Can. J. Remote Sensing, Vol. 32, No. 2, pp. 212–222, 2006

Using airborne lidar to assess the influence of glacier downwasting on water resources in the Canadian Rocky Mountains

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Abstract. Knowledge of the changing dimensions of alpine glacier surfaces is critical from both a water resources and climate change indication perspective. With the development of airborne light detection and ranging (lidar) technologies with the capability to rapidly map large areas of topography at high resolutions, there is a need to assess the utility of this technology for glacier surface change detection and water resources assessment. The study presented here compares two lidar digital elevation models (DEMs) collected 23 months apart in 2000 and 2002 over Peyto Glacier, Canadian Rocky Mountains, for the purposes of intensity image feature recognition and surface downwasting assessment. The 2002 DEM was subtracted from the 2000 DEM to quantify the total and spatial variability in surface downwasting (or growth) within the glacial and periglacial environments. It was found that there was a reduction in volume totaling 33×10^6 m^3 over the Peyto Glacier surface and surrounding ice-cored moraines. This downwasting was estimated to be equivalent to approximately 22×10^6 m^3 of water volume and, after extrapolation, 16% of total basin runoff. The water-equivalent contribution from ice-cored moraines was estimated to be 6% of the total glacier runoff contribution, highlighting the importance of monitoring this component of glacial melt.

Résumé. La connaissance des changements dans la dimension des glaciers alpins est essentielle en tant qu'indice des ressources en eau et de changement du climat. Avec le développement des technologies lidar aéroporté (« light detection and ranging ») qui permettent de cartographier rapidement de vastes étendues de topographie à de hautes résolutions, il est nécessaire d'évaluer l'utilité de cette technologie pour la détection des changements de surface des glaciers et l'évaluation des ressources en eau. Cette étude compare deux modèles numériques d'altitude lidar (MNA) acquis à 23 mois d'intervalle en 2000 et 2002, au-dessus du Glacier Peyto, dans les Rocheuses Canadiennes, pour fins de reconnaissance des caractéristiques des images d'intensité et l'évaluation de la surface de fonte du glacier. Le MNA de 2002 a été soustrait du MNA de 2000 pour quantifier la variabilité totale et spatiale de la surface de fonte (ou croissance) dans les environnements glaciaire et périglaciaire. On a pu observer une réduction du volume totalisant 33×10^6 m^3 pour l'ensemble de la surface du Glacier Peyto et les moraines à noyau de glace environnantes. La fonte a été estimée à approximativement 22×10^6 m^3 du volume d'eau et, après extrapolation, à 16 % du ruissellement total du bassin. La contribution en terme d'équivalent en eau des moraines à noyau de glace a été estimée à 6 % de la contribution totale du glacier et l'importance du suivi de cette composante de la fonte glaciaire a ainsi été soulignée.
[Traduit par la Rédaction]

Introduction

Since the end of the Little Ice Age in the 19th century (Grove, 1988), European and North American alpine glaciers have retreated to higher elevations and lost large volumes of ice (Haeberli et al., 1999). Direct consequences of this glacial "wastage" are an increase of local streamflow above the net income of annual precipitation and increases in global sea level (e.g., Arendt et al., 2002). Observations of glacier wastage in the Eastern Front Range of the Canadian Rockies have been recorded since 1887 (Meek, 1948), and the subsequent effect on basin water yields has been previously explored (Collier, 1958; Henoch, 1971 ; Young, 1991, Hopkinson, 1997; Hopkinson and Young, 1998; Demuth and Pietroniro, 2002). Using photogrammetric interpretation techniques to infer glacier recession and mass balance, it was calculated that glacier loss within the Upper North Saskatchewan Basin (1500 km^2) between 1948 and 1966 equated to 4% of total basin yield (Henoch, 1971). Young (1991) studied glacier loss between 1966 and 1989 in the Mistaya Basin (247 km^2), a subbasin of the Upper North Saskatchewan, and found that total glacier area reduced from 12.1% total basin cover in 1966 to 10.8% in 1989. This areal loss was estimated to be approximately 340×10^6 m^3 of water equivalence, or 6% of basin yield. For the extreme drought year of 1970, it was calculated that approximately 25% of the annual basin yield was derived from glacier wastage (Young, 1991). Hopkinson (1997) compared photogrammetric digital elevation models

Received 13 October 2005. Accepted 17 February 2006.

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(DEMs) of glacierized areas within the Bow Valley to calculate glacier wastage from 1951 to 1993, and Hopkinson and Young (1998) combined these results with interannual meteorological and glacier mass balance data collected at Peyto Glacier to quantify the variable contributions of wastage to river runoff through time. It was estimated that in a severe drought year, the 3% of glacier cover within the Bow River basin above Banff could contribute up to 13% of the annual yield in excess of annual precipitation inputs. Demuth and Pietroniro (2002) examined possible streamflow regime shifts in the eastern slopes of the Canadian Rocky Mountains in association with observed glacier diminution and meteorological evidence for the latter half of the 20th century. They determined that the regulatory effects of glacier cover in the Mistaya Basin appear to be in decline, citing, despite modest increases in precipitation for the region, reduced low and mean flows for the August to October period accompanied by increases in flow variability and somewhat higher maximum flows.

Common to these and many similar studies was the necessity to use photogrammetric image data acquired over long periods of time (e.g., 10 years) so that the actual changes observed in glacier extent and surface elevations would be greater than the margins of error (e.g., Østrem, 1986; Reinhardt and Rentsch, 1986; Rentsch et al., 1990). Photogrammetric errors in glacier extent and elevation are maximized in snow-covered accumulation areas because it can be impossible to accurately define glacier edges, and the lack of surface relief and texture compromises stereo image alignment. For glacier melt investigations over seasonal and interannual time scales, the traditional solution has been to conduct field glacier mass balance investigations to periodically measure mass gain and loss at a network of points and transects distributed over a "representative" glacier for the region (Østrem and Brugman, 1991; Jannson et al., 1999). These field mass balance data are effectively point measures and, given the large glacier areas and manually intensive methods involved, it is difficult to quantify the level of uncertainty involved in extrapolating these point measurements to the complete glacier surface or the regional scale (e.g., Fountain and Vechia, 1999). The study presented here tests relatively new airborne light detection and ranging (lidar) technology that has the potential to both (*i*) bridge the gap between traditional field and photogrammetric alpine glacier mass balance investigations, and (*ii*) extend the capability of glacier volume change assessment into surrounding periglacial environments.

Airborne lidar combines knowledge of the speed of light, the location and orientation of a laser head in four-dimensional space, and the time between laser pulse transmission and reception to determine a fixed coordinate on the ground (Wehr and Lohr, 1999). The positions of laser pulse return survey points on the ground are calculated relative to the aircraft platform trajectory. The trajectory position and orientation are fixed using two differential kinematic global positioning system (GPS) receivers located on the aircraft and on the ground over a known control point and an onboard inertial measurement unit (IMU) to monitor platform pitch, roll, and yaw. Older research-based lidar sensors (or laser altimeters) have been successfully utilized in "profiling" mode for various glaciological applications over Greenland (Krabill et al., 1995), the ice caps and mountain glaciers of the Canadian Arctic Islands (Abdalati et al., 2004), and large glacier complexes in Alaska (Echelmeyer et al., 1996). Within the last 2 years, a satellite laser altimeter (ICESat) has been put into space for the purpose of short-term ice surface elevation monitoring over large Arctic and Antarctic ice sheets (e.g., Csatho et al., 2005). In commercial airborne lidar sensors employing scanning technology, laser pulses are scanned across the flight line, resulting in a "swath" of ground survey points beneath the aircraft. An early demonstration of the efficacy of airborne scanning lidar for glacier surface mapping in an alpine mountain environment was provided by Kennet and Eiken (1997). High correspondence between adjacent laser shots was found, with absolute errors of approximately 10 cm. The utility of multitemporal lidar acquisitions for decimetre-level snow depth mapping was first demonstrated by Hopkinson et al. (2004) over a wooded lowland environment.

The objectives of this study are summarized as follows: (*i*) perform a lidar DEM intercomparison for the Peyto Glacier to quantify surface downwasting volumes on and off the glacier; (*ii*) utilize the information content in lidar active infrared intensity images to delineate snow- and ice-covered regions on the glacier surface; and (*iii*) quantify the influence of the observed glacier downwasting on river runoff.

Study area

Peyto Glacier, at the northern end of the Wapta Icefield and the southwestern corner of the Mistaya basin (247 km^2), lies at the head of the North Saskatchewan River basin, 100 km north of Banff, Alberta (**Figure 1**). Peyto Glacier currently hosts a glaciological research and monitoring station and has been extensively studied since 1966 when it was chosen for inclusion as a reference site for the 1965–1975 International Hydrological Decade (Østrem, 2005) and remains a focal point for much glaciological research activity (Chasmer and Hopkinson, 2001; Watson and Luckman, 2004; Demuth et al., 2005), including investigations into satellite-based techniques for monitoring mass balance (Demuth and Pietroniro, 1999). Peyto Glacier ranges in altitude from approximately 2100 to 3150 m above sea level (asl), covers approximately 9.2 km^2 (approximately 40% of the total glacier cover in the Mistaya Basin), and has undergone significant terminus recession (approx. 1 km) and a long-term net mass balance loss since the start of formal observations in 1966 (Demuth and Keller, 2005; Luckman, 2005).

Methods

Two airborne lidar surveys were conducted over the mountainous headwaters of the South and North Saskatchewan River basins (**Figure 1**) during late 2000 and 2002. The 2000

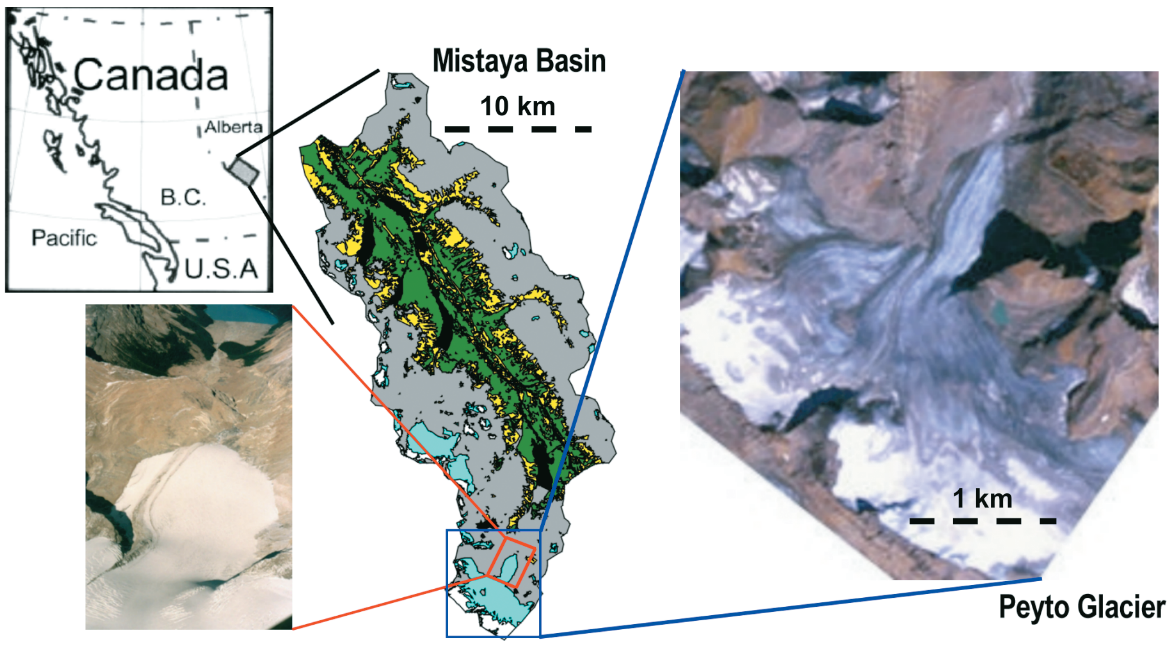

Figure 1. Location of the study area in Alberta and the Mistaya Basin land covers (grey, bare ground; green, forest; yellow, grassland; blue, glacier ice; white, snow). To the right in the figure is a Landsat thematic mapper (TM) false colour composite of Peyto Glacier in September 1998, and to the left is an oblique aerial photograph of the Peyto Glacier terminus on the day of survey, 25 September 2000.

Table 1. Lidar survey parameters for both data acquisitions.

Date	ALTM sensor	PRF (kHz)	Survey altitude (m agl)	Line spacing (m)	Scan rate (Hz)	Scan angle (°)	Point spacing at 1500 m agl (m)
25 Sept. 2000	1225	25	1000–2500	500	20	±20	2.0
22 Aug. 2002	2050	50	1000–2500	500	30	±18	1.2

Note: agl, above ground level; PRF, pulse repetition frequency.

survey covered most of the Wapta Icefield on the Alberta side of the Continental Divide north of Lake Louise (Hopkinson et al., 2001), and the 2002 survey covered just the northern end of the Wapta Icefield and straddled the Continental Divide. Both surveys overlapped in the area of Peyto Glacier at the head of the Mistaya Basin. The first survey was conducted on 25 September 2000 using an Optech Inc. (Toronto, Ont.) 1225 airborne laser terrain mapper (ALTM) shortly after a light snowfall, which covered the glacier surface with up to a few centimetres of fresh snow. The second survey was conducted 23 months later on 22 August 2002 using an ALTM 2050 during warm temperatures and active melt in the glacier ablation zone. The surveys were conducted in early afternoon during clear sky conditions, and in each case all data were registered to a dual-frequency GPS receiver positioned over a survey monument located at Bow Summit on the Icefields Parkway 5 km north of the Peyto Glacier terminus. The ALTM 1225 and 2050 are similar lidar instruments, with the main difference being that the 1225 operates at 25 kHz (i.e., emits 25 000 pulses per second), while the 2050 operates at 50 kHz, and the 1225 has a slightly shorter maximum detection range. These differences do not necessarily impact the accuracy or characteristics of point data on the ground, but the lower frequency and shorter range 1225 will display a reduced sampling density on the ground. Both ALTMs emit a 1064 nm near-infrared wavelength laser pulse with a footprint diameter on the ground of from 0.3 to 0.6 m for the altitudinal ranges experienced. Survey configuration parameters are summarized in **Table 1**.

Several days prior to the second survey, on 16 August 2002, a kinematic ground GPS survey was undertaken for the purpose of validating the airborne lidar data. The purpose of this validation was to quantify the level of vertical error within the data. For lidar elevation data collected over well-defined surfaces, the manufacturer-quoted standard deviation vertical accuracy of the ALTM is ±0.15–0.30 m for the altitudinal ranges experienced in these surveys. Ground validation control points were surveyed at 50 m intervals either side of the steep (~5% gradient) Icefields Parkway on Bow Summit. This was achieved by “stop and go” kinematic surveying using a dual-frequency GPS receiver, which was differentially registered to another dual-frequency GPS base station located over the same control point used to control the lidar data. After the GPS and lidar data were processed, the ground-control data were compared with all laser pulse returns within a 1 m radius of each GPS control point. This was carried out independently for lidar data collected at the start and end of the second survey to assess any drift in accuracy during the airborne survey. Unfortunately, the area covered in the first survey did not overlap with this validation area and so accuracy could not be assessed. However, there is no reason to suspect that accuracy levels would be significantly different from those of the second survey or those reported by Kennet and Eiken (1997). Due to ice melt changes in glacier surface elevation near the time of the surveys and limited field resources, it was not possible to collect GPS validation data over the actual glacier surface during either of the airborne surveys. This does not pose a problem for the analysis though, as laser pulse return accuracy reduces as laser range increases, and the glacier surface elevations lie mostly above those of the highway validation area.

The GPS trajectory, IMU, laser ranges, scan angle, and calibration parameter data were integrated by the service provider (Optech Inc.) to generate the Universal Transverse Mercator (UTM) coordinates and intensity readings of laser pulse returns from the ground surface. (Intensity readings are arbitrarily scaled to an eight-bit range and produce a single-channel image similar to a black and white photograph.) Following delivery of the lidar point data, a 5 km × 5 km area surrounding Peyto Glacier was extracted from both datasets and gridded using an inverse distance weighted algorithm in Surfer® (Golden Software Inc., 2002) to a 2.5 m grid cell spacing. An inverse distance routine was chosen because it maintains point integrity, enables the interpolation of nearby blank cells using a simple distance weighted function, and is relatively fast. Grids were created of both elevation and eight-bit laser pulse intensity. To quantify the volumes of potential glacier downwasting, surface growth, or alpine mass movements over the intervening 23 month period, the 2002 DEM was subtracted from the 2000 DEM.

The DEM change detection analysis was focused on three land covers that are of particular interest from a water resources point of view: glacier surface above the snowline; glacier surface below the snowline; and periglacial ice-cored moraine surrounding the terminus of the glacier (Johnson and Power, 1985). The glacier surface was divided into above- and below-snowline areas because it is logical to assume that most of the volume lost (if any) above the snowline will have been in the form of snow and therefore will have a relatively low density or snow water equivalence (SWE) of approximately 0.3 (30% that of water), whereas the majority of volume lost below the late summer snowline will be in the form of ice or firn and have an SWE approaching 0.9. (No SWE data were collected during this study, but these values are based on field data collected by the authors over several years and are considered reasonable estimates.) Any changes in the surrounding periglacial environment will most likely be due to mass movement or the melting of ice-cored moraines. It should be relatively simple to distinguish between these changes because mass movement will simply act to redistribute volume from one location to another, whereas the melting of ice within moraines will mainly act to reduce rather than redistribute volume.

To isolate the three glacier regions, each was manually digitized from the lidar DEM and intensity images. The glacier boundary for the DEM subtraction process was defined from the 2000 acquisition, and the late summer snowline was identified and digitized from the 2002 data. The regions of lateral ice-cored moraine surrounding the glacier terminus were digitized from a shaded relief image (no intensity) of the 2002 lidar data. This process was eased because the authors have extensive knowledge of the area in question gained from annual field visits over more than a decade of research at Peyto Glacier.

Following the calculation of volume change within each of the three hydrologically important glacier zones, these volumes were multiplied by their estimated SWE values to provide an estimate of total runoff volume lost from the glacier over the 23 month period. To put these volume loss estimates into a water resources context, they were extrapolated up to the Mistaya Basin scale and compared with the total basin runoff monitored by the Water Survey of Canada during this period (Environment Canada, 2005). The extrapolation was performed by assuming that Peyto Glacier was representative of the glacier cover for the whole basin and that glacier area is a reasonable indicator of glacier meltwater production.

Results and discussion

Raw lidar data

For the 2000 survey polygon over Peyto Glacier, approximately 20 000 000 laser pulse returns were recorded, providing an average point density of 0.8/m^2. This point density varied with elevation, however, resulting in better than 1.2/m^2 at high elevations over the accumulation zone and around 0.5/m^2 in the valley bottom. In 2002 there were approximately 48 000 000 returns recorded over the same area, resulting in an average point density of 1.9/m^2, varying from approximately 1.0 to 3.0/m^2 in the valley bottom and upper mountain slopes, respectively. In both survey areas, point density decreased at lower elevations due to a wider swath, but this was slightly compensated by increased swath overlap.

Validation data

The lidar validation data collected over the nearby Icefields Parkway in August 2002 are presented in **Figure 2**. It was found that for two swaths of lidar data collected prior to the glacier survey, there were 516 laser hits within 1 m of the 67 GPS ground-control points collected. For a single swath collected after the glacier survey, this dropped to 248 hits. After comparing raw laser pulse returns with the ground-control points it was found that there was a bias of –0.03 m in the pre-survey lidar swath data and +0.02 m in the post-survey swath data, with a combined root mean square error (RMSE) of 0.07 m. These results demonstrate that there was no systematic elevational bias in the 2002 lidar data. Although horizontal error within the lidar data was not directly investigated, it can be inferred that horizontal error is small (at the decimetre level)

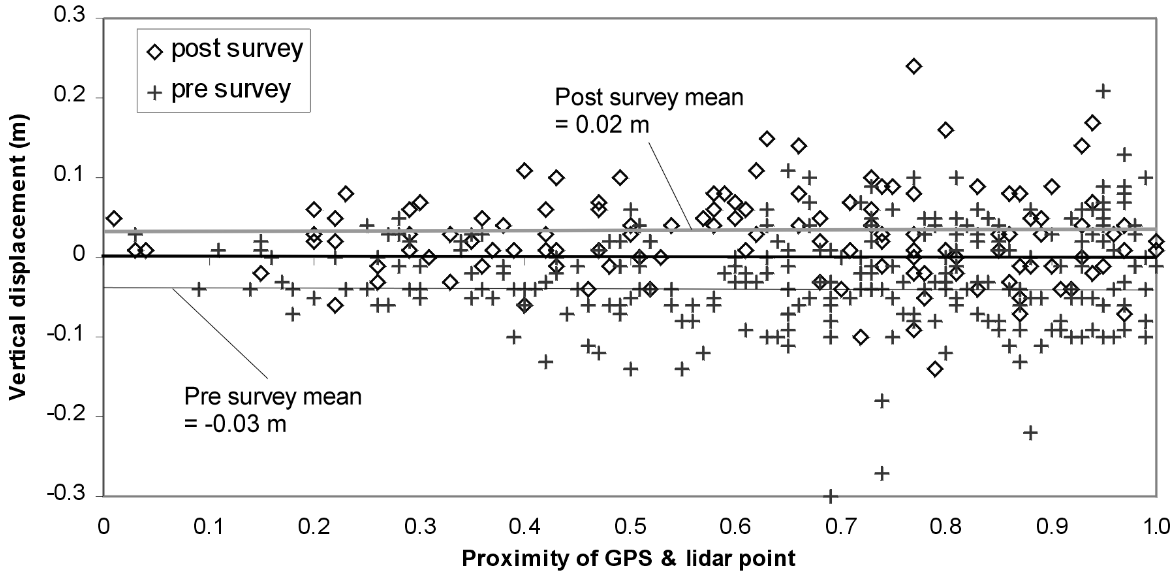

Figure 2. Ground validation GPS data collected over the Icefields Parkway in the vicinity of Peyto Glacier on 22 August 2002.

because the vertical RMSE is low despite the 1 m search radius around control points that were located on a steeply sloping highway surface (Hodgson and Bresnahan, 2004). Notably, the maximum change in elevation across a 1 m radius over a slope of 5% is 0.1 m.

Raster lidar and intensity data

The 2.5 m grid spacing raster DEMs of Peyto Glacier for 2000 and 2002 are presented in **Figure 3**. DEM grey scale shading is provided by draping the active near-infrared lidar intensity image data. Although differences in surface elevation are not discernible in these two DEMs, differences in lidar intensity between the two dates are clearly apparent. In both images, snow produces the most intense laser pulse returns, and bedrock areas at the same elevation are typically less reflective at the 1064 nm wavelength. The most obvious difference between the 2000 and 2002 lidar intensity data is the relatively high reflectivity of the entire glacier surface in 2000 and the low reflectivity of the glacier ablation zone below the clearly visible snowline in 2002. The survey in 2000 occurred the day following a light snowfall that left a shallow "dusting" of snow over the entire glacier surface, whereas snow falling on the valley sides probably melted upon contact. In contrast, the 2002 survey took place during a day of active meltwater production on the glacier surface and bare ice was exposed, thus leaving the late summer snowline clearly visible. Water is an effective absorber of infrared radiation, and the presence of water over the glacier ablation zone would have acted to reduce the amount of laser pulse backscatter.

There are two features of the intensity images in **Figure 3** that appear to have little to do with land cover, namely a gradual reduction in intensity at lower elevations and striping of the data at high elevations over snow cover. Gradual reduction of intensity at lower elevations is the result of larger pulse footprints at longer ranges, leading to a reduction in the pulse energy concentration at the ground surface. Striping in the image over high-elevation snow surfaces is likely influenced by two processes: (*i*) laser pulse ranges are longer at the edge of the swath and, consequently, the pulse energy is less concentrated; and (*ii*) for off-nadir laser pulses occurring near the edge of the swath, any tendency for specular reflection off the snow surface will preferentially distribute laser pulse backscatter away from the sensor. Although these instrument-based variations in intensity are readily apparent, the greatest control on lidar intensity in this glacierized environment is related to land cover (see Lutz et al., 2003).

The thematic content of the active lidar intensity data image is best illustrated in the closeup provided in **Figure 4**. The intensity image in **Figure 4** looks much like a black and white photograph. The land covers of snow, ice, firn, bedrock, and open water are readily distinguishable to the eye. This visual interpretation is particularly aided by the textural information contained in the image, illustrating striations and crevasses in the bare ice, the occurrence of firn at the interface of snow and ice, the large areas of homogeneity associated with snow cover, and linear geological features within bedrock. Unfortunately, this single channel of intensity data alone would be insufficient to accurately separate and classify the land covers discussed due to intensity range overlap, but combined with textural and proximity information, the active infrared intensity image could be used to aid such a classification (this is an area of ongoing research).

Glacier change detection analysis

Areas and depths of surface lowering identified in the DEM subtraction of 2002 from 2000 are illustrated in **Figure 5**. For much of the area surrounding the glacier, there is little to no surface lowering except in areas of small high-elevation hanging glacier and perennial snowpack. For the entire DEM subtraction, the downwasted volume equals 44.7×10^6 m^3. On the glacier surface itself, it is apparent that downwasting during the 2 year period varied from close to 0 m at the highest elevations of the glacier up to over 10 m on parts of the glacier terminus, with an average total glacier surface melt depth of approximately 3.4 m. Melt rate patterns are most variable over the glacier terminus. For example, (*i*) there are small regions of extreme change approaching 20 m due to ice surface collapse at the glacier snout and an icefall; and (*ii*) there is a relatively reduced rate of melt associated with two embedded medial moraines on the western side of the glacier terminus. Of note, downwasting along the western side of the glacier terminus exceeded that along the eastern side by >2 m. This more rapid loss of ice mass is further evidenced by the slight progradation of the medial moraine to the west, a process that has been in evidence since approximately 1995 when ice flux from the western basin of Peyto Glacier no longer provided nourishment to the glacier snout (see ICSI(IAHS)/UNEP/UNESCO/WMO, 2003, p. 29).

Of potentially significant interest from a water resources point of view are the areas of downwasting approaching 10 m observed in areas outside known snow- and ice-covered regions in the periglacial lateral moraines surrounding Peyto Glacier terminus. From experience in the field and limited documentation (Johnson and Power, 1985), these moraines are known to contain ice, and it is most likely that the downwasting observed is due to melting of the internal ice core. The most plausible alternative is active mass movement of the moraines (also known to occur frequently), but this is thought unlikely here for two reasons: (*i*) if the downwasting were the result of a mass movement, then an area of surface growth should be apparent near to and lower in elevation than the area of downwasting, and no such areas are apparent (**Figures 5** and **6**); and (*ii*) despite this being a dynamic alpine environment, no other similar areas of potential mass movement have been identified within the DEM subtraction area.

Outside the glacier and ice-cored moraine areas, it is apparent that the DEM subtraction illustrates other areas of surface downwasting. In many cases, this is likely due to snowpack at high elevations that was present in late September 2000 but was not present in August 2002. However, some areas of apparent downwasting at the 2–3 m level occur as thin linear features (width of a single grid cell) along cliff edges and, although not impossible, are unlikely to be the result of changes in snow cover. These apparent "artifacts" are further evidenced if the areas of negative downwasting (surface growth) are investigated (**Figure 6**). Although no surface growth occurs over the glacier, snow-covered areas, and ice-cored moraine features, there is some apparent growth along many cliff edges totaling 2.2×10^6 m^3, or ~5% of the downwasted volume. It is believed that these areas of almost coincident downwasting (**Figure 5**) and growth (**Figure 6**) are edge effects associated with laser pulse shadowing and potential horizontal error in the 2000 DEM. The accuracy of the 2000 lidar data was not directly assessed, and so the possibility of DEM displacement errors cannot be ignored. Horizontal errors in lidar data are typically at the decimetre level (largest source of error is the differential GPS), however, and will certainly be below the resolution of the 2.5 m DEM grid cell spacing. The most likely

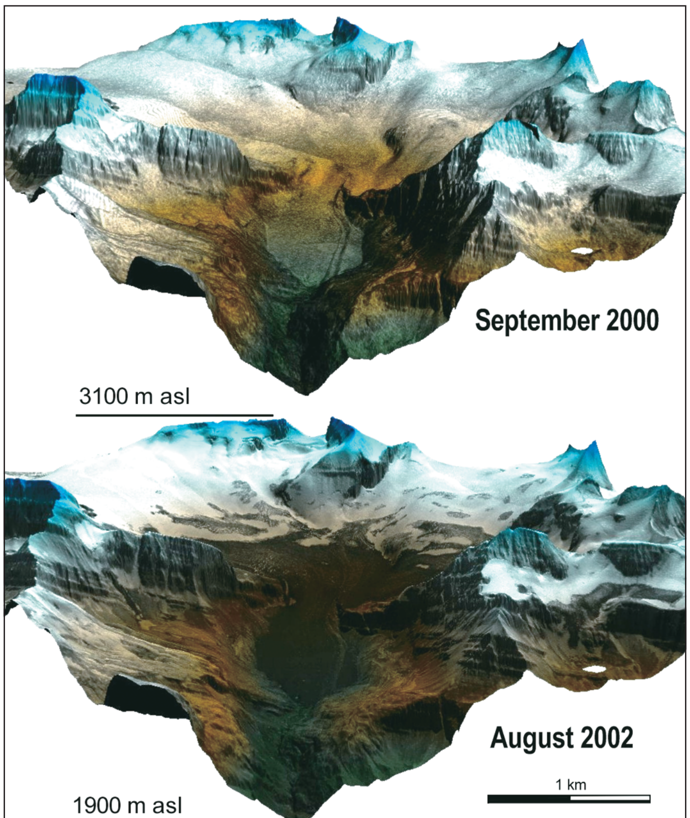

Figure 3. Lidar DEMs with laser intensity grey scale image draped. Elevation colouring from 1900 to 3100 m asl is green to brown to white to blue.

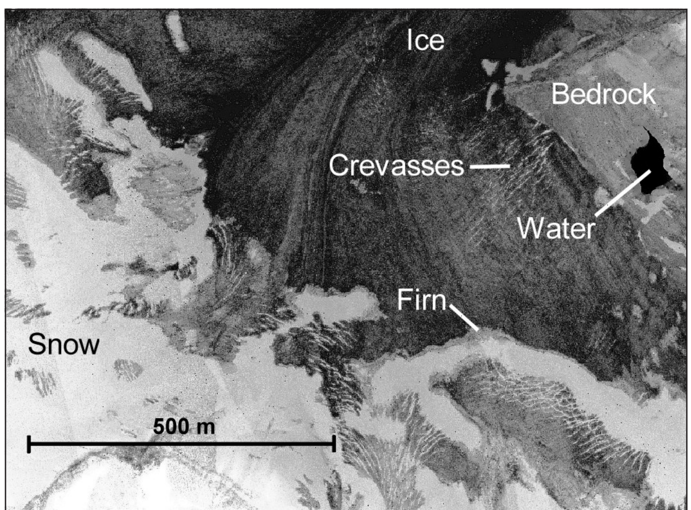

Figure 4. Lidar intensity image closeup in 2002 in the area of snowline on the surface of Peyto Glacier. Glacier facies and main land covers are noted.

cause of edge effects in lidar DEM subtraction data in extremely steep (almost vertical) cliff environments is that due to the limited downwards field of view of the lidar sensor (40° in 2000 and 36° in 2002); the actual sides of cliffs are frequently in the shadow of the laser pulses. Consequently, these edges are not accurately represented in the DEMs, and the net result is a lack of correspondence between cliff wall surfaces for both acquisition dates, leading to the observed coincidence in areas of growth and downwasting. Lidar-based change detection errors due to cliff side edge effects have not previously been documented, but the occurrence of increased vertical error in areas of steep slope has been clearly demonstrated by Hodgson and Bresnahan (2004).

Glacier water resources assessment

Figure 7 illustrates the glacier and periglacial zones of ice-cored moraines and snow and ice cover based on manual interpretation of the elevation and intensity data displayed in **Figures 3** and **4**. It is understood that the ~2600 m asl snowline at the time of the 2002 acquisition is not likely to correspond to the actual end of summer snowline in 2000, but this approach is reasonable for the purpose of apportioning appropriate SWE values to the predominantly snow- and ice-covered areas. Any error will most likely underestimate the elevation of the end of summer snowline in 2000, leading to an overestimation of the predominantly snow-covered area, therefore underestimating the total volume of meltwater lost from the glacier.

The results of the DEM subtraction volume assessment by glacier zone with appropriate SWE values and estimated runoff volume equivalent for Peyto Glacier are presented in **Table 2**.

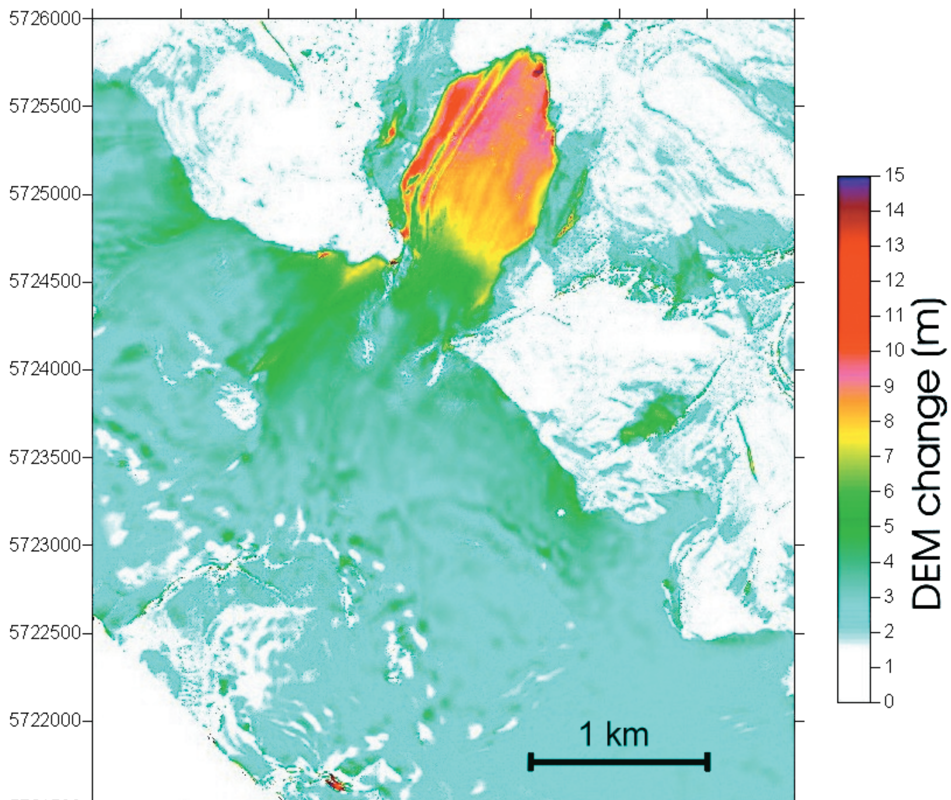

Figure 5. DEM subtraction image (2000–2002): surface downwasting. UTM coordinates are indicated.

Table 2. Glacier DEM subtraction statistics and water resource analysis results after extrapolation up to Mistaya Basin scale.

	Peyto Glacier basin					Mistaya Basin	
Glacier zone	Avg. downwasting (m)	Area (km^2)	Volume loss (×10^6 m^3)	Estimated SWE (%)	Water volume (×10^6 m^3)	Glacier runoff (×10^6 m^3)	Runoff proportion (%)
Above snowline	2.5	4.8	12.1	30	3.6	9.0	2.6
Below snowline	4.4	4.4	19.2	90	17.3	43.3	12.6
Ice-cored moraine	1.3	1.2	1.5	90	1.3	3.3	1.0
Total	3.2	10	33	—	22	56	16

The results of the extrapolation to the Mistaya Basin based on relative glacier proportion and the relative contributions to the total river discharge volume of 345×10^6 m^3 (Environment Canada, 2005) are also presented in **Table 2**. For the 23 month period investigated, it is estimated that approximately 22×10^6 m^3 of water volume was lost from Peyto Glacier, with 6% of this volume originating within ice-cored moraines. This result is important because glacier meltwater generation from periglacial moraine environments is rarely monitored in operational mass balance investigations.

For the extrapolation of these water volume losses to the Mistaya Basin, it was estimated that glacier downwasting contributed approximately 16% of the total river runoff between the lidar acquisition dates. This value is about midway between the 6% long-term average (1966–1989) and 25% drought year (1970) contributions estimated by Young (1991). The Mistaya Basin and several glacierized headwater basins adjacent to it feed the main stem of the North Saskatchewan River. The North Saskatchewan River, before finding its way out of the mountains into the western prairies and water consumers there, provides flow to the Abraham Lake – Bighorn hydroelectric generation facility operated by TransAlta Utilities. Demuth and Pietroniro (2002) determined that approximately one fifth of the total annual flow volume through this facility is provided by a 1 m water equivalent downwasting from glacier sources, placing the current results and the potential value of lidar-based glacier water resources assessments in a valuable perspective. Moreover, notwithstanding the minor uncertainties in the absolute accuracy of the SWE estimations and basin extrapolation performed, these results confirm the findings of many previous studies that glacier downwasting in the Canadian Rockies over recent years has contributed a highly significant proportion of runoff. The major difference here is that the time duration of the study focused on a 2 year period, as opposed to decades.

The decimetre-level accuracy of airborne lidar data combined with the ability to map areas of no surface contrast, such as glacier accumulation zones, suggest that airborne lidar acquisitions could potentially be carried out up to several times in a single year to monitor temporal snowline progression and glacier surface downwasting. Even in a single day, summertime surface lowering on the terminus of a temperate glacier can easily exceed the vertical accuracy of lidar data, and so the minimum repeat survey interval during peak ablation periods could be a matter of days, rather than the several year repeat survey cycle typically required with aerial photography. Practically, the relatively high cost of airborne lidar would prevent most researchers from using such an approach. As costs come down and technical capabilities increase, however, it might be possible to supplement some of the manually intensive field investigations with seasonal, annual, or biennial data collections over larger areas than can be monitored by field crews.

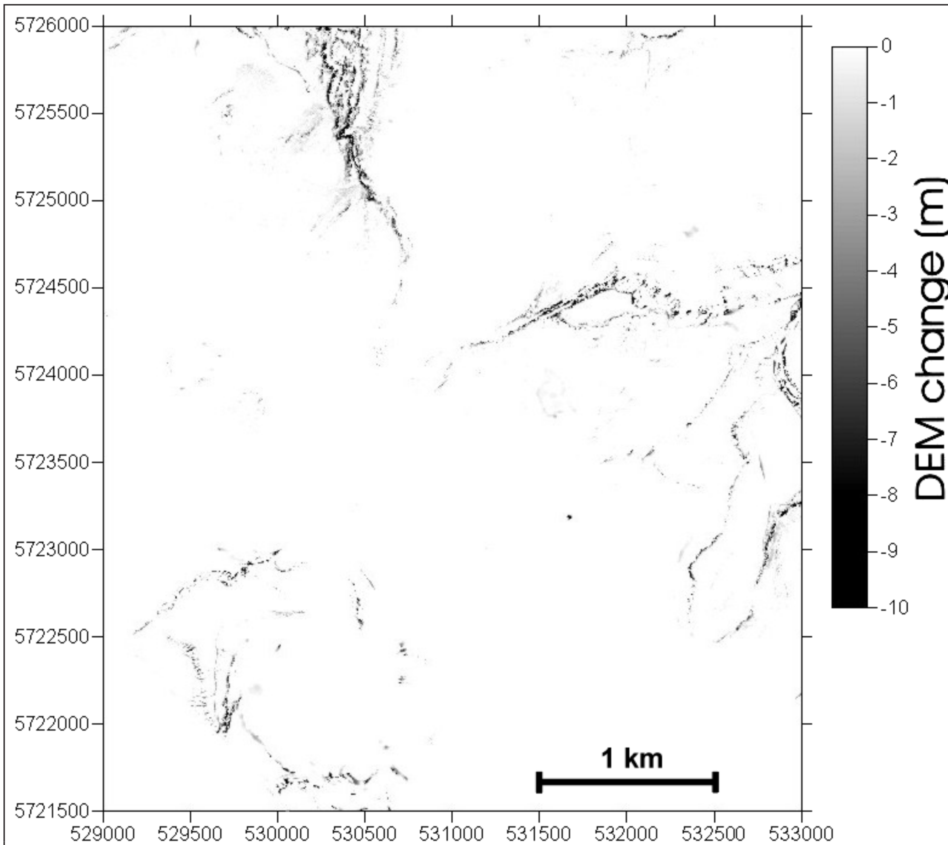

Figure 6. DEM subtraction image (2000–2002): surface growth.

Concluding remarks

Airborne lidar data have the ability to map all areas of a glacier surface at high accuracy and high resolution. Although lidar is predominantly a survey ranging technology for topographic mapping purposes, the active infrared imaging capability produces thematic intensity information that can be used to aid with the interpretation of surface features. There are several advantages of lidar DEM generation over traditional hardcopy or softcopy stereo photogrammetric glacier surface topographic mapping:

(1) *Directly digital survey point data* — There is no need for manual or software-based conversion of stereo images to elevation data.

(2) *Speed* — Lidar data can be processed to DEMs faster than traditional photogrammetric methods, and subsequent DEM subtraction is a simple task.

(3) *Surface texture not necessary* — Stereo photogrammetry requires image texture to align features in the stereopair and generate height data. Laser pulse return survey points reflect directly from the surface, even if there is no surface texture or contrast. This is particularly significant in glacier accumulation areas, where the high reflectivity of snow ensures strong laser pulse backscatter. The implication here is that lidar data are ideal for mapping surface elevations in the accumulation zone, where changes in surface elevation can be an order of magnitude less than those in the less reflective ablation zone.

(4) *Lidar is an active remote sensing technology* — Lidar is less influenced by local lighting conditions at the time of survey (e.g., can fly at night), and the data are not detrimentally impacted by sunlight shadows, which are a significant challenge to photogrammetric interpretation in areas of high relief.

Figure 7. Zones of meltwater production over Peyto Glacier.

Although lidar remote sensing cannot replace information gathered in the field such as snow and firn density, there are some advantages over fieldwork: (*i*) lidar acquisitions can cover the entire glacier surface (or a suite of glaciers) at very high resolution, whereas field data are typically collected for a sparse network of points; (*ii*) lidar acquisitions are less susceptible to human error, as most of the processing can be automated; (*iii*) data acquisition and processing are much faster (but more expensive); and (*iv*) areas outside the traditional field survey site are easily assessed, e.g., ice-cored moraines, areas of unacceptable hazard, and small steep inaccessible glaciers.

Unless meltwater processes and features are of particular interest, lidar surveys would best be planned for time periods of minimal melt to increase the chance of strong laser pulse backscatter, e.g., night time, spring (prior to the main onset of melt), or fall (after melt has receded). These are also the prescribed times for annual field mass balance data collection, and so glaciological lidar survey logistics would optimally be planned to coincide with annual mass balance activities.

For the 23 month period investigated, it was found that there was a reduction in volume totaling 33×10^6 m^3 over the Peyto Glacier surface and surrounding ice-cored moraines. This downwasting was estimated to be equivalent to approximately 22×10^6 m^3 of water volume and, after extrapolation, 16% of the Mistaya Basin runoff. The water equivalent contribution from ice-cored moraines alone was estimated at 6% of the total glacier basin runoff contribution. This observation is significant because glacier meltwater generation from periglacial moraine environments is rarely monitored and clearly illustrates that these areas should be considered in glacial water resource assessments. It is worth noting that many of the previous glacier water resource studies carried out in this region have ignored this potentially important component of runoff in their calculations.

For glaciers shrinking with time, the meltwater contribution will reduce and downstream water resources will be negatively impacted. By conducting airborne lidar data acquisitions at annual or biennial intervals over regions of glacier cover, it would be possible to document and study the spatiotemporal variations in glacier contributions to runoff at far higher resolutions and at greater accuracy than possible using traditional aerial photogrammetry and field mass balance studies alone. Perhaps the most valuable use of multitemporal lidar data in a glacier water resources context would be in assisting with the development and validation of physical climate – glacier melt runoff models for water resources prediction.

Acknowledgements

The Canadian Consortium for Lidar Environmental Applications Research is acknowledged for coordinating survey logistics, Mike Sitar and Bill Kalbfleisch of Optech Incorporated are acknowledged for collecting and processing the lidar data, Airborne Energy Solutions is acknowledged for providing an aircraft and flight crew for the second lidar survey. Laura Chasmer, Reculver Enterprises, Terry Beck, John Barlow, and Stella Heenan are acknowledged for assistance in the field. Michael N. Demuth acknowledges funding from the Canadian Government Action Plan 2000 Systematic Climate Observation Programme – Cryosphere.

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