

Intensified paraglacial slope failures due to accelerating downwasting of a temperate glacier in Mt. Gongga, Southeastern Tibet Plateau

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Abstract. Topographic development via paraglacial slope failure (PSF) represents a complex interplay between geological structure, climate, and glacial denudation. Where debris generated by PSFs is deposited on the surface of a glacier, this debris can increase the extent or thickness of a supraglacial debris-cover, in turn modifying glacier ablation and affecting meltwater generation. ~~To date, This study pays little attention has been paid to the~~ intensity and frequency of PSFs in a glacierised, monsoon temperate regions of Southeast Tibet [Plateau \(SETP\)](#), ~~a region that has experienced the most remarkable accelerating ice mass loss among High Mountain Asia (HMA) during past decades.~~ In our case, We mapped PSFs along the 5 km-long, 0.5 km-width, west-east trending ice tongue of Hailuoguo Glacier (HLG), a well-monitored monsoon temperate valley glacier in Mt. Gongga, using repeat satellite- and unpiloted aerial vehicle (UAV)-derived imagery between 1990 and 2020. Accompanying with the observed glacier retreat and thinning, the overall paraglacial bare ground area (PBGA) increased from 0.31±0.27 km² in 1990 to 1.38±0.06 km² in 2020, with decadal expansion rates from ~0.01 km² a⁻¹ in 1990-2000 and 0.02 km² a⁻¹ in 2000-2011, to 0.08 km² a⁻¹ in 2011-2020, indicating an intensified paraglacial failure process. Three types of PSF were identified: (A), including (A) rock fall/rockfall, (B) (B) sediment-mantled slopes slide and collapse, and (C) (C) gully headwards erosion, with a total area of 0.75±0.03 km² in 2020, were identified and documented based on recently repeating high-resolution UAV mappings. The formation, evolution, and current state-status of these typical PSFs and discuss these aspects with relation are generally related to the history of glacier dynamics and paraglacial geomorphological history adjustments, and also influenced and/or disturbed by the fluctuation of air temperature/precipitation and their combinations. Despite a slightly decreasing trend of annual precipitation was observed at our studied site, the absolute high-amount precipitation in Mt. Gongga as well as other monsoon-dominated deglaciating mountain areas must have played important roles in the intensified denudation, nested processes, and failure of the paraglacial slopes. South-facing slopes (true left of HLG) showed more destabilization (56% of total PSFs area) and higher PSF activity than north-facing slopes (44% of total PSFs area). We observed annual average rates of downslope sliding for type B PSFs of 1.6–2.6±0.04 cm d⁻¹, whereas the

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average upward denudation rate for type C PSFs was $0.7 \pm 0.39 \pm 0.31 \text{ cm d}^{-1}$. We show that type A PSFs are non-ice-contact rock falls/collapses that occur as a long-term paraglacial response following glacier downwasting and the exposure of steep rocky cliffs and which could also be influenced by precipitation, freeze-thaw cycling, earthquakes or other factors. In contrast, type B and C PSFs are a more immediate response to recent glacier downwasting. We further argue that the accelerating downwasting of glaciers are used as a preparatory or triggering factor, which could directly or indirectly cause the PSFs. We also found some unstable slopes in the lower slope angle areas which may be related to the slope material and the failure process.

1 Introduction

The thinning and retreat of mountain glaciers exposes new, unstable landscapes which are susceptible to rapid geomorphological changes (i.e., with a high entropy). Sparsely vegetated or unvegetated drift-mantled slopes are particularly susceptible to be modified by gravitational, aeolian, and fluvial processes and rapidly reworked by debris flows, rock avalanches, and slope-wash (Ballantyne, 2003; Ballantyne, 2002; Deline et al., 2015a; Eichel et al., 2013). Glacier downwasting can destabilize slopes through undercutting and, simultaneously, the progressive loss of buttress exerted by ice loading on its adjacent slopes may result in rock stress-releases, scilicet “debuttressing”, altering the state of stress that exists within the slope accordingly. Such slope failures initiate four possible modes of response: (1) large-scale catastrophic rock slides and rock avalanches (Kirkbride and Deline, 2018; Fischer et al., 2010); (2) ice-contact slope movements (McColl and Davies, 2013); and (3) periodic small-scale rock topples or ~~rock fall~~ rockfalls (Cook et al., 2013); ~~(4)~~ and (4) deep-seated gravitational creep (Deline et al., 2015b; Ballantyne et al., 2014); ~~and (5) paraglacial debris cones and valley fills (Ballantyne, 2002)~~. These four types of response provide a useful framework for examining the processes and geomorphological consequences of slope adjustment after deglaciation. These responses can be further divided into two types: rock slope failures and sediment slope failures, which are usually described collectively as paraglacial slope failures (PSFs). PSFs encompass failure of steep rock walls and lateral moraine slopes following glacier downwasting (Church and Ryder, 1972; Fickert and Grüniger, 2018) and are widely distributed in deglaciating or deglaciating landscapes. PSFs constitute a key mechanism for rapid degradation of recently glacial landscapes, as they contribute to the disaggregation of large portions of valley sides and the transformation from U-shaped to V-shaped valleys. High-frequency, low-magnitude PSFs can transport a considerable volume of debris onto glacier surfaces (Smith et al., 2020), thereby facilitating the accumulation of the supraglacial moraine. Because thin debris covers enhance ablation, whilst thicker covers suppress it (Fyffe et al., 2020), debris supply dynamics ultimately affect the glacial ablation and meltwater production (Rowan et al., 2018). In addition, accompanied by relatively rare but occasional rain storm events, those unsorted debris are very likely transformed into debris flows and cascading geo-disasters that threaten downstream infrastructure, freshwater availability, and the safety of residents and tourists (Hewitt et al., 2011; Reznichenko et al., 2012).

Monsoonal temperate glaciers in the Southeastern (SE) Tibetan Plateau (SETP) have experienced higher rates of mass loss and ice thinning than other High Mountain Asia (HMA) glacierized regions in past decades (Neckel et al., 2017; Brun et al., 2017), with an average thinning rate of $-0.55 \pm 0.23 \text{ m a}^{-1}$ during 2000 to 2016 (Brun et al., 2017). In addition to seismically active, the combination of a large amount of high-intensive glacial meltwater ablation and abundant/ extremely -monsoonal precipitation during the summer monsoon makes SE-Tibet one of the most susceptible regions for the glacier or water-related geo-hazards (Yao et al., 2019a), such as glacial debris flows, ice/snow avalanches, glacier-related landslides, and glacial lake outburst floods (Fan et al., 2019; Cheng et al., 2010; Xu et al., 2012). Further or example, a total of at least four glacier-related landslides (1990-2018, (Liu et al., 2010; He et al., 2008; Pan et al., 2012; Cao et al., 2019; Liu et al., 2018; Liu and Liu, 2010)), and twelve glacial lake outburst floods (1931-2014, (Liu et al., 2019b; Yao et al., 2014)) incidents have been recorded across the SETP Tibetan Plateau. Mass movements resulting from large-scale slope failures routinely form temporary valley-blocking natural dams (Liu et al., 2019c), behind which large lakes can develop and eventually outburst. Mass movements originated from tributary valleys where glacier recession and permafrost thaw have reduced slope stability has likely contributed to these large-scale slope failures (Zou et al., 2020; Korup et al., 2010). For example, more than half of the debris flows recorded in the Linzhi Area, SE Tibet, SETP can be sourced to a were cryospheric trigger (Hu et al., 2011). Further, a total of four glacier related landslides (1990-2018, (Liu et al., 2010; He et al., 2008; Pan et al., 2012; Cao et al., 2019; Liu et al., 2018; Liu and Liu, 2010)), and twelve glacial lake outburst floods (1931-2014, (Liu et al., 2019b; Yao et al., 2014)) incidents have been recorded across the SE Tibetan Plateau. These hazards have caused severe economic losses and heavy casualties and have affected socioeconomic development. Glacier destabilization itself was also one of the concerned sources of the cascade hazard events, such as historically reported surge induced catastrophes (Zhang, 1985) and recent ice avalanche induced debris flow that blocks the Yarlung Tsangpo river (Chen et al., 2020; Käab et al., 2021). These cascading geo-hazards have caused severe economic losses or some heavy casualties to SETP local communities.

With populations and economies expanding, it is anticipated that the magnitude and frequency of glacier-related hazard in the SETP will increase in near future (Yao et al., 2019b) since the accelerating glacial mass loss and permafrost degradation due to climate warming will continue to destabilize the paraglacial landscapes (McColl, 2012). It is anticipated that accelerating glacial mass loss and permafrost degradation due to climate warming will continue to destabilize the paraglacial landscapes and thus increase the frequency of related hazards in the SE Tibet Plateau.

Mt. Gongga is located on the southeastern edge of the Tibetan Plateau, in the geological transitional zone between the Plateau and the Sichuan Basin (Liu and Zhang, 2017). It is a large natural reserve with medium human disturbance and a relatively developed glacier tourism sector. According to the Second Glacier Inventory in China (Liu et al., 2015), there are 75 temperate glaciers in Mt. Gongga, of which five larger valley glaciers have a length >10 km, including Hailuoguo Glacier, Mozigou Glacier, Yanzigou Glacier and Nanmenguangou Glacier on the eastern slope, and Gongba Glacier on the western slope (Li et al., 2010). In recent decades, remarkable retreat and thinning of these glaciers has been widely reported (Liu et al., 2010; He et

100 al., 2008; Pan et al., 2012; Cao et al., 2019; Liu et al., 2018; Liu and Liu, 2010) and catastrophic glacial geomorphological processes or glacier related hazards, such as glacial debris flows and landslides, occur frequently in the Mt. Gongga region (Xu et al., 2007; Cai et al., 2021). PSFs in these catchments are generally considered to occur on steep rocky terrain and manifest as mixed ice/snow/rock avalanche and rockfall originating from surrounding walls and triggered by frost weathering processes. Most glaciers on Mt. Gongga have a considerable surface debris cover in their ablation zones and are bordered by
105 unconsolidated lateral terminal moraines in the periglacial zones.

While a growing body of research studies focusing on the process of paraglacial hillslopes destabilization of in the European Alpine (Curry et al., 2006; Kirkbride and Deline, 2018), Southern Alps (Cody et al., 2020; McColl, 2012), and Cordillera Blanca (Andes) (Emmer et al., 2020) and Himalayas (van Woerkom et al., 2019), yet few cases have been reported for the transient condition of paraglacial slopes in the deglaciating the representation of evidential findings in the SE-Tibetan Plateau (low latitude region) is still unknown. To addresses
110 In this gap study, we select the Hailuoguo Glacier (HLG), a monsoon temperate glacier in Mt. Gongga that has been well documented and observed since the early 20th century) and suffered glacial debris flows and landslides, for a detailed case study site to study on the interactions between glacier shrinkage and paraglacial- slope interaction adjustments in SE Tibet during the past decades.

In this study we carried out investigations on the PSFs processes of Hailuoguo Glacier (HLG) a typical temperate glacier located on the east slope of Mt. Gongga. Our investigations are based on the analysis of historical satellite imagery images and recent field-based high-resolution the field-phototopography mappings using imagery acquired from an
115 unpiloted aerial vehicle (UAV), combined with on-site geomorphological observations and measurements. The main objectives of this research are to:

- A. (A) map and quantify the spatiotemporal variability of PSFs map and quantify slope failures and topographic change around the lower tongue of Hailuoguo Glacier through based on time-time-series image comparison; (B) ;
 - B. C classify the PSFs, analyse their topographic conditions describe and discuss the spatial distribution, spatiotemporal evolution, and discuss their possible foreign-physical mechanisms; ;
 - C. (C) discuss the geomorphic and environmental effects of these slope processes by exploring the and further discuss possible linkages between PSFs, climate change, and glacier downwasting and PSFs in a typical monsoon-dominated region characterised by accelerated glacial and paraglacial denudation.
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2 Study area

Hailuoguo Glacier (29°58.4'N, 101°91.6'E) is one of the largest debris-covered valley glaciers in the Mt. Gongga region (Fig. 1). It is a ~13 km-long, east-facing monsoon temperate glacier, has an area of 24.7 km², and extends in altitude from 2990 m to 7556 m a.s.l. The glacier is ~300-500 m in width, and the wider valley is deeply incised below the accumulation area (where
130 the glacier broadens to ~6 km in width). The upper section of the ice tongue (below the icefall) has a surface gradient of ~10° and is connected to very steep (~55°) lateral slopes on both sides. At a distance of ~1.5 km from the base of the icefall (middle

section of the ice tongue), the glacier surface steepens to $\sim 12^\circ$ and becomes highly crevassed. At a distance of 2 km, the glacier turns its flow direction toward the north-east, and maintains a surface gradient of $\sim 13^\circ$ for the remaining 3 km (lower section of the ice tongue) stretching to the [Little Ice Age \(LIA\) end of the glacier tongue moraine](#). Paralleling with the lower section of the ice tongue, the height of lateral moraines to the current glacier surface is about 165 m, which is comparatively higher than the further upper glacier (~ 86 m at the middle section of ice tongue).

The terminus of HLG has retreated more than 2 km since the LIA (Su and Shi, 2002) and this retreat has accelerated from 12.7 m a^{-1} between 1966–1989 to 27.4 m a^{-1} between 1998–2008. Between 1966 and 2009, the mean ice surface elevation of its lower tongue had lowered at a rate of $1.1 \pm 0.4 \text{ m a}^{-1}$ (Zhang et al., 2010). Due to a suitable local thermal (warm) and moisture (wet) climatic conditions, vegetation is able to quickly establish itself on the exposed periglacial bare ground in glacier forelands and lateral moraine slopes, and even on some supraglacial debris-covered areas that are largely stagnant. The LIA preglacial zone (2980–2800 m) is characterized by extremely fast primary vegetation succession, and hosts an integrated community ranging from cold-adapted herbaceous species to *Abies fabri* (conifer pine) forest. *Abies fabri* forest patches are also seen along both lateral sides of the ice tongue on the accumulated lateral moraine, which has been relatively stable since the LIA.

Due to its low altitude, easy accessibility, and adjacency to the forests and hot springs, HLG and its surrounding areas have been exploited for tourism since 1987. A glacier ropeway connects the two lateral moraines and transports visitors across the lower part of the ice tongue and provides access to a viewpoint on the southern side of the valley (S2 on Fig. 1) from where the ice tongue can be overlooked and accessed via trail. Between 2000 and 2011, the number of annual visitors increased from 44,000 to 384,000 (Zhu, 2015), and in 2019 the number reached $\sim 2,852,600$ (Haiguanju, 2020). The increasing popularity of the glacier comes at a time when tourism facilities and infrastructure are becoming frequently disturbed due to paraglacial ~~landsliding~~ landslides, debris flows, and flash floods (Xu et al., 2007; Cai et al., 2021). Beyond the objectives outlined above, there is a need to more fully understand the nature of slope failures in the vicinity so that these failures might be better anticipated, and their potential impacts mitigated where possible.

3 Data and methods

3.1 Paraglacial slope failures (PSFs) mapping and classification

~~Given a warm and humid climate condition, vegetation colonisation is very fast (1-2 years) in the HLG paraglacial environment. Since~~ Like many monsoonal temperate glaciers in SETP, the lower part of the HLG tongue and its adjacent slopes are located below the local tree line, any newly developed PSFs could be readily recognized from the changed paraglacial exposed bare ground area (PEBGA). ~~To map the extents of PSFs for addressing objective A,~~ We firstly ~~we~~ extracted the paraglacial PEBGA non-vegetated areas by classifying the land surface with vegetated and unvegetated areas using with the Normalized

Difference Vegetation Index (NDVI), which was calculated using reflected red and near-infrared band values of satellite images. The PBGAs~~PSFs~~ were then extracted by excluding the ~~glacier-covered~~ areas ~~covered by the glacier extents (GCAs)~~ to generate an initial mapping of PSF. ~~Some areas of PBGA showed an interannual change or a sudden change in visual shape. However, due to the climate conditions, vegetation colonisation is extremely fast in HLG environment~~ For better inter-annual comparisons, we then manually removed those patches and areas where the PBGA has changed due to vegetation colonisation in some paraglacial slopes and in all glacier foreland, ~~some changed PBGA caused by vegetation colonisation which, mainly in the glacier foreland, were manually removed. Finally, those to keep the remaining unstable slope areas were~~ final mapped as PSFs. A total of 8 satellite images between 1990 and 2020 (Table 1), including Sentinel-2 (10m), RapidEye (5m), PlanetScope (PL, 3m), were used to extract the PSFs. These data constitute a multi-temporal and dynamic observation of HLG and its surrounding paraglacial environments. Due to the strong influence of the monsoon, the HLG is often covered with thick clouds in summer, rendering 75% of the available summer satellite images unusable. However, we successfully screened and synthesized several Landsat or Sentinel-2 cloudless images in 1990, 2000, 2016, and 2018 using the Google Earth Engine platform. ~~Shadows caused by the relative angle between the sun, ground objects, and sensors will reduce the value of NDVI, but by adjusting the threshold, the vegetated and non-vegetated areas can still be differentiated~~ NDVI can eliminate a part of the effect of hill shade caused by the low angle of the sun on ground recognition. Therefore, we can use cloudless images of in multiple seasons (spring, autumn, and summer) to realize automatic extraction of PSFs boundaries. Of the seasonal data, the PSF boundaries extracted from images acquired in the northern hemisphere summer are generally suffered less suffered from the terrain shadow than other seasons and can be used directly after validation, and the boundaries extracted from other seasons need to be manually corrected partly.

To enable more detailed mapping of recent PSF extents, UAV sorties were flown on 31 August 2016, 07 June 2017, and 15 May 2019 using a DJI Phantom 4 Pro UAV, and 19 August 2018 using a DJI Phantom 4 RTK UAV which combination of a global navigation satellite system (GNSS) with a mean horizontal accuracy quality of 0.01 m + 1 ppm* (RMS) in XY (<https://www.dji.com/uk/phantom-4-rtk/info#specs/>), and input photographs were stitched using Structure from Motion (SfM) software ContextCapture Center Master to create a time series of orthomosaic aerial images at 0.1m resolution. However, our earlier UAV surveys were routed with a limited area of off-glacier terrain that it was less effectively mapped by photograph overlapping (i.e., section 3.2). This design aspect of the UAV surveys, combined with steeply topographic constraints on the UAV flight area, meant that not all ice-marginal slopes were successfully mapped on the final orthomosaics as well as for the later UAV surveys (Fig. S1). All UAV images are co-registered using an orthorectified PL images acquired on 16 August 2018, which was found to be perfectly co-registered with a 12.5m hills-shade of ALOS PALSAR DEM when manual comparing their topography textures (e.g., terrain ridges and vertexes) from the peak of Mt. Gongga (7556 m a.s.l.) to the trimlines of the glacier close to its terminus (~3000 m a.s.l.). To execute the UAV images co-registration, a total number of 54

* 1 ppm means the error has a 1mm increase for every 1 km of movement from the aircraft/drone.

features (Fig. S1) were selected as ground control points on stable ground surfaces (e.g., exposed bed-rock, trees, ~~and or some~~ building ~~vertices~~) ~~around the ice tongue on the both~~ PL image and UAV images. ~~and~~ Their corresponding altitudes were then extracted from the ALOS PALSAR DEM. ~~Finally~~ Overall, the final reported quality of the co-registered UAV images ~~successfully occupied positions~~ were quite satisfactory (with a total- and (maximum) RMS error of: 1.22 and (1.98) pixel ~~respectively, from which the calculated i.e. a mean horizontal quality in XY is error of of 0.15 m in XY).~~

~~Additionally, an additional error of ±0.5 pixels was estimated to calculate~~ include all the uncertainties of visual interpretation and automatically extracted areas (i.e. multiply linear error and perimeter, e.g. the linear error of Landsat images are 15m, Sentinel 2 images are 5 m, and of PlanetScope images are ~1.56 m) (Salerno et al., 2012; Haritashya et al., 2018). ~~Our~~

workflow is summarized in Fig. 2.

According to the principles of systematization, standardization, operability, and scalability, the PSF are classified combining the knowledge of the basic slope material composition, erosion type, visual shape, and event magnitude obtained from field investigation and UAV data in HLG, and the classifications proposed by Ballantyne (2002), McColl (2012), Jarman (2006), and Hungr et al. (2014). A classification standard for PSF systems in SETP is proposed, which is divided into two major categories: rock slope failure and sediment slope failure; and five sub-categories: rock avalanches, ~~rock fall~~ rockfall, deep-seated gravitational slope deformations, sediment-mantled slope slide, and gully headward erosion (Tab. S1).

3.32 Slope movement and outline change headscarp erosion rates

To quantify the rate of slope surface displacement speed of slopes movement between 2016 and 2020 for address objective A, we selected 20-40 points as trackable features used QGIS software to identify between 20-40 feature tie points that were located on easily trackable features including of large rocks, paths, or infrastructures discolouration areas on a series of UAV mapped slopes (B1-B4 in Fig. S2, Fig. S32). We manually tracked the location displacement of each point in the QGIS software and calculated their mean horizontal displacements annually. In some For cases that, the displacement movement of the the slope itself is unapparent less notability or extremely low; but the headward backwasting these same slopes have is detectable significant headscarp erosion. To, we quantify their rates of headscarp erosion, we. Based on used the PSF boundaries outlined by delineated on five higher- resolution remote sensing satellite images from 2002 to 2019 (Google Earth SPOT-5 imagery for 2002, RapidEye images for 2011, 2014, and 2015, and PlanetScope image for 2019). to we calculated at the mean distance and annual retreat rates for these headscarps via using the QGIS Average Nearest Neighbor Neighbour Analysis procedure.

3.3.2 Glacier dynamics ~~observations~~

Since ~~the~~ evolution of paraglacial slope and their topographic conditions are closely related to the glacier dynamics (Ballantyne and Benn, 1994; Ballantyne, 2002), we thus analysed the geomorphological processes and implications of retreat, thinning, and slowdown of the HLG and their relationships with the PSFs development. Many scholars have done ~~Detailed research mapping~~ on the ~~area changes~~ retreat and thinning of the HLG over the past ~~years~~ decades has been well documented and reported (Li et al., 2010; He et al., 2008; Liu et al., 2018; Zhang et al., 2010; Liu et al., 2010). ~~We extend the boundary of G~~ glacier terminus retreat history was extended to 202019 using ~~some newly archived~~ satellite images used in this study (Fig. 1 and Table 1). ~~Zhang et al. (2010) reported a mean surface lowering rate of $1.1 \pm 0.4 \text{ m a}^{-1}$ between 1966 and 2009 for the lower part of HLG ice tongue. Using hydrological balance approach, Liu et al. (2010) estimated a thinning rate of 0.5 ± 0.4 to $0.7 \pm 0.4 \text{ m a}^{-1}$ (1994–2004) for the whole HLG area. A more recent investigation by Cao et al. (2019) updated the period to 2015 and gave an overall mean ice surface lowering rate of $0.54 \pm 0.04 \text{ m a}^{-1}$ for all glaciers in Mt. Gongga. In this study, we compile above results and extended it to 2016 following Brun et al. (2017), who published a regional dataset of glacier surface elevation changes for the High Mountain Asia derived by differencing ASTER DEMs between 2000 and 2016. We employed the TopoDEM (1966) reported by Zhang et al. (2010), the Shuttle Radar Topography Mission (SRTM, 2000) 30m DEM (Farr et al., 2007), and ~~thea~~ calculated 2016 DEM ~~calculated using based on the 2000-2016 the glacier mean annual surface elevation change s between 2000 and 2016 for the High Mountain Asia published rate by from Brun et al. (2017) ASTER-DEM difference between 2000 and 2016~~ to analyse the surface elevation changes of HLG between 1966 and 2016. Surface elevation changes along five profile-lines in longitudinal (A-A' ~~in~~ along the glacier central flow line) and transverse (B-B', C-C', D-D', and E-E' ~~perpendicular to the glacier central flow line~~) on the lower part of HLG (Fig. 1) were examined and compared. The four transverse lines were examined approximately ~~cover along the every three~~ types of PSFs (definition ~~below in section 4.2~~) and a ~~certain distance is maintained in each transverse profile for comparison. Glacier terminus retreat history was extended to 2019 using satellite images used in this study (Fig. 1).~~~~

For ice flow dynamics, the earliest observations of surface velocity of the HLG were during 1982-1991 field expeditions, during which the location changes of several stakes along the ice tongue were repeatedly measured. Unfortunately, the original coordinates data of those measurements (e.g., the precise geographic locations of the stakes) was not offered and results are published only as a velocity isoline map with point velocity value indicated. ~~Zhang et al. (2010) has reported a multi-decadal slowdown of the HLG ice tongue between 1980s, 1990 and 2008, when an updated stake-based ice velocity was conducted during the 2008 summer.~~ Using 38 SAR images acquired by PALSAR-1/2 satellites from 2007 to 2018, Liu et al. (2019a) extracted annual surface displacement velocities of the HLG between 2007 and 2018. Here we compared the long-term ice flow velocity changes of the HLG (also checked along the five profile-lines mentioned above), based on three-periods results of 1982-1983, 2007-2011, and 2014-2018. ~~The velocity in 1982-1983 is based on a published velocity map (scanned and shown in Fig. S4), which was ~~ere~~ calculated and extrapolated from in-situ measurements of stake locations using the total~~

260 ~~station-. The velocities during 2007-2011 and 2014-2018 were derived from ALOS/PAL(SAR satellites using the derived feature tracking method by offered by Liu et al. (2019a)).~~

3.3 Slope movement and outline change rate

265 ~~To quantify the surface displacement speed of slopes, we used QGIS software to identify between 20-40 tie points on a series of slopes (B1-B4 in Fig. 6, Fig. S2). We manually tracked the displacement of each point and calculated the mean horizontal displacement. In some cases, the displacement of the slope itself is unapparent or extremely low, but these same slopes have detectable headscarp erosion. To quantify rates of headscarp erosion, we used the PSF boundaries outlined by five high-resolution remote sensing images from 2002 to 2019 (Google Earth SPOT-5 imagery for 2002, RapidEye images for 2011, 2014 and 2015, and PlanetScope image for 2019) to calculate a mean distance and annual retreat rate for these headscarps.~~

3.4 Meteorological data

270 ~~Meteorological conditions nearby the HLG were diagnosed To discuss their possible forcing mechanisms and/or the climate change effect of impacts on the development of PSFs for address the objective B and C. The d~~Daily air temperature and precipitation data (1988/01/01--2018/12/31) ~~were used in this study were sourced from~~observed by the Subalpine Ecosystem Observation Station (3000 m a.s.l., 2 km from glacier terminus), and provided by the Gongga Alpine Ecosystem Observation and Experiment Station (Gongga Mountain+ Station, 3000 m a.s.l., 2 km to the glacier terminus) with a standard automatic weather station (AWS)- installed and managed by the Chinese Ecological Research Network (CERN; <http://www.cern.ac.cn/>). We also ~~obtain~~collected the manually observed daily temperature data (observed at 2:00 am, 8:00 am, 2:00 pm, 8:00 pm every day)- by a staff of Mt. Gongga Station) to compensate for the missed AWS data between July and September 2017 due to equipment inspection and between 29 September and 15 October 2018 due to electrical power failures ~~during this period.~~ During the period 1988-2018, the observed mean annual temperature at 3000 m a.s.l. was 4.5 °C. Rain gauges recorded an average annual ~~number average~~ of 314 days with precipitation with and a mean annual amount of 1912 mm precipitation at 3000 m a.s.l., of which 88% amount was concentrated in the ablation seasons (April to October) and ~42% was concentrated in summer months (July to September).

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4 Results

4.1 Retreating, thinning, and deceleration of the H_Lailuogou Glacier

285 Glacier outlines in 2002, 2016, and 202019 (Fig. 1c) were manually delineated based on high resolution images (Google Earth SPOT-5 imagery for 2002, and UAV images for 2016, and PL imagery for 202019). Comparison of these outlines shows that the glacier tongue area has reduced from 2.30 ± 0.06 km² to $1.952-06 \pm 0.02$ km² (average 0.098 ± 0.03 km² a⁻¹) between 2016 and 202019 compared with the period 2002-2016, when it reduced from 2.65 ± 0.01 km² to 2.30 ± 0.06 km² (average 0.03 ± 0.01 km² a⁻¹). Between 2002 and 2016, the position of the glacier terminus showed a moderate retreat (6 ± 0.44 m a⁻¹); whereas

290 during the following ~~four~~three years (2016-20~~20~~19), the terminus retreated more than ~~220±50±1.56~~ m (~~~54±0.39~~ m a⁻¹). Field observations indicate that the current glacier terminus area was no longer covered by ~~a~~ thicker debris ~~cover~~ as previous status, and frequent collapse along the subglacial outlet channel became the major backwasting process causing the accelerated terminus retreat.

295 The lower part of the HLG tongue also showed continuous narrowing as it retreats due to ice thinning. Ice surface elevation and velocity along five profile lines (Fig. 3) show that the ice tongue has experienced substantial ice loss and slowdown over the past decades. The longitudinal line (A-A') along the glacial flow direction runs through the entire ablation zone. Between 1966 and 2000, we observed negligible to small changes in the surface elevation of the upper ice tongue (-0.5~0 m a⁻¹, between 3400 to 3700 m a.s.l), with a mean lowering ~~the~~ rate of -0.11 m a⁻¹. However, the ice tongue below 3200 m a.s.l (3~4.5 km to
300 the base of the icefall) thinned remarkably as the highest lowering rate up to -2.2 m a⁻¹ near the glacier terminus. In contrast, the thinning rate of ~~the~~ upper ice tongue has greatly increased between 2000 and 2016, with the surface elevation change rate remaining at around -2.0 m a⁻¹. On the other hand, the lower part of ~~the~~ ice tongue (below 3400m) shows a decreasing thinning rate towards the terminus. For transverse profiles B-B' and C-C', rates of surface elevation lowering were much higher during
305 the past 50 years, with thinning rates remaining around -0.6 m a⁻¹ and -0.9 m a⁻¹, respectively.

Analysis of ice surface velocities during three periods (1982-1983, 2007-2011, and 2014-2018) in the past 38 years (Fig. 3c) indicates that the lower ablation area of HLG has experienced ~~a~~ gradual slowdown, with the rate of this deceleration decreasing
310 of ~~up~~glacier (Fig. 3c, profile A-A') and with increasing proximity to the lateral margins (Fig. 3c, profiles B-E). Ice surface velocities along all transverse cross sections ~~have~~s gradually decreased, with the greatest deceleration occurring along ~~with~~
profiles B-B' to D-D' (mean rate of 0.26 m a⁻¹) and less along the E-E' section (mean rate of 0.06 m a⁻¹). Note that remarkable decelerations ~~that~~ happened across the whole transverse profile of D-D' during our observation periods have led the ice tongue below almost stagnated (with ~~a~~ velocity less than 0.1 m a⁻¹) during 2014-2018.

4.2 Paraglacial slope failures

315 Mapped extents of the ~~paraglacial collapsed areas~~PBGAs between 1990 and 2020 were presented in Fig. 4. The ~~extents of~~
~~PB~~BGA shows continual expansion during the observation period, ~~increased from 0.31±0.27 km² in 1990 to 1.38±0.06 km² in 2020~~, with a total areal increase of 1.07±0.32 km². ~~Its decadal expansion rates increased from ~0.01 km² a⁻¹ in 1990-2000 and 0.02 km² a⁻¹ in 2000-2011, to ~0.08 km² a⁻¹ in 2011-2020, which was~~ approximately proportionate to the annual decrease in the GCA. Due to ~~a~~ transient rock-fall below the icefall ~~occurred between~~ September ~~and~~ November 2018, the ~~PBGA area~~
320 increased significantly, with an expansion rate up to ~~~0.11 km² a⁻¹ (10.43%) from 2018-2019~~ within one year. In general, the north-facing slope (located on the true right side of the glacier) exhibits more stability ~~than the south-facing slope, where 56% of the total PBGA was mapped and lower frequency of PSFs.~~

325 ~~According to the classification method in Tab. S1. By combining visual analysis of our time series remote sensing and UAV imagery with knowledge of slope material composition, erosion type, and event magnitude, we~~ identified three typical styles of paraglacial slope failure ~~within the PBGA, with a total area of $0.75 \pm 0.03 \text{ km}^2$ in 2020, according to the classification method in Tab. S1 that broadly with classifications proposed by Ballantyne (2002) and McColl (2012) (Fig. 5a):~~

- 330 A. ~~R~~rock-fall, ~~$-0.06 \pm 0.01 \text{ km}^2$ in 2020, 8%~~ of the total PSF area.
B. ~~S~~sediment-mantled slopes slide, ~~$0.37 \pm 0.01 \text{ km}^2$ in 2020, 49%~~ of the total PSF area. ~~and collapse~~
C. ~~G~~ully headward erosion, ~~$0.32 \pm 0.01 \text{ km}^2$ in 2020, 43%~~ of the total PSF area.

335 ~~Based on the calculated surface slope map from the 2016 DEM (Fig. S5) as well as field verifications (Fig. S6), the Type B and C PSFs (with a mean surface slope of 29° and 32° , respectively) usually show lower slopes in their unstable areas than stable areas ($40\text{-}60^\circ$). The ~~m~~Mean slope of the Type A PSF is about 54° , which is within the range of the stable slope.~~

~~Below we will present a detailed case study descriptive analysis of for each type of PSF observed at HLG below, and provide a summary of the dimensions and typology of for each specific PSFs identified in Fig. 5a in Table 2.~~

340 ~~4.2.1 Rock-falls~~ (PSF type A)

Different magnitude rock-falls are common at exposed steep bedrock terrain on both sides of HLG. ~~Evidence of a~~ recent ~~large single~~ rock-fall event (Type A, Fig. 5b) ~~was~~ occurred around October 15, 2018 ~~originating from a~~ south-west facing paraglacial slope ~~high-hanging above the upper HLG ice tongue (4000 m a.s.l., ~450 m high from the glacier surface) at a distance of ~0.3 km from the base of the icefall (Fig. 5b). The rockfall deposit and the existing glacier debris cover are slightly~~ different in colour and grain size and can thus be clearly delineated on the glacier surface, both on field photograph and on ~~remote sensing imagery (Fig. 5b and Fig. S7). The~~ ~~rock fall~~ final deposition area of the rockfall covers a projected area of ~~$\sim 47,000 \text{ m}^2$ is 283 m in width, 200 m in length, 450 m in height from the glacier surface, stretch in~~ covers a vertical height of 380 m, ~~and slope length of 472 m, and a 2D area of $\sim 47,000 \text{ m}^2$. The (runout length was approximately $\sim 365 \text{ m}$) and the drop height 40 m.~~ Based on the extent of the main detachment zone, the deposition thickness (3-5 m estimated during the field visit) and area (Fig. 5b), the total release volume of the rockfall is $1,000\text{-}10,000 \text{ m}^3$. The deposit corresponds to an estimated release volume of $60,000\text{-}100,000 \text{ m}^3$ of light green granodiorite rock detached from $\sim 4000 \text{ m a.s.l.}$ on a steep south-north facing slope (Fig. 5b). The thickness of the deposit was estimated during a field visit to be 3-5 m and the volumetric estimate is based on the extent of the main detachment zone, and the deposit thickness and area (Fig. 5b). The failed rock block amalgamated additional material from below the main detachment zone and ran out on to the surface of HLG, resting supraglacially at ~~around 3580 m a.s.l., demonstrating that is possible for sizeable volumes of rock fall to be delivered directly to the supraglacial~~

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environment in the glacier ablation zone, where it can contribute to debris layer thickening. The rock-fall deposit and the existing glacier debris cover are slightly different in colour and grain size and can thus be some clearly delineated on the glacier surface, both in the field, and on remote sensing imagery (Fig. 5b).

360 We also observed ~~other several suspected~~ major rock-fall scars on the lower part of the valley wall in close proximity to this scar-deposit (i.e., up to 260–400 m above the glacier surface; Fig. 5b and 5c) suggesting that numerous ~~similar smaller~~ scale rock-falls have occurred in this locality. Since the rock surface has been partially weathered and most of the bedrock has been covered by vegetation such as mosses and shrubs, we speculate that these rock-falls may have occurred earlier and ~~are~~ have not been documented by remote sensing images or literature.

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Except for the 2018 large rockfall, ~~However, the vertical joints of exposed bedrock on both sides of the glacier are well developed, and small magnitude rock-falls occur more frequently (Fig. 5a, Fig. S73). Based on UAV images and field investigation, we found identified at least 15 fresh small-magnitude rock-falls in view of their evident talus depositions based on UAV images and field investigation (Fig. 5a, Fig. S7). These small-scale rockfalls are found located on both sides of the lower paraglacial slopes and events have a source area ranging from 59 to 3028 m² on the paraglacial slopes, each with a mean area of 750 m². Their disintegrating rock-mass was are located between 3100 and 3500 m a.s.l. with the a mean vertical distance between from the base and glacier surface is are of about 110 m from their lowest breakpoints to the glacier surface. But, unfortunately, because of due to their small sizes and without continuous observations (e.g., time-lapse photography), we cannot determine the exactly exact time when they happened. These collapsed rock-falls falling on the glacier surface of with different magnitude have obviously become are one of the the important main ways inputs for supraglacial debris delivery to the glacier surface in the lower part of the HLG ice tongue.~~

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4.2.2 Sediment-mantled slopes slide ~~and collapse~~ (PSF type B)

We identified evidence of four major sediment-mantled slope slides ~~and collapse~~ (Type B, B1-B4, Fig. 5a). Combined, these features cover an area of $\sim 370,000$ m² (2019-PL) and are located on both north- and south-facing valley sides. The 2D area of Type B PSFs steadily expanded ~~through four processes: glacier downwasting exposing more of the slope, lateral expansion of the failure mass, and headward expansion from retrogressive failure or degradation of the scarp.~~ over our monitoring period (Fig. 4), ~~The with a total area increased by of 297,000 m² from 1990 to 2020, and the an area expansion rate was of 10.16% a⁻¹ from 1990 to 2020.~~

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B1 (3500 m a.s.l, Fig. S26a) is located on a north-facing lateral moraine slope at a distance of 1.5 km from the base of the icefall, and is 114 m wide, 1035 m long, and 112,424 m² in area. Between 2017 and 2019 the exposed area of this feature B1

slope increased by 12,125 m², or a percentage increase of 12.09 %. A landslide with an area of 53,000 m² is included as a nested feature within B1 (48.28% of B1 area), and evidence of superimposed gullying is also found on the eastern, western, and northern segments of this feature. ~~According to the conceptual model designed by Eichel et al. (2018), there are three stages which describe the transition from active to stable sediment mantled slopes: (a) gullying, (b) solifluction, (c) stabilization. The B1 feature is typical of stage A, and is characterized by active gullying and evidence of debris flows, slope wash, slope slides, combining to produce a complex slope landform which hosts pioneer vegetation species and is very geomorphologically active.~~ The UAV images in 2016 did not cover the B1 area completely, so we extracted 23 common tie points across UAV images from 2017 to 2019 to manually quantify the surface displacement rate; the slope showed downslope displacement of 1.96±0.04 cm d⁻¹, and a maximum of 2.08±0.04 cm d⁻¹ in the period 2017-2018.

Feature B2 (3150 m a.s.l, Fig. S26b) is the largest type B PSF and is located on the true left, south-facing moraine slope close to the glacier terminus (3240-3120 m a.s.l.). It is fan-shaped with a width of ~262 m, a length of 644 m, a height of ~120 m, and a total area of 122,738 m². In contrast to B1, this feature is characterized as a single landslide without any nested features (e.g.e.g., gullies). Visual aAnalysis of satellite imagery shows that detectable slope movement began around the year 2000, which is consistent with the onset of accelerated lowering of the glacier surface in this region and accompanying debuttressing of ice-marginal topography. We selected 33 tie points evenly distributed in the B2 landslide area on the four-year UAV images (2016-2019) to monitor its surface displacement, which revealed that the landslide has ~~moved~~fallen by an average of 2.63±0.04 m a⁻¹ in the UAV monitoring period, and the affected area has increased by 7,414m² via headscarp erosion. The highest rate of displacement was 4.32 cm d⁻¹ and occurred between 2017-2018. Between 2011 and 2019, the collapsed area of B2 has expanded by 35,000 m², with an expansion rate of 4.99% a⁻¹. The landslide has a vertical glide distance of 48 m, and a horizontal displacement of 70 m. In the period 2017-2018 landslide activity forced the closure of a zigzag trail path (Fig. 5e) which was used for accessing the glacier.

Across the valley from B2, we identify landslide B3 (3100 m a.s.l, Fig. 5f, Fig. 6c), which is 805 m in length, 132 in width, and 63,241 m² in area and, like B2, is located on a lateral moraine close to the glacier terminus. The landslide has been effectively divided into five zones, delineated by four gullies (Fig. 5f). Analysis of satellite imagery shows that the landslide began to develop around 2013, when a headscarp is first detectable. Feature tracking (33 tie points) analysis on repeat UAV images shows that the landslide has moved down with an average rate of 1.65±0.04 cm d⁻¹ between 2016 and 2019, with the highest rate of 1.97±0.04 cm d⁻¹ occurring in the period 2017-2018.

Feature B4 (Fig. S26d) is also located on the north-facing (true right) lateral moraine slope of the glacier, approximately 3.5 km from the base of the icefall. It is ~103 m in height, 993 m in length, and covers an area of 73,270 m². Geomorphologically, this feature is the most complex of the type B PSFs, in that it represents a transition slopeform that it exhibits landsliding behavior in two distinct zones at either end (covering an area of 18,244 m², or 24.90% of the sediment-mantled moraine slope

in this area) and also exhibits gully headward erosion (i.e., PSF Type C). Feature tracking analysis of 37 tie points indicates that the landslide moved downslope at an average rate of $1.66 \pm 0.04 \text{ cm d}^{-1}$ between 2016 and 2019, with a maximum rate of $2.63 \pm 0.04 \text{ cm d}^{-1}$ in 2017-2018.

4.2.3 Gully headward erosion (PSF type C)

The three major paraglacial gully headward erosion areas (C1-C3, Fig. 5a) are located at the intersections between three tributary streams which are fed by seasonally snowmelt and the main trunk of the HLG ice tongue. They have a total area of $\sim 324,000 \text{ m}^2$ in 2019. The UAV images did not cover the entire areas of Type C slopes, therefore we used five-PlanetScope, RapidEye, and Google Earth images from 2002, 2011-2019 to supplement these data and monitor the development of these features (Fig. S87). Our mapping results show that the total area of these three gullies has expanded by $\sim 93,000 \text{ m}^2$ between 2011 and 2019, with an annual expansion rate of $5.02\% \text{ a}^{-1}$.

C1 is located on the northern slope of HLG at an altitude of 3200 m (Fig. 5g; Fig. S87a). In 2019 it had a length of 849 m, a width of 312 m and an area of $139,135 \text{ m}^2$. It is adjacent to a major tributary stream that drains the northern side of the valley, and which intersects (and bisects) the true left lateral moraine where the glacier turns to flow eastward to its terminus. Field inspection of exposed surfaces at C1 reveals that it comprises a block of thick debris and sand deposits with some finer material, which was previously colonized by vegetation before being denuded by flowing water. In the period 2011-2015, the area of the gully expanded upslope at a rate of 10.44 m a^{-1} , and by 2019 the location of headward erosion was more clearly concentrated in the meltwater tributary channel (Fig. S87a). Between 2011 and 2019, the average upward denudation rate of the feature was 3.39 cm d^{-1} (12.20 m a^{-1}) and the exposed area had increased by $45,449 \text{ m}^2$, or 48.59% from 2011 (Tab. 2).

Gully C2 is situated on the southern slope (true right lateral moraine) of HLG at about 3200 m a.s.l (Fig. 5h; Fig. S87b) and in 2019 extended $\sim 160 \text{ m}$ in width, $\sim 270 \text{ m}$ in length, and $24,248 \text{ m}^2$ in area. The exposed area of the gully expanded upslope along the path of a meltwater-fed tributary stream, with a gradient of $\sim 36^\circ$ close to the HLG moraine, and which originates from Hailuogou No. 3 Glacier ($29^\circ 32.41' \text{ N}$, $101^\circ 58.05' \text{ E}$). This tributary stream connects directly to the subglacial water system of HLG. The gully is most actively eroding upstream of the point at which it connects to HLG, with an average upward denudation rate of 0.76 cm d^{-1} between 2002 and 2019, producing an increase in the exposed sediment-covered area of $11,923 \text{ m}^2$ in the same period.

Gully C3 is also located on the southern slope of HLG at 3500 m a.s.l (Fig. 5i; Fig. S87c), around $\sim 800 \text{ m}$ west of gully C2. The gully is formed by a tributary stream which is fed by meltwater from Hailuogou No. 2 Glacier ($29^\circ 32.82' \text{ N}$, $101^\circ 56.92' \text{ E}$), which became detached from HLG sometime after the 1930s (Liu and Zhang, 2017) and has since retreated to the edge of an ice scarp ridge. The gully is filled with glaciofluvially transported glacial sediment and is deeply incised. Like C2,

meltwater also flows into HLG glacier subglacially. Since 2002, expansion of the sediment-mantled area of this gully has occurred on the right (east) side of the gully and has recently begun to expand up along the left (west) bank of the channel. We expand the area of the gully to incorporate adjacent unvegetated lateral moraine, which also shows evidence of gullying and headward erosion. The total area of C3 increased by 14.3%, from 109,500 m² in 2002 to 160,474 m² in 2019.

460 5 Discussion

5.1 Possible forcing mechanism of ~~the three different types of~~ PSFs in HLG

Many potential factors, include glacial history (mostly downwasting or debuitressing in HLG since Little Ice Age), rock structure (i.e., joint), seismicity, and meteorological disturbances (i.e., precipitation, temperature, and freeze-thaw cycling), have been generally considered as preconditioning, preparatory or triggering factors that combine to produce a PSF (McColl, 465 2012). In the discussion below we refer to these factors to discuss their relative importance in forcing the different types of PSF that we observed ~~d~~ at the Hailuoguo-HL Glacier.

5.1.1 Rock-fall

~~Small-scale rockfalls are commonly found sourcing from exposed bedrock walls on both sides of the HLG ice tongue. These exposed bedrock walls are generally granite rocks characterised by well-developed vertical joints (Fig. S6 and S7), which make the slope more prone to failure or more likely failure under given triggers (Draebing and Krautblatter, 2019). In addition to glacier erosional steepening (Herman et al., 2021), the exposure of these bedrocks can also accelerate the weathering process and rock strength degradation (Matsuoka, 2008). Intensification of freeze-thaw conditions during deglaciation may have led to more enhanced rockfall activity since winter seasons in the HLG environment is cold enough to cause frozen water within rock fractures and pore spaces. During monsoon seasons, the warm humid environment can also be a stimulative factor leading to intense and rapid chemical weathering of the exposed rock wall (Li et al., 2019). However, the frequency and magnitude dynamics of these small-scale rockfalls are difficult to be determined by this study since it is difficult to determine their specific occurring specific time was unknown and many formal rockfalls may be overlapped by later ones during our investigation period. In the following part of of small rock falls occurred (as mentioned in subsection 4.2.1 above), this section, we will focus on discussing possible forcing mechanisms of the discuss the impact factors of the a larger-scale rock~~
470 ~~fall~~
475 ~~rockfall event that occurred in 2018, which we could confirm its occurring time (around 15 Oct. 2018) and estimate its magnitude from UAV surveys.~~
480 ~~fall~~

The 2018 ~~rock fall~~rockfall (Fig. 5b) represents a rapid non-ice contact rock collapse adjacent to an area of the glacier ~~that which~~ has experienced remarkable (80-100 m) thinning since its Little Ice Age (LIA) maximum (Fig. 5c). More widely in the 485 Mt. Gongga region, glacial and paraglacial landform assemblages display a strong influence of Late Pleistocene and Holocene glaciations, the most striking example of which are the deeply incised trunk and tributary valleys formed by higher rates of

glacier erosion (Liu et al., 2009), glaciofluvial activity, and monsoonal precipitation; as such, paraglacial slopes are strongly modified by local glacial history, making this an important preconditioning and preparatory factor for ~~rock fall~~rockfall. Anecdotally, small-scale rock collapses occur all year round on both sides of HLG (Fig. 5a; Fig. S73), especially from those rock slopes exhibiting vertical jointing. Our field investigations indicate that the main detachment zone of the 2018 ~~rock fall~~rockfall has no faults but is highly jointed, which facilitates liquid water ingress and hydraulic erosion and is also conducive to promoting fracturing via freeze-thaw and ice segregation processes (Rodríguez-Rodríguez et al., 2018) which gradually loosens the rock block and might also be considered a trigger in causing blocks to eventually break away from the rock valley walls (Fischer et al., 2010).

~~Precipitation and temperature observations near the glacier were analysed to better understand the role of key meteorological factors in causing the large rock fall in 2018.~~ The annual mean temperature was relatively low in 2018 (4.5°C) compared to the preceding ~~four~~three years (5.0°C, Fig. 6a9). ~~Fig. 6bTab. 3 shows the antecedent rainfall in the five to ten days before the rock fall~~rockfall occurred (5-20 Oct 2018) and compares antecedent rainfall statistics between five years (2014-2018), number of days from 2014 to 2018 with different daily precipitation totals. The mean daily precipitation between 5 and 20 Oct 2018 is 5.89 mm which is significantly higher than in 2014, 2015, and 2017, although not significant compared with 2016, the value is still high. We find that 2018 shows a slight precipitation intensity anomaly; the number of days with precipitation totals < 60 mm d⁻¹ is broadly similar to the preceding four years, however, the daily maximum (61mm, 30 June 2018) exceeded that of the previous four years. A prolonged monsoon, which lasted to the middle of October, was also observed in 2018, and only one day without precipitation was recorded in the 25 days between 14 September and 09 October (mean daily precipitation of 7.5mm) during which the rock fall occurred. Additionally, ~~the Ddifferences in the daily mean temperature between September to October 2018 and September to October 2014-2017 were relatively large (Fig. 6c-S4; from September to October 2018, a large amount of daily temperature data was missing from the automatic observation and was therefore offset by manual observations (MO), as mentioned in subsection 3.4 above);~~ the daily mean temperature was between 0.4 to 5.3°C from 01 to 09 October 2018 compared to a range of 3.6-12.92°C for the preceding four years. From 20 to 29 September, the mean daily temperature ~~(the observation on 30 September is missing)~~ was similar to the preceding four years with a range of 6.6-13.3°C. The temperature lapse rate (0.0065°C m⁻¹ in humid air, (Hemond and Fechner, 2015)) have shown that when the temperature at the Gongga Mt. Station (3000 m a.s.l.) drops to about 6°C, the temperature on the mountain at 4000 m a.s.l. approaches 0°C and ~~begins to freeze~~ing of water begins. We, therefore, speculate that the abundant precipitation in the early days caused a large amount of liquid water to ingress the rock fissure, then the frost heave caused the rock mass to eventually rupture (e.g. (Hartmeyer et al., 2020)). We finally suggest that abnormal precipitation and low temperature in 2018 may have acted as a preparatory factor and triggering factor for the observed ~~rock fall~~rockfall, respectively.

~~Rock fall~~Rockfall and other mass movements can be triggered by seismic activity, which can also act as a preparatory factor through its ability to cause rock damage (Huggel et al., 2007). The HLG region is seismically active, and in the last five years

has recorded 9 seismic events ranging from 2.9-3.8 in magnitude, all of which occurred in the period 2016-2017 (China Earthquake Administration, <https://www.cea.gov.cn/>). Although no significant seismic events were observed immediately prior to the 2018 ~~rock fall~~rockfall, rock mass damage associated with the historical seismic activity may have acted as a preparatory factor for the 2018 ~~rock fall~~rockfall and other mass movements from deglaciated slopes in the wider catchment.

525 5.1.2 Sediment-mantled slopes slide ~~and collapse~~

Type B PSFs are largely associated with lateral moraine instability and collapse. Elsewhere (north-facing slopes, Fig. S9) in the catchment we observe glacially smoothed and polished bedrock surfaces with steep inclination angles (a product of the geological, glacial, and climatic history of the catchment), and we infer that the failure of these unconsolidated slopes is caused by glacier downwasting and debuttressing (Cody et al., 2020), combined with a material angle of repose which is lower than
530 the inclination of the underlying bedrock surface; sediment-mantled slopes ~~hosting~~ showing evidence of instability typically have a slope angle of $\sim 29.5^\circ$, whilst the inclination of exposed bedrock slopes close to the elevation of the present-day glacier surface is $\sim 45^\circ$. Whilst historically the glacier has essentially ‘propped up’ the lateral moraines, rapid reduction in the elevation of the glacier surface has directly contributed to slope instability, which is increasing in speed, corresponding to findings in van Woerkom et al. (2019).

535 Debris flow may also be a preparatory factor causing slope instability. A gully developing process was observed within Type B failures (as mentioned in subsection 4.2.2 above). Based on 17 years (2002-2019) RS monitoring of the B3 slope (Fig. S10), for example, we found that the surficial debris flow occurred before the hillslope movement. Firstly, some debris flows occurred, forming 3 gullies, and no slide was evident in 2002. Secondly, the debris flow gullies gradually expanded, the number
540 increased to 5, the slope slid slightly, and the slide cracks were starting to form around in 2013. Finally, the debris flow gullies increased to 6 and expanded further (the largest gully is about 130 m wide at its widest point), the slope slide significantly (up to 2 cm d⁻¹ between 2017 and 2018; Fig. S2), and the cracks increased in response to rapid glacier downwasting in 2019, which is different from the discovery of the Fox glacier in New Zealand by Cody et al. (2020).

545 The regional and local climate, which is characterized by abundant precipitation during the monsoon season, enables rapid succession of vegetation on deglaciated slopes. However, although this vegetation is extensive in its coverage, particularly on slopes immediately above the lateral moraines, it mostly comprises species with a shallow rooting depth ~~that which~~ do not have a strong capacity to increase slope stability, especially at larger scales; shrub vegetation growing on the unstable B2 and B3 slopes ~~are~~is relatively young and ~~does~~ not mitigate deep translational failure, whereby unconsolidated sediment slides along
550 the interface between the overlying moraine and steep underlying bedrock. We also observed that the displacement of all type B PSFs reached their maximum rate during the period 2017-2018, and upper parts of the slope failures speed up to the same extent as the lower parts (Fig. S3), which may in part be related to increased air temperature (promoting enhanced glacier downwasting) and precipitation extremes in 2018.

5.1.3 Gully headward erosion

555 Glacier downwasting and meltwater from deglaciating tributary catchments enhance erosion of ice-marginal gullies and contribute to the expansion of actively eroding slopes in these landscapes; headward erosion of sidewall tributary gullies occurs as the local base level (i.e., the HLG glacier surface) falls (Williams and Koppes, 2020; Schiefer and Gilbert, 2007), and this effect is illustrated clearly at PSF C1 (Fig. 5g).

560 The upstream sediments were transported ~~along the transport~~ and accumulated ~~along the gullies~~ to both sides of the glacier, with a fast erosion ~~rate~~, for instance, the part with the largest change in ~~area of C1~~ ~~area moved~~ ~~travels~~ about 150 m in both horizontal and vertical directions. Therefore, we argue that surface fluvial erosion and glacier debuitressing simultaneously trigger the instability of the type C slopes (Dusik et al., 2019).

565 All the three major type C slopes are developed along the tributary streams, in which settings slope slides are usually limited but surface fluvial erosion plays the primary role. There should exist a seasonal plus ~~oref~~ enhanced ~~or uprush~~ ~~headward~~ erosion rates, i.e., during the monsoon rainstorm seasons. However, we still could not track this process due to the lack of higher resolution observations in the current study. Nevertheless, it is suggested that this type of paraglacial adjustment is still in active process based on the current~~ly~~ observed situation at both lateral sides of the ~~HLG Hailuoguo Glacier~~. As the increase of
570 the exposed area and the erosionable baseline, a period of accelerated sediment/debris flux to the surface or base of the glacier is expected in the following years.

5.2 Paraglacial geomorphology process in deglaciating monsoonal temperate environments Relationships between climate, glacier evolution, local topography and PSF development

Meteorological observations at the Gongga Mountain Station (Fig.1) show that the regional mean annual temperature has increased by >1 °C and annual precipitation has decreased ~~at~~ a rate of 9.13 mm a⁻¹ over the past 30 years (Fig. 6a). Warming and a weakened monsoon, as also occurred at other parts of the SETP (Yao et al., 2012), have induced recent remarkable downwasting of HLG and serves as a preparatory or triggering factor for PSFs. Our case study at the HLG has demonstrated that paraglacial slopes in the deglaciating monsoon temperate environment ~~are~~ characterised by the geomorphology process with multi types, fast responding, and a high rate of denudation. In Mt. Gongga and most SETP monsoon dominate regions, a
580 climate of warm-wet synchronization is the primary precondition driving the physical or hydrothermal dynamics of both glacier and off-glacier processes.

5.2.1 Impact of the monsoonal climatic conditions

Climatic conditions (e.g., seasonal distribution and multi-year fluctuation of temperature and precipitation) can ~~also~~ directly affect slope stability (McColl, 2012; Coe, 2020). Climate at the HLG is strongly affected by the southeast monsoon (An et al.,
585 2015; Lau and Yang, 1997) characterised by a warm and wet summer and relative colder and drier winter (Liu et al., 2010).

According to the observation of Gongga station at 3000 m a.s.l. during the period 1988-2018, the mean annual temperature near the HLG was 4.5 °C, but the recorded highest summer temperature was 27 °C in 2010 and the lowest winter temperature was -16.8 °C in 2016 (Fig. 6d). The mean annual maximum temperature range between 1988 and 2018 was close to 40°C, with a slightly increasing trend since 2001 (Fig. 6d). This large diurnal (Fig. 6c) and annual (Fig. 6a) variation of temperature at the HLG could affect the slope freeze-thaw process and destabilize paraglacial slopes through thermodynamics (Fischer et al., 2012; Curry et al., 2006).

The rain gauge recorded an average annual number of 314 days and a mean annual amount of 1912 mm precipitation, of which 88% amount was concentrated in ablation seasons (April to October) and ~42% was concentrated in summer (July to September). Abundant rainfall in the monsoon area results in the absolute high-amount precipitation in Mt. Gongga has further promoted the instability of slopes. Due to frequent summer rainstorms, small-scale debris flows are commonly found in both lateral sides of the HLG valley. These tributary flash floods or small-scale debris flows sometimes flow over/through the destabilized lateral moraine, furtherly disturbing the slopes and promoting the slide. The occurrence of nested processes in Type B (Fig. 5f, S8b, and S113) is similar to with that these debris² flow galleys observed at lower moraine slips reported by Cody et al. (2020) at paraglacial slopes in South Alps temperate glaciers, where the local annual precipitation is observed several times higher than our study area (Kerr et al., 2018). In addition, the combination of extreme temperature and precipitation conditions can also trigger slope instability (as mentioned in subsection 5.1.1 above - the relatively low temperature and high precipitation in 2018 may be the cause of rockfall).

5.2.2 Interaction between paraglacial slope process and dynamics of a temperate glacier

Temperate glaciers in monsoon conditions are generally show more remarkable and fast responded to the change of temperature and precipitation than cold glaciers (He et al., 2003; Su and Shi, 2002), characterised by high mass turnover and fast flow rate (Oerlemans, 1997), and developed en- and sub-glacial drainage systems (Fountain and Walder, 1998). Glacier downwasting can trigger the failure of Type B and C (as mentioned in subsection 5.1.2 and 5.1.3 above). According to Fig. 3 and 4, in profile D-D', the D' side has been thinned (with a mean rate of -1.0 m a⁻¹) and slowed (the mean daily velocity changed by -0.27 m d⁻¹) more significantly than that on the D side (with a mean rate of 0 m a⁻¹ and the mean daily velocity changed by -0.14 m d⁻¹, respectively) in the latest study period, resulting in the slope failure on D' side has been faster. The exposed slopes may increase the absorption of long-wave thermal radiation on the surface, contributing to the melting of glaciers in nearby areas. Profile E-E' showed uniform thinning in both two periods (Fig. 3b, -1.0 m a⁻¹), caused the landslides to appear on both sides. For both profiles B-B' and C-C', the thinning rate changed from ~0 m a⁻¹ in 1966-2000 to ~-2 m a⁻¹ in 2000-2016 (Fig. 3b), which may be related to the inner stress adjustment in the glacier - the ice mass of upstream replenishment the acceleration loss of downstream. Both sides of the profile B-B' are mainly steep bedrock, with a limited accumulation of lateral moraine materials, such that type A is the dominant PSF. The glacier downwasting is mainly used as a preparatory

620 factor for the slope instability, here. The relationship between climatic change, glacier downwasting, and PSF the three can be shown in Fig. 7.

625 Despite a slowdown in recent decades (Fig. 3c), the flow velocity of HLG is still higher than most mountain glaciers in Himalaya, Tian Shan, and inner Tibet (Bhushan et al., 2018; Wang et al., 2016; Zhang et al., 2010; Ke et al., 2013). Previous work has quantified the evolution of the glacier's subglacial and englacial hydrology, and revealed a highly efficient hydrological system that is maintained in both summer and winter months (Liu and Liu, 2010); an abundance of meltwater and subglacial and englacial debris (which we infer because of the debris-covered nature of the glacier, e.g. (Miles et al., 2021)) act as effective "grinding tools" for glacial abrasion. The estimated erosion rate is 2.2-11.4 mm a⁻¹ (Based on the current glacier thickness and flow velocity, a conservative estimate of the glacier bedrock erosion depth is about 1-5 m) which is consistent with other temperate glaciers but higher than the continental glaciers (0.1-1.0 mm a⁻¹)(Liu et al., 2009). A high erosion rate
630 contributes to valley incision and the steepening of valley flanks, which increase in exposed area and angle and therefore likely to become more prone to instability.

The intense mass flux due to PSFs, on the other hand, can deliver abundant debris materials to the glacier system. According to Fig 4b, the PBGA was equivalent to ~11% of the GCA in 1990 and increased to ~69% in 2020, providing an ample source of sediment for the glacial environment. For instance, there is are muchany debris that fell onto the glacier surface from rockfalls and debris slide/flow process. We calculated the total areal of all observed rockfalls covered 62216 m² (volume class: 10⁴~10⁵ m³); according to Scherler et al., (2018) the supraglacial debris cover of HLG is 2.71 km², as a result, the total areal contributions to supraglacial debris-cover of the rockfalls is 2.3%. Due to the high supraglacial debris-cover of HLG (11 %), the contribution rate of rockfalls observed in this study is lower than that of the European Alps and the Southern Alps of New
640 Zealand rockfalls of the same class (Fischer et al., 2012). We also observed a limited number of materials that are delivered to the supraglacial environment through direct roll (Fig. S118 (a); the sediments are more dispersed compared to rockfalls), collapse (Fig. S118 (b)), and debris flow (Fig. S118 (c); faster changes). Among them, two collapsed parts of the B2 slope were quantified by using UAV imagery in the 718 days from 2016/8/31 to 2018/8/19, the collapsed area increased by 94% in total, with an increased rate of 8 m² d⁻¹. These sediment delivery process increasing the range and thickness of the supraglacial debris-cover, which in turn affected the surface energy balance for melting and therefore downwasting rate of the glacier, which will thus influence the rate of runoff generation and its contribution to the sea level rise from glacierised catchments. Additionally, some processes (e.g., Type C slopes) can also deliver materials to the sub-glacial environment through runoff (Fig. S118 (d)). Their contribution to glacial sediments is hard to quantify, but it is clear that this process does result in a long-term and steady sediments supply to the glacier.

650 Finally, failing rock debris may sink into the glacier if the stress they exert exceeds the resistance provided by the glacier ice since rock is higher in density than ice. This geomorphological phenomenon has been identified in the Southern Alps of New

Zealand (McColl and Davies, 2013), where mountain glaciers occupy equally steep valleys. Field evidence from the monitoring of the B2 slope by UAV images for four consecutive years (Fig S6b) indicates that the glacier in this vicinity has narrowed or squeezed. The direction of the glacier movement at the boundary with B2 changes as B2 advances, which causes the original arc of the glacier boundary to be destroyed. The greatest change in the location of the glacier boundary bordering slope B2 is during the period 2017-2018, which is consistent with the fastest displacement speed ($\sim 4.32 \text{ cm d}^{-1}$) of the slope during the wider monitoring campaign. Our results may imply that the weight of the moraine may be sufficient to deform the glacier ice, as hypothesized by McColl and Davies (2013).

5.2.3 Other geomorphological and environmental implications

Similar to other studies (Dunning et al., 2015;Glueer et al., 2020;Hedding et al., 2020), our analyses show a temporal and spatial component to PSF development following rapid deglaciation of the HLG. Following many thousands of annual thermohydronechanical loading cycles, which promote rock damage (Grämiger et al., 2017;Glueer et al., 2020) the bedrock slopes bordering HLG are well-prepared for failure, and this response is beginning to manifest as specific triggering events occur and/or mechanical rock mass thresholds are crossed. Similarly, unconsolidated lateral moraines show signs of increasing deformation and translational movement in response to glacier downwasting and debuttreasing; we hypothesize that this will continue until critical angles of repose are reached, which will be followed by vegetation colonisation and soil development (Eichel et al., 2018).

~~With respect to the terrain aspect, we found that (He et al., 2003;Su and Shi, 2002;Oerlemans, 1997;Fountain and Walder, 1998) Meteorological observations at nearby Gongga Mountain Station (Fig.1) show that the regional mean annual temperature has increased by about 1°C (Fig. 69) over the past 30 years. Accelerating downwasting of HLG in response to climatic warming serves as a preparatory or triggering factor for PSFs. Through the influence of temperature and precipitation, climatic factors can directly affect slope (in)stability (McColl, 2012;Coe, 2020). Diurnal (Fig. S11) and annual (Fig. 6) variation of temperature may affect the slope freeze-thaw process (Fischer et al., 2012;Curry et al., 2006). Abundant rainfall in the monsoon area results in the absolute high amount precipitation in Mt. Gongga has further promoted the instability of slopes. Small-scale debris flows are common, which is also the main reason for the occurrence of nested processes in Type B (Fig. 5f, S8b, and S13). The combination of extreme temperature and precipitation conditions can also trigger slope instability (as mentioned in subsection 5.1.1 above – the relatively low temperature and high precipitation in 2018 may be the cause of rock fall). Qand on the other hand, climatic factors it can indirectly affect the slope by promoting rock damage over repeated cycles of glacial advance and retreat (Grämiger et al., 2017), and, during periods of sustained negative mass balance (characterized by glacier downwasting and terminus retreat) through slope debuttreasing and the failure of consolidated and unconsolidated slopes.~~

685 ~~Glacier downwasting can trigger the failure of Type B and C (as mentioned in subsection 5.1.2 and 5.1.3 above). According to Fig. 3 and 4, in profile D-D', the D' side has been thinned (with a mean rate of 1.0 m a⁻¹) and slowed (the mean daily velocity changed by 0.27 m d⁻¹) more significantly than that on the D side (with a mean rate of 0 m a⁻¹ and the mean daily velocity changed by 0.14 m d⁻¹, respectively) in the latest study period, resulting in the slope failure on D' side has been faster. The exposed slopes may increase the absorption of long wave thermal radiation on the surface, contributing to the melting of glaciers in nearby areas. Profile E-E' showed uniform thinning in both two periods (Fig. 3b, 1.0 m a⁻¹), caused the landslides to appear on both sides. For both profiles B-B' and C-C', the thinning rate changed from 0 m a⁻¹ in 1966-2000 to 2 m a⁻¹ in 2000-2016 (Fig. 3b), which may be related to the inner stress adjustment in the glacier—the ice mass of upstream replenishment the acceleration loss of downstream. Both sides of the profile B-B' are mainly steep bedrock, with a limited accumulation of lateral moraine materials, such that type A is the dominant PSF. The glacier downwasting is mainly used as a preparatory factor for the slope instability, here. The relationship between the three can be shown in Fig. 7.~~
690 ~~5.2.2 Local topography and PSF development~~

695 ~~Despite a slowdown in recent decades (Fig. 3c), the flow velocity of HLG/Hailuoguo Glacier is still higher than most mountain glaciers in Himalaya, Tian Shan, and inner Tibet (Bhushan et al., 2018; Wang et al., 2016; Zhang et al., 2010; Ke et al., 2013). Previous work has quantified the evolution of the glacier's subglacial and englacial hydrology, and revealed a highly efficient hydrological system that is maintained in both summer and winter months (Liu and Liu, 2010); an abundance of meltwater and subglacial and englacial debris (which we infer because of the debris-covered nature of the glacier, e.g. (Miles et al., 2021)) act as effective “grinding tools” for glacial abrasion. The estimated erosion rate is 2.2-11.4 mm a⁻¹ (Based on the current glacier thickness and flow velocity, a conservative estimate of the glacier bedrock erosion depth is about 1-5 m) which is consistent with other temperate glaciers but higher than the continental glaciers (0.1-1.0 mm a⁻¹) (Liu et al., 2009). A high erosion rate contributes to valley incision and the steepening of valley flanks, which increase in exposed area and angle and therefore likely to become more prone to instability.~~

700 ~~South-facing slopes show more of instabilities, both in terms of magnitude and frequency. First one thing firstly, it may could be because of related to the differences in the availability of material (Fig. S9; i.e. asymmetrical deposition of glacial drift and moraine construction on either side of the valley), with more sediment on the south-facing slopes and slope angles (Fig. S9). For another thing Secondly, it is maybecould also be related to because of the differences in glacier surface altitude and ice thinning rate, which This is particularly obvious compare compared to the C-C', D-D', and E-E' profiles. It can be seen from profile D-D' in Fig. 3 a, b that the altitude and thinning rate of the glacier under the south-facing slope are is much greater than that on the opposite side (ice thinning rate of difference was 1.5 m a⁻¹), which may be caused by the lower surface temperature due to the topographic shading on the glacier areas under the north-facing slope (Liao et al., 2020). Therefore, PSFs and glaciers downwasting show the same temporal and spatial movement in temporal and spatial. This observed pattern further indicates that there is a direct connection between glacier downwasting and PSFs occurrence. Additionally, the unstable slopes are more likely to occur in areas with lower slopes surface gradients (all-around 30°, as mentioned in subsection 4.2 above) is~~

contrary to the general conclusion of the many landslides study - the steeper the slope, the stronger the shear stress and the lower the factor of safety (McColl, 2015), which may be related to the slope material and/or the slope adjustment after failure process.

5.2.3 The contribution of PSFs to supraglacial and sub-glacial environment

According to Fig 4b, the PBGA was equivalent to ~11% of the GCA in 1990 and increased to ~69% in 2020, providing an ample source of sediment for the glacial environment. For instance, there are At the same time, many a large number of debris fell onto the glacier surface from rock falls and debris slide/flow process. We calculated the total areal of all observed rock falls covered 62216 m² (volume class: 10⁴-10⁵ m³); according to Scherler et al., (2018) the supraglacial debris cover of HLG is 2.71 km², as a result, the total areal contributions to supraglacial debris cover of the rock falls is 2.3%. Due to the high supraglacial debris cover of HLG (11 %), the contribution rate of rockfalls observed in this study is lower than that of Europe Alps and Southern Alps of New Zealand rock falls of the same class (Fischer et al., 2012). We also observed a limited number of materials that are delivered to the supraglacial environment through direct roll (Fig. S8 (a); the sediments are more dispersed compared to rock falls), collapse (Fig. S8 (b)), and debris flow (Fig. S8 (c); faster changes). Among them, two collapsed parts of the B2 slope were quantified by using UAV imagery in the 718 days from 2016/8/31 to 2018/8/19, the collapsed area increased by 94% in total, with an increased rate of 8 m²·d⁻¹. These sediment delivery process increasing the range and thickness of the supraglacial debris cover, which in turn affected the surface energy balance for melting and therefore downwasting rate of the glacier, which will thus influence the rate of runoff generation and its contribution to the sea level rise from glacierised catchments, temperature and downwasting of the glacier and the climate. Additionally, some process (e.g., Type C slopes) can also deliver materials to sub-glacial environment through runoff (Fig. S8 (d)). Their contribution to glacial sediments is hard to quantify, but it is clear that this process does result in a long-term and steady sediments supply to the glacier.

5.2.4 A conjectural model of paraglacial slope evolution and sediment delivery

Based on the above analysis, we suggest a conjectural paraglacial slope evolution and slope sediment delivery model of HLG (Fig. 8).

After the glacier was downwasting from the initial state (Stage I), the upper part of the steep moraine slope quickly destabilized, making the entire slope slow sliding, corresponding to those findings by van Woerkom et al. (2019), Ballantyne (2013), and Cully et al. (2006); then the moraine slope slowly slides down (Stage II; which were observed in Type B and part of Type C) and some part of them is exfoliated with underneath bedrock exposed. During the exposure of moraine, vegetation may be colonized, or gullies may be formed by debris (or water) flows washing away (stage II a); when the gullies gradually expand, headward erosion may occur in the upper of the gullies (Stage II b; which were observed in Type C). Sediments at the base of the slope or fell onto the glacier surface are transferred again as the glacier moves (Stage III); until the slope is steepest (>50°)

when moraine has been removed and bedrock is completely exposed to the ground and may collapse through some disturbances, finally (Stage IV; Type A).

5.3 Geomorphological and environmental implications

755 Similar to other studies (Dunning et al., 2015; Glueer et al., 2020; Hedding et al., 2020) our analyses show a temporal and spatial component to PSF development following rapid deglaciation. Following many thousands of annual thermo-hydrromechanical loading cycles, which promote rock damage (Grämiger et al., 2017; Glueer et al., 2020) the bedrock slopes bordering HLG are well-prepared for failure, and this response is beginning to manifest as specific triggering events occur and/or mechanical rock mass thresholds are crossed. Similarly, unconsolidated lateral moraines show signs of increasing deformation and translational movement in response to glacier downwasting and debuitressing; we hypothesize that this will continue until critical angles of
760 repose are reached, which will be followed by vegetation colonization and advanced soil development (Eichel et al., 2018):

Earlier in this article, we posited that the buttressing effect of ice prevented slope movement, and that slope deformation that we observed were largely a response to debuitressing. In the case of lateral moraine evolution, this is likely to be true. However, it is feasible that, since ice is lower in density than rock, failing *rock* slopes may move *into* the glacier if the stress they exert
765 exceeds the resistance provided by the glacier ice. This geomorphological phenomena has been identified in the Southern Alps of New Zealand (McColl and Davies, 2013), where mountain glaciers occupy equally steep valleys. Field evidence from the monitoring of the B2 slope by UAV images for four consecutive years (Fig S6b) indicates that the glacier in this vicinity has narrowed or squeezed. The direction of the glacier movement at the boundary with B2 changes as B2 advances, which causes the original arc of the glacier boundary to be destroyed. The greatest change in the location of the glacier boundary
770 bordering slope B2 aire during the period 2017–2018, which is consistent with the fastest displacement speed (-4.32 cm d^{-1}) of the slope during the wider monitoring campaign. Our results may imply that the weight of the moraine may be sufficient to deform the glacier ice, as hypothesized by McColl and Davies (2013).

775 Due to the warm and humid climate of the region, the LIA preglacial zone (2980–2800 m) of Hailuoguo Glacier is characterized by a fast primary ecological succession landscape, characterized by succession community from cold-adapted herbaceous to *Abies fabri* forest. Glacier downwasting and permafrost thaw have led to accelerated paraglacial erosion and increased frequency of occurred the proglacial debris flow and flash flood, which has occasionally disturbed the established preglacial vegetation (Lu and Gao, 1992). Accumulated surface moraine debris near the lowest ice tongue has suppressed local ice ablation and promoted ice stagnation, and in some locations, this stagnation has led to the establishment of supraglacial
780 vegetation, although this colonization is typically ephemeral due to ice cliff backwasting, for example:

6 Conclusion

We used repeat ~~mappings by~~ UAV and satellite remote sensing ~~imagery~~ as the basis for identifying and analysing the evolution of three styles of ~~PSF paraglacial slope failure~~ at ~~HLailougou~~ Glacier between 1990 and 2020, and explore these results in the context of their potential driving mechanisms. Over ~~this the investigation~~ period, the glacier terminus has retreated ~ 4510 m (~~175~~ $m a^{-1}$), its surface has down-wasted by $-0.88 m a^{-1}$, with thinning observed over 83.50% of the ablation zone study area, and the glacier velocity has slowed from a mean of $0.32 m d^{-1}$ (period 1982 to 1983) to $0.11 m d^{-1}$ (2014 to 2018). Rapid downwasting of the glacier surface has exposed oversteepened ice-marginal slope topography, which shows evidence of the overall PBGA increased from $0.31 \pm 0.27 km^2$ in 1990 to $1.38 \pm 0.06 km^2$ in 2020; and which show evidence of widespread instability in the form of ~~(A \ddagger) rock fall~~ rockfall and ~~debris avalanching~~ from bedrock slopes, ~~(B \ddagger) slide~~ collapse of unconsolidated lateral moraines, and ~~(C \ddagger)~~ increased erosion activity in tributary valleys, with a total area of $0.74 \pm 0.03 km^2$ in 2020. South-facing valley slopes (true left of the glacier) exhibited more destabilization (56% of the total PSFs area) and ~~higher PSF activity~~ than north-facing (true right) valley slopes (44% of the total PSFs area). Set against a background of frequent, small-scale ~~rock fall~~ rockfalls that are anecdotally recorded in the area, a large ~~rock fall~~ rockfall occurred in Autumn 2018. Non-ice-contact ~~rock fall~~ rockfalls in deglaciating catchments are a well-established, short- to long-term response of paraglacial slopes following glacier downwasting and rock slope exposure, however, analysis of antecedent meteorological conditions suggests that ~~an abundant precipitation abnormally long monsoon~~ and low temperature may have served to prepare, and perhaps trigger this rock slope failure. Deformation of sediment-mantled moraine slopes (mean $1.6-2.6 \pm 0.04 cm d^{-1}$) and an increase in erosion activity in ice-marginal tributary valleys caused by a drop in local base level (gully headward erosion rates are $= 0.7-3.39 cm d^{-1}$) have occurred in tandem with recent glacier downwasting. The PSFs and even the whole PBGA providing an ample source of sediment for the glacial environment. At the base of the analysis of paraglacial slope evolution and slope sediment delivery, we speculated that the occurrence of some unstable slopes in the lower slope angle areas may be related to the slope material and the failure process.- Field evidence indicates that the glacier ice body adjacent to unstable rock and sediment-mantled slopes has narrowed, or 'squeezed', and we hypothesize that this may be the result of ice deformation caused by ice marginal slope displacement and loading, but which requires further field investigation.- In general, the formation, evolution, and current status of these typical PSFs are generally related to the history of glacier dynamics and paraglacial geomorphological adjustments, and also influenced and/or disturbed by the fluctuation of air temperature/precipitation and their combinations. Longer-term monitoring will provide a clearer picture of the feedbacks between (accelerating) glacier downwasting, climatic conditions, and paraglacial landscape response in this data-poor region.

810 Data availability

The paraglacial slope failure shape files can be requested by email from the first author zhongyan19@mails.ucas.ac.cn

Author contributions

QL and XL initiated the underlying research project and obtained the funding. QL developed the research goal and designed the study. QL, YN, BZ, JC, HL and GL performed the primary UAV data. QL and YZ conducted and analysed the data. YZ, 815 QL, MW, YN and FP wrote the paper.

Competing interests

The authors declare that they have no conflict of interest.

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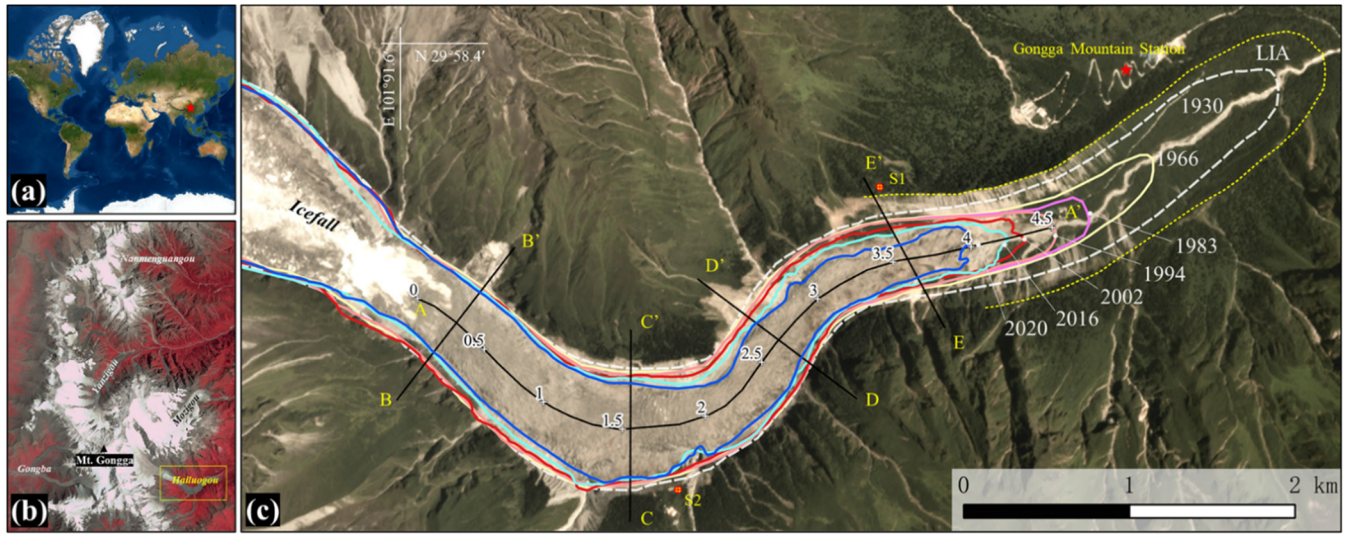
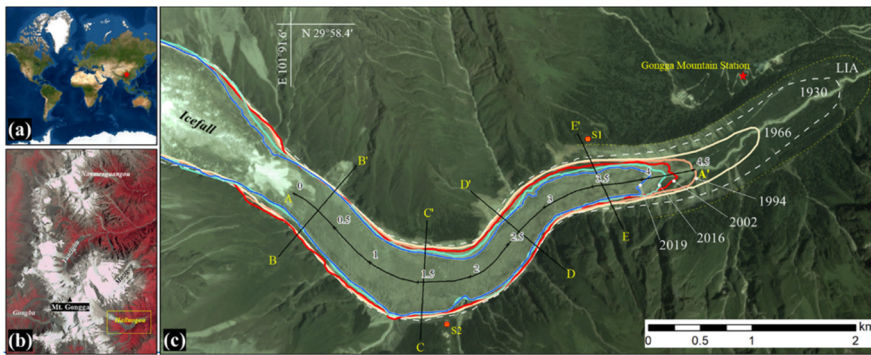
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Figure 1: Map showing the location of Mt. Gongga (red star), the background image is from ESRI's world basemap (a), several large glaciers around the peak of Mt. Gongga based on Landsat image (b), and retreating history of HLG since the Little Ice Age based on PlanetScope imagery (c). S1 and S2 are tourist sightseen stands on both sides of lateral moraines, and the red star indicates the location of Gongga Mountain Station. Longitudinal (A-A') and transverse (B-B', etc.) lines are set to examine the variation of flow velocities and surface elevations (Fig. 3) of the ice tongue.

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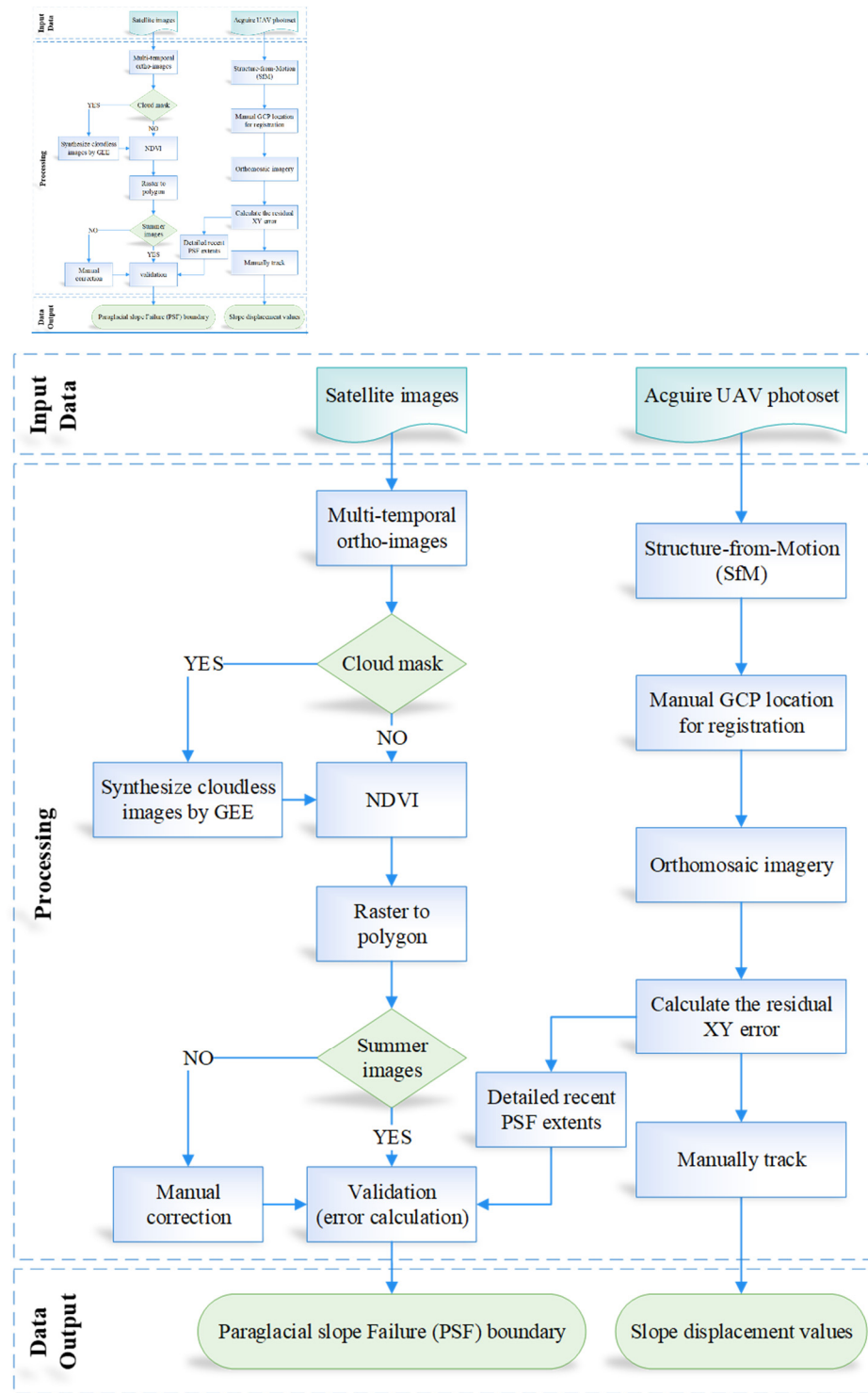


Figure 2: Workflow of the methodology followed to mapping the PSFs (changes) and tracking the displacement from multi-temporal image data.

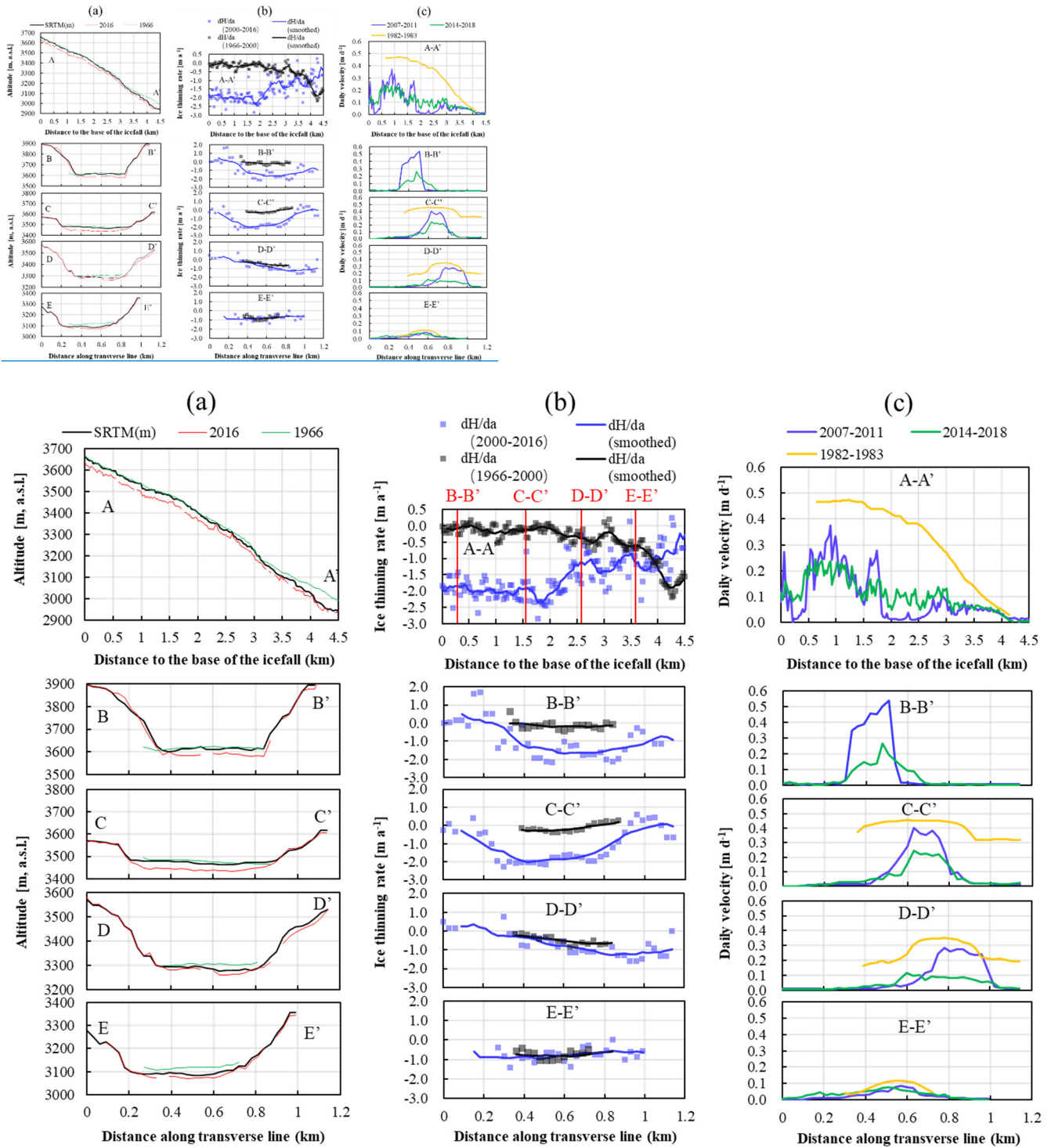


Figure 3: Comparison of ice surface elevations, [average](#) annual ice thinning rates (Brun et al., 2017), and velocity changes (Liu et al., 2019a; Zhang et al., 2010) along [with](#) profiles A-A' to E-E' in Figure 1.

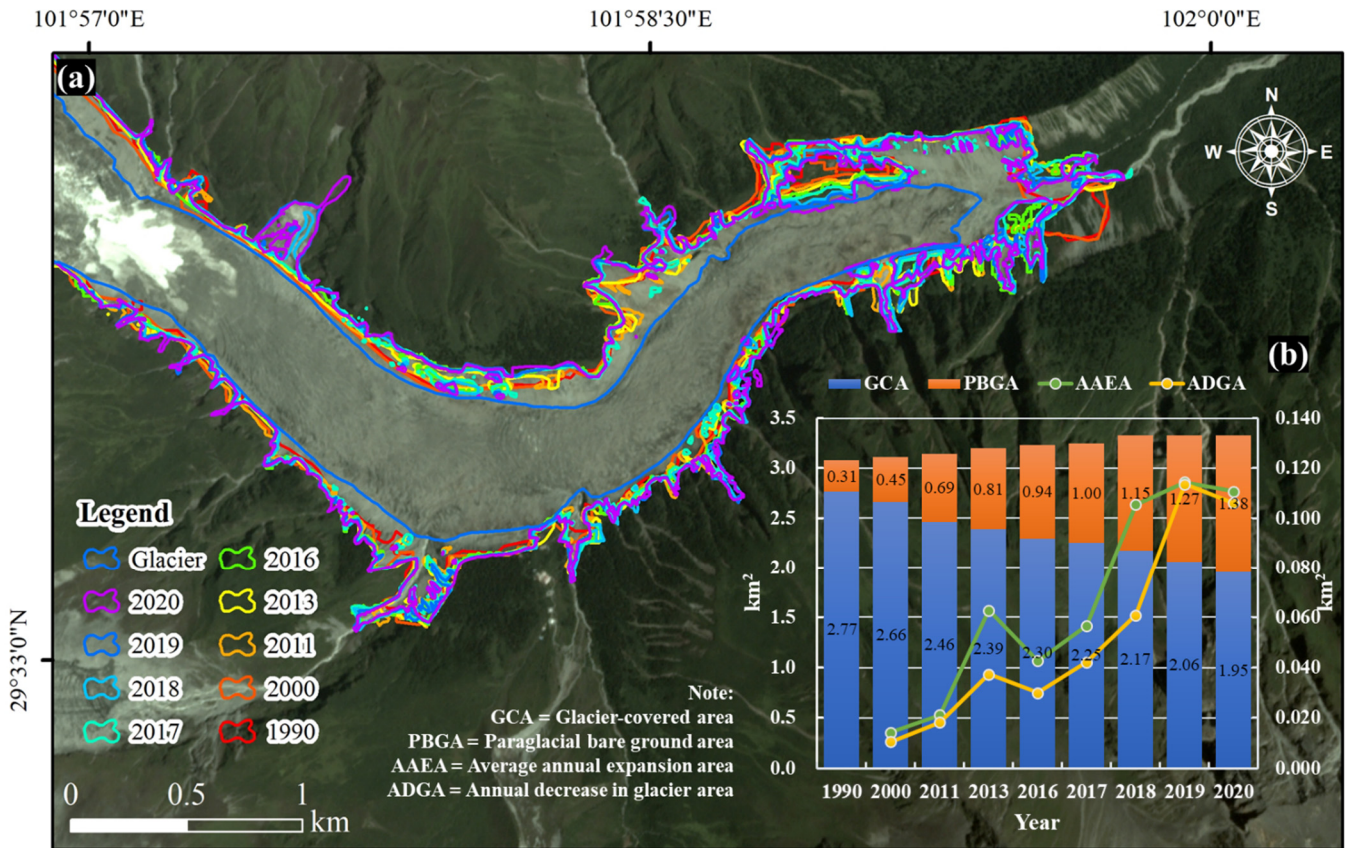
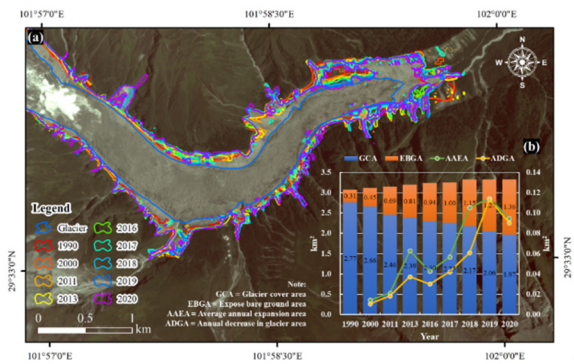
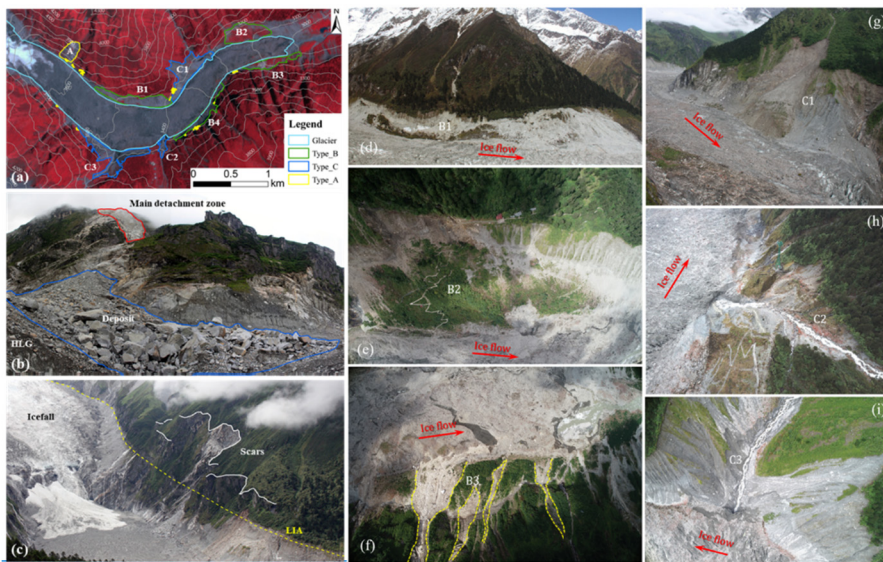


Figure 4: (a) Mapping results of PSFs in the HLG between 1990 and 2020. The glacier boundary (blue line) is mapped by a PlanetScope image acquired on August 16, 2019 (background). (b) Changes of the glacier-covered area (GCA, blue) and the paraglacial bare ground area (PBGA, orange) between 1990 and 2020. The green line indicates the average annual expansion area (AAEA) of PBGA. The yellow line indicates the annual decrease in glacier area (ADGA).

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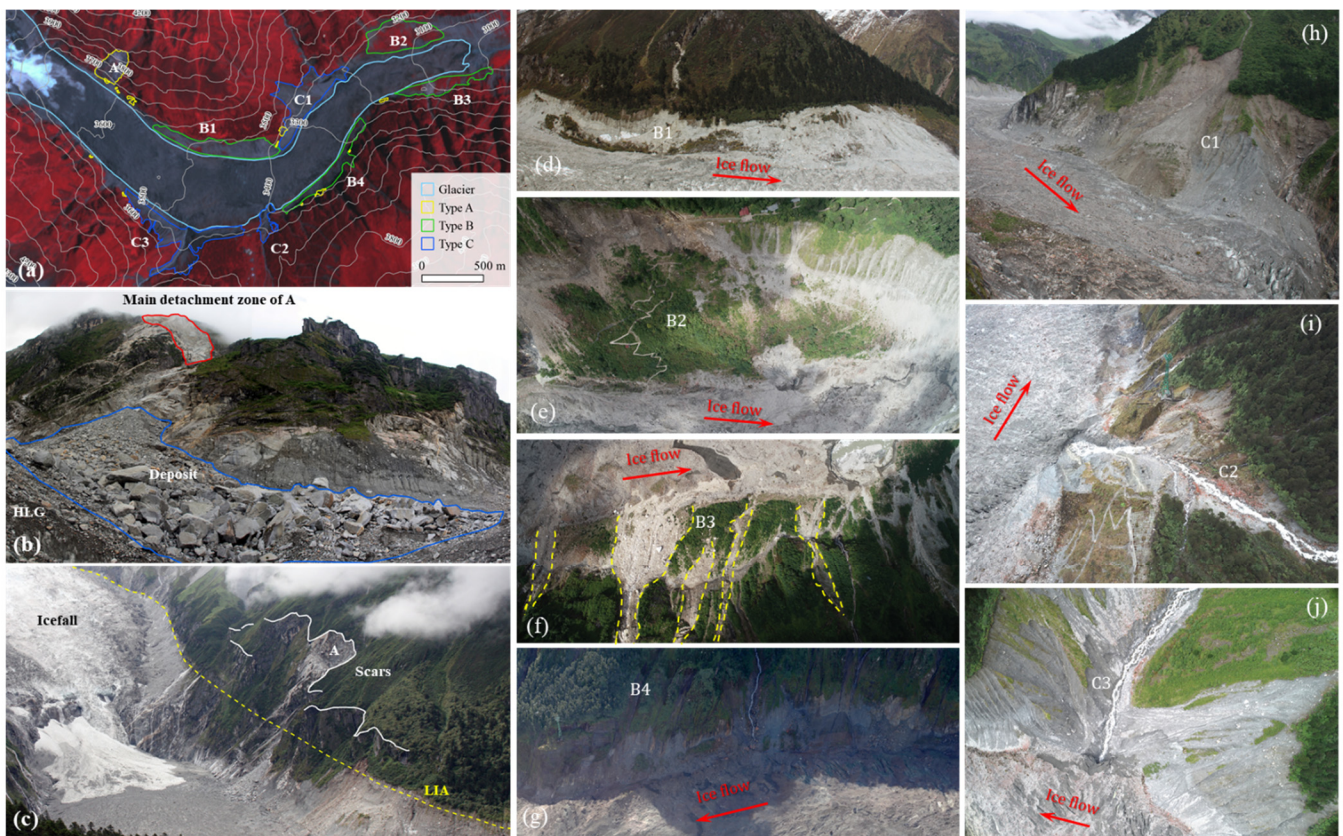


Figure 5: (a) The distribution of three types of PSFs based on Landsat image. (b–e) The particulars of type A failures in the upper part of the HLG's ice tongue. Main detachment zone (red), Deposit (blue). (c) The scars (white lines) of the surrounding of the rockfall A. Subplots (d, e, f, and g–f) and (g–h, i and j) are closer photographs of Type B and Type C failures, respectively, field photo by Qiao Liu.

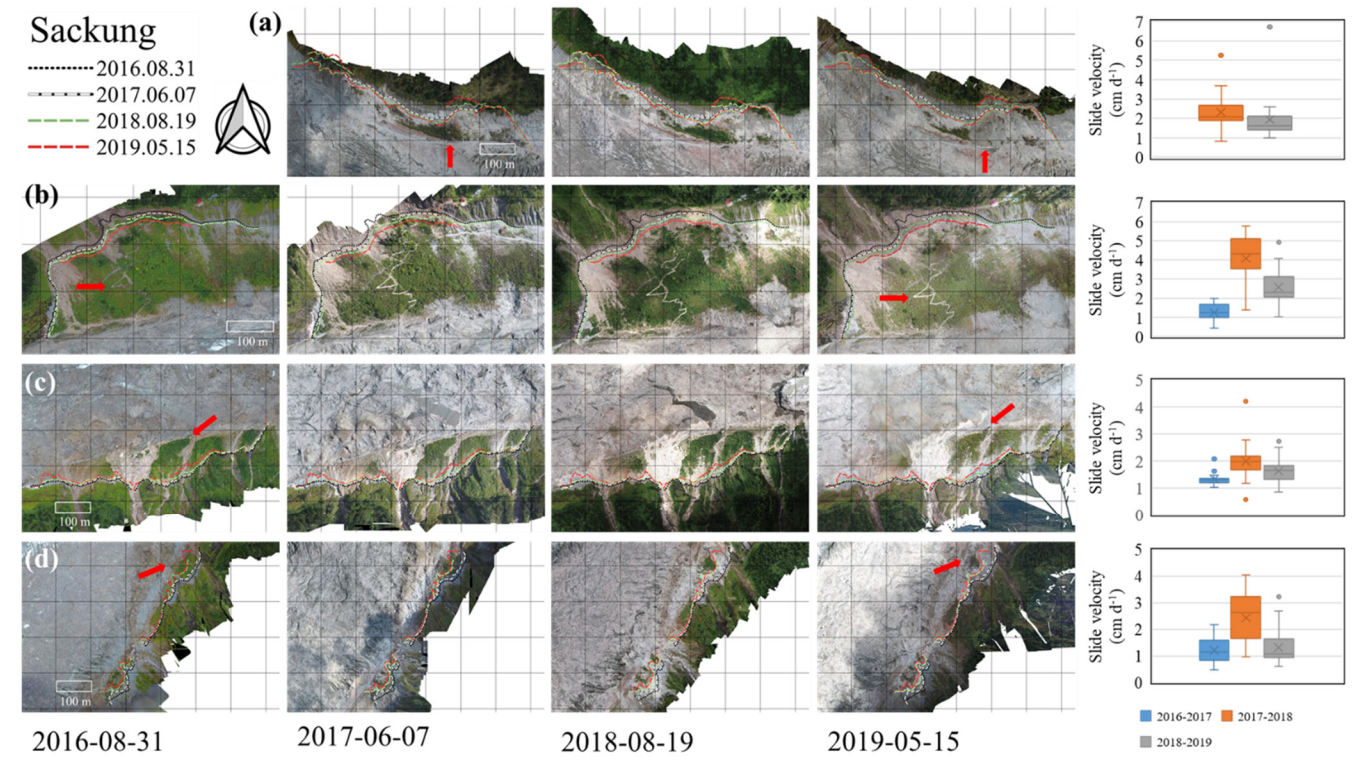


Figure 6: Slopes slides and its velocity of type B. (a) B1, (b) B2, (c) B3, (d) B4 based on UAV images by Qiao Liu et al. (this figure was removed to Supplementary file)

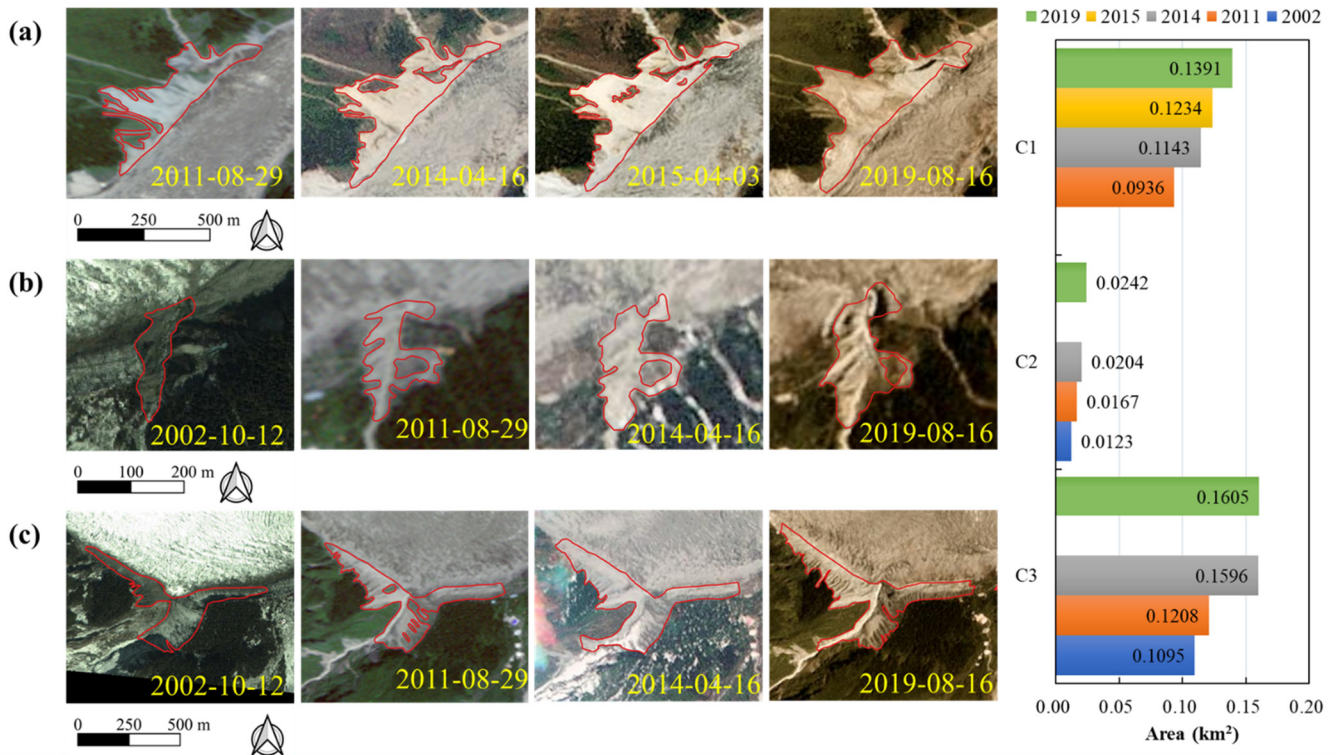


Figure 7: Slopes range and area changes of type C. (a) C1, (b) C2, (c) C3 based on RapidEye, PlanetScope and © Google Earth (SPOT5) images. (this figure was removed to Supplementary file)

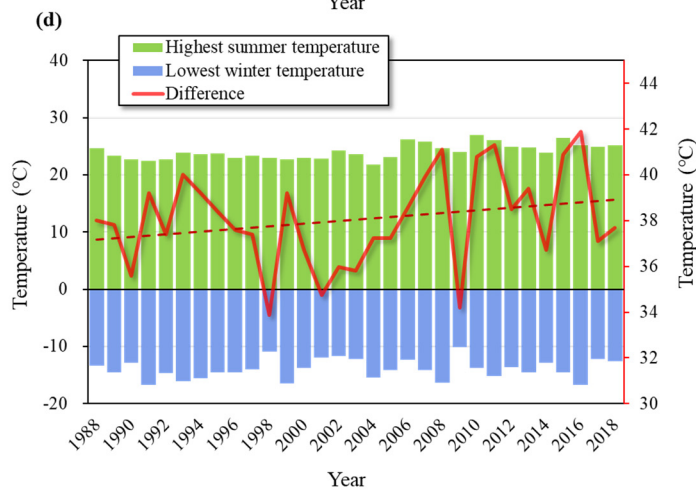
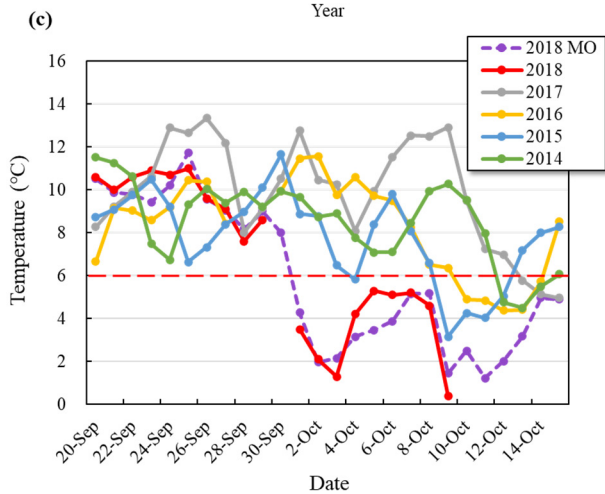
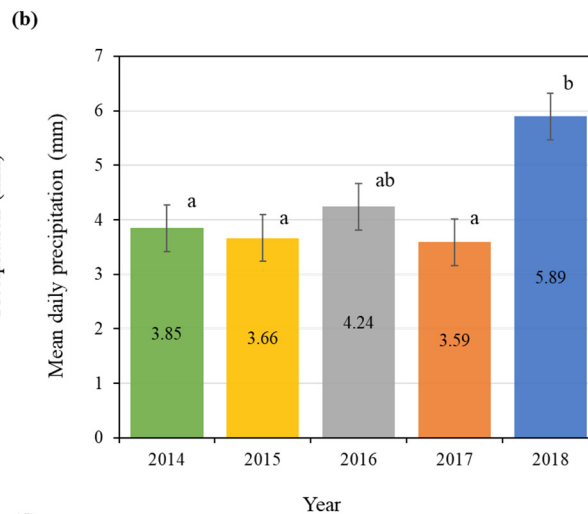
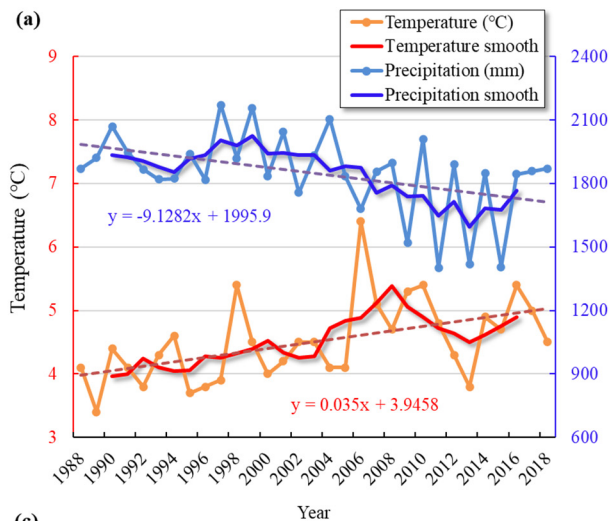
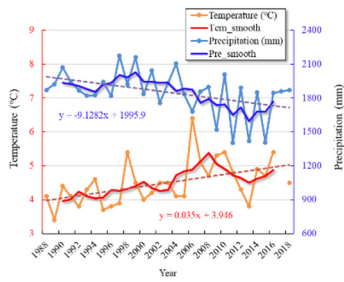
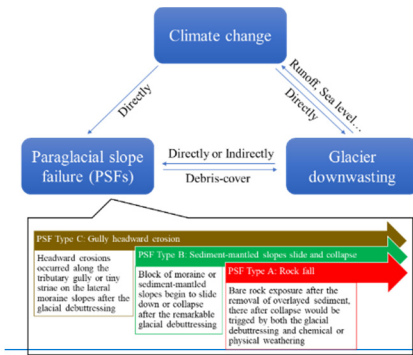
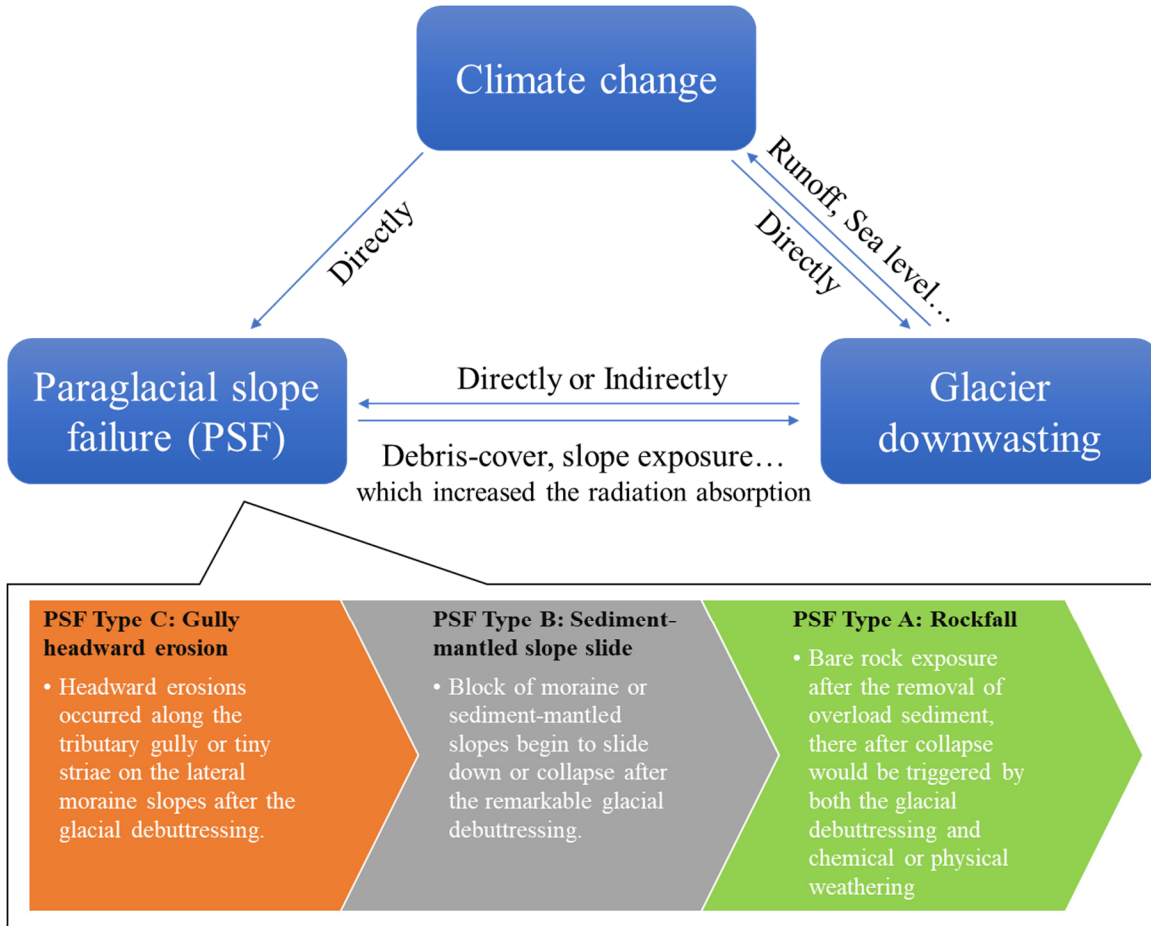


Figure 6: Meteorological data. (a) Mean annual air temperature (orange) and annual precipitation (blue) were recorded at the 3000 m station. The temperature data for 2017 are from manual observations. Between 1990 and 2016, the moving average for temperature and precipitation has been calculated. (b) Differences in the mean daily precipitation between 5-20 Oct 2018 and 5-20 Oct 2014-2017. Analysis of Variance (ANOVA) was used to investigate the difference of mean daily precipitation between five years, it found that mean daily precipitation in 2018 was significantly higher than that in 2014, 2015, and 2017 ($p < 0.05$). (c) Differences in the daily mean temperature between September to October 2018 and September to October 2014-2017, MO means manual observation. (d) The average of the highest summer temperature (green bar) and lowest winter temperature (blue bar) of each year, and their differences (red line).

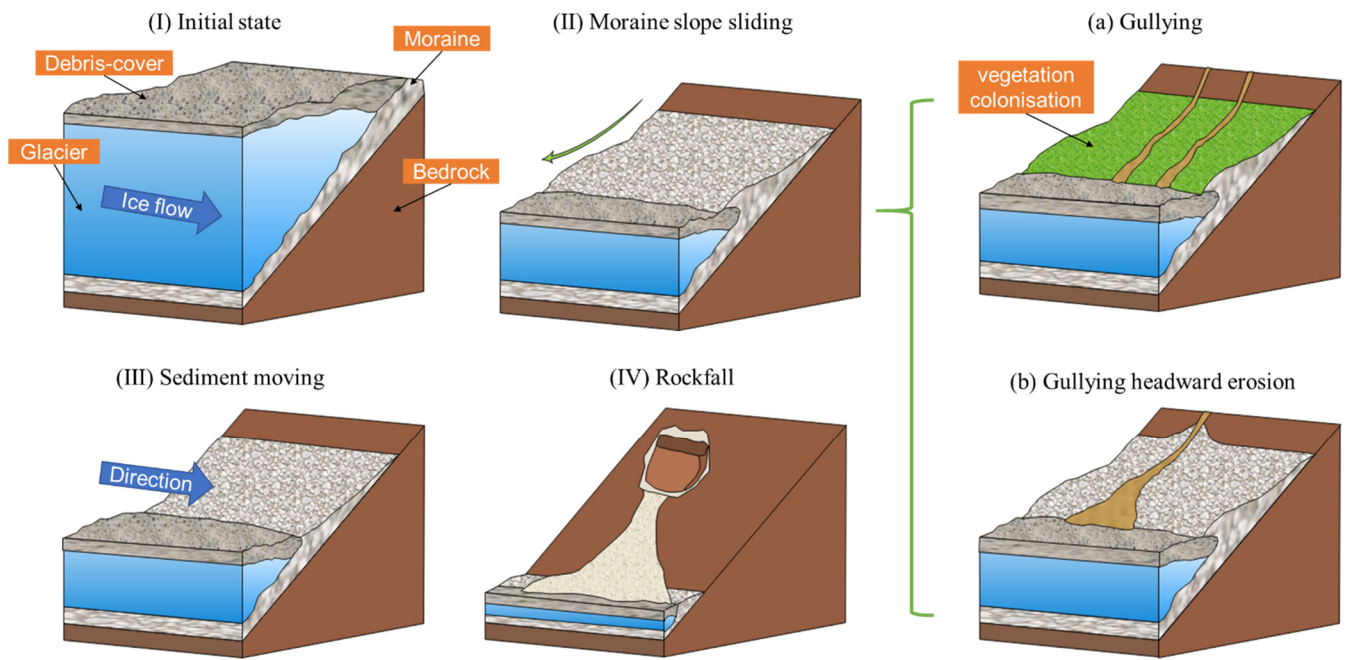


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Figure 78: The relationship among PSFs, ongoing climate change, and glacier downwasting. Climate change can directly trigger the PSF through extreme precipitation and sudden increase/decrease of temperature or indirectly trigger the PSF by glacier downwasting, which can also be used as a preparatory factor to indirectly trigger PSF (e.g., rockfalls). At the same time, many debris fell into the glacier surface, increasing the range and thickness of the supraglacial debris-cover, which in turn affected the surface energy balance for melting and therefore downwasting rate of the glacier, which will thus influence the rate of runoff generation and its contribution to the sea level rise from glacierised catchments.



1100 [Figure 8: A conjectural model of paraglacial slope evolution and sediment delivery.](#)

Table 1: Satellite/UAV data used to map the PSFs extents

Sensor Type	Acquiring Date (YYYY.MM.DD)	Near Infrared (NIR)	Red (R)	Spatial Resolution (m)
Landsat TM	1990.07.08/2000.08.20	Band4	Band3	30
Sentinel 2	2016.05.05/2018.08.23	Band8	Band4	10
RapidEye	2011.08.29/2013.05.26/2014.04.16/2015.04.03	Band5	Band3	5
PlanetScope	2017.07.17/2019.08.16/2020.08.20	Band4	Band3	3.125
Google Earth	2002.10.12 (SPOT5)	Band3	Band2	2.5
DJ-UAV	2016.08.31/2017.06.07/2018.08.19/2019.05.15	-	-	0.1

Table 2: Dimensions of PSFs in the study area. We selected periods of high-resolution images with the most obvious terrain changes, the PlanetScope image (2019) for Type A, the UAV images (2016-2019, Fig. S1) for Type B, the PlanetScope, RapidEye, and © Google Earth images (2002, 2011, 2014, 2015, 2019) for Type C (locations are shown in Fig. 5a).

PSFs type ID	Length (m)	Width (m)	Area (m ²)	Displacement speed / Upper edge retreat rate (cm d ⁻¹)	Increase in exposed area (m ²)
A	200	283	47,000	-	-
B1	1035	114	112,424	1.96±0.04/-	12,125 (2016-2019)
B2	644	262	122,738	2.63±0.04/-	7,414 (2016-2019)
B3	805	132	63,241	1.65±0.04/-	8,528 (2016-2019)
B4	993	103	73,270	1.66±0.04/-	10,130 (2016-2019)
C1	849	312	139,135	-/3.39±0.20	45,499 (2011-2019)
C2	164	269	24,248	-/0.76±0.11	11,923 (2002-2019)
C3	1097	512	160,474	-/1.15±0.15	50,989 (2002-2019)

Table 3: Precipitation data from 2014 to 2018

	Days (Precipitation >0mm)	Days (Precipitation >20mm)	Days (Precipitation >40mm)	Days (Precipitation >60mm)
2014	302	21	0	0
2015	245	15	0	0
2016	271	25	3	0
2017	278	21	1	0
2018	269	19	2	1

Supplemental Information for “Intensified paraglacial slope failures due to accelerating downwasting of a temperate glacier in Mt. Gongga, Southeastern Tibet Plateau”

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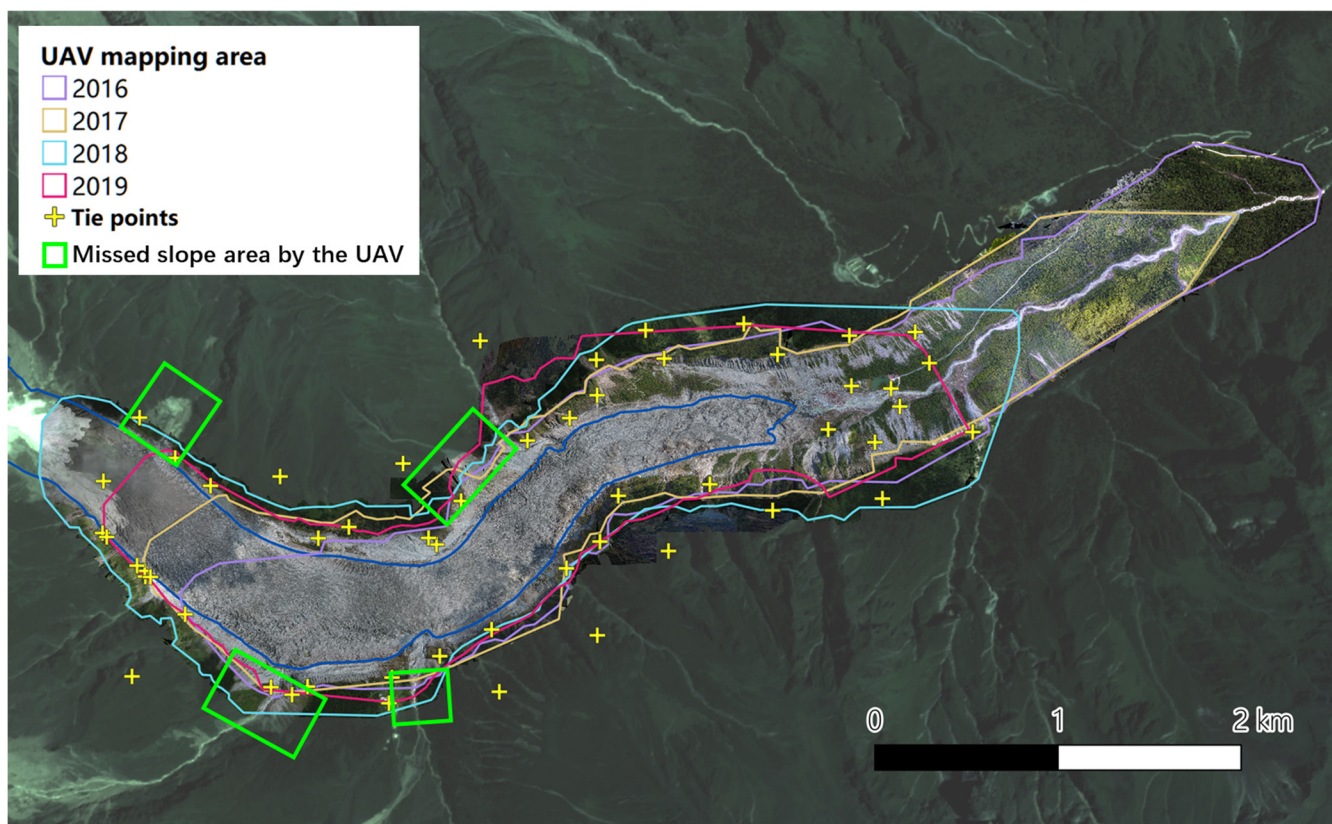
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Supplemental Figures



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Fig. S1: Spatial extents of the four repeated UAV surveys by Qiao Liu et al. and the distribution of tie points selected for imagery co-registration. Note the 'tie points' outside the UAV mapping areas were only used for extrapolation but not for co-registration.

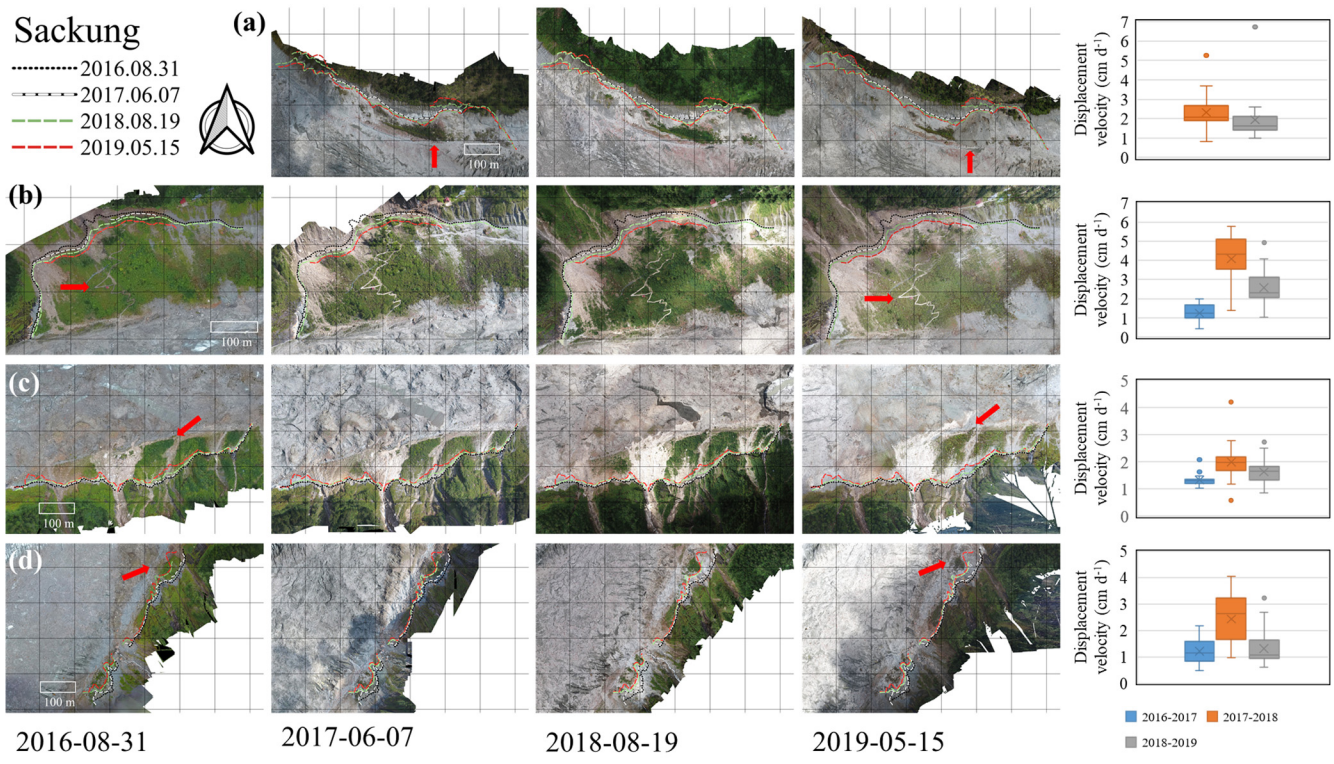
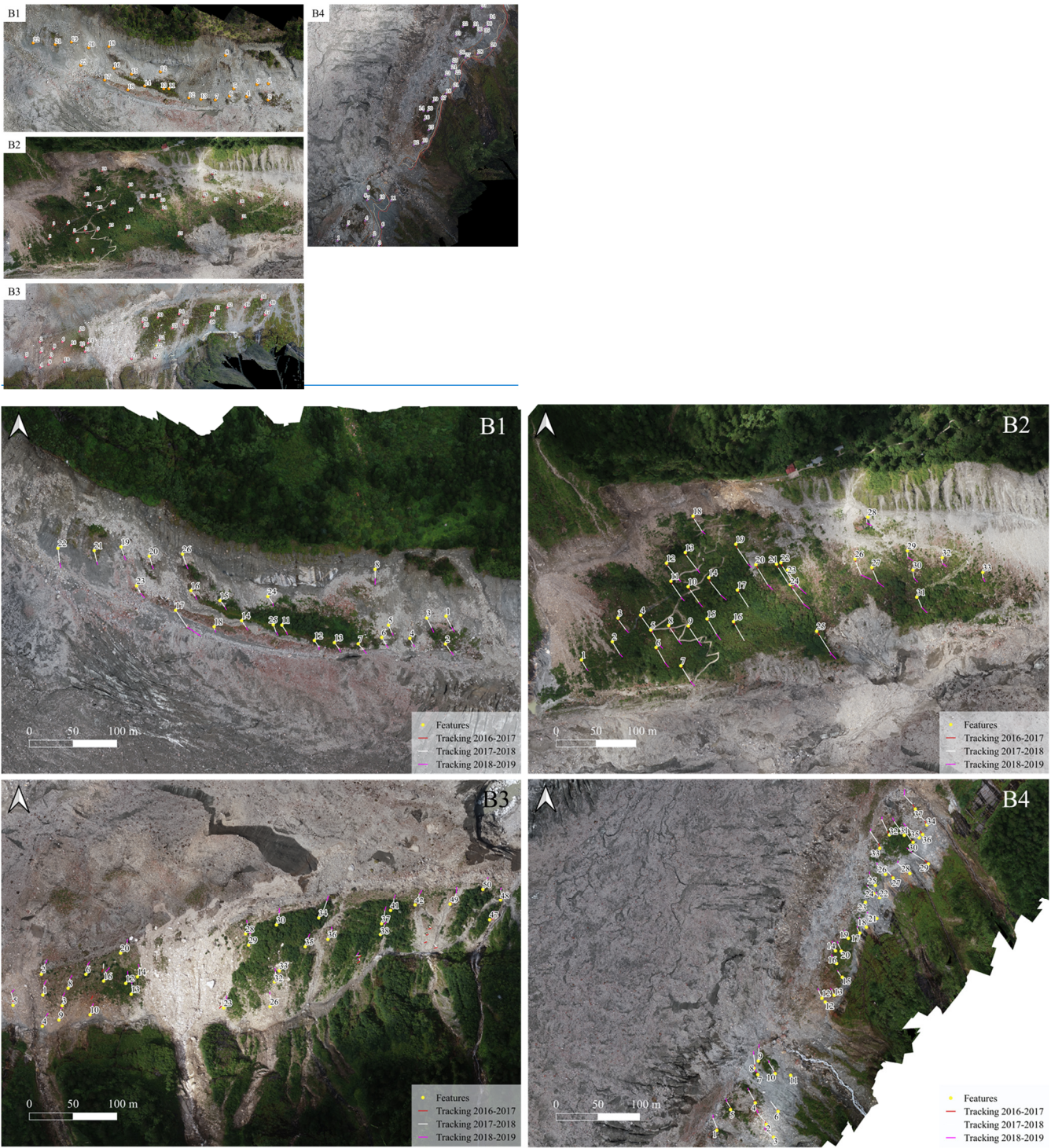


Figure S2: Slopes slides and its velocity of type B. (a) B1, (b) B2, (c) B3, (d) B4 based on UAV images.



30 Fig. S32: Tie points for manually tracked the displacement of the four slopes (B1-B4 in Fig. 6) in UAV imagery.

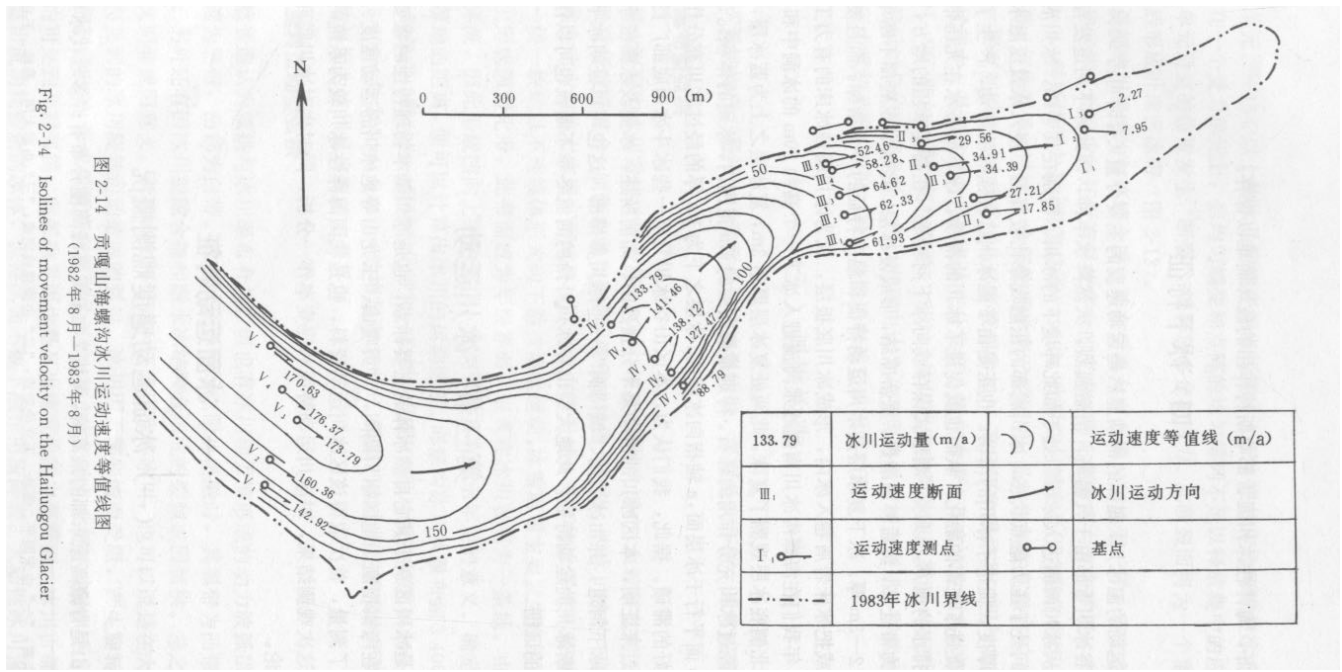
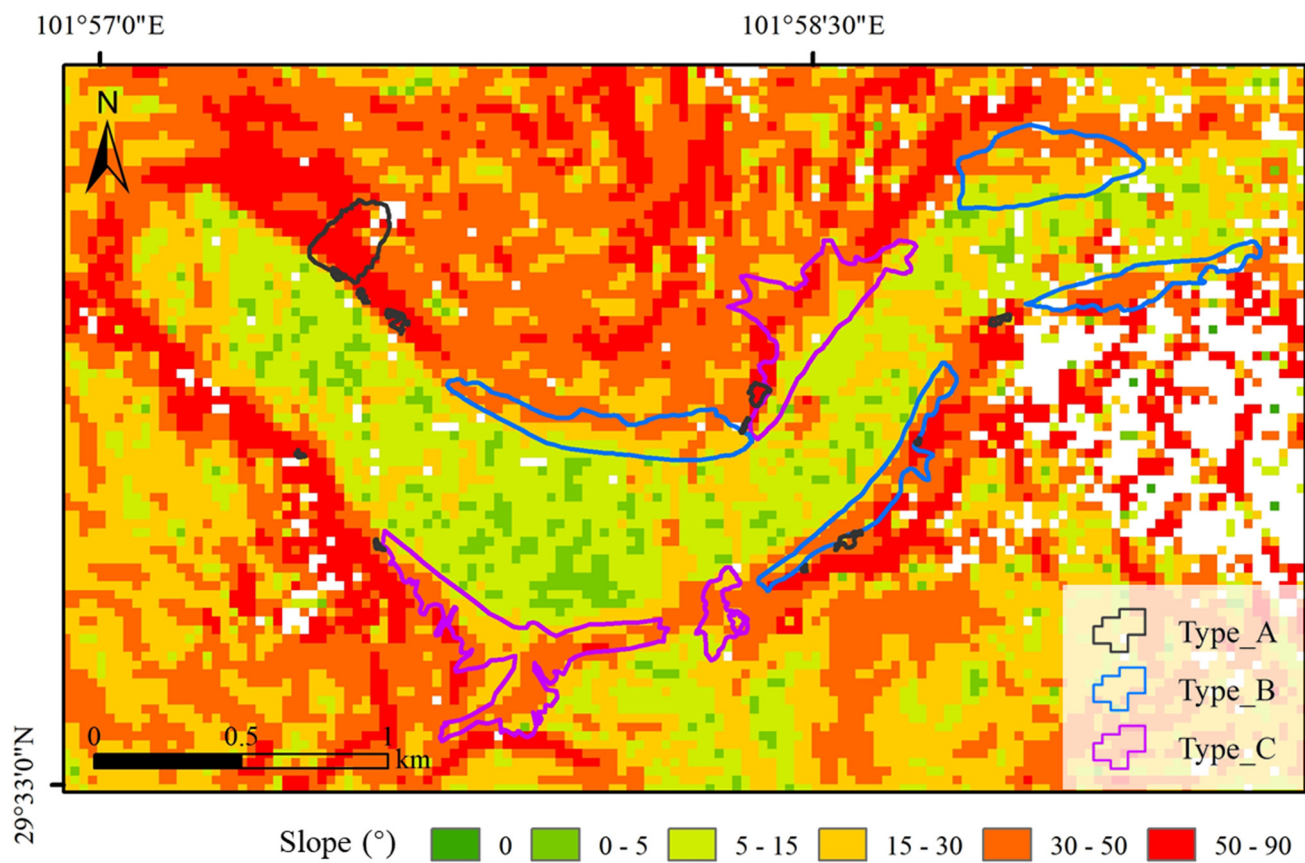
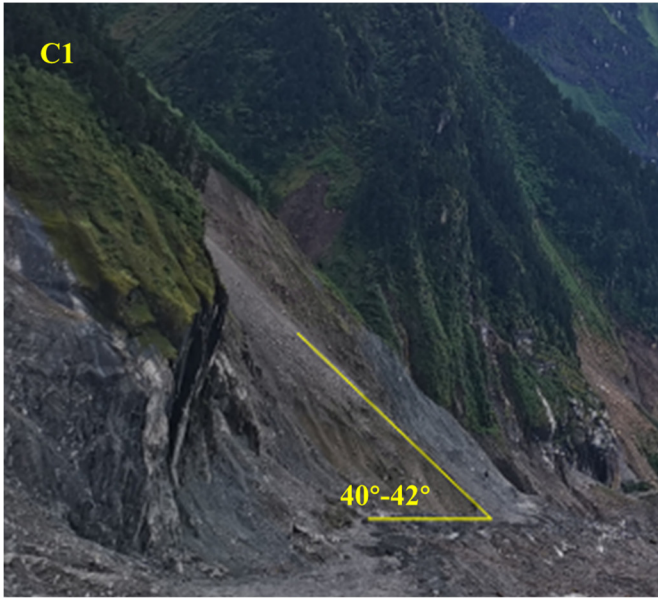
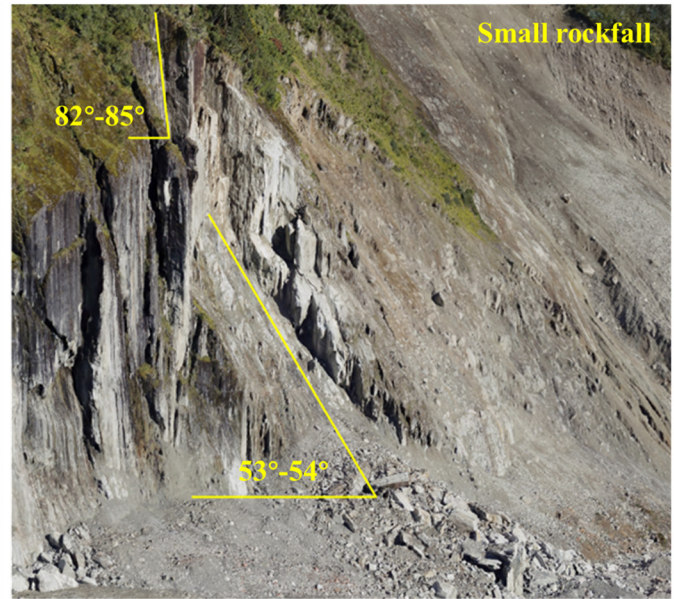


Fig. S4: The scanned picture of HLG velocity between 1982 and 1983.



35 [Fig. S5: The slope anglesSurface gradient map frombased on the 2016 DEM derived using 2000 SRTM and the 2000-2016 surface elevation change rate from , which calculated using the glacier mean annual surface elevation changes between 2000 and 2016 for the High Mountain Asia published by Brun et al. \(2017\).](#)



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Fig. S6: The slope angles of some PSF in field investigation, photographs by Yan Zhong.

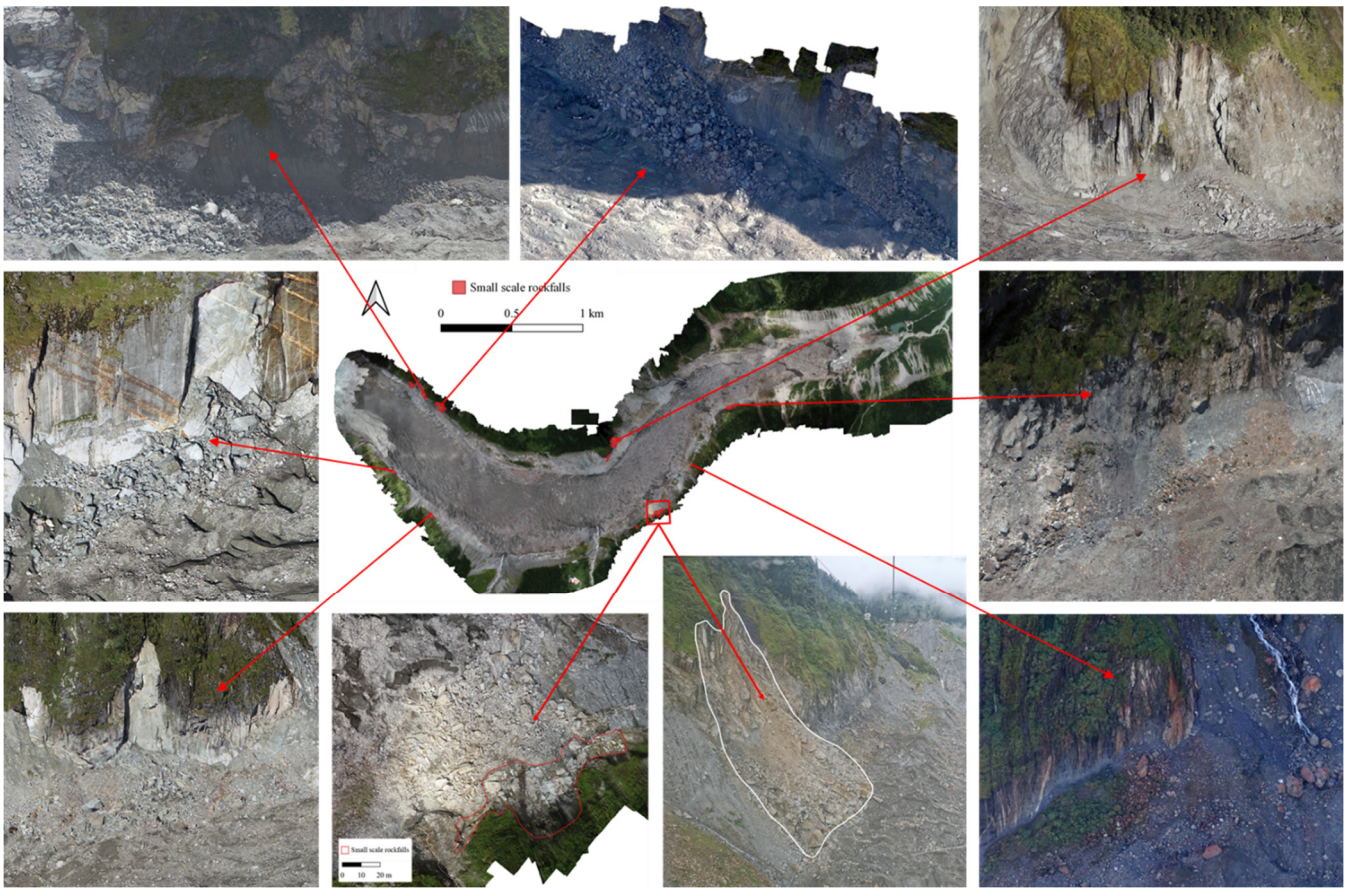


Fig. S73: Detected small magnitude rockfalls from UAV- and field-photographs.

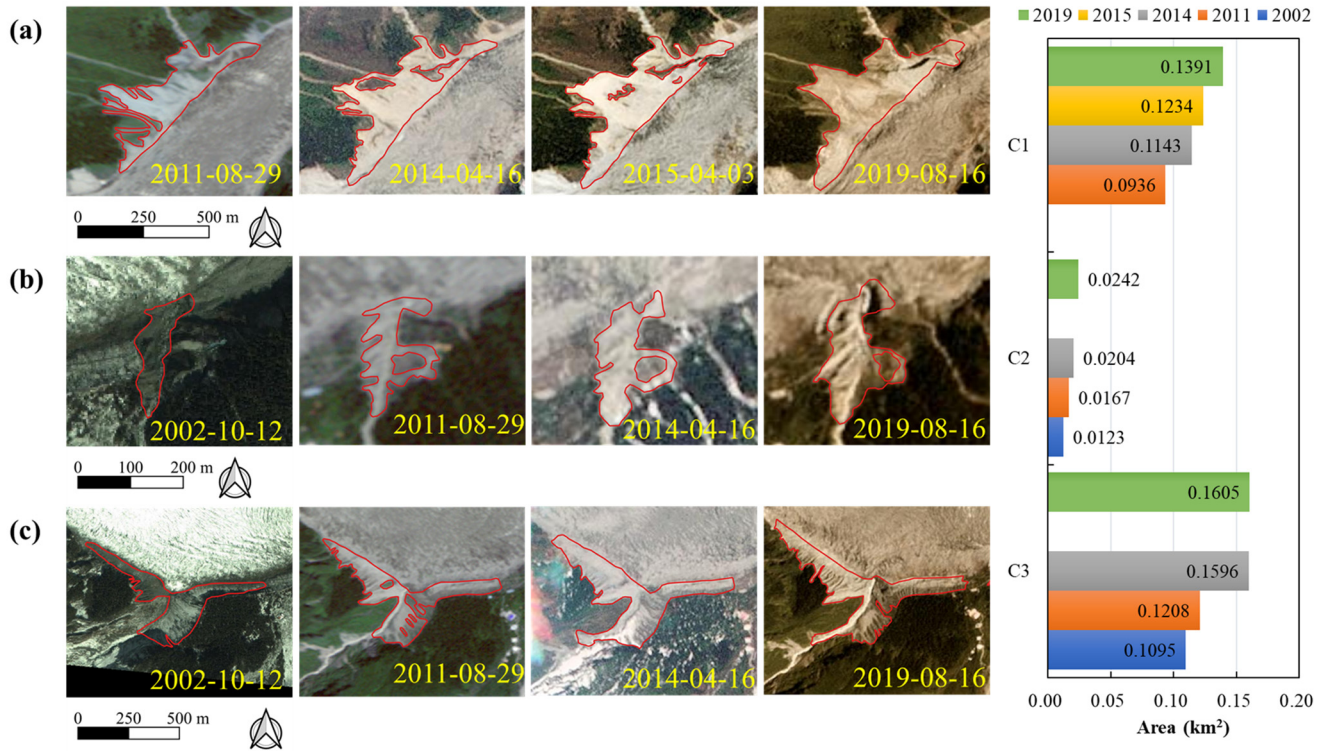


Fig. S8: Slopes range and area changes of type C. (a) C1, (b) C2, (c) C3 based on RapidEye, PlanetScope and © Google Earth (SPOT5) images.

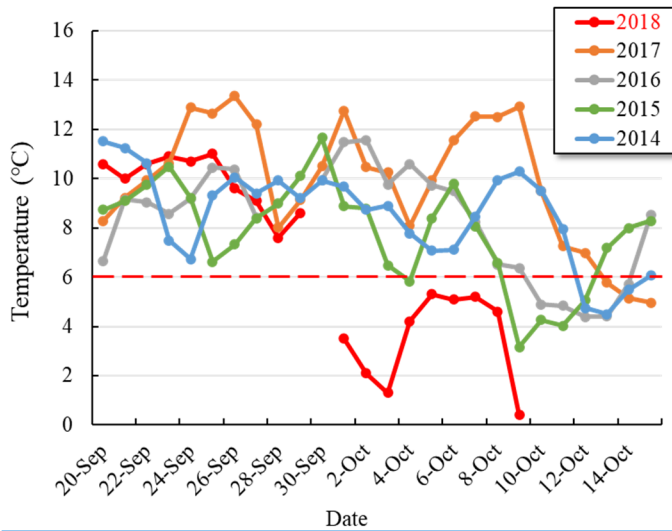


Fig. S4: Differences in the daily mean temperature between September to October 2018 and September to October 2014-2017



Fig. S9: Glacially smoothed and polished bedrock surfaces with steep inclination angles in B1 and its opposite bank, photographs by Yan Zhong.

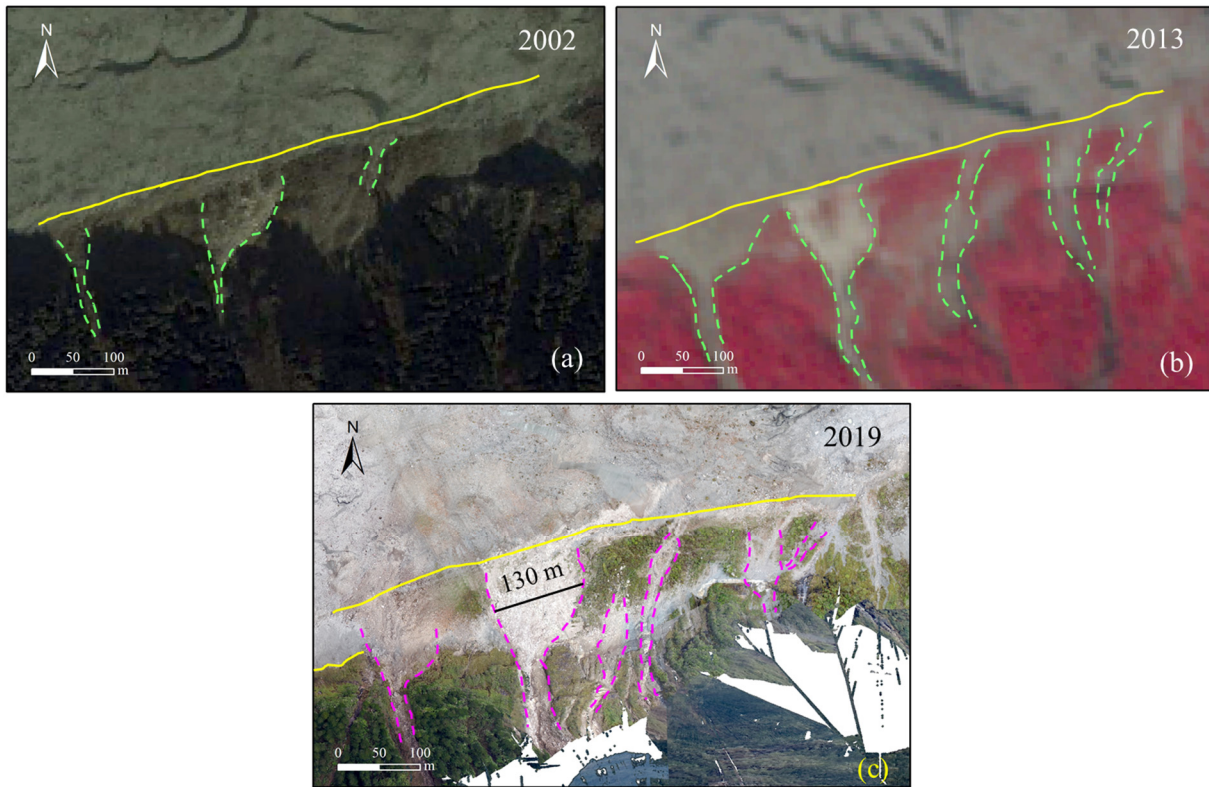


Fig. S10: The gully developing process within B3 between 2002, 2013, and 2019, UAV imagery by Qiao Liu et al.

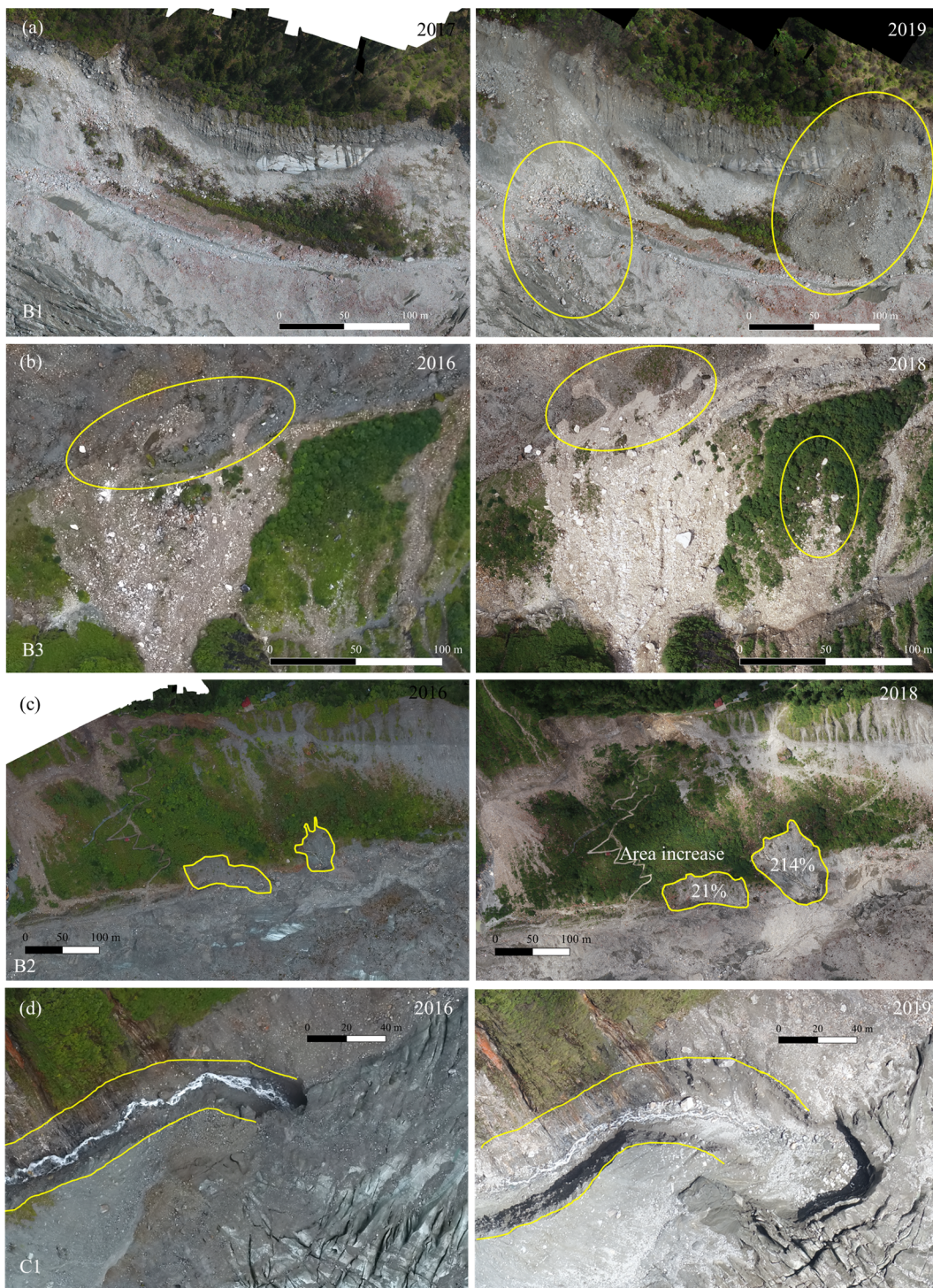


Fig. S11: A limited number of materials that are delivered to the supraglacial or sub-glacial environment through (a) direct rolled (the sediments are more dispersed compared to rockfalls), (b) collapse, (c) debris flow (faster changes), and (d) stream, UAV imagery by Qiao Liu et al.

65 [Supplemental Table](#)**Tab. S1 PSF classification**

<u>Categories</u>		<u>Sub-categories</u>		<u>Classification Standard</u>	<u>Classification Result</u>
<u>ID</u>	<u>Name</u>	<u>ID</u>	<u>Name</u>		
1.0	Rock slope failure			Large-scale, catastrophic rock slope failure	
		1.1	Rock avalanche	Volume class: $\geq 10^6$ (m³) (Deline et al., 2015)	=
		1.2	Rock fall	Local-scale, high-frequency, and discrete rockfalls Volume class: $\leq 10^6$ (m³) (McColl, 2012)	A
		1.3	Deep-seated gravitational slope deformations	Extremely slow flows or displacements of bedrock (McColl, 2012)	=
2.0	Sediment slope failure			Rock mass slides along the shear plane	
		2.1	Sediment-mantled slope slide	Shape: arc or strip (Ballantyne, 2002;Cody et al., 2020;Hungr et al., 2014)	B1-B4
		2.2	Gulley headward erosion	Strong headward erosion is added based on Type 2.1 Shape: triangle	C1-C3

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