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ABSTRACT. Annual balance measurements on the Lemon Creek Glacier, Alaska conducted by the Juneau Icefield Research Program (JIRP) from 1953 through 1998 provide a continuous 46-year record. This is one of the nine American glaciers selected in a global monitoring network during the International Geophysical year, 1957/58. These data have been acquired primarily by employing consistent ground methods, conducted on similar annual dates and calculated using comparable methodology. The results have been until now fairly precise, but of uncertain accuracy. An adjunct comparison of topographic surface maps of the glacier made in 1957 and 32 years later in 1989 provides a rough determination of glacier surface elevation changes which are clearly of less precision than the compilation of annual ground data. Airborne surface profiling in 1995, and global positioning system leveling transects in 1996–1998 update the record of surface elevation changes over the past decade. The mean glacier ice thickness reductions suggested by these methods from 1957–1989, from 1957–1995 and from 1957–1998 are –13.2 m, –16.4 m, and –21.7 m, respectively. It is of interest that the geodetic interpretations agree fairly well with the trend of sequential balances from ground-level stratigraphic measurements. To date, however, the infrequent mapping methods in this study have yielded specific balances averaging between 5 and 11% less than those resulting from our annual on-site glaciological monitoring. For future studies this can be an important factor. The ground data are, therefore, the ones in which we have most confidence. These show cumulative ice losses of –13.9 m (12.7 m water equivalent w.e.) from 1957–1989, of –19.0 m (-17.1 m w.e.) from 1957–1995, of –24.4 m (22 m w.e.) from 1957–1998, and –24.7 m (22.2 m w.e.) for the total cumulative loss over the full 46 years between 1953 and 1998. Although the balance trend has been increasingly negative it averages –0.48 m/a in w.e. or 0.52 m of ice loss per year.

To refine the reliability of density determinations in this data set the effects of internal accumulation from refrozen meltwater producing diagenetic ice structures in the annual firnpack have been taken into account. An unusual dearth of such structures within the 1997/98 firnpack provided a unique opportunity to facilitate application of the probing technique over broad areas of the névé. This added to our ground truth and verified accuracy of the test-pit measurements used in these long-term mass balance computations.

The glacier's continuing negative mass balance has fueled a terminal retreat of 800 m during the 1953–1998 period. The annual balance trend indicates that despite a higher mean elevation and a higher elevation terminus from thinning and retreat, mean annual balance has been strongly negative since 1977 (–0.78 m/a w.e.). Dramatically increased negative mass balances have occurred in the 1990s, with 1996 and 1997 being the only years on record with no retained accumulation since field observations were initiated in the glacier source areas in 1948.

Introduction

Lemon Creek Glacier, Alaska, was chosen as a representative glacier for the 1958 International Geophysic Year (IGY) global glacier network (Fig. 1). This choice was based on its subarctic latitude location and on the ongoing mass balance studies of the Juneau Icefield Research Program (JIRP) that were initiated in 1948 (Miller 1972; Pelto and Miller 1990). We have continued annual balance measurements on Lemon Creek Glacier through 1998. Based on 1955–1957 vertical aerial photography a 1:10,000 scale map was produced in 1958 for the IGY (Heusser and Marcus 1964). In 1957 Lemon Creek Glacier was 6.4 km long and had an area of 12.7 km^2 (Figs 2 and 3) (Heusser and Marcus 1964). In 1998 we measured the glacier to be 5.6 km long and with an area of 11.8 km^2 (Fig. 3) (Marcus *et al.* 1995). From the head of the glacier at 1300 m to the mean equilibrium line altitude (ELA) at 1050–1100 m the glacier flows northward. In the ablation zone it turns westward terminating at an elevation of 600 m. The glacier can be divided into four sections: (1) steep peripheral northern and eastern margins draining into the main valley portion of the glacier; (2) a relatively large low-angled slope (4°) upper accumulation zone representing the main body of the glacier and flowing north from 1220 m down to 1050 m; (3) a steeper section (6°) in the ablation zone as the glacier flows west from 1050 m down to 850 m; (4) a steep icefall zone (18°) leading to a two-fingered terminus at the elevation of 600 m. The maximum thickness is in section 2.

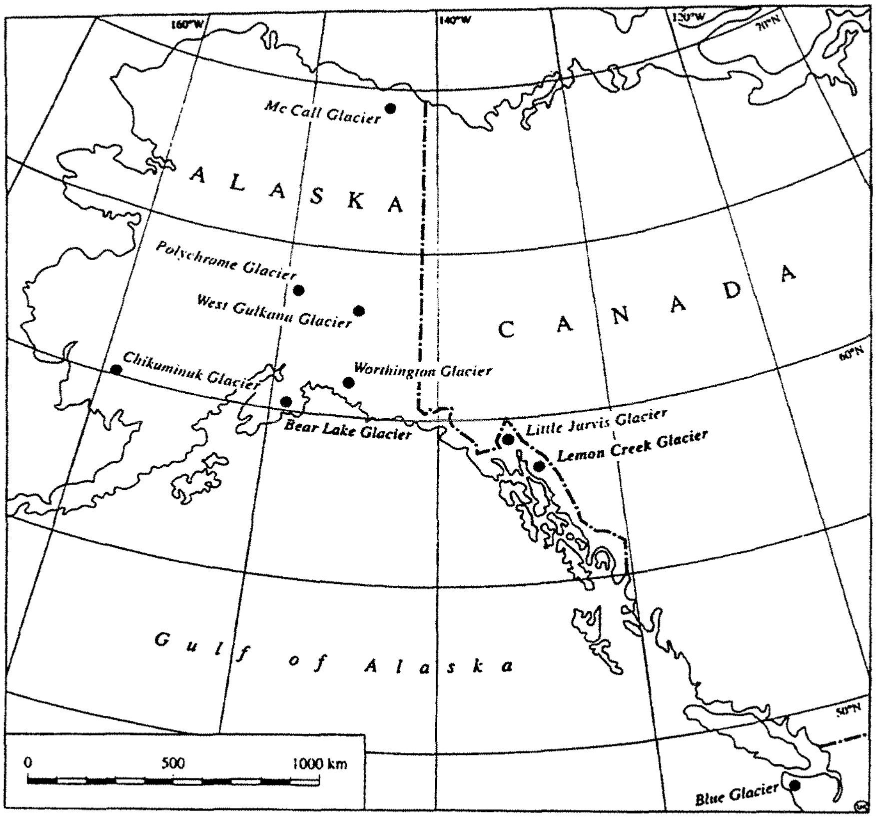

Fig. 1. Location of the nine American glaciers mapped during the International Geophysical Year, 1957–958, showing research site for Lemon Creek Glacier near Juneau, Alaska (American Geographical Society, 1960).

As determined by geophysical means the greatest ice depth here exceeds 200 m at a position about 5 km up-glacier from the icefall (Fig. 4) (Thiel *et al.* 1957; Miller 1972).

This paper will review compilation of the 46-year mass balance record for the glacier (1953–1998). Only cursory mass balance observations were made from 1948 to 1952. On Lemon Creek Glacier no early ablation season or late accumulation season measurements are made, so summer and winter balances cannot be separated. The only previous publication of annual balance is for the 1954–1958 period (Heusser and Marcus 1964). The annual balance record has been given encouraging corroboration by using geodetic methods based on a comparison of the 1:10,000 scale topographic maps made of the glacier in 1957 and 32 years later in 1989 (Marcus *et al.* 1995). Radar altimetry using airborne surface profiling has given a rough documentation of the geodetic mass balance changes from 1989 to 1995 (Sapiano *et al.* 1998). In 1996–1998 more refined application of comparative global positioning system (GPS) surface profiling has provided quite an accurate record of the surface elevation change within that short period of time. The unique success of that technique emboldens us to expand our GPS mass balance measurements in the next few years. A comparison of the results of the occasional geodetic–topographic surveys with those we have obtained from sequential annual stratigraphic measurements indicate in general that the ground truth glaciological records are more dependable. In fact from the comparisons noted later in Table 3, the ground level glaciological measurements are on average between 5 and 11% more accurate. Regardless, the addition of some geodetic surveys helps in assessing errors in the annual balance measurements from the stratigraphic method. This is especially true in cases where there is a dearth of adequate data from the glacier's terminus area.

Mass balance methods

Each year the mass balance of Lemon Creek Glacier has been determined using stratigraphic field measurements of varying distribution and number. At a minimum each year the field studies comprise repeated transient snowline mapping in early summer and the ELA in September, plus net retained

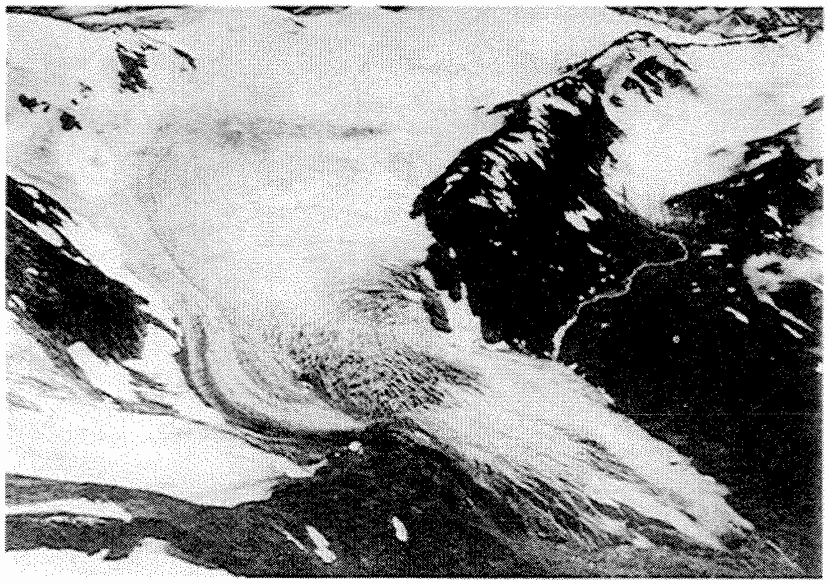

Fig. 2. Oblique aerial photograph of Lemon Creek Glacier, (M.M. Miller) August 13, 1948.

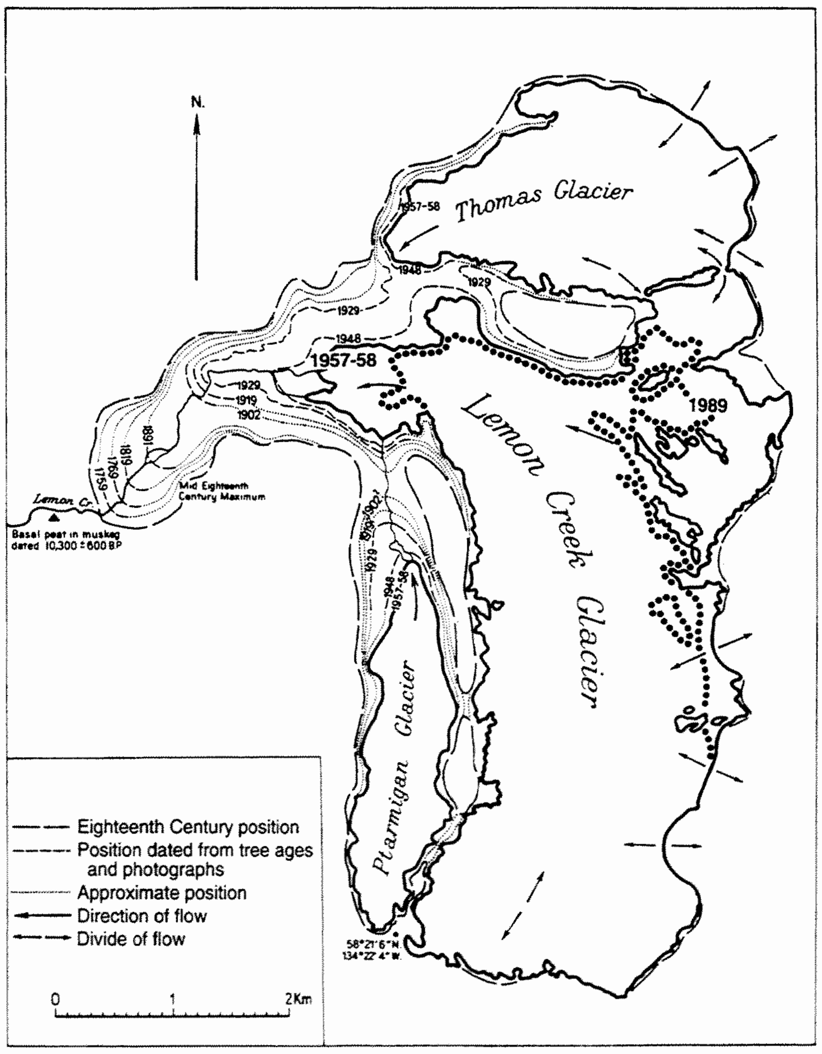

Fig. 3. Historical variations of Lemon Creek Glacier through 1989 (after Marcus *et al.* 1995).

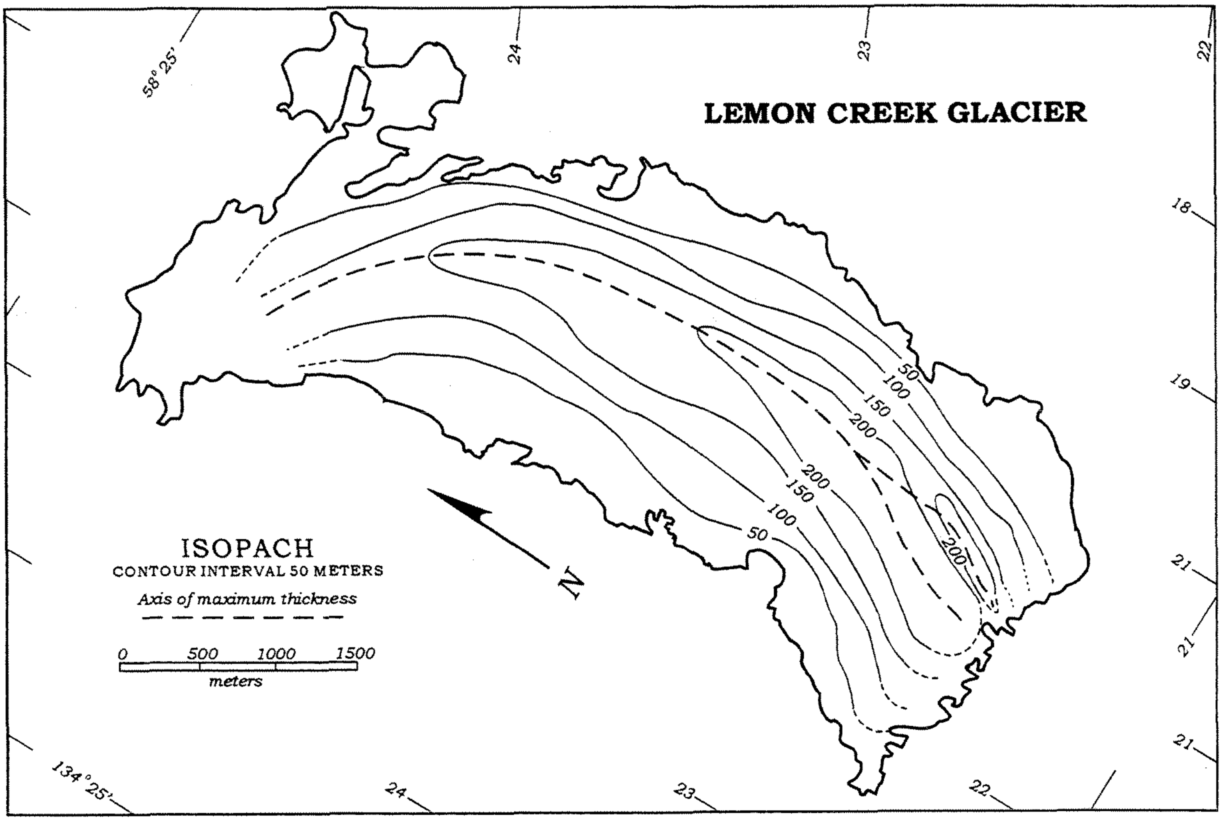

Fig. 4. Isopach sketch map of Lemon Creek Glacier showing general configuration of subglacial floor based on geophysical ice depth records.

accumulation measurements at four key mass balance control sites (locations A to D in Fig. 5).

Each year between July 10 and July 20 we complete a series of test-pits in which the thickness and bulk density of the previous winter's retained accumulation is measured. A continuous density profile from the surface to the base of the annual firnpack provides a direct measure of the annual water equivalent (w.e.) thickness (LaChapelle 1954). The base of the annual accumulation increment is always well identified by a continuous dusty horizon formed on the previous summer surface. On the Lemon Creek Glacier this layer is particularly well developed through each ablation season. LaChapelle (1954) also noted that one of the first characteristics which becomes apparent upon examination of test-pit data is the remarkable uniformity of firn density in vertical profile, as well as in distribution over the glacier and with time during the summer. The average bulk density is determined each year including considerations of diagenetic ice. It has ranged from 0.54 to 0.58 mg/m^3.

In addition to the four standard sites measured every summer, net annual retained accumulation thickness has been observed by probing at several hundred broadly spaced points in the accumulation zones up-glacier from the transient snowline. Additional measurements in the névé area above the transient snowline consisted of rammsonde profiles and crevasse stratigraphy in transects starting near the standard test-pit sites or when possible from lower transient snowlines.

Further to the mass balance methods, ablation stakes, driven or bored deeply into the firn in the accumulation zone, record ablation of the remaining firnpack between the test-pit accumulation measurements in July and the end of the ablation season in early September. This provides an essential measure to adjust the July test-pit accumulation thickness measurements to the end of the ablation season. The maximum number of ablation stakes used during a single season was 200 in 1967. During the several years when more than 30 ablation stakes were emplaced, it was apparent that ablation rates above the 900 m elevation on this glacier were quite consistent. Below the 900 m contour ablation rates increase with decreasing surface elevation. Table 1 lists the mean ablation rates obtained from

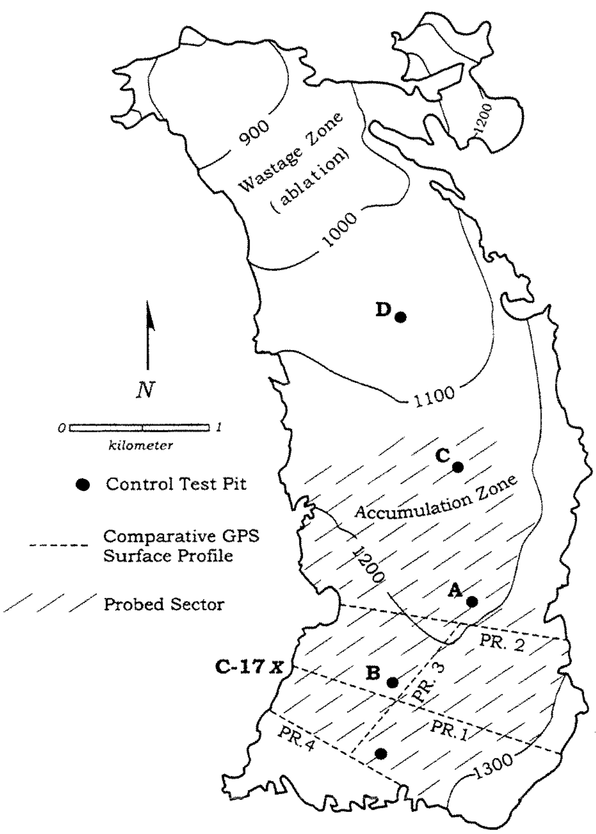

Fig. 5. Location of standard test-pit sites and comparative leveling GPS profiles in main upper névé.

stake ablation measurements at locations used during different ablation seasons. The table illustrates the similarity of ablation at and well above 900 m from July through early September.

The transient snowline position is annually recorded in early July and its highest position, the ELA, in early September to provide a further check

Table 1. Mean daily ablation rates (m/day) over a minimum 36 days recorded during eight different field seasons. The mean daily ablation for each elevation zone is in w.e. and considered to be representative as these are the means of at least three separate measurement sites in each zone.

Year	800 m elevation	1050 m elevation	1175 m elevation
1955	0.060	0.051	0.050
1956	0.068	0.048	0.046
1957	0.062	0.046	0.045
1958	0.052	0.042	0.042
1966	0.055	0.043	0.052
1967	0.060	0.056	0.058
1968	0.058	0.052	0.050
1984	0.060	0:053	0.054

on the amount of ablation. The ELA is a crucial tie point for the glacier's annual balance determination. Calculation of annual balance for each year depends on extrapolations from the standard test-pit sites and the ELA, based on the detailed mass balance measurements made across the glacier covering the intervals 1954–1957, 1965–1969, 1972–1975, 1982–1984, and 1998. Except for the years from 1954–1957 when spot mass balances were calculated by Heusser and Marcus (1964), systematic annual balance has been determined using data from the same five data points, i.e. four master test-pits and again, of course, the ELA.

On JIRP we have used consistent field methods on similar dates to provide comparable records for each year. Walters and Meier (1989) suggest that glacier mass balance can generally be determined using area-weighted data from a single observation point. This can be done, however, only after the weights for data points have been determined from broad and in-depth multi-year mass balance studies, and from calculations made covering the representative area for each of the master reference points. This method, using typically three to five standard measurement points, is currently employed by the USGS at regional glacier sites on Gulkana, Wolverine and South Cascade Glaciers (Krimmel 1994; Trabant and Mayo 1985; March and Trabant 1995). Through the years we have applied a comparable spread of measurements on Lemon Creek Glacier.

Net accumulation–ablation measurements

A detailed map of the net accumulation pattern on the Lemon Creek Glacier has been made from retained accumulation measurements at several hundred locations during some summers both in July and August. Table 2 indicates that indeed the pattern is consistent and provides an accurate assessment of mass balance. In 1998, some 300 accumulation measurements were obtained to supplement and affirm the control record from the standard test-pits. The pattern of mass balance generally remained the same despite glacier thinning and the notably negative balances observed in 1954, 1960, 1967, 1972, 1978, 1983 and 1989 (Fig. 6).

Ablation measurements in the ablation zone (region below the early July transient snowline) were found to have the largest possibility for error. Although extensive ablation stake arrays in boreholes have been employed in some years, this has operationally not been possible in others. Based on

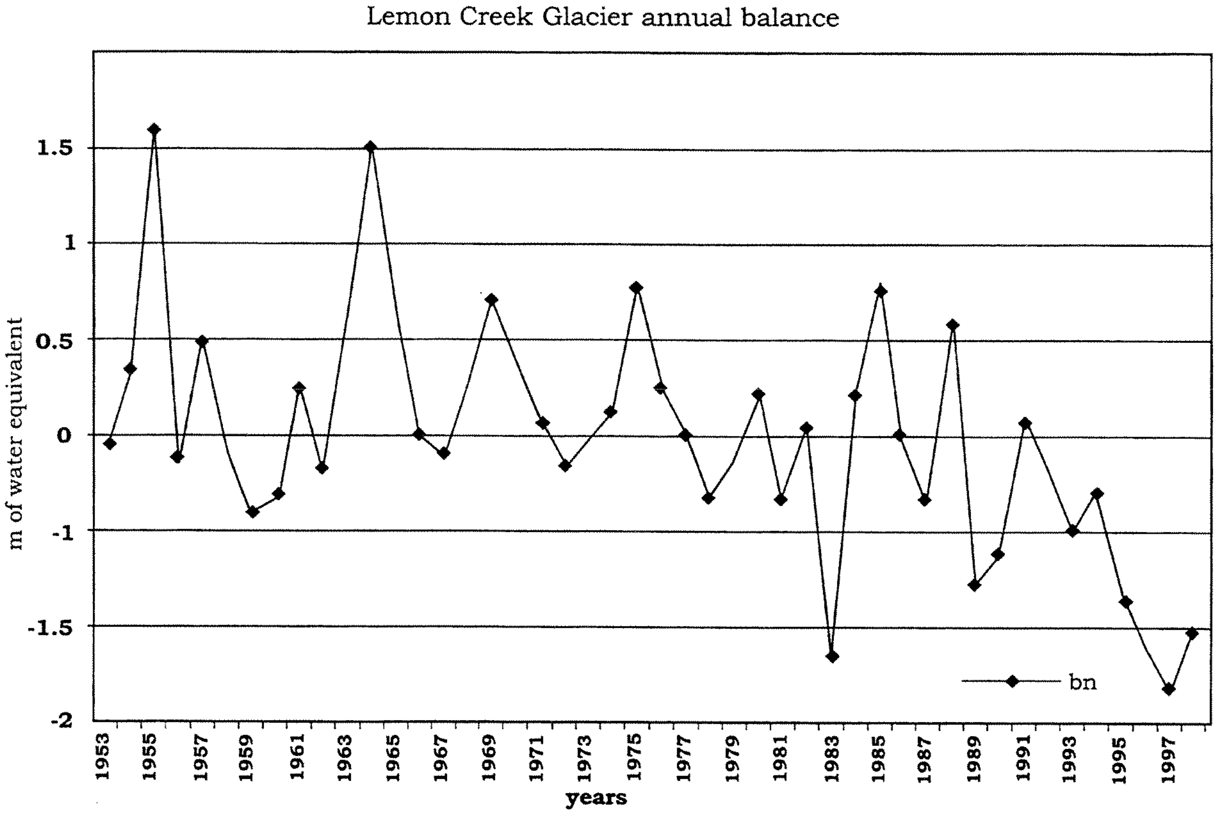

Fig. 6 Lemon Creek Glacier annual balance (bn) record in meters of water equivalent, 1953–1998.

11 years of acquired ablation zone measurements, the distribution of ablation in years of incomplete record has been estimated for July 1 transient snowlines and the September ELAs. Seasonal ablation above the transient snowline has been found to be nearly uniform, while ablation within the ablation zone is not. The July 1 transient snowline sector best represents early season ablation. The change in elevation to the early September ELA sector gives the best measure of ablation for the remainder of the ablation season. Total annual ablation is calculated from the summer season rise in transient snowlines between early July and September. This stems from observed firnpack water equivalence in early July within the zone where the ELA eventually rises in September. The specific ablation between July and early September in that area references the entire ablation zone, using measured summer ablation data from the years listed in Table 1. This assumes the pattern of ablation across the glacier in the ablation zone to be similar from year to year, and that the relationship to ablation in the accumulation zone is relatively consistent. The data in Table 1 support the consistency of ablation in the accumulation zone.

Table 2. Comparison between test-pit control site net accumulation segment thickness (in m) and mean annual net accumulation thickness (in m) at eight other sites within the elevation band used for that control site. Each of control sites A–D have been checked annually. Sites A and B are at 1175+ m elevation; site C is at 1100–1175 m elevation; and site D at 1025–1100 m elevation.

Year	Site A	Site B	Mean	Site C	Mean	Site D	Mean
1955	3.13	3.22	3.28	2.87	2.90	2.10	1.95
1957	2.75	2.81	2.88	2.60	2.73	1.78	1.60
1962	2.80	2.75	2.86	2.45	2.52	1.21	1.14
1965	3.02	3.10	3.14	2.78	2.74	1.72	1.50
1966	2.48	2.59	2.57	2.17	2.28	1.36	1.41
1967	2.53	2.44	2.52	2.25	2.19	1.18	1.05
1969	2.90	2.87	3.01	2.48	2.63	1.66	1.61
1972	2.38	2.36	2.49	2.15	2.15	1.10	1.02
1982	2.45	2.41	2.55	2.20	2.32	1.38	1.15
1984	2.68	2.71	2.78	2.48	2.59	1.65	1.52

Values of mass balance recorded at the principal test-pit sites and the change in transient snowlines are weighted for the respective elevation zone that each represents. The mean value for each zone and the representative site value has been determined. The site net accumulation value divided by the

Table 3. A comparison of changes in net mass balance in water equivalence (w.e.), ice thickness (IT in m), and glacier surface lowering (in m) measured using geodetic methods (IT).

Lemon Creek Glacier	1957–1989	1957–1995	1957–1998	1953–1998
Surface Balance (we)	-12.7	-17.1	-22.0	-22.26
Surface Balance (IT)	-13.9	-19.0	-24.4	-24.7
Geodetic Methods (IT)	-13.2	-16.4	-21.7	X

mean value yields the weight for each site. These values are shown in Table 2. Mass balance control sites A and B are used to determine the mean annual accumulation for the upper sector of the glacier above 1175 m. Site C represents the mean accumulation area for the glacier in the 1100–1175 m elevation zone, and site D represents the mean for the lower elevation zone from 1025 to 1100 m. The change in transient snowline elevation from early July to September is used to determine the mean ablation rate for the ablation zone. It is axiomatic that the glacier's total mass balance in a given year is then the sum of the products of the névé area in each elevation zone and the mean annual balance of each of those zones.

The surface area for each elevation band has been determined from the 1:10,000 surface map of 1957, with the same areas applied up to 1977. From 1977 to 1998 the surface areas applied for computations have been derived from our 1989 JIRP topographic map which is also at a scale of 1:10,000. In comparing these two maps the changes in area of all but the lowest elevation band were less than 1%. Terminal area changes mapped in 1965 have been used for the lowest elevation band area for the 1965–1977 period.

Mass balance record

The mass balance record determined solely from field measurements is given in Fig. 6. This yields a summary mass balance of –22.26 m w.e. from 1953 to 1998, representing a significant thinning of the glacier over the 46-year interval. With an estimated volume of 901.7×10^6 m^3, the loss determined up to 1989 of -131.9×10^6 m^3 was 15% of the total glacier volume (Marcus *et al.* 1995). This geodetic-based determination of long-term 1954–1989 mass balance changes represents a 13.2 m reduction in mean glacier thickness in 35 years. Airborne surface profiling (Sapiano *et al.* 1998) revealed an approximate additional loss of 3.2 m of glacier surface elevation over the six-year period between 1989 and 1995. Comparative GPS surface profiling was carried out by our ground survey team in 1996–1998 on the uppermost névé. In Fig. 5 these profiles are noted as PR 1 to PR 4. With new accuracy they document a surprising additional 4.6 m glacier surface lowering which indicates an accelerated ablation in this highest zone over just the last two years.

Giving confidence in the higher accuracy of our field methods, the annual balance record of –12.7 m w.e. (13.9 m of ice loss) from 1957 to 1989 compares well to the slightly greater –13.2 m of ice thinning suggested by geodetic methods over the slightly longer interval 1954–1989 (Marcus *et al.* 1995). The field annual balance record of –17.1 m w.e. (19.0 m of ice loss) from 1957 to 1995 also matches reasonably well a change of –16.4 m calculated from airborne surface profiles in 1995 when compared to the mapped surface of 1957 (Sapiano *et al.* 1998). This surveying flight was made in late June when ice thickness was 1–2 m greater on average than at the end of the 1995 field season. The technical error in both geodetic surveys is considered to be less than 1.5 m, though the random timing of these surveys reduces their accuracy. Table 3 summarizes and compares the general glacier mass balance changes which have been determined using the three different methods: geodetic airborne surface profiling, comparative geodetic topographic mapping and the more precise stratigraphic field measurements. In general the surface stratigraphic surveys, at least in this study, have proven to be 5 to 11% more reliable.

In terms of trends, the annual stratigraphic balance record for 1957–1976 (bn, Fig. 6) shows a mass balance loss of –0.23 w.e. m/a and that thinning was modest on the upper reaches of the glacier. Since 1977, however, and despite a higher mean elevation and a higher terminus elevation due to glacier retreat, mean annual balances have been increasingly negative, averaging –0.78 w.e. m/a. The record has been particularly negative every year since 1990, being –1.04 w.e. m/a (again note

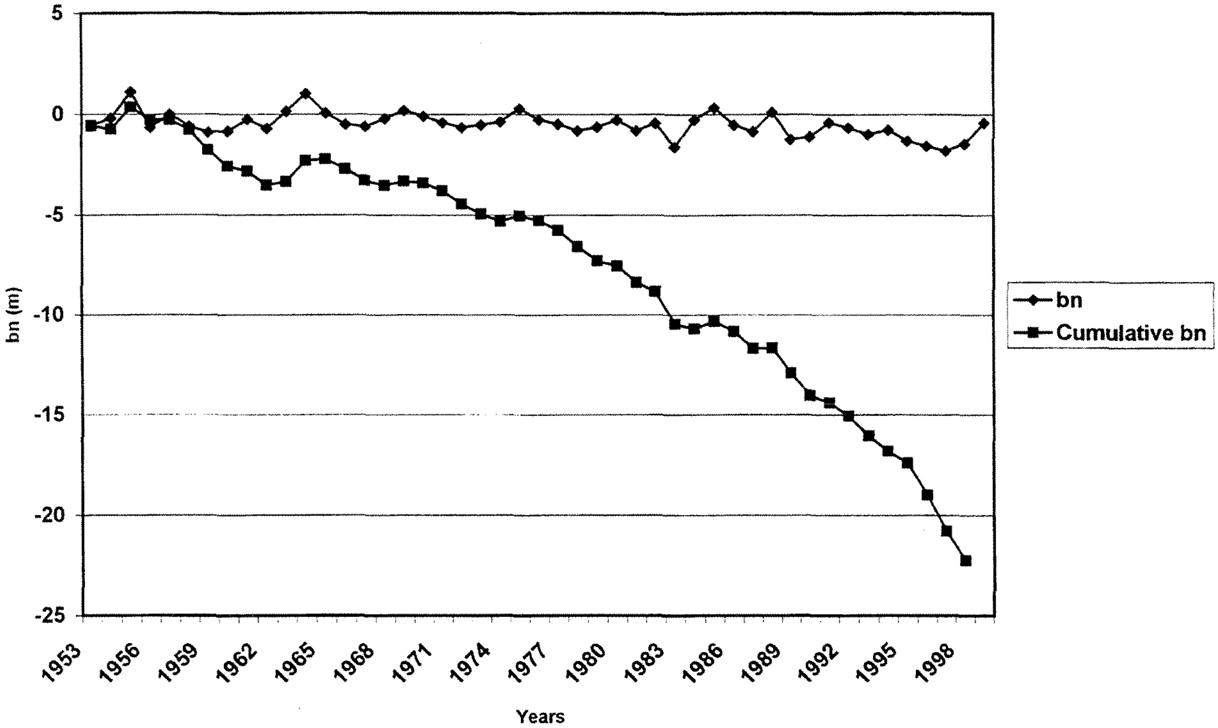

Fig. 7. Cumulative annual mass balance (bn) record in w.e. from 1953 to 1998.

Fig. 6). As a result, over these past eight years the cumulative annual mass balance loss has increased significantly (Fig. 7). In this figure the total cumulative annual mass balance loss over the period of our measurements since 1953 is documented at –22.26 m w.e. This represents a 24.7 m overall lowering of the glacier's surface in the last 46 years.

In 1996 and 1997, no accumulation was retained at all on the Lemon Creek Glacier. This was for the first time since our glaciological observations were initiated in 1948. Significant too is the observation that in 1998, only a small zone of accumulation was retained on the upper part of Observation Peak at the head of the glacier basin, covering less than 1% of the glacier's total accumulation area. Consistent with these conditions and mass balance trends, and as shown in the ELA record for 1948–1998 noted in Fig. 8, the ELA has risen well above the glacier's main névé area in each of the last three years. Fig. 8 also compares ELA variations on Lemon Creek Glacier with those on the Taku Glacier, the latter being the main trunk outlet of the Juneau Icefield 30 km inland. That these variations parallel each other so well reveals the regional climatic significance of the records. The notably higher ELAs on Lemon Creek Glacier are explained by the warmer maritime conditions affecting its coastal location, as well as its more confined and smaller size allowing adjoining bedrock exposures to accentuate late summer ablation.

Discussion of annual balance errors

We recognize that the Lemon Creek Glacier annual balance measurement record has some uncertainties due to logistical and time restrictions leading to some interpretation errors. The ongoing goal, however, has been to minimize such errors and to continue to enhance the record's completeness and reliability. One example is that potential errors in accumulation measurement may occur when meltwater percolates into the current annual firnpack and refreezes there. This internal accumulation (Miller 1954, 1955; Trabant and Mayo 1985) is not measured in most mass balance programs. Bazhev (1986) also noted that while most meltwater that refreezes does so in the latest firnpack, some percolates into underlying older firn and refreezes there. This recaptured segment of ablation appears as diagenetic ice structures. Such secondary structures evidence internal accumulation developed prior to late spring when the snowpack becomes isothermal at 0°C. On Lemon Creek Glacier, as in other glaciers at comparable elevations on the mar-

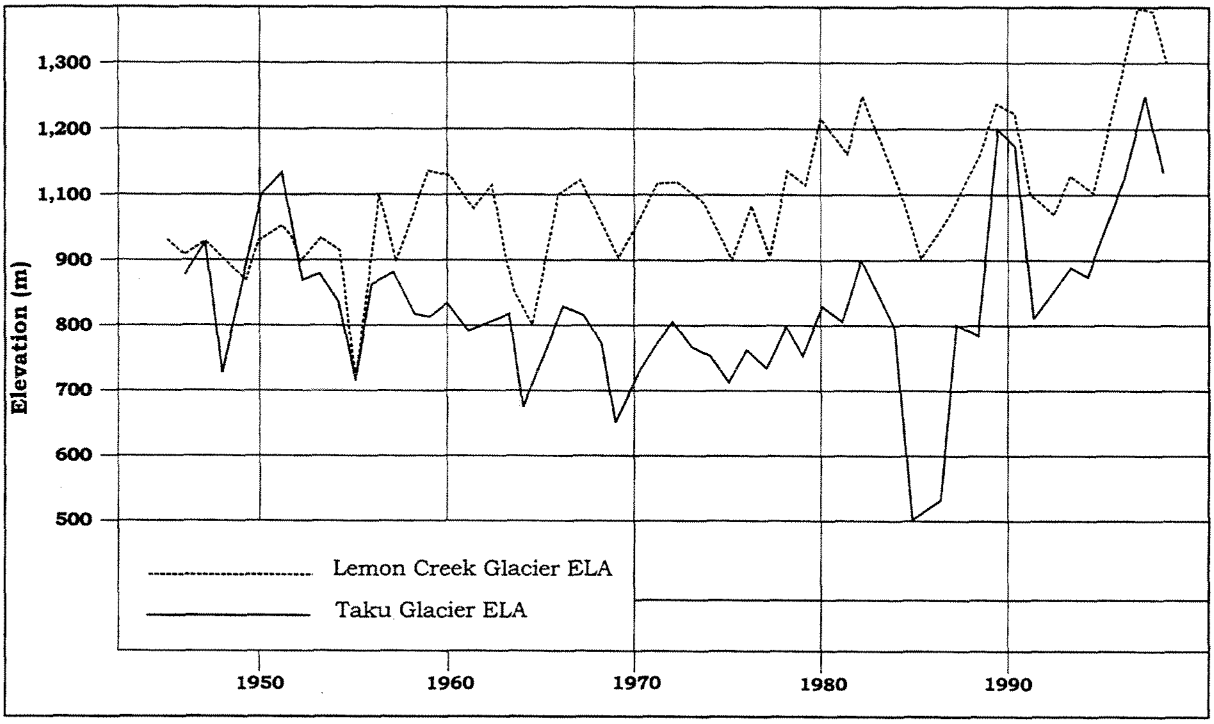

Fig. 8. Variations of the ELA 1946–1998 on Lemon Creek Glacier showing comparison with Taku Glacier..

itime flank of the Juneau Icefield, this process always occurs before June 15 (Miller 1972). Internal accumulation just does not develop after mid-June because of the isothermal conditions which in turn allows any measured surface ablation to represent true summer ablation loss.

To determine how much meltwater is retained in diagenetic ice, the walls of each test-pit have been continually surveyed. Crevasse stratigraphy also reveals these structures, giving another useful source of information. In our records from the two field seasons of 1982 and 1984, an average of 10% of the firn stratigraphy comprised this secondary ice at a density of 0.90. In every year we try to check the bulk water equivalence of the three most recent annual firn segments early in July, and when possible in early August, as well as in the following July. From this we have found that the upper two-year increments often experience a net gain in water equivalence. This suggests that minor internal accumulation is not accounted for when sampling only the one most recent annual accumulation segment. This procedure could be expanded in the future for more accurate assessment of this phenomenon. For most years on Lemon Creek Glacier, however, internal accumulation below the most recent annual firnpack is viewed as negligible.

In 1998 we completed a more detailed study of the upper Lemon Creek Glacier's accumulation zone by invoking supplementary probing at more than 300 locations surrounding the main test-pit sites (Fig. 5). This probing was facilitated by an unusual dearth of diagenetic ice structures in the 1997/98 firnpack. Without such structures to impede our probes, the sounding data closely matched the test-pit measurements, giving us confidence in the stratigraphic record. Along with the abnormally high ELAs (Fig. 8) this corroborates that the last three years have been the most negative in the 46-year mass balance record. This kind of information refines the determination of mass balances by more accurate calculation of bulk densities and elimination of errors from difficulties in mapping internal accumulation. It is apparent that the spring snowpack in each of these recent years was not cold enough to lead to much refreezing of propagated water. This is significant because in most of the previous colder spring increments, 7–11% of the retained annual accumulation has been typically diagenetic ice. Also it is to be noted that failure to retain this recaptured increment of meltwater clearly increased the net ablation in 1996 and 1998. Evidence of warmer snowpacks than usual is illustrated by the winter 1998 temperatures being

5°C above the long-term mean at the Juneau airport at sea level only 10 km from the glacier. Also at the 1300 m elevation at Camp-17 on the edge of the glaciers highest névé, our Tempmentor data logger records have shown that the mean March and April 1998 ambient air temperatures averaged only –4°C which is too warm to maintain the snowpack much below 0°C at a time when the spring melt begins. This failure to recapture meltwater in internal accumulation has maximized the ablation loss on the glacier and abetted the observed recent strongly negative mass balances.

Another potential error involves assessments of ablation in the ablation zone, when based on correlation with ablation at the transient snowline (Table 1). Here errors arise in years in which the ablation pattern is atypical. The relationship of transient snowline changes to observed surface ablation above the ELA is the only potential check on this, albeit an indirect measure.

On Lemon Creek Glacier, ablation during several summers in the accumulation zone has been measured on extensive arrays of stakes. The standard deviation in surface ablation was found to be less than 0.05 w.e. m/month. This gives support to the use of ablation stakes and the late summer ELA to adjust the record of annual firn depths made in July. It also touches on the most serious error resulting from completing annual balance measurements considerably before the end of the true ablation season. For this reason, when possible we have tried to measure annual balances close to the end of the ablation season. We have found, however, when that cannot be done the more general geodetic methods previously discussed do provide useful back-up information. This also includes carefully invoked aerial photography, particularly in determining ELA positions. Helping this situation is the fact that on the Lemon Creek Glacier ablation becomes rapidly reduced after August 25, and so ELA observations made in early September give an appropriate and useful closure to the budget year.

Conclusion

The record of annual mass balance on the Lemon Creek Glacier extends over 46 years and shows an *increasingly negative trend as depicted in* Fig. 8. The total loss on this glacier over that time period has been substantial with a net ice reduction of 24.7 m, or 22.26 m of water equivalent. If this trend continues this glacier will be in a very retractive mode early in the coming century. From regional teleconnectional comparisons with other glaciers in Alaska and review of the seemingly out-of-phase natural climatic variations documented by our other studies on the Juneau Icefield, we consider that these changes most likely are allied to global warming.

This data set has been obtained from a consistent system of yearly measurements using comparable field methods and at similar annual dates. The result is a record in which we have confidence, though it is recognizably not precise. Moreover, comparison of the glaciological results with long-term geodetic determinations from two different measurement methods demonstrates that the annual balance record and the trends it represents are acceptably reliable. Specific winter and summer balances of course cannot be differentiated from the data so far.

The range of inaccuracy observed in applying geodetic methods in this study does not imply that such techniques are not valid but rather that their results should be considered supplemental, with first emphasis on ground truth and the strong field effort that entails. With this in mind the lesson of this documentation is that mass balance measurements, even when there is limited coverage, can be effective if the following three conditions are met: (1) systematic annual stratigraphic measurements are maintained without a breach in the yearly sequence; (2) an independent check is made using supplemental surface remapping, airborne profiling and when possible GPS leveling; and (3) a periodic program of more extensive and detailed measurement is carried out during at least some years to refine the long-term mass balance record and identify likely errors. It should also be kept in mind that methodological refinement of mass balance patterns is a necessary and ongoing process, to be applied in conjunction with continued careful monitoring of the regional climatic trends affecting the interplay between accumulation and ablation.

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