Monitoring of ice avalanche using aerospace and ground information

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Abstract. The article presents the data on ice avalanche in the mountains of the Caucasus and the Alps, obtained as a result of the satellite images’ interpretation in different years. Ice avalanche of hanging glaciers, end parts of glaciers, sections of glaciers on the steep steps of the primary relief, and sections of icefalls were recorded. The activity of ice avalanche in the summer period was revealed. The ejection range of the ice blocks of the Trift glacier in Switzerland in 2017 reached 1,050 m. Ice glaciers were noted on the icefall sections on the Irik, Terskol, Garabashi glaciers (Elbrus city) with an ejection range of up to 330 m. The most active were the rock-stone caving of the hanging glaciers and underlying bedrock in the Kolka glacier comb in 2002 and 2003 and the ice collapses of the advancing glacier on the slope of Kazbek in 2015-2019. Annual ice avalanche from the Bezengi wall marked.

1. Introduction

Ice slips (avalanches) are one of the most destructive slope processes associated with glaciers. In the Alps throughout history, catastrophic collapses of glaciers have repeatedly occurred. In [1], the following data on ice avalanche are given: 1) on August 31, 1597, ice avalanche from the Homattu glacier destroyed the village of Eggen with 81 inhabitants, 2) on August 18, 1792 and September 11, 1895, ice avalanche from the Altels glacier up to 4 million m$^3$ with victims (4 and 6 people) and cattle death [2], 3) on August 30, 1965 as a result of a collapse from the Allalin Glacier with a volume of 2 million m$^3$ 88 people died - the builders of the dam (Figure 1) [3].

Figure 1. The collapse of the Allalin Glacier (photo 1965. https://www.swissinfo.ch/eng/mountain-tragedy_remembering-mattmark/41625894)
Ice avalanche can occur as a result of bedrock collapses underlying the glaciers, or are caused by the rock formations’ impact on glaciers. In these cases, ice-stone landslides occur, for example, the landslides of the Devdorak glacier [4]. In winter, ice slips are often represented by ice-snow avalanches. To assess the destructive impact on the objects in the mountains, information is needed on the ice avalanche statistics in the past, as well as identification of glaciers sections with the potential threat of ice avalanche based on comparisons with similar sites where there were previously collapses in other mountainous regions.

Currently, information about ice avalanche can be obtained as a result of the aerospace information analysis at different times available on different Internet resources, as well as in the messages from social networks.

2. Materials and methods
The studies were conducted based on the interpretation of satellite images, aerial photographs, analysis of photographs and videos, and survey materials. To assess changes in the Kogutai glacier, we used old photographs of 1884, 1932, 1942, and an aerial photograph of 1957. We used satellite images of the Sentinel 2A satellite (10 m resolution) for the period 2015–2019 from the site https://apps.sentinel-hub.com/eo-browser/, the satellite images of WorldView-1 satellites with a resolution of 0.5 m from February 11, 2010 (provided by SCANEX), IRS 1D with a resolution of 5.8 m from September 30, 2004 and August 24, 2005 (provided by the Moscow State University Geoportal), Resource DK dated August 17, 2008 with a resolution of 1.8 m (provided by Planet Research Center), a Quick Bird satellite image from September 25, 2002 (a version of the image from Google Earth) with a spatial resolution of 0.7 m, WorldView 2 from 08/20/2010 0.5 m resolution from the Bing Maps Internet resource. The satellite images were interconnected in the WGS84 coordinate system in the UTM projection at the reference points. Old photographs and aerial photographs were tied to satellite imagery at reference points.

The facts of ice avalanche were revealed visually in comparison with different-time images in the ArcGIS program and in the created GIF animations. Based on the identified contours of the ice landslides, vector layers were built and their morphometric parameters were determined.

3. Research results

3.1. Ice avalanche in the Alps
In [5], the data on the collapse on the Trift Glacier (Vaysmis) on September 10, 2017 are presented. Figure 2 shows the section of the glacier before and after the collapse in Sentinel 2A satellite images and in the video frame https://www.youtube.com/watch?v=OCEzAKtXm1c.

Figure 2. The collapse on the Trift Glacier (Vaysmis): a - September 9, 2017, b - September 29, 2017, c - September 10, 2017. The black arrow shows the direction to the North (as in other figures)
Observations of the Trift glacier were carried out with the aim of warning about a possible collapse of the resort town population in the Zaas valley, located 4 kilometers from the glacier.

It was revealed that at a certain moment the glacier speed increased and reached 2.5-3.5 m / day. Therefore, 220 people from the village were urgently evacuated on September 9 - a day before the collapse. And indeed, the collapse has occurred. The work [5] provides the data on the volume of 400,000 m³. From the satellite images, we determined that the affected area was 0.37 km², and the ice throw distance range is 950-1050 m. As a result of the satellite images’ further analysis, it was revealed that in 2018, the Fletchhorn glacier comb adjacent to the Trift glacier also experienced ice avalanche (Figure 3), the ice throw distance range of which was 970 m.

There were several ice avalanches on the Fletchhorn Glacier, and they occurred in September, as on the Trift Glacier. Ice avalanches on the Fletchhorn glacier were in 1971 and 1989. [1]. In terms of ice throw distance, the collapses on the Trift and Fletchhorn glaciers are comparable to the collapse on the Allalin glacier (Figure 1), but they are significantly inferior to the collapse from the Altels glacier (about 3700 m) in 1895.

**Figure 3.** Collapse on the Fletchhorn Glacier in 2018: a – 15.08.2018, b – 09.09.2018, c – 19.09.2018

3.2 Assessment of the ice avalanche threat from the Kogutai glacier in the Elbrus region

In [6], it was concluded that there is a high degree of ice avalanche threat on the basis of the identified transverse crack in the Kogutai glacier tongue, as well as the information from [7], which mentions the fact of the avalanche disappearance in 1946 from the left side of the Kogutai glacier tongue. In support of the fact that the avalanche disappeared in 1946, a comparison of photographs of 1884 and 1932 has been carried out, where in the photograph of 1932 there is no ice mass on the left side of the glacier, but it is in the photograph of 1884. And in the text of [7] it is noted that in September 1946 the left side of the glacier collapsed. We have analyzed the old photographs by linking them to the satellite imagery and aerial photography (Figure 4).
Figure 4. The ending of the Kogutai glacier tongue in old combined photographs and aerial photographs: a – photo by M. Deshi 1884, b – photo E.N. Lukasheva, c – the photo 1942 (from German film), d – aerial view 1957.

The photos by M. Deshi were used (https://fotki.yandex.ru/next/users/humus777/), E.N. Lukasheva [6], as well as the scan from the pre-sale demo version of the German film of 1942 (https://i.pinimg.com/736x/8b/a3/36/8ba336dc87c4268210a3cd7ea333b260--caucasus-mountains-edelweiss.jpg). As a result of the photographs’ analysis, it can be concluded that the area exposed from ice in 1932 has a transverse protrusion (ridge), which would be an obstacle to the ice mass collapse (shown by an arrow on the fragments b, c). In 1942, the left part of the glacier tongue was completely freed of ice, and by 1957 the longitudinal rocky ledge was completely freed of ice, which in 1942 was partially bare, which also did not contribute to the ice collapse. Consequently, there were no clear signs of the ice large mass disappearance as a result of the collapse. The reduction in the area of the glacier occurred both along the front and from the sides. The left side of the glacier receded faster, since its feeding area is at the lower elevations than the right.

Earlier in [8], the conditions for the transverse cracks’ formation on the glacier for the period 1957-2016 were analyzed, and it was concluded that the transverse cracks on the Kogutai glacier body arise periodically in different areas and are confined to the primary relief ledges’ edges in combination with a certain thickness and width of the glacier. However, there is no reason to consider their appearance as a sign of the glacier collapse threat. Moreover, the main part of the glacier is sandwiched in a longitudinal recess with uneven edges, which create additional friction, preventing the ice mass collapse. The studies have shown that there is no threat of collapse of the intensely degrading Kogutai glacier.

3.3 Ice avalanche of hanging glaciers and ice walls
In the works devoted to the descent of the Kolka glacier in 2002, the data are presented on the numerous collapses of hanging glaciers from the slope of the town of Dzhimaraykhol, which continued before and after the descent of the Kolka glacier. According to [9], the volume of collapsing hanging glaciers before the Kolka glacier collapsed was 18 million m$^3$. In the first years after the Kolka glacier disappeared, its restoration took place actively. At the same time, the former right tributary quickly attacked. The authors of [10, 11] found that the reasons for the rapid advance of the former right tributary in the Kolka glacier are the best condition for its nutrition due to snow drift from the upstream plateau, as well as the ice masses’ sliding left after the Kolka glacier descended into the trough on the slope as a result loss of support from the Kolka glacier. According to our data, the main cause of the right tributary onset in the Kolka glacier in 2006 was the collapse of the hanging glacier (Figure 5, a, b).
Figure 5. Ice avalanche of hanging glaciers and ice walls: a – space image QuickBird 25.09.2002, b – space image DK resource 17.08.2008, c – space image WorldView2 20.08. 2010, space image Sentinel 2A 13.08.2019.

The bulk of the hanging glacier massif (blue border on fragment a) with a volume of about 1.5–2.0 million m³ in the period 2005–2006 in the form of landslides of ice and bedrock, the base collapsed on the former tributary in the Kolka glacier, causing it to move 200 m. With yellow dashed lines on the fragment b the boundaries of the right tributary in the Kolka glacier in 2004 and 2005 are shown below, and at the top is the contour of a collapsing hanging glacier, the blue line is the border of the right tributary in the Kolka glacier in 2008. As a result of the study, hanging glaciers’ collapses were recorded only in the Kolka glacier comb. In the form of the ice-stone landslides, they continue there to the present.

Widespread ice avalanche on the steep ice walls sections - Mount Donguz-Orunbashi, Besengi Wall and other sections. Fig. 5 (fragments c and d) shows a fragment of the Bezengi wall from the top to the foot (fragment c) with an impact zone of one ice avalanche and a section of the ice avalanche deposition zone with a length of 3500 m at the foot of the wall (fragment d). From the Bezengi wall in summer, including September, up to 20-30 ice and ice-snow avalanches occur each year. In this section, the material of ice avalanches was analyzed using the space images of detailed resolution. Figure 5 (fragment c) shows a section of one avalanche deposits’ cone, on which the blocks of ice reach 8–10 m across. The space imagery avalanches can serve as the basis for assessing their risk for tourists, climbers and rescuers.

3.4 Ice crashes on the Bodorku glacier (valley of the Gara-Auzu-Su river in the Chegem river basin) in 2018.

As a result of the multi-temporal satellite images’ analysis, the ice avalanche fact from the Bodorku glacier was revealed (№ 21 on the glaciers scheme [12]) in the Chegem river basin (Figure 6).
Figure 6. Ice avalanche from the Bodorku glacier (fragments of space images Sentinel 2A):

\[ a \sim 29.06.2018, \ b \sim 29.07.2018, \ c \sim 07.10.2018, \ d \sim 29.07.2019 \]

As a result of the satellite images’ GIF-animation analysis, it was revealed that before the collapses, the system of cracks was rebuilt in the glacier tongue, and its movement was noticeably accelerated. The landslides occurred from late July to mid-October 2018, first from the protruding part of the glacier tongue end with a width of about 80 m. Then the ice avalanche covered the entire left part of the glacier tongue. The ice masses’ throw distance range was 450 m to the border of the lake with an area of 10 thousand m$^2$. Perhaps a part of the ice mass fell into the lake and caused a wave in it, since after the collapse, the channel of the watercourse flowing out of the lake became more noticeable in the pictures. In just a year with landslides, the area of the glacier decreased by 12 thousand m$^2$, while from 2017 to 2018 its area was reduced by 5 thousand m$^2$. In Fig. 6 (fragment \(a\)) the red line shows the glacier’s border after landslides, the blue line shows the glacier’s border in June 2018. It could be assumed that if the ice collapse mass were greater, the whole lake could be splashed out with a flash flood.

3.5 Collapses from the advancing former right tributary of the Devdoraki Glacier in 2015-2019.

After the ice-stone collapse in the Devdorak Gorge in 2014 [4], a significant part of the recharge zone of the former right-hand tributary of the Devdorak Glacier was found under the ice avalanche deposits. Due to the additional load, the glacier began to advance, and its left tongue emerged on the Devdorak glacier surface, having traveled more than 400 m. The right tongue and the stones composing its landslide cover having stepped on a steep rocky ledge, became the source of numerous ice avalanches (Figure 7).

The first ice avalanche started in summer of 2015 and then continued for more than three years, almost ending at the end of 2019. During this period, the axial and left parts of the glacier tongue end practically remained in one place. The right part of the glacier tongue advanced 145 m along a relatively shallow section. The ejection range of the masses of ice and rocks fell to 700-800 m.
Figure 7. Collapses of the advancing former right tributary of the Devdoraki Glacier (fragments of space images Sentinel 2A): a – 20.10.2015, b – 27.02.2016, c – 07.04.2016, d – 20.04.2016, e – 05.04.2017, f – 14.10.2017, g – 16.12.2017, h – 24.02.2018, j – 30.04.2018, k – 15.05.2019. The blue line is the boundary of the glacier, the red line is the zone of defeat by ice avalanche.

3.6 Ice avalanche from the icefalls on the Elbrus glaciers

On February 14, 2019, Instagram posted a video of instructor Osman Jappuyev (https://www.instagram.com/os.dja/), dated February 13, which shows the consequences of the ice avalanche site collapse on the Garabashi glacier. After that, there were a lot of messages on the Internet containing the following phrases: “A glacier fell off Elbrus ..., A glacier on Elbrus may descend into the KBR ..., The ice slope of Elbrus went somewhere ..., A huge glacier descended from the slope of Elbrus. ...”. The authors investigated this and other cases of ice avalanche on the Elbrus glaciers using satellite images (Figure 8).
Figure 8. Ice avalanche on the Elbrus glaciers: a - ice avalanche on the Irik glacier (space image Sentinel 2A 04.06.2018), b – ice avalanche on the Terskol glacier (space image Sentinel 2A 28.01.2017), c – ice avalanche on the Garabashi glacier (video frame 13.02.2019), d – ice avalanche on the Terskol glacier (space image WorldView-1 11.02.2010), e – collapse of ice on the Garabashi glacier (space image Sentinel 2A 14.02.2019)

Ice avalanche from the icefall of the Garabashi glacier (Figure 8, c, e) turned out to be far from the largest, both in range (about 130 m) and in the affected area (1.3-1.5 thousand m²). On the Irik glacier, a collapse was recorded with a throw distance range of more than 280 m (Fig. 8, a), and in the long section of the icefall on the Terskol glacier, there were ice avalanches with a throw distance range of ice masses of about 330 m (Fig. 8, b). Such ice avalanches can cause a threat to tourists, climbers and skiers. In August 2004, one tourist died and one suffered from the ice avalanche on the Irik glacier. (http://www.mountain.ru/article/article_display1.php?article_id=139).

Summary
The study of ice avalanches in different mountainous regions showed that this is a fairly common and dangerous phenomenon. Collapses can occur both on the glaciers’ sections ending on steep rocky ledges, and on other glaciers’ sections where there are such ledges. Collapses of hanging glaciers are mainly noted in the Kolka glacier comb, and the collapses from the glaciers’ cliffs on the ice walls are a frequent phenomenon that should be taken into account when conducting the tourist routes and rescue operations in the mountains. Ice avalanches can be one-time, and continue for several days, months and years, depending on the dynamics of the glacier. Large avalanches can lead to the glaciers’ onset. Ice avalanche on the ice can be dangerous when laying the ski slopes and in the recreational complexes and resorts’ operation. Monitoring of ice avalanche using aerospace information makes it possible to identify the hazardous areas and determine the ice avalanche activity when assessing the risks for the population and during the construction and operation of the facilities in the mountains.

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