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Letter

A rapid glacier surge on Mount Tobe Feng, western China, 2015

Kelayayilake Glacier, located on Mount Tobe Feng, western China, surged dramatically during the spring of 2015, accompanied by a glacier avalanche. By July 2015, a glacier area of 8.9 km^2, length, 12 km had been influenced by the surge event. The surge and avalanche swallowed 1000 ha of grazing meadow and damaged 61 herdsmen's houses with hundreds of livestock missing in Akto County, Xinjiang. It caused no human casualties. Glacier surges occur regularly in western China. However, a large-scale surge like that of Kelayayilake Glacier is rare (Quincey and others, 2015). Because most surges take place in rural areas, they often remain unnoticed until they become a hazard, damaging local property.

Glacier surges are short-term events during which a glacier can advance substantially, reaching velocities up to tens or hundreds of times greater than normal (Meier and Post, 1969; Clarke, 1987; Raymond, 1987; Harrison and Post, 2003). Surges can be closely related to other glacial hazards, such as glacial lake outburst floods and debris flows. Global warming has contributed to the retreat of glaciers in many mountainous regions (IPCC, 2014). At the same time the upstream regions of glaciers are becoming wetter, which makes the glaciers more prone to surge. Thus research into glacier surges has gained new attention in the light of global warming (Kargel and others, 2005; Dunse and others, 2015).

Mount Tobe Feng (7530 m a.s.l.), a peak of Kongur, within the West Kunlun Mountains (38°37′N; 75°12′E), is one of the three highest mountains in the southeastern part of the Pamir Plateau. Kelayayilake Glacier is the largest glacier on the northern slope of Mount Tobe Feng (Fig. 1), with a total length of 20.3 km and an equilibrium-line altitude of 4220 m a.s.l. (Guo and others, 2014; Liu and others, 2015). With a total area of 103.17 km^2, most of Kelayayilake Glacier is covered by debris below the snow line. The glacier has a tree-like shape, consisting of the trunk glacier and west branch glacier. It is the west branch of the glacier (center line marked in blue in Fig. 1) that has surged, and is the subject of this paper.

The ablation season of the Kongur glaciated region generally starts in May and ends in September; the period of most rapid melting occurs from June to August (Shangguan and others, 2005), when glacier surges are most likely to occur.

Based on visual interpretation of satellite images, most of the glacier is covered by debris (Fig. 1). Glacial lakes and ponds, visible as dark spots in Fig. 1, can be observed on the surface of the trunk glacier, while the west branch contains fewer such features. The Kelayayilake Glacier terminus hardly moved and the trunk glacier hardly changed during the surge. In March 2015 (Fig. 1b), snow cover can be seen on the glacier, which earlier had been covered by debris. Crevasses in the west branch of the glacier, visible as dark blue to black stripes, developed while the glacier was surging. The yellow line segments in Figures 1a and d, indicate the location of a prominent surface feature on the debris and the white segments indicate the width of the trunk glacier. These markers indicate that the west branch of the glacier surged ~1.2 km down the center line (distance between the dashed and solid yellow lines of Fig. 1d), while the width of the trunk glacier was reduced by 0.3 km where the west branch surged into it (cf. white line segments in Fig. 1d).

The displacement field of the glacier surface is one of the key parameters that can describe glacier surges (Meier and Post, 1969; Kamb and others, 1985), and it is possible to obtain accurate and detailed measurements of glacial surface motion with optical images such as Landsat (Haug and others, 2010; Yang and others, 2013). In this study, the operational use of satellite images has been implemented using the software, COSI-Corr (Co-Registration of Optically Sensed Images and Correlation), which has proven effective in a number of studies including glacial movement (Leprince and others, 2007; Herman and others, 2011). We analyzed 11 Landsat-8 Operational Land Imager images from several months during and before the surge of the west branch of Kelayayilake Glacier to detect fluctuations of the glacier.

Considering the limitations of the images acquired, we separate this surge duration into four periods: March (12–21 March), April (13–22 April), May (8–15 May), and June and July (16 June–11 July). The time interval between each image pair is sufficient to obtain a relatively large displacement while avoiding the signal being buried by noise and we use COSI-Corr calculations to derive the velocity maps for the four periods. With a total length of 15.0 km, the velocity profiles for the west branch center line are extracted from these velocity maps. Along with the elevation of the west branch center line, which is obtained from ASTER Global DEM (GDEM Version 2), these profiles are filtered, providing a smoothing effect. They are shown in Fig. 2. The distance along the west branch center line was selected as the abscissa and the point of origin is the location where the west branch converges with the trunk glacier, i.e. where the glacier appears to be stable. Because the highest ice velocities in this region under normal conditions occur in September, the velocity profile for September 2014 is also shown. These profiles can provide some insight into the evolution of the surge.

Almost all September 2014 values were in the range, 0–50 m month^{-1}. Very few parts in the upstream region had values near or above 100 m month^{-1}. From March to May, the peak velocity rose abruptly (March: ~315 m month^{-1}, April: ~415 m month^{-1}, May: ~605 m month^{-1}). In June and July, it fell to 110 m month^{-1}, clearly demonstrating that the surge was most active during May. From km 13 to km 15 upstream, ice and snow are exposed to air without debris cover (Fig. 1). Even though the terrain varies irregularly in this section (Fig. 2), the glacier's motion was approximately constant. Most of this km 13 to km 15 upstream section is located above the snow line. From km 12 to km 13, the velocity suddenly increased. An increased topographic gradient led to this acceleration. The partial conversion of vertical velocity into a horizontal component contributed to the sudden velocity increase seen in the satellite images. At km ~10.5 (~3750 m a.s.l.) two upstream branches converge into one,

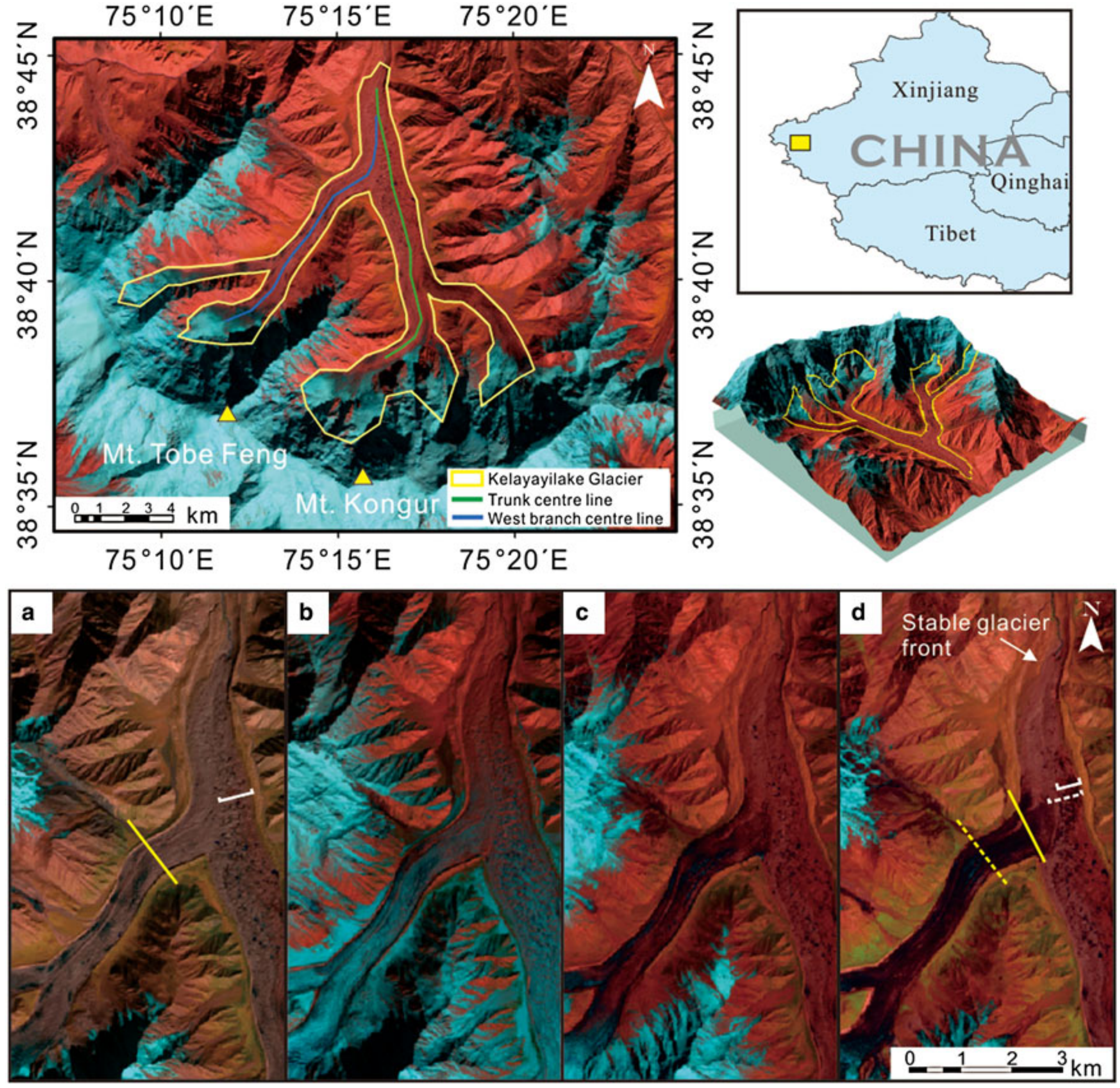

Fig. 1. Landsat-8 image (bands 654 combined) of Kongur, with superimposed Kelayayilake Glacier and glacier center line. The location of the study area in China and a 3-D terrain stereogram are shown. Evolution of the surge: (a) 26 September 2014, (b) 21 March 2015, (c) 15 May 2015, (d) 11 July 2015. The yellow straight lines indicate distinct surface features and their location. The white segments indicate the width of the trunk glacier. The dashed line and segment in (d) show the relative position of each feature in September 2014 before the surge. Note that the blue-white region represents the exposed snow or ice; the red region represents the debris-covered glacier or bare land.

resulting in another velocity increase. For March, April and May, the velocity profiles peaked before the west branch glacier encountered the trunk glacier at a distance of km ~6 and decreased suddenly to almost zero at km 3.3, km 3.1 and km 2.7. For June and July, the velocity profile peaked a little closer to the front of the glacier (at km ~5)

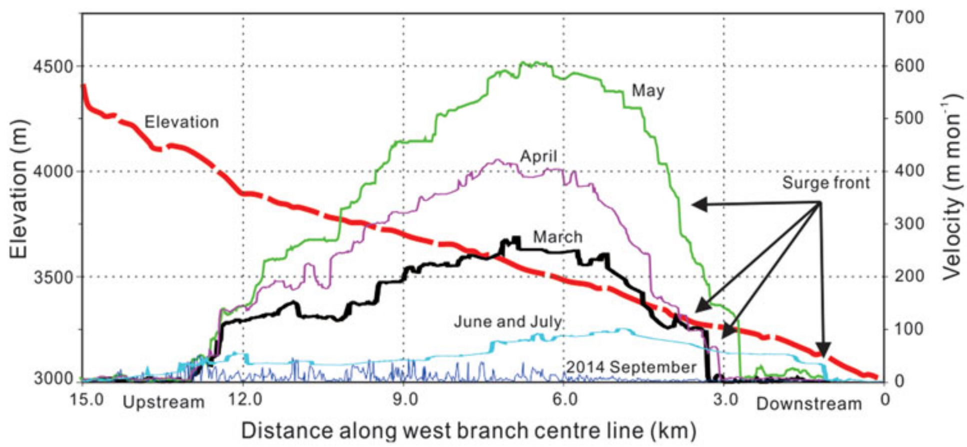

Fig. 2. Center line velocity profiles characterizing the evolution of the Kelayayilake Glacier surge and corresponding elevation of the glacier along the blue center line shown in Fig. 1. Surge fronts for each of the studied periods are noted.

and the surge front located at km 1.5. The glacier front appeared to be stable and showed no apparent motion, indicating that the surge did not impact this area by the time of July 2015. In June and July, when the surge was in its decaying stage, the surge affected a much longer distance, despite velocities as low as 1/6 of those during May in all parts of the glacier. The value of deceleration in the downstream section is higher than the acceleration in the upstream portion of the glacier, even when considering the velocity increase caused by convergence of the two upstream branches. Two factors might contribute to the sudden stop of the surge: (1) the geomorphological change from a narrow passage to a broader valley, and/or (2) the resistance caused by the trunk glacier. It is difficult to identify exactly when the glacier surge was initiated, as the images available for January and February are heavily cloud-covered.

Even though the Kelayayilake Glacier has now ceased surging, a large amount of accumulated glacial material will continue to flow into the trunk glacier. The surge left numerous crevasses on the surging glacier and a changed meltwater flow from the glacier front, along with an increased risk of subglacial lake outburst flood.

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