

Answers to reviewer #1:

- English must be polished and ameliorated by a native speaker - Title: I suggest "mophological factors driving glacial till variations and.."

Answers: we've changed the title and the English will be polished by a native speaker.

Introduction -

26: permafrost degradation instead of retreat -

Answers: We've made the change in the manuscript. See line 28.

34: not clear the expression "traffic/drainage" -

Answers: We've made the change in the manuscript. See line 38.

38-40: not only also in the Andes and elsewhere ! please organize this phrase to be more comprehensinve

Answers: We've made the change in the manuscript. See line 43.

- 62: "lake" after glacier is probably missing

Answers: We've made the change in the manuscript. See line 67.

- 69: not clear what is the meaning of "the perfect object". please rephrase Background

Answers: We've deleted this in the manuscript. See line 74.

In Chinese we all see the perfect object or perfect way to show this is a wonderful case.

- 94-96: not clear why the river channel shading should be relevant for glaciers ?

Answers: 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.

- 114-115: please remove, very poetic but non scientific sentence

Answers: We've deleted this in the manuscript. See line 120.

- 152: Since when has the station been operated ?

Answers: It was built since 1955. See line 161.

- 159-162: not convincing. please explain better

Answers: We've changed this in the manuscript. See line 167~172.

Analysis and results

- 176: mean instead of overall ?

Answers: We've changed this in the manuscript. See line 187.

- 179-184: in all this paragraph one wonders the role of snow vs rainfall in the measurements. Is snowfall measured ? How is it relevant?

Answers: It's a pity that the data on snow is not available so the impact of snow cannot be analyzed.

- 184: what is normal ?

Answers: We've changed this in the manuscript. It means the mean rainfall state See line 195.

- 188 and 195: I don't understand why you say the rainfall increased at line 195 whereas before you said it was reduced. Please check. I am not sure about the hot-dry and hot-wet. In one case it was not so hot, you report

Answers: We've changed this in the manuscript. See line 206.

It's our mistake and we've changed this. Besides we did not study of the weather condition if hot-dry and hot-wet is favorable for debris flows, instead, this is a conclusion by Lu and Li(1989) .

Lu, R. R., and Li, D. J.: Ice-Snow-Melt Debris Flows in the Dongru Longba, Bomi county, Xizang. *J Glac Geocry*, 11(2), 148-160, 1989. (In Chinese)

- 211: please describe what is SPOT and TM

Answers: We've made the change in the manuscript. See line 222~225.

TM image is taken by the No. 4 or 5 thematic mapper carried on the satellite Landsat which is belong to the USA.

Satellite SPOT is short for Systeme Probatoire d'Observation de la Terre belong to France. the SPOT image is taken by this satellite.

- 217: from 2000 - 219-220: values better expressed in hectares

Answers: In this manuscript we did not use hectares considering that it may not useful for the changing of the eastern branch of glacier; instead, the relative glacier retreat rate is applied to show the changing rate.

- 225: equation is not needed, it is just a simple relative variation ratio

Answers: We've delete equation 1.

- 246: not clear, why the increase may have contributed to glacier retreat ? Please check or rephrase

Answers: after deep consideration, we decide to delete this. See line 259.

- 275: how many are several ? not precise !

Answers: We've checked and made some changes. See line 292~293.

Considering the frozen and thawing cycle in the source area, and one day with air temperature larger than 0 could be an exception so we defined the beginning since two or three successive days over 0 °C and none is lower than 0 in the following days.

According to the fluctuation of air temperature, we regards two or three days

- 284-287: but DF1 was a much larger event compared to the others. Not sure about this interpretation.

Answers: We've checked and made some changes. See line 300~307.

- 300: why 5 mm/hr ? not clear

Answers: We've checked and made some changes. See line 320~321.

- 323: sediment instead of soil mass

Answers: We've checked and made some changes. See line 345.

- 336: scope of soil source ? not clear

Answers: We've checked and made some changes and it should be the boundary and which can be applied to calculate the volume. See line 358.

- 336: periglacial

Answers: We've checked and made some changes. See line 358.

- 348: gravitation ? do you mean weight ? better to talk about pressures

Answers: We've checked and made some changes and it should be glacial pressure. See line 371~372.

- 358: depth instead of coverage

Answers: We've checked and made some changes. See line 381.

- 360: not clear "at the junction with the slope"

Answers: We've checked and made some changes and it should be glacial pressure. See line 380~383.

- 360-363: this entire phrase is not clear at all. please rewrite it. Indeed, also Figure 10 (especially C and D) is not clear, and more detailed description should be provided in the caption

Answers: We've paraphrased line 376~383. Also for C and D and we add some explanation to the failure process according to the comment of reviewer #2. See line 428~453.

- 383: scope ?

Answers: We've checked and made some changes. See line 416.

- 384: internal mass of what ?

Answers: We've checked and made some changes. See line 417.

- 391: stepwise manner ? not clear

Answers: We've checked and made some changes. The surface layer should experience the failure first and then the layers below. See line 424.

- 406: glacier limited ? maybe till is missing

Answers: We've checked and made some changes. we want to express that the ice melt water in a short time should be limited as glacier is limited. See line 454~457.

- 412: rainfall related to air temperature fluxes ? this is obvious

Answers: here we want to express that the triggering condition of debris flows in Alps is controlled by rainfall first and the air temperature. See line 461~462.

- 423: is it possible that small events (is failure meaning debris flows? if so should be changed) had cleared the entire

source area from active till ?

Answers: This is in line 476 and we think the small events cannot clear the entire source area.

--the active till is in high area and when it slide along the slope with large gradient, liquefaction can take place to generate

debris flows; of course, some can also deposit in the nearby gully for low energy.

--the small events cannot clear all the active till, or the three large events will be not existed.

- 438: first year of what ?

Answers: We've add more explanation and see it in line 494.

- 440-441: not always unlimited. not clear why its activity depends on glacier retreat

Answers: In the above, four processes has been given. The glacial debutting, the process that active glacial till emergence are all influenced by glacier retreat.

- 443-445: the four phases are quite obvious and could be skipped

Answers: It has been deleted. See line 502

- 455: Figure 5: in the caption "Mean annual air temperature"

Answers: It has been changed. See figure 5.

Answers to Review #2:

1. The acronyms as TM, DF1, DF2, DF3, SPOT should be defined before their use. Moreover, their use in the abstract should be avoided as much as possible.

Answers: We've made the change in the manuscript. See line 222~225.

TM image is taken by the No. 4 or 5 thematic mapper carried on the satellite Landsat which is belong to the USA.

Satellite SPOT is short for Systeme Probatoire d'Observation de la Terre belong to France. the SPOT image is taken by this satellite.

2. As runoff generated debris flows, periglacial debris flows are triggered by a water stream that entrain sediments and forms a solid-liquid wave. Water stream is the result of one or a combination of three factors: runoff due to rainfall, melting ice and outburst floods. Due to this similarity between runoff generated debris flow, authors should introduce something more about runoff generated debris flows: the runoff generated debris flows initiate when a peaked runoff hydrograph (Kean et al., 2012; Rengers et al., 2016 and Gregoretto et al., 2016) flow over or impact debris deposits entraining solid material forming the so called debris flow (Berti and Simoni, 2005; Cannon et al., 2008; Coe et al., 2008; Gregoretto and Dalla Fontana, 2008, Theule et al. 2012, Hurlimann et al., 2014, Degetto et al., 2015, Hu et al., 2016).

Answers: We've made the change in the manuscript. See line 428~453.

Another kind of failure can take place by the increased water stream that entrain sediments and forms a solid-liquid wave if the channel is charged with loose ravel. This kind of water stream could be the combination of the three factors, including rainfall, melting ice or the overflow when the glacier collapse falling down into the downwards water pool. The runoff can generate debris flows when a peaked runoff flow over debris deposits(Kean et al., 2012; Gregoretto et al., 2016) and pose hydrodynamic forces acting on the surface elements of the debris layer(Tognacca et al. 2000, Gregoretto ,2000; 2005). The

concentration of runoff in the channel bottom causes erosion of the debris surface layer and then extends to the layers below with whole or partial mobilization of the bed material. The inclusion of bed material in the water stream generates debris flow (Gregoretti, 2008).

3. The use of rainfall threshold for explaining the effect of the air temperature should better addressed by explaining that first air temperature increase causes melting and as consequence an abundance of stream water. Therefore, respect to runoff generated debris flows, the rainfall needed for providing the exact critical discharge for debris flow triggering is much minus.

Answers: We've made the change in the manuscript. See line 462~474.

The portion of rainfall and air temperature required for debris flows triggering could be negative. Air temperature increase causes melting and water runoff, and the rainfall needed for providing the percolating flows or exact critical discharge for debris flow triggering would be much less. Beside, the required rainfall, like the intensity and duration, may also require other preconditions, such as the distribution of glaciers and frozen glacial tills and the terrain of the source area

4. Upstream noise (line 116) could be due to slides or rock fall triggered by previous rainfall?

Answers:

This noise should be come from the glacier collapse or slide while not the initiate of debris flows.

5. Lines 156-163: debris flow are usually triggered by abundant runoff. Abundant runoff is usually provided by convective rainfalls of high intensity and short duration rainfall (Berti and Simoni, 2005; Gregoretti and Dalla Fontana, 2008). This type of rainfall is characterized by an high spatial variability (Gregoretti et al., 2016). The same authors at line 291 state that a convective storm occurred before DF1 while at the Bomi station no precipitation was recorded. Therefore, please justify in another way the use of the Bomi station. (i.e. data from this station can be used for long-period analysis of cumulative annual rainfall).

Answers: We've made the change in the manuscript. See line 167~172.

According to our statistics on rainfall data in the area, the rainfall often enjoys the similar intensity for the long-term rainfall process from Guxiang to Songzong which means the there is no large rainfall gradient between Tianmo valley and Bomi meteorological station; however, for the convective rainfall process, rainfall can take place in a small area. In the manuscript, we try to combined the rainfall data in Bomi and the memory of the local citizen to make sure the rainfall process.

6. Lines 186: DF2 and DF3 should defined before their use.

Answers:

DF1, DF2 and DF3 has been debris defined in the part of disaster history.

7. Line 208: what is SPOT? Is it the acronym of?

Answers: We've made the change in the manuscript. See line 222~225.

Satellite SPOT is short for Systeme Probatoire d'Observation de la Terre belong to France. the SPOT image is taken by this satellite. We've add this in the manuscript.

8. Line 228: the writer does not understand the unit measurements for the relative glacial retreat provided by equation (1): what is the duration of year n? According to equation (1) D should be 1/n as dimensions (Area/Area = 1).

Answers: We've made the change in the manuscript. See line 240~242.

'n' in the equation stands for the time interval of the TM image series, and n=3.

the relative glacial retreat means the annual glacier retreat for each square kilometers.

According to reviewer 1#, we've delete this equation (1).

9. Lines 300-301: the writer does not understand the meaning of this sentence.

Answers: We've made the change in the manuscript. See line 320~321.

In Figure 9, as the rainfall right before DF1 occurred was not recorded by Bomi metrological station, we added to the rainfall intensity (about 5 mm/h according to the description of the forest guard) before DF1 to account for the storm, which might not reflect the real rainfall process.

10. Lines 330-340: the sentences seem not clear.

Answers: We've made the change in the manuscript. See line 355~362.

We want to make the point that if the water runoff controls the magnitude and frequency of debris flows, larger debris flows could occur before when the larger rainfall process took place. Instead, debris deposits that rainfall or ice melt water can trigger or the water runoff can entrain is regarded as the perquisite.

11. Line 421: this statement (no debris flow occurred) contradicts line 130 (debris flows were triggered).

Answers: We've made the change in the manuscript.

We might not say this clearly that make the reviews difficult to understand.

Line 421 says '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.' And in line 130, this debris flows(DF2) occurred after DF1 while not prior to DF1.

12. There is a clear dependence of debris flow occurrence on the air temperature, while that on rainfall is minus evident (also because direct rainfall measurements are missing in the triggering areas of examined

debris flows). This could be explained by the following consideration: debris flow is generated by runoff and runoff is due to the rainfall precipitated upstream the triggering area. This is the main reason because two debris flows occurred in September. In that month the areas not covered by snow should have reached the largest extension of the year and therefore, runoff in the downstream area should increase. About rainfalls, these could be subjected to a high spatial variability.

Answers: We've made the change in the manuscript. See line 502~507.

Thanks for the comment and we've added some of them in the discussion and conclusion.

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 Alpines are strongly affected by climate warming. 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 melt-water due to higher air temperatures enhances the complexity of the triggering mechanism compared to storm-induced debris flows. In south-eastern Tibetan Plateau where temperate glaciers are widely distributed, numerous periglacial debris flows have occurred in the past 100 years, but none had happened in the Tianmo watershed until 2007. In 2007 and 2010, three large-scale debris flows occurred in the Tianmo watershed. In this research, these three debris flow events were chosen to analyze the impact of the annual meteorological conditions: the antecedent air temperature and meteorological triggers. TM images and field measurement of the nearby glacier suggested that a sharp glacier retreat had existed in the previous one or two years preceding the events, which coincided with the spiked mean annual air temperature. Besides, changing of glacial tills driven by prolonged increase in the air temperature is the prerequisite of periglacial debris flows. Triggers of periglacial debris flows are multiplied and they could be high intensity rainfall as in first debris flows and the third debris flows, or continuous long term rising air temperatures as in the second debris flows.

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

1. Introduction

The alpine environments are strongly vulnerable to climate changes, of which the alpine glaciers and permafrost are the most sensitive in the form of glacier and permafrost ~~degradation~~ (Harris et al, 2009; IPCC, 2013). Glacier and permafrost retreat can induce mass movement, such as landslides, shallow slides, debris, moraine collapses, etc. (Cruden and Hu, 1993; Korup, 2009; McColl, 2012; Stoffel and Huggel, 2012; Fischer et al, 2012), that will be expelled out of the watershed in the form of

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34 debris flows or sediment flux. The debris flow in alpine areas can often bury
35 residential areas, cut off main roads and block rivers (Shang et al, 2003; Cheng et al,
36 2005; Deng et al, 2013) and destroy basic facilities located in downstream, posing a
37 great threat to the local economy and social development. In undeveloped alpine areas
38 such as the south-eastern Tibet where the ~~transportation system~~ is particularly poor or
39 limited, the negative effects produced by debris flows such as cutting off main roads
40 are serious (Cheng et al, 2005).

删除的内容: traffic/drainage

41 Periglacial debris flows occurs in the high alpine areas where there is large areas
42 of glaciers, such as the Tibetan Plateau in China(Shang et al, 2003; Ge et al, 2014),
43 Alps in Europe(Sattler et al, 2011; Stoffel and Huggel,2012), Caucasus Mountains in
44 Russia(Evans et al, 2009) and Andes in northern Canada(Lewkowicz1 and Harris,
45 2005). Periglacial debris flows were reported to be initiated by rainfall (Stoffel et al,
46 2011; Schneuwly-Bollschweiler and Stoffel, 2012), melt-water flow of glacier or ice
47 particle ablation(Arenson and Springman, 2005; Decaulne et al, 2005), or outburst
48 floods from glacier lakes (Chiarle et al, 2007) in different parts of the world, while the
49 multi-triggers for the case is rarely to be read. Because debris flows are commonly
50 triggered by rainfall (Sassa and Wang, 2005; Decaulne et al, 2007; Kean et al, 2013;
51 Takahashi, 2014), the rainfall threshold, intensity and duration has been widely used
52 for debris flow monitoring and giving warning in non-glacier areas (Guzzetti et al,
53 2008).

54 In deglaciation areas, the debris flow threshold can be more difficult to determine.
55 Periglacial debris flows tend to occur in the summer when the thawing of glaciers and
56 glacial tills predominates and melt-water penetrates into the glacial tills at a constant
57 and successive flow. The effect of melt-water appears similar to that of antecedent
58 rainfall (Rahardjo et al, 2008) and is variable in different periods, considering snow
59 and glacier shrinkage and air temperature fluctuation. In the Swiss Alps, melt-water is
60 high in early summer, and as debris flows can be initiated by low total rainstorm,
61 whereas higher total rainstorm are required in late summer or early autumn when the
62 melt-water is low (Stoffel et al, 2011; Schneuwly-Bollschweiler and Stoffel, 2012). In
63 south-eastern Tibetan Plateau, the rainfall threshold given by Chen et al., (2011) is

65 quite wide, and the small rainfall threshold in particular is likely to contain the effect
66 of air temperature. Moreover, periglacial debris flows induced by a sudden release of
67 water from glacier lakes have a close relationship with the rising air temperature (Liu
68 et al, 2014).

69 Fluctuation of air temperature is likely to be quite important in triggering
70 periglacial debris flows. Compared with the storm induced debris flows, the addition
71 of air temperature can greatly enhance the complexity of the initiation of periglacial
72 debris flows. It is of high difficulty to simulate the triggering process by experiment
73 or mathematical simulation, and instead, debris flows cases in the natural environment
74 could be applied. In this research, three debris flow events, after a debris-flow-free
75 period of nearly 100-year, in the Tianmo watershed of the southeastern of the Tibetan
76 Plateau as deglaciation continued are used as examples, and the annual meteorological
77 conditions, antecedent air temperature and triggering conditions prior to debris flows
78 are analyzed to further understand the meteorological triggers and their roles in
79 glacier retreat, glacial till variation and debris flow initiation.

删除的内容: as the perfect object

80 **2. Background**

81 **(1) Study area**

82 The temperate glacier in the Tibetan Plateau is primarily distributed in the
83 Parlung Zangbo Basin and covered a total landmass of 2381.47 km² in 2010 based on
84 TM images (Liu, 2013). Historically, the movement of temperate glacier has produced
85 a large amount of moraines, the depth of which can reach up to 500 m locally (Yuan et
86 al, 2007). In recent decades, there has been a dynamic significant increase in
87 temperature and according to statistics the temperature at the Bomi meteorological
88 station (midstream in the Parlung Zangbo Basin) has rose by 0.23°C/10a from 1969 to
89 2007, resulting in remarkable shrinkage of the glacier(Yang et al, 2010).

90 Tianmo Valley, located in Bomi County and to the south of the Parlung Zangbo
91 River, covers an area of 17.76 km² (29°59'N/95°19'E; Figure 1). This valley has a
92 northeast-southeast orientation and is surrounded by high mountains reaching 5590 m

94 a.s.l. at the southernmost site and 2460 m a.s.l. at the junction of the Parlung Zangbo
95 River. The TM image in 2013 showed the presence of a hanging glacier with an area
96 of 1.42 km² in the upper concave area at an altitude of 4246 m to 4934 m. Bared rock,
97 dipping at an angle of around 60°, emerged below and above the hanging glacier and
98 often covered by everlasting snow. Below 3800m a.s.l., vegetation, including forest
99 and shrub, occupies most of the area (Table 1).

100 The river channel in the watershed is sheltered by shade and not directly affected
101 by sunlight, resulting in less solar radiation and a location at which a small trough
102 glacier can form. In the main channel, the trough glacier extended to 2966 m a.s.l. in
103 2006. The lower part of the trough glacier has been eroded by glacier melt-water flow,
104 and an arch glacier that is vulnerable to high pressure was formed (Figure 2). The
105 remnants of the landslide deposits approximately 10 meters high, which consist of low
106 stability sediment and can be easily entrained by debris flows, can be observed in both
107 sides of the channel.

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

116 (2) Disaster history

117 According to our field interview with local residents, there were no debris flows
118 in approximately 100 years prior to 2007 in Tianmo Valley. The channel was quite
119 narrow before 2007, and the local people could walk across via a wooden bridge to
120 live and farm on the terrace on the west side.

121 On the morning of Sep. 4th, 2007, after the rainfall which did not hit the
122 downstream area ceased, the local forest guard heard a loud noise coming from the

删除的内容: The ecology was in a rather peaceful state at that time

125 upstream area at approximately 18:00; with rainfall which later began in the upstream
126 area at approximately 19:00, following this rainfall was debris flows which rushed out
127 of the Tianmo Channel and subsequently blocked the Parlung Zangbo River; report
128 stated that several debris flows occurred, lasting the entire night. According to the
129 field measurements, approximately 1,340,000 m³ of sediment was transported during
130 this event, resulting in 8 missing persons and deaths. Concurrently within this same
131 time, debris flows occurred in the four nearby valleys (Table 2). According to the size
132 classification proposed by Jakob (2005), which is based on the total volume, peak
133 discharge and inundated area, Size class of debris flows in the five valleys is given in
134 Table 2. This debris flows is listed as DF1 in this paper.

135 At 11:30 on Jul. 25th, 2010, debris flows were again triggered in Tianmo Valley
136 that traced the path of the preceding debris flow deposits and reached the other side of
137 the Parlung Zangbo River. According to Ge et al., (2014), solid mass sediment of
138 approximately 500,000 m³ was carried out (Table 1) and deposited on the cone to
139 block the main river. A barrier lake was formed, and the rising water destroyed the
140 roadbed of G318. The following week also experienced dozens of debris flows in
141 small magnitude. This debris flows is listed as DF2 in this paper.

142 Debris flows occurred again two months later on Sep. 6th (The Ministry of Land
143 and Resources P. R. C., 2010), although we could not determine the exact times
144 sequence of event but according to speculation, these debris flows could have
145 occurred in the early morning before dawn and when the rainfall intensity has reached
146 its maximum(Figure 9), which agrees with the findings of Chen (1991) that periglacial
147 debris flows have historically occurred between 18:00~24:00 in this area. The debris
148 barrier in the main river was consequently increased by an additional 450,000 m³, and
149 the barrier lake was enlarged to maintain 9,000,000 m³ of water. This debris flows is
150 listed as DF3 in this paper.

151 A field investigation revealed that a high percentage of boulders in the
152 downstream area and glacial tills above the trough glacier were quite loose and of
153 high porosity (Figure 2), hence they have low density and can be easily entrained. Our
154 particle size tests on the glacial tills and debris flow deposits indicate a lower clay

155 (d<0.005 mm) content, whereas the debris flow deposits contain more fine particles
156 that are smaller than 10 mm (Figure 4), suggesting that the entrainment supplied a
157 considerable amount of fine particles.

158 (3) Meteorological data

159 The study area is located in a high alpine area where the economy is quite
160 undeveloped with only few meteorological stations. Before 2011, the Bomi
161 meteorological station (since 1955), was the only station in the area, located 54 km
162 away from Tianmo valley at an altitude of 2730 m, and other stations were located
163 more than 200 km away.

164 The Tibetan Plateau is a massive terrace that obstructs the Indian monsoon,
165 causing it to travel through the Yarlung Zangbo Canyon and its tributaries. As the
166 Indian monsoon is transported to higher altitudes, a rainfall gradient emerges in the
167 Parlung Zangbo Basin. However, according to our statistics on rainfall data in the area,
168 the rainfall often enjoys the similar intensity for the long-term rainfall process from
169 Guxiang to Songzong which means the there is no large rainfall gradient between
170 Tianmo valley and Bomi meteorological station; therefore, the rainfall data from the
171 Bomi meteorological station can be used for our study for the long duration rainfall
172 process. In order to conduct further study, another meteorological station was built in
173 2011 near Tianmo Valley.

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

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182 3. Analysis and results

183 (1) Changing of air temperature and rainfall

184 The mean annual air temperature is usually used to reflect the tendency of glacier
185 change (Yang et al, 2015). We collected the mean annual air temperature and annual
186 rainfall data from 1970 to 2014 from the Bomi meteorological station (Figure 5). The
187 record showed that the ~~mean air temperature has increased by approximately 1.5°C in~~
188 the last 45 years, accounting for 0.033°C/a. This air temperature increase was
189 particularly more rapid between 2005~2007, an approximately 0.7°C/3a, which is 7
190 times the average value of the last 45 years. On the other hand, the annual rainfall
191 from 2000 to 2010 was low and it was estimated at 828.2 mm per year. From 2000 to
192 2004, the rainfall during summer (July to September) accounted for approximately 50%
193 of the total annual rainfall; however, only 32% of the rainfall occurred in the summer
194 of 2005~2006, even though the annual rainfall exhibited the same trend. In 2007,
195 rainfall in the summer and the entire year returned to ~~the mean rainfall state,~~

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删除的内容: normal

196 According to Figure 5, a similar trend in the air temperature and rainfall was
197 observed before DF2 and DF3. The air temperature elevated in 2009 to reach the
198 maximum of the last 45 year period, accounting for 10.2 °C; however, the annual
199 rainfall, was only 65% of the average amount; and the summer rainfall, lower than
200 that in 2005 and 2006, reached their minimum values. In 2010, the rainfall was
201 abundant and the annual rainfall increased to 1080.6 mm, which is approximately 30%
202 more than the average value and close to the maximum.

203 The following common traits can be identified from comparing the annual
204 meteorological conditions of DF1, DF2 and DF3. 1) One or two years before the
205 debris flows, the mean annual temperature elevated and the annual rainfall and
206 summer rainfall ~~declined~~. The climate was in a "hot-dry" state. 2) As the temperature
207 gradually decreased, the annual rainfall returned to normal or increased, and the
208 "hot-wet" climate contributed to debris flow initiation (Lu and Li, 1989).

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212 (2) Changing of glacier in Tianmo valley

213 In our research, remote image is collected to analyze the changing of glacier in
214 the source area during the past years. In order to eliminate the effect of snow cover,
215 images were taken in the thawing seasons when the snow cover is limited to enable an
216 easy detection of the glacier from snow. Besides, a bright cloud is still needed to show
217 the watershed clearly; however a difficult case ensues when the rainy season comes
218 in-between the thawing season when the atmosphere is often covered by thick cloud.
219 Further, in order to show glacier retreat and its impact on debris flows properly, the
220 images should be within similar time interval, like 3 years, before and after debris
221 flow events. As the high resolution images are rare to obtain and we could only collect
222 one SPOT image (Take by the satellite of Systeme Probatoire d'Observation de la
223 Terre with a space resolution of 5m) in 2008. To achieve consistency of the images,
224 we collected 5 TM images image (Taken by No. 4 or 5 thematic mapper carried on the
225 satellite Landsat with a space resolution of 30m), taken on Sep. 17th, 2000, Jul. 24th,
226 2003, Sep. 21st, 2006, Sep. 24th, 2009 and Aug. 4th, 2013, respectively.

227 Based on the 5 TM images, we classified the area as glacier, snow, bared land,
228 gully deposition and vegetation in time series (Figure 6), and the area of each is given
229 in Table 1. Figure 6 showed that deglaciation was taking place in Tianmo valley and
230 in particular, the eastern branch had experienced the sharpest deglaciation. In order to
231 show clearly the rapid rate of glacier retreat, a graph was plotted to show the changing
232 of glacier and the eastern branch in Figure 7.

233 Figure 7 shows that glacier in Tianmo valley had been in shrinkage since 2000 to
234 2013, with variation in glacier retreat rate. In 2000~2003, 2003~2006, 2006~2009 and
235 2009~2013, the glacier retreat rate in Tianmo valley corresponds to 0.02, 0.06, 0.027
236 and 0.0075km²/a and 0.0033, 0.01, 0.008 and 0.002 km²/a for the eastern branch.
237 According to these figures the largest glacier retreat rate was in 2003~2006, followed
238 by that in 2006~2009. It is important that glacier area at the beginning should be taken
239 into consideration to judge the changing rate of glacier. The glacier retreat rate is
240 normalized and the relative glacier retreat rate can be calculated based on their area

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242 changing, which is defined as the retreat area of glacier in one year.

243 The relative glacier retreat rate are 11.30, 35.09, 17.43 and $5.17 \cdot 10^{-3} \text{km}^2/\text{a}/\text{km}^2$
244 during 2000~2003, 2003~2006, 2006~2009 and 2009~2013, respectively; whereas, it
245 is 20.83, 66.67, 66.67 and $20.83 \cdot 10^{-3} \text{km}^2/\text{a}/\text{km}^2$ for the eastern branch. These figures
246 show that the relative glacier retreat rate for the eastern branch had shrunk much more
247 sharply between 2000 ~2013.

248 In this research, TM images with 3 year intervals were applied can only get the
249 mean glacier retreat rate. As glacier retreat rate in the 3 three years could be either
250 high or low, field measurement of the nearby glacier is used to show the glacier retreat
251 condition before debris flows. Yang et al.(2015) had conducted field measurement of
252 No.94 Glacier in Parlung Zangbo Basin since 2006 and the field measurement
253 suggests it was in negative balance in 2006~2010(Figure 7). The negative balance
254 reached the maximal in 2009, followed by 2008 and 2006, indicating sharp
255 deglaciation in these three years.

256 When we combined the result of TM image and filed measurement of No. 94
257 Glacier, we observed that it is right before debris flows that glacier in Tianmo valley
258 experienced the sharpest deglaciation in 2006, 2008 and 2009, which was also
259 coincidental with the elevated mean annual air temperature (Figure 5).

260 (3) Antecedent air temperature and rainfall process

261 The air temperature in the source area can be obtained using the vertical decline
262 rate ($0.54^\circ\text{C}/100 \text{m}$). According to this method, the air temperature in the source area
263 was 9.8°C lower than that at the Bomi meteorological station. We collected the daily
264 temperature; that is the lowest temperature, the mean temperature and daily rainfall
265 from June to September in 2007 and 2010 (Figure 8).

266 According to Figure 8, the lowest air temperature was below 0 at the end of June,
267 2007. At the beginning of July, the air temperature started to rise quickly which
268 continued until early September when DF1 occurred, this demonstrates that the high
269 air temperature in July and August contributed to DF1.

270 According to Figure 8, the air temperature was high from early July to late

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275 August, and another high air temperature period emerged in early September. When
276 DF2 occurred in late July the air temperature had reached the maximum for that year,
277 which suggests that the air temperature in early and middle July was responsible for
278 DF2. After DF2 occurred, the air temperature in August began to prepare for DF3.

279 Antecedent air temperature fluctuation includes the air temperature and its
280 duration. The air temperature and duration before debris flows are variable, making
281 them difficult to evaluate. The accumulation of positive air temperature is usually
282 applied to analyze the impact of air temperature on glacier melting (Rango and
283 Martinec, 1995), which can be expressed as:

$$284 \quad T_{PT} = \sum_{i=-n}^0 T_i (T_i > 0) \quad (1)$$

285 Where T_{PT} is the positive air temperature accumulation, °C and T_i is the
286 average daily air temperature; only $T_i > 0$ is included.

287 Because air temperature is successive, it is difficult to determine the beginning of
288 positive air temperature accumulation. Glacial tills can lessen the heat that penetrates
289 into them, and the low air temperature can only contribute to the upper thin layer;
290 moreover, freeze-thaw cycles exist when the lowest air temperature is less than 0°C.
291 From this point of view, the beginning of positive air temperature accumulation is
292 defined as the time at which the lowest air temperature exceeds 0°C for two or three
293 successive days and the following days was higher than 0°C or the last debris flow.

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294 Based on the above method, we can deduce that the positive air temperature
295 accumulation began when the lowest air temperature exceeded 0°C for several
296 successive days, starting on June 28th, 2007 and June 9th, 2010 corresponding to DF1
297 and DF2, respectively, and on July 26th, 2010 for DF3, following DF2. The duration
298 and T_{PT} were calculated for each debris flow event, the result was 69 days and
299 517.9°C, 47 days and 332.1°C, 42 days and 320.4°C (Figure 8) for DF1, DF2, and
300 DF3, respectively. The result showed that T_{PT} for DF1 is much larger than the other
301 two, and which is coincidence to the fact that there was that there was no debris flows

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305 in the past dozens of years and extraordinary external forces such as larger T_{PT} is
306 required to destroyed the long-term balance, the the fully recharged channel could be
307 another reason.

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308 (4) Triggering conditions

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

313 Antecedent rainfall is a factor that favours debris flows. In our analysis, the
314 rainfall over the three days preceding a debris flow event is given in Figure 9.

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

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

335 due to the long term rising air temperature.

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

343 4. Discussion

344 Debris flows initiation is the process when water source provokes the movement
345 of soil sediment. In this research, we found that the three debris flows were triggered
346 by high air temperature and rainfall in DF1, high air temperature in DF2, and rainfall
347 in DF3 respectively. When we analyzed the date and the triggers for these events,
348 various questions came to mind that gave reasons to doubts: 1) Why debris flows did
349 not occur in 2006 or 2009 when deglaciation reached its peak and more ice melt water
350 was present; 2) Why DF1 and DF3 occurred in September when the air temperature
351 and the ice melt water was decreasing; 3) Why was there is no large scale debris flows
352 triggered by the previous heavier storm. It makes us believe that the impact of water
353 source on the magnitude and frequency of debris flows is quite low, or there could be
354 much more debris flows; and instead, soil source, including its magnitude and activity,
355 should be the predominate controller, just as Jakob et al., (2005) pointed out that the
356 recharge of channel should be the prerequisite for debris flows. However, in most
357 situations we cannot reach the source area to detect the soil source and the high-tech
358 remote sensing can just distinguish the boundary of soil source. In the periglacial area
359 where the glacial till is often covered by glacier or everlasting snow, changing of soil
360 source seems to be of high difficulty to detect. In this research, we try to combine the
361 meteorological condition and the literatures to discuss the probable variation of glacial
362 tills before debris flows.

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365 **(1) Variation of glacial till in annual years**

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

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376 The retreat of glaciers and glacial tills with climate warming is quite different.
377 Deglaciation is accompanied by melting of internal ice particles. The melt of internal
378 ice particles can produce active surface layer which can obstruct heat flux from
379 penetrating into the deep layer, result into the melting of internal ice particles lagging
380 behind glacial retreat (Hagg et al, 2008). As strong heat gradient is existed at the
381 surface while quite limited in deep layers, glacial tills with thicker depth always has a
382 relatively slower ablation rate, and the ablation rate of glaciers and internal ice
383 particles, can enjoy the same value at the glacier surface close to the moraine slope.
384 The newly formed bared glacial till is frozen with high ice content, the cohesion of the
385 ice particles renders the bared glacial till with high shearing strength and stability and
386 only the surface layer is of high activity. Therefore, we often see many bare moraine
387 slopes near glaciers, for this reason there were no debris flows of large magnitude in
388 2006 and 2009 when glacier retreat reached the maximal.

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删除的内容: remain at the same pace at the junction with the slope

389 **(2) Variation of glacial till in antecedent days**

390 After the long term cold winter, the whole glacial tills would become frozen. If
391 the regressive glacier was not recovered in the winter, the glacial tills would often be
392 covered by snow. As air temperature increases again, the surface snow would melt

402 first, followed by the internal ice particles. The thawing of internal ice particles would
403 induces a series of changes in the glacial till, which include the following: 1) the
404 thawing will break the bonds of ice particles and increase the instability between ice
405 cracks (Ryzhkin and Petrenko, 1997; Davies et al, 2001); 2) the sharp air temperature
406 fluctuation in high alpine mountainous areas induces a repeated cycle of expansion
407 and contraction in the glacial till that can destroy the mass structure to some extent; 3)
408 the seepage of ice melt-water can deliver fine-grained sediments that were formerly
409 frozen in the ice matrix (Rist, 2007); and 4) the ice melt-water can result in a higher
410 water content and pore water pressure (Christian et al, 2012). These changes in glacial
411 till can sharply decline the soil strength, shifting to an active mass from the uncovered
412 and frozen moraine (Figure 10, B to C). Because the heat conduction in glacial till is
413 quite slow, this process may last for a very long time and also requires a high
414 antecedent air temperature.

415 Heat conduction via the percolation of rainfall and ice melt-water can amplify
416 the depth of active of glacial till (Gruber and Haeberli, 2007), whereas the shelter of
417 surface glacial till can hinder the heat flux from penetrating into the deep layer. At a
418 low air temperature, the heat flux should be constrained to the surface layer, and a
419 large heat gradient due to a high air temperature would contribute much more to the
420 heat flux and ice melt in the deep mass, meaning that the long-term effect of a high air
421 temperature can amplify the active glacial till (Åkerman et al, 2008), under which lies
422 frozen glacial till with a high ice content. The activity of glacial till variations with
423 depth, high in the surface and low in the deep layers, and landslide failure can take
424 place on glacial till slopes in a retrogressive manner, coinciding with long-term air
425 temperature fluctuations although the glacial till is significantly unlimited in
426 deglaciation areas.

427 (3) Failure of glacial tills

428 Failure of glacial could be diversity. Active glacial till slopes with low strength
429 are usually vulnerable, and their failure can occur when the air temperature is above
430 0°C (Arenson and Springman, 2005). Either rainfall, the seepage flow of glacier or ice

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434 particle melt-water could percolate the tills and trigger the failure (Figure10, C to D).
435 This kind is called the shallow landslide type, and the failure mechanism lies in the
436 ablation of internal ice particles and the percolation of melt-water can decrease the
437 soil strength at first (Arenson and Springman, 2005; Decaulne et al, 2005); later, the
438 subsequent rapid percolation of melt-water or rainfall can saturate the glacial till,
439 decrease soil suction and shearing strength and then trigger the shallow landslide
440 failure (Springman et al, 2003; Decaulne and Sæmundsson, 2007; Chiarle et al, 2007).
441 Whether the failure can induce debris flows is still dependent on the ability that it can
442 entrain the debris layer, otherwise, it can deposit and charge the channel.

443 Another kind of failure can take place by the increased water stream that entrain
444 sediments and forms a solid-liquid wave if the channel is charged with loose ravel.
445 This kind of water stream could be the combination of the three factors, including
446 rainfall, melting ice or the overflow when the glacier collapse falling down into the
447 downwards water pool. The runoff can generate debris flows when a peaked runoff
448 flow over debris deposits(Kean et al., 2013; Gregoretti et al., 2016) and pose
449 hydrodynamic forces acting on the surface elements of the debris layer(Tognacca et al.
450 2000, Gregoretti, 2000). The concentration of runoff in the channel bottom causes
451 erosion of the debris surface layer and then extends to the layers below with whole or
452 partial mobilization of the bed material. The inclusion of bed material in the water
453 stream generates debris flow (Gregoretti, 2008).

454 The fluctuation of air temperature within a specific low range can result into
455 limited seepage flow. glacier in one valley is limited, it is unlikely for failure to be
456 triggered by the limited ice melt water in short-term increases of air temperature;
457 instead, prolong air temperature increases it is needed to generate more water flow.
458 Rainfall can initiate debris flows from active glacial tills with a mechanism similar to
459 that of storm-induced debris flows in non-glacier areas (Iverson et al, 1997;
460 Springman et al, 2003; Sassa and Wang, 2005; Gregoretti, 2008; Kean et al., 2012). In
461 the European Alps, periglacial debris flows are mainly provoked by rainfall, which is
462 also related with air temperature fluxes (Stoffel et al, 2011). The portion of rainfall
463 and air temperature required for debris flows triggering could be negative. Air

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the .
As

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percolation would impact the 428 rainfall
intensity and duration required for
periglacial debris flows .

471 temperature increase causes melting and water runoff, and the rainfall needed for
472 providing the percolating flows or exact critical discharge for debris flow triggering
473 would be much less. Beside, the required rainfall, like the rainfall intensity and
474 duration, may also require other preconditions, such as the distribution of glaciers and
475 frozen glacial tills and the terrain of the source area to enhance the debris flow
476 (Lewkowicz and Harris, 2005).

477 The three debris flow events possess similar annual meteorological conditions,
478 except that the positive air temperature accumulation prior to DF1 was significantly
479 larger. DF1 occurred at the end of a prolonged period of high air temperature, prior to
480 this, there were instances of failure but no large-scale debris flows. On July 25th 2010
481 when the daily rainfall particularly reached 20.7 mm, no debris flows were generated
482 because thick active glacial till was still lacking after small failure events. In 2010, the
483 largest daily rainfall occurred on June 7th, accounting for 37.5 mm, at the beginning of
484 an air temperature increase when the glacial till was frozen and had low activity. The
485 lack of glacial till activity was the likely cause of the absence of debris flows. On
486 August 23rd, the daily rainfall was 20.3 mm, the antecedent air temperature
487 accumulation dated from DF2, and the active glacial till was still under development.
488 On September 6th, the antecedent positive air temperature accumulation was smaller,
489 and a low air temperature had emerged previously; however, the high rainfall intensity
490 supplemented this lack of prolonged high air temperature.

491 5. Conclusion

492 Climate changes have serious effects on high mountainous areas, and mass
493 movement of sediments such as periglacial debris flows is increasingly frequent.
494 Prolonged increases in the mean annual air temperature are regarded as very
495 favourable for periglacial debris flows. In particular, the annual “hot-dry” weather
496 condition one or two year earlier was responsible for the three debris flow events in
497 Tianmo valley. Debris flow is usually not initiated in the year when the mean annual
498 air temperature spikes as melting of internal ice particles lags behind the glacial
499 retreat result from the prolong air temperature rise.

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the

502 Glacial till is unlimited in the deglaciated area, while its activity relies on glacial
503 retreat and internal ice particle melting. Changing of glacial tills induced by
504 increasing air temperature is the first step of periglacial debris flows comparing with
505 the storm induced debris flows in non-glacier area, during which the varied air
506 temperature condition with different factor drives the changing and temperature series
507 can remove glaciers, produce bared glacial till and enhance the activity step by step.

508 It is difficult to observe the changes of glacial till in source areas of debris flow,
509 and the analysis of the phase conversion of glacial till in this research is based on the
510 triggering conditions and other literatures. Indeed, the meteorological conditions, such
511 as the antecedent air temperature and meteorological triggers that drive the phase
512 conversion are partly overlapped and difficult to distinguish. In the first study, we
513 hope to distinguish the effect of each meteorological condition and more detail study
514 should be done in further research.

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For periglacial debris flows of 467 a large magnitude, the long-term effect of air temperature is required, although rainfall468 can shorten the antecedent period and generate debris flows earlier. .

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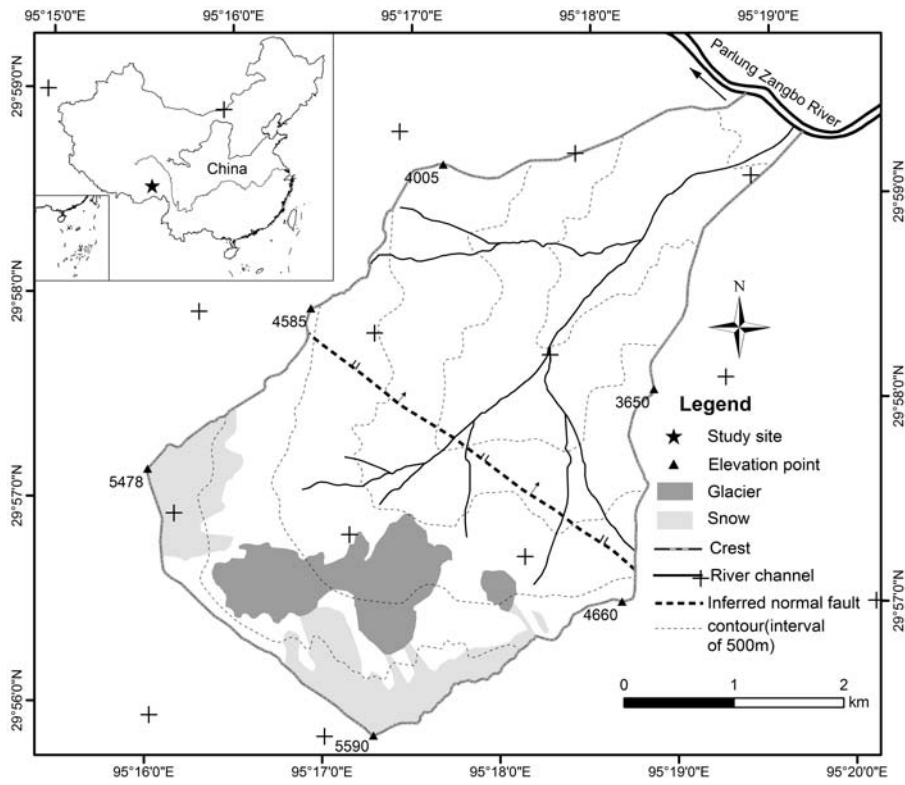
665 Table 1 Changing of glacier, snow, bared land, gully deposition and vegetation in Tianmo valley

Year	Glacier (km ²)	Glacier(eastern branch) (km ²)	Snow (km ²)	Bared 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

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667 Table 2 Basic information of the debris flows in Tianmo and the 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	4 Sep. 2007	6
					25 Jul. 2010	5
					6 Sep. 2010	5
2	Kangbu valley	30°16'N 94°48'E	48.7	1.06	4 Sep. 2007	3
3	Xuewa valley	29°57'N 95°23'E	33.22	0.95	4 Sep. 2007	2
4	Baka valley	29°53'N 95°33'E	22.15	2.46	7 Sep. 2007	3
5	Jiaqing Valley	30°16'N 94°49'E	15.51	1.12	9 Sep. 2007	3



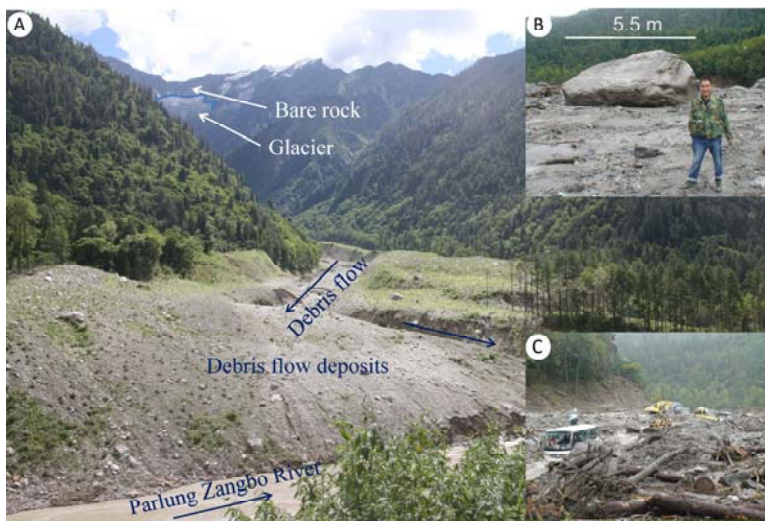
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Figure 1 Location and basic information of Tianmo Valley



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

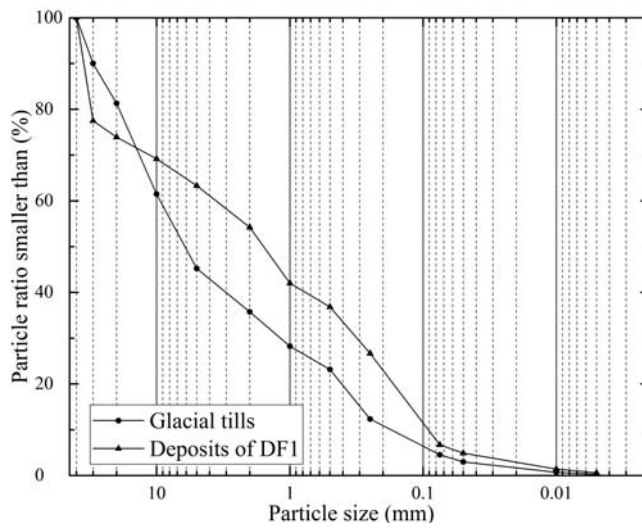


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673 Figure 3 DF1 in 2007(A. Overview of Tianmo debris flows from the downstream area; B& C.

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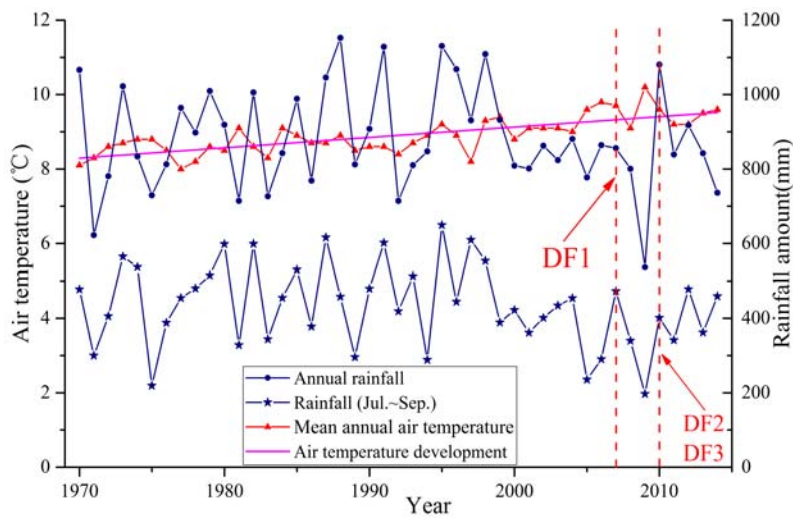
Boulder and debris flow deposits on the north side of the Parlung Zangbo River)



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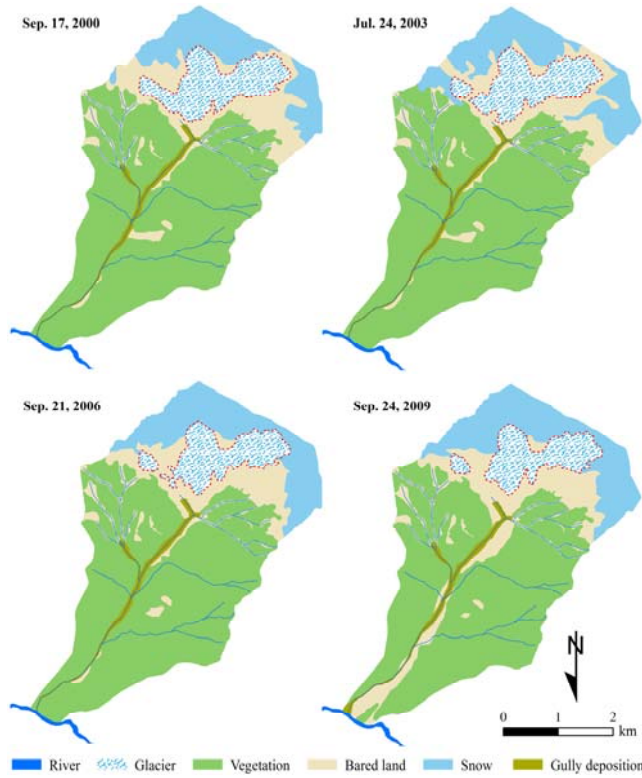
Figure 4 Particle size distributions of the glacial tills and debris flow deposits



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



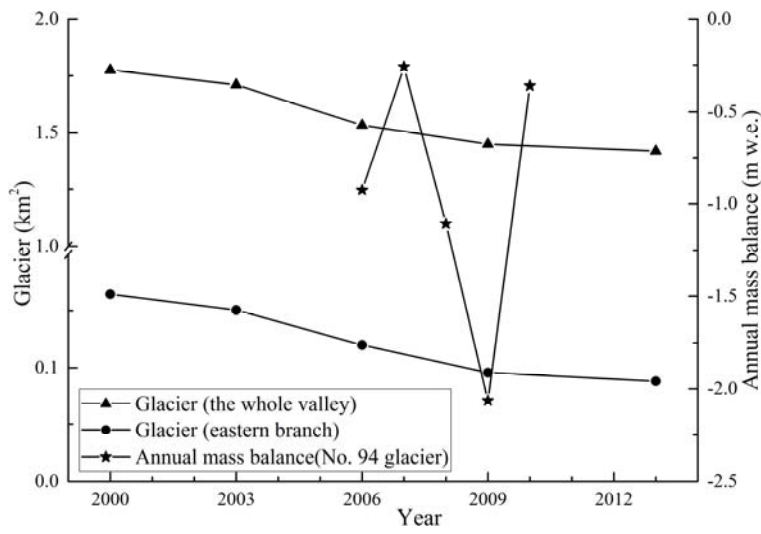
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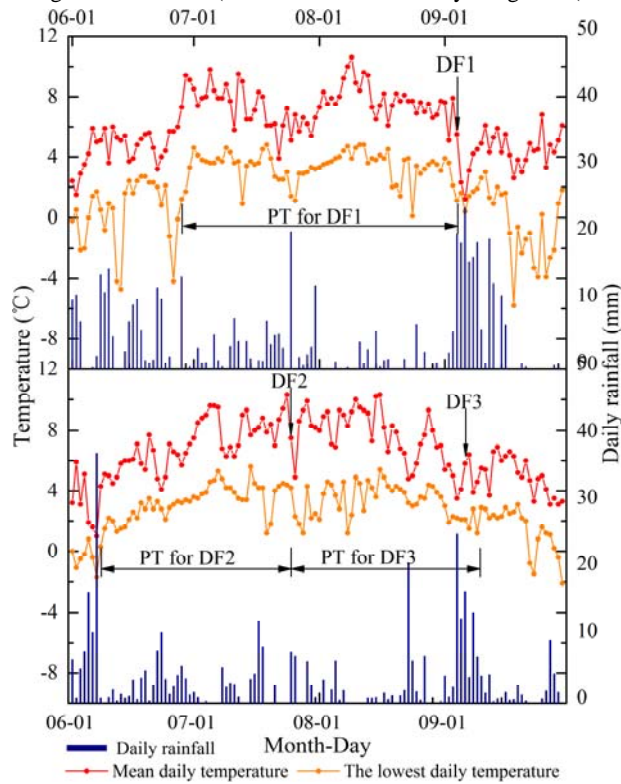
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Figure 6 Distribution and changing of glacier, snow, bared land, gully deposition and vegetation in Tianmo valley



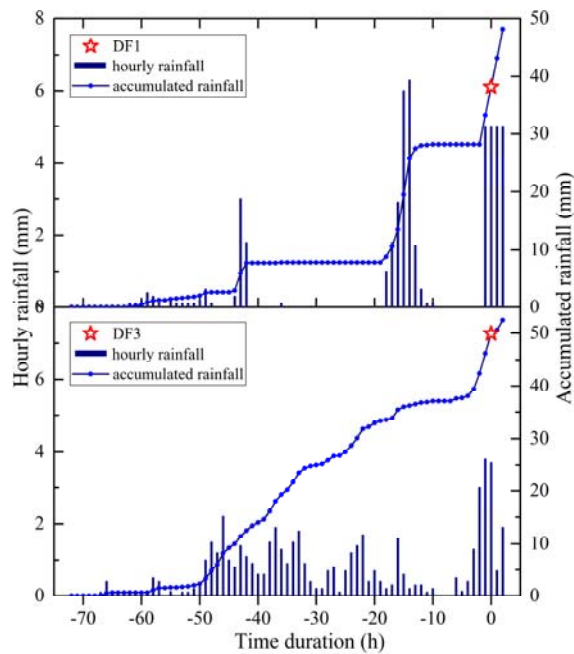
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Figure 7 Changing of glacier via time and the measured annual mass balance for the Parlung No. 94 Glacier (mass balance is edited by Yang et al.(2015))



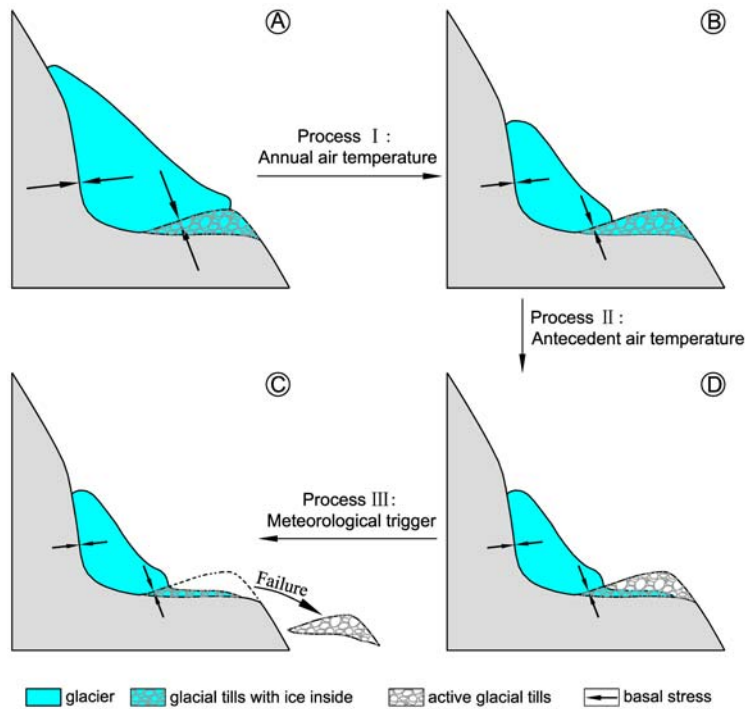
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Figure 8 Air temperature and rainfall before and after DF1, DF2 and DF3



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689 Figure 9 Variation of the rainfall accumulation prior to DF1 and DF3 (no rainfall before DF2)



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