remote sensing

Communication

Emerging Signal of Englacial Debris on One Clean Surface Glacier Based on High Spatial Resolution Remote Sensing Data in Northeastern Tibetan Plateau

Yuwei Wu [1], Wei Zhang [2,*], Shiqiang Zhang [1], Zhonglei Mao [1], Anan Chen [1], Zhen Li [2], Quan Zhang [1], Zhongming Guo [1], Xi Jiang [3] and Yongqing Long [1]

1 Shaanxi Key Laboratory of Earth Surface System and Environmental Carrying Capacity, College of Urban and Environmental Science, Northwest University, Xi'an 710127, China; yuwei.wu@nwu.edu.cn (Y.W.); zhangsq@nwu.edu.cn (S.Z.); maozl@stumail.nwu.edu.cn (Z.M.); aachen@nwu.edu.cn (A.C.); zhangquanzq@nwu.edu.cn (Q.Z.); gzm@nwu.edu.cn (Z.G.); sjzxlyq@nwu.edu.cn (Y.L.)
2 State Key Laboratory of Cryospheric Sciences, Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences, Lanzhou 730000, China; lizhen@lzb.ac.cn
3 Center for Data Assimilation Research and Application, School of Atmospheric Sciences, Nanjing University of Information Science & Technology, Nanjing 210044, China; jiangxi@nuist.edu.cn
* Correspondence: zhangw06@lzb.ac.cn

Abstract: The Tibetan Plateau contains a large number of mountain glaciers with clean surfaces, where englacial debris is generally entrained by the ice flow and exposed at the glacier margins. The long-term observation on one of the typical clean surface glaciers (the Qiyi Glacier, northern Tibetan Plateau) suggests an early emergence of englacial debris on its transport pathway, with accelerated surface melting from the mid-2000s onwards. Given that the englacial debris layers of the tongue part of Qiyi Glacier are approximately parallel to the glacier surface, the continuing melting might be expected to result in the rapid expansion of exposed debris. Compared with the clean surface ice, debris cover at the same elevation reduced glacier mass loss by ~25.4% during a hydrological year (2020–2021), indicating that the early emergence of englacial debris can protect the glacier from climate warming with prolonged life expectance. As such, future glacial runoff will then reach its peak earlier and be followed by a gentler decreasing trend than model projections with constant clean surface ice. These findings imply that the emerging debris on clean surface glacier may mitigate the glacial-runoff risk, which has so far been neglected in projections of future water supplies.

Keywords: high-resolution remote sensing data; exposed debris; Qiyi Glacier; Tibetan Plateau

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1. Introduction

Mountain glaciers on the Tibetan Plateau are an important hydrological buffer in sustaining the seasonal availability of water for most densely populated downstream areas, and, thus, predicting the fate of these glaciers and consequent water supplies are at the forefront of public attention [1–7]. According to whether there is continuous debris cover in the ablation zone, mountain glaciers can be divided into clean-surface and debris-covered glaciers [8]. For clean-surface glaciers, the englacial debris is entrained by ice flow and exposed at the glacier margins. For debris-covered glaciers, supraglacial debris will affect ablation substantially depending on the debris characteristics, particularly for its thickness [9–14]. Theoretically, these two types of glacier states might be mutually transformed for the same glacier as it expands and shrinks with varying ice influx [15–17]. For large valley glaciers with abundant debris material sources, Herreid and Pellicciotti [18] reported that their debris load has evolved from sparse to heavy since the Last Glacial Maximum. Increasing evidence exists that present-day climate warming has resulted in glacier debris cover expanding at higher elevations for typical debris-covered glaciers worldwide, including the Tibetan Plateau [19–22]. In comparison, the transformation of smaller glaciers with a clean-surface to a debris-covered surface will take longer, which hinders research into these glaciers using the available data with a limited record length. A case that clearly occurred is the d'Estelette Glacier in the Italian Alps, where the glacier surface had shifted into typical supraglacial debris cover in the 1990s from the clean-surface type, as shown in photographs from the 1920s [23]. However, despite the fact that the debris changes in smaller glaciers on the western Himalaya has been investigated using the Landsat data [24], the coarse-scale satellite imagery and the paucity of field observation still make it unclear whether such transitions are taking place on the glaciers of the Tibetan Plateau.

In recent years, the rapid development of commercial unmanned aerial vehicle (UAV, or more popularly known as "drone") technologies has made the UAV-based remote sensing data an important complement to satellite images with limited spatial and temporal resolutions [25], particularly for studies of environmental change or surface process over mountain glaciers with a hostile climate and poor approachability. For instance, by using the small UAV (<25 kg) at a relatively low cost, the cm-scale digital orthophotograph map (DOM) and the digital elevation model (DEM) datasets can be obtained to provide a detailed and on-demand map of such rugged mountainous areas [26–28]. In addition to the UAV data, the newly available commercial satellite data of meter/sub-meter resolution (e.g., IKONOS, GeoEye, Orbview, QuickBird, WorldView, etc.) and the declassified high-resolution satellite images from the American reconnaissance program Hexagon (KH-9, 1971–1984) also offer opportunities to fill the gap in observations. Combining all of these data sources, we are enabled to investigate the long-term surface process (from the 1970s) of smaller mountain glaciers (e.g., the Qiyi Glacier) at meter/sub-meter resolutions.

The Qiyi Glacier on the northern Tibetan Plateau (Figure 1d) was the first glacier in the region investigated by Chinese scientists in 1958 [29]. It is a cirque-valley glacier covering an area of 2.6 km^2 with an elevation of 4300–5150 m, and it has long been categorized as a clean-surface glacier [30]. The slopes of the surrounding valley walls are gentle, and the material source of the englacial debris is primarily from sub-glacial erosion, which is transported to the lower part of the glacier by internal ice flow. However, in 2005, a small pile of supraglacial debris was found on the central part of the glacier tongue along the mainstream line for the first time, which has since expanded (Figure 1a–c). This anormal phenomenon makes us wonder whether it turning into a debris-covered glacier for the Qiyi Glacier. To confirm this, we use high-resolution (1 m) satellite images taken from 1972 to 2012 as well as unmanned aerial vehicle-based data (0.06 m) acquired for the lower part of the Qiyi Glacier in 2020 and 2021, and we investigate the progressive exposure of englacial debris on the Qiyi Glacier due to climate warming as well as the mechanisms responsible for this.

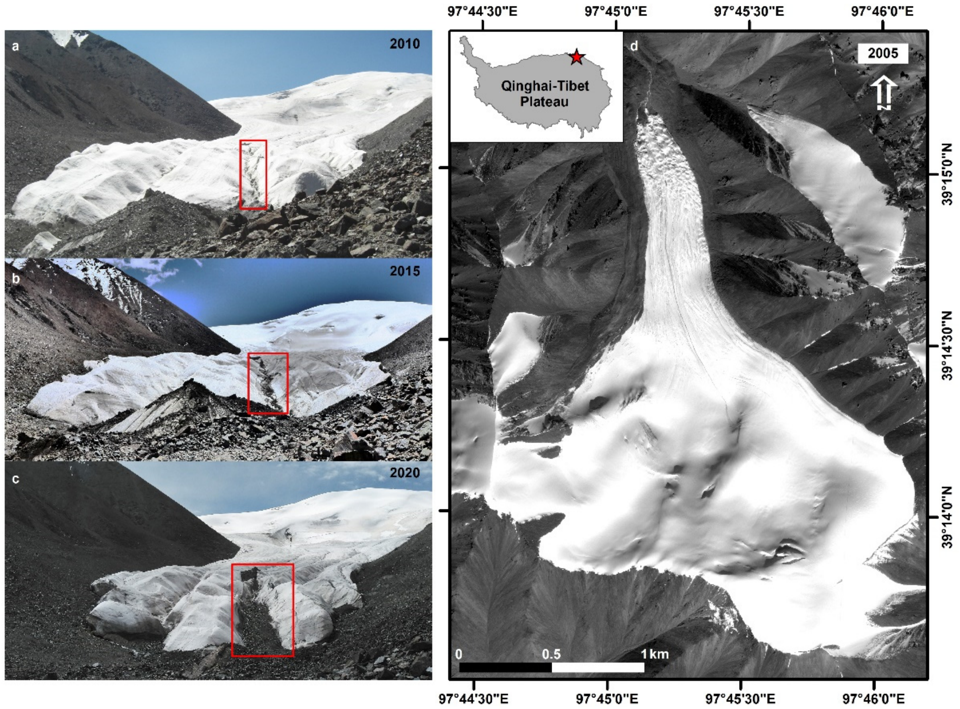

Figure 1. Location of the Qiyi Glacier (red star) and the surface changes of its tongue part from 2010 to 2020, showing the exposure of englacial debris. (**a**–**c**) Photographs were taken in summer 2010, 2015, and 2020, respectively. The red rectangle outlines the area of the most obvious increase in debris cover. (**d**) Orbview-3 satellite image of the Qiyi Glacier on 8 October 2005 (downloaded from the United States Geological Survey).

2. Materials and Methods

To explore the changes in surface debris on the Qiyi Glacier from 1972 to 2021, we used three high-resolution satellite datasets (the 1-m-resolution KeyHole-9 satellite on 30 August 1972, the 1-m-resolution Orbview-3 satellite on 8 October 2005, and the 0.6-m-resolution satellite GeoEye-1 on 23 October 2012), and two high-resolution (0.06 m) digital orthophotograph maps from UAVs taken during the ablation seasons of 2020 and 2021. All these images are cloud-free with no temporary snow. The KH-9 and Orbview-3 data were obtained from the United States Geological Survey, and the GeoEye-1 data are available from the Google Earth Platform. The UVA imagery was captured with a Zenmuse X5S camera and acquired with a commercial drone platform (DJ Matrice 200 RTK) at a height of 400 m above the glacier surface with an identical flight path in both years.

All the satellite images are registered using the UAV DOM data of 2021, from which boulders and rocky outcrops that have not changed position are identified as control points. The errors of the geo-registration are ~1 pixel. All the UVA data and satellite images were re-sampled onto a common 1 m spatial resolution. The border of tongue part of the Qiyi Glacier and its debris cover in 1972, 2005, 2012, and 2020 were retrieved by on-screen digitizing.

The obtained DEM and DOM data from well-matched UVA images in 2020 and 2021 are the key data sources for our analysis of ice mass loss. We used the registration method of Benoit et al. [31] that focuses on the relative position of control points. Firstly, the actual RTK coordinates were considered to be control points for generating the DOM and DEM data in 2021 using pixel4D software (v4.4.12), and from the 2021 DOM the unmoved rocks were identified as control points for the 2020 DOM and the DEM data. The mean absolute errors of the coordinates of check points were 0.002 m (Δx), 0.008 m (Δy), and –0.021 m (Δz), with root-mean-square errors of 0.054 m (Δx), 0.039 m (Δy), and 0.137 m (Δz), respectively. The well-matched UAV images were used to characterize the glacier surface in 2020 and 2021 using visual interpretation. From this, we analyzed the relationship between the glacier surface and its corresponding ice mass change, which had already been obtained by calculating the difference in the DEM between 2020 and 2021.

3. Results

3.1. Spatial Distribution of Englacial Debris

The Qiyi Glacier has undergone continuous retreat since the 1970s [32], and, thus, the spatial distribution of englacial debris can be inferred from the exposed proglacial moraines deposited within the areas between the two glacier outlines in 1972 and 2020. A continuous stratified moraine layer is found to spread across the valley, and it has a thickness of several cm to nearly 1 m (Figure 2c). Below the moraine layer, there is abundant hidden ice that is still being extruded by the moving glacier (see the surface elevation change result in the following section). Ground penetrating radar (GPR) measurements at the glacier terminus in 1984 [33] and 2018 showed that the buried ice is up to 30 m thick (black triangles in Figure 2a), suggesting that the exposed proglacial moraines were derived from the entrained debris in the middle of the glacier. In addition, near-vertical sections of the glacier tongue in 2022 also exhibited one or two debris-rich bands that were tens of cm to >2 m thick (Figure 2d–f), which also implied that debris-rich layers were present below the glacier surface.

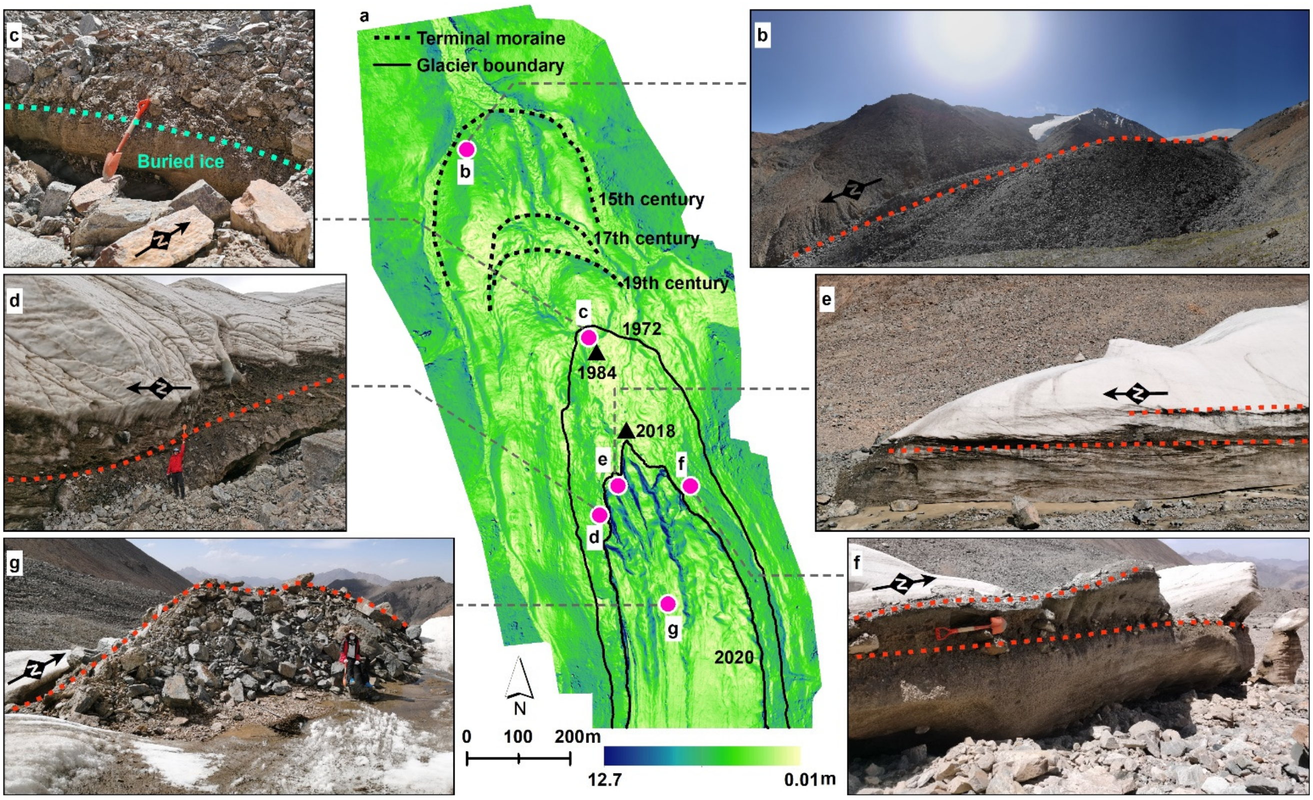

Figure 2. Distribution of proglacial moraines, buried ice, and englacial debris bands of the Qiyi Glacier. (**a**) Topographic relief at 1 m circle radius unit of the Qiyi Glacier in 2021. The dashed lines [34] and solid lines (from remote sensing images) track the retreat of the glacier. The purple dots indicate where the photos (**b**–**g**) were taken in August 2022. The black triangles display sites where the glacier thickness is by GPR. (**b**) Terminal moraines formed in the 15th century. (**c**) Debris and buried ice at the 1972 glacier terminus. (**d**–**f**) Exposed englacial debris bands on the left (**d**), middle (**e**), and right (**f**) sides of the glacier tongue. (**g**) Supraglacial debris on the main streamflow of the glacier tongue. The shovel spade and person are 70 cm long and 175 cm in height, respectively.

3.2. Exposure Mechanisms of Englacial Debris

From 1972 to 2020, the exposed englacial debris increased in extent from the glacier terminus to the interior along the supraglacial river, and from the glacier center line to the glacier margins (Figure 3a). Prior to 2005, most englacial debris was exposed on the frontal part of glacier, where intense surface melting and strong upwelling of ice flow occurs. In 2005, another pile of englacial debris was found at the end of the largest supraglacial river, possibly as a result of its strong incision that enabled the river channel to reach down to the englacial debris layers. Meanwhile, a small mound of debris (red arrow in Figure 3a) was also melted out of the interior of the glacier tongue that has a relatively flat surface, which means that surface melting was now also able to expose the englacial debris. Rapid thinning of the glacier tongue meant that the ends of the two smaller supraglacial rivers became new exposure sites of englacial debris. From 2012 to 2020, two types of debris (i.e., along river channels and from surface melting; Figure 3b) experienced rapid expansion. Predictably, the melt-out debris will become dominant when the glacier is further thinning and receding, which might help to form continuous debris cover on the glacier tongue in the future. The areas of debris cover of different years at various distances to the glacier terminal and their total areas/annual change rate are shown in Table 1.

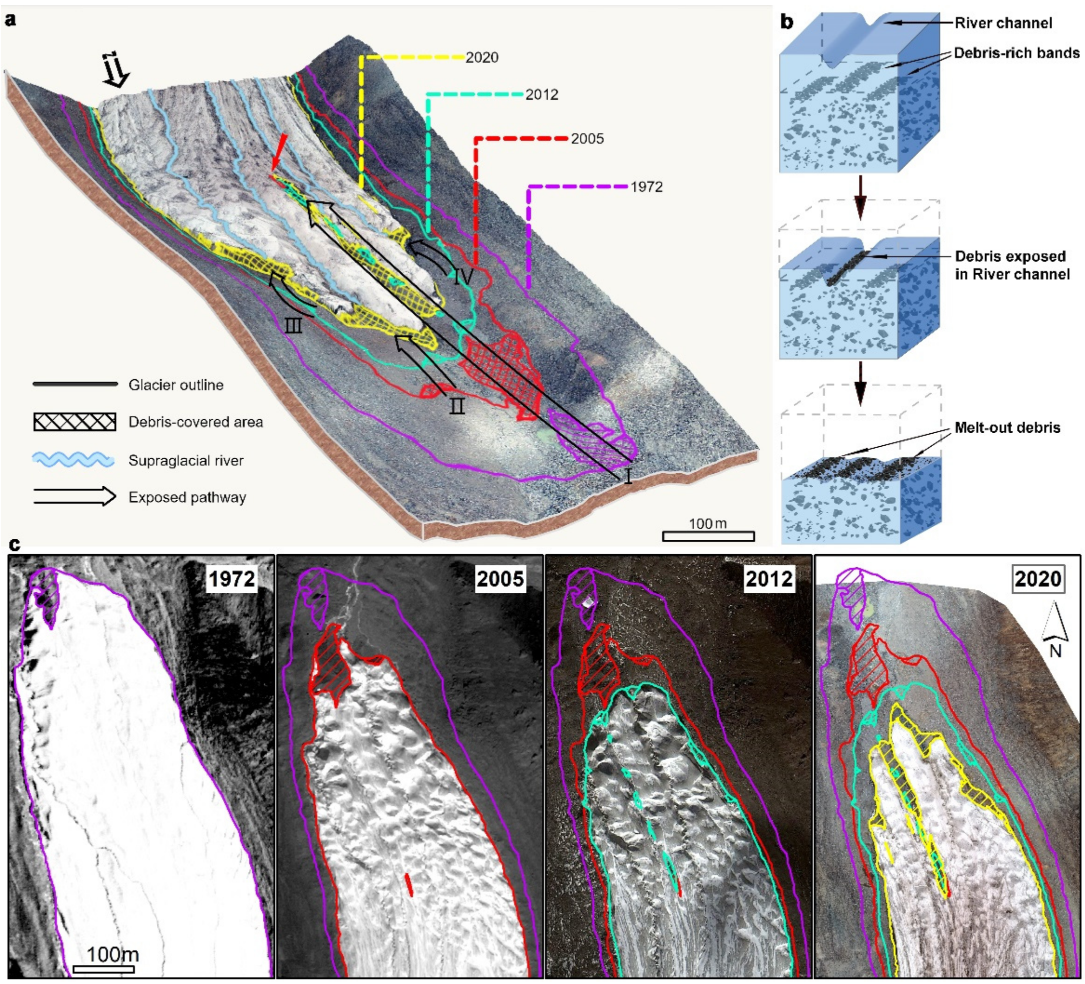

Figure 3. Development of englacial debris on the Qiyi Glacier tongue during 1972–2020. (**a**) Three-dimensional map based on UAV data from August 2021. The black arrows (I to IV) denote the pathways of the spread of englacial debris. The red arrow marks where englacial debris was found on the interior of the glacier tongue for the first time in 2005. (**b**) The exposure process of englacial debris due to incision of a supraglacial river and surface melting of the glacier. (**c**) The Qiyi Glacier surface condition based on satellites and UAV orthoimage data in 1972–2020.

Table 1. The areas of debris cover of different years at various distance to the glacier terminal and their total areas/annual changing rates.

Distance to Glacier Terminal (m)	Debris Cover Area (m^2)				
	1972	**2005**	**2012**	**2020**	**2021**
50	1815.26	1355.98	458.46	828.67	571.57
100	1000.06	2932.51	36.88	1608.89	1796.35
150	0.00	586.28	424.14	1000.19	1225.05
200	0.00	0.00	223.37	1569.82	1890.57
250	0.00	0.00	161.62	493.53	549.43
300	0.00	0.00	118.42	693.17	762.75
350	0.00	0.00	284.43	243.01	272.46
400	0.00	0.00	0.00	8.18	15.64
450	0.00	72.24	0.00	15.06	19.85
500	0.00	54.46	0.00	0.00	0.00
Total debris cover area	2815.32	5001.47	1707.33	6460.52	7103.67
Annual change rate	-	66.25	-470.59	594.15	643.15

3.3. Effects of the Exposed Debris on Glacier Mass Loss

During 2020–2021, the exposed englacial debris was mainly distributed in five zones (A–E in Figure 4a). The main part of zone E is melt-out debris with a thickness of several centimeters, and this glacial till of sand and gravel debris does not fully cover the ice (Figure S1e). By comparison, the debris is much thicker (more than tens of centimeters) in the other four zones (A–C is in river channels; D is melt-out debris), where the unsorted debris of silt-sized glacial flour to large boulders completely covers the glacier (Figure S1a–d).

Supraglacial melting is the main mechanism of ice loss on the Qiyi Glacier, whereas the surface elevation change (SEC; see the Section 2) driven by bottom melting is relatively minor and can be neglected on short timescales. In addition, the difference in the glacier movement-induced SECs within a narrow elevation band is also negligible compared to that of supraglacial melting. Therefore, a comparison of the difference in SECs between the debris-free and debris-covered ice over the same elevation range can be used to analyze the effects of debris cover on glacier mass loss (Figure 4). The relative ice mass loss (RIML) of a given single pixel can be expressed as:

$$\text{RIML} = \text{SEC} \times A \times 900 \tag{1}$$

where the SEC is surface elevation change (Unit: m), A refers to the area of the glacier pixel (m^2), and 900 represents the density of glacier ice (900 kg/m^3). By using Equation (1), the ice mass loss of all of the bare ice pixels and debris-covered pixels can be obtained (including A, A_c, B, B_c, C, C_c, D, D_c, E, and E_c).

Moreover, a field investigation found evidence of a retreat in channel shoulders where debris emerges along rivers, which occurs due to the higher surface temperature of the debris melting more ice of the surrounding slope. This extra part of mass loss was also taken into account for this type of debris (Figure 4c). Therefore, for the total ice mass loss of three of the debris covers along the river channels, the ice mass losses within the entire channel (zones Ar–Cr encircled by thick dashed lines) were compared with the bare ice at the same elevation band (i.e., Ar_c, Br_c, Cr_c) (Figure 4a).

The debris thickness determines whether debris cover mitigates or enhances the glacier melting. For the five debris zones, the ice mass loss of zone E is 35.9% more than that of bare ice at the same elevation band (381 m^3 water equivalent) due to its thin debris cover, whereas the debris in the other four zones (A–D) reduces glacier melting. Compared with bare ice, the net reduction of ice mass loss for all five zones is 4631 m^3 water equivalent (~49.5%). In addition, although the channel slope of rivers with debris has caused an additional ice mass loss (Figure 4b–c), there is still a net reduction of ice mass loss (by 25.4%) for all debris-affected areas (including zone Ar–Cr, D, and E).

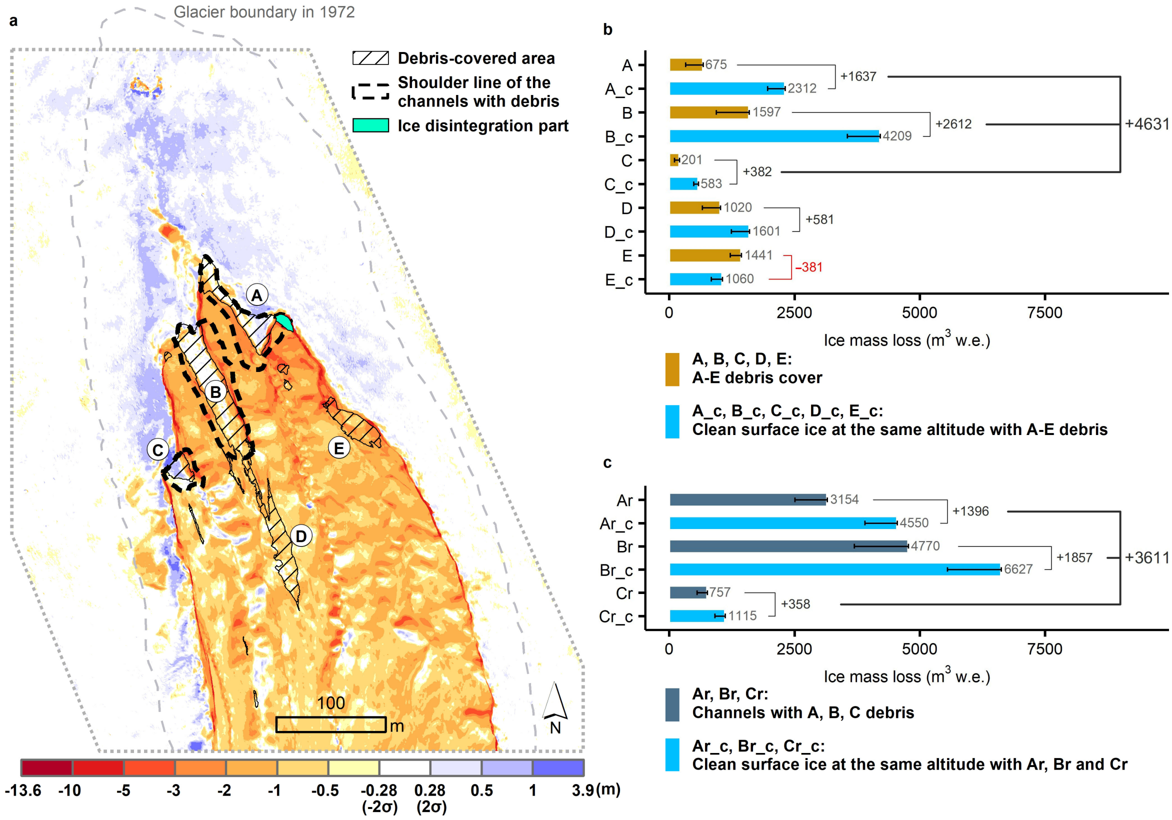

Figure 4. Effects of exposed debris on glacier mass loss in 2020–2021. (**a**) SEC of the Qiyi Glacier from 10 August 2020 to 4 August 2021. A–E are five major zones with exposed supraglacial debris in 2021. The thick black dashed lines are the shoulder lines of the channels with debris (Ar, Br, and Cr). (**b**) Comparison of the ice mass loss between the exposed debris zones and bare ice at the same elevation band. (**c**) Comparison of ice mass loss between the entire channel with debris areas (zones Ar–Cr encircled by thick dashed lines) and bare ice at the same elevation band. The ice mass loss (water equivalent; m^3 w.e.) was obtained from the SECs using a scaling coefficient of 900 kg/m^3 (annotated gray numbers), and the difference in ice mass loss of debris-covered areas (or channels with debris) and bare ice is shown in blue numbers.

4. Discussion

4.1. The Influence of Climate Warming

Over the past few decades, climate warming has resulted in higher equilibrium line altitudes (ELAs) and thinner snow cover on most glaciers on the Tibetan Plateau [35,36]. This is indicative of a decrease in the net ice mass budget in the accumulation zone being associated with slower glacier movement [37–39]. The decreased ice mass input to the glacier tongue and the accelerated surface melting are the main drivers of the early emergence of englacial debris on the transport pathway of a clean-surface glacier. Compared with the d'Estelette Glacier in the Italian Alps, which has experienced a transition from a clean-surface glacier to a debris-covered glacier in the 20th century, the Qiyi Glacier appears to show a more rapid change from sporadic river channel-associated and melt-out debris to obvious supraglacial debris cover in only 15 years, with an increase in debris cover of 1095.8 m^2 from 2020 to 2021.

4.2. The Hydrological Impact of Exposed Debris

The ultimate supraglacial debris cover on the Qiyi glacier is restricted by the internal distribution and enrichment extent of the local englacial debris, which remains hard to directly measure and numerically simulate [40–42]. However, field observation of the Qiyi Glacier has shown an expanding exposed debris on its tongue part over recent years, which is possibly because the englacial debris layers are generally expanding parallel to the surface of the Qiyi Glacier. Further expansion of supraglacial debris will proliferate with the continued glacier thinning, which may eventually trigger the tipping point into heavy debris that will cover the glacier in the future. The single source of debris material may make it difficult for the future debris to cover the places as high as the ELA in the way that the big mountain glaciers did [18], but the enrichment effect of englacial debris in the glacier tongue may result in the presence of continuous englacial debris in the glacier tongue (Figure 5a). Given that the expanding debris cover will seal more ice of the glacier tongue, the tipping point of future glacial runoff will arrive earlier than the current projections using the clean glacier surface (Figure 5b), but beyond this point, the decreasing trend will be gentler, which will provide a buffer for the downstream communities to cope with.

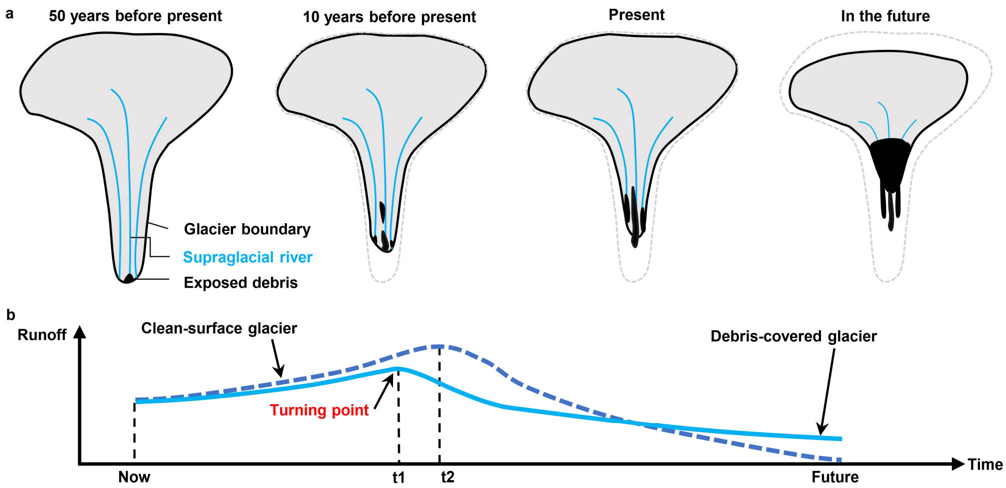

Figure 5. Conceptual model of the Qiyi Glacier showing the transformation from a clean-surface to debris-covered glacier due to climate warming (**a**), and its effect on glacial runoff (**b**).

4.3. Challenges and Potential Solutions

When a glacier transfers from a clean-surface condition to a debris-covered condition, it is very important to capture this transfer signal at its initial stage, which is also a challenging subject. From field investigation and high-resolution UAV images, we find an emerging signal of englacial debris on the Qiyi Glacier, and we can conjecture that such a clean surface glacier may switch into a heavy debris-covered one, but this bold speculation needs more observations if it is to be validated. For instance, based on a more detailed measurement of englacial debris using ground penetrating radar (GPR) combined with the glacier dynamic models, the development of the englacial debris of the Qiyi Glacier might be analyzed in order to obtain more solid results. Nevertheless, it is undeniable that the continuing climate warming has been substantially influencing the fate of the Qiyi glacier. According to our field observations over the past few years, although the percentage of the debris area is still low, the debris cover at the glacier terminal has been expanding upwards to the interior tongue part of the glacier since 2005, and if this change trend continues, it is probable that the Qiyi Glacier will change to a debris-covered condition eventually.

On the other hand, despite the relatively higher uncertainties in the SEC results over the proglacial region due to the absence of control points, its anormal positive changes still deserve further investigation. Theoretically, the positive elevation change can be explained as a result of the extrusion of the moving glacier: when the glacier shrinks as a result of climate warming, the ice above the ground vanishes and its englacial debris is exposed, but there is still abundant hidden ice covered by thick debris. The debris cover can protect the buried ice from further melting (i.e., there is no evident decrease in the surface elevation), whereas the extrusion of the moving glacier might force the surface of the hidden ice to rise (i.e., there is an increase in the surface elevation). In our future field work, we plan to set control points with more accurate RTK in order to verify whether the SEC in the proglacial region has increased or not. If we obtain a positive answer, this would be direct evidence of the existence of hidden ice in the proglacial region, and would be a breakthrough in studies of ice loss estimation during the process of glacier shrinkage.

5. Conclusions

In this study, we have investigated the exposing process of englacial debris of the Qiyi Glacier from 1972 to 2022 and its potential hydrological influences based on the satellite data and UAV images of meter/sub-meter resolutions. Our results indicate that with the ongoing climate warming, the enhanced ice melt would be offset by the sealing effect from emerging englacial debris on the clean-surface of the Qiyi Glacier, which will elongate the life expectance of the glacier and mitigate glacial runoff risk in the near future. Our results also suggest that under the context of continuing climate warming, the transition from a clean surface to a debris-covered glacier is not confined to the large mountain glaciers (e.g., Herreid and Pellicciotti [18]), and is also possible for small glaciers (such as the Qiyi glacier) when certain conditions prevail. We believe that the Qiyi Glacier must not be the only glacier nor the first glacier that is showing an expanding trend of debris, but only the first one where this process has been witnessed with regular in situ observations, and we believe that similar cases will be reported elsewhere on the Tibetan Plateau in future with continuing global warming.

Generally, climatic factors are thought to be the main driving forces of clean surface glacier and glacial runoff changes, whereas intra-glacier feedbacks are often neglected. The emerging englacial debris on the Qiyi Glacier suggests that glacier dynamics must be considered when modeling future glacier and glacial runoff changes. Moreover, the receding and thinning mountain glaciers may trigger anomalous ice mass loss (e.g., ice disintegration; see Figures 4a and S2) at more frequent intervals, which will complicate the glacier system even further [7]. Currently, the increasingly available fine-scale remote sensing data at sub-meter resolution (such as the multi-satellite constellations and microsatellites as well as the UAV) allows us to evaluate how mountain glaciers are responding to a warming climate [28], and this will enhance our understanding of glacier evolution and its hydrological impacts.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/rs15153899/s1: Figure S1: Exposed englacial debris in five zones A–E (a–e, respectively; taken on summer 2022); Figure S2: Ice disintegration in the terminus of the Qiyi Glacier that was first observed on summer 2013. a: ice crevasse; b: ice disintegration from the ice crevasse.

Author Contributions: Conceptualization, Y.W., W.Z. and S.Z.; methodology, Y.W., Z.M. and Q.Z.; software, Y.W. and Z.M.; validation, Y.W., Z.L. and Z.M.; formal analysis, Y.W. and A.C.; investigation, Z.M. and Z.G.; resources, Z.L.; data curation, Z.M., A.C. and Y.L.; writing—original draft preparation, Y.W. and W.Z.; writing—review and editing, Y.W.; visualization, Z.G. and X.J.; supervision, S.Z.; project administration, Y.W. and S.Z.; funding acquisition, Y.W. and S.Z. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to privacy.

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Conflicts of Interest: The authors declare no conflict of interest.

References

1. Bolch, T.; Kulkarni, A.; Kääb, A.; Huggel, C.; Paul, F.; Cogley, J.G.; Frey, H.; Kargel, J.S.; Scheel, M.; Bajracharya, S.; et al. The state and fate of Himalayan glaciers. *Science* **2012**, *336*, 310–314. [CrossRef] [PubMed]
2. Yao, T.D.; Xue, Y.K.; Chen, D.L.; Chen, F.; Thompson, L.; Cui, P.; Koike, T.; Lau, W.K.-M.; Lettenmaier, D.; Mosbrugger, V.; et al. Recent Third Pole's rapid warming accompanies cryospheric melt and water cycle intensification and interactions between monsoon and environment: Multi-disciplinary approach with observation, modeling and analysis. *Bull. Am. Meteorol. Soc.* **2019**, *100*, 423–444. [CrossRef]
3. Kraaijenbrink, P.D.; Bierkens, M.F.P.; Lutz, A.F.; Immerzeel, W.W. Impact of a global temperature rise of 1.5 degrees Celsius on Asia's glaciers. *Nature* **2017**, *549*, 257–260. [CrossRef] [PubMed]
4. Huss, M.; Hock, R. Global-scale hydrological response to future glacier mass loss. *Nat. Clim. Chang.* **2018**, *8*, 135–140. [CrossRef]
5. Hock, R.; Rasul, G.; Adler, C.; Cáceres, B.; Gruber, S.; Hirabayashi, Y.; Jackson, M.; Kääb, A.; Kang, S.; Kutuzov, S.; et al. High Mountain Areas. In *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate*; Pörtner, H.-O., Roberts, D.C., Masson-Delmotte, V., Zhai, P., Tignor, M., Poloczanska, E., Mintenbeck, K., Alegría, A., Nicolai, M., Okem, A., et al., Eds.; Cambridge University Press: Cambridge, UK; New York, NY, USA, 2019; pp. 131–202.
6. Immerzeel, W.W.; Lutz, A.F.; Andrade, M.; Bahl, A.; Biemans, H.; Bolch, T.; Baillie, J.E.M. Importance and vulnerability of the world's water towers. *Nature* **2020**, *577*, 364–369. [CrossRef]
7. Yao, T.; Thompson, L.; Yang, W.; Yu, W.; Gao, Y.; Guo, X.; Yang, X.; Duan, K.; Zhao, H.; Xu, B.; et al. Different glacier status with atmospheric circulations in Tibetan Plateau and surroundings. *Nat. Clim. Chang.* **2012**, *2*, 663–667. [CrossRef]
8. Kirkbride, M.P. Debris-covered glaciers. In *Encyclopedia of Snow, Ice and Glaciers*; Singh, V.P., Singh, P., Haritashya, U.K., Eds.; Springer: Berlin, Germany, 2011; pp. 180–182.
9. Østrem, G. Ice melting under a thin layer of moraine, and the existence of ice cores in moraine ridges. *Geogr. Ann. Ser. A Phys. Geogr.* **1959**, *41*, 228–230. [CrossRef]
10. Reid, T.D.; Brock, B.W. An energy-balance model for debris-covered glaciers including heat conduction through the debris layer. *J. Glaciol.* **2010**, *56*, 903–916. [CrossRef]
11. Scherler, D.; Bookhagen, B.; Strecker, M. Spatially variable response of Himalayan glaciers to climate change affected by debris cover. *Nat. Geosci.* **2011**, *4*, 156–159. [CrossRef]
12. Nicholson, L.; Benn, D.I. Properties of natural supraglacial debris in relation to modelling sub-debris ice ablation. *Earth Surf. Proc. Landf.* **2013**, *38*, 490–501. [CrossRef]
13. Nicholson, L.; Wirbel, A.; Mayer, C.; Lambrecht, A. The challenge of non-stationary feedbacks in modeling the response of debris-covered glaciers to climate forcing. *Front. Earth Sci.* **2021**, *9*, 662695. [CrossRef]
14. Rounce, D.R.; Hock, R.; McNabb, R.W.; Millan, R.; Sommer, C.; Braun, M.H.; Maussion, M.F.; Mouginot, J.; Shean, S.D.E. Distributed global debris thickness estimates reveal debris significantly impacts glacier mass balance. *Geophys. Res. Lett.* **2021**, *48*, e2020GL091311. [CrossRef] [PubMed]
15. Kirkbride, M.P. About the concepts of continuum and age. *Boreas* **1989**, *18*, 87–88. [CrossRef]
16. Kirkbride, M.P. Ice-marginal geomorphology and Holocene expansion of debris-covered Tasman Glacier, New Zealand. In *Debris-Covered Glaciers*; Nakawo, M., Raymond, C.F., Fountain, A., Eds.; IAHS Press: Wallingford, UK, 2000; pp. 211–217.
17. Wirbel, A.; Jarosch, A.H.; Nicholson, L. Modelling debris transport within glaciers by advection in a full-Stokes ice flow model. *Cryosphere* **2018**, *12*, 189–204. [CrossRef]
18. Herreid, S.; Pellicciotti, F. The state of rock debris covering Earth's glaciers. *Nat. Geosci.* **2020**, *13*, 621–627. [CrossRef]
19. Glasser, N.F.; Holt, T.O.; Evans, Z.D.; Davies, B.J.; Pelto, M.; Harrison, S. Recent spatial and temporal variations in debris cover on Patagonian glaciers. *Geomorphology* **2016**, *273*, 202–216. [CrossRef]
20. Xie, F.; Liu, S.; Wu, K.; Zhu, Y.; Gao, Y.; Qi, M.; Duan, S.; Saifullah, M.; Tahir, A.A. Upward expansion of supra-glacial debris cover in the Hunza Valley, Karakoram, during 1990–2019. *Front. Earth Sci.* **2020**, *8*, 308. [CrossRef]
21. Shea, J.M.; Kraaijenbrink, P.D.; Immerzeel, W.W.; Brun, F. Debris Emergence Elevations and Glacier Change. *Front. Earth Sci.* **2021**, *9*, 709957. [CrossRef]
22. Zhang, Y.; Liu, S.; Wang, X. Debris-cover effect in the Tibetan Plateau and surroundings: A review. *J. Glaciol. Geocryol.* **2022**, *44*, 900–913. (In Chinese with English Abstract)
23. Kirkbride, M.P.; Deline, P. The formation of supraglacial debris covers by primary dispersal from transverse englacial debris bands. *Earth Surf. Proc. Landf.* **2013**, *38*, 1779–1792. [CrossRef]
24. Ali, I.; Shukla, A.; Romshoo, S.A. Assessing linkages between spatial facies changes and dimensional variations of glaciers in the upper Indus Basin, western Himalaya. *Geomorphology* **2017**, *284*, 115–129. [CrossRef]
25. Whitehead, K.; Hugenholtz, C.H. Remote sensing of the environment with small unmanned aircraft systems (UASs), part 1: A review of progress and challenges. *J. Unmann. Veh. Sys.* **2014**, *2*, 69–85. [CrossRef]

26. Bhardwaj, A.; Sam, L.; Martín-Torres, F.J.; Kumar, R. UAVs as remote sensing platform in glaciology: Present applications and future prospects. *Remote Sens. Environ.* **2016**, *175*, 196–204. [CrossRef]
27. Śledź, S.; Ewertowski, M.W.; Piekarczyk, J. Applications of unmanned aerial vehicle (UAV) surveys and Structure from Motion photogrammetry in glacial and periglacial geomorphology. *Geomorphology* **2021**, *378*, 107620. [CrossRef]
28. Taylor, L.S.; Quincey, D.J.; Smith, M.W.; Baumhoer, C.A.; McMillan, M.; Mansell, D.T. Remote sensing of the mountain cryosphere: Current capabilities and future opportunities for research. *Prog. Phys. Geogr. Earth Environ.* **2021**, *45*, 931–964. [CrossRef]
29. Science Press. The investigation team on utilization of snow and ice resources in mountain regions, the Chinese Academy of Sciences. In *Report of Investigations of Glaciers in the Qilian Mountains*; Science Press: Beijing, China, 1959. (In Chinese)
30. Liu, S.; Guo, W.; Xu, J. *The Second Glacial Catalogue Data Set of China (v1.0)*; National Cryosphere Desert Data Center: Lanzhou, China, 2019. [CrossRef]
31. Benoit, L.; Gourdon, A.; Vallat, R.; Irarrazaval, I.; Gravey, M.; Lehmann, B.; Prasicek, G.; Graff, D.; Herman, F.; Mariethoz, G. A high-resolution image time series of the Gorner Glacier-Swiss Alps-derived from repeated unmanned aerial vehicle surveys. *Earth Sys. Sci. Data* **2019**, *11*, 579–588. [CrossRef]
32. Shi, Y. *Glaciers and Their Environments in China-the Present, Past and Future*; Science Press: Beijing, China, 2000. (In Chinese)
33. Shi, Y. *Concise Glacier Inventory of China*; Shanghai Popular Science Press: Shanghai, China, 2008.
34. Yang, W.; Zhou, S.; Chiyuki, N.; Wang, X.; Wang, J. The stage-division and environmental significance of moraine in Qiyi glacier, Qilian Shan. *J. Lanzhou Univ. Nat. Sci.* **2006**, *42*, 12–15.
35. Duan, K.; Yao, T.; Wang, N.; Shi, P.; Meng, Y. Changes in equilibrium-line altitude and implications for glacier evolution in the Asian high mountains in the 21st century. *Sci. Chin. Earth Sci.* **2022**, *65*, 1308–1316. [CrossRef]
36. Che, T.; Hao, X.; Dai, L.; Li, H.; Huang, X.; Xiao, L. Snow Cover Variation and Its Impacts over the Qinghai-Tibet Plateau. *Bull. Chin. Acad. Sci.* **2019**, *34*, 1247–1253. (In Chinese with English Abstract)
37. Brun, F.; Berthier, E.; Wagnon, P.; Kääb, A.; Treichler, D. A spatially resolved estimate of High Mountain Asia glacier mass balances from 2000 to 2016. *Nat. Geosci.* **2017**, *10*, 668–673. [CrossRef]
38. Wang, K.; Jing, Z.; Wu, Y.; Deng, Y. Latest survey and study of surface flow features of the Qiyi Glacier in the Qilian Mountains. *J. Glaciol. Geocryol.* **2014**, *36*, 537–545. (In Chinese with English Abstract)
39. Domecq, A.; Gourmelen, N.; Gardner, A.S.; Brun, F.; Goldberg, D.; Nienow, P.W.; Trouvé, E. Twenty-first century glacier slowdown driven by mass loss in High Mountain Asia. *Nat. Geosci.* **2019**, *12*, 22–27.
40. Anderson, R.S.; Anderson, L.S.; Armstrong, W.H.; Rossi, M.W.; Crump, S.E. Glaciation of alpine valleys: The glacier–debris-covered glacier–rock glacier continuum. *Geomorphology* **2018**, *311*, 127–142. [CrossRef]
41. Moore, P.L. Numerical Simulation of Supraglacial Debris Mobility: Implications for Ablation and Landform Genesis. *Front. Earth Sci.* **2021**, *9*, 710131. [CrossRef]
42. Mölg, N.; Ferguson, J.; Bolch, T.; Vieli, A. On the influence of debris cover on glacier morphology: How high-relief structures evolve from smooth surfaces. *Geomorphology* **2020**, *357*, 107092. [CrossRef]