Optical remote sensing monitoring and dynamic analysis of ice avalanche hazards in Midui glacier of Southeast Tibet

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Abstract. Under the background of global warming, glaciers instability in Southeast Tibet, where glaciers are widely distributed, are prominent. Based on the medium-high resolution multi-source satellite data, such as Gaofen-1 (hereinafter referred to as "GF-1"), Gaofen-2 (hereinafter referred to as "GF-2"), and Unmanned Aerial Vehicle (hereinafter referred to as "UAV"), aerial photography, the basic characteristics and changes in ice avalanche hazards in Midui glacier are studied. We summarize the optical remote sensing characteristics of Midui glacier, analyze the dynamic change trend of ice fissures and glacial lake area since 2001, and discuss the possibility of ice avalanche and break of glacial lake in Midui glacier combined with regional geological environment background. The study results showed 6 potential ice avalanches, 15 glacial lakes, 3 moraines, and 21 collapses in Miduiqiu. Since 2001, the scale of potential ice fissures and the area of glacial lakes have increased, and they accelerated in 2014 and 2017, respectively. As a result of the steep-slow-steep ladder-like terrain, a large number of ice fissures at the end of the glacier, numerous loose collapse deposits on both sides of the channel, the strong tectonic activity in Jiali fault zone, and other factors, Midui glacier is likely to destabilize and cause ice avalanche, forming a disaster chain of ice avalanche-glacial lake outburst-debris flow, which directly threatens the Midui village, Midui glacier tourism distribution center, and National Highway 318. If the debris flow moves to the Midui gully mouth and blocks the Parlung Zangbo River, it will form a large disaster chain. Based on the research results, the movement possibility of Midui glacier should be closely monitored for a long time to provide basic information for ice avalanche disaster research and prevention of such events in Southeast Tibet.

Keywords: optical remote sensing monitoring; ice avalanche disaster; Midui glacier; Southeast Tibet

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1. Introduction

Under the background of global warming, glaciers in the Tibetan Plateau, which is a sensitive area of global climate change, have shown an abnormal state in recent years. The amount of ice loss and area shrinkage in Southeast Tibet is the largest, and they are mainly manifested as glacier ablation acceleration and instability; the frequencies of ice avalanches that are closely related to glacier movement increase year by year\textsuperscript{[1, 2]}. Midui glacier is one of the most important marine glaciers in Southeast Tibet. Since the Little Ice Age, Midui glacier has experienced at least four fluctuations, namely, AD 1767 (TM1-LM1), AD 1875 (LM2), AD 1924 (LTM-LM3), and AD 1964 (TM2)\textsuperscript{[3]}. In 1988, glacier instability caused a disaster chain. On July 15, 1988, about 3.62 × 10\textsuperscript{5} m\textsuperscript{3} ice body at the leading edge of Midui glacier collapsed into Guangxie Lake, and the lake water rose by an average of about 1.4 m. The strong glacial lake surge caused the final moraine, which infiltrated the glacier and resulted in its poor resistance to stability and collapse. The maximum peak flow was 1.27 × 10\textsuperscript{3} m\textsuperscript{3}/s, the peak lasted for 0.5 h, and the collapse water was 5.40 × 10\textsuperscript{6} m\textsuperscript{3}. The debris flow, which was caused by the collapse of Guangxie Lake, dipped directly into Parlung Zangbo River and formed a barrier lake. The upstream water level rose rapidly and collapsed after 2.5 h, causing serious damage to National Highway 318 and destroying 18 bridges. A total of 42 km of roads were damaged by water, and the traffic was interrupted for half a year. The scope of disaster influence was evident. Therefore, studying the dynamic changes in glaciers will help in the evaluation of the possible ice avalanche and glacial lake outburst in the future and provide basic data for disaster prevention and mitigation. However, limited studies focused on the basic characteristics and changes in the Midui glacier avalanche hazard. Optical remote sensing monitoring and change analysis of the Midui glacier avalanche hazard based on medium-high resolution multi-source satellite data has practical significance.

2. Overview of the Study Area

2.1. Geographical position

Midui glacier is located in Miduigou watershed between Bomi and Ranwu and belongs to Yupu Township, Bomi County. The glacier is about 8 km from National Highway 318 and about 2 km from Midui village. Midui glacier is one of the most important marine glaciers in Tibet. The drainage area of Miduigou is about 122.9 km\textsuperscript{2}, the highest and lowest points are about 6334 and 3604 m, respectively, the height difference is about 2730 m, the main gully length is about 16 km, and the longitudinal gradient is about 170\%. The Miduigou runs from north to south into the Parlung Zangbo River, in which the gully mouth is located at the left bank of Palalung Zangbo River. The origin of Miduigou is Midui glacier, and the glacier area accounts for about 21\% of the total drainage area. The end of the glacial tongue is Guangxie Lake. The Midui glacier is roughly spread north-south, with a length of 10.2 km and an area of about 25.8 km\textsuperscript{2}. This glacier is a compound valley glacier formed by ice waterfalls with two tributaries (altitude: 4100 m) that intersect to form a unified ice tongue. The gully mouth Midui and the middle of the gully are Midui glacial tourism distribution center and Midui village location, respectively. With Midui village as the boundary, the north ditch of Midui village is deep and narrow, and the south of Midui village is a typical glacier U-shaped valley.

2.2. Optical remote sensing characteristics of Miduigou
According to optical satellite images, 15 glacial lakes, 6 potential ice avalanches, 3 moraines, and 21 collapses occurred in Miduigou (Figure 1).

**Figure 1.** Remote sensing interpretation map of Miduigou.
1: Collapse boundary and main collapse direction; 2: potential ice avalanche; 3: glacial lake; 4: moraine; 5: watershed boundary; 6: number

Among the 15 glacial lakes, the smallest and largest area measure 61 and $2.38 \times 10^5$ m$^2$, respectively, and the total area is $2.67 \times 10^5$ m$^2$ (Table 1). Glacial lake is mainly distributed in moraine deposits, with the lowest elevation situated at 3775 m and the highest at 4651 m, whereas elevation is mainly concentrated at 3800–3900 m.
Table 1. Glacial lake statistics of Miduigou

| name | elevation (m) | area (m²) |
|------|---------------|-----------|
| BH01 | 3776          | 238295    |
| BH02 | 3827          | 6733      |
| BH03 | 3849          | 4282      |
| BH04 | 3880          | 309       |
| BH05 | 3877          | 565       |
| BH06 | 4651          | 13422     |
| BH07 | 3775          | 654       |
| BH08 | 3778          | 370       |
| BH09 | 3779          | 856       |
| BH10 | 3782          | 61        |
| BH11 | 3787          | 125       |
| BH12 | 3788          | 261       |
| BH13 | 3806          | 1086      |
| BH14 | 3910          | 172       |
| BH15 | 3902          | 197       |

Among 6 potential ice avalanches (Table 2) in Miduigou, the minimum area is about $9.54 \times 10^4$ m², the maximum is about $6.64 \times 10^6$ m², and the total area is $1.52 \times 10^7$ m². Potential ice avalanches are mainly distributed at the back of Miduigou. The elevation of the front edge of potential ice avalanches is 4032–5349 m, the elevation of the back edge is 5102–6036 m, the elevation difference between the front and back edges is 109–2004 m, and the elevation difference between the back edge and the gully is 1498–2432 m.

Table 2. Potential ice avalanche statistics of Miduigou

| name | area (m²) | elevation of front edge (m) | elevation of back edge (m) | elevation difference between front and back edge (m) | elevation difference between back edge and the gully (m) |
|------|-----------|----------------------------|---------------------------|------------------------------------------------------|-------------------------------------------------------|
| BC01 | 6637349   | 4032                       | 6036                      | 2004                                                 | 2432                                                  |
| BC02 | 6624639   | 4075                       | 5736                      | 1661                                                 | 2132                                                  |
| BC03 | 675137    | 4962                       | 5208                      | 246                                                  | 1604                                                  |
| BC04 | 95396     | 5349                       | 5458                      | 109                                                  | 1854                                                  |
| BC05 | 261570    | 5155                       | 5287                      | 132                                                  | 1683                                                  |
| BC06 | 891479    | 4574                       | 5102                      | 528                                                  | 1498                                                  |

The main source types are moraine and collapse in Miduigou (Table 3). Three moraines with a total area of about $5 \times 10^6$ m² are mainly distributed in the main ditches at the leading edge of the glacier. A total of 21 collapses, distributed in clusters, had a total area of about $1.34 \times 10^7$ m². The area of collapse accumulation is about $4.24 \times 10^6$ m², and the area of collapse source area is $9.12 \times 10^6$ m², which is mainly distributed in the high and steep slopes of left and right sides of the main ditch.
3. Dynamic Change and Chain Structure Analysis of Ice Avalanche Hazards
Based on the optical remote sensing data of GF-1, GF-2, and UAV aerial photography in Miduiogu from 2001 to 2020, the developments of ice fissures and glacial lakes were compared and analyzed.

Table 3. Moraines and collapse statistics of Miduigou

| name       | disaster types | provenance type    | area (m²) |
|------------|----------------|--------------------|-----------|
| B01        | collapse       | collapse source area | 248912   |
| B02        | collapse       | collapse source area | 704412   |
| B01-B02    | collapse       | collapse accumulation | 104592  |
| B03        | collapse       | collapse source area | 1333013  |
| B04        | collapse       | collapse source area | 1161305  |
| B05        | collapse       | collapse source area | 270875   |
| B06        | collapse       | collapse source area | 181326   |
| B07        | collapse       | collapse source area | 744344   |
| B08        | collapse       | collapse source area | 135879   |
| B09        | collapse       | collapse source area | 196586   |
| B10        | collapse       | collapse source area | 85941    |
| B03-B10    | collapse       | collapse accumulation | 2516994  |
| B11        | collapse       | collapse source area | 242568   |
| B12        | collapse       | collapse source area | 1353157  |
| B13        | collapse       | collapse source area | 651809   |
| B14        | collapse       | collapse source area | 376184   |
| B12-14     | collapse       | collapse accumulation | 781451  |
| B15        | collapse       | collapse source area | 470547   |
| B16        | collapse       | collapse source area | 384580   |
| B17        | collapse       | collapse source area | 121140   |
| B15-B17    | collapse       | collapse accumulation | 462435  |
| B18        | collapse       | collapse source area | 182826   |
| B19        | collapse       | collapse source area | 191247   |
| B18-19     | collapse       | collapse accumulation | 117820  |
| B20        | collapse       | collapse source area | 47064    |
| B21        | collapse       | collapse source area | 40388    |
| BQW01      | \   | moraine       | 543096   |
| BQW02      | \   | moraine       | 4048942  |
| BQW03      | \   | moraine       | 406667   |
At the end of the potential ice avalanche BC02, the number of ice fissures increased gradually from 2001 to 2014, and the number and size increased rapidly from 2014 to 2020. The original small fissures penetrated into large fissures, increasing the instability of the end ice body (Figure 2).

![Figure 2. Comparison of multiphase remote sensing images of ice fissures (BC02) in Midui glacier.](image)

a. Image captured on November 14, 2001; b. image captured on February 12, 2013; c. image captured on November 8, 2014; d. image captured on February 7, 2015; e. image captured on December 12, 2017; f. image captured on October 31, 2020. The red arrow points to an ice fissure.

The water area of the glacial lake BH01 also showed a regular change in 19 years. From 2001 to 2017, it showed a gradually increasing trend. From 2017 to 2020, the water area increased significantly. Thus far, BH01-03 and BH07-13 have penetrated into a large glacial lake (Figures 3a–3f).

The dynamic change in glacial lake BH14 was evident. A small number of annular ice fissures were observed in 2001. As ice fissures increased and gathered glacier melt water, glacial lakes BH14 and BH15 formed initially in 2014–2015. In 2017, the scale of annular ice fissures increased significantly, and the collapse rate of moraine was greater than that of glacier melt water, which caused the glacial lake surface decreased. In 2020, given the acceleration of glacier melt, glacial lake BH14 and BH15 have penetrated into a large glacial lake. In addition, the annular ice fissures expanded to the periphery and connected with glacial lake BH01 (Figures 3g–3l).
Figure 3. Comparison of multiphase remote sensing images of glacial lakes (BH01 and BH14) in Midui glacier.

(a and g) Image captured on November 14, 2001; (b and h) image captured on February 12, 2013; (c and i) image captured on November 8, 2014; (d and j) image captured on February 7, 2015; (e and k) image captured on December 12, 2017; (f and l) image captured on October 31, 2020. a–f represent BH01; g–l represent BH14 and BH15.

In summary, the potential ice avalanche fissures in Miduigou increased from 2001 to 2020, and the instability increased. Glacier melting speed and glacial lake water area gradually expanded. Especially after 2017, the above changes have intensified. Based on the analysis of optical remote sensing images, Midui glacier is currently in an unstable state. A chain disaster of ice avalanche-glacial lake
outburst-debris flow can form a unit that will directly threaten the Midui village and Midui glacier tourism distribution center. In addition, a large disaster chain will form if the debris flow moves to the Midui gully mouth to block the Palalung Zangbo River.

4. Relationship between Ice Avalanche Hazards and Regional Geological Environment

4.1. Stepwise terrain conditions

The Midui glacier development area is a typical stepwise terrain, which is conducive to the formation of ice avalanches (Figure 4). The steep area in the upper part of the glacier easily results in ice and snow collapse, which causes the potential ice avalanche to collapse continuously. The gentle area in the middle is conducive to the accumulation of small-scale collapsed ice, which accumulates a large amount of material sources for the re-ice avalanche. The relatively steep area in the lower part provides terrain conditions for the rapid decline of the ice avalanche to Guangxie Lake. Once large-scale breakups occur in the upper part of the ice, the ice avalanche will wipe out the ice in the middle gentle area and the moraine in the lower part and form a large-scale glacial debris flow into the glacial lake at high speeds, which may lead to a sharp rise in the water level of the glacial lake and outburst.

4.2. Collapse accumulation state on both sides of the channel

A total of 21 collapse deposits exist between Guangxie Lake and National Highway318 in Miduigou. These deposits become loose and fan-shaped along both sides of the gully and are produced in groups. The collapse deposits result in the narrowing of Midui gully channel in most areas, and the recent collapse was evident. Once Guangxie Lake breaks down, it will provide abundant material sources for debris flow (Figure 5).
4.3. Types of glacier

Midui glacier is a marine glacier belonging to the Indian Ocean monsoon subtropical mountain climate zone and is one of the most concentrated areas of marine glacier distribution and development in China[4]. Compared with continental glaciers, marine glaciers are prone to accelerated ablation due to the influence of global temperature rise. In addition, such glaciers move fast and cover long distances[5]. According to the observation data in the warm season of 1990, the Midui glacier ablation amount reached $2.5 \times 10^7$ m$^3$ in June to August, accounting for 38% of the total flow of hydrological section at the mouth of Guangxie Lake in the same period. The velocity of the glacier melting zone is 5.62 m/a to 12.8 m/a, and the general rule is that the velocity on both sides of the glacier is less than that in the middle, the velocity near the end is less than that in the middle, and the velocity on the upper wall of the ice sandwich structure is greater than that on the lower wall[6].

4.4. Ice fissures

Numerous fissures were found on the surface of Midui glacier, and they were concentrated at the end of the broken glacier. From 2001 to 2020, the number of ice fissures in potential avalanches gradually increased. From 2014 to 2020, the growth rate of the number and scale of ice fissures accelerated (Figures 3c–3f). The original small fissures had penetrated into large ones, increasing the instability of the end ice. The sharp increase in the scale of fissures in potential avalanches may lead to the continuous increase in flow water in glaciers and the continuous decrease in friction force. Under the action of gravity, an avalanche will be triggered when the driving force of the downward movement of glaciers is greater than the static friction force.

4.5. Structure condition
The study area belongs to Jiali fault zone, which is located in the core of the convergence and collision between the Eurasian and Indian Ocean plates. This area is the most complex in the southeast margin of the Tibetan Plateau. Jiali fault zone extends along the Yigong Zangbo River valley, which heads toward northwest by west in the west of Tongmai. The zone is divided into northern and southern branches in the east of Tongmai. The northern branch is mainly distributed along the southwest side of Palalung Zangbo River, and it passes through the south side of Ranwu Lake to Guyu Township and extends southeastward. The southern branch continues to extend southeastward after passing through Tongmai. This branch is distributed along Gongri Gabu River after Galongla and composed of multiple faults [7]. Jiali fault zone is not an entire right-lateral strike-slip fault, and its movement properties and rates have piecewise differences in terms of various structural parts. Midui glacier is located in the northern branch of the fault zone, and the fault is roughly distributed along the transition area of Guangxie Lake and ice tongue. The current movement is characterized by weak left-lateral tension [7, 8]. In addition, Jiali fault zone shows a strong uplift on the whole, and the uplift on the south side is stronger than that on the north side [9]. The strike-slip and tensile movement characteristics of Jiali fault provide stress conditions for the expansion of ice fissures, which make the ice body at the end of the glacier more broken. The differential uplift of the south and north sides creates topographic conditions for the fracture of potential ice avalanches. The underlying bedrock of Midui glacier is Paleo-Mesoproterozoic Demala Group Complex, and the lithology is mainly schist, quartz schist, and gneiss. The gneiss in the area is very developed, and bedrock landslide can be possibly induced due to ice avalanche (Figure 6).

**Figure 6.** Simplified geological map of Miduigou (after the 1:250 000 geological map).

1: Glacier coverage area; 2: glacier deposits; 3: granodiorite; 4: monzonitic granite; 5: Mali formation; 6: Laigu formation; 7: Nuocuo formation; 8: Gongbushan formation; 9: Demala Group Complex; 10:
Stratigraphic boundary; 11: Jiali fault; 12: Miduigou watershed boundary

5. Conclusion
(1) Based on the hue, shape, texture, shadow, and other characteristics of the optical remote sensing image, 6 potential ice avalanches, 15 glacier lakes, 3 moraines, and 21 collapses were identified in Midui glacier.
(2) Since 2001, the scale of ice fissures and the water area of ice lakes have increased. In 2014 and 2017, the scale of ice fissures and ice lake showed accelerated growth.
(3) Under the combined action of various factors, such as the steep-slow-steep ladder-like terrain, a large number of ice fissures at the end of the glacier, numerous loose collapse deposits on both sides of the channel, and strong tectonic activity of the Jiali fault zone, Midui glacier may be unstable and cause ice avalanche and will form a chain disaster of ice avalanche-glacial lake outburst-debris flow.

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