The Equilibrium Flow and Positive Mass Balance of the Taku Glacier, Alaska

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ABSTRACT

The Taku Glacier, Alaska has advanced 7.3 km since the late nineteenth century. 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. Annual velocity measurements completed at two profiles above the ELA from 1993-2001 indicate insignificant variations in velocity from summer to summer. Comparison of velocity at a single point along Profile 4, a short distance above the ELA , between 1950-1953 and again from 1997-1998, indicates no seasonal variations in flow. Measurement of surface velocity on Profile 4 from 1950-2000 also indicate a consistent velocity over the long term as well. High basal shear stresses indicate that there is insignificant basal sliding; therefore since internal deformation is the source of velocity, there is no reason to expect seasonal variations of velocity on this glacier. The consistency of velocity over the 50-year period indicates that in the vicinity of the equilibrium line, the flow of the Taku Glacier is in an equilibrium state.

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 (also determined annually in the field). In each case the surface flux is slightly positive versus the volume flux, leading to glacier thickening . From 1950-2000, Taku Glacier has thickened by 20-30 m at Profile 4, 33 km above the terminus; at this profile, the expected surface flux was 5.50×10^8 m^3/a (±10%), while the volume flux range was $5.07\text{-}5.47 \times 10^8$ m^3/a. At profile 7, 43 km above the terminus, the observed surface flux was 1.90×10^8 m^3/a, and the volume flux range was 1.72-1.74 x 10^8 m^3/a. The basal shear stress ranges from 145-195 kPa. Actual volume flux is steadily increasing as the glacier slowly thickens, reflecting a sustained positive mass balance. Unless ablation increases significantly, the result is a volume flux that will sustain a slow ongoing advance.

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 has attracted special attention because of its continuing, century-long advance (Motyka and Post, 1995) while the other primary outlet glaciers of the Juneau Icefield are all in retreat. It is also noteworthy for its continuing positive mass balance (Pelto and Miller, 1990) during a century when alpine glacier mass balances have been dominantly negative (Dyugerov and Meier, 1997). Finally, it is unique as the 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 (113km^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 for 425 m in elevation above the ELA, is a zone where summer ablation is significant (178km^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.

The Taku Glacier has been advancing since 1890: It advanced 5.3 km between 1890 and 1948, continuing its advance 2.0 km since 1948 (Moytka and Post, 199; Pelto and Miller, 1990). 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 will continue to have a positive mass balance given the current climate. While these numbers are not in terms of volume, given the uniform glacier bottom elevation (Nolan and others, 1995), the recent rate of volumetric expansion is likely to also be substantially lower than in the past.

DATA COLLECTION

Surface Mass Balance

JIRP has measured the annual balance of the Taku Glacier from 1946 to 2000 (e.g., Pelto and Miller, 1990). 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). The measurement network consists of 18 locations where mass balance has been assessed in test pits annually since 1946. The majority of the pits are in the region from 950-1400 m. In 1984 and 1998, JIRP measured the mass balance at an additional 500 points in the accumulation area to better determine the distribution of accumulation around these control points. Measurements were taken along profiles at approximately 250 m intervals. The standard deviation for 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 control sites. In addition, the elevation has been determined annually since 1993 on specific tranverse profiles at the same locations, determined using differential GPS as part of the velocity determination program. This will provide an independent measure of mass balance. At this point, however, measurements are restricted to a limited number of years at Profile 4, only corroborating that glacier thickness changes are roughly comparable to the mean annual balance along this profile (Table 1).

Three specific problems have been noted in the initial publication of the mass balance records for these two glaciers (Pelto and Miller, 1990): 1) Field measurements are usually concluded in August, one month prior to the end of the ablation season; 2) surface ablation can reaccumulate as ice lenses and layers, and not escape the glacier system; and 3) only sparse and inconsistent measurement of ablation in the ablation zone has been completed. The third problem will not influence the interpretation of the data in this paper as the flux profiles are in the accumulation zone. Concluding the measurements prior to the end of the ablation season is a logistical problem that cannot be avoided; however, JIRP consistently utilizes rammsonde and crevasses stratigraphic profiles that determine the specific water content of each of the upper 3 to 6 annual layers. The result is that mass balance calculations, which have only been made several years later, rely in part on the verified water content of an annual layer several years after deposition. This has helped identify a region on the Juneau Icefield where most of the surface melting refreezes as internal accumulation.

GPS Survey Methods

Standard rapid-static and real -time differential GPS methods have been employed for all survey work from 1996-2000. 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 were located within one meter of the standard point coordinates (Lang, 1997; McGee, 2000). After establishment of the survey profiles was completed, each profile was surveyed two times, with the time differential between the surveys ranging from 6 to 9 days. For all surveys, a reference receiver was centered and leveled over an appropriate bedrock benchmark. A roving receiver was mounted on an aluminum monopole inserted into the same hole that the survey flag was 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 required only enough time at each flag sufficient to obtain a position fix from the reference receiver.

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, 6 and 7, each with two parallel transverse profiles. In 1999 and 2000, 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 survey locations were 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 ecause 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. Synchronous detonation of the explosives with the seismograph trigger was attempted through the use of FM radios, and because this was never perfect, the long seismograph record allowed for a calculation of the exact detonation time by observing the intersection of the S-wave and P-wave.

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

With the distribution of annual balance more accurately mapped in the lower neve section of the glacier based on the 1998 measurements, 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 flux at Profile 4 was calculated to be $5.5 \times 10^8 \text{ m}^3\text{a}^{-1}$, and $1.90 \times 10^8 \text{ m}^3\text{a}^{-1}$ at Profile 7. The annual balance record shows a markedly less positive trend from 1990-2000 as compared to the 1946-1990 period. The mean annual balance for the 55-year period is 0.32 m/a, representing a total thickening of 18 mwe or 20 m in total ice thickness. The next task in this research is to determine the height changes at survey location along additional profiles, thus providing additional surface balance data each year.

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. 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 flow law for internal deformation suggests that no 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 not occurring.

Observations of velocity at specific stake locations reoccupied each summer along Profile 4 indicate remarkable uniformity of flow from year to year (Table 3). Standard deviation ranges from 0.010-0.020 m/day. Along Profile 7 the variation is slightly less, though spanning the same range. It is not reasonable to expect a glacier of this size to slow down each fall or winter, 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).

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 3. This variation indicates increasing velocity with distance down glacier from the divide at Point 94, to Goat Ridge at Point 13. The one notable deviation from this pattern occurs where the glacier steepens, causing longitudinal extension, where it leaves a 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 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 sharp 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. 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.

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.

The volume flux was determined separately for parallel survey lines along Profiles 4 and 7. A check on the volume flux was provided by the known surface flux. For profile 4, 33 km above the terminus, the expected surface flux was 5.50 x 10^8 m^3a^{-1} (±10%), the volume flux range was 5.07-5.47 x 10^8 m^3a^{-1}, with a mean of 5.27 x 10^8 m^3a^{-1} for the upper line and 5.3 x 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,). For Profile 7, 43 km above the terminus the observed surface flux was 1.89 x 10^8 m^3a^{-1} and the volume flux range was 1.72-1.74 x 10^8 m^3a^{-1}, again indicating a slight glacier thickening above this profile due to a positive mass balance.

CONCLUSION

The results indicate that Taku Glacier has an equilibrium flow, with no significant annual velocity changes in the last 50 years. Furthermore, although seasonal variations have 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 is in excess of the volume flux through each profile. The results, supported by both survey results of JIRP and radio echo sounding by the University of Alaska-Fairbanks (Motyka, personal comm), indicate glacier thickening. The sustained thickening, positive balance, and consistent flux suggest that the glacier terminus will continue to advance, though the advance will continue to be slowed by the proglacial delta and expanding front of the glacier as suggested by Post and Motyka (1995).

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	1996	1997	1998	1999	2000	st dev
10	0.42	0.43	0.41	0.43	0.43	0.009
12	0.53	0.53	0.5	0.52	0.53	0.013
14	0.58	0.57	0.54	0.56	0.59	0.019
16	0.59	0.59	0.58	0.58	0.6	0.008
18	0.59	0.59	0.58	0.6	0.61	0.011
20	0.57	0.59	0.56	0.59	0.6	0.016
22	0.53	0.54	0.52	0.54	0.55	0.011
24	0.43	0.43	0.43	0.45	0.45	0.011
mean	0.53	0.53	0.52	0.53	0.55	0.012

	1996	1997	1998	1999	2000	st dev
11	0.48	0.51	0.49	0.52	0.52	0.018
13	0.56	0.58	0.54	0.59	0.59	0.022
15	0.59	0.6	0.57	0.61	0.61	0.017
17	0.59	0.6	0.58	0.6	0.62	0.015
19	0.61	0.6	0.56	0.6	0.61	0.021
21	0.57	0.58	0.54	0.58	0.58	0.017
23	0.47	0.48	0.46	0.48	0.5	0.015
25	0.3	0.31	0.3	0.31	0.33	0.012
mean	0.52	0.53	0.51	0.54	0.55	0.017

Table 3. Observed velocity each summer at specific survey locations on Profile 4. Note the nearly identical velocity at each location.

	GPS	Field
1994	0.9	0.34
1995	-1.35	-0.46
1996	-0.66	-0.76
1997	-0.44	-1.04
1998	-1.07	-0.68
1999	0.59	0.54
2000	1.32	1.3

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.

	mean
1950	0.58
1952	0.51
1953	0.51
1960	0.53
1967	0.52
1986	0.52
1987	0.51
1996	0.52
1997	0.53
1998	0.51
1999	0.54
2000	0.55
st dev	0.02

Table 2. The mean velocity in m/day from stakes 9-21 on Profile 4 as measured each year in July and August. With the exception of the first year (1950), the velocity has varied less than 10%.

Profile 4UL	1996	1997	1998	1999	2000	Volume	Surface	Difference
Volume Flux	5.33	5.22	5.19	5.23	5.39	5.27	5.5	0.23
Velocity	0.53	0.53	0.52	0.53	0.55			
Profile 4 LL	1996	1997	1998	1999	2000			
Volume Flux	5.25	5.34	5.07	5.38	5.46	5.3	5.5	0.2
Velocity	0.52	0.53	0.52	0.54	0.55			
Profile 7	1996	1997	1998	1999	2000			
Volume Flux	1.73	1.74	1.72	1.74	1.75	1.74	1.9	0.16
Velocity	0.36	0.36	0.36	0.36	0.37			

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Table 4. The calculated volume flux and mean velocity for Profiles 4 and 7 (1996-2000). Velocity is in m/day and 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.

Figure XX. Elevation of stations along Profile IV, Taku Glacier, Alaska.

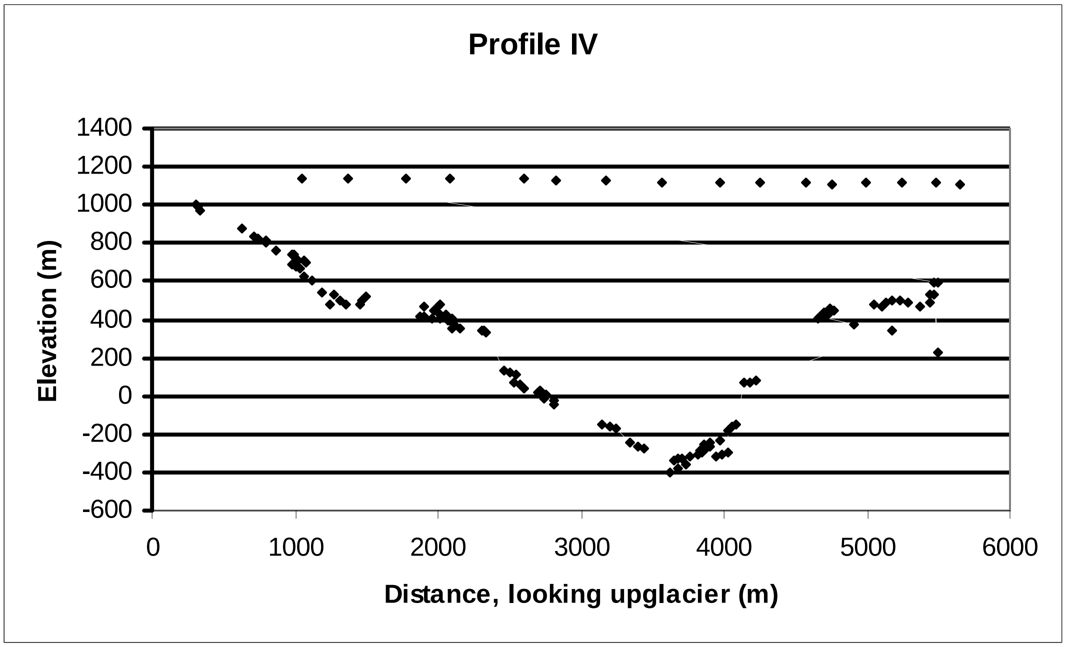
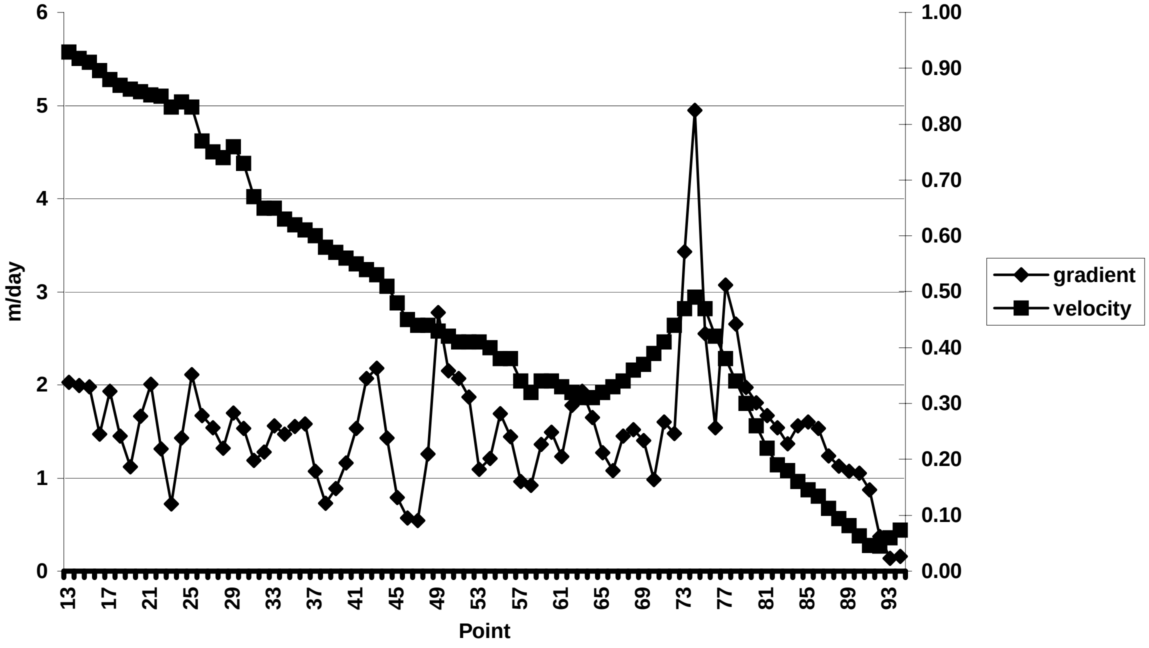


Figure XX. Comparison of gradient and velocity along a longitudinal profile, Taku Glacier, Alaska.



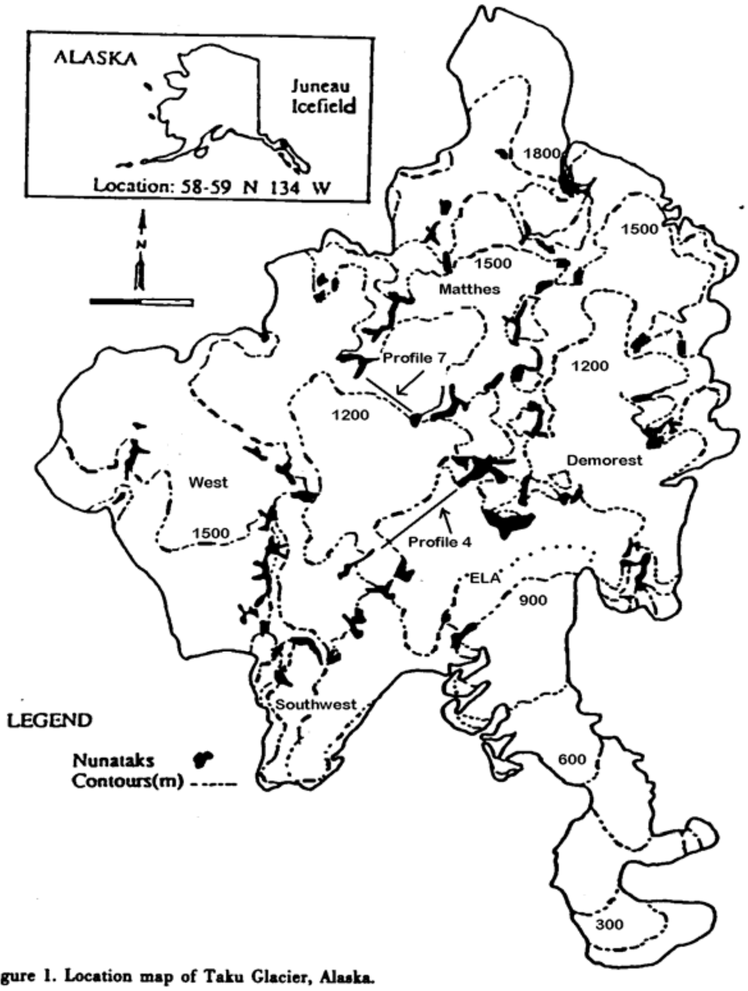
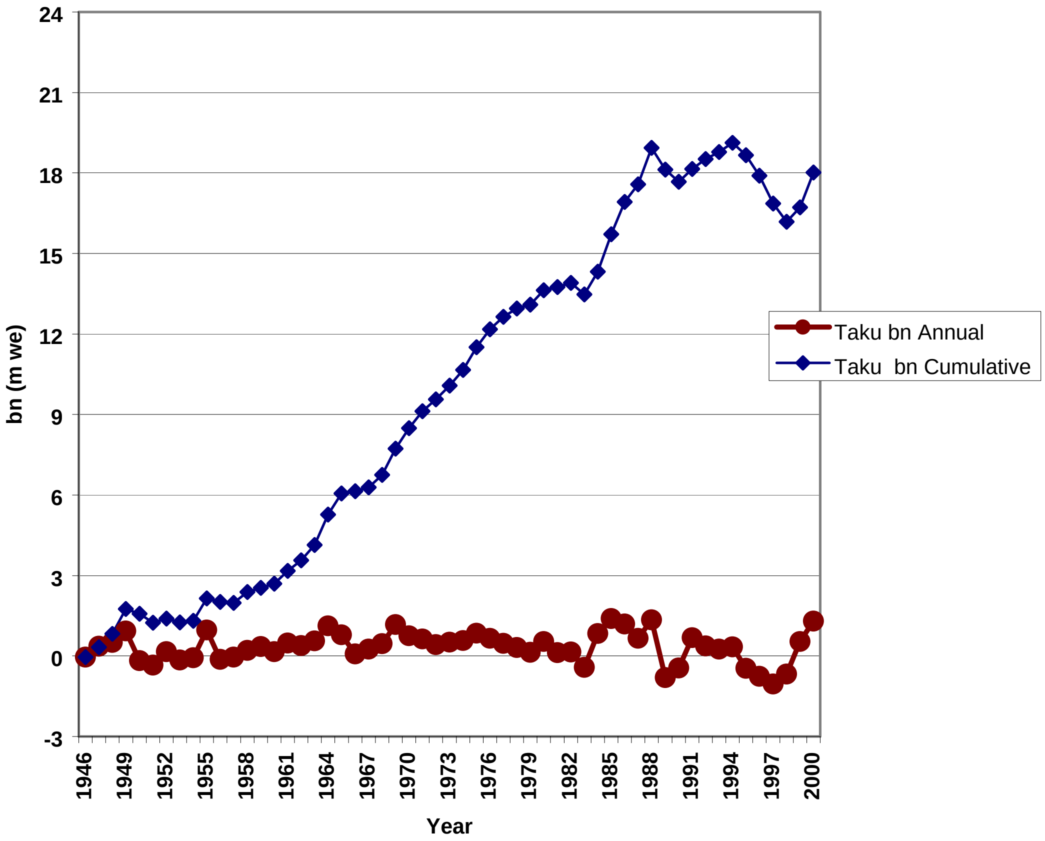


Figure 1. Location map of Taku Glacier, Alaska.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