Volume loss from lower Peyto Glacier, Alberta, Canada, between 1966 and 2010

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ABSTRACT. Mass loss from mountain glaciers contributes to sea-level rise and reduces freshwater availability in glacier-fed river basins, with negative effects on hydropower generation, agriculture and the health of aquatic ecosystems. In this study, we determine the volume of lower Peyto Glacier, Alberta, Canada, from ground-penetrating radar surveys in 2008–10, and compare our volume estimate with previous estimates from 1966 and 1984. The long-term record of mass-balance estimates on Peyto Glacier highlights Peyto’s importance as an ‘index’ glacier for the region. We calculate a mean volume of \( (3.39 \pm 0.30) \times 10^7 \text{m}^3 \) for the glacier snout for the period 2008–10. Glacier volume decreased linearly from 1966 to 2010. If this trend persists, the glacier snout will disappear by ~2019 and Peyto Glacier will have retreated by ~1 km. Our results agree with modelling studies, which suggest that Peyto Glacier and other nearby glaciers along the eastern slopes of the Canadian Rocky Mountains will likely lose 80–90% of their present-day volume by 2100.

KEYWORDS: glacier fluctuations, glacier mass balance, ground-penetrating radar, mountain glaciers

INTRODUCTION

If air temperatures increase as predicted in the next century, mountain glaciers will continue to lose mass (Radic and Hock, 2011). Although mountain glaciers hold only a small fraction of the total terrestrial ice, ice loss from mountain glaciers currently accounts for roughly half the eustatic sea-level rise that occurs because of ice loss to the oceans (Meier and others, 2007; Rignot and others, 2011). Mountain glaciers also regulate freshwater availability by storing water during cold periods and releasing water during warm periods. As mountain glaciers retreat, glacier melt contributes less fresh water to glacier-fed river basins (Comeau and others, 2009). Reduced freshwater availability may negatively affect hydropower generation, agriculture, recreation and the health of aquatic ecosystems (Stahl and Moore, 2006; Jacobsen and others, 2012).

The glaciers of Banff National Park in the Canadian Rocky Mountains attract more than three million tourists per year (Scott and others, 2008; Parks Canada, 2012) and provide water to both the North and South Saskatchewan Rivers, which flow into the agricultural lands of the Canadian prairie provinces. As the Canadian prairie provinces are sensitive to drought (Toyra and others, 2005), glacier and snow melt are important water sources to the region. Several recent studies have assessed glacier mass balance in Banff National Park (e.g. Luckman, 1998; Demuth and Keller, 2006). Marshall and others (2011) showed that glaciers along the eastern slopes of the Canadian Rocky Mountains will likely lose 80–90% of their volume by 2100. Reduced glacier volume will cause a long-term decrease in annual streamflow in the North and South Saskatchewan Rivers, particularly in the late summer (Comeau and others, 2009). In this study, we quantify the volume of lower Peyto Glacier in Banff National Park (Fig. 1; 51°40′41″N, 116°32′50″W) from ground-penetrating radar (GPR) surveys conducted during the period 2008–10. The lower glacier is defined by Holdsworth and others (2006) as the region extending from the glacier terminus to stake 85 (Table 1), or an altitude of ~2300 m a.s.l. Demuth and Keller (2006) found an average equilibrium-line altitude of 2700 m a.s.l. for 1966–95, so the lower glacier is dominated by ablation. In 1984, the lower glacier encompassed ~10% of the glacier area and ~20% of the glacier volume (Holdsworth and others, 2006). We compare our volume estimate from 2008–10 with previous estimates from 1966 and 1984 (Holdsworth and others, 2006) to assess volume change over time and to predict the future mass balance of the glacier.

METHODS

Ice thickness

We measured ice thickness across lower Peyto Glacier using GPR during three fieldwork campaigns from August 2008 to May 2010 (Fig. 1). In August 2008, we recorded five GPR transects across the lower glacier using a Geophysical Survey Systems Inc. (GSSI) SIR-3000 GPR with a 100 MHz antenna. We determined position along the transects using differential GPS, with a base station installed on a high point near the glacier terminus. As we identified bed reflections in only two of the five transects, we returned in September 2009 with a lower-frequency antenna (50 MHz) to further survey the glacier bed. At 50 MHz, we traced bed reflections to ice depths of 70–90 m. Consequently, ice depths still remained poorly constrained over about half of the study area. We hypothesized that this occurred because of dielectric attenuation and englacial scattering due to water within the ice (Kotlyakov and Macheret, 1987) and returned in late winter when water should be absent. We found bed reflections in all five transects recorded in March 2010,
but lost bed reflections at ice depths >80–110 m (Figs 1 and 2). We recorded position along the transects in September 2009 and March 2010 with a handheld GPS. Altogether, we recorded 15 GPR transects during the period 2008–10 and recorded bed reflections in 11 of these transects (Fig. 1).

To better detect bed reflections in the GPR data, we stacked every ten traces along the GPR transects and removed ‘ringing’ by subtracting the mean trace for each transect (Kim and others, 2007). By subtracting the mean trace, we were better able to identify bed reflections in areas where the bed slope was high; in areas where the bed slope was low, we picked the same bed as we would have picked had we only stacked the GPR data. We manually picked bed reflections as the two-way travel time with the minimum power return (Fig. 2). To convert two-way travel time to ice thickness, we set the direct-coupling wave to zero time and used a velocity in ice of 167 m s\(^{-1}\) as determined by Goodman (1975) for the accumulation area of Peyto Glacier. Holdsworth and others (2006) also used this value in their volume calculations for 1966 and 1984. As the radar wave velocity changes with water content (e.g. Bradford and Harper, 2005; Navarro and others, 2005), which is both seasonally and spatially variable across Peyto Glacier, we assume that this velocity is accurate to within ±5 m s\(^{-1}\) and take this uncertainty into account in our volume calculations.

We assessed the precision of our ice-thickness measurements by comparing measured ice thicknesses at locations where the GPR transects cross one another. Measured ice thicknesses can differ at crossover locations due to errors in the position estimates from the handheld GPS or due to our technique for picking the bed. In total, we found 29 crossovers with an average difference of 3.1 ± 2.3 m. As the mean crossover difference across the 2008, 2009 and 2010 campaigns (3.3 ± 2.8 m) was similar to that within the same campaign (3.1 ± 2.0 m), we do not have sufficient resolution to calculate separate ice volume estimates for 2008, 2009 and 2010.

Glacier extent

We determined glacier extent by walking along the glacier margin with a differential GPS in August 2008 (Fig. 1). Glacier extent includes ice-cored moraines. To assess the uncertainty of our mapped glacier extent, we compared our mapped glacier extent with glacier extent in a SPOTMaps (Satellite Pour l’Observation de la Terre) satellite image. Although the SPOTMaps product achieves global coverage by combining orthorectified SPOT 5 images (2.5 m resolution) recorded on different dates, all pixels in the chosen image were recorded on 5 May 2010. We found that the glacier area in August 2008 (7.3 × 10\(^5\) m\(^2\)) was 0.6 × 10\(^5\) m\(^2\) greater than the glacier area in May 2010 (6.7 × 10\(^5\) m\(^2\)).

Volume calculations

We combine our mapped glacier extent from 2008 and ice-thickness measurements from all three years to calculate a single glacier volume estimate for 2008–10. This leads to a well-constrained ice thickness near the glacier terminus. At greater elevations, the ice thickness is not as well constrained, because we could not trace bed reflections along transects CD and EF (Figs 1 and 2). Bed reflections disappear for ~200 m in the middle of these transects. To determine a likely bed depth in this region, we first constrain the...
the bed geometry to a parabola that best fits the measured depths (black curve in Fig. 2d). Glacier beds often approximate the shape of a parabola due to glacier erosion (Svensson, 1959; Graf, 1970; Harbor, 1992). We also consider minimum and maximum constraints on the bed depth in this region (dashed black curves in Fig. 2d). In the minimum case, we interpolate linearly between known depths. In the maximum case, we extrapolate the slopes of known depths to form a triangle. We use the minimum and maximum constraints to assess uncertainty, and the parabolic bed geometry to calculate glacier volume.

Although several different techniques now exist for volume estimation from GPR measurements (Binder and others, 2009; Fischer, 2009), in this study we use a simple Laplacian interpolation between ice-thickness measurements, which performs well in our case. We first resample our measured bed depths and assumed bed depths in transects CD and EF into 10 m gridcells in the east and north directions. At the glacier margin, we constrain the ice thickness to 0 m. We then solve the Laplace equation at each gridcell assuming minimum curvature. Finally, we integrate the interpolated ice thicknesses to calculate a volume estimate for the lower glacier.

Uncertainties in glacier area and thickness contribute to uncertainty in our volume estimate. To assess the uncertainty of our ice-thickness measurements, we consider three possible sources. First, we examine the uncertainty related to our assumed radar wave velocity. Assuming that Goodman (1975) calculated a velocity within ±5 m μs⁻¹ of the true value (e.g. Bradford and Harper, 2005; Navarro and others, 2005), we estimate a volume uncertainty of 0.10 × 10⁷ m³ associated with the radar wave velocity, which is equal to 3% of the estimated volume. Second, we estimate the volume uncertainty associated with our ice-thickness measurements by extrapolating the mean cross-over difference across the glacier area. Finally, we integrate the interpolated ice thicknesses to calculate a volume estimate for the lower glacier.

RESULTS

Figure 3 shows the measured and interpolated ice thicknesses across lower Peyto Glacier, which reach a maximum of 122 m near the middle of transect EF. When we integrate the interpolated ice thicknesses across the glacier area (7.3 × 10⁵ m²), we calculate a volume of (3.39 ± 0.30) × 10⁷ m³, which is 30 ± 3% of the volume calculated for the lower glacier in 1984 (Holdsworth and others, 2006). Figure 4 shows volume estimates for lower Peyto Glacier from 1966–2010. We find a linear decrease in glacier volume at a rate of (3.3 ± 0.2) × 10⁶ m³ a⁻¹. If we extrapolate this trend into the future, the lower glacier will disappear by ~2019.

Table 1 compares individual ice-thickness measurements from 1984 (Holdsworth and others, 2006) with the interpolated ice thicknesses for 2008–10. We find that the glacier has retreated from five of the stakes installed by Holdsworth and others (2006) and, consequently, no glacier ice exists at these locations. Ice thicknesses decreased by 40–98 m between 1984 and 2008–10, with an average thinning rate of 3.0 ± 0.6 m a⁻¹.
DISCUSSION

Similar to other mountain glaciers around the world (Kaser and others, 2006; Meier and others, 2007), Peyto Glacier has retreated significantly since its Little Ice Age maximum in the mid-19th century. Over this period, it has retreated ~3 km and lost ~70% of its volume (Watson and Luckman, 2004; Østrem, 2006). Matulla and others (2009) predict that mass loss will be more sustained and substantial in the future as temperatures increase in the Canadian Rocky Mountains. Comeau and others (2009) found a mass loss of 7.1–8.0 × 10^6 m^3 w.e. a^{-1} for the entire glacier for the period 1966–98, increasing to ~10 × 10^6 m^3 w.e. a^{-1} for the period 2000–02 (Hopkinson and Demuth, 2006). We find that mass loss from the lower glacier ((3.0 ± 0.2) × 10^6 m^3 w.e. a^{-1}) accounts for ~30–40% of the total loss from 1966 to 2010.

Although we cannot directly compare our volume estimate for the lower glacier with previous estimates for the total glacier (Watson and Luckman, 2004; Hopkinson and Demuth, 2006; Comeau and others, 2009), our results agree well with other estimates of glacier thinning (Hopkinson and Demuth, 2006; Comeau and others, 2009; Marshall and others, 2011). We measure thinning rates of 1–5 m a^{-1} across the lower glacier, which are similar to but slightly smaller than those reported by Hopkinson and Demuth (2006) for 2000–02 (2–5 m a^{-1}). We suggest that the slightly higher thinning rates for 2000–02 than for 1966–2010 may be explained by our finding of a linearly decreasing glacier volume over this period (Fig. 4). As the glacier area decreased from 1966 to 2010, thinning rates had to increase over the remaining glacier area to maintain the linear decrease in glacier volume. In fact, Demuth and Keller (2006) found that mass-balance rates became more negative across the lower glacier from 1966 to 1995. By 2100, Marshall and others (2011) predict that the average glacier thinning rate in the Canadian Rocky Mountains will increase from ~1 m w.e. a^{-1} to between 2 and 4 m w.e. a^{-1}, based on the Intergovernmental Panel on Climate Change (IPCC) A1B and B1 emissions scenarios.

The results of this and other studies (Watson and Luckman, 2004; Holdsworth and others, 2006; Matulla and others, 2009) indicate that lower Peyto Glacier is disappearing rapidly. If we extrapolate our finding of a linear decrease in glacier volume from 1966 to 2010 into the future (Fig. 4), the lower glacier will disappear by ~2019 and Peyto Glacier will retreat by ~1 km. As this prediction is based on a linear trend from only three volume estimates, its value is limited. Furthermore, the prediction does not take into account any future changes in ice dynamics. For example, as glacier thinning lowers the surface elevation, glacier melt rates will likely increase and the lower glacier...
may disappear sooner than predicted. As a result, our prediction provides only a ballpark estimate for the disappearance of the lower glacier, indicating that it will likely disappear within the next few decades.

Like Peyto Glacier, many glaciers in western Canada are retreating. From 1985 to 2005, glacier area in western Canada decreased by \( \sim 11 \pm 4\% \) (Bolch and others, 2010). In particular, Peyto Glacier and other glaciers along the eastern slopes of the Canadian Rocky Mountains lost 25 \( \pm 4\% \) of their area over this period (Bolch and others, 2010). Our results agree well with this regional trend: from 1984 to 2008, lower Peyto Glacier lost \( \sim 40\% \) of its area.

As a result, we suggest that future studies should continue to monitor glacier mass balance in the region and other nearby glaciers will lose an additional 80–90\% of their present-day volume. As glaciers in the region continue to retreat, decreased freshwater availability may contribute to water shortages in the Canadian prairie provinces (Töyrä and others, 2005; Comeau and others, 2009), with negative effects on ecosystems, hydropower generation and agriculture. As a result, we suggest that future studies should continue to monitor glacier mass balance in the region and its effects on freshwater availability.

**CONCLUSIONS**

We calculate a mean volume of \((3.39 \pm 0.30) \times 10^7\ m^3\) for lower Peyto Glacier from 2008 to 2010. When we compare our volume estimate with previous volume estimates (Holdsworth and others, 2006), we find that the volume of the lower glacier decreased linearly from 1966 to 2010, with an annual loss of \((3.3 \pm 0.2) \times 10^6\ m^3\ \text{a}^{-1}\). If this trend persists into the future, the lower glacier will disappear by \( \sim 2019\) and Peyto Glacier will have retreated by \( \sim 1\ km\). As the glaciers of the Canadian Rocky Mountains are important for tourism and freshwater availability, future studies should continue to monitor glacier mass balance in the region.

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