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Topographic controls on the surging behaviour of Sabche Glacier, Nepal (1967 to 2017)

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ABSTRACT

Using a combination of Landsat, Pléiades and CORONA satellite imagery from 1967 to 2017, we map changes in the terminus position, ice surface velocity and surface elevation of Sabche Glacier, and report the first observations of surging behaviour in central Nepal. Our observations show that Sabche Glacier surged four times over the last 50 years. The three most recent surges occurred at 10 to 11-year cycles, which is one of the shortest surge cycles ever recorded. Detailed analysis of the most recent surge (2012 onwards), indicates that the glacier advanced 2.2 km and experienced maximum velocities of 1.6 ± 0.10 m day^{-1}. During this surge, there was a surface elevation gain at the terminus of up to 90 ± 6.19 m a^{-1}, with a corresponding surface lowering of between 10 ± 6.19 and 60 ± 6.19 m a^{-1}, 3 km up-glacier of the terminus. This transfer of mass amounted to a volume of $\sim 2.7 \times 10^7 \pm 0.1 \times 10^7$ $m^3 a^{-1}$. Sabche Glacier is the first surge-type glacier to be observed in the central Himalayas, but this is consistent with a previous global analysis which indicates that surge-type glaciers should exist in the region. We hypothesise that the surge is at least partially controlled by subglacial topography, whereby a major subglacial overdeepening and constriction 3 km up-glacier of the terminus provides resistance to glacier flow from the accumulation area to the ablation area. This overdeepening appears to store mass until a threshold is crossed, after which the glacier flows out of the subglacial depression and rapidly surges over a bedrock lip and down the valley. Thus, whilst the surges are likely to be facilitated by subglacial processes (e.g. changes in subglacial hydrology and/or basal thermal regime), the topographic setting of the glacier appears to be modulating both the timing and duration of each surge.

1. Introduction

Surge-type glaciers fluctuate between long periods (10s to 100 s of years) of slow flow and shorter periods (1 to 10 years) of faster flow, during which ice surface velocities increase by up to three orders of magnitude (e.g. Clarke et al., 1984; Jiskoot et al., 1998; Meier and Post, 1969). These oscillations are not thought to be directly triggered by external climate forcing, but rather by internal instabilities, linked to changing conditions at the glacier bed (Meier and Post, 1969; Sevestre and Benn, 2015; Sharp, 1988). During the slow, or quiescent, phase of the surge cycle, ice builds up in a reservoir area, and is then transferred rapidly down-glacier to a receiving area, during the fast, or surge, phase (e.g. Meier and Post, 1969; Murray et al., 2000). There is a distinct pattern in the global distribution of surge-type glaciers, with large clusters found in Alaska-Yukon, Arctic Canada, Greenland, Iceland, Svalbard, and High Mountain Asia, while very few have been recorded in other regions such as the European Alps or Scandinavia (Jiskoot et al., 1998; Sevestre and Benn, 2015; Sharp, 1988). While the lengths of the surge and quiescent phases tend to be consistent for individual surge-type glaciers, marked differences have been observed between these different geographic regions (e.g. Meier and Post, 1969; Murray et al., 2003; Sevestre and Benn, 2015). Glaciers in Svalbard tend to have surge periods lasting between 3 and 10 years and quiescent periods lasting between 50 and 500 years (Dowdeswell et al., 1991). In contrast, surge-type glaciers in Alaska-Yukon, the Pamirs, and Iceland, have much shorter surge (1 to 3 years) and quiescent (20 to 40 years) phases (Dowdeswell et al., 1991; Murray et al., 2003). These observed differences have led to the development of two main theories to explain surge-type glacier behaviour through either a thermal (Clarke et al., 1984; Murray et al., 2003) or hydrological (Kamb, 1987) mechanism. Thermally-driven glacier surges, common in Svalbard, are thought to be triggered by changes in the basal thermal regime, whereby a surge-front of warm-based and fast-flowing ice propagates down-glacier into stagnant cold-based ice and activates it into surging (Clarke et al., 1984; Murray et al., 1998). Thermal glacier surges can also be influenced by changes in the amount of bed deformation occurring under the glacier

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(Clarke et al., 1984; Jiskoot et al., 1998). In contrast to thermally-driven surges, temperate glaciers, such as Variegated Glacier (Kamb et al., 1985) and West Fork Glacier (Harrison et al., 1994) in Alaska, are thought to surge due to changes in their basal hydrology. Specifically, surging occurs when an efficient subglacial hydrological system switches to an inefficient cavity system generating increased water pressures at the bed and promoting rapid basal sliding (Kamb, 1987).

While surge-type glaciers are rare, constituting $< 1\%$ of glaciers worldwide (Jiskoot et al., 1998), they can provide valuable insight into glacier dynamics and the mechanisms triggering surge-type behaviour and fast glacier flow (Clarke, 1987). They can also present major hazards in populated areas through their influence on glacial lake outburst floods (GLOFs), rapid meltwater and sediment release, and the over-riding of infrastructure (Haeberli et al., 2002; Kääb et al., 2005; Richardson and Reynolds, 2000). Moreover, knowledge of the spatial distribution of surge-type glaciers is vital for separating internal glacier dynamics from the climate change signal. This is especially important in High Mountain Asia, as the spatial distribution of surge-type glaciers in the region is highly variable (Sevestre and Benn, 2015) and the region is undergoing accelerated glacier changes due to climatic forcing (Gardelle et al., 2012; Gardelle et al., 2013; Kääb et al., 2012).

Surge-type glaciers in High Mountain Asia have been well-documented in the Karakoram (Copland et al., 2009; Copland et al., 2011; Gardner and Hewitt, 1990; Hewitt, 2007; Quincey et al., 2011), Pamirs (Dolgoushin and Osipova, 1975; Kotlyakov et al., 2008) and Tien Shan (Dolgoushin and Osipova, 1975; Pieczonka and Bolch, 2015). However, no glacier surges have been recorded in the central Himalayas, which we define as the section of the Himalayan range extending from Northern India to Bhutan (Fig. 1). Despite this, Sevestre and Benn (2015) predicted that surge-type glaciers should occur in this region using the species distribution model Maxent. The model used climatic (mean annual temperature (MAT) and mean annual precipitation (MAP)) and geometric (glacier length and slope) data to predict the global distribution of surge-type glaciers. This is based on the compilation of a geodatabase of known surge-type glaciers which revealed that they preferentially cluster within a distinct climatic envelope (with an MAT range of -12 to $+8\,^{\circ}\text{C}$ and an MAP range of 165 to $2155\ \text{mm a}^{-1}$) and that they tend to be longer and have shallower mean surface slopes than normal glaciers in these regions (Sevestre and Benn, 2015). In High Mountain Asia, the model accurately predicted the likelihood of surge-type glaciers in the Pamirs, Karakoram and Tien Shan. It also predicted surge-type glaciers in the central Himalayas, but they noted the absence of observations of surging in this region and speculated that the model might be over-predicting their occurrence (Sevestre and Benn, 2015).

In this paper, we use observations of frontal position, ice surface velocity and surface elevation change to identify a surge-type glacier in the large (10 km wide) Sabche cirque basin in the Annapurna-Manaslu (A-M) region in central Nepal, hereafter referred to as Sabche Glacier. This represents the first surge-type glacier to be recorded in the central Himalayas. We compare its characteristics to surge-type glaciers elsewhere in High Mountain Asia and other geographic regions, and discuss the possible mechanisms controlling its behaviour.

2. Study site

Sabche Glacier (28.56° N, 84.01° E) (Fig. 1) is in the south-west of the A-M region, on the south-east facing slope of Annapurna III (location in Fig. 1C). It is one of the larger glaciers in the A-M region with an area of $9.1\ \text{km}^2$ in 2014. It has a mean surface slope of 28.2°, a mean aspect of 178° and descends across a large altitudinal range, from 7489 to 3773 m asl, based on a glacier outline we digitised from a Landsat 8 scene from 1st December 2015 (Table S1). Over half of the glacier's area ($5.2\ \text{km}^2$, 57%) is covered in supraglacial debris and it sits in the steep-sided, bowl-shaped Sabche basin, and flows into a narrow outlet, forming a long (3 km) glacier tongue (Fig. 1C).

Sabche Glacier is located at the head of, and feeds into, the Seti Gandaki river, which flows through highly populated areas, including Pokhara (population ~400,000), located 30 km down-stream. The Seti Gandaki river has a history of dramatic, and occasionally deadly,

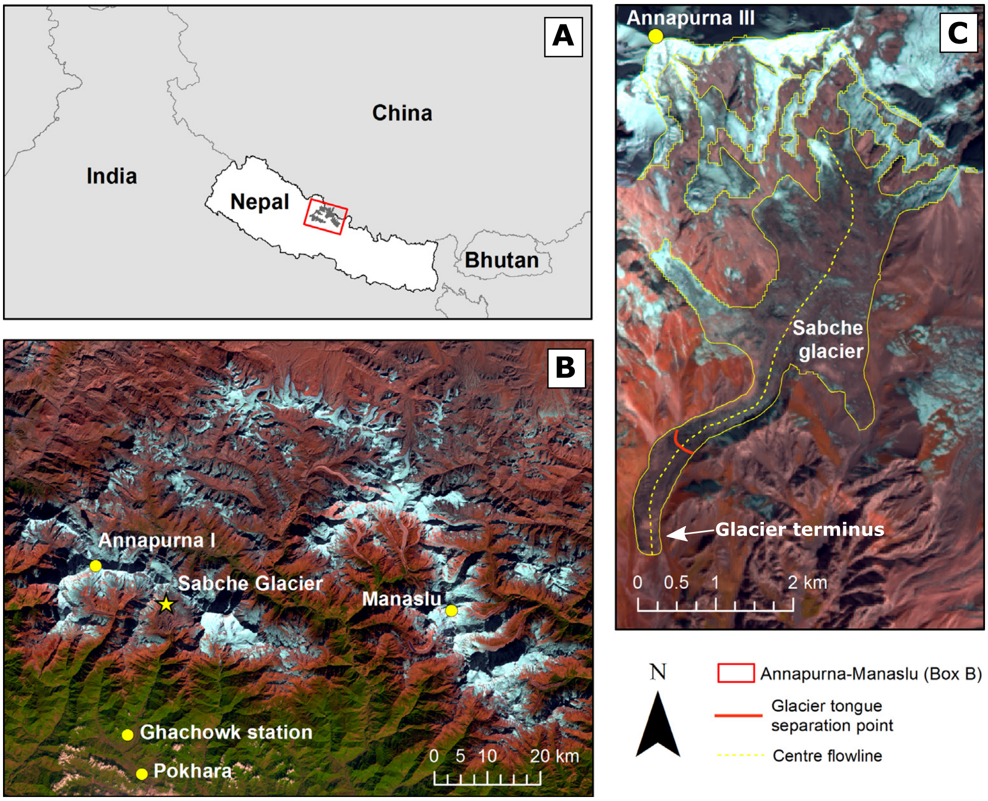

Fig. 1. Study area map. A) Location of the central Himalayas and the A-M region in Nepal, B) location of Sabche Glacier in the A-M region, Pokhara and Ghachowk hydrological station and C) map of Sabche Glacier with the central flowline (yellow dotted line), the approximate position of the recurring separation point between the main body of the glacier and its tongue (red line) and the location of Annapurna III. The white arrow indicates the location of the glacier terminus. The base image is a pan-sharpened Landsat 8 scene from 1st December 2015, courtesy of USGS. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)