UAV Mapping of Debris Covered Glacier Change, Llaca Glacier, Cordillera Blanca, Peru.

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ABSTRACT

The glaciers of the Cordillera Blanca Peru are rapidly retreating as a result of climate change, altering timing, quantity and quality of water available to downstream users. Furthermore, an increase in the number and size of proglacial lakes associated with these melting glaciers is increasing the risk of glacier lake outburst floods (GLOFs). Understanding how these glaciers are changing and their connection to proglacial lake systems is thus of critical importance. Most satellite data are too coarse for studying small mountain glaciers and are often affected by cloud cover, while traditional airborne photogrammetry and LiDAR are costly. Recent developments have made Unmanned Aerial Vehicles (UAVs) viable and potentially transformative method for studying glacier change at high spatial resolution, on demand and at relatively low cost.

Using a custom designed high altitude hexacopter we have completed repeat aerial surveys (2014 and 2015) of the debris covered Llaca glacier tongue and proglacial lake system. Analysis of highly accurate 10cm DEM's and orthomosaics reveals highly heterogeneous changes in the glacier surface. The most rapid areas of ice loss were associated with exposed ice cliffs and melt water ponds on the glacier surface. Significant subsidence and low surface velocities were also measured on the sediments within the pro-glacial lake, indicating the presence of extensive regions of buried ice and continued connection to the glacier tongue. Only limited horizontal retreat of the glacier tongue was recorded, indicating that simple measurements of changes in aerial extent are inadequate for understanding actual changes in glacier ice quantity.

Keywords: UAV, UAS, Glacier Change, Structure from Motion, Remote Sensing, Cordillera Blanca, Peru.

INTRODUCTION

The Cordillera Blanca stretches over 180km along the Peruvian Andes. This range is the most glacierised tropical region on Earth and contains the majority of Peru's glaciers. Glacier melt from the western catchments drains to the Rio Santa, contributing up to two thirds of dry season stream flow (Mark et al., 2005). Rapid glacier recession driven primarily by rising temperatures is causing significant shifts in the local hydrology (Kaser et al., 2003; Mark and Seltzer, 2003; Mark et al., 2010). Most recently Burns and Nolin (2014) calculated a 25% reduction in glacier area from 1987 to 2010. Similarly, Racoviteanu et al. (2008) calculated a 22.4% reduction from 1970 to 2003 with an increase in the rate of retreat from 1970, and a rise in glacier terminus elevation of 113m. Glacier changes are altering the timing, quantity and quality of water available to downstream users (Kaser et al., 2003; Mark and Seltzer, 2003; Mark et al., 2005; Juen et al., 2007; Mark and McKenzie, 2007;  

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Barae et al., 2009, 2012), and having profound impacts on livelihoods and ecology within the Rio Santa basin (Mark et al., 2010; Bury et al., 2011, 2013). Additionally, rapidly melting glaciers are increasing the size and number of proglacial lakes within the region and increasing natural hazard risks posed by glacier lake outburst floods (GLOFs) (Huggel et al., 2002; Carey, 2008; Carey et al., 2012; Portocarrero, 2014). Understanding how these glaciers are changing and their connection to proglacial lake systems is thus of critical importance. However, typical methods of quantifying glacier change are either too coarse for studying small mountain glaciers (satellite data), are labor intensive and provide minimal understanding of spatial heterogeneity (point measurements) or are very costly (airborne and terrestrial LiDAR and photogrammetry). However, recent developments have made Unmanned Aerial Vehicle (UAV) technology in conjunction with structure from motion (SfM) photogrammetry a viable and potentially transformative method for studying glacier dynamics at high spatial resolution, on demand and at low (relative) cost (Whitehead et al., 2013; Immerzeel et al., 2014; Kraaijenbrink et al., 2015; Bhardwaj et al., 2016).

LLACA GLACIER

Llaca glacier is a relatively narrow (0.5km wide) glacial valley located directly above the city of Huaraz which lies at roughly the midpoint of the Cordillera Blanca. The glacier terminates at 4500masl into a moraine dammed proglacial lake. The glacier tongue is roughly 1.3km long and is covered by a thick (>1m) layer of debris, primarily derived from collapse of the over steepened lateral moraines to the north and south. The glacier is fed by a large alpine cirque roughly 5.5km wide with a headwall elevation of over 5500m including the summits of Vallunaraju (5686m) and Ranrapalca (6162m). The accumulation zone above approximately 5000masl is large in comparison to the constricted valley, which in addition to the insulation effect of a thick debris cover, allows this glacier to extend to a much lower elevation than most glaciers in the Cordillera Blanca that typically terminate between 4800-5100masl. Large piles of sediment are located in the upper (eastern) half of the proglacial lake. Their evolution and connection to the glacier are of particular interest as they may contribute to lake instability and GLOF risk.

Figure 1. Llaca valley is located within the Rio Santa basin (left pane) near the middle of the Cordillera Blanca, directly above the city of Huaraz. The debris covered Llaca glacier tongue and proglacial lake (left pane) with total survey area (yellow line), glacier survey area (blue line) and UAV launch point (red circle) marked.

METHOD

GNSS Survey

Before each survey one day was spent installing visible ground control point (GCP) targets across the survey area; 14 in 2014 and 11 in 2015. Additional unmarked 'check points' were surveyed (18 in 2014, and 13 in 2015) for accuracy assessment of the derived DEM surfaces for each year. Positions were surveyed using a stop and go post processing GNSS survey methodology. Each
position was occupied for 5 minutes at a 1Hz sampling rate, and collected with a Topcon GRS1 L1 receiver and a Topcon PG-A1 antenna. Base station data was collected from atop the terminal moraine (~1-2km baseline) using a Topcon Hiper SR L1/L2 integrated receiver/antenna. The base station position was calculated using the Natural Resources Canada (NRCAN) Precise Point Positioning (PPP) online system. Rover positions were post processed using Topcon Tool Magnet desktop software. Final point position errors were estimated at <1cm horizontal, <2cm vertical for 2014 and <3.5cm horizontal, <4.5cm vertical for 2015.

UAV Flights

UAV surveys of Llaca glacier were completed on 23 July 2014 and 28 July 2015. A custom designed and built hexacopter platform was used for both surveys. This platform was specially designed to operate at altitudes over 4000masl, and has been extensively tested at elevations up to 5500masl within the Peruvian Andes (Wigmore, 2015; Wigmore et al., 2016). The UAV uses a 3DR Pixhawk autopilot which is capable of fully autonomous navigation by following predetermined GPS waypoints/flightpaths. A survey grid was created that covered the lower debris covered glacier tongue and the debris filled section of the proglacial lake. The UAV was flown at an above ground level of 110m, giving a pixel ground resolution of 3.5cm. Following ground survey UAV flights were completed in about two hours at around midday to minimize impacts of shading from glacier surface features. Approximately six 10-12minutes flights were completed on each survey date. Images were collected in nadir position with a Canon S110 camera booting the Canon Hack Development Kit (CHDK) (chdk.wikia.com) and running a custom script (kap_uav.lua) (chdk.wikia.com/wiki/KAP_UAV_Exposure_Control_Script) that enables image capture at set intervals (in this case 3 seconds) with predefined exposure settings. A total of 601 images were taken in 2014 and 929 images in 2015.

Data Processing

All images were processed using the SfM workflow as implemented in Agisoft Photoscan Professional version 1.1.X (Verhoeven, 2011; Photoscan, 2013). This software is proprietary and the exact algorithms used are not available however the basic principles are the same as those described elsewhere (Lowe, 2004; Snavely et al., 2008; Szeliski, 2010; Fonstad et al., 2013). Final Digital Elevation Models (DEMs) and orthomosaics (red, green, blue) were output for each date at 10cm and 5cm resolutions respectively.

Glacier elevation changes were calculated by subtracting the 2014 DEM from the 2015 DEM in ArcMap, meaning that negative values indicate elevation (ice) loss. Glacier surface velocities were calculated through manual feature tracking of 72 well distributed features (large boulders) across the glacier surface. Velocity fields were calculated using spline interpolation in ArcMap from the feature tracks. To investigate the role of melt ponds and ice cliffs in controlling surface melt patterns horizontal movement of the glacier surface must be removed so that the same geographic locations are being compared across an image pair. To do this the 2015 orthomosaic was georectified in ArcMap using the calculated velocity vectors (feature tracks), i.e. movement from 2014 to 2015 was removed from the image, allowing direct comparison of the changes in surface features between the two image pairs. Measurements of these change vectors were then made to calculate rates of ice cliff recession and melt pond expansion.
FINDINGS

Glacier Mapping

Figure 2. Results of Llaca glacier mapping on 23 July 2014 and 28 July 2015. 10cm DEM for each year with 5cm RGB orthomosaic draped over DEM surface. Yellow boundary indicates the overlap zone from both survey dates. Blue boundary is debris covered glacier extent in 2014. Yellow circles are ground control point (GCP) locations used to georectify the SfM model. Pink squares are check points where GNSS elevation is compared to DEM elevation to estimate accuracy of SfM DEMs for each date.

Aerial survey results are presented in Figure 2 and include a 10cm DEM and 5cm orthomosaic. Locations of ground control targets (GCP’s) and points used for accuracy assessment of the DEM are marked. SfM tie point matching error is sub pixel (0.63 pixels in 2014 and 0.43 pixels in 2015) for both dates at a 3.5cm pixel ground resolution. These values indicate the quality of the SfM processing in deriving the model. GCP positional error within the SfM model is 0.002m (2014) and 0.003m (2015) which is a measure of the difference between expected and actual positions of the GCPs within the SfM model. External validation of the 10cm DEM was assessed by calculating the elevation difference between the GNSS measured elevation and the DEM elevation at the check points and GCP locations. A histogram of these differences is presented in Figure 3. Most errors are less than +/-5cm and all are within +/-10cm except for 2014 check points. The 2014 check point error estimate is likely higher than reality because check points were located ‘completely random’ i.e. atop rocks, within depressions, etc., and these small surface features are flattened by the DEM resulting in over estimation of DEM error. In 2015 check points were located in areas where elevation was fairly uniform within a roughly 50cm diameter. Consequently, error estimates are lower, and probably more realistic.
Figure 3. Histogram plot of elevation differences (errors) between check points and GCP surveyed elevations and DEM elevations for 2014 and 2015 respectively. Note: negative values indicate underestimation of DEM surface with respect to surveyed positions and thus imply flattening of the DEM surface. Most errors are less than +/-5cm and all within +/-10cm except for 2014 check points. Large 2014 check point errors are assumed to be the result of poor location selection.

Visual inspection of these datasets reveals significant changes in the glacier surface occurred between 2014 and 2015, including the lateral migration of ice cliffs, collapse of the calving face and appearance/disappearance of surface melt ponds. Significant changes have also visibly occurred within the proglacial lake system, notably changes in pond dimensions and locations, suggesting buried ice remains within these sediments and melting can cause elevation changes and shift hydrologic pathways. Observation of these fine scale changes in the glacier surface could not be readily and inexpensively obtained using other technologies.

**Glacier Change**

The 2014 DEM was subtracted from the 2015 DEM to quantify elevation change and calculate total ice volume change (Figure 4a and b). Negative values indicate ice loss for a given 10cm pixel location in meters. The total ice volume loss from 2014 to 2015 for the glacier area (blue polygon) was 156,000m$^3$, equivalent to a mean elevation change of -0.75m between the survey dates. It is important to note that despite this considerable loss of ice volume, the glacier terminus experienced very little horizontal retreat. This shows how important quantifying glacier volume is for assessing changes in these glaciers, as simple area loss calculations (e.g. from aerial/satellite imagery) would indicate little to no glacier change had occurred between the survey dates. Manual feature tracking reveals a maximum surface velocity of 27m/yr in the upper section, slowing to 4m/yr at the glacier terminus (Figure 4c). Low surface velocities of 0.5-2m/yr were also measured over the sediments in the proglacial lake, suggesting that they remain connected to the glacier and are being pushed downslope by it.
The pattern of ice loss is highly heterogeneous. The greatest ice loss was at the calving face, where 18m of vertical ice loss was measured. Directly behind the calving face considerable ice mass was also lost, suggesting that the calving face provided a buttressing effect for the area behind. Large amounts of ice loss (over 10m of elevation decrease) were also measured in association with exposed ice cliffs and surface melt ponds on the glacier surface. Due to the thick (>1m) debris cover, the ice surface is insulated from direct solar radiation, reducing the rate of ice melt and allowing the glacier to persist at this relatively low elevation. When this debris mantle is removed, as at an ice cliff, the ice is directly exposed and melts rapidly. Ice cliff retreat rates of up to 25m/yr were measured (Figure 5). Similarly, meltwater ponds on the glacier surface lower the surface albedo and warm up in the equatorial sun. This warm water penetrates to the glacier surface and increases melt rates. Rapid drainage of these ponds through sub and supra glacial channels can further increase rates of ice loss.

Areas of elevation gain were also observed. Elevation gain is attributed primarily to the movement of large surface features (e.g. boulders, ridges, cliffs) through the scene between the survey dates, as opposed to accumulation. For example, the largest elevation gain is visible in the upper right corner of Figure 4b, and close inspection of the orthomosaic shows that a large boulder moved through the scene atop the glacier resulting in a measured elevation increase at its location in 2015 and an equivalent elevation decrease at its location in 2014. Inspection of other regions of elevation gain can be attributed to the movement of similar surface features. Another possible explanation for increases in elevation is ice emergence, where the glacier is pushed upwards due to topographic features on the glacier bed or significant changes in glacier flow direction. However, in this section of the glacier neither of these scenarios is likely, so ice emergence is unlikely to have contributed to the observed elevation increases.
Figure 5. Rapid retreat of ice cliffs across the glacier surface. Yellow arrows indicate horizontal movement of ice cliff position from 2014 (left) to 2015 (right); with a maximum rate of 25m/year. NOTE: 2015 images have been shifted (georectified) to 2014 positions based on velocity vectors (Figure 4c), i.e. horizontal glacier movement is removed so that the same location relative to glacier surface is compared.

The proglacial lake can be divided into two sections. The lower section is a large contiguous water body that begins at the lower (southern) edge of the survey area. The lake level is controlled by a reinforced dam at the lake outflow, installed as part of lake stabilization efforts by the Huaraz glaciology office in the 1970's (Portocarrero, 2014). This section of the lake remains relatively static due to these mitigation efforts and was not included in the UAV survey. The upper section is a combination of mixed glacial sediments from fine clays to large boulders and ponds that are up to 1.4ha in area. Extensive changes were detected within this section of the lake. Notably, the appearance, disappearance, expansion and contraction of ponds during the one-year survey interval (Figures 1 and 6). These coincided with up to 5-10m of elevation loss, indicating that large masses of relict glacier ice remain buried within the lake sediments (Figures 4a and 6). Pond elevations are offset from one another and sit up to 4m above the elevation of the main lake. Minimal surface drainage features are evident indicating that many of these ponds are hydrologically disconnected. This situation could contribute to increased lake instability as rapid drainage of these larger perched ponds could result in flooding of the lower lake and potential overtopping of the control dam. As the proglacial lake expands up valley (north) due to continued glacier recession, this risk is likely to increase as the lake becomes closer and more exposed to avalanche and landslide paths from the steep slopes of the valley headwall.
CONCLUSIONS

This study deployed an autonomous UAV to map changes over the debris covered Llaca glacier in the Peruvian Cordillera Blanca from July 2014 to 2015. The custom-built hexacopter UAV proved highly capable of operating out of line of sight within high altitude (>5000masl) complex mountain topography. Glacier change at Llaca between the UAV survey dates was highly heterogeneous. Average ice loss over the glacier survey area was 0.75m, equivalent to a total loss of 156,000m³. Debris cover, exposed ice cliffs and surface ponds control patterns of observed glacier change. Additionally, significant changes were observed within the proglacial lake and may increase potential GLOF risk. The extreme heterogeneity of this environment is impossible to observe and measure using traditional methods of field survey and/or satellite remote sensing. DEMs constructed with UAV/SfM can provide unique insights into glacier changes that are difficult and costly to obtain through other high spatial resolution methods like TLS, airborne LiDAR and photogrammetry. The continued development of methods and technology for increasing the maximum survey area (i.e. increasing flight time) and minimizing required ground control (due to accessibility limitations) is essential for the further application of this method to glaciological research.

ACKNOWLEDGEMENTS

This study was co-funded by NSF Grants: BCS-1010550 and BCS-1434248, The American Philosophical Society, The American Geographical Society, The Explorers Club, The Geological Society of America and The Ohio State University Office of International Affairs. Additional support in the form of GNSS equipment loan for 2014 was provided by the UNAVCO Facility with support from the National Science Foundation (NSF) and National Aeronautics and Space Administration (NASA) under NSF Cooperative Agreement No. EAR-0735156. Permission to operate the UAV within the Huascaran National Park was provided by the Parque Nacional Huascaran Office in Huaraz.
REFERENCES


