Glacial Debris Flow Blockage Event (2018) in the Sedongpu Basin of the Yarlung Zangbo River, China: Occurrence Factors and its Implications

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Abstract

The cryospheric disasters, especially glacier disasters and permafrost disasters, has arose great risks to people's lives in Tibetan Plateau under climate warming. In this paper, the glacial debris flow blockage event on October 17th, 2018, in the Sedongpu basin of the Yarlung Zangbo River is taken as an example to analyse the occurrence and development of glacier disasters in the region. It is found that the topography and climate background determine the hazard happens periodically, and they are fundamental for the weak vulnerability here. It can be reflected by the glacier dynamic simulation with Elmer/Ice model, which showed that the ice flow was extremely fast. Both heavy rain and an earthquake were triggering factors of the ice avalanche that led to the glacial debris flow. Combining analysis with documented records, we also proposed an assessment procedure for disaster-prone glaciers in this region, with key identification indices such as the type of glacier, presence of debris, slope of glacier, etc. The results indicated that the glacier disasters may seriously affected the Sichuan-Tibet Highway and local people. This synthesis study has extensive applicability and practical significance in glacier disaster prevention and mitigation under a changing climate.

1 Introduction

The frequency and intensity of cryosphere disasters are increasing and have caused great loss under climate warming. Especially in Qinghai-Tibetan Plateau, melting of frozen soil has induced a series of eco-environment challenges and engineering hazards, e.g. thawing of Qinghai-Tibet Railway (Wang and Wen, 2020). Glaciers, as it is normally far away from main human activities, got less attention during past. Nevertheless, the occurrence of glacier disasters seems accelerating recently and have caused huge influence. For example, Karayalak glacier in eastern Pamir surged, and flooded 1000 hectare grassland and many houses in 4 May 2015 (Ding et al., 2018); then two glaciers near Aru Co collapsed on 17 July and 21 September 2016, and killed nine people (Kääb et al. 2018; Gillbert et al., 2018). It arose many research interests (e.g. Shangguan et al., 2017; Tong et al., 2018; Liu et al., 2019).

The southeast Tibet is a landslide and other geological disasters prone area, so it is also called “Natural Disaster Museum”. Cryospheric components, especially glaciers and snow cover, are well developed, it supplies a lot to the rivers passing through and feeds the local people (Yao et al., 2017; You et al., 2009; Shangguan et al., 2017). At the same time, these glaciers are also a threat to them for debris flow or ice avalanche is easy to happen. The glacier shrinkage and hydrological responses occurring in basins associated with the Yarlung Zangbo River (YZR) are remarkable and have attracted intense attention because these rivers provide water to large numbers of people not only on the Qinghai-Tibetan Plateau but also South Asia (e.g., Zhang, 1985; Liu et al., 2014; Li et al., 2014; Nie et al., 2012). There were many debris flow events records. For example, in YZR Sedongpu basin, up to 4 large scale river blocking events induced by debris blow during 2018~2019 (Tong et al., 2018; Liu et al., 2019).

It is well known that the Qinghai-Tibetan Plateau is sensitive to human activity and the retreat of glaciers may produce more frequent ice avalanches/surges (e.g. Pritchard, 2019; Hock et al., 2021). Studies on the
formation mechanism, occurrence process and damage related to glacial debris flows are of great significance to the mitigation and prevention of disasters (Faillettaz et al., 2015). Topography, precipitation, air temperature are considered as main factors initiating glacier disasters, plus others like the sudden emptying of ice-marginal lakes, increase in pore water pressure (Harris, 2005; GAPHAZ, 2017). However, due to the lack of field observation and research examples, the contribution of these elements is difficult to quantitatively evaluate.

On October 17th, 2018, a glacial debris flow/rock fall landslide caused by ice avalanches occurred in the Sedongpu basin of YZR, near the village of Jiala, Milin County, Linzhi city (http://tibet.news.cn/2018-10/18/c_129974597.htm). It blocked the river and drowned several villages, emergency management measures were carried out immediately to manage the barrier lake. Fortunately, the landslide dam eroded away 3 weeks later. Besides, this area has experienced many glacier disasters and some preliminary studies have been done (e.g., Zhang, 1985; Tong et al., 2018; Liu et al., 2019; Hu et al., 2018). It provides an opportunity to carry out in-depth analysis of glacial debris flows and an extensive estimation of the potential disasters associated with glacial changes in the adjacent basins.

2 Study Area

The Sedongpu basin (29.81°N, 94.91°E, Figure 1) locates on the western flank of the Jialabailei peak, opposite of the Nagabawa peak, where is famous with the “Great Bend” of the YZR Basin as the river flows approximately 180 degrees around Nagabawa (Li et al., 2008; Huang et al., 2013; Nie, 2012). The highest elevation in the basin is 7294 m a.s.l. at the main peak of the Jialabailei peak, while the lowest point is 2746 m a.s.l.. According to Tong (2018), the average slope is approximately 35° and the basin area is ~68 km².

Like the other glaciers in the YZR basin, the glaciers present in the Sedongpu basin are mostly monsoonal temperate glaciers and characterized by the presence of debris mantles in the ablation zones that can originate from various sources (Yao et al., 2010; Zhang et al., 2013). These glaciers receive snowfall in summer mostly while simultaneously experiencing high rates of ablation, producing a characteristically high ice flow velocity and shear strength. Glacial debris flows, rock fall and landslides occur frequently on the side of the Jialabailei peak, the western bank of the Great Canyon Region of the YZR (Figure 1).

3 Data And Methods

3.1 Data and processing

In this study, multi-sources data, including remote sensing products, digital elevation models and seismic records, were used to analyse the characteristics of glacier and the mechanism of the glacier disaster.

A total of 2 Sentinel-2A images were downloaded from the Sentinel-2 database (http://sentinel-pds.s3website.eu-central-1.amazonaws.com). Sentinel-2 distributed top-of-atmosphere (TOA) reflectance values that were radio-metrically and geometrically corrected, including ortho-rectification and spatial
registration to a global reference system with sub-pixel accuracy. The band-11 data were rescaled (using nearest-neighbour resampling) to 10 m resolution for consistency with the Sentinel-2 optical bands. Moreover, images acquired during winter are mostly devoid of seasonal snow, which may cause an overestimation of glacier area. The images are available on the USGS (United States Geological Survey, http://glovis.usgs.gov/). A total of 18 Landsat TM/ETM+/OLI/TIRS and Sentinel-2A/MSI were used in this study (Table 1). For Landsat 8 data, we dilated the cloud mask by 200 m (10 Sentinel-2 pixels) to account for uncertainty in the cloud-masking procedure, and manually checked the images for shadowing elsewhere.

Topographic maps at a scale of 1:100,000 were derived from aerial photographs in 1970. The Shuttle Radar Topography Mission (SRTM) DEM was jointly measured by the National Aeronautics and Space Administration (NASA) and the Department of Defense National Imaging and Mapping (NIMA) of the USA. The V4.1 data were revised with a new interpolation algorithm by the International Center for Tropical Agriculture (CIAT) and are considered to be better than the previous versions by filling voids in the SRTM90. The nominal absolute elevation data accuracy is ±16 m, and the absolute accuracy of the plane surface is ±20 m.

The first Glacier Inventory of China (GIC) data were also consulted to aid in interpreting the glacier vector data. This data was provided by the Cold and Arid Regions Environmental and Engineering Research Institute (CAREERI), Chinese Academy of Sciences. Data on earthquakes in the region of the Sedongpu basin were from the China Seismological Network (http://news.ceic.ac.cn).

Meteorological data from Linzhi meteorological station were supplied by the Chinese Meteorological Science Data Sharing Service Network (http://cdc.cma.gov.cn). The ERA-Interim product produced by the European Centre for Medium-range Weather Forecasting (ECMWF) was used to calculate the trend of the solid-liquid precipitation ratio on a fixed grid of 0.75°.

### 3.2 Methods

Preprocessing of image data included accurate geometric correction and image enhancement. The root mean square error (RMSE) of the geometric correction was less than one pixel. All the data are presented in the Universal Transverse Mercator (UTM) coordinate system, and the topographic maps are referenced to the World Geodetic System 1984 (WGS84).

The distinguish of debris-covered glaciers using remote sensing techniques is a well-known challenge (Hempel, 2005; Bolch et al., 2007). Debris hampers the mapping of the actual ice snout by means of space-borne imagery due to the spectral similarity to the surrounding bedrock (Figure 2). In our study, a preliminary glacier boundary was generated automatically using the band ratio method for clean ice (Bolch et al., 2007). Generally, the band spectrum approach means that the spectral value of the debris-covered region is higher than bare rock, and this analysis can be combined with manual interpretation to produce glacier boundary. Principal component analysis (PCA) was also performed to determine the spectral differences between bare rock and debris-covered glaciers, in the software ENVI with bands 5
and 7 centred and standardized (Figure 3). Ridgelines of the Sedongpu basin are extracted from the SRTM DEM in order to determine the number of glaciers.

In addition, a detailed database of historical glacier hazards is compiled for the Sedongpu basin and regions nearby, based on previous scientific literature, reports, media news, and assessments of observations (e.g. Xu et al., 1988; Chen et al., 2011). These data were re-analysed and arranged to analyse the temporal and spatial patterns of glacier hazards in the study area.

### 3.3 Uncertainties

Errors in the glacier boundaries from remote sensing images were controlled by the image resolution and co-registration error. The uncertainty can be calculated by the following formulae (Hall et al., 2003; Silverio et al., 2005):

\[
U_T = \sqrt{\sum \lambda^2} + \sqrt{\sum \varepsilon^2} 
\]

\[
U_A = 2U_T \sqrt{\sum \lambda^2} + \sqrt{\sum \varepsilon^2} 
\]

where \( U_T \) is the uncertainty of glacier length; \( \lambda \) is the image resolution; \( \varepsilon \) is the co-registration errors between each image and the topographic map; and \( U_A \) is the uncertainty in glacier area. The uncertainty in glacier-change area measurements is calculated with an accuracy of ±0.003 km\(^2\) using TM or ETM+ imagery and ±0.002 km\(^2\) for Sentinel-2A MSI.

### 4 Results And Discussion

#### 4.1 Blockage event process

The event occurred on the side of the Jialabailei peak, the left bank of the YZR Great Canyon Region. It can be seen from the field photographs that the body blocking the Sedongpu basin was composed of debris, mud, rock and ice, proving that it was a glacial debris flow caused by an ice avalanche and glacial meltwater.

Figure 4a shows a large amount of loosely moraine debris flow on the steep slope near the glacier, which is an important precondition for the formation of glacier disaster. When an ice avalanche occurred at the glacier upstream, the fast-moving ice mass intensely scraped and eroded the debris in the Dongpu glacier downstream, and the debris accumulated along the valley and formed a dam. Then, the water level kept rising (Figure 4b), threatening the village Jala and electric facilities (Figure 4c and 4d).

In summary, the river blockage incident on October 17th, 2018, was induced by a large-scale ice avalanche from the Dongpu glacier in Sedongpu basin, which was similar to but much larger compared to the previous event.

#### 4.2 Historical glacier disasters
Due to the high logistic requirements and difficult working conditions, in situ studies on glacier disasters are rare, and most of which were supported by remote sensing techniques (e.g. Yao et al., 2010). Without the availability of other options, we also used a variety of high- to medium-resolution satellite images from 2017 to 2018 to identify the glacial debris flow events here (Figure 5). In conjunction with the historical database of glacier hazards in the Sedongpu basin (Table 2), we can find that many villages have been threatened by glacier hazards or disasters, including Zhibai village, Gega village, Gu village, Pailong village, Songrao village, Bitong village, Baka village, Layue village, Suotong village, Galang village, and Jiala village, most of which are on the left bank of the Yarlung Zangbo River (Table 2 and Figure 6). The ice avalanches, glacial lake outburst floods, glacier surges and glacial debris flows have caused severe damage and shaped the local living, but the glacial debris flow is the dominant hazards (e.g., Wang and Zhang, 2015; Cheng et al., 2008; 2009). Based on the location frequency of occurrence, we can find that Nanjiabawa Peak was the most dangerous place. Besides, these cryosphere disasters typically occurred between May and September, coinciding with the period of intense ablation of monsoonal temperate glaciers, as Zhang et al. (2013) has pointed out.

4.3 Diagnostic of influencing factors

Many previous researchers have studied the factors influencing glacier disasters, including weather, hydrological conditions, active tectonics and topography (e.g., Tong et al., 2018; Liu et al., 2019). In this paper, we analysed the effects of climate change, topography, precipitation, earthquake, debris cover and the internal glacial conditions.

4.3.1 Climate change

Due to its high elevation and vast extent, the Qinghai-Tibetan Plateau features large climate variability. The southeaste area have been experiencing a faster and more persistent warming than the other areas since the 1970s (Liu and Chen, 2000; Zhang et al., 2015; An et al., 2016). Some studies also found amplification effect in higher regions (e.g. An et al., 2017). As mentioned above, the Sedongpu basin locates in the south eastern part of the Qinghai-Tibetan Plateau, and is experiencing an extremely rapid warming rate due to the southwest monsoon from the Indian Ocean. The monsoon brings heavy precipitation in the region, including all glacial mass.

Based on the meteorological observation records of Linzhi Station, the warming rate was large than 0.40°C/10 a (p > 0.01) during 1960-2017 (Figure 7), which is two times higher than the global average (IPCC, 2017). Accompanied, the marine glaciers were experiencing substantial mass loss and large-scale shrinkage (Nie et al., 2012; 2013). Generally, the warming in cold seasons has had no direct effect on the melting of glaciers, but it can weaken the cold storage of glaciers, strengthen the sensitivity of glaciers to climate change, and increase the intensity of the glacial melting in summer. Successive hot summer could potentially warm the frozen ice-bedrock interface, resulting in a reduction of the basal support. Sometimes, the ice-bedrock interface can produce meltwater due to pressure and basal warming, it will lead to the basal shear resistance abatement and promote a stronger instability. These processes could cause ice break-off events (Zhang et al., 2013).
No exception, all 12 glaciers in Sedongpu basin have retreated a lot since 1996 (Figure 8), seen from the Landsat and Sentinel-2A remote sensing data. The average area reduction rates of these glaciers ranged from 0.26~8.29% during the periods of 1996~2004, 2004~2015 and 2015~2018. Overall, the total glacial area of the basin decreased by 9.65 km$^2$ (22.67%) from 1996 to 2018. At the same time, the snow equilibrium line rose, and the ablation area expanded. It can be inferred that additional glacial runoff has flowed to the Yarlung Zangbo River and a lot of glacial debris has accumulated in the glacial downstream. The potential destructive capacity of glacier disasters has thus risen simultaneously.

### 4.3.2 Topography

Except climate, glaciers are also product of topography (Zhang 2007; Zhang et al., 2013). Basin topography determines the volume, shape, and velocity of the glacier. The glacier geometry adjustment influencing by climate change, named glacier volume response time, can be assessed approximately by the ratio of the glacier thickness to the glacier terminus ablation (Harrison et al., 2001).

The elevation difference from the top to the bottom (A to B in Figure 9) of the glaciers in the Sedongpu basin is about 3500 m, and the average slope is as high as 48°. This condition is favourable not only for abundant precipitation from orographic-convective clouds, but also for rapid ice flow. In the upper part of the glacier (Figure 9c, 9d), the slope is extremely steep, leading to a high instability of ice and snow, and will further result in snow/ice avalanches and collapses.

Compared with the upstream of the Sedongpu basin, the downstream valley is relatively narrow. Glacial debris and moraine deposits would accumulate along with melting and small-scale snow/ice avalanches. Consequently, the destructive capacity of next large-scale ice avalanche increases. In some cases, large-scale avalanches can mobilize the debris and induce large-scale landslide debris flow initiation.

### 4.3.3 Glacier dynamics

To study mountain glacier dynamics as a result of climate forcing, one method is to solve partial differential equations for glacier dynamics and thermodynamics based on a function of ice geometry (e.g., length, slope, width, and bedrock topography), temperature and model integration time (Zhang et al., 2015). Previous studies have shown that volume response times range from decades for marine glaciers (wet and warm) to thousands of years for continental glaciers (dry and cold) (e.g., Raper and Braithwaite, 2009). However, there is only limited in situ information in the basin, we can only use dynamic model to exploring the possible thresholds of its flow pattern with different schemes.

Elmer/Ice was chosen in this study, for it is proved a valid tool to simulate the glacial ice flow, especially in mountain glaciers (Ai et al, 2019). Considered the classic theory (e.g. Peterson, 1981) and filed experience, the mesh size was set to 80m and the mean ice thicknesses of two scenarios were given at approximately 28 m (S1) and 100 m (S2), respectively. The initial parameters were given in Table 3. The two important parameters, Glen enhancement factor ($E$) and the basal friction parameter ($\beta$), were set to 2.0 and 0.06 respectively, in both simulations.
In S2 case, the maximum ice flow velocity is 705.0 m/a. S1 is much slower, 72.8 m/a, but it is still a very rapid speed compared with the other glaciers (Figure 10). The location with highest ice flow is coincidence with the ice avalanche initial point. It indicates that the basin can not hold two much ice in such a steep topography. Plus the heavy precipitation here, the volume response time of the glacier should be very short, at least shorter than most of glaciers.

### 4.3.3 Earthquakes

Like landslide, debris flows commonly occur after earthquake. They can destroy roads and vehicles, blocked rivers, formed dammed lakes, and submerged villages, resulting in significant loss of life and property damage. For example, Ms 8.0 Wenchuan Earthquake in South China on May 12, 2008, produced debris flows (Guo et al., 2016). Different with precipitation, which is considered as the immediate triggering factor, earthquake is thought to be responsible for the massive accumulation of loose mass (Chen et al., 2010).

The YZR Great Canyon Region lies in the East Himalayan syntaxis or tectonic knot, formed by the collision of the Indian plate and the Eurasian plate. The area features active crustal compression, rotational strike-slip faulting and uplift. There were many great earthquakes, such as the Ms 7.3 earthquake on August 14th, 1932, and the Ms 8.6 earthquake on August 15th, 1950 (Liu et al. 2019). Based on data and assessment of the China Seismological Network, seismicity was active in the Jialabailei peak region since 2010. In the recent 3 years (2017-2019), there were as many as 18 earthquakes, of which 11 had magnitudes of Ms 3-3.9, 5 had magnitudes of Ms 4-4.9, one had a magnitude of Ms 5.9 and one had a magnitude of Ms 6.9 (Figure 11). Compared with the southern bank of the River, the northern bank has more earthquakes and most of them happened near the Jialabailei peak. After the Linzhi 6.9 Ms earthquake, the deformation associated with glacial debris flows in the Sedongpu basin was further aggravated, and the central deformation was significantly higher in this region than in other regions (Tong et al., 2018; Zhao et al., 2019), indicating that the earthquake had a clearly destructive effect and direct influence on the glaciers. One evidence is that Dongpu Glacier ice velocity accelerated after the Linzhi 6.9 Ms earthquake, showed by remote sensing images. Other study also proposed that an earthquake in Naqu (about 10 min before the landslide event) also played an important role in triggering the Sedongpu debris flow blockage event (Wang et al., 2020). However, the Linzhi earthquake was the decisive factor in this event, as the significant acceleration of glacier ice velocity after the Linzhi earthquake while the Naqu earthquake magnitude was 4.1 Ms and the long distance weaken the impact.

As previous study showed that during the earthquake process, it breaks the state of glaciers and with the occurrence of raptures, under the aftershock persistent disturbance, the glacier subglacial system would be destroyed (Post., 1967). Sometimes, ruptures in the glacial bedrock induced by earthquake, could potentially propagated through the ice. Surface meltwater might then inject to the ice/bedrock interface, leading to the initiation and development of instability, and complicating the glacier behaviour greatly.

### 4.3.4 Precipitation
The YZR Great Canyon Region features some of the highest precipitation levels in the world (Yao et al., 2010). During 1960-2017, the annual average precipitation of Linzhi station reached up to 1248.5 mm/a, with increased rate by 2.3 mm/a during 1960-2017 (similar to the results of Zhang et al., 2018). Combined with ERA-Interim to calculate the total precipitation, and found the annual average precipitation varied from 800-1700 mm/a during 1979-2018. The ERA-Interim values are consistent with estimation by the meteorological observation at Linzhi station (Figure 12).

The influence of precipitation on glaciers is complex. The solid phase of precipitation, i.e., snow, can modulate heat transfer in terrestrial environments by increasing the surface albedo, thereby strengthening the stability of glaciers. But rain can trigger snow/firm/ice ablation through reducing surface albedo and releasing latent heat. Observations and modelling have proven that rainfall has accelerated the warming and melting of snow/ice in some cryospheric areas (Dou et al., 2019). If rain occurs in the ablation area, it may flow to the glacier bottom through surface melt ponds/conduits and then accelerate the glacier ice flow (Zhang et al., 2013). In Sedongpu basin, the precipitation obviously increased in summer, meanwhile the snow/rain ratio dramatically decreased during 1979-2018 (Figure 12b). It indicates more and more rain has fall on, and should have played a substantial role in shaping these glaciers, especially the downstream debris part (as mentioned above, the terminuses have retreated and the equilibrium line has risen). It is worth noting that, 5 days before the first avalanche (October 12, 2018), a heavy rainfall happened (Figure 12c).

4.3.5 Debris-cover in the glacier ablation area

Studies have shown that ablation areas covered with debris retreated at a lower rate than many other non-debris-covered glaciers on the Qinghai-Tibetan Plateau (Scherler et al., 2011; Dobhal et al., 2013). If the terminal area is covered with debris, the ice volume loss in the upper ablation area (at higher altitudes) can be greater in magnitude than the terminus (Dobhal et al., 2013). Compared to clean ice, a 1-cm-thick debris cover can reduce the energy flux available for melting by 33% if the debris is dry and by 11% if the debris is wet (Nicholson et al., 2006). The debris cover is well developed here, especially on the large valley glaciers, where a large area of the ablation zone is covered by thick debris that extends to relatively high elevations (Benn et al., 2012). However, there is also downside, the expansion of debris area also provides more mass and enhances the destructiveness of debris flows.

Due to the periodic surges of the glacier, it is hard to quantitate the area of the debris area and its evolution. But we have reason to believe that the debris was well accumulated before the events.

4.3.6 Glacier thermal conditions

Compared with continental glacier, the maritime glacier has a higher englacial temperature distribution, especially in the basal part (Ai et al., 2014). So it is more responsive to climate warming, and predominantly features basal sliding and highly developed subglacial hydrology system (Cuffey and Paterson, 2010). In fact, the basal sliding is determined mainly by the subglacial hydrology, and peaks in
conjunction with the maximum of the liquid water storage (normally in autumn). The amount of stored water may increase over several years and can be released catastrophically.

Generally, the temperate ice layer is formed from internal heat dissipation and can in turn influence the physical features of the ice, such as the flow law parameter, thereby impacting the internal deformation of glacier ice (Funk et al., 1994). This is especially common in the glaciers whose firm basin experiences warming by the refreezing heat of melt water in summer. It can eventually transport more temperate ice to downstream and accelerate the glacier movements (Wang et al., 2018). In the ablation area, the basal temperate ice can also warm the overlying cold layer when it is advected upwards with the internal water refreezing (Greve and Blatter, 2009). According to Faillettaz et al. (2015), hanging glaciers also contain a temperate zone, although it is categorized as avalanching glacier that is partly frozen to the underlying bedrock.

### 4.4 Assessment of potential disaster-prone glaciers

As one of the geological disasters, the occurrence of glacier disaster is very likely to increase with the climate warming and the rapid retreat of glaciers, for the foreseeable future (Salzmannet al., 2004; Vilimeket al., 2005; Qin et al., 2009; 2018). So we assessed the vulnerability of the glaciers in the studied area by the expert scoring method (as used in Ding et al., 2018). The specific evaluation basis is shown in Table 4.

According to this method, 8 potential hot spots were identified in buffer zones of 50 km and 20 km of the Sedongpu basin (Figure 13). These glacier disaster-prone areas are relatively close to electric power facilities, transport infrastructure and villages, such as Layuecun, Pailongcun, Tangduicun. And the glaciers in the areas are characterized by large amounts of debris, large elevation difference, high glacier velocity and short distance to rivers or railways. Especially, 6 hot spots are very close to Sichuan-Tibet Highway. Once glacier disasters occur, they may have a huge impact on local people and transportation. The 20 km buffer zone is dominated by glacier surges and glacial debris flows in Zelongnong glacier of Mt. Nanjiabawa, and glacial debris flows in the Sedongpu basin of Mt. Jialabailei. Notably, glacier disasters have occurred mainly on the left bank of the YZR, which may be associated with heavy precipitation related to the Fohn effect. In other words, precipitation is one of main trigger factors in this region.

### 5 Conclusions And Prospective

This paper focuses on the glacial debris flow blockage event in the Sedongpu basin, the Yarlung Zangbo River, which present a comprehensive analysis of this glacier disaster. Some summary are as follows:

To predict, prevent and reduce glacier disaster, a cataloguing of glacier types based on the identification index proposed in section 4.4 may help. Upon the fully consideration on geological and climatic conditions, more attentions should be paid to large glaciers, for moraines and water storage (mainly glacial lake) are carriers of destructive force. Usually, short-term heavy rainfall is regarded as a triggering
factor for landslides and debris flows and has been considered in almost all researches/early warning schemes, because it brings massive melting in glaciers and rising in glacial lakes, leading to debris flows, glacial lake outbursts, etc. We recommend earthquake as an important factor of glacier hazards/disasters, for it can rupture the internal glacier structure from a large distance and trigger a collapse a few months later. In addition, environmental protection, such as afforestation, construction of infrastructure in non-disaster-prone areas and strengthening local people’s awareness of disaster prevention are invaluable.

The cryosphere is considered as an amplification of climate change, especially the Arctic, west Antarctica, and the Tibetan Plateau (Xiao et al., 2015; Qin et al., 2018). Under global warming, the increase in air temperature at high-elevation areas is obviously greater than the global mean (An et al., 2017), accompanied with shrinking glaciers and intensified glacial activities all over the world (Pritchard, 2019; Milillo et al., 2019; Maurer et al., 2019). Except Sedongpu basin, the frequency and scale of debris flows in Tibetan Plateau are likely to increase sharply in the future. Some of severe cases may block the large rivers and threaten people downstream, for example, the events on the Jinshajiang River on October 11th 2018 and on the Alakananda/Dhauliganga rivers in the state of Uttarakhand, India, on February 7th 2021. The YZR is no exception too.

Nevertheless, this study is mainly carried out with some assumptions and qualitative analysis, as the other Himalayan glaciers. Insufficiency field data (e.g. mass balance, ice thickness, velocity, etc.) make it difficult to develop a coherent picture. The suggestions we propose may have many deficiencies. Therefore, countries around Tibetan Plateau should enlarge the investment into the monitoring, research and early warning of glacier disasters.

**Declarations**

**Data availability.** Remote sensing data used in this paper is available at http://sentinel-pds.s3website.eu-central-1.amazonaws.com . The Glacier Inventory of China data can be downloaded from http://westdc.westgis.ac.cn/zh-hans/data/ . Meteorological data is available at http://cdc.cma.gov.cn .

**Author contributions.** MHD and CDX provided the topic and idea, BJH, MHD, CDX and WJS coordinated the study and carried out the analysis; STA carried out the ice-flow model analysis; MHD and BJH drafted the paper, STA, YTW, JYW and XWZ edited the paper. All authors contributed to the analysis, discussion and interpretation of the results.

**Competing interests.** The authors declare that they have no conflict of interest.

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Tables

| ID                  | Receive date | Sensor | Resolution (m) | Path |
|---------------------|--------------|--------|----------------|------|
| LC8135039_03920150725 | 2015-07-25   | OLI/TIRS | 30/15          | 135/039 |
| LC5135039_03920040507 | 2004-05-07   | TM     | 30             | 135/039 |
| LC5135039_03919960415 | 1996-04-15   | TM     | 30             | 135/039 |
| LC5135039_03919870407 | 1987-04-07   | TM     | 30             | 135/039 |
| L1C_T46RFT_A004120   | 2017-12-20   | MSI    | 10             | T46RFT |
| L1C_T46RFT_A004263   | 2017-12-30   | MSI    | 10             | T46RFT |
| L1C_T46RFT_A008982   | 2018-11-25   | MSI    | 10             | T46RFT |
| L1C_T46RFT_A009268   | 2018-12-15   | MSI    | 10             | T46RFT |
| L1C_T46RFT_A017533   | 2018-10-31   | MSI    | 10             | T46RFT |
| L1C_T46RFT_A017962   | 2018-11-30   | MSI    | 10             | T46RFT |
| L1C_T46RFU_A004120   | 2017-12-20   | MSI    | 10             | T46RFT |
| L1C_T46RFU_A004263   | 2017-12-30   | MSI    | 10             | T46RFT |
| L1C_T46RFU_A008982   | 2018-11-25   | MSI    | 10             | T46RFT |
| L1C_T46RFU_A009268   | 2018-12-15   | MSI    | 10             | T46RFT |
| L1C_T46RFU_A017533   | 2018-10-31   | MSI    | 10             | T46RFT |
| L1C_T46RFU_A017962   | 2018-11-30   | MSI    | 10             | T46RFT |
## Table 2
Historical glacier hazard events in the Sedongpu basin

| Date          | Location          | Hazard type                           | Reference                        | Village Affected   |
|---------------|-------------------|---------------------------------------|----------------------------------|--------------------|
| 1950, 1968, 1984 | Zenong glacier   | Glacier debris flows, Glacier surge  | Wang et al., 2015 Han et al., 2018 Zhang, 2007 | Zhibai village, Gega village |
| 1953, 1972, 2005 | Guxiang Valley  | Glacier debris flows, GLOF            | Wang et al., 2014 Xu et al., 1988 Chen et al., 2011 | Gu village |
| 1983-1985     | Peilong Valley   | Glacier debris flows, GLOF, ice avalanches | Cheng et al., 2009 Cheng et al., 2008 Tang et al., 2003 | Pailong village |
| 2007          | Tianmo Valley    | Glacier debris flows                  | Deng et al., 2013                | Songrao village    |
| 2007          | Bitong Valley    | Glacier debris flows                  | Deng et al., 2013                | Bitong village     |
| 2007          | Baka Valley      | Glacier debris flows                  | Deng et al., 2013                | Baka village       |
| Unknown       | Layue            | Glacier debris flows                  | Hu et al., 2018                  | Layue village      |
| Unknown       | Suotong Valley   | Glacier debris flows                  | Hu et al., 2011                  | Suotong village    |
| Unknown       | Gelang Valley    | Glacier debris flows                  | Hu et al., 2011                  | Galang village     |
| 2017, 2018    | Sedongpu basin   | Glacier debris flows, Glacier avalanches | This study                      | Jiala village      |
Table 3
The parameter of the ice-flow model

| Symbol | Description                  | Value and unit |
|--------|------------------------------|----------------|
| \( p \) | Ice density                 | 910 kg m\(^{-3}\) |
| \( g \) | Gravitational acceleration  | 9.81 kg s\(^{-2}\) |
| \( n \) | Glen exponent               | 3              |
| \( A_0 \) | Rate factor               |                |
|        | When \( T \leq -10^\circ C \) | \( 2.89 \times 10^{-13} \) s\(^{-1}\) Pa\(^{-3}\) |
|        | When \( T > -10^\circ C \)  | \( 2.43 \times 10^{-13} \) s\(^{-1}\) Pa\(^{-3}\) |
| \( Q \) | Creep activation energy    |                |
|        | When \( T \leq -10^\circ C \) | 60 kJ mol\(^{-1}\) |
|        | When \( T > -10^\circ C \)  | 115 kJ mol\(^{-1}\) |
| \( R \) | Gas constant               | 8.31 J kg\(^{-1}\) K\(^{-1}\) |

Table 4
The specific evaluation basis for glacier disasters

| ID | Parameter                  | Specific evaluation basis                                      |
|----|----------------------------|-----------------------------------------------------------------|
| 1  | Type of glacier            | Ganging glacier                                                 |
| 2  | elevation differences      | 2000 m                                                          |
| 3  | Slope of glacier           | Over 30°                                                        |
| 4  | Debris                     | Debris-covered development in ablation area                    |
| 5  | Glacier velocities         | Increase by one order or more than one order                    |
| 6  | Ice avalanche              | Have record of ice avalanche                                   |
| 7  | Precipitation              | Liquid precipitation upward trend                               |
| 8  | Ablation condition         | Intensive ablation period                                      |

Figures
Figure 1

Location of the Sedongpu basin, YarlungZangbo River, the image is Landsat8 in 2015. Note that the Dongpu glacier is the largest glacier in the Sedongpu basin
Figure 2

Spectra of clean glacier, bare rock and debris-covered glacier surfaces with (a): with TM (b): with MSI.
Figure 3

Glacier boundary of Sedongpu basin identified by Google Earth and PCA analysis (The image is from Google Earth with year of 2016)
Figure 4

Photographs of the conditions following a glacial debris flow event: (a) the dammed lake and the barrier body; (b) the rising water level of the barrier lake; (c) flooding in the village Jala; (d) the electric power department cut the power to prevent accidents (http://www.xinhuanet.com/photo/2018-10/18/c_129974593.htm)
Figure 5

Examples of river-blocking events on images of Sentinel-2 in Yarlung Zangbo River: (a) 2017/12/30; (b) 2018/10/31; (c) 2018/11/25; (d) 2018/12/15; the blue box is the region blocking the river
Figure 6

Frequency distributions of ice avalanches, glacial lake outburst floods, glacier surges and glacial debris flows during 1950s~2018
Figure 7

(a) The variations in annual average air temperature and summer air temperature during 1960-2017. (b) The variations in annual average precipitation and summer precipitation during 1960-2017. (c) The variations in averaged monthly temperature and total precipitation during 1960-2017. All data are sourced from the Linzhi meteorological station.
Figure 8

Glacier area and annual variation in the Sedongpu basin since 1996. (a) Glacier boundary and glacier number in 2004 with Landsat 5; (b) Glacier area in 1996, 2004, 2015 and 2018.
Figure 9

Glacier terrain and elevation difference of the Dongpu glacier. (a) Points A to B on the Dongpu glacier as an example of the measurement of elevation differences. (b) The aspect of the Sedongpu basin. (c) The slope of the Sedongpu basin. (d) The elevation difference between points A and B on the Dongpu glacier.
Simulated glacial ice flow velocities using Elmer/Ice with parameters in Table 3. a) Left pane shows the scenario with mean ice thickness of 28 m, which has a maximum ice flow velocity of 72.8 m/a; b) Right pane shows the scenario with mean ice thickness of 100 m, which has a maximum ice flow velocity of 705 m/a.

Figure 11
Distribution of earthquakes during 2017-2019 in this region, the background image is Sentinel-2 in 2018.

Figure 12

(a) Total precipitation on Dongpu glacier from ERA-Interim data. (b) Snow/rain ratio for glaciers in the Sedongpu region from ERA-Interim data. (c) Daily precipitation before and after the glacial/rock debris flow event in 2018 from the Linzhi meteorological station.
Figure 13

Glacier disaster-prone region identified between Linzhi county and Bomi county, southeastern part of the YarlungZangbo River Basin