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Destructive debris flows occur frequently on glacierized Mount Nyenchen Tanglha, Bomi, Tibet. Since 1953, hundreds of such flows have occurred in the Guxiang valley during periods of atypically hot or rainy weather in summer or early autumn. From 1964 to 1965, 95 debris flows were documented at a temporary debris flow observation station; 25 of these debris flows with a peak discharge Q_{max} above 50 m^3/s were considered in the present study. Supported by meteorological data from the nearby Bomi station, statistical analysis showed that outburst debris flows from the Guxiang glacier are highly correlated with atypical weather. Finally, the conditional probability of a debris flow from the Guxiang glacier as a function of daily rainfall R and maximum temperature T_{max} for rainy days (R $\geq$ 5 mm) and dry days (R $<$ 5 mm) is suggested as a plausible link between weather and outbursts of debris flow.

Keywords: Glacial debris flow; Kolmogorov–Smirnov test; meteorological conditions; Tibet.
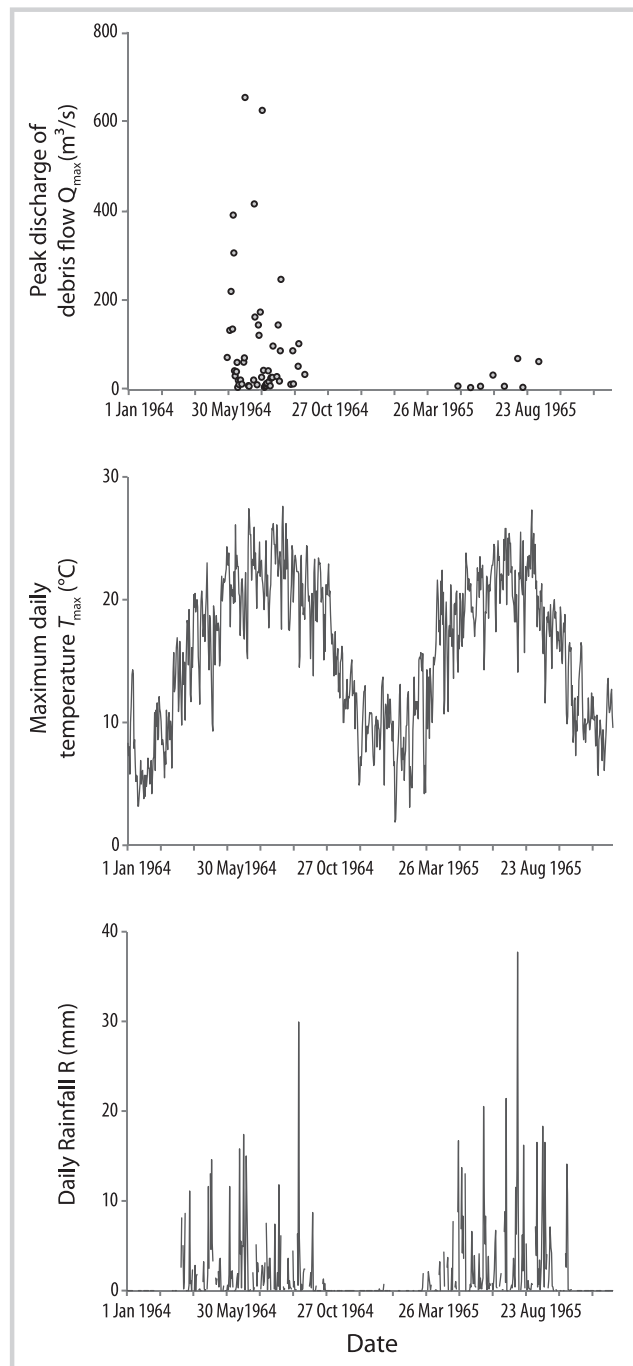
Introduction

Destructive debris flows frequently move along the stream valleys of the glacierized Mount Nyenchen Tanglha, which is widely covered by the largest maritime glacier in Tibet. These debris flows are generally considered to originate as glacial outburst floods (Richardson 1968; Crandell 1971; Du et al 1984a, 1984b; Driedger and Fountain 1989; Walder and Driedger 1995; Walder and Fountain 1997; Clague and Evans 2000; Richardson and Reynolds 2000; Bardou and Delaloye 2004; Liu et al 2011), which are usually induced by glacial lake outbursts, meltwater, etc (Richardson 1968; Crandell 1971; Du et al 1984a, 1984b; Driedger and Fountain 1989; Walder and Fountain 1997; Clague and Evans 2000; Richardson and Reynolds 2000). Many researchers have already pointed out that precipitation also plays a major role in the initiation of debris flows in Guxiang (Zhang 1980; Du et al 1984a, 1984b). The transformation from water flood to debris flow generally occurs in channels cut into stagnant ice and glacially derived deposition or right up to the glacier termini (Du et al 1984a, 1984b; Driedger and Fountain 1989; Walder and Driedger 1995; Walder and Fountain 1997; Clague and Evans 2000; Richardson and Reynolds 2000; Liu et al 2011). On 29 September 1953, the greatest debris flow in the history of Guxiang occurred, moving

1.1×10^7 m^3 of debris into the Palongzangbu River and forming a barrier lake 1–2 km wide and 5 km long (Zhang 1980; Du et al 1984a, 1984b; Chengdu Institute of Mountain Hazards and Environment, Chinese Academy of Sciences, Ministry of Water Resources 1999). Since then, during periods of atypically hot or rainy weather in summer or early autumn (Du et al 1984a, 1984b; Wang et al 1984), debris flows from the Guxiang glacier have repeatedly occurred. These hazards have seriously damaged the G318 national highway and facilities constructed alongside the road, causing large economic losses.

From 1964 to 1965, a temporary debris flow observation station was operated by the Lanzhou Institute of Glaciology and Cryopedology near the debris flow outlet from the Guxiang valley, and 95 flows were recorded (Wang et al 1984; Figure 1). In all the documented events during these 2 years, there were 25 debris flows with a peak discharge Q_{max} above 50 m^3/s. Our analysis considers these 25 flows primarily because of the 3 following reasons: First, in these 2 years, all debris flows were recorded professionally at the observation station, which provided our researchers with accurate and detailed data. Second, debris flows with greater discharge have a greater destructive power, especially these 25 flows with peak discharge Q_{max} above 50 m^3/s (Wang et al 1984).

FIGURE 1 Debris flows in Guxiang and the measured values of daily rainfall and maximum daily temperature at Bomi during 1964–1965. (Source: Debris flows, adapted from Wang et al [1984]; meteorological data for rainfall and temperature adapted from China Meteorological Administration [1973])


years 1964–1965, we determine through statistical analysis that debris flows are predictable in the sense that they are highly correlated with the measured daily rainfall R and maximum temperature T_{max}. Finally, the conditional probability of a debris flow from the Guxiang glacier as a function of daily rainfall R and maximum temperature T_{max} for rainy days ($R \geq 5$mm) and dry days ($R < 5$ mm) is suggested as a plausible link between weather and outburst debris flows.

Description of the study area

Guxiang valley is a tributary of the Palongzangbu River at latitude $29°54.73'$N and longitude $95°27.00'$E (Figure 2). It is located in the low-altitude mountain region on the south side of Mount Nyenchen Tanglha and is usually influenced by the southwest monsoon from the Indian Ocean. The Guxiang glacier is a typical maritime glacier, in that it receives a large amount of precipitation and is exposed to high temperatures (Shi et al 1964; Du et al 1984a, 1984b). The Guxiang catchment area is 26 km^2 with a 6 km channel length, and the snow cover is usually above 5000 m above sea level (asl). Driven by avalanche activity, masses of snow/ice drop into the lower-altitude regions of cirques and scarps between 4000–5000 m asl, shaping 6 hanging/cirque glaciers, among which the termini of some extend to altitudes as low as 3700 m asl, which is far beneath the snow line. Consequently, these debris-rich hanging/cirque glaciers do not "self-regenerate"; they melt fast and mainly depend on snow/ice avalanches for their supply (Shi et al 1964). These characteristics of the Guxiang glacier support the water and material supply for most or all of the debris flows.

Considering the evolution of the Guxiang valley before 1953, outlet streams from the active glacier ice emerged and flowed along the valley, their water depth was less than 10 m, and no evidence of debris flows was found (Du et al 1984a, 1984b). After the most catastrophic debris flow occurred in 1953, ceaseless head and lateral erosion arose and developed, resulting in a rapid evolution of geomorphology in the Guxiang valley. In detail, currently, head erosion has extended the flow path over 800 m toward the head of the catchment, exposing more and more bedrock at the site of the headwater. On the other hand, numerous bank collapses or slides have occurred in the channel bed due to the deep incision caused by lateral erosion. Thus, the width of the channel bed has been broadened from less than 10 m to 100 m (Chengdu Institute of Mountain Hazards and Environment, Chinese Academy of Sciences, Ministry of Water Resources 1999). Moreover, under the conditions of strong incision, the amount of loose material that could be entrained by floods has increased significantly. Finally, outburst floods are transformed into debris flows as they pass through the incised reach (Zhang 1980; Du et al 1984a, 1984b; Chengdu Institute of Mountain Hazards

Third, among all the debris flow data collected, peak discharge Q_{max} provided the best data set.

In the present paper, we first summarize the geomorphic conditions supporting the water and material origin for most or all of the debris flows. Then, supported by meteorological data measured at the Bomi station for the months May–September in the

FIGURE 2 Location of the study area and geomorphic conditions for the occurrence of debris flow. (Map by Jiankang Liu)
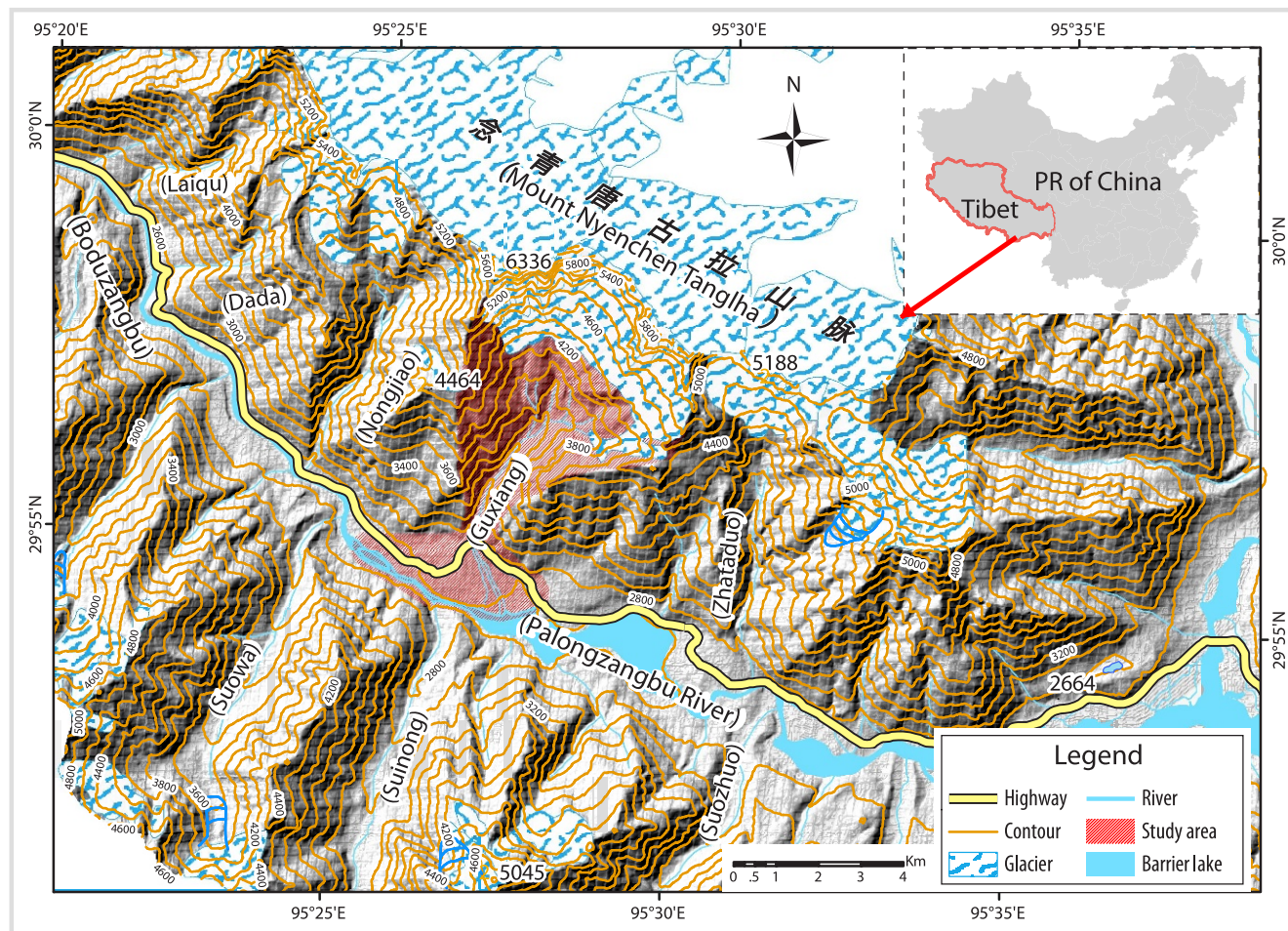

Relationship between debris flows and weather

As noted by many researchers (Shi et al 1964; Zhang 1980; Du et al 1984a, 1984b; Wang et al 1984), all debris flows from the Guxiang glacier since 1953 have usually occurred in the months May–September. Generally, 2 distinct mechanisms can occur during the initiation phase of a debris flow: precipitation or meltwater induced by high temperature, both of which can generate a flood and even convert it to a debris flow. Precipitation has a direct influence on triggering debris flows, but the general rise in temperature in the region of a maritime glacier also plays an important role. The increase in temperature can enhance the processes of glacier/ice melt, inducing floods that in turn initiate debris flows. Indeed, Zhang (1980), Driedger and Fountain (1989), Walder and Driedger (1995), and Hock (2005) have demonstrated that high

temperature has a significant effect on the formation of floods and debris flows.

In order to test whether debris flows are correlated with atypical weather conditions, and whether the measured meteorological data might be useful predictors of debris flow occurrence, we employed the meteorological data measured by a weather station near the Guxiang glacier and performed various statistical analyses on rainfall and daily temperature. Earlier research by Zhang (1980), Hock (2003, 2005), and He et al (2008) demonstrated that the melting rate of ice/snow, and the runoff of meltwater, achieve their peak discharge very near the daily maximum temperature, and, therefore, we adopt the maximum value as the index of daily temperature. Elevation is the main influence on temperature, including the maximum temperature. However, our ultimate aim in this paper is to test whether the measured meteorological data might be useful predictors of debris flow occurrence, and, therefore, the dependency of temperature trends on height is beyond our consideration.

FIGURE 3 Cumulative distribution functions for debris flows, and measured values of daily rainfall at the Bomi station for the months May–September in 1964–1965. The Kolmogorov–Smirnov statistic d_{max} is indicated.

FIGURE 4 Cumulative distribution functions for debris flows, and measured values of maximum daily temperature at the Bomi station for the months May–September in 1964–1965. The Kolmogorov–Smirnov statistic d_{max} is indicated.
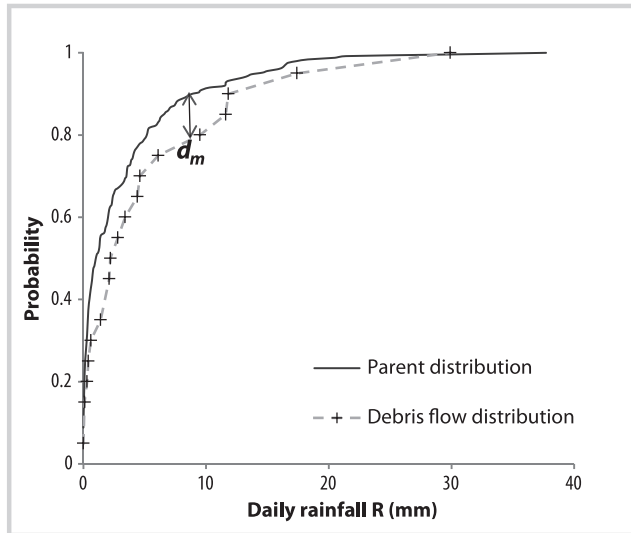
On the south side of Mount Nyenchen Tanglha, the National Weather Service maintains several stations, 2 of which are relatively close to the study area: one at Bomi, about 30 km northwest of the Guxiang glacier, at an elevation of 2250 m, and the other at Linzhi, 100 km southwest of the Guxiang glacier at an elevation of 3000 m. Statistical analysis shows that the published values of maximum daily temperature T_{max} at these 2 stations are well correlated. However, due to a number of missing data, values of daily rainfall R are only generally correlated. For the data during the period under consideration, linear regressions give the expressions below:

$$T_{max}(\text{Linzhi}) = 0.88 T_{max}(\text{Bomi}) + 10.1 \quad (r^2 = 0.84), \quad (1)$$

$$R(\text{Linzhi}) = 0.80 R(\text{Bomi}) + 10.1 \quad (r^2 = 0.48), \quad (2)$$

where T_{max} is the maximum daily temperature in Celsius, R is the daily rainfall, and r^2 is the coefficient of determination.

The available data suggest that temperature and precipitation in the south of Mount Nyenchen Tanglha are spatially coherent. In what follows, we assume that meteorological data from Bomi, which is the closest station to the study area, may be employed as representative of conditions in the Guxiang valley. In our analysis, meteorological data are restricted to 1964–1965 because debris flow dates are not accurately documented for other years. The data for the months May–September used in the analysis approximately encompass the meteorological conditions for debris flows in the Guxiang valley. Actually, debris flow dates under consideration ranged from 13 May to 24 September (Wang et al 1984).

The statistical distributions of daily rainfall R and maximum daily temperature T_{max} at Bomi are shown in
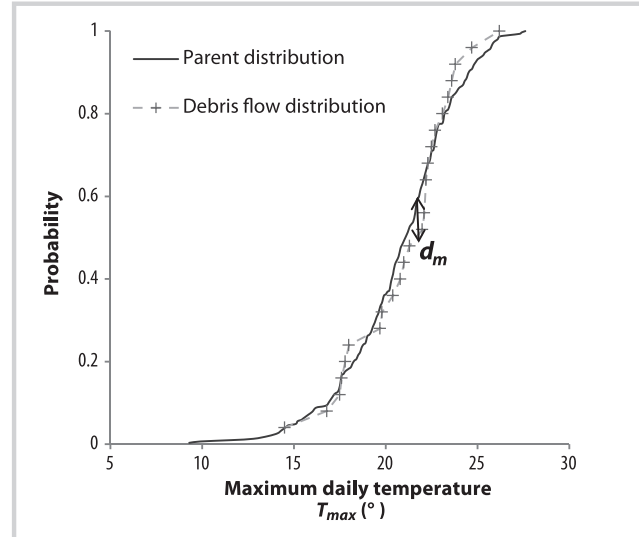
Figures 3 and 4. (Days with missing values of meteorological data were excluded in compiling the figures.) The solid curve in each figure is the cumulative distribution function (henceforth CDF); the crosses connected by dashed lines show the distributions for days on which debris flows from the Guxiang glacier occurred. In order to test whether the probability that the distributions of meteorological data for those days on which debris flows occurred are drawn at random from the CDFs, the 2-sample Kolmogorov-Smirnov test, which is a test for goodness of fit (Conover 1971), is utilized in our analysis. The statistic for the 2-sample, 2-sided Kolmogorov-Smirnov test is defined by the module of the maximum vertical distance d_{max} between the CDF and the stepwise sample curve connecting values measured on days of debris flow occurrence (Figures 3 and 4) and the sample sizes of the curves to be compared (m, n). In our case, m is the number of samples in the CDFs; n is the number of debris flows in the sample curve. Critical values for the maximum difference $d_{\alpha[n]}$ when sample sizes are small can be found in Rohlf and Sokal (1981). When sample sizes are large, $d_{\alpha[n]}$ is calculated from the following expression:

$$d_{\alpha[n]} = K_\alpha \sqrt{(m+n)/(mn)}, \quad (3)$$

where

$$K_\alpha = \sqrt{(-\ln[\alpha/2])/2}, \quad (4)$$

and α is the level of significance (Rohlf and Sokal 1981). For a test of the null hypothesis (H_0), which states that the sample population (days with debris flows) is drawn appropriately at random from the parent population, versus the broad alternative that H_0 is not true, we reject H_0 if $d_{max} \geq d_{\alpha[n]}$ or we accept H_0 if $d_{max} < d_{\alpha[n]}$.

TABLE 1   Results of Kolmogorov–Smirnov test for rainfall data measured at Bomi station. Debris flows with missing values in meteorological data in the periods under consideration were excluded from the analysis. (Significance level α values 0.05.)

Type of rainfall data	Number of debris flows in sample (n)	K-S statistic (d_{max})	Critical value ($d_{\alpha[n]}$)	Notes
Daily	20	0.248	0.316	Number of debris flows dropped due to missing values in meteorological data in periods under consideration
Daily average, all 2-day periods	19	0.187	0.326	
Daily average, all 3-day periods	17	0.201	0.345	
Daily average, all 4-day periods	14	0.232	0.381	
Daily, all rainy days ($R \geq 5$ mm)	6	0.372	0.586	
Daily average, 2-day rainy periods ($R \geq 5$ mm)	6	0.417	0.586	
Daily average, 3-day rainy periods ($R \geq 5$ mm)	5	0.425	0.639	
Daily average, 4-day rainy periods ($R \geq 5$ mm)	4	0.273	0.710	

In the present analysis, the Kolmogorov–Smirnov test is preferred to the chi-square test for small sample sizes (Conover 1971), and the significance level α is given a value of 0.05.

Results are shown in the top halves of Tables 1 and 2 for the cases illustrated by Figures 3 and 4, as well as for analogous tests using a 2-, 3-, and 4-day moving average of daily rainfall and maximum daily temperature. (For moving averages, the last day of the averaging window is always the day of debris flow). All test results show that every measured test statistic d_{max} is less than its corresponding critical value $d_{\alpha[n]}$, which indicates that the sample population (days with debris flows) is drawn at random from the parent population. However, one can note that both temperature and precipitation can influence the occurrence of debris flows (Du et al 1984a, 1984b; Wang et al 1984; Walder and Driedger 1995; Walder and Fountain 1997).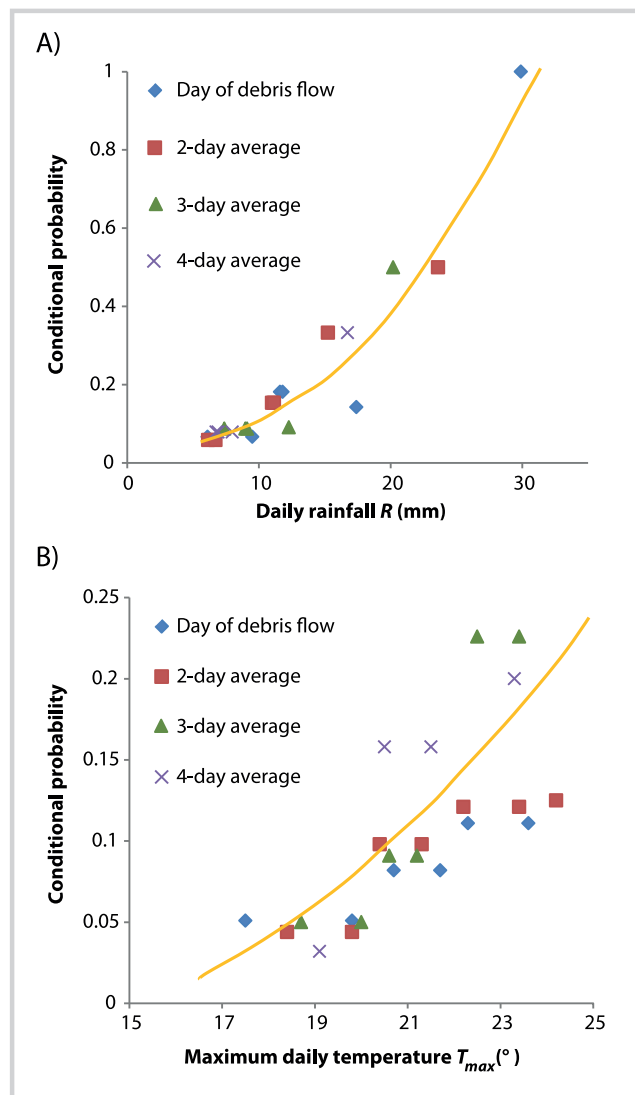 It is important to exclude the problem of mutual interference between factors when we discuss the relationship between outburst debris flow and these 2 meteorological parameters, in order to make stronger statements on our cases.

Figure 3 shows that there are 2 distinct subpopulations in the data for days with debris flows: dry days ($R < 5$ mm) and rainy days ($R \geq 5$ mm). Indeed, researchers have demonstrated that the threshold of daily rainfall that can initiate a debris flow is about 5 mm (Chengdu Institute of Mountain Hazards and Environment, Chinese Academy of Sciences, Ministry of Water Resources 1999). Therefore, in order to distinguish whether precipitation or meltwater induced by high temperature plays a major role in the initiation of debris flow, we define that days with $R < 5$ mm are dry days and that days with $R \geq 5$ mm are rainy days. In detail, temperature plays a leading role in the initiation of debris flows on the dry days, and precipitation is the major

TABLE 2   Results of Kolmogorov–Smirnov test for maximum temperature data measured at Bomi station. Debris flows with missing values in meteorological data in the periods under consideration were excluded from the analysis. (Significance level α values 0.05.)

Type of temperature data	Number of debris flows in sample (n)	K-S statistics (d_{max})	Critical value ($d_{\alpha[n]}$)	Notes
Daily	25	0.138	0.283	
Daily average, all 2-day periods	25	0.102	0.283	
Daily average, all 3-day periods	25	0.148	0.283	
Daily average, all 4-day periods	25	0.180	0.283	
Daily, all dry days ($R < 5$ mm)	14	0.193	0.376	Number of debris flows dropped due to missing values in meteorological data in periods under consideration
Daily average, 2-day dry periods ($R < 5$ mm)	13	0.186	0.393	
Daily average, 3-day dry periods ($R < 5$ mm)	13	0.230	0.396	
Daily average, 4-day dry periods ($R < 5$ mm)	10	0.243	0.451	

highly correlated with atypical weather, and in particular, with relatively rainy or hot weather. Many researchers have reached similar conclusions (Shi et al 1964; Du et al 1984a, 1984b; Wang et al 1984; Zhang 1980; Chengdu Institute of Mountain Hazards and Environment, Chinese Academy of Sciences, Ministry of Water Resources 1999), but they did not support their statements with statistical tests.

The conditional probability P_c of a debris flow from the Guxiang glacier, presumably as a function of R and T_{max} during the years 1964–1965, for the 2 subpopulations noted above, is shown in Figure 5a and 5b. The conditional probability is the relative frequency of the occurrence of debris flows given a particular value of R or T_{max}. There are fairly clear relations between P_c and either R or T_{max} measured on the day of a debris flow; for progressively longer averaging periods, the trends are not so obvious, owing at least partly to the fact that averaging "compresses" the range of R and T_{max}. Based on the fitted lines between P_c and meteorological data, it is plausible to predict outburst debris flow probabilities by using the measured values of R and T_{max} at the Bomi station. For example, during the period under consideration, the probability of a debris flow on any day with more than 20 mm of precipitation was about 0.44, and on a day with a temperature higher than 22°C, the probability was 0.125.

Tendencies of global warming have been observed in recent decades (Houghton et al 1990, 1992; Jones and Wigley 1990; IPCC 1996), and such trends have been reported for the Tibetan Plateau (Liu et al 2006; You et al 2008; Kang et al 2010). In the months May–September of 1964–1965, there were only 21 days on which the maximum daily temperature was greater than 25°C. However, in the same months of 2007, there were 35 days where the daily maximum temperature exceeded 25°C. After 1965, the observation station stopped taking measurements. Since then, all geohazards, including debris flows, have only been roughly recorded by the Highway Administration.

Fortunately, debris flows in 2007 were relatively better recorded. Therefore, we employed the meteorological data in the months of May–September 2007 to predict outburst debris flow probabilities, and then we compared the predicted results with the events actually recorded (Table 3). Table 3 shows that on the rainy days ($R \geq 5$ mm), 6 days are predicted for which the probability of a debris flow is greater than 0.40, and there are 3 days on which a debris flow occurred. For the dry days ($R < 5$ mm), 14 days are predicted for which the probability of a debris flow is greater than 0.40, and there are 7 days on which a debris flow occurred. It should be noted that the probability in mid-May was predicted as 1.00, but no events of debris flows were documented; this could be due to several reasons. First, in the early rainy season, rainfall mainly affects the saturation and liquefaction of the soil,

influence on the rainy days. In order to discuss these relationships between debris flow and meteorological conditions, with less mutual interference, we examined the statistical distribution of rainfall (in our case, days with $R \geq 5$ mm) excluding dry days and that of maximum temperature (in our case, days with $R < 5$ mm) excluding rainy days. Results are shown in the bottom halves of Tables 1 and 2, for tests using daily data and moving averages as before. All test results show that every measured test statistic d_{max} is less than its critical value $d_{\alpha[n]}$, which indicates that these cumulative distributions exhibit a high goodness of fit and that the sample population (days with debris flows) is drawn at random from the 2 subpopulations.

Based on these tests for goodness of fit, we can conclude that debris flows from Guxiang glacier are

TABLE 3 Predicted results and documented debris flow events in Guxiang for the months May–September in 2007. (Source: debris flow data adapted from the Highway Administration of Tibet [2007])

Date in 2007	Rainfall (mm)	Maximum daily temperature (°C)	Predicted probability of debris flow				Description of debris flows (DF)
			Daily	2-day average	3-day average	4-day average	
5.11	27.1	16.6	0.75	0.18	0.09	0.07	No DF documented
5.15	32.6	14.7	1	0.27	0.13	0.11	
5.16	45	7.1	1	1	0.70	0.38	
6.26	0	27.7	0.42	0.31	0.20	0.14	
6.29	0	28.4	0.49	0.36	0.33	0.35	
6.3	0	28.2	0.47	0.48	0.40	0.36	
7.5	0.1	28	0.45	0.23	0.19	0.16	
7.12	4.2	27.8	0.43	0.17	0.14	0.17	Several continuous DFs ($\sim$4.5 $\times$ 10^4 m^3 debris moved out and deposited)
7.13	0	29.4	0.63	0.52	0.26	0.20	
7.25	20.7	21.9	0.42	0.11	0.08	0.07	
8.1	0.3	28.3	0.48	0.37	0.19	0.16	
8.2	0	29.2	0.60	0.54	0.44	0.25	
8.3	0	27.9	0.44	0.51	0.50	0.44	
8.8	0.3	28.2	0.47	0.39	0.30	0.23	Several continuous DFs ($\sim$1.2 $\times$ 10^4 m^3 debris moved out and deposited)
8.9	0	29.1	0.58	0.52	0.44	0.36	
8.12	0.8	28	0.45	0.29	0.28	0.32	No DF documented
8.13	3	28.2	0.47	0.46	0.34	0.30	
8.2	0.1	27.8	0.43	0.31	0.19	0.18	
9.4	20.4	21.6	0.41	0.16	0.10	0.07	Several continuous DFs after rainy days ($\sim$1.6 $\times$ 10^4 m^3 debris moved out and deposited)
9.6	24.2	13.4	0.59	0.46	0.44	0.29	

but it fails to form a debris flow. Second, weather conditions are far more complicated in mountainous terrain, and the meteorological data measured at Bomi could be different from that at the Guxiang glacier. Third, the events that happened in these periods have not been documented or even investigated by the local administration. However, it is satisfactory to note that when the predicted probability is greater than 0.40, 50% of these days correlate with periods of debris flow, and, therefore, we can conclude that it is plausible to predict outburst debris flow probabilities by using meteorological data measured at the Bomi station.

Conclusions and discussions

Guxiang glacier, located in the south of Mount Nyenchen Tanglha, is a typical example of a maritime glacier in Tibet, and it released 95 debris flows during 1964–1965, including 25 with peak discharge Q_{max} above 50 m^3/s. Presumably, favorable geomorphic factors and characteristics of maritime glaciers account for the initial conditions for most or all of the debris flows. In the present paper, supported by statistical tests, we have proven that debris flows are highly correlated with atypical weather, and in particular, with relatively rainy or hot weather. Moreover,

with less mutual interference between meteorological conditions, we have also proven that there are highly correlated relationships between debris flows and both rainfall excluding dry days, and maximum temperature excluding rainy days. Finally, the conditional probability of a debris flow from Guxiang glacier as a plausible function of rainfall and maximum temperature for rainy days ($R \geq 5$ mm) and dry days ($R < 5$ mm) is suggested to predict outburst debris flow probabilities by using the measured values of meteorological data from Bomi station.

However, in order to predict the probability of outburst debris flows from Guxiang glacier, additional factors must be considered besides those values measured values at Bomi station. First, meteorological data measured at Bomi are just a rough representation of the complicated weather conditions in Guxiang glacier. Second, debris flows have moved masses of debris out of the valley, causing a significant change in material source, which also plays an important role in the initiation of debris flows.

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