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Juneau Icefield Mass Balance Program 1946–2011

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Abstract. The annual surface mass balance records of the Lemon Creek Glacier and Taku Glacier observed by the Juneau Icefield Research Program are the longest continuous glacier annual mass balance data sets in North America. Annual surface mass balance (B_a) measured on Taku Glacier averaged +0.40 m a^{-1} from 1946–1985, and −0.08 m a^{-1} from 1986–2011. The recent annual mass balance decline has resulted in the cessation of the long-term thickening of the glacier. Mean B_a 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 cumulative change in annual surface mass balance is −26.6 m water equivalent, a 29 m of ice thinning over the 55 yr. Snow-pit measurements spanning the accumulation zone, and probing transects above the transient snow line (TSL) on Taku Glacier, indicate a consistent surface mass balance gradient from year to year. Observations of the rate of TSL rise on Lemon Creek Glacier and Taku Glacier indicate a comparatively consistent migration rate of 3.8 to 4.1 m d^{-1}. The relationship between TSL on Lemon Creek Glacier 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 surface mass balance of the Juneau Icefield since 1946, with principal efforts focused on Lemon Creek Glacier and Taku Glacier. This database is the longest direct measurement of surface mass balance in North America. The data are reported to the World Glacier Monitoring Service (WGMS) annually and made available through the Advanced Cooperative Arctic Data and Information Service (ACADIS). This paper reports on three data sets: (1) annual surface mass balance (B_a) record of the Taku and Lemon Creek glaciers, including their annually calculated equilibrium line altitude (ELA) and accumulation area ratio (AAR), as well as evaluation of validation and potential errors; (2) probing transects above the transient snow line (TSL; snow line at time of observation) in 1984, 1998, 2004, 2005 and 2010; and (3) satellite image-determined transient snow line 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). The Juneau Icefield straddles the Coast Range of southeast Alaska. The glaciers of the Juneau Icefield west of the crest experience an exceptionally maritime climate, with annual precipitation of around 3000–4000 mm water equivalent (w.e.) and an average annual temperature at the equilibrium line altitude (ELA) of −1 °C. Crucial to the survival of a glacier is its annual mass balance (B_a), i.e., the difference between accumulation and ablation (melting and sublimation) (Cogley et al., 2011). B_a is the most sensitive climate indicator of a glacier. A glacier with a sustained negative annual mass balance is out of equilibrium and will tend to thin and retreat. A glacier with a sustained positive annual mass balance is out of equilibrium and will tend to thicken and advance. It is crucial that we continue to maintain the invaluable climate–glacier data set and provide it to the World Glacier Monitoring Service (WGMS).

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 671 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 a.s.l. (113 km^2), descends the trunk valley with no tributaries joining the glacier, with the single distributary tongue, Hole in the Wall, branching off from the main glacier 9 km above the terminus. (2) The lower firn zone, extending from the ELA at 925 m a.s.l. up to 1350 m, is a zone where summer ablation is significant (178 km^2). All of the main tributary glaciers (Southwest, Northwest, Matthes, and Demorest) join in this zone. (3) The upper firn zone extends from 1350 m a.s.l. to the head of the glacier at 2200 m a.s.l. (380 km^2), comprising the principal accumulation region for each tributary except the Southwest Branch. Ablation is limited in this upper firn zone, with much of the summer meltwater refreezing within the firn, and limited sun cup development. This zone has a unique low backscatter signature in synthetic aperture radar (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; Motyka and Echelmeyer, 2003), while all other outlet glaciers of the Juneau Icefield are retreating. Taku Glacier is also the thickest glacier yet measured in Alaska, 1477 m at an elevation of 800 m (Nolan et al., 1995). Taku Glacier is noteworthy for its positive annual 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, 1999; 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 1957/58 International Geophysical Year 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 1953 (Miller, 1972; Miller and Pelto, 1999). JIRP has continued annual surface mass 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 km^2 (Heusser and Marcus, 1964). In 1998 the glacier was 5.6 km long and had an area of 11.8 km^2 (Marcus et al., 1995). From the head of the glacier at 1450 m a.s.l. to the mean ELA at 1050–1100 m a.s.l. the glacier flows northward; in the ablation zone the glacier turns westward, terminating at 750 m a.s.l. The glacier is divided into four sections: (1) steep peripheral northern and western margins draining into the main valley portion of the glacier; (2) a low slope (4^0) upper accumulation zone from 1220 m a.s.l. to 1050 m a.s.l.; (3) a steeper section (6^0) in the ablation zone as the glacier turns west from 1050–850 m a.s.l.; and (4) an icefall (18^0) leading to the two fingered termini at 600 m a.s.l. This latter section was present up through 2005, but has now melted away and the terminus is at 750 m a.s.l. 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, with an average of 10–13 m a^{-1} between 1998 and 2009.

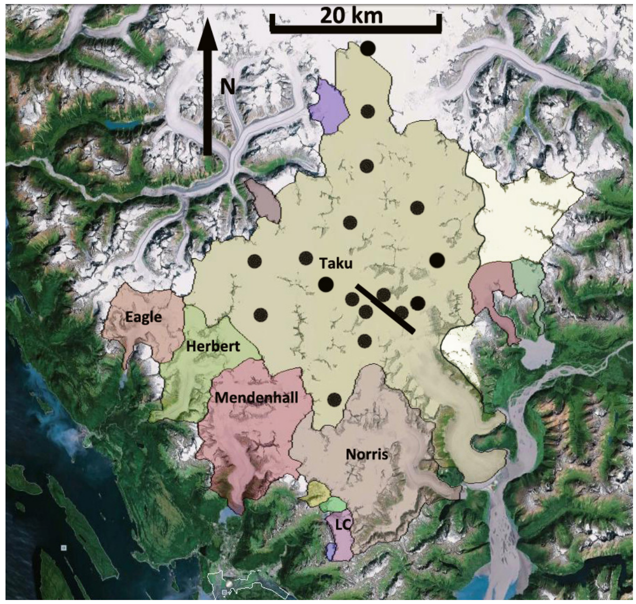

Figure 1. Base map of the Juneau Icefield, indicating the glaciers examined in this study. LC = Lemon Creek Glacier, bold black line = Probing transect on Taku Glacier. Black dots = snow pit locations on Taku Glacier.

3 Surface 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 as follows: (1) snow pits at fixed locations on Taku Glacier and Lemon Creek Glacier, ranging in elevation from 950 m to 1800 m a.s.l. (at each snow pit the water

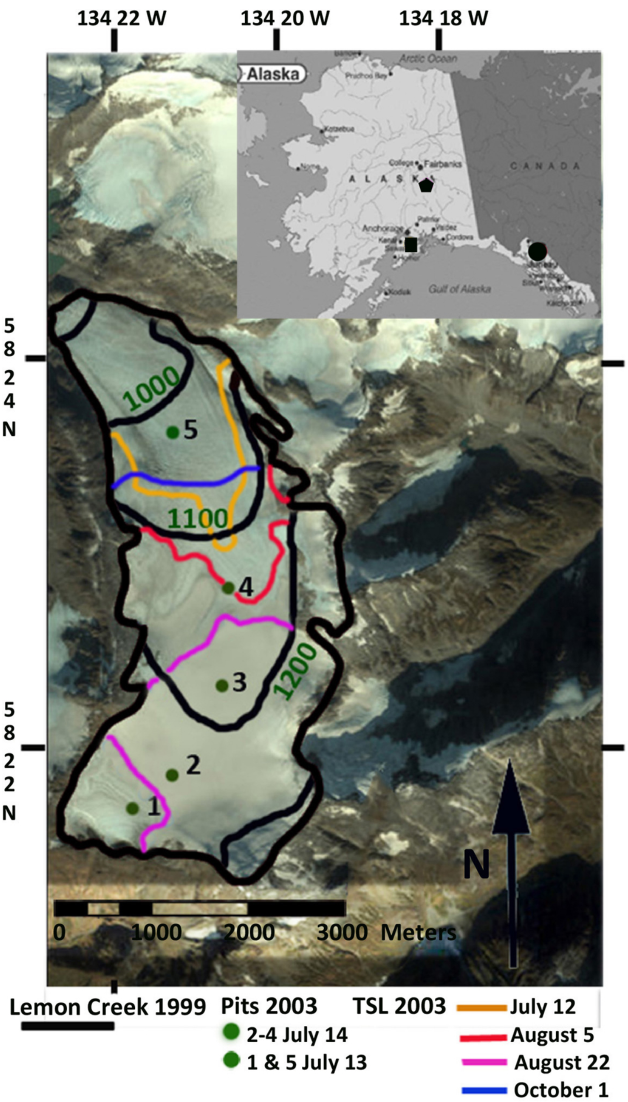

Figure 2. Map of Lemon Creek Glacier indicating primary snow pit locations, and the TSL location on specific dates in 2003. The black circle indicates the location of Lemon Creek Glacier, pentagon Gulkana Glacier and square Wolverine glacier.

equivalent (w.e.) is directly measured through the entire annual snow pack profile); (2) short-term ablation measurements at snow pits and along survey profiles with repeated height measurements of the stakes; and (3) observation of the TSL and ELA that allow ablation adjustments to snow pack.

3.1 Snow pits

The standard method used by JIRP to measure accumulation is the snow pit. Each snow pit 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 snow pit is accurate identification of the depth. The previous summer surface is well developed by the end of the ablation season on the Lemon Creek Glacier and below 1500 m a.s.l. on Taku Glacier (LaChapelle, 1954). Typically, a snow pit reaches the previous summer's surface, rather than blue ice, although it is not uncommon for a snow pit in the vicinity of the ELA to reach glacier ice. The previous summer's surface is a laterally continuous surface that typically has undergone several freeze/thaw cycles and often has a low density depth hoar just above it. In surface mass balance the unit of assessment is the snow water equivalent (SWE) of the snow pack. This is the mass per unit area of water that would be yielded were the snow pack melted, and is the product of snow depth and snow density. The density of the snow pack 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 remarkable uniformity of snow density in vertical profile and distribution over the glacier, and with time during the mid- to late summer. LaChapelle (1954) found the density of the snow pack to be 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). From 2003 to 2013, standard techniques have been used in density measurement through the depth profile of each snow pit; mean density has been 540 kg m^{-3}, with a standard deviation of 30 kg m^{-3}. Since there is no dry snow zone on the Lemon Creek or Taku glaciers, there is no difference in density with elevation. Ramage et al. (2000) found that surface wetness, grain size and density were all uniform across the icefield surface. Despite this fact, density is measured at each snow pit, in part because this is an excellent training tool.

Snow depth can be verified in shallow snow pack, those less than 3.5 m, using probing or crevasse stratigraphy. Measurements of retained accumulation in a snow pit are completed during July and August, and are adjusted to end of the balance year values based on the variation of the TSL, observed ablation and surface mass balance profile (Pelto and Miller, 1990; Miller and Pelto, 1999).

For each of the 17 locations where snow pits are utilized on Taku Glacier and 5 locations on Lemon Creek Glacier, the snow pit is dug at a fixed location, verified using GPS. Once on site, the southern wall of the snow pit is marked off in order to prevent contaminating any density measurement that will be taken; the south wall of the snow pit is selected for density measurement in order to mitigate any error that may come from ablation caused by direct sunlight on the snow pit wall. A snow pit is always dug at least 50 cm into the previous year's firn 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 horizontally every ten centimeters down the vertical profile of the snow pit into the previous year's layer and the

Figure 3. Snow pit location 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.

density measured. The final step of the snow pit observations 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 900 kg m^{-3}.

Due to the presence of ice within the snow pack, we report water equivalent depths rather than snow water equivalent depths. The w.e. for each snow pit is calculated using measurement of snow depth, snow density, total thickness of ice lenses within the snow pack, and an assumed density of ice.

$$\text{w.e.} = d_s\overline{\rho_s} + d_i\overline{\rho_i} \quad (1)$$

Where d_s is the depth of snow minus the sum thickness of all ice lenses, multiplied by $\overline{\rho_s}$ the mean column density of snow sampled horizontally in 10 cm intervals unless ice is present. Water equivalent ice lenses present in snow pack is accounted with d_i as the sum thickness of all ice lenses present along vertical profile of snow pack, multiplied by $\overline{\rho_i}$ an assumed ice density of 900 kg m^{-3}. The sum of snow water equivalent and ice water equivalent quantifies the water equivalent for each snow pit location.

On Taku Glacier, six of the snow pit sites are near the ELA ranging from 950–1200 m a.s.l., six are located at 1200–1400 m a.s.l. and five are located at 1400–1800 m a.s.l. altitude. Compared with Gulkana Glacier (19 km^2) and Wolverine Glacier (18 km^2), where the USGS annually assesses glacier mass balance from 3 to 4 measurement sites, the number of measurements on Taku Glacier is large (March and Trabant, 1996; Mayo et al., 2004). However, because the size of the Taku Glacier is more than an order of magnitude larger than either Gulkana or Wolverine glaciers, 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 nonexistent in the ablation zone. On Gulkana Glacier there is one site in the ablation zone, 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 site in the accumulation zone (Mayo et al., 2004). Van Beusekom et al. (2010) noted that the result on Wolverine Glacier was that the annual surface mass balance record differed from the geodetic record, leading to an adjustment to the long-term B_a record using a degree day based mass balance model. 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 measurement sites at each elevation, and in each tributary, which provides a more robust basis for annual mass balance gradient; the disadvantage is that the areal extent over which the extrapolations are made is larger. Current work using high frequency ground penetrating radar to precisely assess the annual mass balance retained snow depth in more detail is in progress.

3.2 Ablation assessment

Ablation is also observed annually during the field season, at snow pit locations, survey stakes located along survey lines where repeat surveys are completed, and through satellite observations of the migration of the TSL since 1998 (Pelto and Miller, 1990; Pelto et al., 2008). These ablation stakes, driven into the snow in the accumulation zone record the ablation of the remaining snow pack in the accumulation zone, between the time of snow pit measurements in July and the end of the ablation season in early September. This provides an essential measure for adjusting the July accumulation thickness snow pit 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 the ablation rate above 900 m a.s.l. is nearly constant on the Lemon Creek Glacier, whereas below 900 m a.s.l. the ablation rate increases with decreasing surface elevation.

On Lemon Creek Glacier from 1998–2011 the average ablation observed over a 162 day period 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 was 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 mass balance profile is adjusted based on the ELA, on measurements of ablation in nine different years from 1950 to 1997, including annual ablation measurements on cross survey profiles since 1998. The resulting ablation is a maximum at the terminus, at 12 m a^{-1} (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. Boyce et al. (2007) noted ablation on neighboring Mendenhall Glacier at elevations from 0–300 m a.s.l. ranged from 10 to 14 m in 1998, 2000, 2003, 2004 and 2005.

3.3 Probing and crevasse stratigraphy

The snow pit is a point measurement of w.e. amidst the vast expanse of the icefield. To address the representativeness of snow pits and the associated error resulting from extrapolating from snow pits; in 1984, 1998, 2004, 2005 and 2010, JIRP measured the mass balance at an additional 100–500 points in the accumulation area with probing transects that extend outward from snow pits, to better determine the distribution of accumulation around a snow pit location. 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 snow pit 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 snow pack because the ice layers have comparatively soft unconsolidated snow 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, 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 to a point measurement yielded by probing or the small scale view provided by a snow pit. 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 for validation.

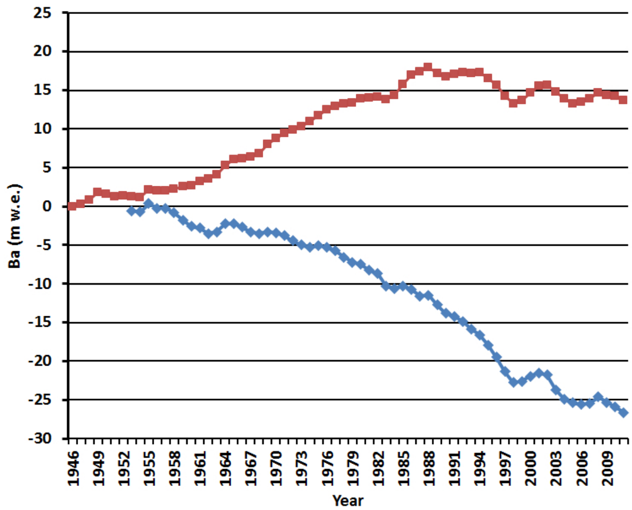

Figure 4. Cumulative annual surface mass balance record of Taku Glacier (red) and Lemon Creek Glacier (blue).

4 Results

4.1 Annual surface mass balance record

On Taku Glacier, the annual ELA has risen 60 m from the 1946–1985 period to the 1986–2010 period. Mean B_a during the two periods were +0.40 and −0.08 m w.e. a^{-1}, respectively, indicative of the snow line rise resulting in cessation of the long-term thickening of the glacier (Table 1). This cumulative change in B_a from 1946–2011 is +13.7 m w.e. (Fig. 4). The long-term positive B_a mass balance is continuing to drive glacier 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).

Mean B_a on Lemon Creek Glacier has declined from −0.3 m w.e. a^{-1} for the 1953–1985 period to −0.60 m w.e. a^{-1} during the 1986–2011 period. The cumulative change B_a is −26.6 m, a 29 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) on Taku Glacier, extrapolation to the end of the mass balance year from snow pit measurements in July or early August, infrequent measurements 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 a mass balance profile from nine years of ablation data to extrapolate mass balance in the ablation zone; and (3) validation of snow depth variation using probing transects (see next

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

Year	Taku Ba (mm w.e.)	LC Ba (mm w.e.)	LC cumulative B_a (mm w.e.)	Taku cumulative B_a (mm w.e.)	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	1080	40	84
1954	−70	−180	−740	1180	1160	1025	58	68
1955	970	1120	380	2150	950	810	90	86
1956	−130	−640	−260	2020	1010	1075	40	84
1957	−40	0	−260	1980	980	1000	62	85
1958	210	−580	−840	2190	780	1040	52	91
1959	350	−900	−1740	2540	1000	1150	33	84
1960	160	−820	−2560	2700	1010	1130	35	84
1961	480	−240	−2800	3180	930	1080	40	87
1962	390	−690	−3490	3570	915	1110	37	88
1963	570	170	−3320	4140	950	970	66	86
1964	1130	1040	−2280	5270	885	885	80	90
1965	790	80	−2200	6060	900	980	65	90
1966	80	−490	−2690	6140	875	1100	38	89
1967	250	−600	−3290	6390	750	1130	36	91
1968	460	−220	−3510	6850	810	1060	58	90
1969	1170	210	−3300	8020	965	1000	63	86
1970	760	−90	−3390	8780	930	1060	58	91
1971	630	−400	−3790	9410	885	1110	39	88
1972	420	−650	−4440	9830	730	1140	34	92
1973	520	−520	−4960	10 350	825	1110	39	90
1974	580	−370	−5330	10 930	850	1090	42	89
1975	850	290	−5040	11 780	800	1010	63	90
1976	660	−250	−5290	12 440	850	1080	48	89
1977	470	−480	−5770	12 910	885	1110	40	88
1978	310	−800	−6570	13 220	915	1150	35	87
1979	140	−630	−7200	13 360	950	1110	40	86
1980	540	−270	−7470	13 900	870	1100	42	89
1981	120	−810	−8280	14 020	980	1120	40	85
1982	150	−430	−8710	14 170	950	1070	51	86
1983	−420	−1620	−10 330	13 750	1085	1220	17	79
1984	640	−250	−10 580	14 390	875	1010	65	89
1985	1400	330	−10 250	15 790	600	965	75	93
1986	1200	−510	−10 760	16 990	720	1070	51	92
1987	390	−840	−11 600	17 380	910	1100	43	88
1988	600	110	−11 490	17 980	890	1000	69	88
1989	−810	−1240	−12 730	17 170	1115	1130	40	74
1990	−450	−1110	−13 840	16 720	1080	1125	42	79
1991	380	−380	−14 220	17 100	900	1050	60	88
1992	170	−660	−14 880	17 270	940	1075	54	86
1993	−40	−980	−15 860	17 230	980	1130	43	85
1994	90	−760	−16 620	17 320	970	1100	46	85
1995	−760	−1310	−17 930	16 560	1050	1150	38	81
1996	−960	−1580	−19 510	15 600	1150	1370	5	68
1997	−1340	−1810	−21 320	14 260	1225	1400	5	60
1998	−980	−1460	−22 780	13 280	1120	1300	7	73
1999	400	200	−22 580	13 680	900	1020	68	88
2000	1030	650	−21 930	14 710	750	900	82	91
2001	880	400	−21 530	15 590	850	950	77	89
2002	100	−250	−21 780	15 690	975	1025	67	88
2003	−900	−1900	−23 680	14 790	1100	1400	5	77
2004	−830	−1250	−24 930	13 960	1100	1150	59	86
2005	−720	−470	−25 400	13 240	1050	1050	61	86
2006	230	−170	−25 570	13 470	975	1025	68	86
2007	480	150	−25 420	13 950	930	1000	72	87
2008	750	800	−24 620	14 700	800	920	80	90
2009	−310	−700	−25 320	14 390	960	1060	51	86
2010	−120	−580	−25 900	14 270	1000	1075	55	83
2011	−550	−720	−26 620	13 720	1025	1100	47	82

section). The principal error is due to the lack of data from the ablation zone. The mass balance profile for the glacier in the ablation zone is based solely on ablation measurements. These data indicate a consistent gradient in the ablation zone. The profile is adjusted to zero at the observed ELA. Annual observations of ablation are not a standard method because of costs and logistics; this does add uncertainty in the mass balance assessment. The mass balance gradient in the ablation zone published by Miller and Pelto (1990) for Taku Glacier has been verified by independent work by Motyka and Echelmeyer (2003) on Taku Glacier and on neighboring Mendenhall Glacier (Boyce et al., 2007).

The Taku Glacier annual surface mass balance record has been validated with geodetic balances 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 surface elevation 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 consistent ice dynamics from 1950 to 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 $+0.69\,\mathrm{m\,a^{-1}}$ from 1948 to 1993 and $-0.28\,\mathrm{m\,a^{-1}}$ from 1993 to 1997 (Arendt, 2006). The observed mean B_a for these periods from field observations is $+0.38\,\mathrm{m\,a^{-1}}$ for 1948–1993 and $-0.60\,\mathrm{m\,a^{-1}}$ for 1993–1997. The direct measurement record includes the large negative mass balance of 1997, while the laser altimetry only includes part of the 1997 ablation season and would tend to underestimate thinning by a small amount (Sapiano et al., 1998). Repeat laser altimetry profiling indicates a B_a of $-0.21\,\mathrm{m\,a^{-1}}$ for the 1993–2007 period, compared to the JIRP mean B_a of $-0.16\,\mathrm{m\,a^{-1}}$. Comparisons of surface elevations from the 2000 Shuttle Radar Topography Mission and a DEM derived from the 1948 USGS mapping indicate a mean B_a of $+0.45\,\mathrm{m\,a^{-1}}$ versus the JIRP record of $+0.27\,\mathrm{m\,a^{-1}}$ 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 annual surface mass balance record of the Taku Glacier.

On Lemon Creek Glacier the annual surface mass balance record determined from field measurement yields a cumulative mass balance of −26.6 m w.e. from 1953 to 2011. The cumulative B_a record of −12.7 m w.e. (13.9 m of ice thickness) from 1957 to 1989 compares well to the thinning identified from geodetic methods of 1957–1989 of −13.2 (Marcus et al., 1995). The cumulative B_a record of −17.1 m w.e. (−19.0 m of ice thickness) from the period 1957–1995 compares favorably to an observed ice thickness of −16.4 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 −12.9 m surface elevation change, equivalent to a cumulative annual mass balance of −11.5 m w.e. compared to annual surface mass balance of −9.7 m w.e. from 1994–2007. The error in both geodetic programs is less than 1.5 m. In each of the three time intervals using two different ice surface elevation change assessment techniques, the B_a record is confirmed. Future work addressing the minor discrepancies between the geodetic and direct measurement records is currently being reviewed.

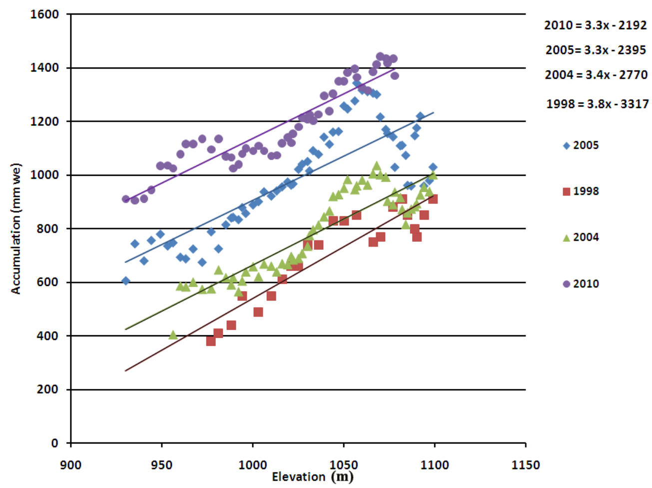

Figure 5. Taku Glacier mass balance profile determined from probing in various years. Note the similar gradient in this elevation range of the Taku Glacier in July near the ELA.

5 Probing transects for determination of balance gradient

Mauri Pelto in late July of 1984, 1998; Matt Beedle in late July of 2004, 2005; and Chris McNeil in late July of 2010, 2011 measured the mass balance along a transect from near the TSL at 900 to 1150 m 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 mass balance gradient is determined using data from an elevation of 925 to 1100 m a.s.l., as this is the interval with consistent data each year.

The mass balance gradient determined from probing between 925 and 1100 m a.s.l. ranges from 3.3 to $3.8\,\mathrm{mm\,m^{-1}}$, with a mean of $3.5\,\mathrm{mm\,m^{-1}}$. The mass 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 this transect from the best fit linear regression is 40 mm. The mass balance gradient can be compared to that determined directly from snow pit measurements at TKGTP5 and DGTP1 at 1000 m a.s.l. on the Taku Glacier (Pelto, 2011). On the date that each snow pit is excavated, the difference between measured w.e. at each snow pit and the TSL elevation on that date provides a direct surface

Table 2. Accumulation measurements on longitudinal probing transect from 990 to 1100 m a.s.l. above the TSL on Taku Glacier in July 1998, 2004, 2005 and 2010.

Pt. Name	Easting	Northing	Elevation (m a.s.l.)	1998 (mm w.e.)	2004 (mm w.e.)	2005 (mm w.e.)	2010 (mm w.e.)
P1	541911	6501411	1099	910	1001	1030	
P2	542013	6501311	1097		938	980	
P3	542115	6501200	1094	850	954	960	
P4	542217	6501111	1092		925	1221	
P5	542319	6501000	1090	770	893	1177	
P6	542454	6500911	1089	800	882	1148	
P7	542568	6500800	1087		873	960	
P8	542669	6500712	1085	850	859	962	
P9	542783	6500601	1084		815	1075	
P10	542885	6500501	1082	910	871	1112	
P11	542998	6500412	1081		916	1110	
P12	543100	6500312	1078		936	1030	1370
P13	543202	6500201	1077	880	889	1143	1434
P14	543304	6500101	1074		902	1156	1419
P15	543395	6500012	1073		992	1171	1435
P16	543519	6499901	1070	770	1001	1218	1443
P17	543599	6499801	1068		1035	1302	1413
P18	543712	6499701	1066	750	1004	1307	1385
P19	543814	6499612	1063		963	1312	1316
P20	543905	6499512	1060		981	1318	1327
P21	543996	6499412	1057	850	959	1344	1365
P22	544086	6499312	1056		945	1278	1396
P23	544189	6499201	1052		983	1278	1383
P24	544291	6499113	1050	830	950	1259	1350
P25	544393	6499001	1047		927	1164	1350
P26	544495	6498901	1044	830	920	1161	1303
P27	544574	6498813	1042		866	1116	1238
P28	544688	6498713	1039		844	1142	1295
P29	544790	6498602	1036	740	814	1078	1226
P30	544903	6498513	1033		796	1092	1202
P31	544994	6498391	1031		774	1016	1225
P32	545074	6498302	1030	740	734	1052	1208
P33	545187	6498202	1027		707	1041	1213
P34	545289	6498102	1025	660	689	1022	1180
P35	545380	6498002	1022		684	968	1154
P36	545482	6497891	1021	660	697	963	1120
P37	545562	6497791	1019		666	975	1141
P38	545642	6497713	1016	610	670	957	1118
P39	545733	6497613	1013		639	941	1073
P40	545846	6497513	1010	550	661	922	1071
P41	545948	6497425	1006		668	938	1090
P42	546039	6497313	1003	560	621	901	1109
P43	546130	6497213	1000		659	889	1090
P44	546232	6497102	996	490	639	858	1099
P45	546323	6497025	994		605	879	1079
P46	546414	6496914	992	550	565	834	1040
P47	546516	6496803	989		617	843	1025
P48	546607	6496714	988	440	590	841	1066
P49	546698	6496603	985		617	815	1070
P50	546800	6496503	981	410	646	726	1135
P51	546891	6496403	977		576	789	1096
P52	547005	6496314	972	380	574	675	1135
P53	547107	6496214	967		601	725	1116
P54	547198	6496114	963		583	688	1116
P55	547300	6496003	960	360	587	694	1077
P56	547391	6495903	956		405	680	1025
P57	547494	6495792	953	310	330	606	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

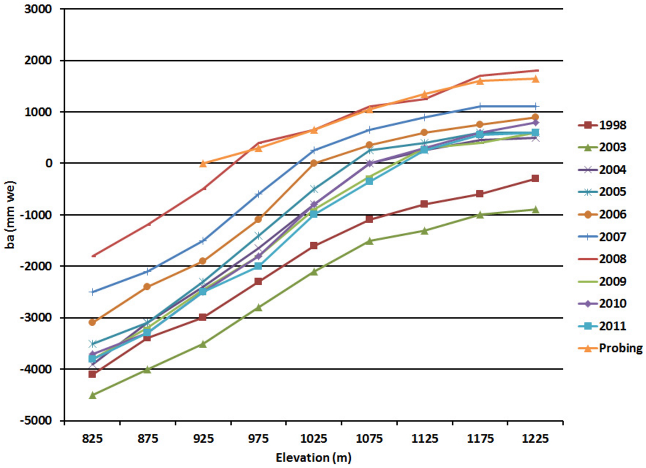

Figure 6. Annual surface mass balance profile on Lemon Creek Glacier for 1998 and 2003–2011, and probing gradient from 1998.

mass balance gradient measurement. The mass balance gradient derived from the snow pits was 2.6–3.5 mm m^{-1}. This is less than that for probing, but the TSL on the date of snow pit excavation is almost always lower than the lowest elevation of the probing transects and represents a lower elevation band of 800 to 1000 m a.s.l.

On Lemon Creek Glacier the mass balance gradient generated annually from the ELA and snow pit elevations illustrates the similarity of the mass balance gradient from year to year. The mass balance gradient parallels the probed gradient in 1998 and has a range of 4.6 to 5.1 mm m^{-1} (Fig. 6).

Balance gradient from TSL variation

The TSL is readily identifiable on 34 Landsat scenes acquired from 1995 to 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. Selected scenes are cloud free at the TSL and because of low surrounding mountain slopes shadows are not an issue. 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. on 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 (Mernild et al., 2013). 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. The 15 day or greater time period is chosen because errors in TSL elevation assessment are constant regardless of time

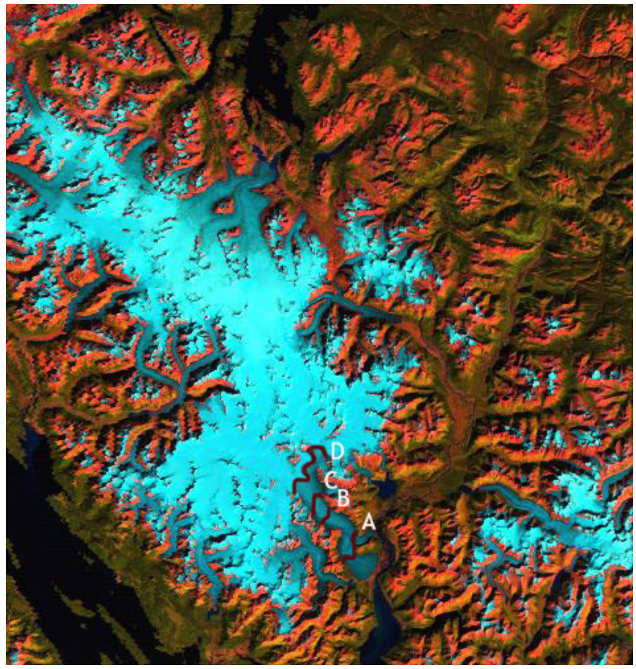

Figure 7. TSL identification on Taku Glacier in 2006 Landsat image from 9/14/2006. A = 5/26/2006, B = 7/5/2006, C = 7/28/2006, D = 9/14/2006.

period length; hence longer time periods reduce the error in calculation of the rate of rise.

For example, in 2006 the TSL was identified in five Landsat images on Taku Glacier. The TSL in 2006 rose from 370 m a.s.l. on 26 May to 575 m a.s.l. on 10 June, 730 m a.s.l. on 5 July, 760 m a.s.l. on 29 July, and finally 975 m a.s.l. 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 periods averages 4.1±0.9 m d^{-1} during the July–September period, for the elevation range between 750–1100 m a.s.l. (Table 3; Fig. 7).

The TSL for Lemon Creek Glacier was 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 (Rabatel et al., 2005; Hock et al., 2007; Pelto, 2011). Use of the latter ensures

Table 3. Transient snow line 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. Rate of rise is not calculated for Taku Glacier if the TSL is below 800 m a.s.l.

Date (mm/dd/yyyy)	LC TSL (m a.s.l.)	Lemon Creek TSL rate of rise (m d^{-1})	Taku TSL (m a.s.l.)	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		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

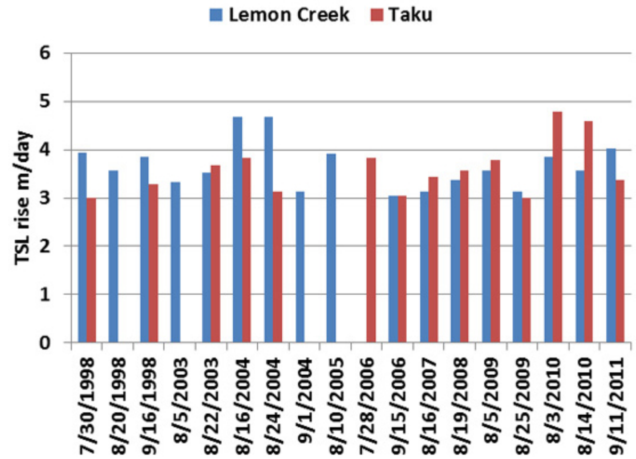

Figure 8. TSL elevation rise rate on Taku Glacier and Lemon Creek Glacier for selected periods of at least 15 days where the TSL could be identified using Landsat imagery. The date given is the end of the period. Table 3 contains the raw data.

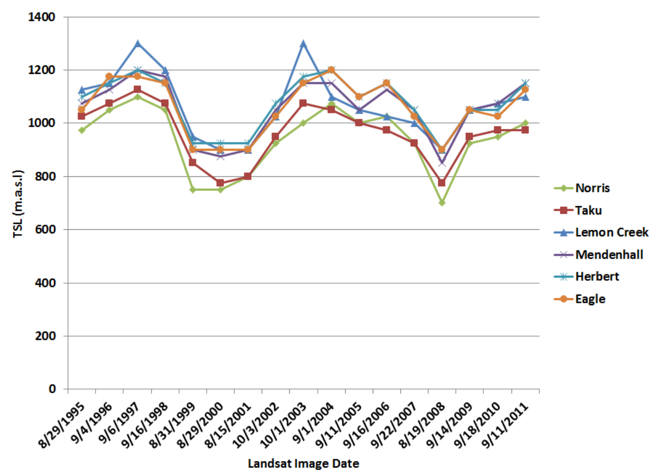

Figure 9. Transient snow line elevation on the same date on six Juneau Icefield glaciers, 1995–2011.

having an observation 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 to 2011: Eagle, Herbert, Lemon Creek, Mendenhall, Norris and Taku (Table 4; Fig. 9). The observed TSL between glaciers is highly correlated for all glaciers with R^2 exceeding 0.82 in all cases. 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, which will allow a more precise determination of the ELA. 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 date of the end of the ablation season can be determined from climate records. The ELA in turn is a good indicator of B_a (Rabatel et al., 2005). The World Glacier Monitoring Service derives plots of ELA versus B_a each year for each glacier. The plots generated for the WGMS (2011) from Lemon Creek Glacier are below. The fit is not good for Taku Glacier, $R^2 = 0.66$ (Fig. 10). The fit for Lemon Creek Glacier is excellent for the ELA-B_a, $R^2 = 0.87$ (Fig. 11).

7 Conclusions

The annual surface mass balance record from Lemon Creek Glacier and Taku Glacier illustrates a decline in B_a mass balance for both glaciers after 1985. Independent geodetic observations of glacier mass balance validate the long-term changes quantified by the B_a for both glaciers. Going forward it is important to utilize both ground penetrating radar and satellite imagery to better quantify variations in

Table 4. TSL observation (m a.s.l.) on the same date from Landsat Images on six Juneau Icefield glaciers.

Date (mm/dd/yyyy)	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

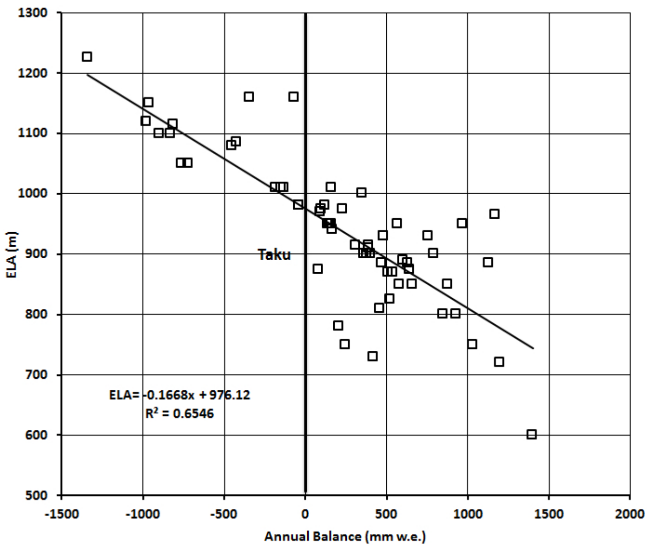

Figure 10. Relationship of Taku Glacier annual surface mass balance and the ELA.

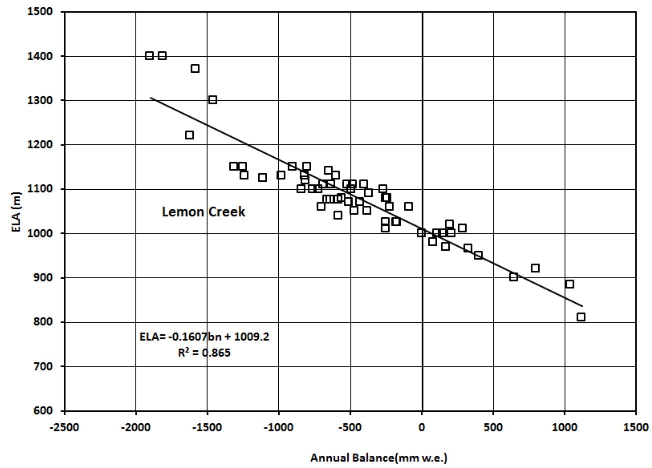

Figure 11. Relationship of Lemon Creek Glacier annual surface mass balance and the ELA.

accumulation and ablation across the glacier. The mass balance records also warrant the detailed investigation that has been undertaken on Wolverine Glacier and Gulkana Glacier to better evaluate potential error.

The mass balance profile and 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 B_a on Taku Glacier and Lemon Creek Glacier, and, as such, determination of this relationship for other Juneau Icefield glaciers utilizing simultaneous TSL variations with Lemon Creek and Taku Glacier has value. Taku Glacier has a large surface area in the vicinity of the ELA, which makes the glacier sensitive to small changes in the ELA and small changes in the balance profile near the ELA. Both would reduce the correlation between ELA and B_a. Continued use of direct field observations of the mass balance gradient and TSL variation should help better identify not only the ELA, but aid in adjusting the annual mass balance gradient in this critical interval (Mernild et al., 2013).

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