# Postgraduate research grant report: How does supraglacial debris influence the response of Himalayan glaciers to climate change?

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## 1. Introduction

The Himalaya contains the largest area of ice outside of the Polar Regions, and has the largest volume of mountain glaciers in the world (Bolch et al., 2012). One third of the world's population rely on these glaciers as a water resource, with meltwater from these glaciers acting as a buffer in the periods between the South Asian Summer Monsoon (June to September, subsequently referred to as the monsoon) and winter precipitation, releasing water at a steady rate into rivers such as the Bramaputra and the Ganges (Immerzeel et al., 2013). The monsoon is a dominate control on glacier mass balance in the Himalaya, causing accumulation and ablation to occur simultaneously during the summer, resulting in glaciers which are highly sensitive to summer temperatures and precipitation (Kadota et al., 1993). During the last two decades an ongoing trend of climate warming and changes in precipitation patterns have been observed in the Himalaya (Salerno et al., 2015), whilst an increased rate of glacier ablation and an overall reduction in glacier mass throughout the region has also been observed over the same period (Bolch et al., 2011; Nuimura et al., 2012; Thakuri et al., 2014).

Many glaciers in the Central Himalaya are debris covered, with one third of glacier area in the Nepal Himalaya completely covered with rock debris (Thakuri et al., 2014). The presence of a surface debris layer on a glacier affects glacier ablation rate (Jansson and Fredin, 2002; Kirkbride, 2000). A supraglacial debris layer has the potential to vary both spatially and temporally across a glacier due to variations in such parameters as debris thickness, albedo, surface roughness, clast size, lithology and surface temperature (Collier et al., 2014; Lejeune et al., 2013; Reznichenko et al., 2010). Debris surface temperature has been utilised previously to determine debris thickness distribution across a glacier surface through a combined use of field surface temperature and thermal satellite data (e.g. Foster et al., 2012; Mihalcea et al., 2008a; 2008b; Ragettli et al., 2015; Rounce and mckinney, 2014; Schauwecker et al., 2015). The application of surface temperature in such a way is based on the premise that increasing debris thicknesses is associated with higher surface temperatures, due to less influence from cold propagating up from the underlying ice (Mihalcea et al., 2006).

## 2. Study aim

Through collection and analysis of surface temperature data at a number of points across a debris-covered glacier surface, an understanding of spatial variability in surface temperature can be achieved. By extending this data collection through the monsoon temporal variations in surface temperature can be observed, and the influence of the monsoon in surface temperature variability for Himalayan glaciers, such as Khumbu Glacier, can be determined. By combining such data and associated site characteristics it will not only be possible to identify to what extent glacier surface temperature varies in space and time, but also to determine the controlling parameters on glacier SEB and heat transfer for debris-covered ice. A greater understanding of the variability of surface temperature and the processes which control it will allow glacier SEB and debris thickness to be calculated with greater confidence. Ultimately this will lead to a greater understanding of how a debris layer affects glacier mass balance.

## 3. Study area

Khumbu Glacier, located in the Central Himalaya (27°56'N, 86°56'E), is ~17 km long and has an area of 27 km$^2$ including the tributaries Changri Nup and Changri Shar Glaciers which make up 11.4 km$^2$ of the glacier area (Figure 1) (Arendt et al., 2012; Bolch et al., 2008). Khumbu Glacier flows from the southwest flanks of Mount Everest at 8230 m a.s.l. to ~ 4900 m a.s.l. with the equilibrium line altitude situated at an elevation of 5600 m a.s.l, within the Khumbu Icefall, below which is the low gradient ablation area of Khumbu Glacier (Benn and Lehmkuhl, 2000; Inoue and Nagoshi, 1977) Changri Nup and Shar, previously attached to Khumbu Glacier, now feed meltwater to Khumbu glacier.

Khumbu Glacier is representative of many large Himalayan debris-covered glaciers, exhibiting a low gradient, slow flowing ablation area with extensive debris cover (Hambrey et al., 2008). The glacier has a mean velocity of ~ 30 m $a^{-1}$, flowing at ~ 70 m $a^{-1}$ near the base of the icefall, whilst the lower 3 – 4 km of the glacier having little to no flow (Quincey et al., 2009) The ablation area of Khumbu Glacier is almost entirely debris covered, containing granitic and schistose lithologies consistent to a provenance from the surrounding mountains (Iwata et al., 1980; Nuimura et al., 2011). The lower regions of the ablation zone are in the early stages of soil formation and are partially vegetated (Kadota et al., 2000). The extensive debris cover has resulted in differential ablation across the ablation area, resulting in high relief and the formation of supraglacial ponds and ice cliffs (Hambrey et al., 2008; Iwata et al., 1980; Wessels et al., 2002). Surface lowering of the ablation area due to such differential ablation has occurred on the order of –0.38 ± 0.07 m $a^{-1}$ between 1970 and 2007, the rate of which has increased since 2010 (Benn et al., 2012; Nakawo et al., 1999; Nuimura et al., 2012).

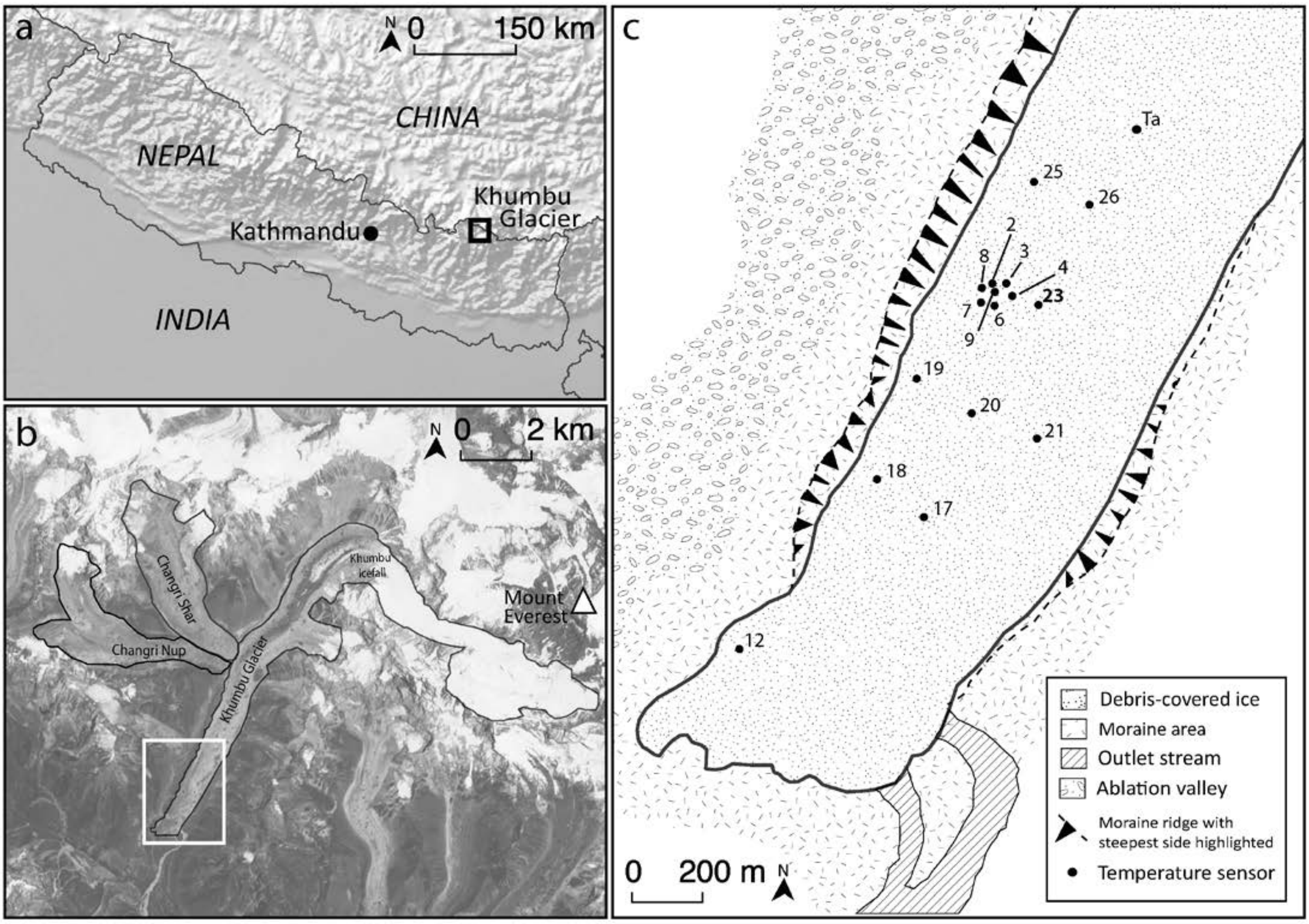


**Figure 1.** The study site location a) in a regional context, b) in relation to Mt Everest, showing the extent of Khumbu Glacier, c) the study area and sites at which temperature sensors were placed, with corresponding temperature sensor ID.

## 4. Fieldwork

Surface temperature ($T_s$) was measured using thermochron iButton™ temperature sensors (model number DS1921G). iButton™ temperature sensors measure temperature between – 30 and + 70 ° C, recording at 0.5 °C increments to an accuracy of ± 1 °C. Each of the 64 temperature sensors was placed in a polyethylene bag tied with a 0.5 m length of pink survey string, to protect the temperature sensor from water damage and for help in their relocation. iButton™ temperature sensors were installed on the debris surface with a representative cover of debris found at that site placed on the sensor, to shield them from direct incoming solar radiation which would cause them to record unrealistically high surface temperatures.

Although 64 iButton™ temperature sensors were installed on the debris cover of Khumbu Glacier, 48 were lost due to movement of the debris cover and formation of supraglacial ponds over the monsoon, and subsequent burying or movement of the temperature sensors. Consequently, 16 temperature sensors, located in the lower section of the glacier (Figure 1c), were analysed in this study for the period between the 23rd May 2014 (Day of Year (DOY) 143) and 30th July 2014 (DOY 211) at hourly intervals (Figure 1c). Data was collected on the hour for the duration of this period. For analysis the first 48 hours of $T_s$ data were discarded to allow the temperature sensors to equilibrate to $T_s$, and the final day of measurements were discarded as a full 24-hour period was not recorded.

## 5. Future work

Surface temperature data collected during fieldwork is currently being analysed alongside surface morphology data also collected to identify spatio-temporal variations in surface temperature over a monsoon season on Khumbu Glacier, and the controls on these variations. Using the results of this study the morphological parameters identified as most important in the control of surface temperature will be incorporated into a theorectical surface energy balance model to determine whether such variation in these parameters is significant to calculated enegy balance and heat transfer throught he debris layer. The developed surface energy balance model will then be incorporated into a 3-D ice flow model to determine the response of Khumbu Glacier to debris transport and climatic changes.

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