MASS BALANCE of the TAKU GLACIER, ALASKA from 1946 to 1986

by

Mauri S. Pelto and Maynard M. Miller

FOUNDATION FOR GLACIER & ENVIRONMENTAL RESEARCH
PACIFIC SCIENCE CENTER, SEATTLE WA 98109
and
GLACIOLOGICAL & ARTIC SCIENCES INSTITUTE
University of Idaho, Moscow ID 83843

Reprinted from
NORTHWEST SCIENCE
Vol. 64, No. 3, pp. 121—130
1990

M. S. Pelto, Nichols College, Department of Environmental Science, Dudley, Massachusetts 01570

and

M. M. Miller, Foundation for Glacier and Environmental Research, Moscow, Idaho 83843

Mass Balance of the Taku Glacier, Alaska from 1946 to 1986

Abstract

The Taku Glacier is a temperate, maritime glacier of the Juneau Icefield, southeast Alaska. This glacier is the largest of the icefield, and has advanced 6.8 km since 1890, 1.6 km since 1948. The mass balance record of the Taku Glacier (1946-1986) indicates that the glacier's continued advance has been due to positive mass balance. The mean annual balance during the 1946-1986 period was +0.37 ± 0.06 meters/year (m/a) of water equivalent. Due to the large surplus balance of the previous 40 years the Taku Glacier will continue to advance for the remainder of this century.

Introduction

Since 1946 the Juneau Icefield has been the site of extensive annual field measurements conducted by the Juneau Icefield Research Program (JIRP). In 1949 JIRP came under the aegis of the American Geographic Society with support from the Office for Naval Research (ONR). After completion of the ONR contract in 1957, support was received from the Foundation for Glacier and Environmental Research. Since then JIRP has been under the direction of Maynard Miller. Annual field measurements include determination of the equilibrium line altitude (ELA), balance gradient, glacier surface velocity, glacier surface level, heat balance, surface meteorology and terminus fluctuations. The main emphasis has been on the Taku Glacier (Figure 1 and 2), the icefield's largest glacier (671 km^2).

Taku Glacier is divided into three zones: the ablation zone (113 km^2) below the equilibrium line altitude (ELA), the lower neve region (178 km^2) extending for 400 m in elevation above the ELA, and the upper neve region (380 km^2) occurring more than 400 m above the ELA. These are climatic zones. The ablation zone is primarily sensitive to ablation season temperature, the upper neve zone is primarily sensitive to accumulation season precipitation, and the lower neve zone is sensitive to both accumulation season precipitation and ablation season temperature. Taku Glacier has eight primary tributaries and two terminus tongues; the main glacier terminus and the Hole-in-the-Wall terminus. The Hole-in-the-Wall Glacier branches off of the main Taku Glacier, five kilometers from the main terminus. In this study the Hole-in-the-Wall Glacier is not referred to separately since in a mass balance assessment it is part of the Taku Glacier.

Mass Balance Measurement Methods

The mass balance measured on the Taku Glacier is a surface balance. The techniques used are the standard stratigraphic methods described in detail by (LaChapelle 1954, Miller 1956, Nielsen 1957, Hubley 1957, Heusser and Marcus 1964), and described briefly below. The measurements are carried out from late June through mid-September, thus actual winter (October-April) and summer (May-September) balance are not determined, only annual balance is determined. The annual balance of the Taku Glacier is largely based on measurements at 19 fixed sites conducted at the same time each year, using the same methods.

In the accumulation zone snowpits and crevasse stratigraphy are used to determine snow depth. Water equivalent is measured in a continuous vertical profile through the annual snow layer. Probing is not an accurate technique due to the presence of ice lenses. In the ablation zone, ablation stakes are drilled into the firn or ice and the surface ablation measured. The product of surface density and surface level change yields ablation. It must be emphasized that ablation records seldom span the entire ablation season.

A number of additional techniques have been used in recent years to reduce and better understand the sources of errors in employing the above methods of annual balance measurement. Ablation triangles are used to determine annual ablation instead of individual ablation stakes. Each ablation triangle consists of three stakes

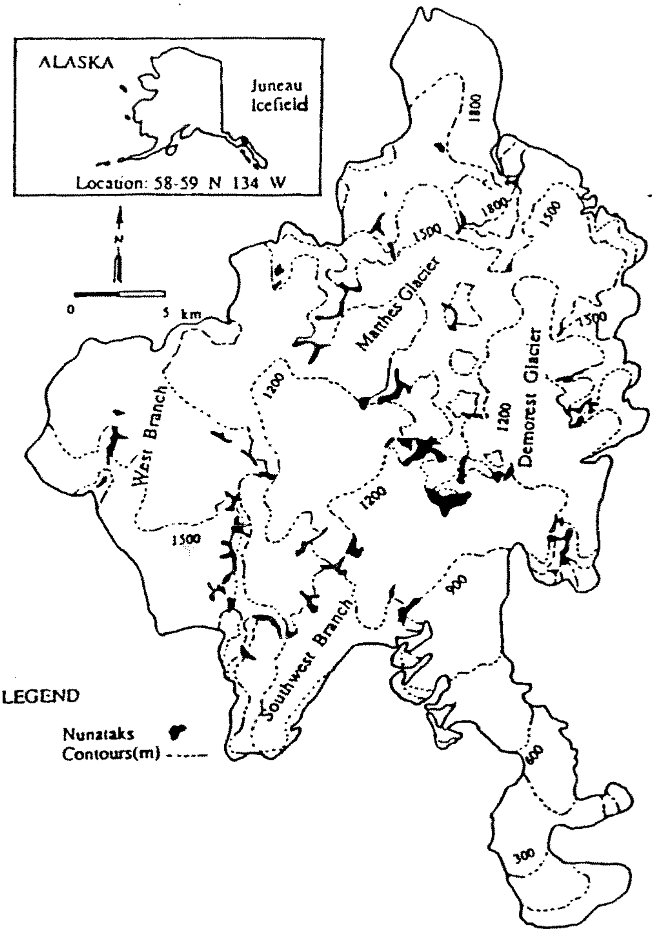


Figure 1. Location map of Taku Glacier, Alaska.

driven or drilled into the glacier 3 m apart, forming an equilateral triangle. Hubley (1957) pointed out the major sources of error associated with using ablation stakes: failure to measure density, failure to monitor the water content of the entire accumulation layer, and the use of data from only one point on a variable glacier surface. To reduce such errors, daily measurements of surface ablation are made at nine locations on the triangle perimeter. The mean surface ablation value is multiplied by the measured surface density to obtain ablation. This method indicates an increased variance of 0.01 m/day in ablation determination using a single point versus using multiple points. This error compounded daily would result in significant cumulative error for the entire ablation season.

The major error in the ablation studies arises from inability to conduct studies at the beginning and conclusion of the ablation season on an annual basis. Extrapolations are used based on data from multi-year ablation studies and

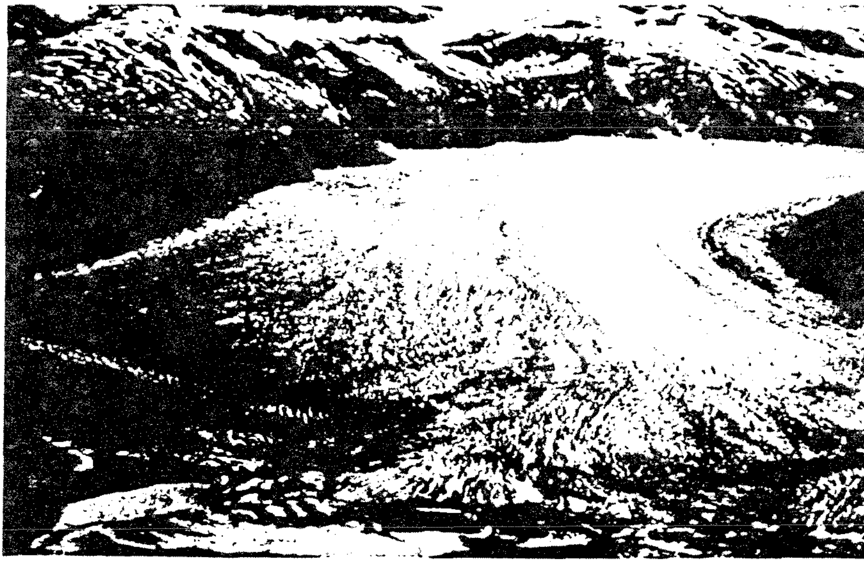


Figure 2. Terminus of the Taku Glacier in 1981.

ablation studies that have continued into the accumulation season in 1950, 1951, 1952, 1964, 1961, 1965, 1973, 1974, and 1982 (Miller 1956, Miller 1963). The second major error is the sparseness of ablation measurements.

Errors in mass balance calculation due to not considering internal accumulation on Alaskan glacier are significant (Mayo and Trabant 1984). Internal accumulation is the refreezing of meltwater within the snow and firn pack. Only meltwater that escapes the glacier is ablation. Internal accumulation is estimated based on bulk density measurements of the upper four accumulation layers. Correlation of stratigraphic layers on a yearly basis indicates that in the first three years after burial the accumulation layer will receive from downward percolation approximately the amount of meltwater that the layer lost while at the surface. Due to densification and diagenetic structures impeding flow, there is negligible percolation through more than the first four annual layers. This attribute has been noted on temperate glaciers in the Caucasus Mountains as well (Bahzev 1986). On the Taku Glacier above 1600 m ablation is limited as most meltwater is retained in the snow and firn pack as internal accumulation. Internal accumulation increases with elevation, comprising 10 percent of the annual accumulation at 1000 m, 10-14 percent at 1200 m and 15-21 percent between 1400 m and 2100 m (Leighton 1952, Miller 1963). Below 1400 m much of the meltwater escapes the glacier system quickly and is ablation.

Errors can arise in accumulation measurements due to small scale variations of firn-snowpack depth and density. To determine this error the snowpack depth and density was checked at 40 locations in a 1000 m^2 area at different elevations and in different years (Pelto 1984). The standard deviation was only ± 0.07 m of water equivalent in a 1 to 2 m snowpack. As noted by (LaChapelle 1954, Hubley 1954, Miller 1956), the density of the summer snowpack on the Taku Glacier is a remarkably uniform 0.54-0.62 kg/m during the latter portion of the ablation period, from the surface to the base of the annual accumulation layer.

Spot measurements of mass balance can be extrapolated on Taku Glacier because of the consistency of accumulation and ablation over sizable areas. In the accumulation zone this is largely due to the fact that wind drifting and avalanching are not important sources of accumulation. The comparatively smooth surface of the Taku Glacier results in even deposition, erosion and melting of the snowpack. During the majority of the ablation season, low complete cloud cover persists. The result is a uniform heat budget, and consequently uniform ablation at the surface of the glacier over regions at the same elevation. These factors allow a lower sampling density in mass balance determination on the Taku Glacier than is typical.

Annual Balance Calculation

The methods described above have not always been strictly followed by the several hundred researchers who have gathered mass balance data on the Taku Glacier. The methods do allow use of less comprehensive data as 40 years of study has yielded an excellent understanding of the mass balance variation on the Taku Glacier and problems in measuring it. Although no mass balance results have been previously published for the Taku Glacier, now after 40 consecutive years of extensive measurements sufficient mass balance data exists to accurately reconstruct the annual balance history of the Taku Glacier for the 1946 to 1986 period.

The Taku Glacier mass balance record is the longest in North America. However, the record must be treated with care as there are limitations to the accuracy of the record. Despite the inaccuracies this record is a valuable climatic record for the Coast Range of Alaska.

Limitations to the mass balance record are: (1) The density of measurements averages 1 per 13 km², and are particularly sparse in the ablation zone. (2) Measurements are usually concluded by early September. At this time the accumulation season has begun in the accumulation zone, but not in the ablation zone. (3) Data acquisition in the ablation zone does not usually extend over the entire ablation season and is often not undertaken on the lower 12 km of the Taku Glacier. (4) Measurements have been carried out by several hundred different researchers.

However, mitigating these limitations are: (1) Since 1946 measurements have been completed annually at 18 specific locations on the Taku Glacier (Figure 3). Measurements at these 18 sites

Figure 3. Location of the 18 sites where annual mass balance measurements have been completed since 1946.

are completed each year using the same methods at the same time of the year. Each year these measurements are supplemented by other measurements, but the balance gradient used in reconstructing annual balance is largely based on these 18 measurement sites. The mass balance calculations are then consistent and precise. Climatic interpretations are not limited by the aforementioned systematic errors. (2) Measurements carried out throughout the ablation season in nine different years are used to extrapolate ablation data to the end of the ablation period. (3) The balance gradient of the Taku Glacier in the ablation zone has a constant shape that is known, but does shift with respect to altitude (Mayo 1984, Pelto 1987). The balance gradient shape is fixed with respect to elevation annually using the ELA. Thus, the ablation rate at any elevation can be determined. (4) Errors due to the number of researchers is limited by the fact that all are trained to use the same methods, and that at least one experienced researcher supervises each measurement.

All available mass balance measurement data are used to construct a mean mass balance gradient and mass balance map for the entire glacier (Figures 4 and 5). Mass balance data for each individual year was compiled and contoured. In areas where data gaps exist mass balance contours are extrapolated, based on the mean mass balance contour pattern, with the magnitude of each mass balance contour adjusted to fit the existing data from that year (Figure 5). A mean mass balance map for the entire glacier is completed and the mass balance for the glacier is calculated by integration.

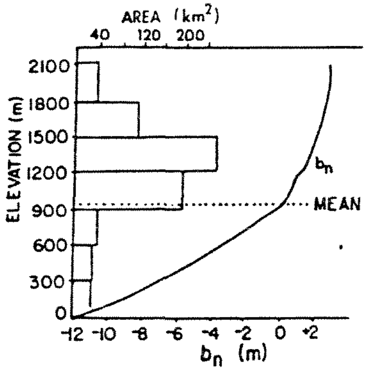


Figure 4. Balance gradient and area elevation curve for Taku Glacier.

The annual balance (bn), the sum of the products of the mean annual balance (bz) and the glacier surface area (Az) within each 160 m elevation zone of the Taku Glacier (Figures 4 and 5). Equation 1 is used to calculate annual balance.

$$bn = Az\ bz/At \qquad (1)$$

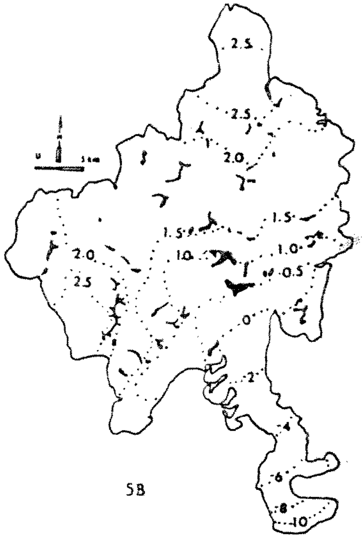
In equation 1, At is the total glacier area. Standard errors reported are for one standard deviation of the observed fluctuation in direct mass balance measurements. Below the ELA on the Taku Glacier mass balance calculations rely solely on ablation studies, with an estimated average annual balance error of ± 0.20 m. The lack of measurements in the ablation zone cause a high but systematic error. The error is again limited by the uniformity of ablation which can be accurately estimated from the observed balance gradient. In the lower neve zone the average error is ± 0.15 m, due primarily to the failure in conducting measurements to the absolute conclusion of the ablation season. The upper neve zone has an error of ± 0.10 m resulting from a lower than ideal sampling density. All of the latter errors are random. The error in annual balance measurements for the entire Taku Glacier is ± 0.14 m, dropping to ± 0.08 m for any given ten-year period. The annual balance record for the Taku Glacier during the 1946-1985 period is shown in Table 1.

Mass Balance and Climatic Trends

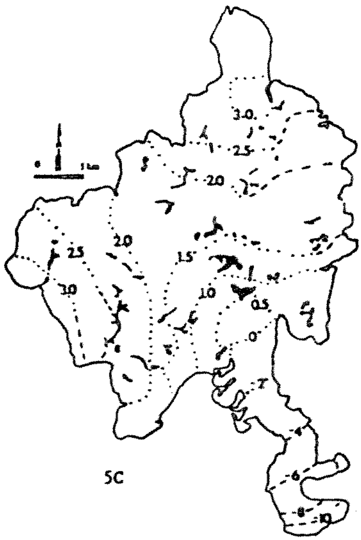
The mass balance record of the Taku Glacier from 1946-1986 can be divided into six segments (Figure 6). (1) 1946-1949 was a period of positive annual balance, resulting from high winter cyclonic activity. (2) From 1950 to 1957 a period of negative annual balance due to below normal accumulation temperatures was associated with decreased cyclonic activity. (3) The 1958-1962 period had increasing annual balances as winter temperature and precipitation increased. (4) During the 1964-1975 period, cool ablation season temperatures and above average winter precipitation caused large surplus annual balances. The low winter temperatures of this period were noted throughout the northern hemisphere, in an analysis of 191 weather stations, and did not reflect decreased cyclonic activity (Kelly *et al.* 1982). (5) From 1976 to 1983 temperatures rose rapidly during both accumulation and ablation seasons. The increased ablation offset increased accumulation, and low surplus annual balances resulted. (6) 1984 through 1988 was a period of extreme positive mass balance, caused by record winter warmth and high accumulation season cyclonic activity. The prevailing wind direction shifted for the first time since 1946 from southeast to east-southeast. The true nature and *cause of this last climatic fluctuation are not yet* clear.

Each of the six periods mentioned above indicates a change in local weather noted in Juneau and a change in mass balance on the Taku Glacier. This analysis demonstrates that Juneau weather records can be useful in predicting glacier regimen for Taku Glacier if fluctuations in weather caused by local, regional or global scale variation of atmospheric circulation are distinguished.

5A



5B



5C

Figure 5a. 1962 mass balance map of the Taku Glacier, in meters of water equivalent. Measurement sites indicated by t.
5b. Mean mass balance map of Taku Glacier (1946-1986).
5c. 1962 mass balance map of the Taku Glacier used to calculate annual balance. This is a composite of 5a and 5b. The contour pattern in 5b is used to fill in data gaps in 5a. The magnitude for these contours are assigned based on data from neighboring points.

TABLE 1. The annual equilibrium line altitude (ELA), annual net balance (b_n) in millimeters of water equivalent and number of measurement sites for the Taku Glacier, Alaska from 1946 to 1986.

Year	ELA	b_n	Data points
1946	980 m	− 40 mm	38
1947	900	360	40
1948	870	510	43
1949	800	930	71
1950	1010	−180	74
1951	1160	−340	79
1952	950	160	93
1953	1010	−150	82
1954	980	− 70	57
1955	780	970	34
1956	1000	−130	37
1957	1010	− 40	35
1958	930	210	63
1959	915	350	59
1960	950	160	51
1961	885	480	47
1962	900	390	71
1963	875	570	41
1964	750	1130	62
1965	810	790	57
1966	965	80	48
1967	930	250	53
1968	885	460	46
1969	730	1170	44
1970	825	760	37
1971	850	630	56
1972	880	420	35
1973	870	520	39
1974	850	580	44
1975	800	850	52
1976	850	660	38
1977	885	470	49
1978	915	310	47
1979	950	140	34
1980	870	540	38
1981	980	120	43
1982	950	150	91
1983	1085	−420	86
1984	875	640	178
1985	600	1400	39
1986	720	1200	43
Mean	910	370	55

Recent Glacier History

The mass balance of southeast Alaskan glaciers is dictated by (1) the calving flux, (2) the percentage of a glacier's total area within the maximum accumulation area (MAA) and, (3) most importantly, the accumulation area ratio (AAR). AAR is the percentage of a glacier's total area above the ELA (Meier and Post 1962). AAR is reported as a percentage. In southeast Alaska the maximum accumulation zone is the region where mean accumulation season temperatures are −5 to −11°C (Pelto 1987). Changes in the regimen of glaciers that are not surging occur only when AAR and MAA cross threshold values necessary to maintain equilibrium (Mercer 1961). Below the threshold values negative mass balances cause glacier retreat. Above the threshold values positive mass balances lead to glacier advance. The Taku Glacier is not a surging glacier and has had a negligible calving rate since 1946. Thus, only AAR and MAA determine its present behavior. The threshold value for AAR and MAA are 67 and 50 for a low calving rate or non-calving glacier (Pelto 1987).

The Taku Glacier and its distributary tongue the Hole-in-the-Wall Glacier began advancing in the 1890s from a retracted position. At this time the glacier had an AAR of 88 and a MAA of 64, more than sufficient to maintain a strong advance behind the protective terminus shoal built by the glacier (Field 1952). The advance continued behind the progressing terminus shoal, which was effectively a push moraine (Miller 1963). By 1948 the main terminus had advanced 5.3 km from its retracted position, a rate of 88 m/year, and was no longer calving. The AAR was 86 and the MAA was 63 providing a strong positive mass balance that has driven an additional 1.5 km advance of the main terminus since 1948, a rate of 37 m/year. Today the Taku Glacier does not calve and with an AAR of 82 and a MAA of 62 still has a strong positive mass balance, which will enable the glacier to advance for the remainder of this century. The Taku Glacier is in the advance stage of the Alaskan tidewater glacier advance-retreat cycle, and is comparatively insensitive to climate at present. Figure 7 shows the terminus behavior of the Taku Glacier, Hole-in-the-Wall Glacier, and Norris Glacier since 1890. The Hole-in-the-Wall terminus has advanced 3.2 km since 1890, at a rate of 33 m/year. The Hole-in-the-Wall Glacier is a spillover tongue of the Taku Glacier and has a parallel history. The Norris Glacier has an AAR of 61 and a MAA of 38, values that are well below equilibrium threshold values, resulting in 1.8 km retreat since 1890.

The reduced advance rate of recent decades is caused by the expanding terminal front (Field 1952, Miller 1963), not declining mass balance. Heusser (1952) attributed the Taku Glacier's advance to a series of ice waves and not to positive

Figure 6. Five year running mean of accumulation season temperature (Tw), ablation season temperature (Ts) and mass balance (bn) of Taku Glacier.

mass balance. Small ice waves are present 10 to 20 km above the terminus, but they are infrequent and not of a scale that could cause a continuous advance over a period of thirty years. It is evident that the advance of the Taku Glacier is due to a positive mass balance.

Summary

The annual balance record for the Taku Glacier assembled from existing JIRP data provides the longest continuous record in North America. The Taku Glacier has had a positive balance for almost the entire period (Figure 6). The mean annual balance during the 1946-1986 period on Taku Glacier has been +0.37 m/year ± 0.06 m/year. The positive mass balance of the past forty years will allow the glacier to continue to advance for the remainder of this century regardless of climatic variations.

The annual balance record for the Taku Glacier and Juneau weather records indicate a significant climatic fluctuation beginning in 1976. Temperatures increased sharply for each season of the year in the Arctic Basin during this period (Kelly *et al.* 1983). The true nature of the climatic trend is not clear. What is clear are the unparalleled extremes of climate in southeast Alaska during the last decade.

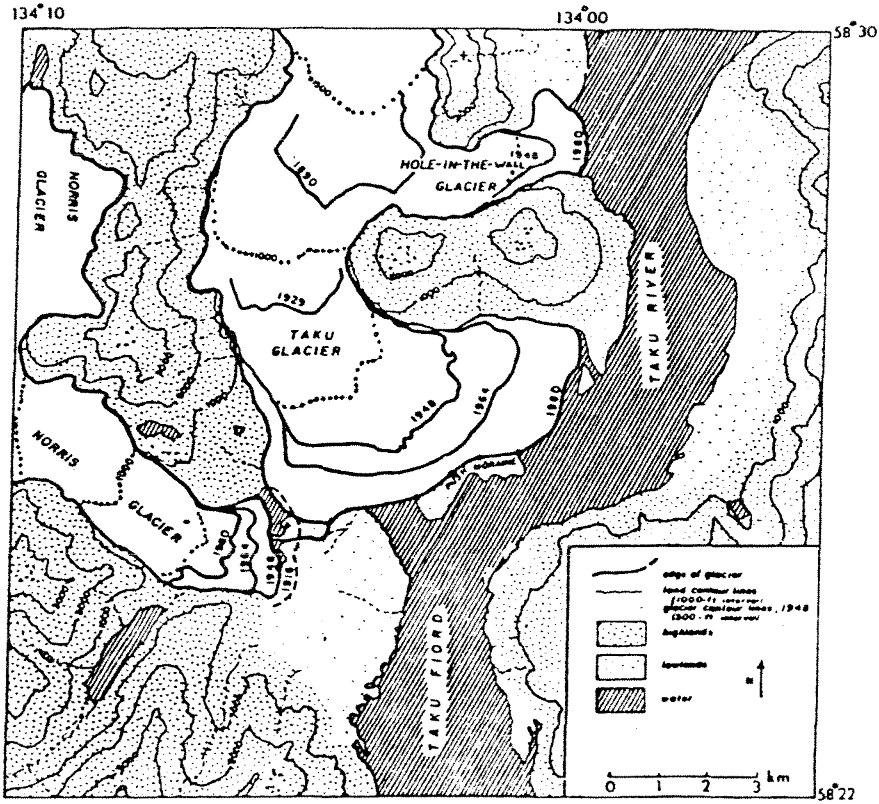


Figure 7. Terminus behavior of Taku Glacier, Norris Glacier and Hole-in-the-Wall Glacier.

Literature Cited

Field, W. O. 1952. Glaciers—historians of climate. Geograph. Rev. 42:337-345.

Heusser, C. J. 1952. Geobotanical studies on the Taku Glacier anomaly. Geograph. Rev. 42:224-239.

Heusser, C. J., and M. G. Marcus. 1964. Surface movement, hydrologic change and equilibrium flow on Lemon Creek Glacier, Alaska. J. Glaciol. 2:437-440.

Hubley, R. C. 1954. The problem of short period measurements of snow ablation. J. Glaciol. 2:437-440.

Hubley, R. C. 1957. An analysis of surface energy during the ablation season on Lemon Creek Glacier, Alaska. Trans. Amer. Geophys. Union 38:68-86.

Kelly, Jones, Cherry, and Tavakol. 1982. Variations in surface air temperatures: part two Arctic Regions, 1881-1980. Monthly Weather Rev. 110:1-22.

LaChapelle, E. R. 1954. Snow studies of the Juneau Icefield. American Geographic Society, Juneau Icefield Research Program Report 9.

Leighton, R. B. 1952. Meltwater investigations in the Taku Glacier firn, Juneau Icefield, Alaska. American Geographic Society, Juneau Icefield Research Program Report 2.

Mayo, L. R. 1984. Glacier mass balance and runoff research in the U.S.A. Geograf. Ann. 66A:215-227.

Mayo, L. R., and C. Trabant. 1985. Estimation and effects of internal accumulation and glacier mass balance in SW Canada during the IHD, 1965-1974. Ann. Glaciol. 6:113-117.

Mercer, J. H. 1961. *The response of fjord glaciers to changes in the firn limit.* J. Glaciol. 3:850-858.

Miller, M. M. 1954. Juneau Icefield Research Program. American Geographic Society, Juneau Icefield Research Program Report 7.

__________. 1956. Contributions to the glacial geology and glaciology of the Juneau Icefield, SE Alaska. U.S. Office of Naval Research, ONR-83001.

__________. 1963. Taku Glacier evaluation study. State of Alaska Department of Highways and U.S. Department of Commerce.

__________. 1973. A total systems study of the climate-glacier relationships and the stress instability of ice. National Geographic Society Research Reports, 1966 Projects: 157-196.

Received 19 January 1989
Accepted for publication 6 December 1989

__________. 1975. Mountain and glacier terrain study and related investigations in the Juneau Icefield Region, Alaska-Canada. U.S. Army Research Office, Durham, North Carolina.

Nielsen, L. E. 1957. Preliminary study on the regimen and movement of the Taku Glacier, Alaska. Bull. Geol. Soc. Amer. 68:171-180.

Pelto, M. S. 1987. Mass balance of southeast Alaska and northwest British Columbia glaciers from 1976 to 1984: methods and results. Ann. Glaciol. 9:189-194.