to reviewer #2: DF2 stand for the debris flows occurred on 19:00, September 4, 2007. The other debris flows took place in the nearby 4 valleys as in Table 2.

~~is~~ are given in Table 2. ~~The Tianmo Valley is debris flow events is listed as DF1 in this paper.~~

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 ParlungZangbo River. According to Ge et al.~~,~~ (2014), a solid ~~mass~~ sediment mass of approximately 500,000 m^3 was carried to ~~out~~ (Table 1) and deposited ~~on the con~~in the channel and blocked~~to block~~ the main river. A barrier lake was formed, and the rising water destroyed the roadbed of G318. ~~The following week also experienced~~ D~~d~~ozens of ~~debris flows in~~ small-magnitude debris flows occurred in the following week. This debris flow events~~s~~ is listed as DF2 in this paper.

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~~s~~ sequence of the events. ~~but a~~According to speculation, ~~these~~ the debris flows could have occurred in the early morning before dawn ~~and~~ when the rainfall intensity ~~has~~ reached its maximum (Figure 9). This theory~~, which~~ agrees with the findings of Chen (1991), who found that periglacial debris flows ~~have~~ 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 ~~maintain~~ 9,000,000 m^3 of water. This debris flow events~~s~~ is listed as DF3 in this paper.

A field investigation revealed that a high percentage of boulders in the downstream area and glacial tills above the trough glacier ~~were~~ are ~~quite~~ loose and ~~of~~ high porosity rocks (Figure 2); ~~,~~ hence, they have low density and can be easily entrained. Our particle size tests of~~n~~ the glacial tills and debris flow deposits indicate a low~~er~~ 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 ~~the~~ entrainment ~~supplied~~ 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 ~~quite~~ relatively undeveloped ~~with~~ and ~~only~~ few meteorological stations exist. Before 2011,

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批注 [A12]: Answer to reviewer #2: These debris flows or this debris flow?

the Bomi meteorological station (~~since~~ established in1955) was the only station in the area. It is~~,~~ located 54 km ~~away~~ from TianmoV~~v~~alley at an ~~altitude~~ 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~~altitudes, a rainfall gradient emerges in the Parlung Zangbo Basin. However, according to ~~our statistics on~~the rainfall data ~~in~~ from the area, ~~the~~ rainfall often ~~enjoys~~ exhibits ~~the~~ a similar intensity ~~for~~ as that of the long-term rainfall process from Guxiang to Songzong, which ~~means~~ suggests that ~~the there is no~~a large rainfall gradient does not exist between TianmoV~~v~~alley and Bomi meteorological station; therefore, the rainfall data from ~~the~~ Bomi meteorological station ~~can~~ could be used ~~for~~ in our study. ~~In order to~~To conduct ~~further~~ additional studies~~study~~, another meteorological station was built in 2011 near Tianmo Valley.

It has been established that the air temperature decreases with altitude~~; therefore~~ ; 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/1000~~m~~ m over the ~~whole~~ 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 ~~a~~ planar distributions, the air temperature at the geometric centre of the glacier and permafrost can be used to ~~analyze~~ analyse the temperature process.

3. Analysis and results

(1) ~~Changing of~~ A~~a~~ir temperature and rainfall changes

The mean annual air temperature is ~~usually~~ generally used to reflect the ~~tendency~~ trends of glacier change (Yang et al., 2015). We collected ~~the~~ 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 ~~in~~ over the ~~last~~ past 45 years at a rate of ~~,accounting for~~

批注 [A13]: Answer to reviewer #1: not really the right verb !

批注 [A14]: Answer to reviewer #2: please substitute can with could

0.033 °C/a. This air temperature increase was particularly ~~more~~ rapid between 2005 and ~~~~~2007 ~~,an~~ at approximately 0.7 °C/3a, which is 7 times the average value ~~of~~ over the ~~last~~ past 45 years. ~~On the other hand~~However, the annual rainfall from 2000 to 2010 was low and~~it was~~ estimated ~~at~~ 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 ~~the~~ a ~~same~~ similar trend. In 2007, rainfall in the summer and the entire year returned to the mean rainfall state.

~~According to~~ Figure 5 shows~~,a~~ similar ~~trend in the~~ air temperature and rainfall ~~was observed~~trends before DF2 and DF3. The air temperature ~~elevated~~ increased in 2009 ~~to reach~~and reached the maximum temperature over ~~of~~ the ~~last~~ past 45 years ~~period~~ of ~~,accounting for~~ 10.2 °C; however, the annual rainfall~~,~~ was only 65% of the average amount; and the summer rainfall, which was~~,~~ lower than that in 2005 and 2006, reached ~~their~~ a minimum value~~s~~. In 2010, ~~the~~ 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 ~~from~~ by comparing the annual meteorological conditions of DF1, DF2 and DF3:~~.~~ 1) o~~O~~ne or two years before the debris flows, the mean annual temperature ~~elevated~~ increased and the annual rainfall and summer rainfall ~~declined~~decreased. ~~The~~ Additionally, the climate was in a "hot-dry" state;~~.~~ 2) As the temperature gradually decreased, the annual rainfall returned to normal or increased, and ~~the~~ a "hot-wet" climate state contributed to debris flow initiation (Lu and Li, 1989).

(2) Changing of glacier in TianmoV~~v~~alley

In our ~~research~~study, remote images~~is~~ were collected to ~~analyze~~ analyse the ~~changing of~~ glacier changes in the source area ~~during the past~~in recent years. ~~In order to~~To eliminate the effect of snow cover, images were taken in the thawing seasons when ~~the~~ snow cover is limited, enabling ~~to enable an~~ easy detection of ~~the~~ glaciers ~~from~~ and snow~~. Besides,~~. Moreover, an image taken on a bright, cloudless day is still needed to show the watershed clearly~~; however ~~; however, a difficult case ~~ensues ~~is encountered when the rainy season ~~comes in-between~~begins during the thawing season, as~~when ~~the atmosphere is often covered by thick clouds. Furthermore, ~~in order toto~~to ~~show ~~illustrate glacier retreat and its impact on debris flows properly, the images should be within similar time intervals, ~~like ~~ such as 3 years, before and after debris flow events. ~~As the ~~H~~h~~igh-resolution images are rare, ~~to obtain ~~and we could only collect one SPOT image (ta~~Ta~~ken ~~b~~by the ~~satellite of ~~Systeme Probatoired'Observation de la Terre satellite with a ~~space ~~spatial resolution of 5~~5m~~ m) in 2008. To achieve ~~consistency of the ~~image consistency~~s~~, we collected 5 TM images ~~image ~~(t~~T~~aken by the No. 4 or 5 thematic mapper~~s~~ ~~carried ~~on the ~~satellite ~~Landsat satellite with a ~~space ~~spatial resolution of 30~~0m~~ m)~~,~~ taken on September~~.~~ 17th~~th~~, 2000, July~~.~~ 24th~~th~~, 2003, September~~.~~ 21st~~st~~, 2006, September~~.~~ 24th~~th~~, 2009 and August~~.~~ 4th~~th~~, 2013~~, respectively~~.

Based on the 5 TM images, we classified the area as glacier, snow, bare~~d~~ land, gully deposit~~ion~~ and vegetation in time series (Figure 6), and the area of each is given in Table 1. Figure 6 shows~~ed~~ that deglaciation ~~was taking place~~occurred in Tianmo V~~v~~alley; ~~and in particular~~notably, the eastern branch ~~had ~~has experienced ~~the sharpest ~~considerable deglaciation. ~~In order to~~To ~~show ~~clearly show the rapid rate of glacial~~er~~ retreat in the entire basin and eastern branch, a graph of retreat was plotted, ~~to show the changing of glacier and the eastern branch~~as shown in Figure 7.

Figure 7 shows that the glacier in TianmoV~~v~~alley ~~had ~~shrank from ~~been in shrinkagesince ~~2000 to 2013, with variable rates of~~tionin ~~glacier retreat~~ rate~~. In 2000~2003, 2003~2006, 2006~2009 and 2009~2013, the glacier retreat rates in Tianmo V~~v~~alley ~~corresponds to~~were 0.02, 0.06, 0.027 and 0.0075~~5km~~ km^2/a, respectively, and those of the eastern branch were 0.0033, 0.01, 0.008 and 0.002 km^2/a, respectively~~ for the eastern branch~~. According to ~~these ~~the figures, the largest glacier retreat rate was observed in 2003~2006, followed by that in 2006~2009. ~~It is important that~~The glacier area at the beginning should be ~~taken into consideration~~noted to ~~judge ~~assess the ~~changing ~~rate of change of the glacier. The glacier retreat rate ~~is ~~can be normalized, and the relative glacier retreat rate can be

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批注 [A15]: Answer to reviewer #2: Confused sentence calculated based on ~~theis~~this ~~area~~ change in area~~ing~~.

The relative glacier retreat rate~~s~~ ~~are~~ were 11.30, 35.09, 17.43 and 5.17 $10^{-3}km^2/a/km^2$ ~~during~~ in ~~–~~2000~2003, 2003~2006, 2006~2009 and 2009~2013, respectively; ~~whereas, it is~~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. ~~These figures show that the~~The relative glacier retreat rate ~~for~~ of the eastern branch ~~had shrunk much more~~ decreased sharply between 2000 ~2013.

In this ~~research~~study, TM images ~~with~~ over 3-year intervals were applied ~~can only get~~ 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 ~~is~~ were used to show the glacier retreat condition before debris flows occurred. Yang et al. (2015) ~~had~~ conducted field measurements of the No.94 Glacier in the Parlung Zangbo Basin since 2006, and the field measurements suggest~~s~~ it ~~was~~ had ~~in~~ a negative balance ~~in~~ from 2006~2010 (Figure 7). The negative balance reached a maximum level ~~the maximal~~ in 2009, followed by 2008 and 2006, indicating ~~sharp~~ rapid deglaciation in these three years.

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

批注 [A16]: Answer to reviewer #2: field instead of file

(3) Antecedent air temperature and rainfall ~~process~~

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

2007 and 2010 (Figure 8).

批注 [A17]: Answer to reviewer #2: confused sentence

~~According to~~ 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~~ This ~~demonstrates~~ trend suggests that the high air temperatures in July and August contributed to DF1.

~~According to Figure 8~~Additionally, the air temperature was high from early July to late August, and another high air temperature period ~~emerged~~ 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~~dle~~-July was responsible for DF2. After DF2 occurred, the air temperature in August ~~began to prepare for~~varied towards the conditions that caused DF3.

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

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

w~~W~~here T_{PT} is ~~the~~ 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 ~~lessen~~ decrease the heat that penetrates into them, and the low air temperature is ~~can~~ only ~~contribute to~~observed in the upper thin layer.~~;~~M~~m~~oreover, freeze-thaw cycles exist when the lowest air temperature is less than 0°C. From this ~~point of view~~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 ~~the~~ positive air temperature accumulation began when the lowest air temperature exceeded 0°C for several successive days beginning~~, starting~~ on June 28th~~th~~, 2007, ~~and~~ June 9th~~th~~, 2010, and July 26th, 2010, which correspond~~corresponding~~ to DF1, ~~and~~ DF2 and DF3, respectively~~,~~ ~~and on July 26th, 2010 for DF3, following DF2~~. The duration and T_{PT} were calculated for each debris flow event~~,~~. ~~the~~ The results~~was~~ 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 ~~is~~ was much larger than the other two T_{PT} values, ~~and~~ which ~~is coincidence~~coincides with ~~to~~ the fact that there was no debris flows in the past dozens of years, and extraordinary external forces such as large ~~,~~ T_{PT} ~~is~~ are required to ~~destroyed~~disrupt the long-term balance.

(4) Triggering conditions

The continuous nature of ~~the~~ air temperature limits the possibility for debris flows triggered by a sole abrupt increase in air temperature. ~~;and since~~Since ~~the~~ previous air temperature trends cannot be neglected, it is of no sense to study air temperature triggers.

Antecedent rainfall is a factor that favours debris flows. 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, ~~,and~~ which continued through July and August. ~~The~~ 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 ~~to the rainfall intensity (about 5~~approximately 5 mm/h of rainfall intensity (according to the description ~~of~~ provided by the forest guard)~~)~~ before DF1 to account for the storm, which migh~~t nt~~t 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 ~~had~~ paved the ~~road~~ way for DF1.

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批注 [A18]: Answer to reviewer #1: "to" is not needed, right ?

Considering a large deglaciated area, several other periglacial debris flows simultaneously ~~also~~ occurred near Tianmo Valley (Deng et al., 2013), which suggests the advantageous meteorological conditions for debris flow initiation.

DF2 ~~took place~~occurred when the air temperature reached ~~the~~ a peak in 2010. The thaw season began in the middle of June, and ~~the~~ T_{PT} reached 332.1 °C. On July 24th, one day before DF2, the air temperature reached ~~the~~ a maximum value for that year. The rainfall record at the Bomi meteorological station shows that there had been no rainfall several days preceding DF2, and the local citizens also ~~did not observe any~~observed no rain ~~either~~. The trigger of DF2 was likely the continuous percolation of melt-water due to the long-term ~~rising~~ increase in air temperature.

According to field interviews, several debris flows of small magnitude ~~had also~~ occurred before DF3. The air temperature decreased in late August but increased to another high ~~peak~~ value before DF3, and the T_{PT} reached 320.4 °C. Rainfall began 2 days prior to DF3 and was steady 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

~~Debris flows initiation is the process when of a water source provokes provoking the movement of soil sediments.~~ In this ~~research~~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.~~three debris flows were triggered by high air temperature and rainfall in during DF1, high air temperature in during DF2, and rainfall in during DF3 respectively3.~~ When we ~~analyzed~~ analysed the dates and ~~the~~ triggers ~~for~~ of these events, various questions ~~came to mind~~should be settled first ~~that gave reasons to doubts~~: 1) ~~W~~why did debris flows ~~did~~ not occur in 2006 or 2009 when deglaciation reached its peak and more ice meltwater was present; 2) ~~W~~why did DF1 and DF3 occur~~red~~ in September when the air temperature and

批注 [A19]: Answers to reviewer #1: this definition is a bit rough. It could be skipped.

批注 [A20]: Answers to reviewer #2: it should be the triggering factors of the three debris flows, were.....

批注 [A21]: Answers to reviewer #1: too gergal volume of ~~the~~ ice meltwater ~~was~~ were decreasing; and 3) w~~W~~hy ~~was~~ were there ~~is~~ no large-scale debris flows triggered by ~~the~~ previous ~~heavier~~ heavy storms. ~~It makes us~~Based on our results, we believe that the impact of the water source on the magnitude and frequency of debris flows is ~~quite~~ relatively small~~low~~, or ~~there could be much~~ more debris flows would form during the early larger storm;~~;and~~ instead, the soil source, including ~~its~~ the associated magnitude and activity, ~~should~~ may be the predominant~~te~~ control~~ler~~, ~~just~~ as reported by Jakob et al.~~,~~ (2005), who~~pointed out~~noted that ~~the recharge of~~ channel recharge is a~~should be the~~ prerequisite for debris flows. However, in most situations, we cannot reach the source area to detect the soil source, and ~~the~~ high-tech remote sensing can ~~just~~ only distinguish the boundary of the soil source. In the periglacial area where ~~the~~ glacial till is often covered by glacier or everlasting snow, ~~changing of~~a change in the soil source ~~seems to be of~~would be highly difficult~~ty~~ to detect. In this ~~research~~study, we ~~try to~~ combine the meteorological conditions and ~~the~~ literature reports~~s~~ to discuss the ~~probable~~ likely variations~~of~~ in glacial tills before debris flows.

(1) Annual v~~V~~ariations~~of~~ in glacial till~~in annual years~~

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 ~~°in~~over the ~~last~~ 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 ~~a~~ large ~~amount~~ 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 ~~with~~ due to climate warming ~~is~~ are quite different. Deglaciation is accompanied by the melting of internal ice particles,

批注 [A22]: Answers to reviewer #2: Confused sentence which~~.The melt of internal ice particles~~ can produce an active surface layer ~~which~~ that can obstruct heat fluxes from penetrating into the deep layer and~~,~~ result ~~into~~ in the melting of internal ice particles ~~lagging~~ at a rate slower than that of ~~behind~~ glacial retreat (Takeuchi et al., 2000). ~~As~~ Because a strong heat gradient ~~is existedexists~~occurs at the surface ~~while~~ but is ~~quite~~ limited in deep layers, glacial tills with thicker coverage always ~~has a~~have relatively thinner thawed~~ing~~ layers, and the ablation rates of glaciers and internal ice particles ~~can enjoy the same~~are similar~~value~~ to that at the glacier surface and close to the moraine slope. The newly formed bare~~d~~ glacial till is frozen with a high ice content.~~,~~ T~~t~~he cohesion of the ice particles ~~renders~~ creates ~~the~~ a bare~~d~~ glacial till with high shearing strength and stability, and only the surface layer is ~~of high~~highly active ~~activity~~. ~~Therefore~~~~Thus, we often see many bare moraine slopes near glaciers.~~ Therefore, ~~for this reason there were~~ no debris flows of large magnitude were observed in 2006 and 2009 when glacier retreat reached ~~the~~ a ~~maximal~~maximum and the active glacial till is quite limited .

(2) Variation~~of~~ in glacial till ~~in~~ on antecedent days

After the long, ~~term~~ cold winter, ~~the whole~~ glacial tills ~~would~~ become frozen. If ~~the~~ a regressive glacier ~~was~~ does not recover~~ed~~ in the winter, ~~the~~ glacial tills ~~would often be~~are covered by snow. As the air temperature increases again, the surface snow ~~would~~ melts first, followed by the internal ice particles. The thawing of internal ice particles ~~would~~ 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~~s~~ 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 melt-water can ~~deliver~~ transport fine-grained sediments that were formerly frozen in the ice matrix (Rist, 2007); and 4) the ice melt-water can result in a higher water content and pore water pressure (Christian et al., 2012). These changes in glacial till can sharply ~~decline~~ decrease the soil strength, shifting to an active mass from ~~the~~ an uncovered and frozen moraine

批注 [A23]: Answer to reviewer #1: occurs ?

批注 [A24]: Answer to reviewer #1: similarly to above, not really the correct verb

批注 [A25]: Answers to reviewer #2: Confused sentence

批注 [A26]: Answers to reviewer #2: ..there were no debris flows of large magnitude... explain why—the newly formed glacial till is of high shearing strength and low activity, leading to the low possibility of shallow landslide occurring.

(Figure 10~~,~~ B to C). Because ~~the~~ heat conduction in glacial till is ~~quite~~ relatively slow, this process may last for a very long time and ~~also~~ require~~s~~ a high antecedent air temperature.

Heat conduction via the percolation of rainfall and ice melt-water can amplify the depth of active ~~active of~~ glacial till (Gruber and Haeberli, 2007), whereas ~~the shelter of~~covering the surface glacial till can hinder ~~the~~ 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, ~~,meaning that~~ the long-term effect of a high air temperature can amplify the active glacial till (Noetzli et al., 2007; Åkerman and Johansson, 2008~~Åkerman et al., 2008~~), under which lies frozen glacial till with a high ice content. The activity of glacial till ~~variations~~ varies with depth from~~,~~ high ~~in~~ at the surface ~~and~~ 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, ~~although~~ as active ~~the~~ glacial till is ~~significantly largely unlimited~~relatively limited in ~~deglaciation~~ deglaciated areas.

(3) Failure of glacial tills

~~Failure of Gglacial could be diversityfailure can vary~~ 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 ~~0℃~~°C (Arenson and Springman, 2005). ~~Either~~ Rainfall or ice melt water induced by air temperature can ~~, the seepage flow of a glacier or ice particle melt-water could percolate the throughtills and~~ trigger the failure (Figure 10 ~~,~~ C to D). This ~~kind~~ type of event is called ~~the~~ a shallow landslide ~~type~~, and the failure mechanism lies in the ablation of internal ice particles and the percolation of melt-water, which can initially decrease the soil strength ~~at first~~ (Arenson and Springman, 2005; Decaulne et al., 2005). ~~;~~Later, the subsequent rapid percolation of ice melt-water or heavy rainfall can saturate the ~~till~~ debris, decrease soil suction and shearing strength, and form seepage flows that

批注 **[A27]:** Answers to reviewer #2: retrogressive manner means failure will take place at the surface active layer, followed by the deeper layer with increase of its activity

批注 **[A28]:** Answers to reviewer #1: what do you mean ? "different factors can lead to glacial till failure" ?

批注 **[A29]:** Answers to reviewer #2: Authors should distinguish triggering factors from the triggering mechanisms.

can~~matrix.Tthe glacial till decrease soil suction and shearing strength~~~~of the glacial till decrease and~~ ~~then~~ 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 ~~still~~ dependent on ~~the~~ its ability ~~that it can~~to entrain the debris layer, in which care the ~~,otherwise, it can~~debris is deposited ~~and~~ ~~c~~as the flow moves through~~harge~~ the channel.

Another ~~kind~~ type of failure ~~can~~might take place when a 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., 2013; Takahashi, 2014), which is more determined by channel bed slope and grain size of debris (Tognaccaet al., 2000; Gregoretti, 2000; Armanini and Gregoretti, 2005; Kean et al., 2013). ~~by~~This ~~kind~~ type of ~~water stream~~channelized runoff could be ~~the~~ a combination of ~~the~~ three factors: ~~,including~~ rainfall, melting ice or the overflow that forms when ~~the~~ a glacier collapses ~~falling down into the downwards~~downward into a water pool. Mechanism of this process lies in the hydrodynamic forces, created by the channelized runoff, ~~(Kean et al., 2013; Gregoretti et al., 2016) and pose createhydrodynamic forces acting that~~ acting on the surface elements of the debris layer and surpassing resistence of the sediment (Tognaccaet al., 2000~~,~~; Gregoretti, 2000; Armanini and Gregoretti, 2005; Prancevic et al., 2014). The concentration of runoff in the channel bottom causes the erosion of the debris surface layer forming a solid-liquid current at first, ~~and~~ then extends to the layers below with whole or partial mobilization and debris flows was generated (Gregoretti and Dalla Fontana, 2008). ~~, resulting in with whole or partial mobilizationof the bed material. The inclusion of bed material inthe flowing waterwater stream generates a debris flow (Gregoretti and Fontana, 2008).~~

Therefore, debris flows initiated from seepage flow that leads to a landslide failure or channelized runoff that entrain sediments in the periglacial area is similar with the mechanism of debris flows initiation in non-glacier areas~~The Ffluctuationsof in air temperature within a specific low range can result into in limited seepage flow. As Because the glacier in is limited to one valley is limited, it is unlikely for that~~

批注 [A30]: Answer to reviewer 2#: reference of Gregoretti (2008) is missing and that at line 426 it should be Gregoretti and Dalla Fontana (2008).

批注 [A31]: Answer to reviewer 2#: I suggest the authors a better description of triggering mechanism.....

批注 [A32]: Answer to reviewer 2#: reference of Gregoretti (2008) is missing and that at line 426 it should be Gregoretti and Dalla Fontana (2008).

批注 [A33]: Answer to reviewer 2#: reference of Gregoretti (2008) is missing and that at line 426 it should be Gregoretti and Dalla Fontana (2008).

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~~failure to can be triggered by a the limited amount of ice meltwater in due to short-term increases of in air temperature; instead, prolonged air temperature increases it isare needed to generate more water flow. Rainfall can initiate debris flows from active glacial tills with via a mechanism similar to that of associated with storm-induced debris flows in non-glacier areas~~ (Iverson et al., 1997; Springman et al., 2003; Sassa and Wang, 2005; Gregoretti and Dalla Fontana, ~~Gregoretti,~~ 2008; Kean et al., ~~2012~~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 ~~with~~ to air temperature fluxes (Stoffel et al~~,~~., 2011). ~~The~~Additionally, the ~~portion of~~values of rainfall and air temperature required ~~for~~ to trigger debris flows ~~triggering~~ could be ~~negative~~inversely correlated. Air temperature increases~~causes~~ can cause melting and water runoff; thus,~~,and~~ the rainfall ~~needed~~ required to create~~for providing thepercolating flows~~percolation flows or ~~exact~~ critical discharge ~~for~~ to trigger a debris flow ~~triggering~~ would be much less. ~~Beside~~In addition, the ~~required rainfall, like the~~intensity and duration of the required rainfall~~,~~ may ~~also~~ require other preconditions, such as ~~the~~ 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 ~~possess~~ were associated with similar annual meteorological conditions, except that the positive air temperature accumulation prior to DF1 was ~~significantly large~~largest~~r~~. DF1 occurred at the end of a prolonged period of high air temperature, prior to this, there were instances of failure but no large-scale debris flows. On July 25th, ~~th~~ 2010, when the daily rainfall ~~particularly~~ reached 20.7 mm, no debris flows were generated because thick active glacial till was still lacking after small failure events. 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 and had low activity. The lack of glacial till activity was the likely cause of the absence of debris flows. On August 23rd, the daily rainfall was 20.3 mm, the antecedent air temperature accumulation ~~dated~~ had remained stable since ~~from~~ DF2~~,~~ and ~~the~~ active glacial till was still ~~under development~~developing. On

批注 [A34]: Answer to reviewer 2#: Delete the sentence at line 420-423 and write Therefore, runoff provided by rainfall, seepage flow and melting ice or glacier collapse can initiate debris flow with the same mechanism of the runoff generated debris flows in non-glacier areas (Iverson et al., 1997, Kean et al., 2012).

批注 [A35]: Answer to reviewer 1#: negative ? what does this mean ?

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September 6^{th}, the antecedent positive air temperature accumulation was ~~smaller~~small, and a low air temperature ~~had emerged~~was observed previously; however, the high rainfall intensity supplemented this lack of prolonged high air temperature.

5. Conclusion

Climate changes have serious effects ~~on~~ in high mountainous areas, and the mass movement of sediments such as periglacial debris flows ~~is~~ 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~~earlier~~ prior ~~was~~ were responsible for ~~the~~ three debris flow events in Tianmo V~~v~~alley. Debris flows~~is usually~~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 ~~the~~ a prolonged increase in air temperature~~ rise~~.

Glacial till is unlimited in ~~the~~ deglaciated areas, ~~while~~ and its activity relies on glacial retreat and internal ice particle melting. ~~Changing of~~ G~~g~~lacial till changes~~s~~ induced by ~~increasing~~ increased air temperature ~~is~~ are the first steps ~~of~~ in forming periglacial debris flows ~~comparing with~~compared to~~the~~ storm-induced debris flows in non-glacier areas. Glacial tills ~~need~~ require a four-phase ~~experience~~ process prior to debris flow occurrence. In this process,~~during which the varied~~the variable air temperature condition ~~with~~ due to different factors drives the ~~changing~~ glacial till changes, and temperature ~~series~~ increases can cause glacier recession~~remove glaciers~~, produce bare~~d~~ glacial till and enhance the glacial till activity~~ step by step~~. Debris flows ~~could~~ can ~~occurr~~occur when a ~~enough~~ sufficient amount of active glacial till ~~is~~ exists ~~existed~~ and rainfall-induced seepage or ~~water~~ runoff is more likely to generate debris flows.

> 批注 [A36]: Answer to reviewer 2#: Confused sentence

> 批注 [A37]: Answers to reviewer #1: remove glaciers ? do you mean "cause glacier recession or even disappearance" ?

> 批注 [A38]: Answer to reviewer 2#: Confused sentence

It is difficult to observe ~~the changes of~~ glacial till changes in source areas of debris flows, and the analysis of the phase conversion of glacial till in this ~~research~~ study is based on the triggering conditions and other literature findings~~s~~. Indeed, the meteorological conditions, such as the antecedent air temperature and meteorological triggers that drive the phase conversion, are partly ~~overlapped~~ coupled and difficult to distinguish. In ~~the first~~future~~study~~studies, we hope to ~~distinguish~~ determine the effect of each meteorological condition, and more ~~detail~~ detailed ~~study~~ studies should be ~~done~~ performed~~ in further research~~.

Acknowledgements:This research was supported by the National Natural Science Foundation of China (grant n~~N~~os. 41190084, 41402283 and 41371038) and the "135" project of IMHE, CAS. We wish to acknowledge the editors of~~in~~the Natural Hazards and Earth System Science Editorial Office and the anonymous reviewers for their constructive comments, which helped us ~~in improving~~improve the contents and presentation of the manuscript.

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Table 1 ~~Changes in~~Changes in glacier, snow, bare~~d~~ land, gully deposition and vegetation in Tianmo V~~v~~alley

Year	Glacier (km^2)	Glacier(eastern branch) (km^2)	Snow (km^2)	Bare~~d~~ 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 ~~of~~ regarding the debris flows in Tianmo Valley and ~~the~~ nearby valleys

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

带格式表格

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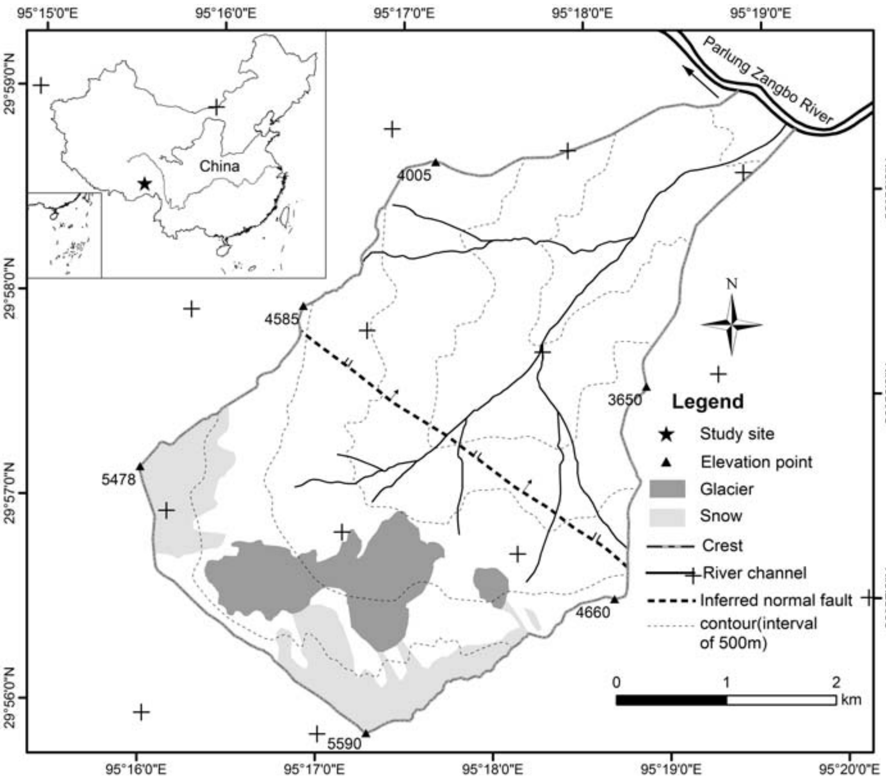

Figure 1 Location ~~and basic information of~~of Tianmo Valley and related information

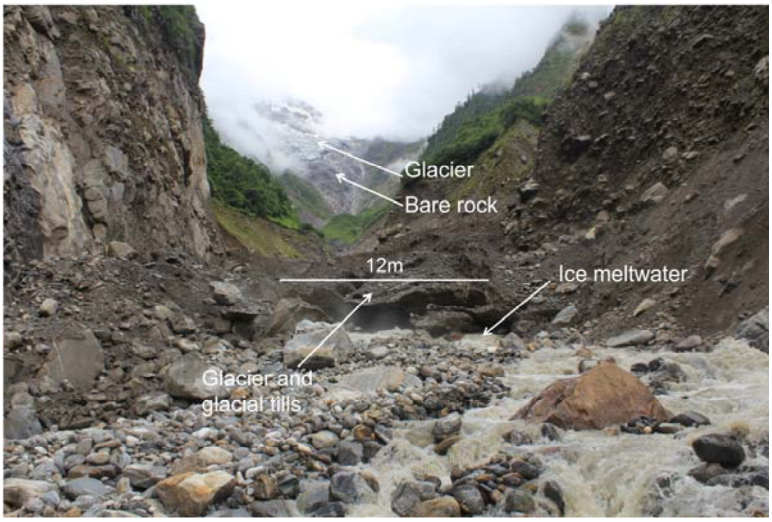

Figure 2 Overview of the valley from the channel(in 2014)

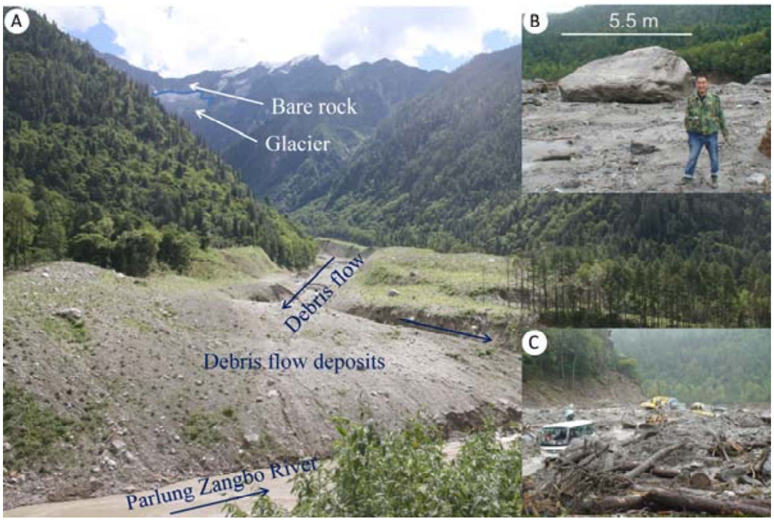

Figure 3 DF1 in 2007(A. Overview of the Tianmo debris flows from the downstream area; B& C. Boulder and debris flow deposits on the north side of the Parlung Zangbo River)

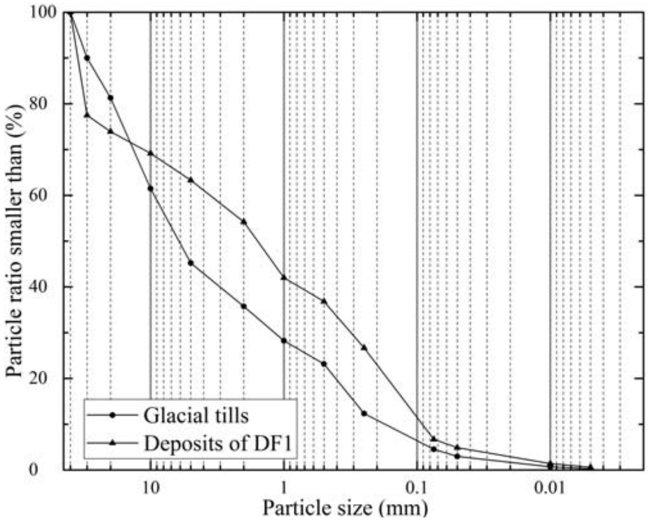

Figure 4 Particle size distributions of the glacial tills and debris flow deposits

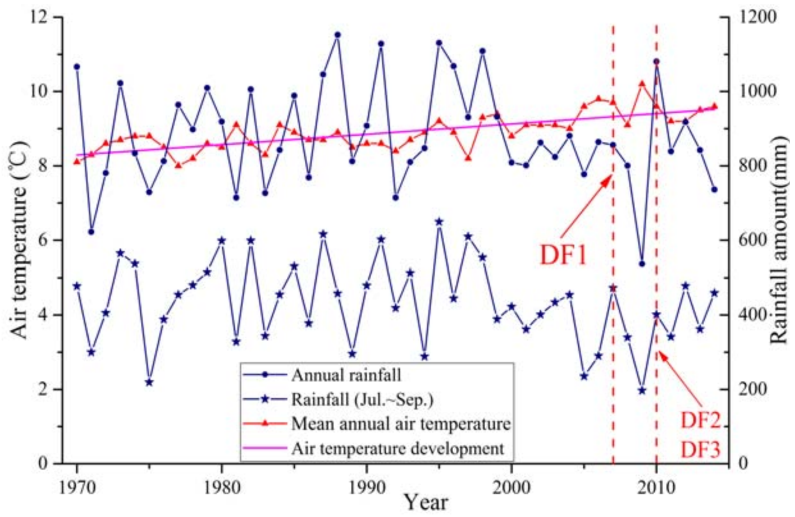

Figure 5 Variation ~~of~~ in the mean annual air temperature and rainfall ~~in~~ at Bomi from~~,~~ 1970 to 2014

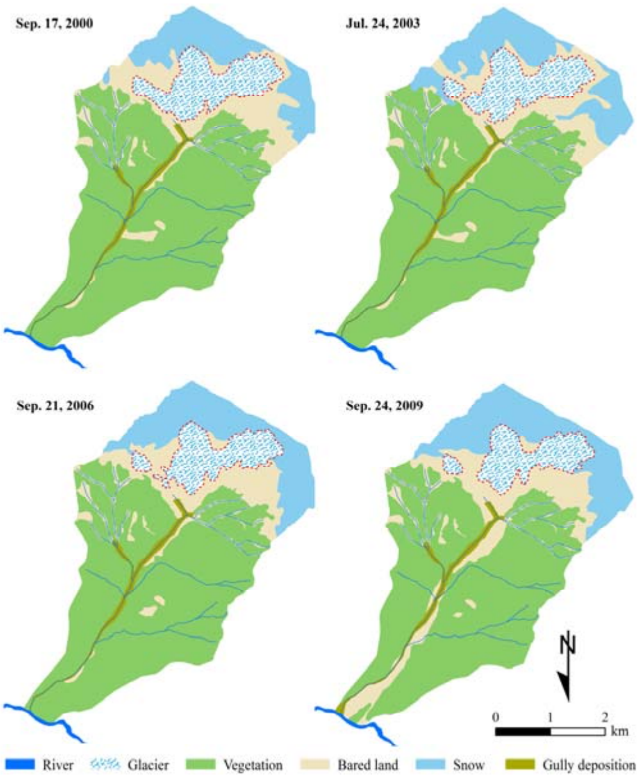

Figure 6 Distribution and ~~changing of~~changes in glacier, snow, bare~~d~~ land, gully deposition and vegetation in Tianmo V~~v~~alley

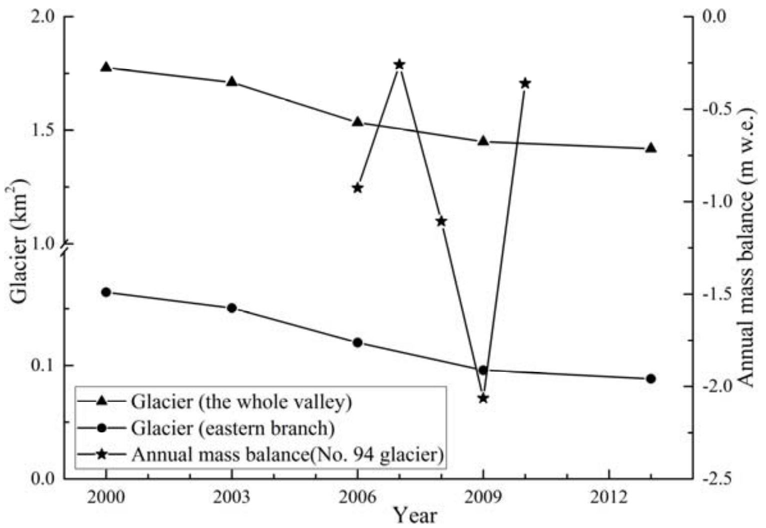

Figure 7 ~~Changing of~~Changes in glacier ~~via~~ over time and the measured annual mass balance ~~for~~ of the Parlung No. 94 Glacier (mass balance ~~is~~ was edited ~~by~~ from Yang et al.(2015))

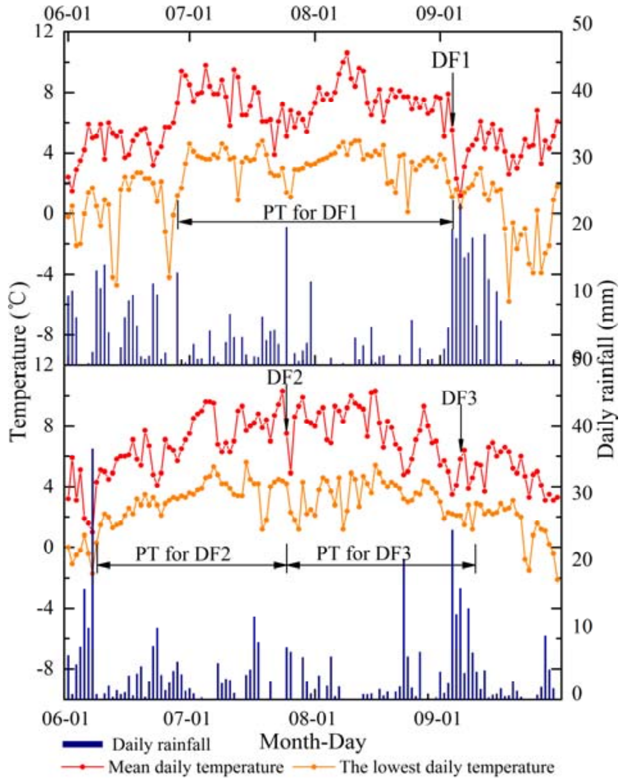

Figure 8 Air temperature and rainfall before and after DF1, DF2 and DF3

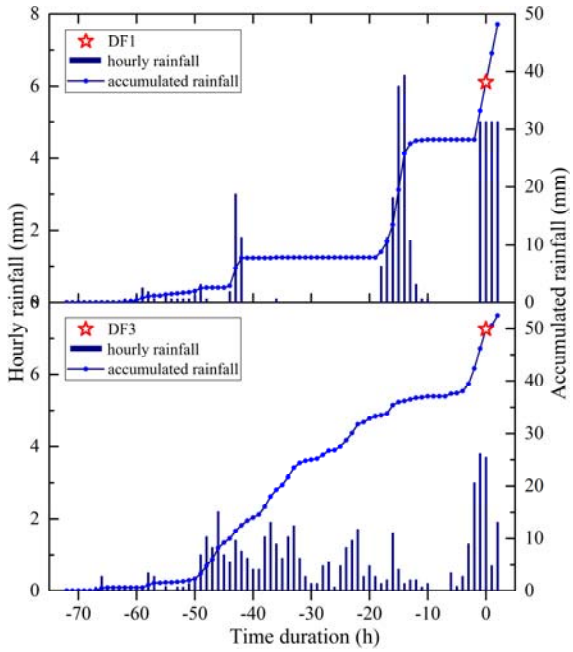

Figure 9 Variationsof thein rainfall accumulation prior to DF1 and DF3 (no rainfall before DF2)

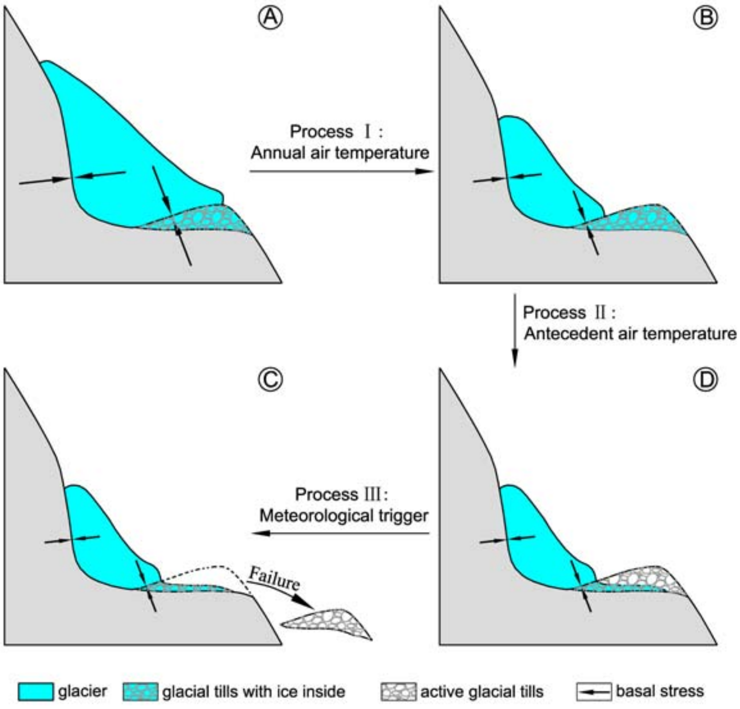

Figure 10 Changes in a glacier and frozen glacial till before periglacial debris flow initiation(A: glacial-covered glacial tills; B: uncovered and frozen glacial tills; C: active glacial tills; D: failure of glacial tills)