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The impacts of climate change on chains of geological hazards on the Tibetan Plateau and its margins

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ABSTRACT: As the Third Pole of the Earth, Tibet Plateau (TP) is sensitive to climate change which induces complex geo-environmental changes and hydrological patterns. In recent years, with increasing environmental temperatures, there have been growing numbers of geological hazards that produced significant threats and damage to the settlements, hydropower stations, and transportation infrastructures in this tectonically active region. However, the mechanism causing such chains of geological hazards is not well understood. Therefore, studies on glacial-related geohazards induced by climate change in the Tibetan Plateau region have become an emerging hot issue. In this paper, we introduce five common types of cascading hazards induced by climate change and their possible mechanisms. Some representative cases are discussed. We provide a brief review of studies related to the impact of climate change on chains of geohazards on the TP and its margins, and highlight future research directions.

RÉSUMÉ : En tant que troisième pôle de la Terre, le plateau du Tibet (PT) est sensible au changement climatique qui induit des changements géo-environnementaux et formes hydrologiques complexes. Au cours des dernières années, avec l'augmentation des températures environnementales, il y a eu un nombre croissant de risques géologiques qui ont produit des menaces et des dommages importants pour la population, les centrales hydroélectriques et les infrastructures de transport dans cette région tectoniquement active. Cependant, le mécanisme à l'origine de telles chaînes de risques géologiques n'est pas bien compris. Par conséquent, les études sur les géorisques liés aux glaciers et donc induits par le changement climatique dans la région du plateau tibétain sont devenues très importantes. Dans cet article, nous présentons cinq types de dangers en cascade induits par le changement climatique et leurs mécanismes possibles. Certains cas représentatifs sont discutés. Nous fournissons un bref examen des études liées à l'impact du changement climatique sur les chaînes de géorisques sur le PT et le long de ses frontières, et mettons en évidence les orientations futures de la recherche.

KEYWORDS: Climate change, Tibetan Plateau, Geohazard chains, Rock-ice avalanche

1 INTRODUCTION

Tibetan Plateau (TP), as the Third Pole of earth and the Water Tower of Asia, acted as the driver and amplifier of climate change (Yang et al. 2014). The average warming rate of the TP (0.46 ℃·decade-1) is approximately 1.5 times of the global average warming rate (0.32 ℃·decade-1) (Zhang et al. 2020). It means the changing of temperature in the TP is more sensitive to climate change. The TP has been experiencing significant environmental changes in the past few decades. The major changes on TP are driven by glacier retreat, glacial lake outburst floods (GLOFs), landslides and debris flows caused by warming-induced changes, etc., with severe repercussions on the socio-economic condition in the region.

Accompanied by climate change, earthquakes, and rainstorms, there are increasing numbers of geological hazards on the Tibetan Plateau and its margins. The Yigong landslide in 2000 was one of the most catastrophic landslides worldwide, resulting in enormous casualties and property losses in China and India. 300 Mm^3 of debris blocked the Yigong River for about 62 days, resulting in reservoir volume increasing to about 2.015 Gm^3. The corresponding catastrophic breaching caused a massive outburst of flood in the Yarlung Zangpo (in Tibet) and the Dihang (in India) rivers (Delaney and Evans 2015; Kang et al. 2017; Zhou et al. 2016). Adjacent to the Yigong landslide, Tianmo Valley did not suffer from debris flows for approximately 100 years before 2007. However, approximately 1.34 Mm^3 sediment was transported from the channel in 2007, causing eight persons missing. Subsequently, two debris flow events occurred in 2010, generating a dam lake with a volume of 90 Mm^3, inundating the highway G318 (Deng et al. 2017; Wei et al. 2018). Sedongpu ice-rock avalanche-debris flows, located on the left bank of Yarlung Zangbo River, have temporarily blocked the river many times since 2012. Interestingly, according to satellite images, it nearly slumbered between the 1960s and 2012. However, it has been activated since 2012, especially after the 2017 Ms 6.9 Milin earthquake. Many studies in the Sedongpu region proposed that frequent geohazard events have a close connection to climate change (Chen et al. 2020; Jia et al. 2019; Li et al. 2021).

In addition, TP is a region with intensive tectonic deformation and high-level earthquake activity (Huang and Fan 2013; Wang et al. 2011). Strong earthquakes, caused by the continental collision, weakened and fractured the steep mountain slopes, increasing the probability of geological disasters (Fan et al. 2019a; Jiang et al. 2021). The influence of the Wenchuan earthquake on geological hazards has been well documented, especially on the spatio-temporal evolution of landslides and debris flows (Fan et al. 2018; Fan et al. 2019b), the formation of landslide dams and dammed lakes (Fan et al. 2021b; Fan et al. 2020), the enhancing sedimentary transportation (Dai et al. 2021; Fan et al. 2019a; Fan et al. 2021a), the vegetation recovering (Yunus et al. 2020), etc. In the TP region, the freeze-thaw process caused by climate change can further cause strength degradation of the rock mass in high mountain regions and enhance the possibility of slope instability (Krautblatter et al. 2013). Furthermore, post-seismic debris flows induced by extreme rainfall events are of significant concern in the seismically affected zones (Jiang et al. 2021). Under the effects of climate change, along with strong seismic activities, geological hazards could be prone to present a considerable threat to society.

TP experienced a significant increase in air temperature especially in the past 50 years, the increasing rate of air temperature has been twice the global average, reaching 0.3-0.4 ℃ every ten years (Yao et al. 2019). With such a rapid rate of climate change in the past decades, there has been an accelerated rate of glacier mass loss (−0.18 to −0.7 m w.e. yr^{-1}) since the mid-1990s (Bolch et al. 2012; Brun et al. 2017). The retreat of glaciers and excessive rains gradually expanded glacial lakes at the low-lying lands and formed a potential source of flooding

(Clague and Evans 2000; Mool et al. 2001; Song et al. 2016; Wang et al. 2020). Climate change has increased the natural disasters in the region at an alarming rate. These rapid changes on TP and their effects on the downstream area, although studied extensively, lack a clear understanding of the cascading effects.

This paper introduces five types of geohazard chains induced by climate change and the mechanisms associated with them on the Tibetan Plateau and its margins. We briefly reviewed recent studies related, presented a few representative cases of chains of geological hazards, and highlighted future research directions.

2 TYPES OF CLIMATE CHANGE INDUCED CHAINS OF GEOLOGICAL HAZARDS ON TIBETAN PLATEAU REGIONS

2.1 *Climatically induced cascading hazards after strong earthquakes*

Strong earthquakes are typical of TP region, resulted by continent-continent collision. International Seismological Center (ISC) database reports over 7200 earthquakes between 1975 and 2015 on the Tibetan Plateau margin. Well known examples include 2008 Wenchuan (M_w 7.9), and 2015 Nepal (M_w 7.5) cases, both of them caused numerous landslides in the mountain slopes, loss of life and infrastructure damages, see Figure 1. Remobilizations of the coseismic landslide deposits in the form of debris flows during subsequent rainy periods are the common geological hazard in areas affected by earthquake-induced landslides (Fan et al. 2019a).

The 2008 Wenchuan earthquake triggered the largest number of coseismic landslides on record: ~200,000 (Xu et al. 2014). After this event, extensive debris remobilizations were occurred continuously for several years, even multiple times in the same deposit (Fan et al. 2021a). They often resulted in human losses and damage to property and infrastructure. The prediction of post-seismic landslides is almost based on analysing the relationship between debris flows initiation and cumulative rainfall. We noticed that the triggering rainfall intensities of post-seismic debris flows evolve with time. Based on 172 triggering rainfalls and 2396 non-triggering rainfalls of debris flows from 2008 to 2013 after the Wenchuan earthquake, we analysed the evolution of probabilistic rainfall thresholds for post-seismic debris flows using a Bayesian technique and found that rainfall thresholds significantly decrease compared with pre-earthquake events initially and later tend to increase annually (Jiang et al. 2021). Meanwhile, the triggering rainfall characteristics tend to gradually change from a short-duration high-intensity pattern to a long-duration and low-intensity pattern.

Elevated frequency of debris flows has been reported also after the 2015 Gorkha earthquake in Nepal (Dahlquist & West 2019) and 2017 Juizhaigou earthquake in China (Fan et al. 2021a). Nevertheless, studies show that the rates of debris remobilisations and post-seismic landslides eventually return to a pre-earthquake level in a few years (Marc et al. 2015; Fan et al. 2019a). The decay timescale of major post-seismic landslide disturbance appears to be a few years to several decades (Fan et al. 2019a). For example, after M_w 7.6 Chi-Chi earthquake of 1999, the affected areas progressively returned to the pre-earthquake condition within seven to ten years; whereas that for Wenchuan is more than 10 years. It is also worth to note that there were catastrophic reactivations during major rainstorm events in Wenchuan (e.g., 12th August 2010 rainstorm, 4th July 2011 storm and 9th July 2013 storm). Hence, extreme rainfall variability needs to be taken into account in projections of landslide decay assessments.

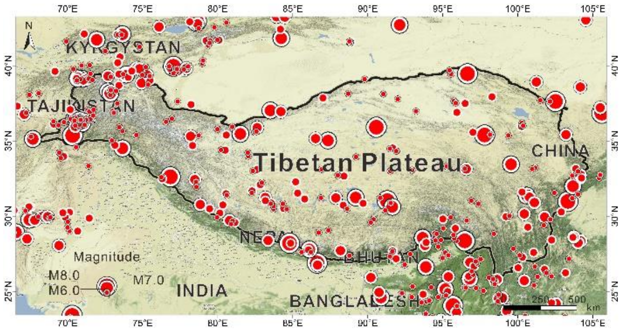

Figure 1. The distribution of strong earthquakes in the Tibetan Plateau and its margins. Earthquakes in this region are according to the Earthquake Hazards program dataset (https://earthquake.usgs.gov/earthquakes). Size of filled circles corresponds to earthquake magnitude. The background Terrain is from the Stamen Design open-source maps (http://maps.stamen.com/).

2.2 *Climate change-induced slope failures in permafrost regions on TP*

Permafrost related slopes failures are typical examples of climate-change-induced geohazards. The 0.5 ℃ additional warming is a severe threat to cold permafrost regions like the Qinghai-Tibet plateau. The frequency of extreme weather-related geohazards is increasing, and freeze-thaw induced slope failures in permafrost regions are not exempt. Over 1,500,000 km^2 area of Qinghai-Tibet plateau consists of permafrost (Zhou et al. 2018; Niu et al. 2005). During thawing, shear strength reduction occurs in ice-rich sediments within the active layer and triggers slope failures. Driven by the increasing demand for infrastructure development, transport networks encounter thaw induced-permafrost slope failures along the new engineering corridors (Niu et al. 2014). Studies in the recent decades' efforts on understanding the types of these slope failures as retrogressive flows, thaw slumps, and gelifluction (Wei et al. 2006). Of these types, retrogressive failures and active layer detachment thaw slumps are prominent. Terrian factors, i.e., slope, aspect, deposits characteristics, temperature, and ground-ice content, control these slope failures' spatial distribution (Niu et al. 2005). External triggering factors of these slope failures are increased temperature (thawing), heavy summer precipitation, and occasionally an earthquake. Studies have identified a 253% increase in thaw slumps in the last decade (Luo et al. 2019). With the rise of air temperature during the thawing season and abundant precipitation related to extreme-weather events under climate change, it is vital to expect the trend to prolong.

2.3 *Climate change-induced ice/rock mass strength degradation and cascading hazards*

The temperature of ice is one of the most important factors affecting the strength of ice (Petrovic 2003). The influence of temperature rise on ice strength mainly includes three aspects: directly reducing the strength of ice, the temperature stress that causes cracks in the ice, and the melting of ice reduces the confining pressure of the ice. The existing research results show that when the ice temperature is above -30°C, its strength decreases significantly with the increase of the ice temperature (Chang et al. 2021). Uneven temperature changes will produce temperature stress, causing cracks in the ice, thereby reducing the strength of the ice layer. In addition, the mechanical properties of ice, like rocks, are also significantly affected by the stress environment in which it is placed. When the upper ice layer melts, the confining pressure of the lower ice layer decreases, which will also cause the loss of its strength.

On the other hand, the increase in temperature will also lead to changes in the structure of the ice layer. It can be clearly found in the field survey that the snow line has raised as the temperature rises. As for the ice layer on the slope surface, the lower part becomes thinner due to the rising temperature, and the upper part becomes thicker due to further snowfall, which causes the slope of the ice layer to increase, and the ice layer is prone to instability (Kääb et al. 2018). In addition, the melting of the lower ice layer also produces an effect similar to "excavating the foot of a slope", which easily induces the collapse of the ice layer.

Due to above reasons, ice avalanches have continued to occur on TP in recent years. For example, in 2016, two large-scale ice avalanches occurred in the Ngari area of the Tibet Autonomous Region, causing serious casualties and property losses (Kääb et al. 2018). Ice avalanches can also cause cascading disasters such as glacial lake outbursts. The ice body falling into the glacial lake can stir up huge surges, swelling through the dam and then causing the dam to break (Cook et al. 2016).

The increase in temperature not only leads to a decrease in the strength of the ice, but also causes damage to the mechanical properties of the rock mass. Freeze-thaw is generally considered to be one of the leading mechanisms for the deterioration of rock mechanical properties in cold regions (Huang et al. 2020). Climate warming will gradually increase the severity and area of freeze-thaw damage on TP. The infiltration of ice and snow melt is another major factor that causes rock mass instability in cold regions. Water infiltration not only lubricates the joints and cracks of the rock mass, but also generates hydrodynamic pressure and hydrostatic pressure, and even leads to liquefaction of the sliding surface, which further promotes the generation and development of landslides or collapses.

On the TP and its margin regions, active tectonic movements coupled with long-term geological evolution processes such as freeze-thaw cycles, dry-wet cycles, loading and unloading, have formed potentially unstable rock masses in many areas. In addition to the infiltration of ice and snow melt water, climate change can also lead to extreme weather such as heavy rainfall, rapid changes in hydrological conditions often become a direct factor inducing the instability of dangerous rock masses. The aforementioned Yigong landslide that occurred in 2000 was caused by the coupling of such long-term and short-term inducing factors (Li et al. 2020; Zhou et al. 2016), see Figure 2a.

The Chamoli ice and rock avalanche that occurred in 2021 in India also has a similar initiation mechanism, Figure 2a (Shugar et al. 2021). Existing research results have shown that in the years before the event completely collapsed, obvious seasonal deformation characteristics have been revealed: the ice rock mass deforms in summer, but remains stable in other seasons (Pandey et al. 2021). In the winter when the avalanche occurred, significant abnormal temperature changes also appeared. This further confirms that the hydrological driving factors caused by climate change have an important influence in the evolution of such events.

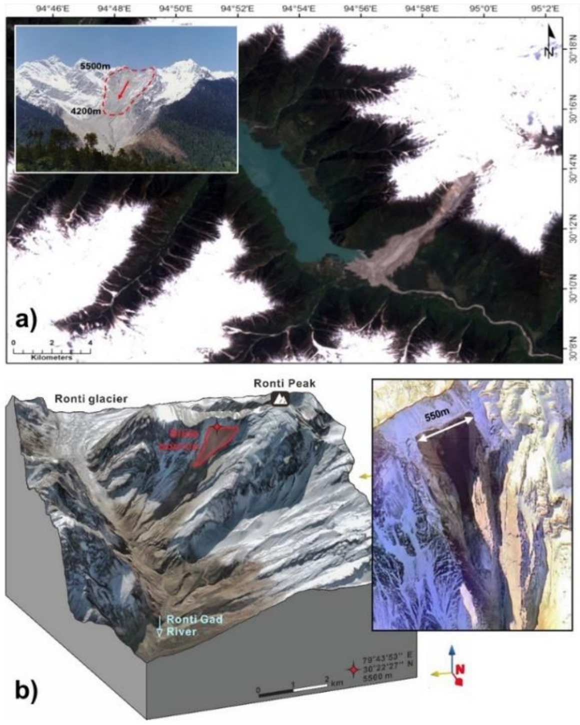

Figure 2. (a) The catastrophic Yigong Landslide occurred in 2000 in TP, and (b) the Chamoli ice-rock avalanches occurred in 2021 in India

2.4 *Climate change-induced debris flows and flash floods*

As a common type of natural hazard in mountainous areas, debris flow is usually a mixed flow of rocks, mud, water and air (Iverson 1997; Hürlimann et al. 2019). The velocity and impact force of a debris flow could be tremendous, imposing serious threats to people, properties, and infrastructure in the affected areas. Due to favourable natural environments for geohazards, the southeast of the Tibetan Plateau suffers serious debris flow hazards, which are initiated by intensive rainstorms, maritime monsoon glacier melting, glacial avalanches and glacial lake outburst floods (GLOFs) (Wei et al. 2018). Especially, with the effect of climatic warming, the occurrence of debris flows becomes more frequent. Previous studies have demonstrated that three key factors may contribute to the triggering of debris flows, including steep slope, availability of sediment and input water flow (Mcguire et al. 2017). On one hand, climatic warming will induce glacier retreat and permafrost degradation, which will expose more moraine and rock slopes. The new-exposed moraine will be the supplement sediment for debris flows, which will promote the activities of debris flows (Walter et al. 2020). On the other hand, the high temperature will accelerate the melting of the glaciers, the meltwater will be transformed into the runoff in the channel. The effect of meltwater for the initiation of debris flow is similar to that of antecedent rainfall. The melted water will saturate the moraine, which makes the moraine into a water-filled state. Under the action of heavy rainfall in the later period, the moraine deposits in the channel will be easily washed away to transfer a debris flow (Kumar et al. 2018). At the same time, in the background of climate warming, the climatic characteristics in the TP increasingly show a trend that the rainfall and high temperature will occur in the same period, that is, the strong melting of glaciers occurs in summer, and this is also the season of concentrated precipitation. The superposition of concentrated rainfall and high temperature will enhance the volume of water supply in the channel and promote the occurrence of debris flows under the coupling effect of glacial-melting and intensive rainfall (Deng et al. 2017). In addition, climatic warming will also increase the numbers and volumes of moraine-dammed lakes with the possibility of hazardous debris flows induced by Glacial Lake Outburst Floods (GLOFs) in the Tibetan Plateau.

Due to climate change, glaciers in the TP have shown an accelerating retreat (Dussaillant et al. 2019; Fujita and Ageta 2000; Kääb et al. 2018; Ke et al. 2017; Yao et al. 2012). By 2015, the area of glaciers has decreased by about 178 km^2 since 1999 (Bhattacharya et al. 2021). The increased melting volume of glaciers has largely increased the frequency of mass movements, especially debris flows (Aggarwal et al. 2017; Muneeb et al. 2021; Ashraf et al. 2012; Cook et al.2018; Veh et al. 2019). In the past sixty years, many large debris flows took place in the Tibetan Plateau, especially along the Yarlung River (Wang et al. 2021). These debris flows severely impacted the Sichuan-Tibet highway (State Highway G318) along the right bank of Parlung River, and the highway was frequently closed for long periods (Zou et al. 2019). On 29th Sep 1953, a mega glacier debris flow with a leading head of 40m occurred in the Guxiang Gully, the sediment transport volume of the debris flow was about 17.1×10^6 m^3 (Zou et al. 2020; Dang et al. 2009). A huge debris flow accumulation fan with an area of 4.2 km^2 also formed at the mouth of the gully and blocked the Parlung River, a tributary of the Yarlung River. The debris flow event caused more than 140 deaths and a large amount of arable land was buried (You 2001). On September 4 of 2007, July 25–31 and September 5–8 of 2010, three large-scale debris flows took place in the Tianmo gully, a tributary of the Parlung River (Figure 3) (Wei et al. 2018; Deng et al. 2017; Wang et al. 2018). All the three debris flow events blocked Parlung river and produced dammed lakes. The outburst flow intensively scoured the foot of the high terrace at opposite bank and made it collapse, resulting in the ruin of State Highway G318 base and the interruption of traffic (Zou et al. 2020; Ge et al. 2014). The distribution of large-scale geohazards in the south-eastern of the TP is shown in Figure 4 and Table 1.

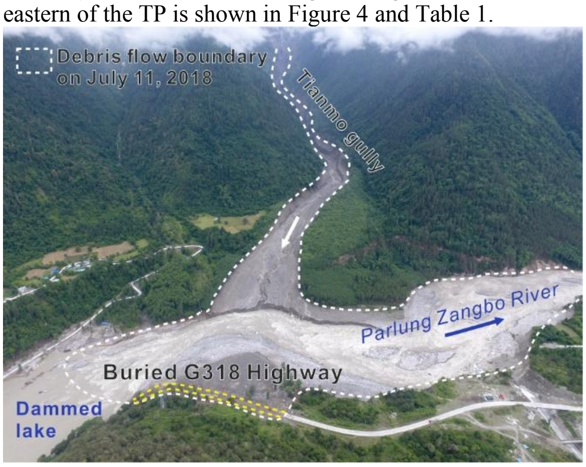

Figure 3. The Tianmo debris flow destroyed the G318 Highway in TP

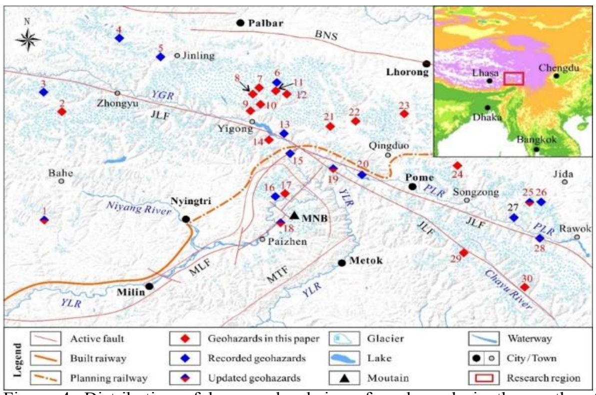

Figure 4. Distribution of large-scale chains of geohazards in the southeastern Tibetan Plateau

Table 1. Details of rock-ice avalanche in the Tibetan Plateau

ID	Location	Latitude	Longitude	Date	Type	References
1	Yigong	30.23	95.00	2000.04.09	Rock-ice avalanche	Li et al. 2020
2	Aru	34.03	82.25	2016.07.17	Glacier/ice avalanche	Kääb et al. 2018
		34.01	82.26	2016.09.02	Glacier/ice avalanche	
3	Yarlong Tsangpu (Sedongpu)	29.81	94.92	Before 2014		Liqiang et al. 2018
				2014		
				2017.10.22		
				2017.11		
				2017.12		
				2018.01		
				2018.07.06		
				2018.10.17	Rock-ice avalanche	
				2018.10.29	Rock-ice avalanche	
4	Amney Machen	34.82	99.43	2004.02.10	Glacier/ice avalanche	Paul 2019
				2007.10.08		
				2016.10.06		
5	Yulong Mountain	27.09	100.19	2004.03.12	Rock-ice avalanche	Zhang et al. 2007
6	Peilong gully			1968-1977?	Glacier landslide	Li et al. 2021; Wang et al. 1999
7	Jiubie Peak in Kongur Mountains	38.71	75.27	2015.05	Glacier surge and ice avalanche	Li et al. 2016
8	Zelongnong glacier	29.62	94.99	1950.08.15	Glacier surge/avalanche	
				1968.09.02		
				1984.04.13		
9	Kunlun Mountain	35.75	93.53	2001.11.14	Ice avalanche	van der Woerd et al., 2004
10	North Terong glacier	34.33	77.16	2000.04.05	Rock-ice avalanche	Bhutyani and Mahto 2018

2.5 *Climate change-induced glacier retreat and chains of hazards*

Due to climate change, glacier retreating, as well as increasing number of glacial lakes nurturing by glacier retreating process, are hot issues emerging during recent years, especially regional inventories and spatial-temporal evolution analysis (Dehecq et al. 2018; Chen et al. 2021; Dou et al. 2021a; Wang et al. 2020). The TP climate is under the combined effects of the East Asian and South Asian monsoons and of the westerlies, resulting in inhomogeneous distribution and variation of glacier and glacial lakes (Chen et al. 2021; Yang et al. 2014).

The satellite images with the least cloud cover and the least mountain shadows were selected by the relevant algorithms, and based on Google Earth Engine using image fusion techniques (Gorelick et al. 2017; Kumar and Mutanga 2018), we fused the 42833 Landsat satellite images into three images of different periods (1990-1999, 2000-2012 and 2013-209) over the past three decades, followed by subsequent processing using © ArcGIS Pro and © ENVI software, including manual cross-checking and correction by image interpreters (Figure 5). Based on this we produced an updated inventory of TP glacial lakes with complete data for three periods (Dou et al. 2021b). In the last thress decades, our inventory showed that the number and area of glacial lakes in TP region had increased by 3285 and 258.82 km^2, respectively (Figure 6). There area, however, decreased in the western Pamir and the eastern Hindu Kush due to reduced rainfall rates (Dou et al. 2021a).

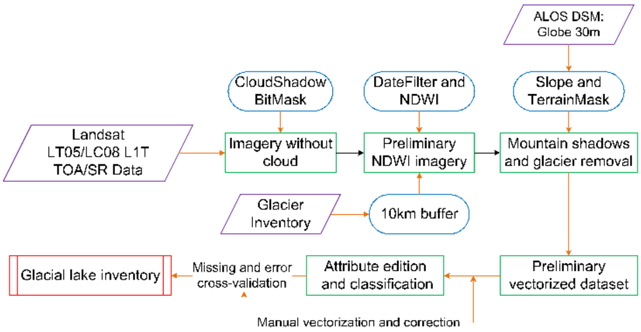

Figure 5. Flowchart of the glacial lake automatic extraction and mapping workflow

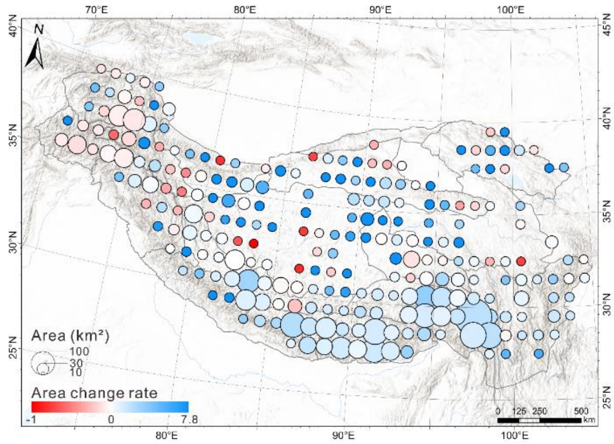

Figure 6. Area change rate of glacial lakes from the first period (1990-1999) to the last period (2013-2019) on 1°×1° grids. The circle size represents the total glacial lake area in the first period of each grid

The accompanied GLOFs aggravated with glacier retreat and glacial lakes expansion. Benefit from remote sensing development, archived glacial lakes and GLOF database are established to explore their spatial-temporal evolution (Zheng et al. 2021a; Veh et al. 2019; Veh et al. 2020). Since 1900, more than 100 GLOFs have originated in the Himalayas, causing damage to bridges, road, houses and other infrastructure (Zhang et al. 2022; Nie et al. 2018; Zheng et al. 2021b). More than 50% of catastrophic moraine dam failures ascribed to rock/ice avalanche in the Himalaya (Allen et al. 2016). Similarly, some research revealed that 26 out of 33 glacial lakes outburst are related to rock/ice avalanche in TB region (Liu et al. 2019). Therefore, exploring the process and mechanisms of those chains of hazards is essential for risk assessment.

With the development of urbanization and hydropower projects booming in TB, downstream impact of GLOFs is urgent for policy-makers and research scientists (Dubey and Goyal 2020). Some large-scale analyses have been made to assess and predict dangerous glacial lake (Allen Simon et al. 2019; Zheng et al. 2021a). Apart from regional analysis, individual case also made detailed assessment by numerical simulation or other methods (Westoby et al. 2014; Mergili et al. 2017). However, accurate assessment was impeded by nearly inaccessible of glacial lake on TP, and limited accessible cases seemed crucial to acknowledge the characteristics of glacial lakes on TP.

3 MECHANISM OF CLIMATE CHANGE INDUCED CASCADING HAZARDS

3.1 *Post-seismic landslides and debris flows driven by climatic forces*

The coseismic deposits are typically constituted by loose materials with significant amounts of fines, hence are susceptible to sudden collapse and liquefaction upon loss of suction or pore water pressure increase (Hu et al. 2017, 2018). Hence the major factor for the post-seismic landslides and debris remobilization in earthquake affected areas are found to be the volumes of coseismic deposits and rainfall intensities (Dadson et al. 2004; Hovius et al. 1997; Marc et al. 2016). Other than the above, multiple mechanisms may also be at play (Kincey et al. 2021); essential controls seem to be the sizes, topography, landcover, and hydrological conditions, the healing or removal of seismically damaged layers, climatic factors, and the legacy of previous earthquakes (Marc et al. 2021; Tanyaş et al. 2021a, 2021b; Tian et al. 2020). The decay of post-seismic landslide activities is controlled by various processes, including the progressive exhaustion of the hillslope and channel material, precipitation regime, and hillslope healing due to revegetation, grain coarsening and consolidation (Domènech et al. 2019; Fan et al. 2018, 2019a). An important one among these is the recovery of vegetation growth (Lin et al. 2006; Saba et al. 2010; Yang et al. 2017, 2018; Fan et al. 2018). Yunus et al. (2020) by analyzing decadal evolution of vegetation recovery in the affected region showed that post-earthquake landslide activity returned to the pre-earthquake level within 18 years. Tanyas et al. (2021a) reported that quick recovery of post-seismic landslides, also correlated with the seasonality of precipitation. According to them, a prolonged precipitation makes the recovery process quicken.

3.2 *Initiation and runout mechanism of rock-ice avalanches-debris flows*

Rock-ice avalanches and resulting debris flows origination in mountain permafrost regions are more significant threats of climate change regarding the scale and nature of impacts of these geohazards. In comparison, the magnitude of the long-runout rock-ice avalanches were always enormous; their frequency in the recent decade has increased, possibly due to climate change (Huggel et al. 2010; Schneider et al. 2011; Schneider et al. 2013; Cloutier et al. 2017). Unlike the progress in understanding the initiation and runout mechanisms of warmer region rock-avalanches (Hungr 2006; Korup 2011; Shugar et al. 2013; Dufresne et al. 2016), there are critical gaps in our knowledge on rock-ice avalanches (Pudasaini & Krautblatter 2014; Yu et al. 2020; Sansone et al. 2021). Similar to rock avalanches triggered by an earthquake, studies explain a few instances of earthquake-triggered rock-ice avalanches on TP (van der Woerd et al. 2004). However, the initiation mechanism is still speculative for many climate-weather driven rock-ice avalanches (Martha et al. 2021; Shugar et al. 2021). Debris flows origination from rock-ice avalanches are a more significant threat than rock-ice avalanches (Yu et al. 2020). Cold region permafrost debris flows multiply the impact of rock-ice avalanches into glaciers. Permafrost debris flows are more common in Tibet (Ge et al. 2014; Deng et al. 2017; Wei et al. 2018). Yu et al. (2020) separate the initiation mechanism of debris flow into geomechanically related and hydraulically related groups. Geomechanically triggered debris flows originate through rock-ice avalanches and liquefaction of moraine deposits (Noetzli et al. 2006; Jiskoot 2011; Carey et al. 2012), and hydraulically triggered debris flow originate through heavy rainfall and/or rapid ice/snowmelt runoff.

3.3 *Mechanism of moraine dam breach*

Moraine dam breach and subsequent flooding are typical examples of climate change induced-cascading hazards on TP (Montgomery et al. 2004; Korup & Montgomery 2008). Recent events of rock-avalanche and rock-ice avalanche landslide damming events highlight the climate emergency on TP and also signifies the importance and threat of these transboundary geohazards. The impacts of moraine dam breach are cascading in nature due of sequential triggering of secondary hazards i.e., flash floods, and debris flows (Cui et al. 2010; Cui et al. 2013; Xiangang et al. 2017; Bazai et al. 2021). Recent reviews on the formation and stability and breach mechanisms of landslide dams highlight the present state of knowledge and gaps in understanding of dam breach mechanisms and modelling (Fan et al. 2020; Fan et al. 2021b; Zhong et al. 2021). However, detailed studies on moraine dam failure are few (Neupane et al. 2019). Moraine dams are mechanistically weaker compared to landslide dams due to their mixed grain composition, morphology and sloping positions (Neupane et al. 2019). The width to height ratio of moraine dams is found to be smaller than landslide dams (Evans 1986; Clague & Evans 1994; Evans et al. 1996). Neupane et al. (2019) differentiate types of moraine dams using their sediment height and composition. Triggering or initiation of a moraine dams are referred to thawing of ice-rich sediments, sudden impact of snow/ice/rock/rock-ice avalanches into glacial lakes, tectonic events i.e., earthquake triggering these mass movements, and extreme-hydro-meteorological events like abrupt snowmelt, and heavy precipitation. While the onset of failures is known for the reasons above, the instability of dam breach is driven by wave overtopping, erosion (both internal and external), seepage and slope failures. These are similar mechanisms of landslide dam breach. However, moraine-dam breach is characterised by thermo-hydro-mechanical changes that dynamically take place during failure (Hewitt 1999; Korup & Tweed 2007; Neupane et al. 2019).

4 CONCLUSIONS

In the Tibetan Plateau and it's margins, the impact of climate change is evident from the concurrent, cascading, and chains of geohazards in recent decades (Lu et. al. 2019). Both tectonic driven and climate driven geological processes have converted to geohazards due to enhanced activity i.e., glacier retreat, glacial lake outburst floods (GLOFs), cloud outburst events, flooding and landslides caused by warming-induced changes. With the rise of air temperature during the thawing season and abundant precipitation related to extreme-weather events under climate change, it is vital to expect the trend to prolong. This brief review emphasizes the following directions for future research outlook:

The Tibetan Plateau is one of the most sensitive regions in the world to climate change, and also one of the most tectonically active regions with frequent strong earthquakes. The climatic and tectonic conditions and their coupling effects on causing geological hazards on TP are not well understood.

Efforts have been made in generating glacier and glacier lake inventories, but there is still a data gap in all different types of geological hazards for the whole TP. Most of database cover only specific areas. Both spatial and temporal resolution of database need to be improved.

Based on the abovementioned multi-temporal inventory of multi-hazards, the spatio-temporal evolution of geological hazards for the whole TP can be analysed. How their evolution responses to climate change and tectonic movements needs more studies in the future.

Early recognition and warning of cascading hazards on TP based on multi-source remote sensing data and monitoring system are crucial to control their potential risk. Seismic monitoring system might be a useful method to monitoring potential hazards in the inaccessible regions.

The initiation and runout mechanisms of large rock-ice avalanches and debris flows, especially the thermo-hydro-mechanical coupling mechanism need to be further studied by field monitoring and laboratory tests.

Risk prediction of future hazards by considering different magnitudes of earthquakes, climate change and their coupling effect is in high need of risk control of cascading hazards on TP. To this end, numerical models based on mechanism research will be very helpful.

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