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Twentieth-century Changes in the Thickness and Extent of Arapaho Glacier, Front Range, Colorado

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Abstract

Changes in Arapaho Glacier, Front Range, Colorado, are determined using historical maps, aerial photography, and field surveys using ground penetrating radar (GPR) and Global Positioning System data. Arapaho Glacier lost 52% of its area during the 20th century, decreasing from 0.34 to 0.16 km^2. Between 1900 and 1999 glacial area loss rates increased from an average of 1500 m^2 yr^{-1} to 2400 m^2 yr^{-1}. Average glacial thinning between 1900 and 1960 was 0.76 m yr^{-1}, but slowed to 0.10 m yr^{-1} between 1960 and 2005. Its maximum thickness is approximately 15 m. If recent trends in area loss continue, Arapaho Glacier may disappear in as few as 65 years. However, the decline in thinning rate suggests that the glacier is retreating into a corner of its upper cirque in which increased inputs of snow from direct precipitation and avalanching, and decreased insolation will greatly slow its rate of retreat. This may be generally true for many temperate-latitude cirque glaciers.

Introduction

Small glaciers in alpine cirques are sensitive indicators of climate. Worldwide, small glaciers are retreating, and in doing so are contributing significantly to sea level rise (Lemke et al., 2007; Meier et al., 2007, 2003). Locally, small glaciers can be significant sources of water, particularly in late summer for arid temperate climates, and tracking the decline of these glaciers can provide important information for water resource planning groups (Barnett et al., 2005). In the western U.S., small glaciers and ice fields are generally in rapid decline, but tracking changes in the rates of decline as the glaciers continue to shrink in area and recede into sheltered cirques may refine estimates of when seasonal runoff changes will occur.

Arapaho Glacier is located in the Colorado Front Range approximately 32 km due west of Boulder (Fig. 1). It occupies an east-facing cirque oriented at approximately 115°, and ranges in elevation from approximately 3700 to 4040 m a.s.l. (Alford, 1973). At 40.02°N, 105.64°W, Arapaho Glacier is characterized by an arid temperate climate in which specific local conditions can vary greatly from day to day and distinct accumulation and ablation seasons exist. The largest, southernmost, and perhaps only active glacier in Colorado (Waldrop, 1964), it lies within the City of Boulder's watershed on the eastern slope of the Continental Divide.

Arapaho Glacier has both receded and thinned substantially during the last century (Fig. 2). Its ablation in late summer provides a consistent source of water to the Boulder watershed once seasonal snowpack has melted. Residents of Boulder and its surrounding communities therefore have a vested interest in understanding Arapaho Glacier's past, present, and future changes. Understanding these changes may also prove useful for climate studies, since current and past glacial changes are related to past climate conditions. Moreover, current and past glacial changes may allow prediction of glacial changes associated with future climate conditions (Paterson, 1994; Andrews, 1975). Here we present new area, thickness, and thinning data for Arapaho Glacier that complement a limited historical data set.

The first known study of Arapaho Glacier was published in 1900 (Lee, 1900). Shortly thereafter several studies were published that characterized its short-term changes (Fenneman, 1902; Henderson, 1904, 1905, 1910). These early studies suggested that during the first decade of the 20th century Arapaho Glacier was thinning and receding at a rapid pace. Fenneman (1902) and Henderson (1910) reported that the glacier's area was approximately one-half square mile, or 1.3 km^2. From crevasse soundings, Fenneman (1902) reported ice thickness to be at least 16 m, but noted that the glacier was probably much thicker. Henderson (1910) reported a maximum thickness of no more than about 32 m. These area and thickness measurements were highly uncertain,

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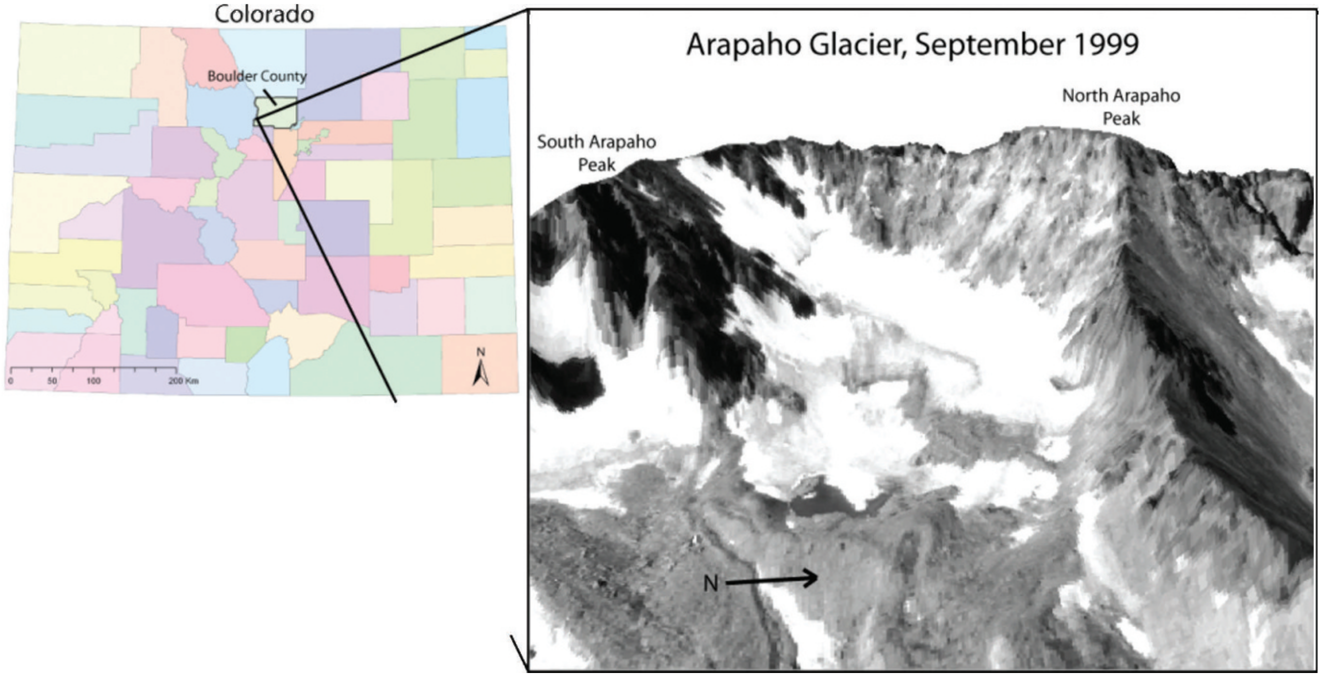

FIGURE 1. Location map and expanded oblique view of Arapaho Glacier looking approximately west (40.02°N, 105.64°W). The continental divide runs along the western side of Arapaho Cirque between North and South Arapaho Peaks. The expanded image was created by draping an aerial photograph over a digital elevation model (DEM).

and thus should be considered educated estimates at best. More than four decades later, Ives (1951) reported a thickness of approximately 25–130 m and an area of 0.41 km^2. Ives' (1951) estimates indicated that Arapaho Glacier had lost a substantial portion of its area and had probably thinned during the first half of the 20th century.

In his landmark study, Waldrop (1964) reported a glacial area of 0.25 km^2 as of 1960. Based on photographs taken near the turn of the 20th century, and comparisons with a planimetric map by Fenneman (1902), Waldrop (1964) also provided an estimate of glacial area in 1900: 0.34 km^2. Considering the size of the Arapaho cirque, it is likely that Waldrop's (1964) area estimates were more accurate than earlier estimates reported by Fenneman (1902), Henderson (1910), and Ives (1951). In 1960 Waldrop (1964) also measured a maximum bergschrund depth of 14.6 m, a maximum crevasse depth of 17.5 m, and estimated total thinning between 1900 and 1960 to be 32.3 ± 6.5 m. This thinning estimate was based on the same planimetric map and photographs as his 1900

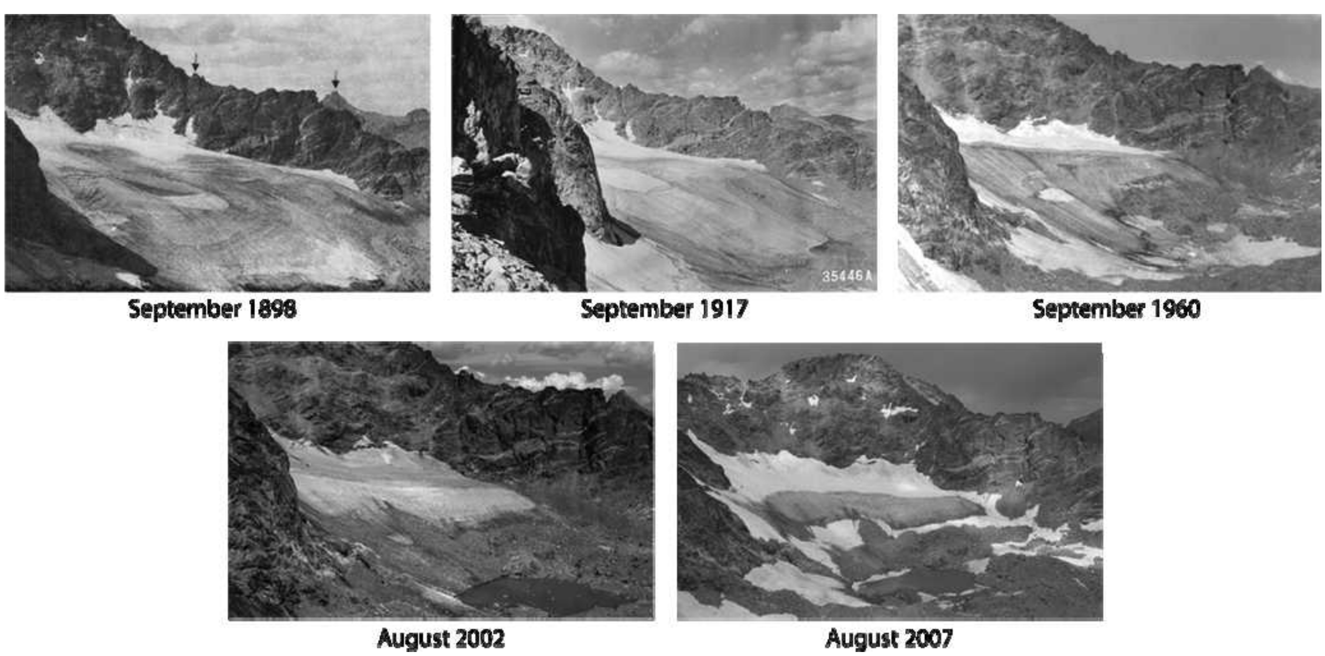

FIGURE 2. Photograph series showing recession and thinning of Arapaho Glacier between 1898 and 2007. All photographs show view looking northwestward from a saddle area on the south side of the cirque. Note the substantial changes in area and thickness between 1900 and 1960 and smaller changes between 1960 and 2007.

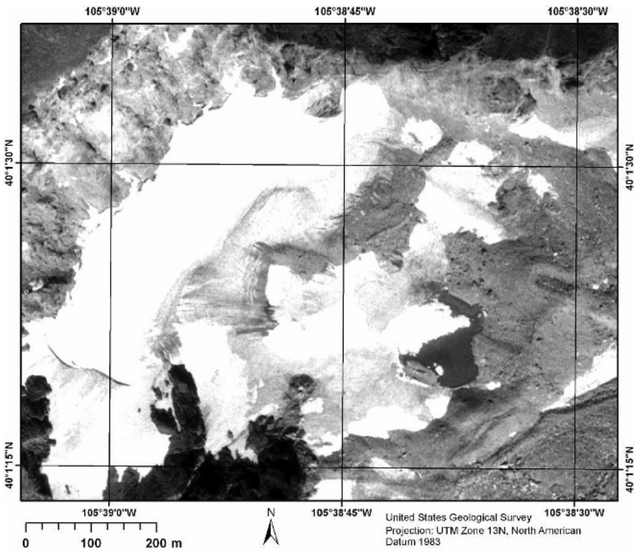

FIGURE 3. Aerial photograph from 13 September 1999 (U.S. Geological Survey).

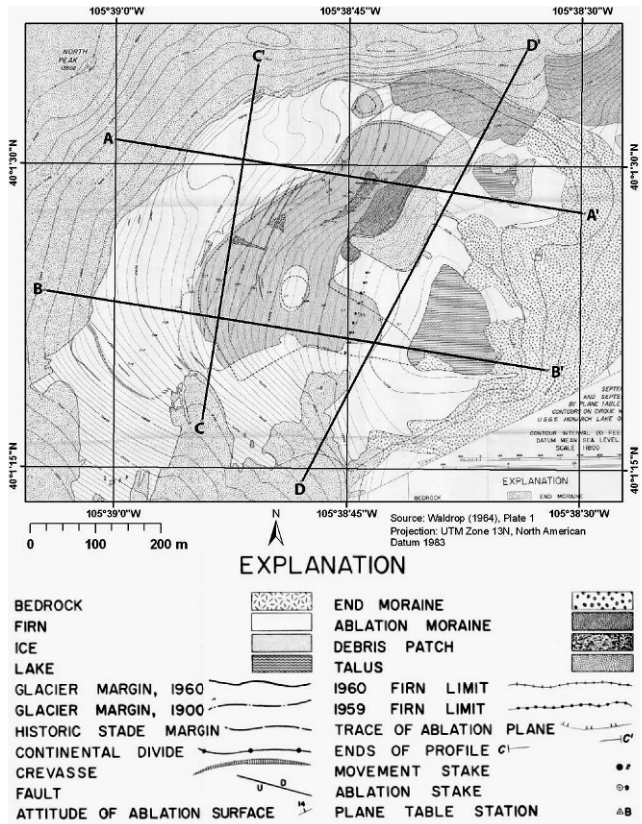

FIGURE 4. The digitized plane table map from Waldrop (1964).

area estimate, complemented with field observations and a plane table map created from data collected during the summers of 1959 and 1960.

Johnson (1979) reported a maximum bergschrund depth of greater than 22 m in 1972, a 1973 area of approximately 0.23 km^2, and a minimum thickness of 30–50 m. In an unpublished study, Pfeffer (2003) calculated thinning between 1960 and 2003 to be 30 m. Using data from nearby Arikaree Glacier, Dyurgerov and Meier (2005) reconstructed a thinning rate of 0.9 m yr^{-1} between 1960 and 2003. Although it has been the subject of several other studies (Thornbury, 1928; Outcalt and MacPhail, 1965; Harris, 1968; Alford, 1973; Reheis, 1975; Benedict, 1985), no other thickness, thinning, or area measurements were found in the literature. Moreover, the ice thickness and area measurements that have been reported are highly uncertain. The data reported by Waldrop (1964) appear to be the best documented, and was thus drawn on extensively during this study.

In order to constrain the most recent status and changes of Arapaho Glacier, ice thickness was measured for this study using a ground penetrating radar (GPR) survey conducted in late October 2007. Glacial area as of September 1999 was measured using a rectified aerial photograph, and surface elevation profiles were created from a fall 2005 digital elevation model (DEM). Glacial area measurements and elevation profiles were compared with data reported by Waldrop (1964) to produce area loss and thinning rates during the 20th century. By comparing ice thickness measurements with calculated area loss and thinning rates, we have developed an approximate timeline for the recent history and potential short-term future of Arapaho Glacier. This timeline is of great significance to both climate researchers and local residents. In this paper we present the first successful GPR study of Arapaho Glacier, complemented by a series of new area loss and ice thinning data. Moreover, this study marks the first accurate determination of Arapaho Glacier's thickness, an important measurement for understanding its past and future changes.

Methods

Recent glacial area was determined by tracing the terminus and bergschrund of the glacier on a rectified vertical-view, 2-m-per-pixel resolution raster image taken 13 September 1999 and obtained online courtesy of the United States Geological Survey (USGS) (Fig. 3). Unfortunately no other precision aerial photographs were available for area comparisons; earlier glacial areas were derived from a digitized version of the plane table map created by Waldrop (1964). The plane table map (Fig. 4) was scanned, and then rectified manually in a GIS software package by scaling, shifting and rotating it until the shape, size and position of the cirque in the map matched that of the 1999 aerial photograph. No geographic referencing information was included with the plane table map, so a more precise manual referencing technique was also applied: fixed geographic features present in the map were marked and linked to control points representing the same features in the aerial photograph from 1999. A second-order polynomial referencing function was then applied to the digitized map, automatically shifting and deforming it to align to the geo-referenced control points.

The RMS error of the resultant map was 0.24 m, which represents the error associated with map deformation in any one direction caused by the application of a geo-referencing function. In actuality, the uncertainty associated with geo-referencing of this type is somewhat higher, due to several factors. They include: (1) misinterpretation of shapes and features in the reference photograph due to light and shadow effects, (2) the limited resolution of both the reference image and the digitized map, (3) the error inherent to the original plane table map ($\pm$5 m), and (4) small changes in topography over time due to erosion.

Glacial extents in 1900, 1960, and 1999 were traced from the digitized plane table map and the aerial photograph. Both the plane table map and the aerial photograph showed glacial conditions in late summer, limiting tracing errors caused by snow cover. Tracing error was no greater than 2 m. However, tracing of the glacier's extent in 1999 was still complicated by snow and

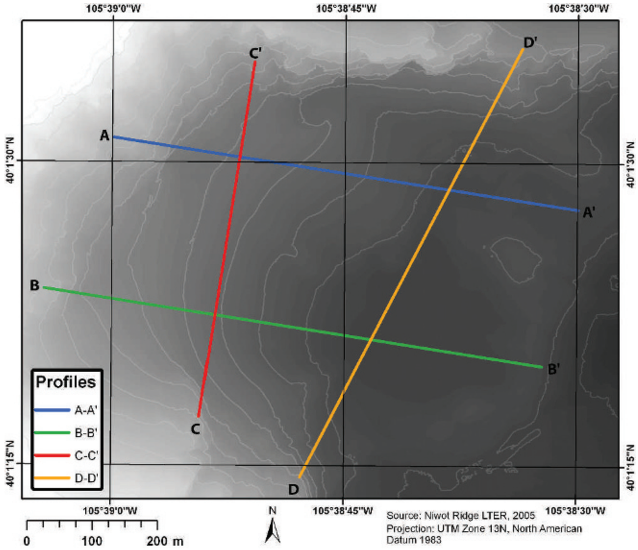

FIGURE 5. Map of elevation profile lines projected over the 2005 DEM. Elevation data (accurate to within 1 m) were extracted from the 2005 DEM along each profile line.

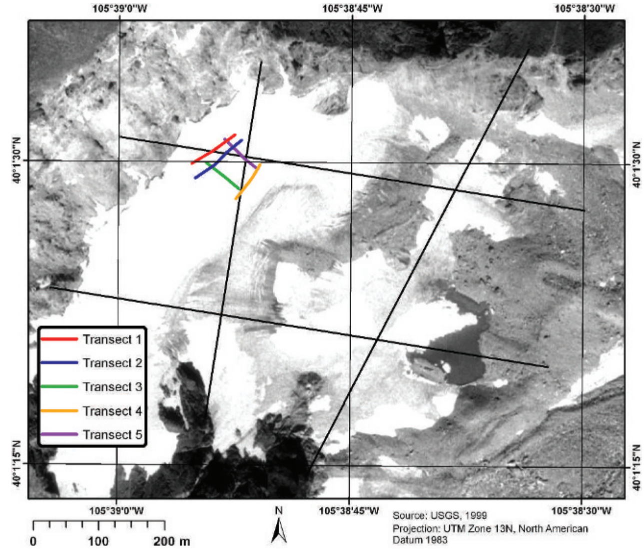

FIGURE 6. GPR transect lines projected on the aerial photograph from 13 September 1999. NE–SW trending transects run approximately parallel to topographic contours, NW–SE trending transects run approximately perpendicular. Actual transects intersect at all possible points. Discrepancy in projection is due to handheld GPS point uncertainties.

shadows present in the aerial photograph, as well as its limited resolution. To address this problem, various recent photographs (Fig. 2) and field observations were used as a guide. The estimated total uncertainty of the 1999 area measurement is 5%. Polygon shape files were created from the extent traces and their respective areas were compared to obtain area change rates for the 1900–1960 and 1960–1999 periods.

A rectified 1-m-resolution digital elevation model (DEM) was obtained courtesy of the Niwot Ridge Long Term Ecological Research program (NWT LTER). The DEM was created from highly accurate light detection and ranging (LIDAR) data collected in the fall of 2005. Using the digitized plane table map (Fig. 4), profile lines that matched the positions of the elevation profiles developed by Waldrop (1964) were drawn across the DEM (Fig. 5). Elevations were then extracted from the DEM along each profile line at a sampling distance of approximately 1 m. Waldrop's (1964) elevation profiles from 1900 and 1960 were digitized and compared with the profile data obtained from the 2005 DEM. Resultant elevation differences were used to obtain an average annual thinning rate between 1960 and 2005. Average annual thinning between 1900 and 1960 was calculated from Waldrop's (1964) total thinning estimate.

The uncertainty of our thinning measurements depends on the geographic and topographic uncertainty of the digitized plane table map, as well as the uncertainty of elevations extracted from the 2005 DEM. Since profile lines A–A′ and B–B′ trend down-flow (Fig. 5), small lateral shifts in their positions do not significantly change the measured elevations of the glacier's surface. Thus the uncertainty of the A–A′ and B–B′ profiles for 1960 is dominated by the topographic uncertainty of the plane table map. For 2005, uncertainty over A–A′ and B–B′ is dominated by the uncertainty of the DEM. Thinning measurement uncertainties for A–A′ and B–B′ in 1960 and 2005 are ±3.2 m and ±1.0 m, respectively. Profile lines C–C′ and D–D′ trend across-flow. Thus, 1960 elevation uncertainties are dependent on both the geographic and topographic uncertainties of the plane table map, and 2005 elevation uncertainties are dependent on the geographic uncertainty of the digitized map and the topographic uncertainty of the DEM. The uncertainties of the C–C′ and D–D′ elevation profiles from 1960 and 2005, then, are ±5.9 m and ±5.0 m, respectively.

Mis-registration of profile locations in the direction of glacial flow is the most important factor in determining the uncertainty of the elevation change measurements. For a given slope α, mis-registration by a distance of x (m) down-flow will lead to an elevation error of $v = x*\tan(\alpha)$. Thus, for $x = 1$ m and $\alpha = 20°$, actual error for the elevation change measurement would be 0.4 m. Assuming the surface of the glacier has a constant slope over short distances (<5 m) across-flow, minute changes in the location of the profiles trending down-flow will not significantly affect elevation results along the profiles. The same changes in the position of the across-flow profiles will, however, have a large effect on elevations obtained over the entire length of the profiles because the surface of the glacier does not have a constant slope over long distances (>10 m) in the across-flow direction.

On 29 October 2007 a GPR survey was conducted on the northwest corner of Arapaho Glacier near its bergschrund at the west headwall in an effort to ascertain both ice thickness and the form of the basal contact (Fig. 6). Data were collected along six short survey lines, or transects, by towing a 250 Mhz shielded radar unit (Målå Geoscience RAMAC system) at a slow walking pace. Two-way travel time (TWTT) data were continuously recorded along each transect. Radar pulses were triggered at regular distance intervals of 0.2 m (a nominal value; distance interval re-calibrated during post-processing) using a calibrated wheel mounted at the rear of the radar unit. Data were continuously recorded using a laptop PC, while a GPS unit linked to the laptop's acquisition software recorded GPS points along each transect.

Four of the six transects trended approximately NE–SW, perpendicular to the direction of glacial flow, and two trended approximately NW–SE, parallel to the direction of flow. Transects were between 61 and 86 m in length (see Appendix A for detailed GPR data collection parameters). New data collection parameters were set for the sixth and final transect (run along the same path as transect 1; Fig. 6) such that the data obtained from the transect

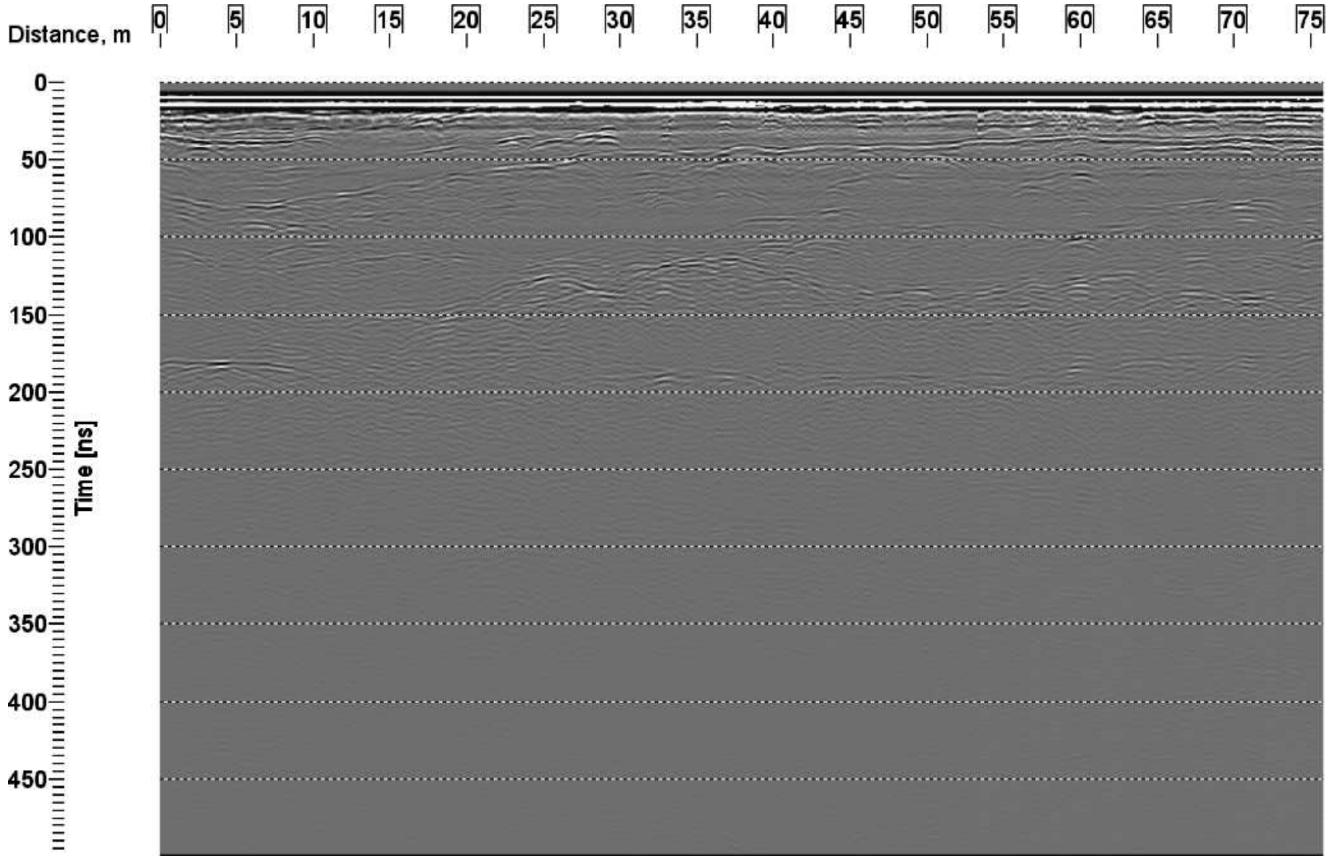

FIGURE 7. Raw GPR subsurface profile (transect 1) from 29 October 2007. Strong direct wave reflections are visible at the top of the profile, followed at depth by weaker subsurface reflections. Note the decreasing amplitude of reflections with increased time (depth) as a result of signal spreading and absorption.

line 6 would show reflectors at greater depths than the first five transects. Other than to confirm that there were no other potential ice-bedrock-interface reflectors than those identified in transects 1–5, transect 6 was not considered in this study.

Data from the October 2007 expedition were collected using a directional, shielded system designed to minimize ringing and reflections from surface features. An earlier attempt to collect GPR data using a simple 10 MHz radar system in March 2007 produced noisy, convoluted data that revealed no distinct subsurface reflectors. The poor quality of the data was likely due to ''ringing'' of unshielded radar waves between the steep rocky walls of the tight cirque and the radar antennas. Unshielded 25 MHz profiles acquired in June 2004 also produced similarly uninterpretable results.

At the time of data acquisition snow depth was measured to be between 0.8 and 1 m. Air temperature was above freezing, and the surface of the snow was wet with meltwater. However, the temperature of the snow-ice interface, measured at several locations, was between -2.4 and -1.9 °C, indicating a minimum amount of signal-reducing surface meltwater. There was no evidence to suggest that abundant water was present within the subsurface or within the glacier, which otherwise might have affected the radar results.

The raw GPR profiles collected in October 2007 show very strong direct wave signals and other noise partially obscuring the subsurface layering data (Fig. 7). In order to resolve the snow-ice and ice-bedrock contacts accurately, the profiles were filtered using several simple processing routines: (1) constant background signals (averaged over the entire length of each transect) were removed from each trace, eliminating the strong direct wave signal and other background noise (e.g. signal reflections from people, equipment, and cirque walls); (2) the zero position of each profile's time window was adjusted to match the position of the snow surface using snow depth measurements; (3) a DC shift correction was applied; (4) signal amplitude of each trace was adjusted to maintain constant RMS total amplitude with depth; and (5) elevations from the 2005 DEM, and positions from the co-collected GPS data, were used to correct profiles 3 and 5 for topography. It was not necessary to correct profiles 1, 2, and 4 for topography as elevations along each varied by no more than about 1 m. The time window of each profile was then cropped, removing the regions where no coherent reflections were observed. The locations of the snow-ice and ice-bedrock contacts in each profile were then interpreted (Figs. 8.1 and 8.2) using appropriate radar signal velocity models in which signal velocities in ice and dry snow were 0.17 m ns^{-1} and 0.23 m ns^{-1}, respectively. The two-way travel times (TWTTs) of each contact were converted into depth values at a distance interval of 0.2 m. Snow-ice contact depths were subtracted from ice-bedrock contact depths to obtain ice thickness measurements.

The accuracy of our ice thickness determination is largely dependent on correct interpretation of the radar profiles. In the profiles, determining the location of the snow-ice interface is much less difficult than determining the location of the basal contact. Besides being at shallower depths (thus having higher signal-to-noise ratios and stronger reflections), the snow-ice interface is

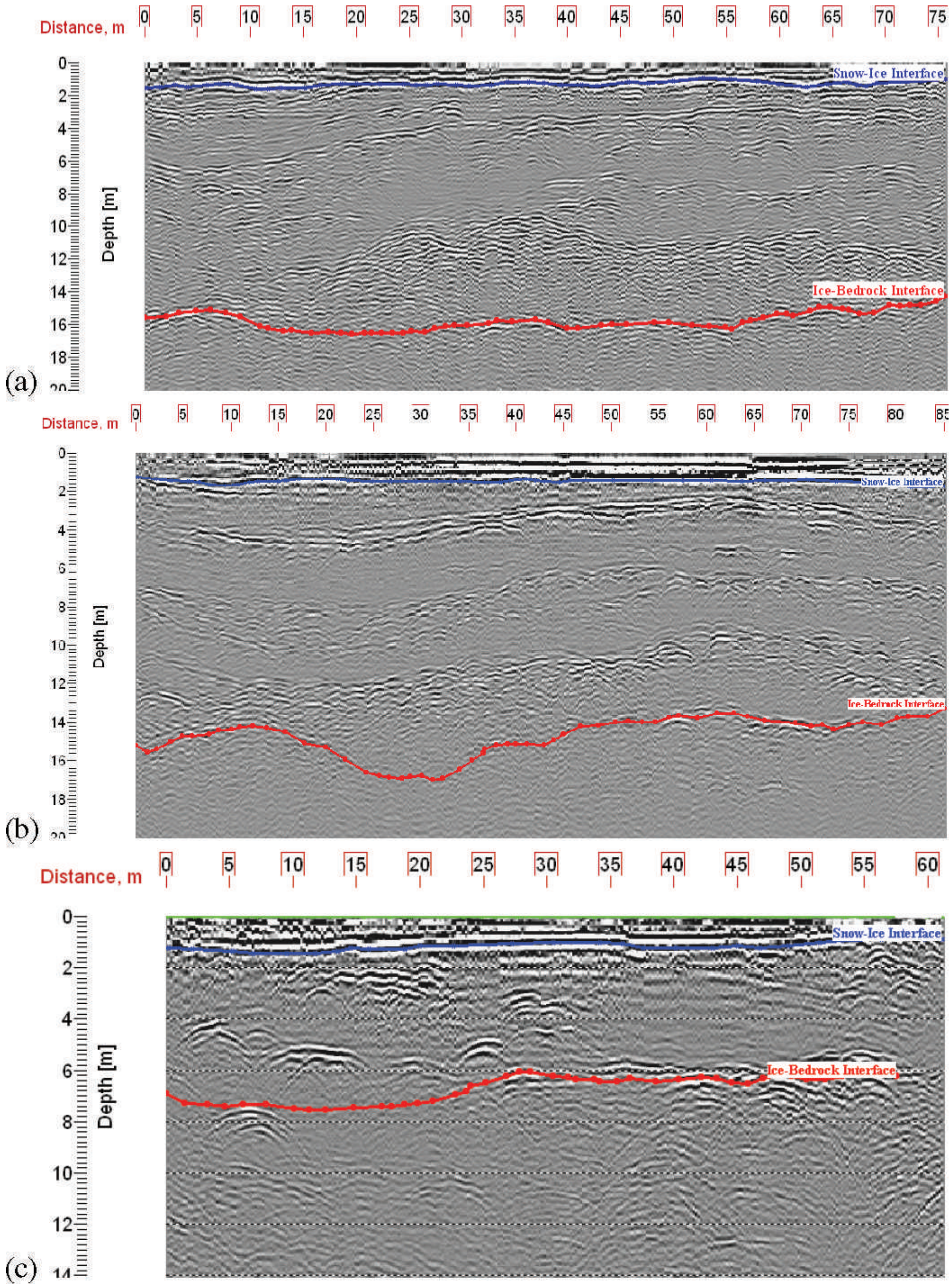

FIGURE 8.1. Processed and interpreted contour-parallel subsurface profiles 1 (a), 2 (b), and 4 (c). The snow-ice interface and basal contact of the glacier are shown. Note the ~10 m decrease in depth to the basal contact between profiles 1 and 2 and profile 4. Ice layers and entrained rock debris are visible in all profiles. Vertical exaggerations in (a), (b), and (c) are 1.4, 2.7, and 2.0, respectively.

relatively smooth, making interpretation of its location more straightforward. Moreover, snow depth was directly measured at one location during the radar survey in October 2007, which aided in interpretation. The basal contact on the other hand, is highly irregular, and basal reflections are both discontinuous and weak due to the shielding effect of entrained debris and signal spreading with depth.

The accuracy of thickness measurements also depends on the accuracy of the velocity model used to convert TWTTs to depths. The snow and ice velocities used were not experimentally determined, and thus are only approximate. However, normal-move-out analyses of discreet reflectors in each profile show that the velocities used were accurate to within about 0.01 m*ns^{-1}, or 4–6%. This translates to a depth uncertainty of about ±1 m. Thus, accounting for an estimated contact interpretation uncertainty of ±0.5 m, the estimated uncertainty of ice thickness measurements presented here is ±1.5 m.

Results

The areas of Arapaho Glacier in 1900 and in 1960, as measured from the digitized and geo-referenced plane table map, were 0.34 km^2 and 0.25 km^2, respectively. These measurements agree very closely with the values reported by Waldrop (1964) (Table 1), suggesting that the digitized plane table map was transformed correctly during geo-referencing. Assuming a constant rate of change, Arapaho Glacier lost approximately 1500 m^2 of area each year between 1900 and 1960 (Fig. 9). Under the same assumption, and if Johnson's (1979) measurement of glacial area in 1973 was accurate, then between 1960 and 1973 Arapaho Glacier decreased in area at an average rate of 1900 m^2 yr^{-1}, and between 1973 and 1999 it decreased in area by 2400 m^2 yr^{-1}. If Johnson's (1979) measurement is disregarded, the average annual loss rate between 1960 and 1999 was 2300 m^2 yr^{-1}. Given observed fluctuations in Arapaho Glacier's mass balance over

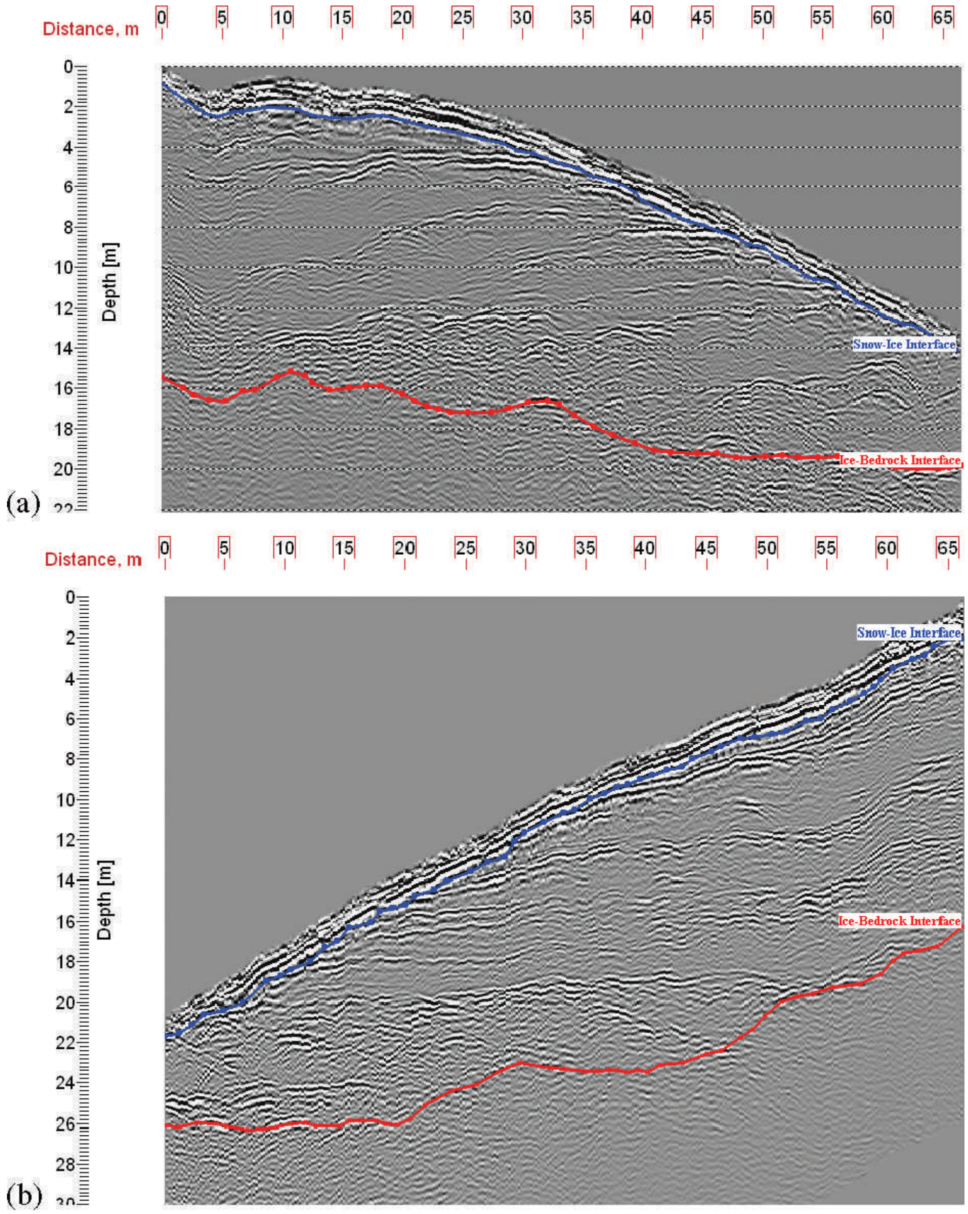

FIGURE 8.2. Processed and interpreted contour-perpendicular subsurface profiles 3 (a) and 5 (b). The snow-ice interface and basal contact of the glacier are shown. Note the rapid pinching of the glacier down-slope and the stepped, irregular shape of the basal contact. Ice layers and entrained rock debris are visible in all profiles. Vertical exaggerations in (a) and (b) are 1.6 and 1.7, respectively.

TABLE 1

Area and area changes of Arapaho Glacier during the 20th century. Values reported by Waldrop (1964) for 1900 and 1960 were nearly identical to the values obtained using GIS techniques.

Area				
Year	Calculated (m^2)	Reported (m^2)	Source	% Difference
1900	338,282	340,000	Waldrop (1964)	0.0051
1960	250,764	251,000	Waldrop (1964)	0.0009
1973	—	225,000	Johnson (1979)	—
1999	162,027	—		—

Area Change			
Period	Calculated (m^2)	Reported (m^2)	Calculated Change Rate (m^2 yr^{-1})
1900 to 1960	−87,518	−89,000	−1,500
1960 to 1973	−25,764	—	−1,900
1973 to 1999	−62,973	—	−2,400
1960 to 1999	−88,737	—	−2,300

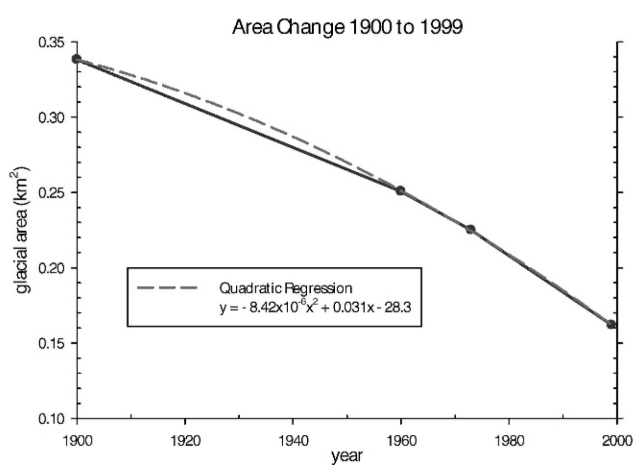

FIGURE 9. Plot of areas in 1900, 1960, 1973, and 1999. The slopes of the solid lines represent the linear rate of area change between two years. The dashed curve is a quadratic regression fitted to all data points. Steepening slopes of solid lines indicates an increase in the rate at which Arapaho Glacier lost area during the 20th century.

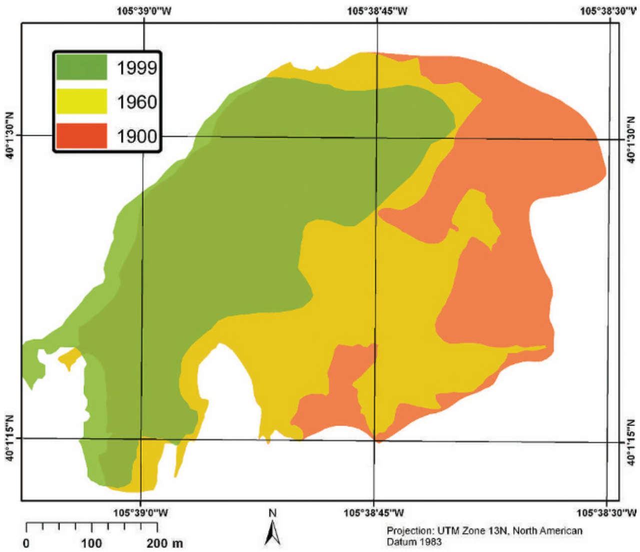

FIGURE 10. Map showing glacial extents in 1900, 1960, and 1999. The northern lobe of the glacier receded dramatically between 1900 and 1960. Between 1960 and 1999 area loss was almost exclusively associated with recession of the southern lobe; the northern lobe changed little. Note the difference in positioning of the 1999 trace relative to the 1900 and 1960 traces. This is likely due to slightly inaccurate positioning during geo-referencing.

short time scales (Henderson, 1904; Waldrop, 1964; Johnson, 1979), it is highly unlikely that the rate of area change remained constant from year to year during the time periods analyzed. Nonetheless, the area change rates obtained here can be used to draw an important conclusion about the glacier's behavior during the 20th century: on average, the rate at which Arapaho Glacier lost area increased significantly between 1900 and 1999 (Fig. 9).

The shape of Arapaho Glacier also changed dramatically during the 20th century (Fig. 10). In 1900 its terminus had a "W" shape, and was divided into distinct northern and southern lobes. By 1960 its northern lobe had nearly disappeared and the southern lobe had both changed shape and lost area, receding behind a meltwater lake (Fig. 2). Between 1960 and 1999, however, its northern lobe changed very little while its southern lobe lost much of its area and receded to a position more than 100 m west of the meltwater lake (Fig. 2). Thus, the majority of measured area loss between 1960 and 1999 occurred in the southern lobe. Comparison of glacial extents indicates an inconsistency in the geo-referenced position of the digitized plane table map relative to the actual geographic position of the glacier (Fig. 10). So although plane table map was correctly transformed during geo-referencing, its positioning was not entirely accurate.

Elevation profile comparisons (Fig. 11) show that thinning between 1960 and 2005 was substantially less than between 1900 and 1960. Along A–A′, thinning since 1960 occurred over much of the glacier's length, whereas along B–B′, the majority of thinning occurred between the steepest portion of the glacier ($\sim$100 m down-slope of the bergschrund) and its terminus. This thinning pattern correlates well with the observed pattern of area loss. Unlike B–B′, profile C–C′ shows a relatively uniform region of thinning across the entire width of the glacier. D–D′ does not show any significant evidence of thinning between 1960 and 2005. Inconsistencies in the form and position of the cirque walls between the 1960 and 1900 profiles and the 2005 DEM profiles (most pronounced in C–C′ and D–D′) again show that although the scaling of the digitized plane table map was correct, its geographic positioning was slightly inaccurate. This illustrates the substantial margin of error associated with comparing these profiles. Nonetheless, all potential errors considered, results show that total thinning between 1900 and 1960 was significantly greater than between 1960 and 2005.

Between 1960 and 2005 thinning along A–A′ averaged 5.4 $\pm$ 3.4 m (Fig. 11). Along B–B′ and C–C′ thinning averaged 3.7 $\pm$ 3.4 m and 4.3 $\pm$ 7.7 m, respectively. Since data comparisons of profile D–D′ did not show any significant evidence of thinning, average thinning for this profile was not calculated. The uncertainty of average thinning measured along C–C′, $\pm$7.7 m, does not rule out the possibility that Arapaho Glacier's thickness increased between 1960 and 2005. However, given that the glacier receded substantially between 1960 and 2005, and that thinning measurements along A–A′ and B–B′ (which cross C–C′) show that significant thinning did indeed occur during the same period, average thinning along C–C′ was probably between 0 and 12 m. Total average thinning between 1960 and 2005, calculated from A–A′, B–B′, and C–C′, was 4.5 $\pm$ 9.1 m. On average, then, between 1960 and 2005, Arapaho Glacier thinned at a rate of 0.10 $\pm$ 0.20 m yr^{-1}. Between 1900 and 1960, the differences reported by Waldrop (1964) in comparisons of his plane table map with the earlier 1900 mapping indicate a mean thinning rate of 0.76 $\pm$ 0.15 m yr^{-1}. The relatively low error for the earlier estimate is derived from Waldrop's assessment of the errors in the difference between his 1900 and 1960 profiles at 20%.

Ice thicknesses measured from the GPR profiles oriented NE–SW (across-flow) show much less variation than ice thicknesses measured parallel to glacial flow (Fig. 8). The mean slope of the basal contact, although irregularly shaped, is shallower than that of the glacier's surface. Thus the glacier "pinches out" as it extends down valley; in just 65 m Arapaho Glacier's thickness decreases by about 10 m. A comparison of the basal contact in profile 1 (the profile collected nearest the bergschrund) with the basal contact in profile 4 (the profile collected furthest down valley) clearly illustrates this relationship. Such strong down-valley gradient in thickness indicates that the average thickness of Arapaho Glacier is probably less than the maximum thickness measured. Maximum measured ice thickness in October 2007 was 15.5 $\pm$ 1.5 m. The minimum ice thickness measured in our profiles was 4.4 $\pm$ 1.5 m, and the average thickness over the entire GPR survey was 11.0 $\pm$ 1.5 m. If the average thickness of the glacier over the GPR survey is considered representative of the average thickness of the entire glacier, and glacial extent in 1999 is considered representative of the glacier's extent in October 2007, then its volume in October 2007 was approximately 1.8 $\times$ 10^{-3} km^3. This is likely an overestimate, as there were extensive fringing areas surrounding our GPR profiles where the glacial ice was presumably thinner, and area retreat between 1999 and 2007 is not accounted for. Table 2 summarizes thickness measurements from all profiles.

If these thinning rates are extrapolated into the past, our results show that in the early part of the 20th century Henderson (1910) greatly underestimated the thickness of Arapaho Glacier, while Ives (1951) and Johnson (1979) overestimated its thickness. If the average rate of thinning between 1960 and 2005 continues into the future, and the maximum thickness measured here is assumed to be the maximum ice thickness of the entire glacier, Arapaho Glacier will cease to exist sometime between the years 2136 and 2200. However, assuming area, not thickness, is the largest control on its future and that the average rate of area loss between 1973 and 1999 continues, Arapaho Glacier could completely disappear by 2085.

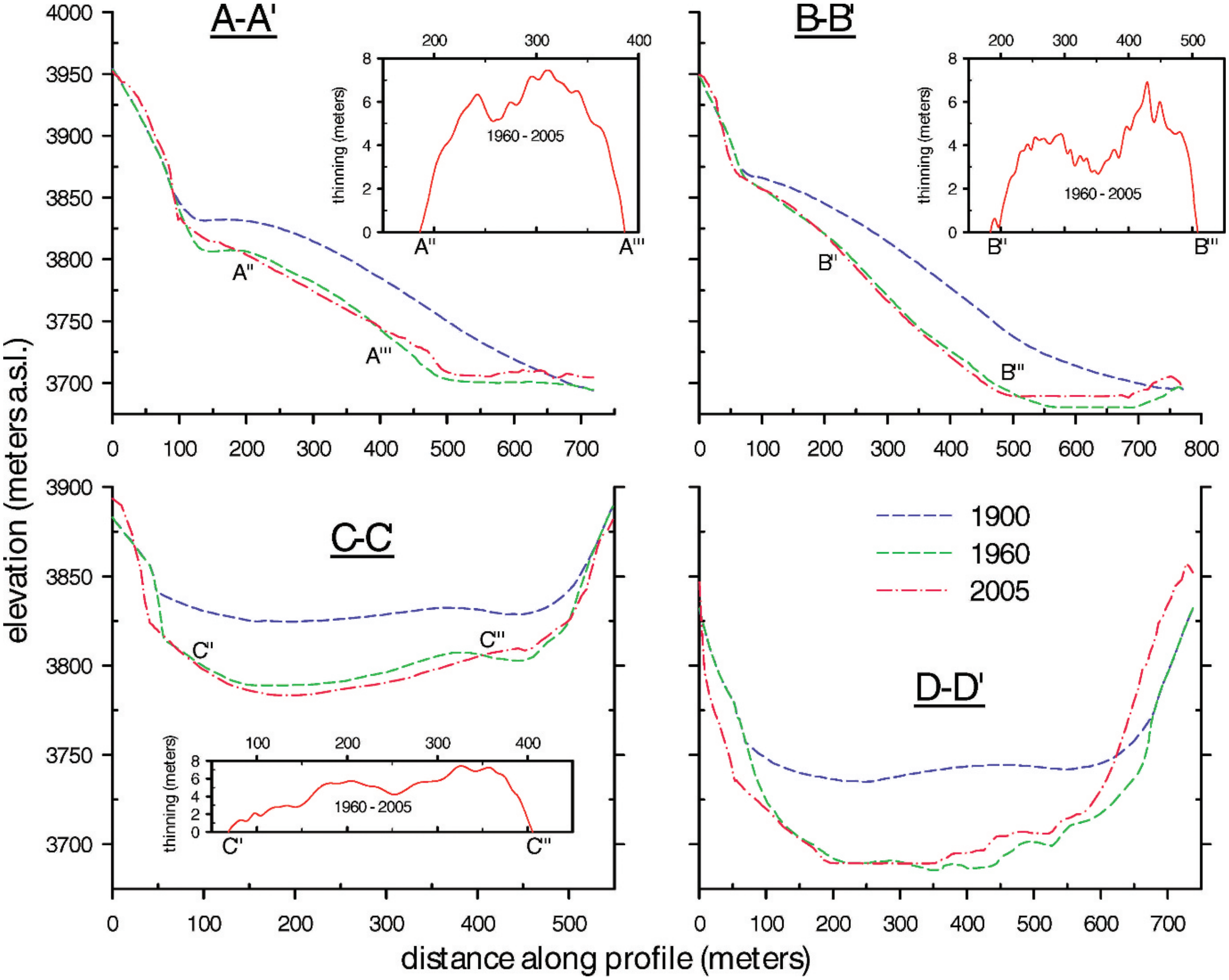

FIGURE 11. Elevation profiles A–A′, B–B′, C–C′, and D–D′. Inset graphs show total thinning at several points long the profiles. Average thinning along each profile was calculated from these values. No appreciable thinning occurred along D–D′ between 1960 and 1999.

Discussion

The total average thinning between 1960 and 2005 determined here is more than 25 m less than the average thinning between 1960 and 2003 determined by Pfeffer (2003). The 1960 to 2005 thinning rate determined here, 0.10 ± 0.20 m yr^{-1}, is also significantly less than the reconstructed thinning rate of 0.9 ± 0.1 m yr^{-1} between 1960 and 2003 reported by Dyurgerov and Meier (2005). In the same study, Dyurgerov and Meier (2005) also calculated a partially reconstructed thinning rate of 0.7 ± 0.1 m yr^{-1} for nearby Arikaree Glacier, another Front Range glacier the lies some 3.2 km north of Arapaho Glacier. When considering such large inconsistencies, it is important to acknowledge the potential positional inaccuracy of the geo-referenced plane table map, as implied by area-trace and elevation profile comparisons (Figs. 10 and 11), and the resultant uncertainty of our thinning measurements. It is also important to acknowledge the potential pitfalls in the methods used to produce the conflicting data, such that any differences between the data reported here and data reported elsewhere can be explained.

As a check for positional inaccuracies in our measurements, several control points were mapped using GPS data collected in October 2009. The plane table map was re-referenced using the GPS points with negligible effect on thinning measurements, suggesting relatively accurate initial positioning. Moreover, manually shifting the digitized map's geographic position both across- and down-flow by as much as 10 m produced nearly identical thinning results along profiles A–A′ and B–B′. Thinning along C–C′ showed greater dependence on the position of the

TABLE 2

Maximum, minimum, and average thicknesses calculated for each GPR profile and overall.

	Ice Thickness (m)		
Transect	Maximum	Minimum	Average
1	15.3	13.3	14.5
2	15.5	11.6	13.3
3	14.5	6	10.3
4	6.2	5.2	5.6
5	15	4.4	11.5
Overall	15.5	4.4	11

profiles obtained from the map, but at no point did any of the elevation profiles show evidence for thinning outside the range of uncertainty. Thus we are confident that positional inaccuracies are not responsible for the discrepancy between our measurements and the previously reported data.

Pfeffer (2003) based his conclusions on elevation comparisons along a single profile line. Elevations in 1960 were taken from Waldrop's (1964) elevation profile B–B′. Elevations in 2003 were determined using photogrammetric methods along the same profile line, making his thinning measurement vulnerable both to errors in position and the error of the elevation profile from 1960, similarly to our own. However, a careful visual assessment of the image series in Figure 2 supports our conclusion that the thinning rate between 1900 and 1960 was significantly greater than the thinning rate between 1960 and 2005. Pfeffer's (2003) data does not reflect this trend. Thus, insofar as the measurements by Waldrop (1964) are considered accurate (which was a precept of both this study and Pfeffer's), we believe that the thinning values reported here are more accurate than those reported by Pfeffer (2003).

The average thinning rate between 1960 and 2003 reported by Dyurgerov and Meier (2005) is a reconstructed value calculated using a point-degree-day (PDD) ablation model and 5 years of direct mass balance measurements from Arikaree Glacier (a nearby Front Range glacier) and Arapaho Glacier. As a first-order approximation of thinning we believe this method to be an excellent tool, but maintain our confidence in the thinning rate reported here for two major reasons. First, as with Pfeffer's (2003) results, the photographic record does not support such a significant rate of thinning. Second, although Arikaree Glacier and Arapaho Glacier have similar elevations and aspects, and are located in the same region of the Front Range, these factors alone are not sufficient to determine a direct correlation between them; detailed accumulation and incident shortwave solar radiation, or insolation, data for each would be necessary to determine such a relationship (Alford, 1973). In the absence of a correlation based upon these data an accurate picture of Arapaho Glacier's mass balance history would be very difficult to reconstruct. Furthermore, even if such a correlation could be established it would require many years of coherent data to produce an accurate mass balance reconstruction. Given the inconsistent and variable mass balance of Arapaho Glacier (Henderson, 1904; Waldrop, 1964; Johnson, 1979), the five years of data used by Dyurgerov and Meier (2005) is, in any case, insufficient to produce an accurate mass balance reconstruction. Similarly, it is no surprise that the measured thinning rate of Arikaree Glacier was different than that measured here for Arapaho Glacier; differences in the shape, size and slope of each glacier's cirque and the resulting variance of accumulation and insolation that would thus be expected between them suggest that Arapaho and Arikaree probably have very different mass balance histories.

Nonetheless, even if our thinning measurements are considered low and their maximum uncertainty is applied, average thinning between 1900 and 1960 was still more than twice the average thinning measured here for the 1960 to 2005 period. The photographic record strongly supports this trend. We therefore maintain that the total thinning of Arapaho Glacier between 1960 and 2005 was significantly less than it was between 1900 and 1960.

The rate at which Arapaho Glacier has been losing area, on the other hand, has apparently increased over the course of the 20th century. Thus, although it has both thinned and lost a considerable portion of its area, Arapaho Glacier's recent changes have in large part been limited to its extent; its thickness, relative to its area, has remained somewhat stable in recent decades. Since localized accumulation and insolation patterns have the greatest bearing on the mass balance of Front Range glaciers (Alford, 1973), it is crucial that these factors are examined when attempting to explain Arapaho Glacier's peculiar pattern of retreat.

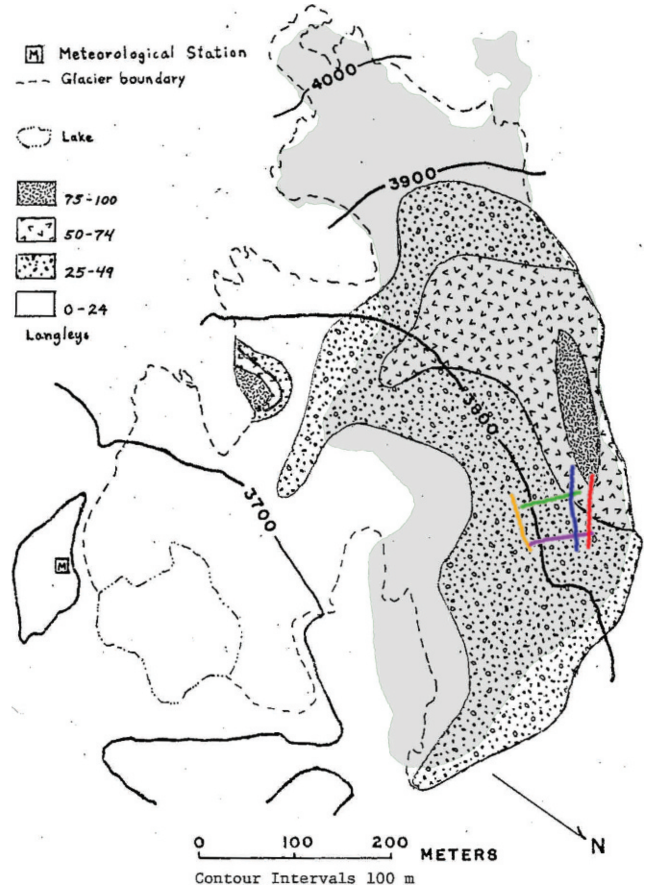

FIGURE 12. Map of modeled shading and resulting loss of shortwave radiation for Arapaho Glacier relative to flat-Earth value (Johnson, 1979). One Langley (insolation unit) equals 41,840 J m^{-2}. Gray overlain region shows the extent of glacier in 1999. Positions of GPR transects are shown (Fig. 6). Note the similarity between areas with heavy shading (solar radiation loss) and the current extent of the glacier, suggesting a strong inverse relationship between glacial extent and insolation. Also note the positioning of the GPR profiles—in an area of low insolation (high shading) and high accumulation. Also note that the "tongue" of the glacier at the top (SW) of the map receives sunlight at high incidence angle and is not significantly shaded; this region of the glacier shows very little if any change (Fig. 10).

Beyond normal snow accumulation, Arapaho Glacier is sustained by large amounts of snow deposited in its cirque by wind transport and avalanching (Waldrop, 1964; Outcalt and MacPhail, 1965). Field observations in March and October of 2007 and October 2009 also suggest, as has been suggested before (Johnson, 1979), that the majority of secondary snow is deposited immediately adjacent to the western headwall of the cirque and directly on top of the thickest portion of the glacier. Also observed in 2007 was the shortened period of each day that the same region is exposed to direct sunlight. Thus the region of Arapaho Glacier that still exists occupies the basin of the cirque adjacent to the western headwall because it is this region that receives both the most snow and least solar radiation. A map from Johnson (1979) showing the region of the cirque that receives the least amount of insolation very closely matches the extent of the glacier in 1999 (Fig. 12). This insolation-accumulation pattern supports the suggestion that the maximum ice thickness measured is likely the maximum thickness of the entire glacier, since the GPR survey was conducted in the region of very low insolation and highest accumulation.

The importance of the high-accumulation zone in the modern mass balance of Arapaho Glacier may also be seen in the down-flow profiles (Fig. 8.2). Truncation of layering by the ice surface indicates intense ablation as distance increases from the headwall. However, at the very top of the glacier the layering and surface are nearly parallel, indicating some net accumulation and therefore some sustaining annual snow mass within 15–20 m of the uppermost part of the profiles. Note that the near-parallel relationship of reflectors within the glacier (with the exception of the lowest layer, where entrained debris may be scattering much of the return radar signal) implies that no earlier period of intense ablation is recorded within the remaining ice. In sum, the glacier is maintained predominantly by local mass balance, redistribution by flow is negligible, and radar profiles show that the accumulation area is extremely narrow: immediately adjacent the western headwall (the avalanche and wind-drift zone).

Although more detailed investigations of snow accumulation and insolation are required to clearly define such a relationship, heavy accumulation and a lack of exposure to solar radiation over a limited region of Arapaho Glacier may be enabling sustained ice thickness while simultaneously allowing for rapid area loss, thus explaining the unique pattern of retreat reported here.

Presumably, if climate remains stable, there will come a time when snow accumulation balances insolation-driven ablation. At such time both the thickness and area of Arapaho Glacier may reach steady state or require much higher rates of climate warming to alter. This possibility suggests that the survival estimate we discuss for Arapaho Glacier may be an underestimate; it is possible that Arapaho Glacier will continue to exist in some form for many decades to come. Judging from recent photographic comparisons (Fig. 2) and the marked decrease in thinning rate between 1960 and 2005, we believe that the rate at which Arapaho Glacier is losing area is also now slowing, indicating that it may already be on its way to a smaller but sustained existence.

However, it is unlikely that the climate will remain stable. Increased greenhouse gases in the atmosphere are forcing a warmer climate. As a result, overall accumulation on Arapaho Glacier will likely drop as some precipitation that once fell as snow begins to fall as rain, and as the length of the annual melt season increases. Warming that began in the mid to late 19th century initiated the glacier's retreat, and as warming continues its retreat will likely also continue. So although it may be able to retreat into a region of the cirque where it is stable, it is also possible that continued climate forcing will destabilize the glacier enough to cause its complete disappearance.

Conclusion

Although limited by the availability, accuracy, and integration of past data, this study illustrates important past trends and current aspects of Arapaho Glacier. Over the course of the 20th century, Arapaho Glacier has shown a pattern of increasingly rapid area loss and decreasingly rapid thinning. Its average maximum thickness, inferred from the region of the glacier where GPR data were collected, is 15.5 m. It covers an area of 0.16 km^2 and its volume is approximately 1.8×10^{-3} km^3. If past trends continue, Arapaho Glacier could cease to exist in as few as 65 years. Observed 20th century trends may or may not continue, but augmenting the data presented here with repeated GPR analysis and future studies of accumulation and insolation patterns, and thickness and area measurements, will help to constrain the future of Arapaho Glacier as well as provide a valuable data set for climatological studies.

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References Cited

Alford, D. L., 1973: Cirque glaciers of the Colorado Front Range: mesoscale aspects of a glacier environment. PhD thesis. Department of Geography, University of Colorado at Boulder.

Andrews, J. T., 1975: *Glacial Systems, an Approach to Glaciers and Their Environments.* Environmental Systems Series. North Scituate, Massachusetts: Duxbury Press.

Barnett, T. P., Adam, J. C., and Lettenmaier, D. P., 2005: Potential impacts of a warming climate on water availability in snow-dominated regions. *Nature*, 438: doi:10.1038/nature04141.

Benedict, J. B., 1985: *Arapaho Pass; glacial geology and archeology at the crest of the Colorado Front Range*. Ward, Colorado: Center for Mountain Archeology, Research Report No. 3.

Dyurgerov, M. B., and Meier, M. F., 2005: *Glaciers and the changing Earth system: a 2004 snapshot*. Boulder, Colorado: Institute of Arctic, Antarctic and Alpine Research, University of Colorado, Occasional Paper No. 58.

Fenneman, N. M., 1902: The Arapahoe Glacier in 1902. *Journal of Geology*, 10: 839–851.

Harris, S. A., 1968: Till fabrics and speed of movement of the Arapahoe Glacier, Colorado. *The Professional Geographer*, 20(3): 195–198.

Henderson, J., 1904: Arapahoe Glacier in 1903. *Journal of Geology*, 12: 30–33.

Henderson, J., 1905: Arapahoe Glacier in 1905. *Journal of Geology*, 13: 556.

Henderson, J., 1910: Extinct and existing glaciers of Colorado. *University of Colorado Studies*, 8(1): 33–76.

Ives, R. L., 1951: Modern glaciers of the Arapaho massif, Colorado. *The Scientific Monthly*, 13: 25–36.

Johnson, J. B., 1979: Mass balance and aspects of the glacier environment, Front Range, Colorado, 1969–1973. PhD thesis. Department of Geological Sciences, University of Colorado at Boulder.

Lee, W. T., 1900: The glacier of Mt. Arapahoe, Colorado. *Journal of Geology*, 8: 647–654.

Lemke, P., Ren, J., Alley, R. B., Allison, I., Carrasco, J., Flato, G., Fujii, Y., Kaser, G., Mote, P., Thomas, R. H., and Zhang, T., 2007: Observations: changes in snow, ice and frozen ground. *In*

Solomon, S. (ed.), *Climate change 2007: the physical science basis; summary for policymakers, technical summary and frequently asked questions. Part of the Working Group I contribution to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Nairobi: published for the Intergovernmental Panel on Climate Change by UNEP, 337–383.

Meier, M. F., Dyurgerov, M. B., and McCabe, G. J., 2003: The health of glaciers: recent changes in glacier regime. *Climatic Change*, 59(1–2): 123–125, doi: 10.1023/A:1024410528427.

Meier, M. F., Dyurgerov, M. B., Rick, U. R., O'Neel, S., Pfeffer, W. T., Anderson, R. S., Anderson, S. P., and Glaznovsky, A. F., 2007: Small glaciers dominate eustatic sea-level rise in the 21st century. *Science*, 317(5841): 1064–1067.

Outcalt, S. I., and MacPhail, D. D., 1965: A survey of neoglaciation in the Front Range of Colorado. *University of Colorado Studies Series in Earth Sciences*, 4.

Paterson, W. S. B., 1994: *The Physics of Glaciers.* Third edition. Tarrytown, New York: Elsevier Science Inc.

Pfeffer, W. T., 2003: Unpublished photogrammetric survey. Contact: pfeffer@tintin.colorado.edu.

Reheis, M. J., 1975: Source, transportation and deposition of debris on Arapaho Glacier, Front Range, Colorado, U.S.A. *Journal of Glaciology*, 14: 407–420.

Thornbury, W. D., 1928: Glaciation on the east side of the Colorado Front Range between James Peak and Longs Peak. MS thesis. Department of Geological Sciences, University of Colorado at Boulder.

Waldrop, H. A., 1964: Arapaho Glacier; a sixty-year record. *University of Colorado Studies Series in Geology*, 3.

MS accepted January 2010

Appendix A

GPR unit: MALÅ Geoscience RAMAC™ 250 MHz shielded system. Data acquisition software: RAMAC™ GroundVision™, MALÅ Geoscience. Data processing software: RadExplorer™, DECO Geophysical

GPR Collection Parameters, 29 October 2007	
Transects 1–5	
Samples	1042
Sampling Frequency	1658 s^{-1}
Signal/Trace distance interval	0.20 m
Antenna frequency	250 MHz
Antenna separation	0.36 m
Time window	628 ns
Stacks	32
Transect 6	
Samples	2002
Sampling Frequency	1658 s^{-1}
Signal/Trace distance interval	0.30 m
Antenna frequency	250 MHz
Antenna separation	0.36 m
Time window	1207 ns
Stacks	32

Transect Dimensions

Transect	Length	# Traces
1	75.97	377
2	85.44	424
3	66.7	331
4	61.46	305
5	66.5	330
6	55.87	186