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Brief Communications: Observations of a Glacier Outburst Flood from Lhotse Glacier, Everest Area, Nepal

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Abstract

Glacier outburst floods with origins from Lhotse Glacier, located in the Everest region of Nepal, have occurred during the transitional early monsoon season in each of the last two years. The most recent event was witnessed by the investigators on 12 June 2016. Observations regarding the magnitude of the 2016 outburst flood and a reconstruction of the flood path immediately following the event are presented. These observations highlight the lack of existing knowledge regarding these glacier hazards and provide valuable insight to help spur future investigations.

1 Introduction

Glacier outburst floods occur when stored glacier water is suddenly unleashed downstream. Triggering mechanisms of these outburst floods include mass movement entering a proglacial lake, dam failure, volcanic or geothermal activity, and heavy rainfall, among others (Richardson and Reynolds, 2000; Carrivick and Tweed, 2016). In the Himalaya, a specific subset of outburst floods called glacial lake outburst floods (GLOFs) has received the most attention with respect to hazards, likely because of their potentially large societal impact (e.g., Vuichard and Zimmermann, 1987). In contrast, glacier outburst floods in the Himalaya, herein referring to outburst floods that are not generated by a proglacial lake, have received relatively little attention. This lack of attention is likely due to their apparent smaller magnitudes and our current inability to model triggering mechanisms and their potential flood extent. While they are a known hazard

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and discussed in the literature (e.g., Richardson and Reynolds, 2000), few studies in Asia have investigated these hazards in detail (Richardson and Quincey, 2009).

Glacier outburst floods can occur sub-, en-, or supra-glacially when hydrostatic pressure exceeds the structural capacity of the damming body, when stored water is connected to an area of lower hydraulic potential, when drainage channels are progressively englarged, and/or when catastrophic glacier buoyancy occurs (Richardson and Reynolds, 2000; Gulley and Benn, 2007). For debris-covered glaciers, the drainage of supraglacial ponds commonly occurs through englacial conduits, which facilitate connections to areas of lower hydraulic potential (Gulley and Benn, 2007). These englacial conduits develop on debris-covered glaciers in the Himalaya through cut-and-closure mechanisms associated with meltwater streams, the exploitation of high permeability areas that provide alternative pathways to the impermeable glacier ice, and through hydrofracturing processes (Gulley and Benn, 2007; Benn et al., 2009; Gulley et al., 2009a; Gulley et al., 2009b).

During the last half century, debris-covered glaciers in the Everest region have experienced significant mass loss, which has led to the development of glacial lakes and supraglacial ponds (Benn et al., 2012). Proglacial lakes may develop if the surface gradient of the glacier is gentle (< 2°), while steeper gradients (> 2°) will help drain these ponds (Quincey et al., 2007). This causes supraglacial ponds to have large temporal variations as they frequently drain and fill (Horodyskyj, 2015; Watson et al., 2016). Their drainage can occur on the glacier's surface, subsurface, and/or englacially (Benn et al., 2012).

Lhotse Glacier (27°54'12" N, 86°52'40" E) is an avalanche-fed debris-covered glacier that extends 8.5 km from the peak of Lhotse (8501 m) to the glacier's terminus (4800 m). The lowest 3.5 km of the glacier is relatively stagnant with many supraglacial ponds. The upper 4 km, located beneath the headwall of Lhotse, is still quite active as seen by its highly crevassed features and its supraglacial ponds (Quincey et al., 2007). The terminus of the glacier is relatively steep (> 6°), which facilitates the drainage of supraglacial ponds and prevents the development of a large proglacial lake (Quincey et al., 2007). As these supraglacial ponds drain and fill, they can cover up to 1.3-2.5% of the debris-covered glacier's surface at any time (Watson et al., 2016). Speleological surveys conducted at Lhotse Glacier found that cut-and-closure mechanisms and the exploitation of high permeability areas were the main contributors to the development of englacial conduits and the drainage of supraglacial ponds (Gulley and Benn, 2007).

2 Methods

The glacier outburst flood that occurred on 12 June 2016 was observed from the southern lateral moraine of Lhotse Glacier by the investigators (Figure 1), which provided opportunities to photograph, record, and observe the event as it unfolded. Flow measurements at 4:30 p.m., approximately 3-4 hours after the peak discharge, were estimated from cross sectional areas and float velocities using bundles of sticks in a relatively straight section of the channel below the village of Chukung (27°54’03” N, 86°51’46” E). Average velocity for the flow measurements was assumed to be 85% of the float velocity. Uncertainty associated with the flow measurements accounts for errors in river width (± 1 m), depths (± 0.3 m), float distance (± 1 m), and time (± 1 s). Peak flow was conservatively estimated using the same average velocity with cross sectional areas derived from high water marks.

During 14-21 June 2016, investigators conducted a field assessment on Lhotse Glacier to reconstruct the flood path. Key features, which included bare ice faces, entrances and exits of englacial conduits, sinkholes, collapsed tunnels, and ponds, were examined, photographed, and measured using a handheld GPS (Garmin Montana) and a laser range finder (Nikon Forestry Pro). Bio-indicators were also documented to assist reconstruction efforts. These indicators included visual observations of recently uprooted and displaced alpine shrubs providing insight into the surficial flood path. The presence of high water marks or wet, fine sediment that indicated potential sinkholes or drained ponds were also recorded. A WorldView-2 pan sharpened satellite image (0.5 m) from 14 May 2016 was used as a background image to reconstruct flood path and assess the presence of ponds prior to the flood when possible. High resolution satellite images were not available to assess the drainage of ponds after the flood event. Given the large temporal changes associated with the draining and filling of these melt ponds, pond drainage volumes were not estimated.

3 Results

Direct observations: At 11:40 a.m. on 12 June 2016, three landslide-like features began flowing almost simultaneously down a south-facing slope of Lhotse Glacier, followed by large amounts of discharging water from three apparent englacial conduits and one supraglacial stream (Figure

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1, 2A). At the same time, large amounts of sediment-laden water was observed discharging from multiple englacial conduits and supraglacial channels, located 200 m west of these landslide-like features, which was flowing into the main channel (Figure 2B). Around 12:10 p.m., an additional supraglacial torrent and two supraglacial streams, located upglacier and to the east of the initial observations, joined the floodwater discharging from this initial area. The discharging water immediately began ponding and quickly breached the pond allowing the floodwater to propagate downstream and join the pre-existing main channel in addition to creating a secondary channel down the southern lateral moraine (Figures 1, 2B). During this time, channel banks composed of ice and debris were severely undercut as the floodwater melted the surrounding ice as well.

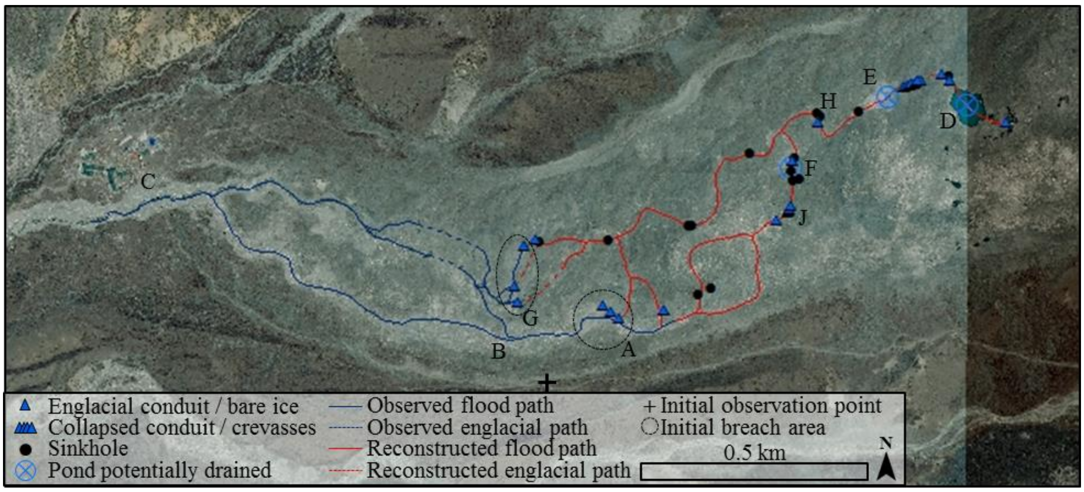

Figure 1. Observations and reconstruction of the glacier outburst flood from Lhotse Glacier on 12 June 2016 showing the observed and reconstructed flood path down to the village of Chukung. Letters correspond to key features in Figure 2.

The main channel continued to flow downstream until it re-entered englacial conduits (Figure 1), which created an "ice bridge" that allowed investigators to cross the secondary and main channel once the peak flow started subsiding around 1-1:30 p.m. At 4:25 p.m., discharge was measured to be 32 ± 14 $m^3 s^{-1}$ at a point below Chukung. Peak discharge was estimated retroactively to be 210 ± 43 $m^3 s^{-1}$. This estimate is considered to be conservative because it uses average velocity measurements taken over 3 hours after peak discharge. Minimal damage was caused to the community of Chukung. The main damage was the loss of a pedestrian bridge, an outbuilding,

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and small amounts of floodwater in the courtyard of one lodge. The local community members credited recently constructed gabions (Figure 2C) for protecting their lodges from further damage (see supplementary material for footage of the observed events). Water levels appeared to return to normal stages within 24 hours.

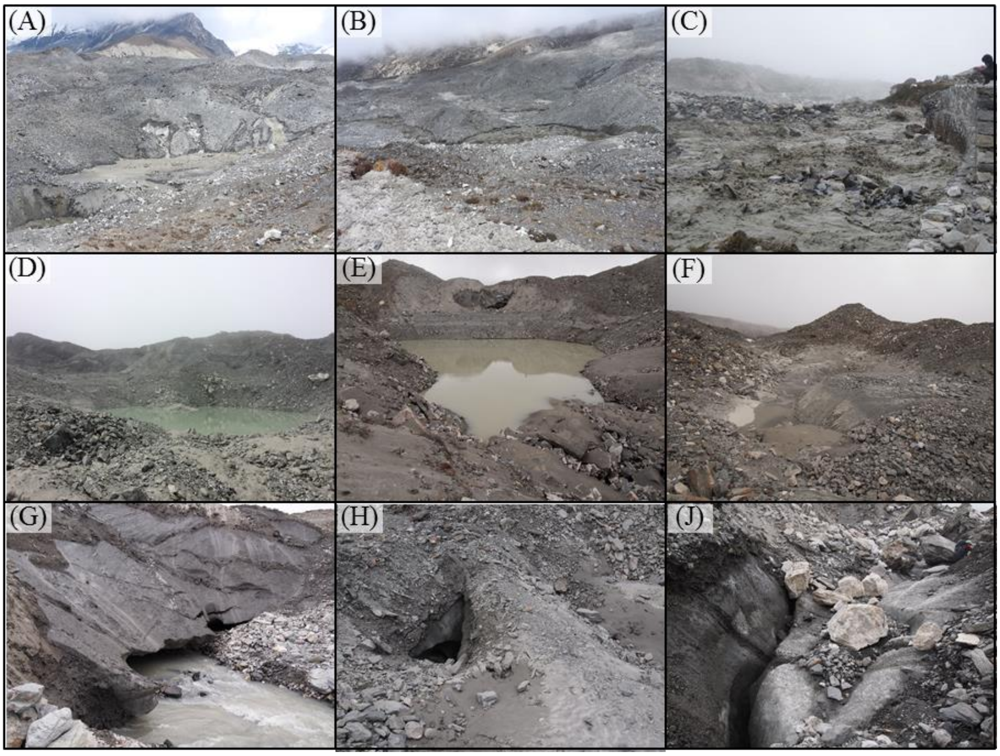

Figure 2. Key features of the glacier outburst flood from Lhotse Glacier: (A) englacial and supraglacial flooding where the event was first observed, (B) main channels of flood path during the flood's peak, (C) flood undercutting the gabions at Chukung, at 2:19 p.m., shortly after estimated peak flow, (D) potentially drained pond with large bare ice faces behind it, (E) potentially drained pond with a collapsed englacial conduit behind it, (F) potentially drained pond with sinkholes, (G) meltwater exiting the glacier into the main channel via a large englacial conduit, (H) a vertical englacial conduit and sinkholes with wet, fine sediment indicating a drainage pathway, and (J) large vertical crevasses with clean ice likely from the supraglacial flood path.

Post-flood observations: A detailed field assessment of Lhotse Glacier was conducted to reconstruct the glacier outburst flood by identifying potential flood pathways, englacial conduits, sinkholes, and drained ponds (Figure 1). Satellite imagery from 14 May 2016 reveals a sizeable supraglacial pond (27°54’20” N, 86°53’27” E) located directly beneath a large bare ice face

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(~10-20 m) that was considerably smaller during our field assessment (Figure 2D). This pond also had fine, wet sediment along its slopes and had a series of bare ice, sinkholes, and englacial conduits located immediately downstream, which would have facilitated its drainage. This was the pond located the furthest upglacier that appeared to have recently drained, although it is possible that the flood originated further upstream via the drainage of other supra- or subglacial ponds. A detailed assessment of all the supraglacial ponds and terrain upglacier was unable to be conducted due to time limitations.

This ponded water likely entered a series of englacial conduits and potentially supraglacial pathways before entering another supraglacial pond located ~200 m downglacier (Figure 1). This second supraglacial pond had similar indicators of having recently drained (Figure 2E), although the satellite image does not show a large supraglacial pond. It is possible that meltwater filled the pond between the glacier outburst flood and the time when the satellite image was acquired. A collapsed englacial conduit was observed between these two ponds (Figure 1) in addition to a series of sinkholes and the entrance to an englacial conduit immediately downstream of the pond (Figure 2H). Based on recently uprooted and displaced alpine shrubs, the flood appeared to continue downstream where it branched into multiple paths (Figure 1). The southern branch appears to have entered a third supraglacial pond (Figure 2F), which had similar indicators and large sinkholes. Downstream of this third pond was a small valley that was littered with areas of clean ice and deep crevasses (Figure 2J). It appears that this supraglacial pathway and englacial conduits fed into the flood torrent that joined the initial discharge at 12:10 p.m (Figure 1). The other branch showed signs of supraglacial and englacial pathways in the form of bio-indicators, sinkholes, and englacial conduits as well, which appear to have contributed to the heavy flow that was observed at the main channel as well (Figure 2G).

4 Discussion

Due to the sub-, en-, and supraglacial nature of these events, glacier outburst floods are difficult to study in detail, which provides challenges to understanding their frequency and magnitude. One of the easiest ways to observe these outburst floods would be the use of repeat high resolution satellite imagery such that the drainage of supraglacial lakes could be quantified. However, the large temporal and spatial changes that these supraglacial ponds experience make it challenging to obtain imagery that captures a flood event (Figure 3). Furthermore, remote

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sensing does not provide any information regarding the sub- or englacial pathways of the flood. Hence, the direct observations of the glacier outburst flood from Lhotse Glacier and the ensuing field assessment immediately after the event provide unique insight into the triggering mechanisms, flood path, and magnitude of these events that has rarely been captured before.

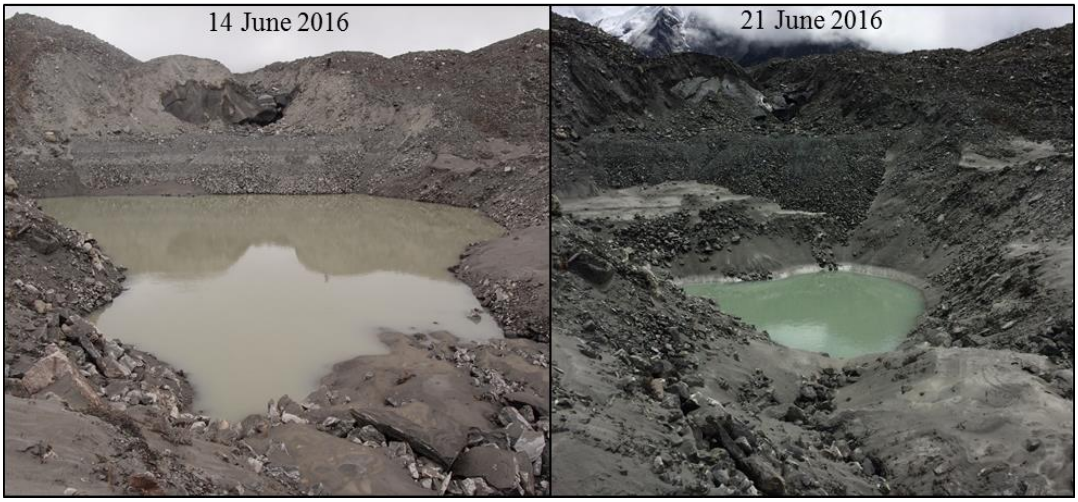

Figure 3. Repeat photography of a supraglacial pond on Lhotse Glacier showcasing the large temporal changes.

The first direct observations of the glacier outburst flood were three landslide-like features generated by water being discharged through englacial conduits. This sudden discharge was likely due to the hydrostatic pressures exceeding the cryostatic pressure that was previously constraining the water stored englacially (Richardson and Reynolds, 2000). As this flood occurred in mid-June, there was ample time for these englacial conduits to be filled with glacier meltwater. The discharge of this water would open outlets of lower hydraulic potential that would facilitate the drainage of englacial and supraglacial waters (Gulley and Benn, 2007). Another possibility is that the flood started further upglacier and as this floodwater propagated downglacier, the englacial conduits were overburdened, which eventually caused them to rupture. This would help explain the supraglacial flood paths that were observed during the field assessment. Conduits and sinkholes that were located along the supraglacial flood paths could have helped transport the floodwater into these englacial conduits causing the rupture and discharge that was first observed. The actual triggering mechanism is likely a combination of these various processes. Once the glacier outburst flood is initiated, a meltwater feedback is

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generated where the discharging water causes additional melt of ice thereby greatly increasing the magnitude of the flood, which was observed during this event.

Based on the timing of the flood, meltwater storage likely had an important role in the cause of the outburst flood, which would also explain how drained ponds that were not apparent in the satellite image from 14 May 2016 were filled before the flood event. Additionally, the observed event from Lhotse Glacier was the second event in the last two years. On the night of 25 May 2015, another glacier outburst flood originating from Lhotse Glacier occurred (Sherpa, L., personal communication, 09 June 2015). A similar event reportedly occurred in early May 2016 in the vicinity of the “crampon put-on point” (5600 m) of Island Peak (6189 m) that damaged sections of the high and low basecamp regions (Sherpa, P.T., personal communication, 18 June 2016). The timing of these events during the transitional pre-monsoon season suggests that the sub- and englacial hydrological system may play an important role. Specifically, during the early melt season the drainage network may be distributed and inefficient, which causes the buildup of stored water until the glacier outburst flood suddenly releases the water and opens new efficient channels similar to the evolution of subglacial hydrological systems in the Arctic (Carr et al., 2013). The repetitive nature of these events at Lhotse Glacier presents potential opportunities to more thoroughly investigate the triggering mechanisms, pathway, and size of these events through methodically tasked high resolution imagery analysis and the deployment of specific field equipment, e.g., time-lapse cameras, pressure sensors, and flow measurements.

5 Conclusions

The direct observations of the glacier outburst flood from Lhotse Glacier are the first time in the Himalaya that scientists have witnessed an event in real-time, to the authors’ knowledge, which provides valuable information regarding the triggering mechanisms and the magnitude of these events. The detailed field assessment in the immediate days following the event assisted efforts to reconstruct the flood path and showed that in-situ observations are critical for understanding these hazards as the supraglacial hydrology changes rapidly. The sub-, en-, and supraglacial nature of these events also highlights our lack of knowledge; however, these events appear to be occurring repetitively at Lhotse Glacier, which provides a unique opportunity to conduct more thorough investigations in the future. This will be important as improving our understanding of the frequency and magnitude of these events has important economic and social implications for downstream communities and hydropower companies.

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Supplementary Material

Video footage of the glacier outburst flood from 12 June 2016 may be found at http://www.crwr.utexas.edu/video/Lhotse_Flood_Supplement_V3.mp4.