The Equilibrium Flow and Mass Balance of the Taku Glacier, Alaska, 1950–2005

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ABSTRACT

The Taku Glacier, Alaska, has advanced 7.5 km since the late nineteenth century, while all other primary outlet glaciers of the Juneau Icefield are in retreat. The Juneau Icefield Research Program (JIRP) has completed field work on the Taku Glacier annually since 1946. The thickest known alpine temperate glacier, it has a maximum measured depth of 1480 m. The Taku is a tidewater glacier that formerly calved, but is now advancing slowly over its outwash delta. Velocity measured over a twelve-month span and annual summer velocity measurements completed at Profile 4 slightly above the ELA from 1950–2004 indicate insignificant variations in velocity seasonally or from year to year . The consistency of velocity over the 50-year period indicates that in the vicinity of the equilibrium line, the flow of the Taku Glacier has been in an equilibrium state.

Surface mass balance was positive from 1946–1988 averaging +0.42 m/a. This led to glacier thickening. From 1988–2005 an important change has occurred the annual balance has been –0.17m/a, and the glacier thickness has stopped increasing.

Field measurements of ice depth and surface velocity allow calculation of the volume flux. Volume flux is then compared with the surface balance flux from the accumulation zone determined annually in the field. On each profile the mean surface balance flux 1946–2005 is positive versus the annually determined volume flux, leading to glacier thickening. From 1950–2000, Taku Glacier thickened by 20–30 m at Profile 4, 33 km above the terminus. At this profile, the expected surface flux for equilibrium is 5.50×10^8 m^3/a (±10%), while the calculated volume flux range is $5.00–5.47 \times 10^8$ m^3/a. At Profile 7, 43 km above the terminus, the observed surface flux above Profile 7 is 1.90×10^8 m^3/a, and the volume flux range is $1.72–1.74 \times 10^8$ m^3/a

INTRODUCTION

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. It attracts special attention because of its continuing, century-long advance (Motyka and Post, 1995), while every other outlet glaciers of the Juneau Icefield is retreating. Taku Glacier is also noteworthy for its positive mass balance from 1946–1988 (Pelto and Miller, 1990), during a period when alpine glacier mass balances have been dominantly negative (Dyugerov and Meier, 1997). Finally, it is unique as the

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thickest alpine glacier yet measured, with a fjord extending 38–48 km upglacier from its terminus (Nolan and others, 1995).

The Juneau Icefield Research Program (JIRP) has completed field work on the Taku Glacier annually since 1946 (Miller, 1963; Pelto and Miller, 1990). In this paper we present a data set for the Taku Glacier that is unique in its temporal and spatial extent containing:

1) Multi-year surface transverse velocity data from three profiles, spanning 50 years on one profile; 2) Seismic profiling depth data on the same profiles; 3) Centerline longitudinal velocity transects from the glacier divide to the ablation zone; and 4) Multi-year surface mass balance data. From this data we can determine surface balance and volume balance transfers. This provides a field-based quantitative determination of the volume flux at multiple locations and hence constraints on the future behavior of the Taku Glacier.

The glacier is divided into three zones that describe both mass balance and flow dynamics: (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 only the distributary tongue, Hole in the Wall, leaving the glacier 11 km above the terminus. (2) The lower neve zone, extending from the ELA at 925 m to 1350 m, is a zone where summer ablation is significant (178 km^2). All the main tributaries (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 (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 firnpack. This results in a unique signature in SAR imagery (Ramage et al., 2000).

The Taku Glacier has been advancing since 1890: It advanced 5.3 km between 1890 and 1948 (Moytka and Post, 199; Pelto and Miller, 1990). The glacier advanced 1.8 km from 1948–1988, and 0.4 km from 1988 to 2003. The advance rate measured by distance is slowing. The rate of advance is best assessed in terms of area as the terminus lobe is spreading out on a terminus shoal. Motyka and Post (1995) noted that the rate from 1948–1963 was 0.428 km^2/year, 0.345 km^2/year from 1963–1979 and 0.11 km^2/year from 1979–1988. The slowing of the advance has been attributed to the impedance of the terminus outwash plain shoal (Motyka and Post, 1995), but it has also been conjectured as due to the inability of the mass balance to sustain this advance. With an AAR of 82, Taku Glacier had a continuously positive mass balance from 1946–1994, that has driven the continued advance (Pelto and Miller, 1990). From 1988–2005 mass balance has been slightly negative.

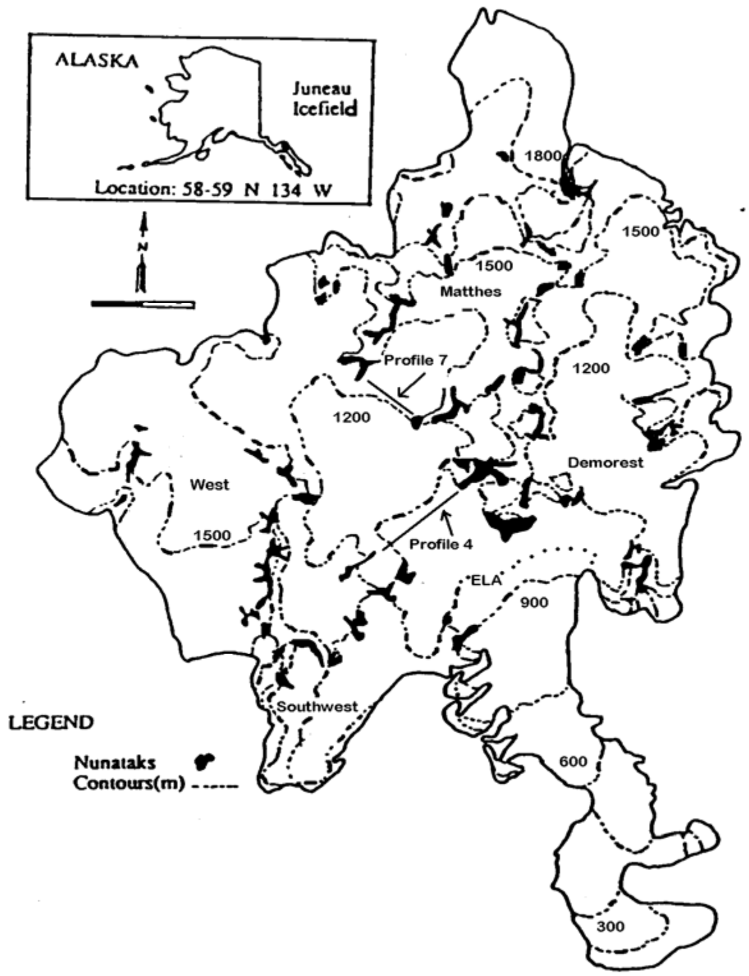

Figure 1. Location map for Taku Glacier.

DATA COLLECTION

Surface Mass Balance

JIRP has measured the annual balance of the Taku Glacier from 1946 to 2005 (Pelto and Miller, 1990; Miller and Pelto, 1999). Glacier annual mass balance is the difference between the net snow accumulation and net ablation over one hydrologic year. On non-calving glaciers, such as the present Taku Glacier, surface mass balance observations are used to identify changes in glacier volume. JIRP has relied on applying consistent methods at standard measurement sites (Pelto and Miller, 1990; Miller and Pelto, 1999). Taku Glacier mass balance measurements are similar to those used on the Lemon Creek Glacier. The primary difference between the two is the much larger extent of the Taku Glacier (671 km^2). On the Taku Glacier, JIRP digs 17 test pits at fixed sites, monitors the migration of the transient snow line, and locates the final ELA position at the end of the balance year (Pelto and Miller, 1990). These measurements of retained accumulation are taken during late July and early August and must be adjusted to end of the balance year values.

This is done via daily ablation rates derived through stake measurements and migration of the transient snow line (Miller and Pelto, 1999).

Possible errors for the Taku Glacier mass balance record include sparse density of measurement points (1 per 13 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 annual (since 1946) measurements at 17 fixed locations, using nine years of ablation data to extrapolate mass balance in the ablation zone, using a balance gradient derived from the 17 fixed sites and known values for the ablation zone that shifts in altitude from year to year based on the ELA, and through supervision of field work by at least one experienced researcher (i.e., Matt Beedle from 2003–2005).

The measurement network consists of 17 locations where mass balance has been assessed in test pits annually since 1946. The majority of the snowpits are in the region from 950–1400 m. In 1984, 1998 and 2004, 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. The standard deviation for measurements sites within 3 km, with less than a 100 m elevation change, was ±0.09 m/a; this indicates the consistency of mass balance around the snowpit sites.

Another possible source of error is the assumption that the density measured at test pits is representative of a larger area. However, a study at 40 points within 1 km^2 at different elevations in different years resulted in a standard deviation of ±0.07 meters of water equivalent (m w.e.) in a snow pack of 1 to 2 m, displaying the highly uniform density of snow on the Taku Glacier (Pelto and Miller, 1990).

An independent check of mass balance is now available in the form of direct measurement of the surface elevation of the glacier at specific points. The elevation has been determined annually since 1993 at fixed locations along Profile 4 using differential GPS as part of the velocity surveying program. GPS annual elevation change measurements along Profile 4 at 1100 m show a strong correlation with annual mass balance measurements. This would be expected as elevation at the mean ELA is likely to rise with increased accumulation during years of positive mass balance, and fall with increased ablation during years of negative mass balance. For the period 1993 to 2004, correlation between the average surface elevation change of a 31-point profile across the Taku Glacier and net mass balance is 0.77 (95% significance). This provides an independent validation for Taku Glacier record (Table 1).

GPS Survey Methods

Standard rapid-static and real-time differential GPS methods have been employed for all survey work from 1996–2004. A key objective of the surveying program is to collect data that allows quantitative comparison of surface movements and surface elevation change from year to year. In order to ensure the consistency of year-to-year movement and elevation data, all survey flags are located within one meter of the standard point coordinates (Lang, 1997; McGee, 2000). After establishment of each survey profile is complete, each profile is surveyed two times, with the time differential between the surveys ranging from 6 to 9 days. For all surveys, a reference receiver is centered and leveled over an appropriate bedrock benchmark. A roving receiver is mounted on an aluminum monopole inserted into the same hole that the survey flag is placed. The height above the snow surface of the antenna is noted. For rapid-static work, the roving receiver collected readings at 15-second intervals for 10 to 20 minutes at each flag. Real-time methods require only enough time at each flag sufficient to obtain a position fix from the reference receiver.

Table 1. Comparison of GPS measured height change on Profile 4 and the mean annual balance of the Taku Glacier. The GPS data is strictly in height, and the field measurement in meters of water equivalent.

Year	Taku bn	Pro 4 Ht. Ch.
1994	0.09	0.09
1995	–0.76	–1.33
1996	–0.96	–0.67
1997	–1.34	–0.46
1998	–0.98	–1.06
1999	0.4	0.59
2000	1.03	1.42
2001	0.88	0.9
2002	0.45	–0.7
2003	–0.9	–1.64
2004	–0.23	0.63
2005	0.02	–0.29
	Correlation =	0.77

The major focus of the survey program is to continue the annual survey of standard movement profiles on the Taku Glacier and its main tributaries. In this study we focus on transects 4 and 7. Profile 4 has an upper line and a lower line separated by 0.5 km. In 1999, 2000 and 2004, a longitudinal profile down the centerline of the Matthes Branch and the Taku Glacier, from the glacier divide (located 65 km from the terminus), down to 24 km above the terminus. The surface velocity was observed at survey locations spaced 0.5 km apart. The surface slope was determined between each survey location.

Seismic Methods

Seismic methods are required to determine ice depths on transverse profiles because of the thickness of the Taku Glacier (Nolan and others, 1995). The seismic program completed measurements of ice thickness along eight transects across the glacier, each following the same transects and using the same points used in the GPS movement and elevation surveys.

The seismic methods used for determining ice thickness are typical. A Bison 9024 series seismograph was used with 24 high-frequency (100 Hz) geophones to record the seismic signals produced by explosive charges. The geophones were spaced at 30 meter intervals along profile lines that are perpendicular to the direction of glacier flow, covering 690 meters with each geophone spread. Explosive detonations (shots) were generally made at 500 meter intervals from each end of the geophone spread, to a maximum distance of 2000 meters. Shot and geophone locations were surveyed using standard differential GPS surveying techniques, accurate to ±5 cm. Up to twelve shots were taken on each profile, with up to four reflectors evident on each shot's record. The seismograph was normally set to record two seconds of data, recording at a 0.25 ms sampling rate. The energy for a shot was produced by 4 to 20 sticks of Kinepak (1/3 stick) explosive (ammonium nitrate and petroleum distillate combination), buried approximately 1 meter deep in the firn.

Reflections from the glacier bed were generally clear and easy to recognize on the records by their frequency, character, and distinct moveout times. Migrations were completed using the common-depth-point technique described in Dobrin (1960) and adapted by Sprenke and others (1997). Calculations were made using a constant ice velocity of 3660 m/s, a value determined from P-wave first arrival times. The migration and geomorphic profiling process is based on the simplifying assumption that the glacier cross-sections are two-dimensional. The results on Profile 4 match closely the results of Nolan and others (1995) with a maximum depth of 1450 m in this study versus 1400 m.

DATA OBSERVATIONS

Mass Balance

The annual balance record shows a markedly positive trend from 1946–1988 period. The mean annual balance for the 42-year period is 0.42 m/a, representing a total thickening of 17.5 m w.e or 20 m in total ice thickness. From 1988–2005 mass balance changed significantly and has been slightly negative averaging –0.17 m/a, a 3 m w.e. loss, or 3.3 meters of glacier thickness change (Figure 2). A comparison of surface height change along Profile 4 from 1993–2004 and mean surface balance yield –3.5 m and –2.7 m respectively. The next task in this research program is to determine the height changes at survey location along additional profiles over an extended period, thus providing additional surface balance data each year.

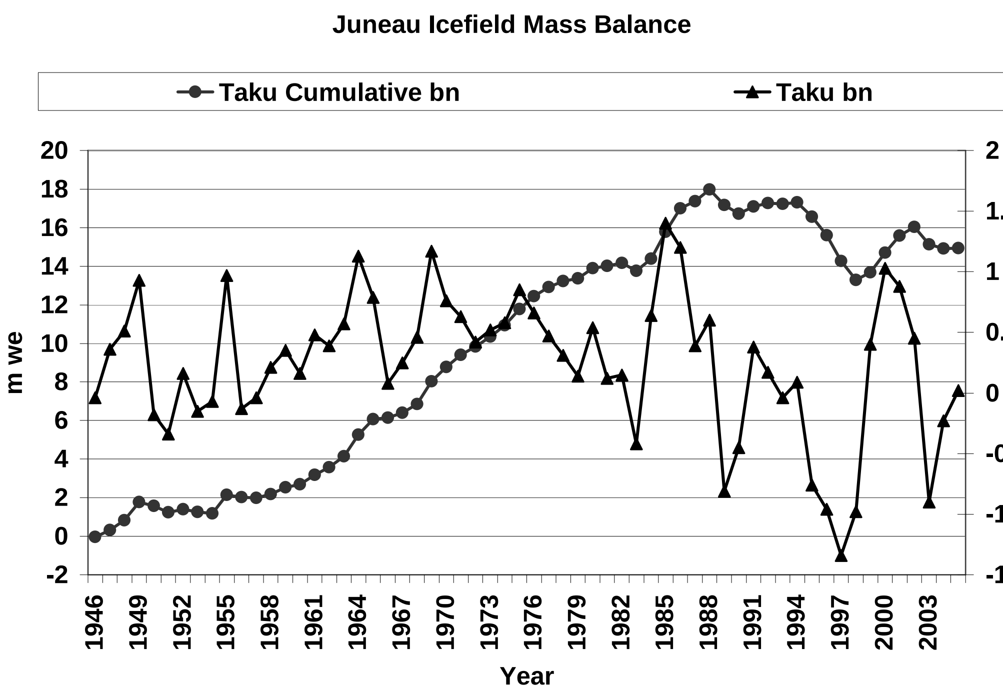

Figure 2. Annual and cumulative mass balance of the Taku Glacier 1946–2005.

With the distribution of annual balance more accurately mapped in the lower neve section of the glacier based on the 1998, 2003 and 2004 combined snowpit and probing measurements, mean annual surface flux was determined both for the glacier region above Profile 4 and Profile 7, summing the products of the area observed between each 0.2 m mass balance interval and the annual balance for that interval. The surface flux accumulating above at Profile 4 was calculated to be 5.5×10^8 m^3a^{-1}, and 1.90×10^8 m^3a^{-1} above Profile 7.

Transverse Velocity Profiles

Surface velocity has been constant over a 50-year period on the Taku Glacier at Profile 4 (Table 2) (Miller, 1963; Dallenbach and Welsch, 1993; Lang, 1995 and 1997 and McGee, 1998 and 2000). In addition, velocity shows no significant variations seasonally, based on year round measurement of the movement of the top of a glacier borehole and the associated semi-permanent camp from 1950–1953 along Profile 4 (Miller, 1963). Movement of a meteorologic station instrument that endured from 1997 to 1998 on Profile 4 provided a second measure of mean annual velocity. In the former case mean annual velocity was 0.60 m/day, and in the latter case 0.61 m/day. The mean observed velocity for these same locations during the summer is 0.61 m/day. A magnet was buried in the glacier in July 2003 and then checked in July 2004 to identify annual glacier velocity at Profile 4. The annual velocity was 0.587 m/day and the summer velocity was 0.588 m/day. Observations of velocity at specific stake locations reoccupied each summer along Profile 4 indicate remarkable uniformity of flow from year to year (Table 3; Figure 3). Standard deviation ranges from 0.010–0.020 m/day. Along Profile 7 the variation is slightly less, though spanning the same range.

Table 2 Mean summer surface velocity measured in the center of Profile 4 from 1950–2004. Survey locations are identical from 1996–2004. The velocity for the other years is the mean of locations between the current locations of Point 10 and Point 24.

Year	Velocity (m/day)
1950	0.58
1952	0.51
1953	0.51
1960	0.53
1967	0.52
1986	0.52
1987	0.51
1996	0.53
1997	0.53
1998	0.52
1999	0.53
2000	0.55
2001	0.55
2004	0.52
st dev	0.02

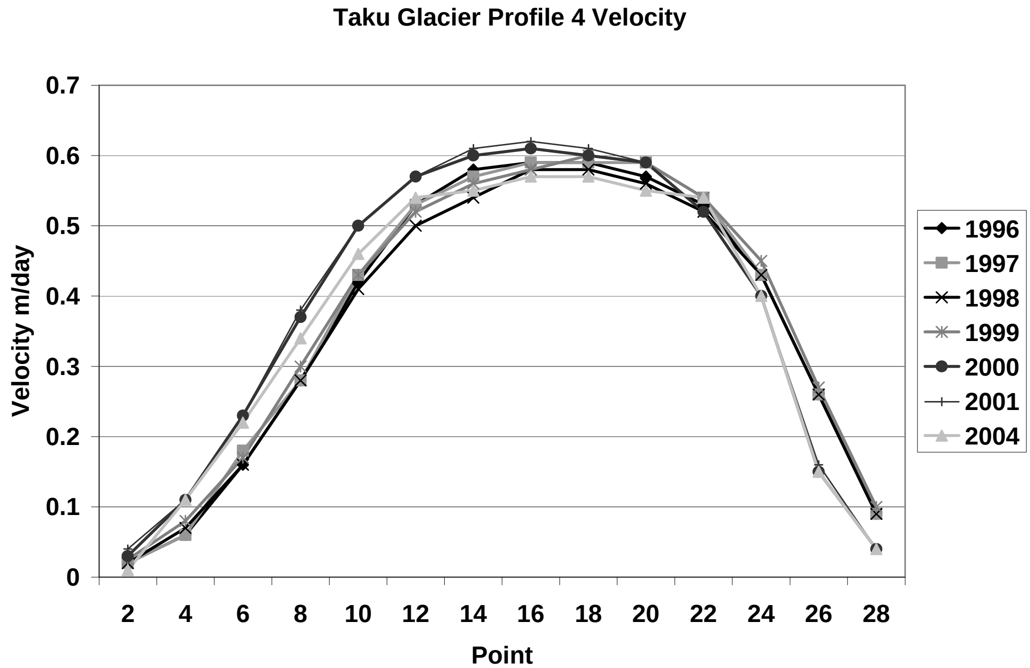

Figure 3. Observed surface velocity along Taku Glacier Profile 4 Lower Line. The lack of significant change is evident.

Most temperate glaciers have a substantial component of glacier sliding that depends on bed hydrology, hence displaying seasonal variations. Taku Glacier, however, has exceptionally thick ice, and a low basal gradient. The flow law for internal deformation suggests that negligible basal sliding is taking place in the accumulation zone (Nolan and others, 1995). The lack of seasonal velocity changes noted in this study and the remarkable uniformity in velocity suggest that sliding is a minor part of the glacier velocity at Profile 4. It is not reasonable to expect a glacier of this size to slow down each fall or winter, and then accelerate to exactly the same speed the following summer. This tendency has been noted on four other repeat profiles on the Taku Glacier (McGee, 2000).

Table 3. Observed velocity each summer at specific survey locations on Profile 4. Note the nearly identical velocity at each location. Mean standard deviation in velocity is below 0.02 m/day.

Point	1996	1997	1998	1999	2000	2001	2004	st dev
10	0.42	0.43	0.41	0.43	0.43	0.5	0.46	0.031
12	0.53	0.53	0.5	0.52	0.53	0.57	0.54	0.021
14	0.58	0.57	0.56	0.56	0.59	0.61	0.55	0.024
16	0.59	0.59	0.58	0.58	0.6	0.62	0.57	0.016
18	0.59	0.59	0.58	0.6	0.61	0.61	0.57	0.015
20	0.57	0.59	0.56	0.59	0.6	0.59	0.55	0.019
22	0.53	0.54	0.52	0.54	0.55	0.52	0.54	0.011
24	0.43	0.43	0.43	0.45	0.45	0.4	0.4	0.021
mean	0.53	0.53	0.52	0.53	0.55	0.55	0.52	0.013

Longitudinal Profile

The variation in velocity along the longitudinal profile from Goat Ridge at 800 m elevation, 12 km from the terminus, up the main trunk of the glacier, along the Matthes Branch, to the ice divide is shown in Figure 4. This variation indicates increasing velocity with distance down glacier from the divide at Point 94, to Goat Ridge just below the ELA at Point 13. The one notable deviation from this pattern occurs where the glacier steepens, causing longitudinal extension. At this point Taku Glacier leaves the high plateau and enters the narrower valley of the Matthes Branch. The surface velocity increase lags the change in surface slope by several kilometers. The glacier then slows under longitudinal compression as the surface slope declines. The velocity along this longitudinal profile has been repeated in 2001 and 2004 the maximum velocity change was 0.02 m/day and the mean change for each point was 0.004 m/day. Again, indicating the annual and seasonal consistency of velocity along the glacier and the equilibrium nature of its flow (Figure 4).

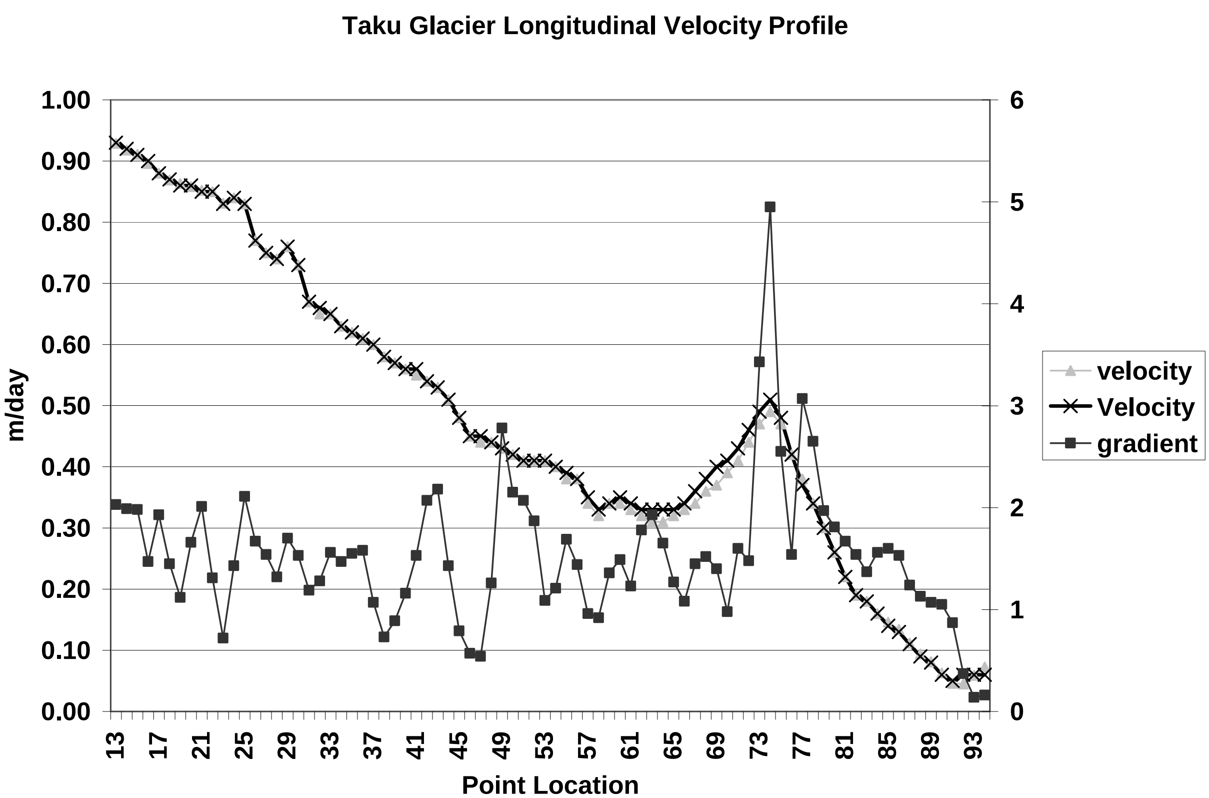

Figure 4. Comparison of gradient and velocity along a longitudinal profile, Taku Glacier, Alaska.

Thickness

The greatest thickness of the Taku Glacier was noted to be 1477 m at Goat Ridge, 22 km above the terminus (Nolan and others, 1995). The centerline depth of the glacier remains thicker than 1400 m at Profile 4, 33 km up glacier, and 1100 m at Profile 7, 44 km upglacier. It is likely that the Taku Glacier centerline depth is greater than 1100 m in thickness the entire distance between these points, based on the consistency in the velocity increase from Profile 7 to Goat Ridge. The minimum basal elevation at Profile 4 is approximately –350 m, and is 300 m at Profile 7. Given the relatively uniform changes in slope of the glacier and velocity between the profiles it is likely that the fjord threshold is near the mid-point between the locations.

The increase in slope from Point 54 to Point 50 (Figure 3) and then decrease is the most likely location of the sea level threshold. Point 49–52 are 39–40 km from the terminus slope, supporting the hypothesis of Nolan and others (1995) that the threshold was from 38–48 km above the terminus. The steady increase in velocity with distance below this point and the consistency of velocity with time both argue for an equilibrium flow of the Taku Glacier.

The transverse bed profile at Profile 4 indicates benches on both the east and west sides of the glacier (Figure 5). The bench on the east side in an extension of the North Basin that is at the base of Taku B and just north of Camp 10. The bench on the west side lacks a clear surface topographic connection. Profile 7 lacks any benches and has a much more u-shaped profile.

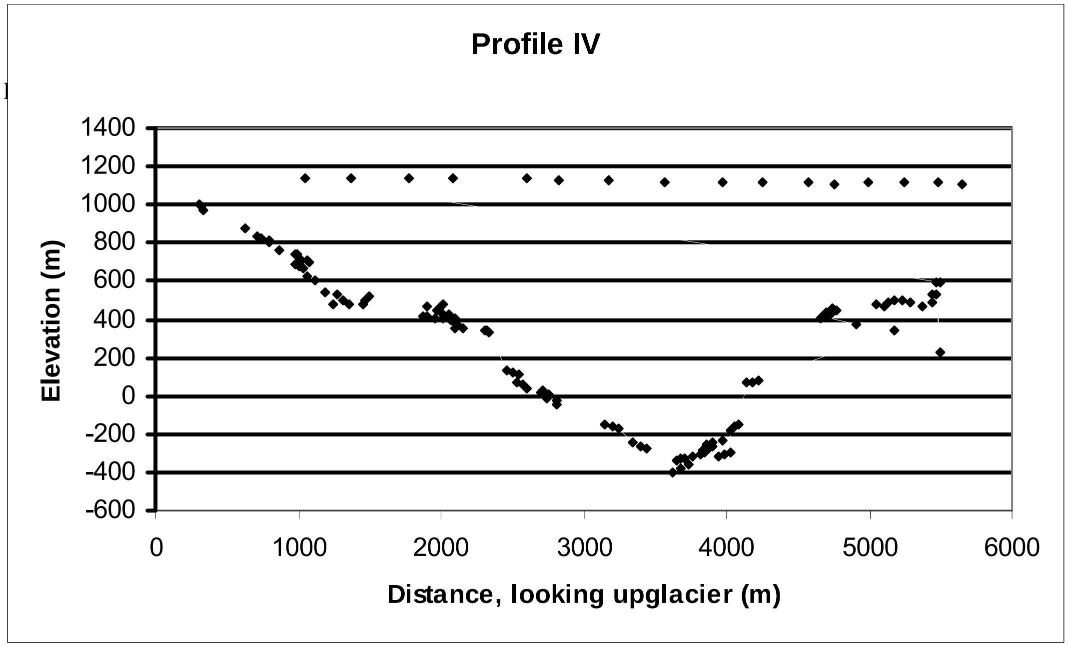

Figure 5. Surface elevation of stations along Profile IV and seismically determined bottom topography along the profile, Taku Glacier, Alaska.

CALCULATION OF VOLUME FLUX

With direct measurement of surface velocity, ice thickness and width for each increment of glacier width on the profiles, the only unknown in determining volume flux is determination of depth average velocity. Several points led Nolan and others (1995) to conclude that basal sliding is minimal; most importantly, calculation of basal shear stresses yielded values of 125 kPa. We determined basal shear stress to be 120–180 kPa along Profile 4, and 75 to 100 kPa along Profile 7. These values are beyond that at which basal sliding would be anticipated. In addition, the consistency in velocity from year to year at each point indicates that there is probably negligible seasonal fluctuation in velocity in the accumulation zone. This has been confirmed by annual velocity observations. It is not reasonable to expect velocity each summer to be within ±5% if seasonal variations in velocity were significant. Following the lead of Nolan and others (1995) and Nye (1965) we have assumed the depth averaged velocity is 0.8 the observed surface velocity.

The mean velocity between each two survey flags is used to represent the average velocity for that width increment of the glacier. The mean depth for that width increment from the seismic profile is then determined. The product of the width of the increment and depth of the increment provide the mean cross-sectional area. The mean surface velocity for each increment is converted to a mean depth averaged velocity by multiplying by 0.8.

Table 4. The calculated volume flux at Profile 4. Volume flux is in m^3/year. Annual values are followed by a comparison of the mean volume flux, mean observed surface flux and the difference between them. The difference in this case is a positive surface flux. The volume flux is determined from annual measurements. The surface flux is the mean for the 1946–2004 period.

	1996	1997	1998	1999	2000	2001	2004	Mean	Surface	Difference
4LL	5.25	5.34	5.07	5.38	5.42	5.41	5.20	5.27	5.5	0.20
4UL	5.33	5.22	5.19	5.23	5.33	5.39	5.17	5.25	5.5	0.23

The volume flux was determined separately for parallel survey lines along Profiles 4 (upper line and lower line) and for the Profile 7 lower line. For profile 4, 33 km above the terminus, the expected surface flux was 5.50×10^8 m^3a^{-1} ($\pm$10%), the volume flux range was $5.00–5.47 \times 10^8$ m^3a^{-1}, with a mean of 5.25×10^8 m^3a^{-1} for the upper line and 5.27×10^8 m^3a^{-1} for the lower line. This indicates a slightly positive balance and glacier thickening above Profile 4. Glacier thickening in the range of 30 m has been suggested for this section of the glacier (Motyka, personal communication). For Profile 7, 43 km above the terminus the observed surface flux was 1.90×10^8 m^3a^{-1} and the volume flux range was $1.72–1.74 \times 10^8$ m^3a^{-1}, again indicating a slight glacier thickening above this profile due to a positive mass balance. The calculated volume flux is based on the 1946–2004 average mass balance profile for the glacier and not for a given year. The surface flux during recent negative balance years would obviously give a lower surface flux value.

CONCLUSION

The results indicate that Taku Glacier has had an equilibrium flow, with no significant annual velocity changes in the last 50 years. Furthermore, although seasonal variations had been expected (Miller, 1963), observations of velocity throughout the year indicate no seasonal variations, probably due to high basal shear stress which prevents sliding. The surface mass balance accumulating above each profile in the last half century is in excess of the volume flux through each profile. The result, supported by both survey results of JIRP and radio echo sounding by the University of Alaska–Fairbanks (Nolan et al., 1995), is glacier thickening. The sustained thickening, positive balance, and consistent flux of the 1946–1988 period suggested that the glacier terminus would continue to advance (Pelto and Miller, 1990). From 1988–2005 the mass balance has been negative, though the volume flux at Profile 4 has not declined appreciably. The reduced mass balance, if it continues, along with the proglacial delta and expanding front of the glacier Post and Motyka (1995), should lead to a reduction in the advance rate. The significant change in glacier mass balance beginning in 1988 is expected to influence the glacier velocity, volume flux and eventually the terminus, if it is sustained. Given the slow response time of this glacier to climate change, if sustained it would not for sometime. The glacier velocity did not change appreciably as the glacier thickened by 10–20 m at Profile 4 and it is expected that it would take a thinning of more than this to substantially alter glacier velocity.

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