Juneau Icefield Mass Balance Program 1946–2011

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Abstract

The mass balance records of the Lemon Creek Glacier and Taku Glacier observed by the Juneau Icefield Research Program are the longest continuous glacier mass balance data sets in North America. On Taku Glacier annual mass balance averaged +0.40 m a$^{-1}$ from 1946–1985 and −0.08 m a$^{-1}$ from 1986–2011. The recent mass balance decline has resulted in the cessation of the long term thickening of the glacier. Mean annual mass balance on Lemon Creek Glacier has declined from −0.30 m a$^{-1}$ for the 1953–1985 period to −0.60 m a$^{-1}$ during the 1986–2011 period. The overall mass balance change is −26.6 m water equivalent, a 29 m of ice thinning over the 55 yr. Probing transects above the transient snow line (TSL) indicate a consistent balance gradient from year to year. Observations of the rate of summer TSL rise on Lemon Creek and Taku Glacier indicate a comparatively consistent rate of 3.8 to 4.1 m d$^{-1}$. The relationship between TSL on Lemon Creek and Taku Glacier to other Juneau Icefield glaciers, Norris, Mendenhall, Herbert, and Eagle, is strong with correlations exceeding 0.82 in all cases.

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1 Introduction

The Juneau Icefield Research Program (JIRP) is the longest ongoing program of its kind in North America, facilitating arctic and alpine education and expeditionary training in the fields of climate science, glaciology and glacial geology. JIRP has examined the mass balance of the Juneau Icefield since 1946, with principal efforts focused on Lemon Creek Glacier and Taku Glacier. This database is the longest glacier field measurement mass balance data set in North America. The data are reported to the World Glacier Monitoring Service (WGMS) annually and is available through the Advanced Cooperative Arctic Data and Information Service (ACADIS). This paper reports
on three data sets: (1) annual mass balance record of Taku and Lemon Creek Glacier including the equilibrium line altitude (ELA) and accumulation area ratio (AAR) annually, including evaluation of validation and potential errors; (2) probing transects above the TSL in 1984, 1998, 2004, 2005 and 2010; (3) satellite image determined transient snowline observations and rate of rise on Lemon Creek and Taku Glaciers and TSL variations on six glaciers of the Juneau Icefield from 1995–2011 (Eagle, Herbert, Lemon Creek, Mendenhall, Norris and Taku).

2 Field area

2.1 Taku Glacier

Taku Glacier is a temperate, maritime valley glacier in the Coast Mountains of Alaska. With an area of 775 km$^2$, it is the principal outlet glacier of the Juneau Icefield (Fig. 1). Taku Glacier can be divided into three zones with differing mass balance and flow characteristics: (1) The ablation zone, below the mean annual ELA of 925 m (113 km$^2$), descends the trunk valley with no tributaries joining the glacier, and the single distributary tongue, Hole in the Wall, branches off from the main glacier 9 km above the terminus. (2) The lower neve zone, extending from the ELA at 925 m up to 1350 m, is a zone where summer ablation is significant (178 km$^2$). All of the main tributary glaciers (Southwest, West, Matthes, Demorest, and Hades Highway) join in this zone. (3) The upper neve zone extends from 1350 m to the head of the glacier at 2200 m (380 km$^2$), comprising the principal accumulation region for each tributary except the Southwest Branch. Ablation is limited in this zone, with much of the summer meltwater refreezing within the firn. This refreezing results in a unique signature in SAR imagery (Ramage et al., 2000).

Taku Glacier attracts special attention because of its continuing, century-long advance (Pelto and Miller, 1990; Post and Motyka, 1995), while all other outlet glaciers of the Juneau Icefield are retreating. Taku Glacier is also the thickest glacier yet measured
in Alaska at 1375 m (Nolan et al., 1995). Taku Glacier is noteworthy for its positive mass balance from 1946–1988, which resulted from the cessation of calving around 1950 (Pelto and Miller, 1990). The positive mass balance resulting from this dynamic change with calving cessation gives the glacier an unusually high AAR (accumulation area ratio: percentage of glacier in accumulation zone at end of hydrologic year) for a non-calving glacier and makes the glacier relatively insensitive to climate change (Miller and Pelto, 1990; Pelto et al, 2008; Criscitiello et al., 2010).

2.2 Lemon Creek Glacier

Lemon Creek Glacier, Alaska was chosen as a representative glacier for the 1958 IGY global glacier network. This choice was based on its sub-arctic latitude and on the ongoing mass balance program of (JIRP) that had begun in 1948 (Miller, 1972; Pelto and Miller, 1990). JIRP has continued annual balance measurements on Lemon Creek Glacier through the present (Fig. 2). In 1957 Lemon Creek Glacier was 6.4 km long and had an area of 12.67 km² (Heusser and Marcus, 1964). In 1998 the glacier was 5.6 km long and had an area of 11.8 km² (Marcus et al., 1995). From the head of the glacier at 1450 m to the mean ELA at 1050–1100 m the glacier flows northward, in the ablation zone the glacier turns westward terminating at 600 m. The glacier can be divided into four sections: (1) Steep peripheral northern and western margins draining into the main valley portion of the glacier. (2) A low slope (4°) upper accumulation zone from 1220 m to 1050 m. (3) A steeper section (6°) in the ablation zone as the glacier turns west from 1050–850 m. (4) An icefall (18°) leading to the two fingered termini at 600 m. The maximum thickness exceeding 200 m is 1 km above the icefall (Miller, 1972). Lemon Creek Glacier has retreated 1200 m since 1948 and 800 m since 1957, an average of 10–13 m a⁻¹ between 1998 and 2009.
3 Mass balance methods

JIRP has relied on applying consistent mass balance methods at standard measurement sites (Pelto and Miller, 1990; Miller and Pelto, 1999; Pelto, 2011). The key annual measurements are: (1) Snowpits at fixed locations on Taku Glacier and Lemon Creek Glacier ranging in elevation from 950 to 1800 m by which the snow water equivalent (SWE) through the entire annual snowpack profile is directly measured. (2) Ablation measurements at survey stakes along survey profiles, along with repeat height measurements of the stakes. (3) Observations of the TSL (transient snow line; snowline at the time of observation) and ELA (equilibrium line altitude: snowline at the end of the melt season) that allow ablation adjustments to snowpack.

3.1 Snowpits

The standard snowpack measurement method used by JIRP is the snowpit. Each snowpit is excavated down to the previous summer surface, identified by a dirty and/or ice horizon and density discontinuity. The most important aspect of the snowpit is accurate identification of the depth. The previous annual layer is well developed during each ablation season on the Lemon Creek Glacier and below 1500 m on Taku Glacier (LaChapelle, 1954). Typically, snowpits hit the previous summer’s firn surface, rather than blue ice. The summer’s surface is a laterally continuous surface that typically had undergone several freeze/thaw cycles and often has a low density depth hoar just above it. In mass balance the key element is the snow water equivalent (SWE) of the snowpack. This is the mass per unit area of water that would be yielded were the snowpack melted and is the product of depth and snow density. The density of the snowpack is quite variable during the winter and spring, but by July the mean density is generally consistent from year to year and location to location on the Juneau Icefield. LaChapelle (1954) noted that one of the first characteristics apparent upon examination of the snowpit profiles is the remarkable uniformity of firn density in a vertical profile, and in distribution over the glacier, and with time during the summer. LaChapelle
(1954) found that snowpack density is consistently 540–565 kg m$^{-3}$ after early July on the Taku Glacier; this has been observed by many other detailed studies since (Pelto and Miller, 1990). Despite this fact, density is measured in all snowpit profiles, in part because this is an excellent training tool.

Snow depth can be verified in shallower snowpacks, those less than 3.5 m, using probing or crevasse stratigraphy. Measurements of retained accumulation in the snowpits are completed during late July and August, and are adjusted to end of the balance year values based on the variations of the TSL, observed ablation and the measured balance gradient (Pelto and Miller, 1990; Miller and Pelto, 1999).

For each of the 17 locations where snow pits are utilized on Taku Glacier and 10 locations on Lemon Creek Glacier, a snow pit is dug at a fixed location, verified using GPS. Once onsite, the southern wall of the snow pit is marked off in order to prevent contaminating any density measurements that will be taken; the south wall of the pit is selected for density measurements in order to mitigate any error that may come from ablation caused by direct sunlight on the snow pit wall. Snow pits are always dug at least 50 cm into the previous year’s firn pack in order to ensure continuity of the layer. Once the snow pit is dug down into the previous year’s layer, the southern wall of the snow pit is shaved back to expose a flat, clean face from the top of the snow pit down into the previous year’s layer, this face is used to take density measurements of the snow pack. Using a 500 cc snow corer, samples are taken every ten centimeters down the vertical profile of the snow pit into the previous year’s layer and the density measured. The final step of the snow pit survey is to record all ice lenses present in the vertical profile of the snow pack (Fig. 3). An ice lens is a horizontal layer of ice formed when water percolates through the snow pack, hits a denser and/or colder layer of snow, spreads out laterally, and refreezes. The depth, thickness, and continuity of all ice lenses are recorded. Due to the small size of these features the density of the lens is assumed at 0.9 g cm$^{-3}$.

On Taku Glacier, six of the snowpit sites are near the ELA ranging from 950–1200 m, six are located at 1200–1400 m and five are located at 1400–1800 m altitude.
Compared with Gulkana Glacier (19 km$^2$) and Wolverine Glacier (18 km$^2$), where the USGS annually assesses glacier mass balance from 3–4 measurement sites, the number of measurements on Taku Glacier is large (Mayo et al., 2004; March and Trabant, 1996). However, because the size of the Taku Glacier is more than an order of magnitude larger than either Gulkana or Wolverine glacier, the measurement density is still lower than at the Alaskan benchmark glaciers. Furthermore, the distribution of annual measurements on Taku Glacier is skewed toward the ELA, and is non-existent in the ablation zone. On Gulkana Glacier there is one site in the ablation zone, and two sites near the ELA, and no sites in the upper 600 m of the glacier (March and Trabant, 1996). On Wolverine Glacier there is one site in the ablation zone, one site at the ELA and one in the accumulation zone (Mayo et al., 2004). Because of these differences, extrapolations of mass balance from observations sites are commonly made, and represent a consistent source of error in Alaskan glacier mass balance assessments (Miller and Pelto, 1999). The advantage on Taku Glacier is that there are multiple measurements sites at each elevation, which provides a more robust basis for annual extrapolation of mass balance change with elevation; the disadvantage is that the areal extent over which the extrapolations are made is larger.

### 3.2 Ablation assessment

Ablation is also observed annually during the field season, both at survey stakes located along lines where repeat surveys are completed and through satellite observations of the migration of the TSL (Pelto and Miller, 1990; Pelto et al., 2008). Ablation stakes, driven into the snow in the accumulation zone record the ablation of the remaining snowpack in the accumulation zone, between the time of snowpit accumulation measurement in July and the end of the ablation season in early September. This provides an essential measure for adjusting the July accumulation thickness snowpit measurements to the end of the ablation season. On Lemon Creek Glacier, the maximum number of such ablation stakes used during a single season was 200 in 1967.
During the several years where more than 30 ablation stakes were emplaced, it is apparent that ablation rates above 900 m are nearly constant on the Lemon Creek Glacier, whereas below 900 m ablation rates increases with decreasing surface elevation (Fig. 2).

On Lemon Creek Glacier from 1998–2011 the average ablation observed over a period 162 days was 0.031 m d$^{-1}$. The maximum ablation observed over a period of at least 4 consecutive days was 0.039 m d$^{-1}$ in 2005 and the minimum was 0.029 m d$^{-1}$ in 2006. On Taku Glacier at 1120 m for the 1998–2011 period, average ablation over a span of 127 days is 0.027 m d$^{-1}$. Ablation for at least 4 consecutive days ranged from a high of 0.033 m d$^{-1}$ in 2005 to a low of 0.022 m d$^{-1}$ in 1999.

On Taku Glacier in the ablation zone, the balance gradient is adjusted based on the ELA, on measurements of ablation in nine different years from 1950–1997, and annual ablation measurements on cross survey profiles since 1998. The resulting ablation peaks at 12 m a$^{-1}$ at the terminus (Pelto and Miller, 1990). Independent examination of ablation at the terminus (Motyka and Echelmeyer, 2003), has identified ablation rates at the terminus of 12–14 m a$^{-1}$ during two slightly warmer than usual ablation seasons 2003 and 2004.

### 3.3 Probing and crevasse stratigraphy

The snowpits represent point measurements of SWE amidst the vast expanse of the icefield. How representative are these measurements? To address this question and to estimate the error resulting from extrapolating from snowpits; in 1984, 1998, 2004, 2005 and 2010, JIRP measured the mass balance at an additional 100–500 points with probing transects in the accumulation area to better determine the distribution of accumulation around the snowpit locations. Measurements were taken along profiles at 100–250 m intervals. At each measurement point three depth measurements were made 25 m apart. The standard deviation for measurements sites within 25 m of each other was 7 mm and 17 mm for sites within 100 m of each other; this indicates the consistency of mass balance near snowpit sites.
Retained accumulation thickness has been observed at up to 300 points in a single summer season on Lemon Creek Glacier (1998) and 450 measurements on Taku Glacier (1998). Probing is not effective at depths greater than 5 m. The probe used is a 3/4 inch steel probe that easily penetrates ice lenses within the most recent winter snowpack, because the ice layers have comparatively soft unconsolidated firn beneath them. The previous summer surface cannot be penetrated, because the entire layer was melted and refrozen many times, raising its density and cohesion.

Annual layers in the walls of crevasses are often quite obvious. It is similar to reading tree ring width for climate analysis. Crevasse stratigraphy provides a means to view the two dimensional nature of the annual layer, in contrast a point measurement that is yielded by probing or the small scale view provided by a snowpit. Only vertically walled crevasses can be used for these observations. The key to identification of the annual layer in crevasses is the lateral continuity of the ice layer, as no other feature will be continuous. Crevasse stratigraphy is not a standard method used on the Taku Glacier, but has been used since the beginning of the program for validating snow pit snow depth observations in specific regions of the glacier, where snow depths are large and probing cannot be used to validate the snowpits.

4 Results

4.1 Annual mass balance record

On Taku Glacier, the annual ELA has risen 60 m from the 1946–1985 period to the 1986–2010 period. $Ba$ during the two periods were $+0.40$ and $-0.08$ m w.e. a$^{-1}$, respectively, indicative of the snowline rise resulting in cessation of the long term thickening of the glacier (Table 1). This overall mass balance change from 1946–2011 is $+13.7$ m w.e. (Fig. 4). The long term positive mass balance is continuing to drive its advance (Pelto and Miller, 1990; Post and Motyka, 1995; Pelto et al., 2008). All other outlet glaciers of the Juneau Icefield are retreating, and are thus consistent with
the dominantly negative alpine glacier mass balance that has been observed globally (Zemp et al., 2009).

Based on Lemon Creek Glacier has declined from $-0.3 \, \text{m w.e. a}^{-1}$ for the 1953–1985 period to $-0.60 \, \text{m w.e. a}^{-1}$ during the 1986–2011 period. The overall mass balance change is $-26.6 \, \text{m}$, a $29 \, \text{m}$ ice thickness loss over the 55 yr (Table 1).

### 4.2 Mass Balance Record Validation

Possible errors in the mass balance record include the sparse nature of measurement points (1 per 37 km$^2$), extrapolation to the end of the balance year, infrequent measurements of melting in the ablation zone, and measurements carried out by many different investigators. However, Pelto and Miller (1990), suggest that these sources of error are mitigated by: (1) measuring the same locations at the same time using the same methods each year; (2) using nine years of ablation data to extrapolate mass balance in the ablation zone; (3) validation of snow depth variation using probing transects (see next section). The principal error is due to the lack of data from the ablation zone.

The Taku Glacier mass balance record has been validated with geodetic balance information from independent observation of glacier surface elevation change using the ongoing laser altimetry by the University of Alaska, Fairbanks (Sapiano et al., 1998; Arendt et al., 2002; Larsen et al., 2007). This was accomplished from a centerline profile providing a mean glacier thickness change. Surface elevation change is not strictly a measure of mass balance, though it is reported as such (Arendt, 2006). Surface dynamics can also play a role. On Taku Glacier in the vicinity of the ELA annual velocity surveys indicate a consistent ice dynamics from 1950–2006, indicating that surface elevation change should mostly reflect surface mass balance (Pelto et al, 2008). The observed change in Taku Glacier surface elevation was $+0.69 \, \text{m a}^{-1}$ from 1948–1993 and $-0.28 \, \text{m a}^{-1}$ from 1993–1997 (Arendt, 2006). The observed mass balance for these periods from field observations is $+0.38 \, \text{m a}^{-1}$ for 1948–1993 and $-0.60 \, \text{m a}^{-1}$ for 1993–1997. The surface record includes the large negative mass balance of 1997, while the laser altimetry only includes part of the 1997 ablation season and would tend...
Repeat laser altimetry profiling indicates a $Ba$ of $-0.21 \text{ m a}^{-1}$ for the 1993–2007 period, compared to the JIRP mean $Ba$ of $-0.16 \text{ m a}^{-1}$. A comparison of surface elevations from the 2000 Shuttle Radar Topography Mission and a DEM derived from the 1948 USGS mapping indicates a mean $Ba$ of $+0.45 \text{ m a}^{-1}$ versus the JIRP record of $+0.27 \text{ m a}^{-1}$ for the 1948–2000 period (Larsen et al., 2007). The long term observed ice surface elevation changes taken over varied periods using different techniques validates the accuracy of the mass balance record of the Taku Glacier.

On Lemon Creek Glacier the mass balance record determined from field measurements yields a cumulative mass balance of $-26.9 \text{ mm}$ from 1953–2011. The $Ba$ record of $-12.7 \text{ m w.e.}$ (13.9 m of ice thickness) from 1957–1989 compares well to the thinning identified from geodetic methods of 1957–1989 of $-13.2$ (Marcus et al, 1995). The annual balance record of $-17.1 \text{ m w.e.}$ ($-19.0 \text{ m of ice thickness}$) from 1957–1995 compared to an observed ice thickness change of $-16.4 \text{ m}$ (Sapiano et al., 1998). Airborne surface profiling by the University of Alaska-Fairbanks (Sapiano et al., 1998; Larsen et al., 2007) noted an additional $-13.1 \text{ m surface elevation change}$, compared to a surface mass balance of $-10 \text{ m}$ from 1995–2007. The error in both geodetic programs is less than 1.5 m. In each of the three time intervals using two different ice thickness assessment techniques the annual balance record is confirmed.

5 Probing transects for determination of balance gradient

In late July of 1984, 1998 (Mauri Pelto), 2004, 2005 (Matt Beedle) and 2010, 2011 (Chris McNeil), measured the mass balance along transects from near the TSL at 900 to 1150 m in late July on Taku Glacier by probing at a horizontal interval of 200 m. This method allows direct identification of the mass balance gradient at this elevation (Table 2).

The balance gradient determined from probing between 925 and 1100 m ranges from 3.3–3.8 mm m$^{-1}$, with a mean of 3.5 mm m$^{-1}$. The balance gradient has been
consistent on Taku Glacier for each year observed regardless of the respective mass balance (Fig. 5). Standard deviation of accumulation along the transect from the best fit linear regression is 40 mm. The balance gradient can be compared to that determined directly from snowpit measurements at TKGTP5 and DGTP1 at 1000 m on the Taku Glacier (Pelto, 2011). On the date that each snowpit is excavated, the difference between measured SWE at each test pit and the TSL elevation on that date provides a direct balance gradient measurement. The balance gradient derived from the snowpits was 2.6–3.5 mm m\(^{-1}\). This is less than that for probing, but the TSL on the date of snowpit excavation is almost always lower than the lowest elevation of the probing transects and represents a lower elevation band of 800 to 1000 m.

On Lemon Creek Glacier the balance gradient generated annually from the ELA and snowpit elevations illustrates the similarity of the balance gradient from year to year. Above the balance gradient parallels the probed gradient in 1998. The balance gradient ranges from 4.6 to 5.1 mm m\(^{-1}\) (Fig. 6).

**Balance gradient from TSL variation**

The TSL is readily identifiable on 34 scenes acquired from 1995–2011, and was delineated using the software package US Geological Survey Globalization Viewer. The Juneau Icefield falls in path/row 58/19 and 57/19; all images are false color RGB composites, bands 3, 4, and 5, with a 2 % linear stretch applied. The spatial resolution of 30 m, combined with mean surface gradients of 0.04–0.08 m m\(^{-1}\), yields an error of less than ±5 m in TSL elevation. The exception is when the TSL rises to 1200 m a.s.l. or is below 900 m a.s.l. Lemon Creek Glacier; in both cases the surface slopes increases leading to higher error margins. The satellite images were georeferenced in ArcMap 9.3 using five topographically unique reference points. The data frame containing imagery and base map was transformed to NAD_1983_UTM_Zone_8N to ensure spatial accuracy for measurements. For years with multiple images, the rate of rise of the TSL is determined. This rate of rise is only calculated for periods of longer than 15 days.
For example, in 2006 the TSL was identified in five Landsat images on Taku Glacier. The TSL in 2006 rose from 370 m on 26 May, to 575 m on 10 June, 730 m on 5 July, 800 m on 29 July, and finally 980 m on 15 September (Fig. 7; Table 3). The TSL rise ranged from 3.1 to 6.2 m d\(^{-1}\). Mean rise of the TSL for 15 period’s averages 4.1 ± 0.9 m d\(^{-1}\) during the July–September period, for the elevation range between 750–1100 m (Table 3; Fig. 7).

The TSL for Lemon Creek Glacier has been observed for 34 dates from 1998–2011 these observations define 18 time periods for which satellite observations were at least 15 days apart (Table 3; Fig. 8). For Lemon Creek Glacier the observed positive TSL migration rates varied from 3.0 to 5.2 m d\(^{-1}\) with a mean of 4.0 ± 0.6 m d\(^{-1}\). The mean TSL migration rate on Lemon Creek Glacier of 3.8 m d\(^{-1}\) compares well with the mean migration rate of 3.7 m d\(^{-1}\) on nearby Taku Glacier (Pelto, 2011). This suggests a consistency in the rate of rise of the TSL from glacier to glacier and year to year on the Juneau Icefield.

6 ELA-TSL observations

Observations of the TSL and ELA can now be reliably made each year using a combination of less frequent Landsat Imagery, and the daily MODIS images (Pelto, 2011; Hock et al., 2007). Use of the latter insures that observations within a short period of the end of the ablation season. The last usable Landsat image for the ablation season is used to assess the TSL for six glaciers of the Juneau Icefield from 1995–2011 (Table 4; Fig. 9). The observed TSL are highly correlated for these dates on all of the glaciers. This paper presents only a single late season TSL from each year; additional analysis is required to determine the rate of change of TSL in September for each glacier. The ELA can be reasonably estimated from the late season TSL observation on each glacier, once both the rate of rise and the date of the end of the ablation season are known. The ELA in turn is a good indicator of mass balance (Mernild et al., 2013). The World Glacier Monitoring Service derives plots of ELA versus \(B_a\) each year.
The plots generated for the WGMS (2011) from Lemon Creek Glacier are below. The fit is not good for Taku Glacier (Fig. 10). The fit for Lemon Creek Glacier is excellent for the ELA-Ba (Fig. 11).

### 7 Conclusions

The mass balance record from Lemon Creek Glacier and Taku Glacier illustrate a decline in mass balance for both glaciers after 1985. Independent geodetic observations of glacier mass balance validate the long term changes quantified by the $Ba$ for both glaciers. The balance gradient of the Taku Glacier and Lemon Creek Glacier is consistent in the region near the ELA from year to year. The rate of rise of the TSL is relatively consistent from year to year and glacier to glacier on the Juneau Icefield. The ELA provides a reasonable first estimate of $Ba$ on Taku Glacier and Lemon Creek Glacier, and as such determination of this relationship for other Juneau Icefield glacier utilizing simultaneous TSL variations with Lemon Creek and Taku Glacier has value.

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Table 1. Mass balance record of the Taku and Lemon Creek Glacier including annual mass balance (Ba), ELA, AAR and cumulative Ba.

| Year | Taku Ba (mm) | LC Ba (mm) | LC cumulative Ba (mm) | Taku cumulative Ba (mm) | Taku ELA (m) | LC ELA (m) | LC AAR | Taku AAR |
|------|--------------|------------|-----------------------|-------------------------|--------------|------------|--------|---------|
| 1946 | −40          | −40        | 980                   | 85                      |
| 1947 | 360          | 320        | 900                   | 88                      |
| 1948 | 510          | 830        | 870                   | 89                      |
| 1949 | 930          | 1760       | 800                   | 90                      |
| 1950 | −180         | 1580       | 1010                  | 84                      |
| 1951 | −340         | 1240       | 1160                  | 68                      |
| 1952 | 160          | 1400       | 950                   | 86                      |
| 1953 | −150 −560    | −560       | 1250                  | 1010                    |
| 1954 | −70 −180     | −740       | 1180                  | 1160                    |
| 1955 | 970 1120     | 380        | 2150                  | 950                     |
| 1956 | −130 −640    | −260       | 2020                  | 1010                    |
| 1957 | −40 0        | −260       | 1980                  | 980                     |
| 1958 | 210 −580     | −840       | 2190                  | 780                     |
| 1959 | 350 −900     | −1740      | 2540                  | 1000                    |
| 1960 | 160 −820     | −2560      | 2700                  | 1010                    |
| 1961 | 480 −240     | −2800      | 3180                  | 930                     |
| 1962 | 390 −690     | −3490      | 3570                  | 915                     |
| 1963 | 570 170      | −3320      | 4140                  | 950                     |
| 1964 | 1130 1040    | −2280      | 5270                  | 885                     |
| 1965 | 790 80       | −2200      | 6060                  | 900                     |
| 1966 | 80 −490      | −2690      | 6140                  | 875                     |
| 1967 | 250 −600     | −3290      | 6390                  | 750                     |
| 1968 | 460 −220     | −3510      | 6850                  | 810                     |
| 1969 | 1170 210     | −3300      | 8020                  | 965                     |
| 1970 | 760 −90      | −3390      | 8780                  | 930                     |
| 1971 | 630 −400     | −3790      | 9410                  | 885                     |
| 1972 | 420 −650     | −4440      | 9830                  | 730                     |
| 1973 | 520 −520     | −4960      | 10350                 | 825                     |
| 1974 | 580 −370     | −5330      | 10930                 | 850                     |
| 1975 | 850 290      | −5040      | 11780                 | 800                     |
| 1976 | 660 −250     | −5290      | 12440                 | 850                     |
| 1977 | 470 −480     | −5770      | 12910                 | 885                     |
| 1978 | 310 −800     | −6570      | 13220                 | 915                     |
Table 1. Continued.

| Year | Taku \( Ba \) (mm) | LC \( Ba \) (mm) | LC cumulative \( Ba \) (mm) | Taku cumulative \( Ba \) (mm) | Taku ELA (m) | LC ELA (m) | LC AAR | Taku AAR |
|------|---------------------|-----------------|--------------------------|-----------------------------|-------------|-------------|--------|---------|
| 1979 | 140                 | −630            | −720                     | 13360                       | 950         | 1110        | 40     | 86      |
| 1980 | 540                 | −270            | −7470                    | 13900                       | 870         | 1100        | 42     | 89      |
| 1981 | 120                 | −810            | −8280                    | 14020                       | 980         | 1120        | 40     | 85      |
| 1982 | 150                 | −430            | −8710                    | 14170                       | 950         | 1070        | 51     | 86      |
| 1983 | −420               | −1620           | −10330                   | 13750                       | 1085        | 1220        | 17     | 79      |
| 1984 | 640                 | −250            | −10580                   | 14390                       | 875         | 1010        | 65     | 89      |
| 1985 | 1400                | 330             | −10250                   | 15790                       | 600         | 965         | 75     | 93      |
| 1986 | 1200                | −510            | −10760                   | 16990                       | 720         | 1070        | 51     | 92      |
| 1987 | 390                 | −840            | −11600                   | 17380                       | 910         | 1100        | 43     | 88      |
| 1988 | 600                 | 110             | −11490                   | 17980                       | 890         | 1000        | 69     | 88      |
| 1989 | −810               | −1240           | −12730                   | 17170                       | 1115        | 1130        | 40     | 74      |
| 1990 | −450               | −1110           | −13840                   | 16720                       | 1080        | 1125        | 42     | 79      |
| 1991 | 380                 | −380            | −14220                   | 17100                       | 900         | 1050        | 60     | 88      |
| 1992 | 170                 | −660            | −14880                   | 17270                       | 940         | 1075        | 54     | 86      |
| 1993 | −40                 | −980            | −15860                   | 17230                       | 980         | 1130        | 43     | 85      |
| 1994 | 90                  | −760            | −16620                   | 17320                       | 970         | 1100        | 46     | 85      |
| 1995 | −760               | −1310           | −17930                   | 16560                       | 1050        | 1150        | 38     | 81      |
| 1996 | −960               | −1580           | −19510                   | 15600                       | 1150        | 1370        | 5      | 68      |
| 1997 | −1340              | −1810           | −21320                   | 14260                       | 1225        | 1400        | 5      | 60      |
| 1998 | −980               | −1460           | −22780                   | 13280                       | 1120        | 1300        | 7      | 73      |
| 1999 | 400                 | 200             | −22580                   | 13680                       | 900         | 1020        | 68     | 88      |
| 2000 | 1030                | 650             | −21930                   | 14710                       | 750         | 900         | 82     | 91      |
| 2001 | 880                 | 400             | −21530                   | 15590                       | 850         | 950         | 77     | 89      |
| 2002 | 100                 | −250            | −21780                   | 15690                       | 975         | 1025        | 67     | 88      |
| 2003 | −900               | −1900           | −23680                   | 14790                       | 1100        | 1400        | 5      | 77      |
| 2004 | −830               | −1250           | −24930                   | 13960                       | 1100        | 1150        | 59     | 86      |
| 2005 | −720               | −470            | −25400                   | 13240                       | 1050        | 1050        | 61     | 86      |
| 2006 | 230                 | −170            | −25570                   | 13470                       | 975         | 1025        | 68     | 86      |
| 2007 | 480                 | 150             | −25420                   | 13950                       | 930         | 1000        | 72     | 87      |
| 2008 | 750                 | 800             | −24620                   | 14700                       | 800         | 920         | 80     | 90      |
| 2009 | −310               | −700            | −25320                   | 14390                       | 960         | 1060        | 51     | 86      |
| 2010 | −120               | −580            | −25900                   | 14270                       | 1000        | 1075        | 55     | 83      |
| 2011 | −550               | −720            | −26620                   | 13720                       | 1025        | 1100        | 47     | 82      |
Table 2. Accumulation measurement on probing transect above the TSL on Taku Glacier in July 1998, 2004, 2005 and 2010.

| Pt. Name | Easting | Northing | Elevation | 2004 | 2005 | 1998 | 2010 |
|----------|---------|----------|-----------|------|------|------|------|
| P1       | 541911  | 6501411  | 1099      | 1001 | 1030 | 910  |      |
| P2       | 542013  | 6501311  | 1097      | 954  | 960  | 850  |      |
| P3       | 542115  | 6501200  | 1094      | 925  | 1221 |      |      |
| P4       | 542217  | 6501111  | 1092      | 893  | 1177 | 770  |      |
| P5       | 542319  | 6501000  | 1090      | 882  | 1148 | 800  |      |
| P6       | 542454  | 6500911  | 1089      | 873  | 960  |      |      |
| P7       | 542568  | 6500800  | 1087      | 859  | 926  | 850  |      |
| P8       | 542669  | 6500712  | 1085      | 815  | 1075 |      |      |
| P9       | 542783  | 6500601  | 1084      | 871  | 1112 | 910  |      |
| P10      | 542885  | 6500501  | 1082      | 916  | 1110 |      |      |
| P11      | 542998  | 6500412  | 1081      | 936  | 1030 | 1370 |      |
| P12      | 543100  | 6500312  | 1078      | 889  | 1143 | 880  | 1434 |
| P13      | 543202  | 6500201  | 1077      | 902  | 1156 | 1419 |      |
| P14      | 543304  | 6500101  | 1074      | 992  | 1171 | 1435 |      |
| P15      | 543395  | 6500012  | 1073      | 1001 | 1218 | 770  | 1443 |
| P16      | 543519  | 6499901  | 1070      | 1035 | 1302 | 1413 |      |
| P17      | 543599  | 6499801  | 1068      | 1004 | 1307 | 750  | 1385 |
| P18      | 543712  | 6499701  | 1066      | 963  | 1312 | 1316 |      |
| P19      | 543814  | 6499612  | 1063      | 981  | 1318 | 1327 |      |
| P20      | 543905  | 6499512  | 1060      | 959  | 1344 | 850  | 1365 |
| P21      | 543996  | 6499412  | 1057      | 945  | 1278 | 1396 |      |
| P22      | 544086  | 6499312  | 1056      | 983  | 1278 | 1383 |      |
| P23      | 544189  | 6499201  | 1052      | 950  | 1259 | 830  | 1350 |
| P24      | 544291  | 6499113  | 1050      | 927  | 1164 | 1350 |      |
| P25      | 544393  | 6499001  | 1047      | 920  | 1161 | 830  | 1303 |
| P26      | 544495  | 6498901  | 1044      | 866  | 1116 | 1238 |      |
| P27      | 544574  | 6498813  | 1042      | 844  | 1142 | 1295 |      |
| P28      | 544688  | 6498713  | 1039      | 814  | 1078 | 740  | 1226 |
| P29      | 544790  | 6498602  | 1036      | 796  | 1092 | 1202 |      |
| P30      | 544903  | 6498513  | 1033      | 774  | 1016 | 1225 |      |
| P31      | 544994  | 6498391  | 1031      | 734  | 1052 | 1208 |      |
| P32      | 545074  | 6498302  | 1030      | 707  | 1041 | 1213 |      |
| P33      | 545187  | 6498202  | 1027      | 689  | 1022 | 660  | 1180 |
Table 2. Continued.

| Pt. Name | Easting  | Northing  | Elevation | 2004 | 2005 | 1998 | 2010 |
|----------|----------|-----------|-----------|------|------|------|------|
| P35      | 545380   | 6498002   | 1022      | 684  | 968  | 1154 |      |
| P36      | 545482   | 6497891   | 1021      | 697  | 963  | 1120 |      |
| P37      | 545562   | 6497791   | 1019      | 666  | 975  | 1141 |      |
| P38      | 545642   | 6497713   | 1016      | 670  | 957  | 660  | 1118 |
| P39      | 545733   | 6497613   | 1013      | 639  | 941  | 1073 |      |
| P40      | 545846   | 6497513   | 1010      | 661  | 922  | 550  | 1071 |
| P41      | 545948   | 6497425   | 1006      | 668  | 938  | 1090 |      |
| P42      | 546039   | 6497313   | 1003      | 621  | 901  | 560  | 1109 |
| P43      | 546130   | 6497213   | 1000      | 659  | 889  | 1090 |      |
| P44      | 546232   | 6497102   | 996       | 639  | 858  | 490  | 1099 |
| P45      | 546323   | 6497025   | 994       | 605  | 879  | 1079 |      |
| P46      | 546414   | 6496914   | 992       | 565  | 834  | 550  | 1040 |
| P47      | 546516   | 6496803   | 989       | 617  | 843  | 1025 |      |
| P48      | 546607   | 6496714   | 988       | 590  | 841  | 440  | 1066 |
| P49      | 546698   | 6496603   | 985       | 617  | 815  | 1070 |      |
| P50      | 546800   | 6496503   | 981       | 646  | 726  | 410  | 1135 |
| P51      | 546891   | 6496403   | 977       | 576  | 789  | 1096 |      |
| P52      | 547005   | 6496314   | 972       | 574  | 675  | 380  | 1135 |
| P53      | 547107   | 6496214   | 967       | 601  | 725  | 1116 |      |
| P54      | 547198   | 6496114   | 963       | 583  | 688  | 1116 |      |
| P55      | 547300   | 6496003   | 960       | 587  | 694  | 360  | 1077 |
| P56      | 547391   | 6495903   | 956       | 405  | 680  | 1025 |      |
| P57      | 547494   | 6495792   | 953       | 330  | 606  | 310  | 1036 |
| P58      | 547596   | 6495715   | 949       | 780  |      | 1034 |      |
| P59      | 547709   | 6495604   | 944       | 757  |      | 945  |      |
| P60      | 547789   | 6495504   | 940       | 680  |      | 913  |      |
| P61      | 547914   | 6495393   | 935       | 744  |      | 905  |      |
| P62      | 547994   | 6495304   | 930       | 606  |      | 911  |      |
Table 3. Transient snowline observation on Lemon Creek Glacier (LCG) and Taku Glacier (TG), and the respective rates of rise between image dates at least 16 days apart. The date listed is the final date of the measurement interval.

| Date       | LC TSL (m) | Lemon Creek TSL rate of rise (m d$^{-1}$) | Taku TSL (m) | Taku TSL rate of rise (m d$^{-1}$) |
|------------|------------|------------------------------------------|--------------|-------------------------------------|
| 7/11/1998  | 950        |                                          | 850          |                                     |
| 7/30/1998  | 1025       | 3.95                                     | 880          |                                     |
| 8/20/1998  | 1100       | 3.57                                     | 980          | 4.76                                |
| 9/16/1998  | 1200       | 3.85                                     | 1075         | 4.42                                |
| 8/31/1999  | 950        |                                          | 850          |                                     |
| 8/29/2000  | 900        |                                          | 775          |                                     |
| 8/15/2001  | 900        |                                          | 800          |                                     |
| 10/3/2002  | 1025       |                                          | 950          |                                     |
| 7/12/2003  | 1040       |                                          | 915          |                                     |
| 8/5/2003   | 1110       | 3.33                                     | 950          |                                     |
| 8/22/2003  | 1170       | 3.53                                     | 1075         | 3.90                                |
| 7/15/2004  | 950        |                                          | 850          |                                     |
| 8/8/2004   | 1075       | 5.21                                     | 930          | 3.48                                |
| 8/16/2004  | 1100       | 4.69                                     | 950          | 3.13                                |
| 8/24/2004  | 1150       | 4.69                                     | 980          | 3.13                                |
| 9/1/2004   | 1100       | 3.13                                     | 1050         | 6.25                                |
| 8/10/2005  | 1050       | 3.92                                     | 920          |                                     |
| 9/11/2005  | 1050       |                                          | 1000         | 4.06                                |
| 7/29/2006  | 935        |                                          | 760          |                                     |
| 9/15/2006  | 1025       | 3.04                                     | 975          | 4.48                                |
| 8/8/2007   | 875        |                                          | 850          |                                     |
| 8/16/2007  | 925        |                                          | 900          |                                     |
| 9/2/2007   | 1000       | 4.41                                     | 965          | 3.82                                |
| 7/2/2008   | 800        |                                          | 400          |                                     |
| 8/19/2008  | 900        | 3.38                                     | 775          |                                     |
| 7/13/2009  | 900        |                                          | 750          |                                     |
| 8/5/2009   | 975        | 3.57                                     | 825          | 3.26                                |
| 8/29/2009  | 1050       | 3.13                                     | 900          | 3.13                                |
| 9/14/2009  | 1050       |                                          | 950          | 3.13                                |
| 7/8/2010   | 925        |                                          | 580          |                                     |
| 8/3/2010   | 1000       | 3.85                                     | 775          |                                     |
| 8/14/2010  | 1050       | 3.57                                     | 800          |                                     |
| 8/28/2010  | 1075       | 3.26                                     | 900          | 5.00                                |
Table 4. TSL observation on the same date from Landsat Images on six Juneau Icefield glaciers.

| Date    | Norris | Taku  | Lemon Creek | Mendenhall | Herbert | Eagle  |
|---------|--------|-------|-------------|------------|---------|--------|
| 8/29/1995 | 975   | 1025  | 1125        | 1075       | 1100    | 1050   |
| 9/4/1996  | 1050  | 1075  | 1150        | 1125       | 1150    | 1175   |
| 9/6/1997  | 1100  | 1125  | 1300        | 1200       | 1200    | 1175   |
| 9/16/1998 | 1050  | 1075  | 1200        | 1175       | 1150    | 1150   |
| 8/31/1999 | 750   | 850   | 950         | 900        | 925     | 900    |
| 8/29/2000 | 750   | 775   | 900         | 875        | 925     | 900    |
| 8/15/2001 | 800   | 800   | 900         | 900        | 925     | 900    |
| 10/3/2002 | 925   | 950   | 1025        | 1050       | 1075    | 1025   |
| 10/1/2003 | 1000  | 1075  | 1300        | 1150       | 1175    | 1150   |
| 9/1/2004  | 1075  | 1050  | 1100        | 1150       | 1200    | 1200   |
| 9/11/2005 | 1000  | 1000  | 1050        | 1050       | 1100    | 1100   |
| 9/16/2006 | 1025  | 975   | 1025        | 1125       | 1150    | 1150   |
| 9/22/2007 | 925   | 925   | 1000        | 1050       | 1050    | 1025   |
| 8/19/2008 | 700   | 775   | 900         | 850        | 900     | 900    |
| 9/14/2009 | 925   | 950   | 1050        | 1050       | 1050    | 1050   |
| 9/18/2010 | 950   | 975   | 1075        | 1075       | 1050    | 1025   |
| 9/11/2011 | 1000  | 975   | 1100        | 1150       | 1150    | 1125   |
**Fig. 1.** Base map of the Juneau Icefield, indicating the glaciers examined in this study. LC = Lemon Creek Glacier, bold black line = Probing transect on Taku Glacier. Black dots = snowpit locations on Taku Glacier.
Fig. 2. Map of Lemon Creek Glacier indicating primary snow pit locations, and the TSL location on specific dates in 2003.
Fig. 3. Snowpit on Taku Glacier in 2011. Note the ice lenses. Density measurements are being taken from the south wall; the tape measure aids recording ice lens and sample depths.
Fig. 4. Cumulative annual mass balance of Taku (red) and Lemon Creek Glacier (blue).
Fig. 5. Taku Glacier balance gradient determined from probing in various years. Note the similar gradient in this elevation range of the Taku Glacier in July near the ELA.
Fig. 6. Annual balance gradient on Lemon Creek Glacier for 1998 and 2003-2011, and probing gradient from 1998.
**Fig. 7.** TSL identification on Taku Glacier in 2006 Landsat image from 9/14/2006. A = 5/26/2006, B = 7/5/2006, C = 7/28/2006, D = 9/14/2006.
Fig. 8. TSL elevation rise rate on Taku Glacier and Lemon Creek Glacier.
Fig. 9. Transient snowline elevation on the same date on six Juneau Icefield glaciers 1995–2011.
Fig. 10. Relationship of Taku Glacier annual mass balance and the ELA.
Fig. 11. Relationship of Lemon Creek Glacier annual mass balance and the ELA.