Remote Sensing and Hydrology 2010 (Proceedings of a symposium held at Jackson Hole, Wyoming, USA, September 2010) (IAHS Publ. 352, 2012).

Hydrological implications of periglacial expansion in the Peyto Glacier catchment, Canadian Rockies

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Abstract Multi-temporal photogrammetric and lidar-based DEMs collected over the Peyto Glacier (1949, 1966, 1993, 2000, 2010) were analyzed to quantify rates of glacial and periglacial volumetric change. During this time, exposed glacier ice area has reduced by 18% from 14.2 to 11.6 km^2, while the actively downwasting lateral moraine area has increased by 70% from 0.53 to 0.90 km^2. This opposite trend results in an exponential increase in the periglacial areal proportion of actively downwasting surfaces. Mean annual volumetric loss from the glacier surface has been 14 x 10^6 m^3, with active moraine downwasting accounting for a further 0.6 x 10^6 m^3 (4.5%). Moraine volumetric losses from 2000 to 2010 were > 6%, with an additional >2% in small hanging glacier and perennial snow patch areas. These results indicate that while Peyto Glacier is undergoing continuous retreat, runoff from periglacial areas ignored in the mass balance record account for up to 8% of contemporary losses from basin storage. Lidar data were essential to this analysis, as accurate stratification of glacial and periglacial volumetric changes are not normally feasible using traditional field and photogrammetric mass balance techniques.

Keywords lidar, DEM, glaciology, change detection, mass balance

INTRODUCTION

Glaciers in the Canadian Rockies play a key role in moderating downstream runoff but continued recession poses a risk to long term water resources (Demuth *et al*, 2008). As long term storages of exposed ice are lost and glacial runoff decreases, the relative proportion from other sources can increase. Extensive ice-cored moraines exist in the glaciated headwaters of the Rockies (Østrem and Arnold, 1970) and while there have been attempts to model ice melt from these areas (e.g. Nakawo and Young, 1982), mapping and quantifying the presence of ice-core and debris cover thickness has long been considered a challenge (Østrem, 1964). Due to an inability to pinpoint and access debris-covered ice locations, field mass balance campaigns rarely measure ice-core ablation. Furthermore, while geodetic mass balance can be monitored using stereo photogrammetry, such methods can be unreliable over moraines due to shadowing from surrounding peaks. This paper summarizes the findings of a photogrammetric and lidar study of changing surface elevation within Peyto Glacier catchment in the Canadian Rockies (Figure 1).

At Peyto Glacier, extensive ice-core has been observed within lateral moraines following localized slope failures (Johnson and Power, 1985). Contemporary field observations of occasional ice exposures and meltwater seeps at the base of moraines confirm these are hydrologically active areas of Peyto's periglacial landscape. The process of ancient lateral moraine ice-core formation is not known with certainty but the rapid rate of present-day glacial downwasting is visibly increasing ice-cored moraine extent through a process of slope debuttressing and colluvial deposition. This expansion of the periglacial environment is therefore associated with an increase in storage of buried ice. On the northwestern side of Peyto Glacier, this process has led to a positive feedback, whereby the shallow debris cover that travels further onto the glacial ice accelerates melt, while the deeper debris cover at the margins retards melt (Østrem, 1959). This differential melt rate locally increases lateral moraine slope angle, which further reduces slope stability, thus accelerating the entrainment and insulation of glacial ice within the moraine. While these processes are active at Peyto Glacier, the impracticality of in situ monitoring means we have little information on the rates of glacial ice entrainment or of ice-cored moraine downwasting. Using remote sensing to monitor long-term area and elevation changes in both the glacial and periglacial environments, some insight into the potential meltwater contribution from ice-cored moraines is possible.

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METHODS

A record of area and volume changes at Peyto Glacier from 1949 to 2010 was reconstructed by comparing digital elevation models (DEMs) from archived aerial photos (1949, 1966 and 1993) and airborne lidar (2000 and 2010). Photographic stereo pairs covering the Peyto Glacier ablation zone were collected by the Royal Canadian Air Force (1949) and the Department of Energy, Mines and Resources, Canada (1966, 1993). The photo scales were approximately 1:33,000; 1:40,000; 1:50,000, respectively, on diapositives (Geomatics Canada, National Air Photo Library, Ottawa). Ground control data were collected in 1998 using a total station over bedrock terrain features that could be identified on the images. DEMs were derived at 3 m grid spacing for each pair using a digital photogrammetric workstation. The accumulation area surface extents for 1949 and 1966 were digitized from hard copy maps derived from the same air photos, while for 1993 the extent was inferred from a ground survey conducted in 1989. For the 2000 and 2010 DEMs, lidar surveys covering the entire glacier surface were flown during late summer using Optech ALTM (airborne laser terrain mapper) 1225 and 3100 instruments, respectively. These data were registered to a nearby control point using differential GPS. The lidar point data were converted to raster DEMs at 1 m resolution using a triangulated irregular network (TIN) interpolation.

Both the photogrammetric and lidar DEMs were transformed to a common NAD83 horizontal and CGVD28 vertical reference frame to enable direct comparison within a GIS. Exposed glacier ice and active lateral moraine extent for each DEM was manually digitized using both the shaded relief rendering of the DEM and either the black and white image of the air photos or the intensity image of the lidar data (e.g. Arnold *et al*., 2006). Downwasting and volume loss calculations were performed by subtracting the surfaces. The digitized glacier ice extent for each dataset was used as a mask to stratify the difference surfaces into glacial and periglacial areas. Geomorphic and snowpack surface growth was also investigated although is not reported here.

RESULTS & DISCUSSION

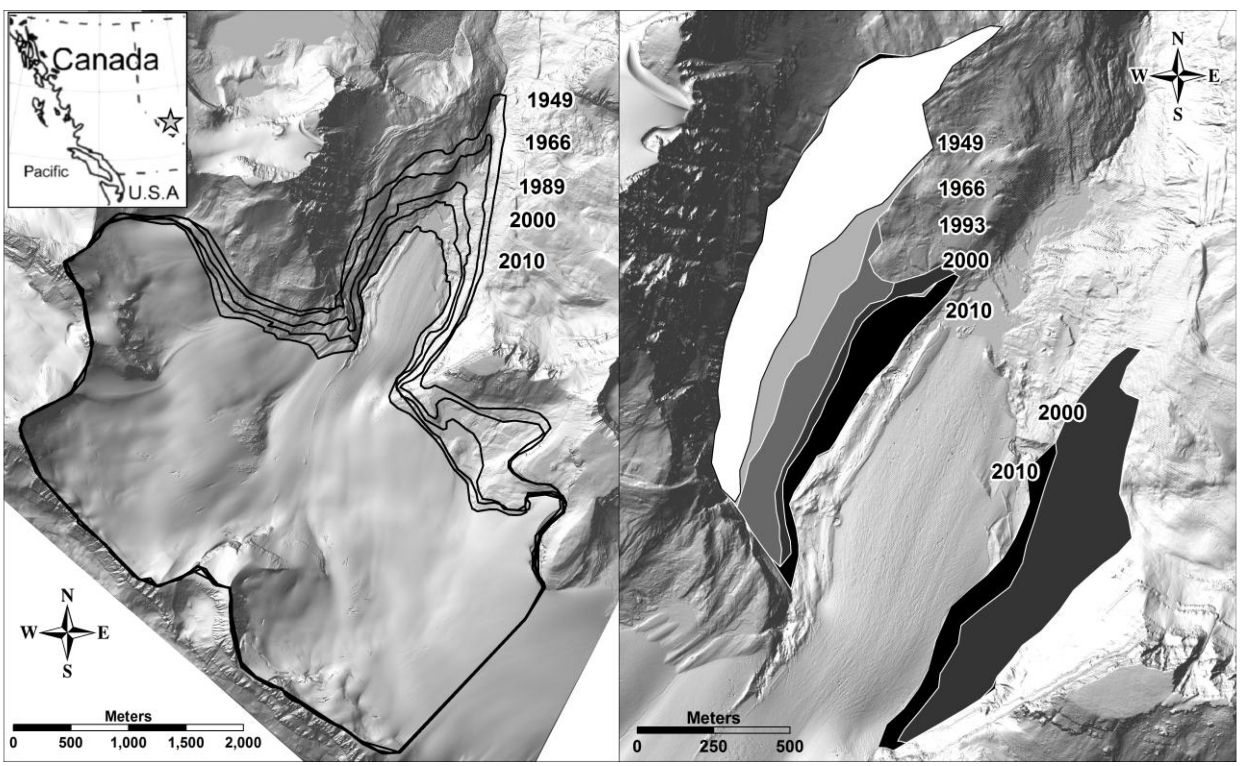

Figure 1. Visible glacier (left) and active lateral moraine (right) extents mapped from air photos in 1949, 1966, 1993 and lidar in 2000 and 2010. Outlines transposed onto surface relief rendering of the 2010 lidar DEM. Study area location inset.

Glacier ice and lateral moraine extents for the years studied are illustrated in Figure 1. The area of exposed glacier ice on the main body of Peyto Glacier reduced from 14.2 km^2 in 1949 to 11.6 km^2 in 2010. This constitutes a total loss of 2.6 km^2 (19%) in area or approximately 14 x 10^6 m^3 yr^{-1} in volume. While air photo DEMs covering the lateral moraines on the northwestern side of the ablation zone were readily generated and compared, the smaller lateral moraine extent on the southeast side could not be accurately digitized from the air photos due to solar shadowing. This area was digitized from the lidar data in 2000 and 2010 and in both years was found equal to ~37% the total moraine area. Assuming this proportion remained constant, the total area of downwasting lateral moraines increased by approximately 70% from 0.53 km^2 in 1949 to 0.90 km^2 in 2010.

Of note, a linear reduction in the exposed glacier ice area of approximately 0.04 km^2 yr^{-1} has been accompanied by an exponential increase in the proportion of actively downwasting lateral moraine area from less than 4% in 1949 to almost 8% in 2010 (Figure 2 left). While these trends reflect the last 61 years of activity at Peyto Glacier, extrapolating forwards suggests that the area of exposed ice cover will completely disappear within 250 years, and lateral moraines will account for 50% of the actively downwasting surface in approximately 150 years. However, such extrapolation is academic and not to be taken too seriously, as glacier area is influenced as much by local geology as it is surface lowering, and it is unlikely that the climatic of the last 60 years represents that of future centuries. Nonetheless, given glacial recession coincides with periglacial expansion, it is reasonable to assume that the proportion of meltwater generation originating from ice-cored lateral moraines will increase at an exponential rate.

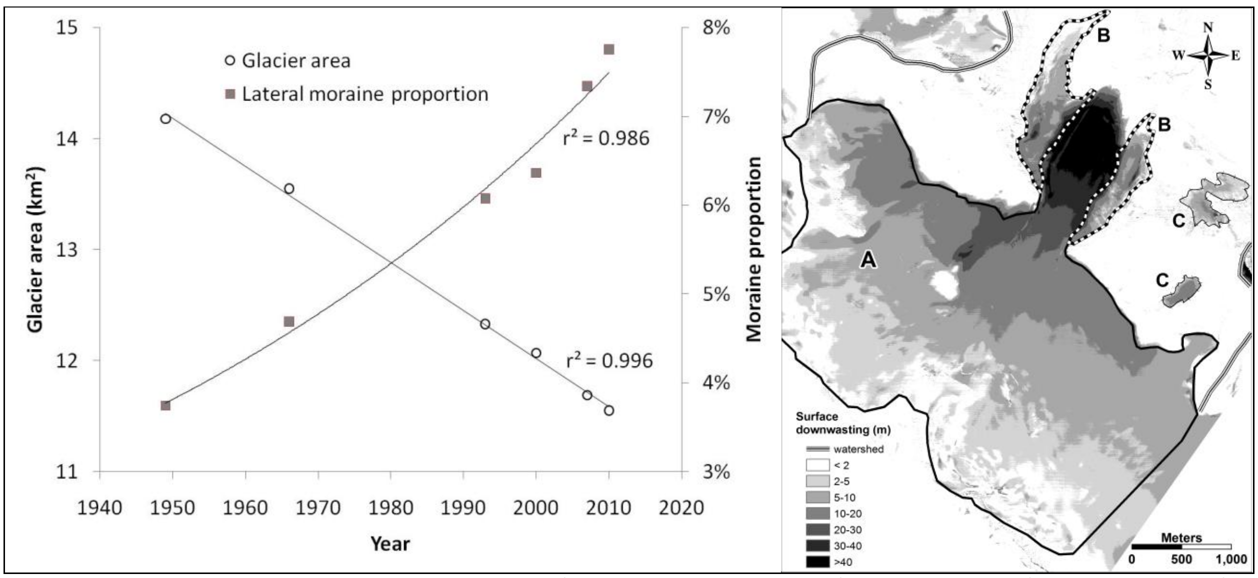

Figure 2. Changing visible glacier area and relative proportion of downwasting lateral moraines from 1949 to 2010 (left) and net decadal surface lowering on and around the Peyto Glacier captured in lidar data from 2000 to 2010. Solid black line is Peyto Glacier extent in 2010, while dashed line illustrates ice-cored lateral moraine. 'A' is the exposed ice; 'B' represents active lateral moraine; 'C' highlights two areas of hanging glacier and perennial ice pack that are disconnected from the main glacier body and are not included in field mass balance measurements.

Surface downwasting for the ten years captured in the lidar imagery, is illustrated in Figure 2 (right). It is clear that while the entire glacier surface has experienced a drop in elevation, surface lowering has exceeded 40 m over the tongue of the glacier, with up to 30 m associated with lateral moraine crests. Some of the moraine downwasting is due to geomorphic slope creep and gravitational redistribution of colluvium, and undoubtedly a fraction of the associated volume is lost through sediment dissolution and direct exports via the sub-glacial drainage system. Consequently, the wastage volumes associated with these periglacial areas represent the upper limit estimate of loss due to ice-core melt. Based on recorded summertime basin yields of ~ 45 x 10^6 m^3 (Young, 1982) and assuming limestone density of 2000 kg m^{-3}, if the observed 0.63 x 10^6 m^3 of downwasted moraine were exported as suspended sediment, the average concentration would have to be 28 g l^{-1}. This is approximately two orders of magnitude greater than concentrations observed in Peyto Creek during the summer of 1987 (Chikita, 1993) and indeed would be an extremely large value for any water body. It is believed, then, that by far the greater proportion of observed lateral moraine wastage is due to internal ice core melt. This means that relative to the monitored glacial component, meltwater from unmonitored moraines has contributed an additional 4.5% over long term or > 6% in the last decade to basin yield. With the areal proportion of active lateral moraine expanding at an exponential rate, this means proportional ice melt contributions from these zones are likely to also increase for some time to come.

Other obvious features in the lidar change detection surface are the areas of glacial downwasting denoted with the letter 'C' in Figure 2. Long term fragmentation of the main body of ice has left behind a small hanging glacier and a stagnant ice patch that are not sampled as part of the field mass balance. The losses from these areas are comparatively small, however, and amount to only 2% of the overall glacial wastage at Peyto. Nonetheless, like the moraine features, not considering these areas will lead to systematic errors in the glacial mass balance and given their high location in the basin, their relative contribution to net balance is likely to increase with time until they disappear.

The areas of downwasting associated with ice-cored lateral moraine and disconnected ice cover together amount to a contemporary ice storage loss that is equal to 8% of the net annual wastage of the exposed glacier area. Extrapolating this proportion to the Bow River at Banff (2200 km^2) based on relative glacier area, and combining with an estimated 12% glacier wastage contribution during drought years (Hopkinson and Young, 1998), we estimate that approximately 1% of the total basin yield during such dry years is currently due to losses from long term periglacial storage.

CONCLUSIONS

Given ice storage losses from periglacial areas are typically not well represented in field or photo-based geodetic mass balance records, the results presented here suggest that for Peyto Glacier: a) the proportion of periglacial runoff contributions from ice-cored moraines are increasing; b) the current mass balance record likely under-estimates the total glacial contribution to basin runoff by up to 8%; c) airborne lidar offers the only practical method of monitoring surface lowering over active lateral moraine areas, highly reflective glacial accumulation zones, and stagnant patches of disconnected (possibly debris covered) ice at high elevations.

ACKNOWLEDGMENTS

The presented research is the result of a monitoring partnership between the Geological Survey of Canada, the Canadian Consortium for LiDAR Environmental Applications Research, and the Applied Geomatics Research Group, Nova Scotia Community College.

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