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Object-based analysis of unmanned aerial vehicle imagery to map and characterise surface features on a debris-covered glacier

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ABSTRACT

Debris-covered glaciers in the Himalaya may have spatially-averaged rates of surface height change that are similar to those observed on bare-ice glaciers, despite the insulating effects of thick debris. Spatially heterogeneous melt patterns caused by the development and evolution of ice cliffs and supraglacial pond systems result in substantial mass losses over time. However, mechanisms controlling the formation and survival of cliffs and ponds remain largely unknown. To study the distribution and characteristics of these surface features we deploy an unmanned aerial vehicle (UAV) over a stretch of the debris-covered Langtang Glacier, Nepal. Acquired images are processed into high-resolution orthomosaics and elevation models with the Structure from Motion (SfM) photogrammetry algorithm. Ice cliffs and ponds are classified using object-based image analysis (OBIA) and their morphology and spatial distribution are analysed and evaluated using object, pixel and point cloud approaches. Results show that ice cliffs are predominantly north-facing, and larger ice cliffs are generally coupled with supraglacial ponds, which may affect their evolution considerably. The spatial distribution of ice cliffs indicates that they are more likely to form in areas where high strain rates are expected. The spatial configuration of ponds over the entire tongue reveals high pond density near confluences, possibly due to closure of conduits via transverse compression. We conclude that the combination of OBIA and UAV imagery is a valuable tool in the semi-automatic and objective analysis of surface features on debris-covered glaciers. The technique may also have potential for upscaling to the use of spaceborne imagery, and the use of UAV-derived point clouds to analyse ice cliff undercuts is promising.

1. Introduction

Glaciers are an important component of the rivers in High Mountain Asia (HMA) that provide a large number of people with water for irrigation, electricity production, sanitation, and religious practices (Immerzeel et al., 2010). With the exception of the Karakoram, glaciers in HMA have experienced negative glacier mass balances over the past decades (Bolch et al., 2012; Gardelle et al., 2012; Kääb et al., 2012, 2015). Sustained negative mass balances have resulted in a decreased volume of ice stored in these mountain ranges. Under current climate projections, accelerated glacier mass loss and increased glacier melt water runoff are expected in the coming decades (Shea et al., 2015). Towards the end of this century, however, the reduction in glacier area and volume will result in decreased ice melt contributions to streamflow (Immerzeel et al., 2013).

To increase our ability to predict and adapt to these future changes induced by climatic change, it is key that we learn more about the melt processes of glaciers in this region. Debris-covered glaciers in particular, which account for about 10% of the glaciers in HMA (Bolch et al., 2012), are relatively understudied because of difficulties in both accessibility and the collection of in situ measurements. Very thin layers of supraglacial debris will enhance ice melt, but buried ice is insulated from melt once a critical debris thickness of a few centimetres is reached (Mattson et al., 1993; Östrem, 1959; Reznichenko et al., 2010). Spatial variability of debris thickness (Nicholson and Benn, 2013) and properties such as albedo, roughness, porosity and moisture content, further complicate the effects of debris cover on local glacier melt (Evatt et al., 2015). The lower

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elevations of debris-covered glaciers, i.e. the areas where melt rates are typically greatest for bare-ice glaciers, generally have thick debris which thins upglacier (e.g. Anderson and Anderson, 2016; Nicholson and Benn, 2013; Rounce et al., 2015). Supraglacial debris should consequently have an overall melt-reducing effect. However, several studies report that debris-covered glaciers in the Himalaya have melt rates similar in magnitude to uninsulated, bare-ice glaciers in the same region and at the same altitude (Gardelle et al., 2013; Kääb et al., 2012).

This debris-cover anomaly (Pellicciotti et al., 2015) may be linked to ice cliffs that form on debris-covered glaciers (Fig. 1) and provide a mechanism for high melt rates because of their low albedo and surface exposure (Sakai et al., 1998). Recent studies confirm that the ice cliffs accelerate melt locally (Buri et al., 2016; Immerzeel et al., 2014; Miles et al., 2016a; Reid and Brock, 2014; Steiner et al., 2015). However, their exact effects on and interplay with larger scale glacier melt dynamics are still largely unknown.

Ice cliffs on debris-covered glaciers are thought to form in three different ways: slumping of debris from steep slopes, calving into supraglacial ponds or by the collapse of englacial voids (Benn et al., 2012). Once ice becomes exposed, a positive surface energy budget will result in ice melt and backwasting of the cliff. The main components of ice cliff energy budget include both direct and diffuse solar radiation as well as longwave radiation from the atmosphere and surrounding debris (Sakai et al., 2002). South-facing ice cliffs (in the northern hemisphere) generally disappear quite quickly after their formation (Buri et al., 2016; Steiner et al., 2015). It is hypothesized that bases of such ice cliffs receive less incoming solar radiation than the tops of the cliffs and experience less ice melt. This causes slope relaxation and eventually burial by debris when the slope becomes less than about 30°(Sakai et al., 2002). In contrast, north-facing cliffs do not experience direct solar radiation because of shading by the cliff itself. The surface energy budget is thus composed mainly of diffuse shortwave radiation and longwave radiation from the surrounding debris and the atmosphere. Because the debris-view factor (Reid and Brock, 2014) is larger at the base, north-facing cliffs experience more incoming longwave radiation there which tends to steepen and sustain the cliffs (Buri et al., 2016; Reid and Brock, 2014; Steiner et al., 2015).

Some ice cliffs have adjacent supraglacial ponds, i.e. water bodies of a similar scale as the ice cliffs that touch the base of the exposed ice (Fig. 1). Observations show that these ponds fill and drain over time (e.g. Benn et al., 2000; Gardelle et al., 2011; Immerzeel et al., 2014; Röhl, 2008; Wessels et al., 2002). Ponds may be filled by surface runoff, englacial conduits, or cliff melt, and drainage occurs via conduits (Benn et al., 2012; Gulley and Benn, 2007). Total pond area on debris-covered glaciers is largest at the onset of the melt season, because of snow and ice melt. As the melt season progresses, and water is transported through the englacial hydraulic system, the drainage efficiency increases (Miles et al., 2016b). Energy stored in the water is transferred to the surrounding ice, conduits are enlarged, and englacial conduit collapse could lead to the formation of ice cliffs (Miles et al., 2016a). Changes in the hydrological regime from a slow distributed drainage to fast channelised drainage also has consequences for glacier velocity and deformation (Bjornsson, 1998; Hewitt, 2011; Mair et al., 2010) and may therefore also contribute to the difference in pond outflux between the seasons.

Fig. 1. Photograph of an ice cliff on Langtang Glacier with an adjacent, partly-drained supraglacial pond typically found on debris-covered glaciers in the Himalaya.

When water is in contact with an exposed ice cliff, energy is transferred from the water to the cliff face through two processes. Firstly, the density/temperature relation of water causes pond circulation and promotes melt along the ice-water interface through this free convection. Secondly, wind fetch may force currents that drive thermal erosion of the exposed subaqueous ice surface (Miles et al., 2016a; Sakai et al., 2009). These processes result in thermal undercutting, notch development, and ice cliff calving (Röhl, 2006).

In recent years there have been many developments in the use of unmanned aerial vehicles (UAVs) for environmental monitoring. As the technology has advanced, their use has become a viable option for scientists to perform detailed remote sensing surveys. At present, UAVs are being used in an increasing number of fields of natural sciences (Colomina and Molina, 2014), and have been proven to be exceptionally useful and a promising tool in glaciology (Bhardwaj et al., 2016; Immerzeel et al., 2014; Kraaijenbrink et al., 2016; Ryan et al., 2015; Westoby et al., 2012, 2016; Whitehead et al., 2013). For debris-covered glaciers, UAVs offer a valuable addition to traditional measurements. Although capable of measuring the true glaciological mass balance, glaciological mass balance measurements on debris-covered glaciers (e.g. Vincent et al., 2016) require the installation of ablation stakes through a debris layer, which disturbs the surface. The spatial and temporal resolution of spaceborne remote sensing imagery is typically too coarse to study glaciers in detail. Satellite revisit periods can be considerable and atmospheric disturbances and clouds can render image scenes useless (Lillesand et al., 2015). UAV imagery fits a gap here as it allows the acquisition of on-demand, high spatial and temporal resolution imagery for continuous surfaces on a medium spatial scale of up to several square kilometres. Overlapping images acquired by UAVs can be used to create highly-accurate 3D-models and orthorectified image mosaics using Structure from Motion (SfM) photogrammetry (Snavely, 2008, 2011; Szeliski, 2011). UAV data are therefore valuable for debris-covered glacier studies, including surface feature morphology (Brun et al., 2016) and energy balance modelling (Buri et al., 2016).

Traditionally, remote sensing image classification and image entity extraction is done using pixel-based image analysis (PBIA). Every pixel is evaluated and grouped together on the image level by means of statistical clustering of pixel values, with or without the use of training samples in the clustering process (Lillesand et al., 2015). When pixel sizes are similar in size or coarser than the entities of interest PBIA is the preferred technique. On the other hand, when dealing with high spatial resolutions the analysis of objects that are constructed by multiple pixels is preferred (Blaschke, 2010; Blaschke et al., 2014). This object-based image analysis (OBIA) requires the segmentation of an image into near-homogeneous groups of pixels, i.e. objects (Baatz and Schäpe, 2000). This is performed by growing objects, starting from a pixel-scale, and iteratively merging them with neighbours. The merges are directed by relative object heterogeneity and internal homogeneity criteria that are based on