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# RECENT VARIATIONS IN MASS NET BUDGETS OF GLACIERS IN WESTERN NORTH AMERICA

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SUMMARY

Accumulation and ablation studies on three glaciers in western Washington during 1957-1961 are analyzed with the aid of graphs showing variation of net budget with altitude. For any one glacier, the graphs are displaced from year to year but show little change in gradient. During any one year, curves for different glaciers reveal minor but important variations, demonstrating the effect of topography and exposure on glacier budgets. Comparable data from other areas show major differences. The vertical gradient in net budget is greatest for glaciers in a zone near the Pacific Ocean from western Washington (14 mm/m) to southeastern Alaska. The gradient decreases in all directions away from this zone and reaches an apparent minimum in northeastern Alaska (2 mm/m).

Yearly determinations of specific net budgets for five glaciers in southeastern Alaska, Montana, and western Washington are reduced to an equivalent basis, and the data extended in time using snowline information. The data show large but generally synchronous variations about equilibrium until 1958, and prevalently negative values from 1958 to 1961.

The data obtained by regime studies are extended with results of aerial photographic reconnaissance. The reconnaissance data show recent increases in glacier activity from the Northern Cascade Range in Washington through the Coast Range of British Columbia to southeastern Alaska. The increased activity is manifest by high accumulation area ratios and a relatively higher percent of glaciers which appear to be advancing. The effect is most pronounced for small, high altitude glaciers. Large, low valley tongues show continued retreat and little or no rejuvenation. The prevalence of healthy net budgets diminishes in all directions from the Coast Range. In the Sierra Nevada, California, and in the Alaska Range, most glacier net budgets have been strongly negative for the last few years. In the Wind River Range in Wyoming net budgets have been even more generally negative. Glacier equilibrium lines are lowest in the Coast Range of southeastern Alaska and British Columbia and occur at higher elevations north, east, and south of this zone.

RÉSUMÉ

Les résultats de recherches sur l'accumulation et l'ablation de trois glaciers dans l'Ouest de l'État de Washington au cours des années 1957-1961 sont analysés à l'aide de courbes qui montrent la variation du bilan en fonction de l'altitude. Pour un glacier donné, les courbes se déplacent d'une année à l'autre, mais on observe peu de changement du gradient. Pour une même année, les courbes de différents glaciers révèlent des variations importantes, bien que de petite ampleur, qui reflètent l'influence de la topographie et de l'orientation sur le bilan. Des recherches analogues poursuivies dans d'autres regions donnent des résultats totalement dfférents. Le gradient vertical du bilan atteint un maximum pour les glaciers se trouvant dans une zone proche du Pacifique s'étendant de l'Ouest de l'État de Washington (14 mm/m) à l'Alaska du Sud-Est. Le gradient diminue de toutes parts quand on s'éloigne de cette zone, et atteint un minimum apparent dans le Nord-Est de l'Alaska (2 mm/m).

Les valeurs annuelles du bilan specifique de cinq glaciers de l'Alaska du Sud-Est, du Montana et de l'Ouest de l'État de Washington sont ramenées à une base commune et les chiffres obtenus sont projettés dans le temps en tenant compte des limites de neige respectives. Il s'avère alors que jusqu'en 1958 le régime des glaciers restait très près du point d'équilibre en dépit d'oscillations généralement synchrones de grande amplitude, et que de 1958 à 1961 les valeurs négatives prédominent.

Les données résultant de l'étude du métabolisme sont généralisées et étendues latéralement au moyen de photographies de reconnaissance aérienne. L'évidence photographique dévoile une activité accrue et récente des glaciers situés dans une

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région s'étendant de la Chaîne des Cascades, dans le Nord de l'État de Washington, jusqu'à l'Alaska du Sud-Est, y compris le «Coast Range» de la Colombie Britannique. Ce renouveau d'activité se manifeste par l'augmentation de l'entendue des aires de accumulation par rapport aux aires l'ablatin, et par l'augmentation relative du nombre de glaciers qui avancent. Les glaciers de faible envergure situés à grande altitude sont particulièrement sensibles à cet effect. Les langues de glace occupant les vallées basses continuent à reculer, et témoignent de peu ou de pas d'activation. La prévalence de bilans excédentaires diminue de toutes parts quand on s'éloigne du «Coast Range». Dans la Sierra Nevada de California et dans les montagnes de de l'«Alaska Range», le bilan de la plupart des glaciers est nettement deficitaire depuis les quelques dernières années. Dans le «Wind River Range» du Wyoming le déficit général est encore plus marqué. Les lignes d'équilibre les plus basses se trouvent dans le «Coast Range» de l'Alaska du Sud-Est et de la Colombie Britannique; au nord, à l'est, et au sud de cette zone, on les trouvé à des altitudes plus élevées.

## 1. Introduction

Almost all of the glaciers in western North America were receding in the years from 1935 to 1950. At about 1945 a climatic change occurred in western Washington, leading to more winter precipitation and cooler summers. The first observed glaciological evidence of this change was a thickening of ice on Nisqually Glacier detected by Johnson in 1946 (Johnson 1949, 1960). By 1955 many of the glaciers in the Northern Cascade Range were advancing in a rather spectacular fashion (Hubley, 1956, p. 671). However, this period of glacial growth in Washington may have come to an end (LaChapelle, 1960). In British Columbia and Alaska much less is known about the present-day variations of glaciers because of the vast extent of relatively uninhabited glacierized territory and the large numbers and diversity of glaciers and icefields.

The purpose of this article is to summarize knowledge of the variations of glacier regimes in the last few years over all of western North America. This will be done in two steps : first, quantitative data which have been collected at a few specific glaciers will be discussed. Conclusions based upon these limited quantitative data will then be extended and compared by a statistical reconnaissance investigation covering many hundreds of glaciers. The reconnaissance survey is absolutely necessary because of the problem of sampling. In northwestern North America there are tens of thousands of glaciers, ranging in size from minute specks to huge masses covering up to 5,700 km$^2$ (1). In almost any area it was possible to find in 1961 some glaciers which were advancing, some retrating, and some almost completely stagnant. Furthermore, many of the glaciers on which detailed investigations were made were selected partly out of consideration of trafficability and logistical problems, and consequently these glaciers are not likely to be entirely representative of general glacier behavior.

Another purpose of this study was to test a new method of extracting quantitative glacier regime data utilizing low-level oblique aerial photography. This aerial photography is relatively efficient in time, personnel, and cost. Although the analysis is partly subjective and involves many approximations, it appears that the broad statistical coverage and the ability to observe large areas quickly late in the ablation season provides very great advantages. Hubley (1956, p. 671) obtained some data on terminus advance or recession of glaciers in Washington using oblique aerial photography. LaChapelle (1960) continued Hubley's work, and later suggested additional ways to utilize low-level oblique aerial photography (LaChapelle, 1962). The aerial reconnaissance supplements in many ways the extensive ground-based reconnaissance carried out concurrently in southern Alaska (Field, 1958).

Attention is focused here on a quantity known as net budget (Meier, 1962). This quantity reflects the growth or shrinkage in the mass of a glacier during a budget year. Some authors have discussed this same quantity using the terms net accumula-

(1) Bering Glacier and tributaries, Chugach Mountains.

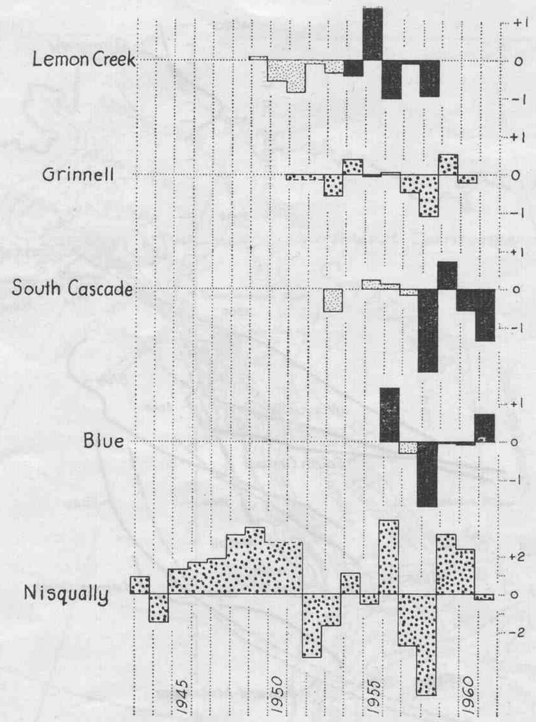


Fig. 1 — Time-variations in specific net budgets for 5 glaciers. Solid bars indicate net budget values which were measured directly. Fine dot pattern indicates that net budget data were obtained from data on accumulation area ratios. Pattern of coarse dots indicates that net budget data were obtained from topographic surveys. Net budget data are presented in m of water-equivalent, averaged over the glacier area. For locations of glaciers, see Figure 3. Lemon Creek Glacier data taken from Heusser and Marcus (1960), Grinnell Glacier data from Johnson (1961), South Cascade Glacier data from Meier (1961) and Meier and Tangborn (1962), Blue Glacier data from LaChapelle (1959, 1960b, 1961), and Nisqually Glacier data from Giles (1960 and personal communication).

tion or net ablation. It is the single best indication of a glacier's instantaneous state of "health".

Net budget determinations have been made on very few glaciers in western North America. Four years of intensive data collection on South Cascade Glacier in western Washington have shown that curves of net budget as a function of altitude are displaced from year to year but do not change greatly in character (Meier, 1961, p. 210). This means that one can predict the approximate net budget of a whole glacier from measurements of only the net budget at a fixed location on the glacier, the altitude of the equilibrium line, or the accumulation area ratio. This assumption is fundamental to much of the following discussion.

## 2. Time variations of net budget

The variation in net budget values as a function of time is shown in Figure 1 for five different glaciers. Net budgets for Lemon Creek, South Cascade, and Blue

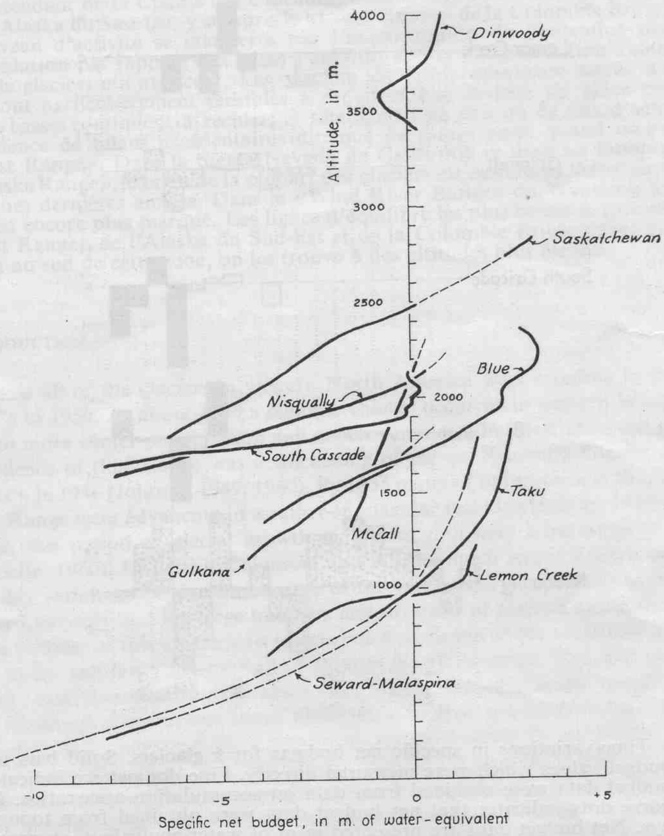


Fig. 2 — Variation of net budget with altitude for 10 glaciers. Curves are dashed where no data exist. For locations of glaciers, see Figure 3. Sources of data are given in Table 1.

Glaciers were obtained by direct measurement on the glacier. These net budget data have been slightly extended in time through knowledge of the accumulation area ratio for years during which no direct measurements were made on the glacier. Net budget values are shown also for Grinnell and Nisqually Glaciers. The values shown for Grinnell Glacier were obtained by topographic surveys of changes in volume of the glacier. These data were then reduced to specific, waterequivalent, net budget values. In the case of Nisqually Glacier the data shown are taken from thickness change data obtained in the vicinity of the equilibrium line only. These data provide only approximate indices to net budget changes because the dynamic response of this glacier to changes in thickness is rather complicated. Thickness changes on the lower tongue of Nisqually Glacier show clearly the complicated effects of kinematic waves and cannot be utilized for these purposes. However, it is believed that the year-to-year variation in thickness at a fixed profile near the usual position of the equilibrium line is at least an approximate index to the net budget of the whole glacier. The results from Nisqually Glacier are especially useful because they extend over a long time interval.

The data shown on Figure 1 indicate that starting in 1944-45 the net budget on

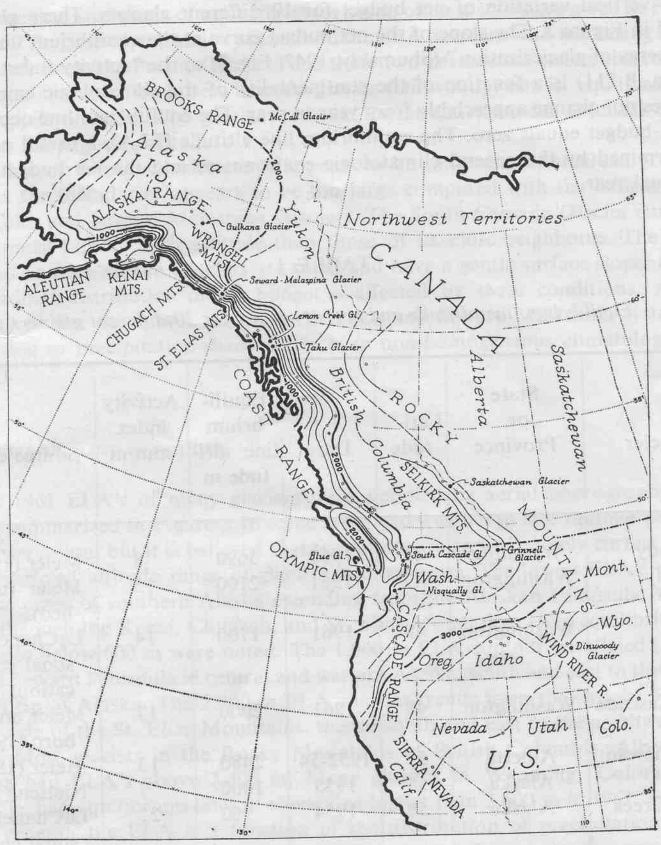


Fig. 3 — Map of Western North America showing locations of certain specific glaciers and important glacierized mountain ranges. Contours indicate the 1961 altitudes of glacier equilibrium lines; the contour interval is 200 m. Contours are dashed where drawn over unglacierized areas or in areas where scant data exist. Small circles indicate points where mean equilibrium line altitudes were determined from many individual glaciers.

Nisqually Glacier was probably positive for seven consecutive years. It was a succession of positive budgets such as these which caused the large changes in glacier activity in Washington State in the 1950's. All five glaciers showed net deficits in 1952-53, 1956-57, and a very strong net deficit in 1957-58. The budget year 1955-56 was one of positive net budgets on all glaciers except the Lemon Creek Glacier in Alaska; most glaciers also experienced a positive net budget in 1958-59. During other years the glaciers did not deviate greatly from equilibrium and behaved in a rather nonsynchronous manner.

### 3. Variations in net budgets with altitude

In order to analyze the geographic variation in glacier regimes it is instructive to study vertical variations in net budgets. In Figure 2 and Table 1 are presented data on the vertical variation of net budget for 10 different glaciers. These glaciers are located in Figure 3. The slope of the net budget curve at the equilibrium line, termed the "energy of glacierization" (Shumskiy, 1947, Fig. 3) or the "activity index" (Meier, 1961, p. B-211) is a function of the continentality of the climatologic environment, and does not change appreciably from year to year. The equilibrium line occurs where the net budget equals zero. The equilibrium line altitude (ELA), a useful parameter, is determined by the general climatologic environment and the net budget for each individual year.

TABLE 1

*Equilibrium line altitude and activity index for 10 different glaciers*

| Glacier | State or Province | Latitude | Date | Equilibrium line altitude m | Activity index mm/m | Source of data |
|---|---|---|---|---|---|---|
| Dinwoody | Wyoming | 43 | 1950 | 3690 | 8 | Meier (1951) |
| Nisqually | Washington | 47 | 1961 | 2100 | 15 | Meier (unpublished) |
| Blue | Washington | 48 | 1961 | 1700 | 14 | LaChapelle (personal communication) |
| South Cascade | Washington | 48 | 1961 | 2000 | 17 | Meier and Tangborn (1962) |
| Saskatchewan | Alberta | 52 | 1952-54 | 2480 | 13 | Meier (1960) |
| Taku | Alaska | 58 | 1953 | 1000 | 7 | Nielsen (1957) |
| Lemon Creek | Alaska | 58 | 1954 | 960 | 22 | LaChapelle (personal communication) |
| Seward- Malaspina | Alaska | 60 | 1949 | 1000 | 5 | Sharp (1951) |
| Gulkana | Alaska | 63 | 1961 | 1730 | 8 | Péwé (personal commnication) |
| McCall | Alaska | 69 | 1957 | 2100 | 2 | Keeler (1958) |

Nisqually and South Cascade Glaciers are located in the Cascade Range of Washington, and are about 180 km apart (Fig. 3). Nisqually Glacier is a fast-moving, narrow, steep, southward-flowing valley glacier. South Cascade Glacier is a sluggish, gently-sloping, northward-flowing valley glacier. The two net budget curves are rather similar. The Blue Glacier is located about 210 km west of South Cascade Glacier in the Olympic Mountains. It is a very active glacier which originates in a series of high cirques, plunges down steep ice falls, and coalesces to form an active, valley tongue which flows in a curving north to northwest direction. The activity index for the Blue Glacier is of similar order to that for South Cascade and Nisqually Glaciers. Its ELA is very different, reflecting a strongly positive net budget in 1961 whereas South Cascade had a fairly strong net deficit. Thus it appears that these glaciers in one rather small area do show net budget-altitude curves which are generally similar.

The vertical variations of net budgets for seven other glaciers are given in Figure 2 and Table 1. In general, the activity index and the ELA decrease with increasing latitude and distance from the Pacific Ocean. Thus these two parameters reflect the continentality of the climate. The lowest latitude glacier (Dinwoody) has its equilibrium line at the highest altitude. The glacier with the lowest activity index (McCall Glacier) occurs at the highest latitude.

The Lemon Creek Glacier curve appears to be somewhat anomalous. The activity index for this glacier appears to be too large compared with the indices for the nearby Taku and Seward-Malaspina Glaciers. The South Cascade Glacier curve also changes more rapidly with altitude than those of its close neighbours. The Lemon Creek and South Cascade Glaciers are small and have a gentle surface slope. Perhaps the altitudinal distribution of net budget is affected by these conditions. Another possibility is that the curves for the large Taku and Seward-Malaspina systems are unusual due to precipitation-shadow effects (a non-homogeneous climatologic environment).

## 4. Equilibrium line altitudes

The 1961 ELA's of many glaciers were sampled by aerial photography; these data are summarized in Figure 3. In some areas bad weather in late summer prevented direct observation, but it is believed that the results are approximately correct because of the restricted altitude range of glaciers in those areas. The lowest ELA's occurred along the coast of southern Alaska extending from the Alaskan Peninsula (Aleutian Range) through the Kenai, Chugach, and St. Elias Mountains. Here equilibrium lines at altitudes below 600 m were noted. The 1,000 m ELA contour paralleled the coast from the Seward Peninsula in central and western Alaska, south and east to the extreme southern tip of Alaska. The 2,000 m ELA contour trends from the Brooks Range to the east side of the St. Elias Mountains, thence south and east to the northwest tip of Oregon. Most glaciers in the Rocky Mountains of British Columbia, Alberta, and Montana had ELA's above 2,400 m. Many glaciers in Wyoming, Colorado, and California had equilibrium lines at elevations higher than 3,600 m in 1961.

In general, the ELA is a function of the distribution of precipitation. Consequently precipitation shadow effects east and north of major mountain ranges are very pronounced. This accounts for the rather complicated pattern around Vancouver Island (southwestern British Columbia) and in the vicinity of the Selkirk Mountains. The steep slope in the ELA's across the Chugach, St. Elias, and Coast Range Mountains is also due to the orographic effect; in the St. Elias Mountains the ELA's rise from 763 m near the coast to 2,225 m at 110 km further inland, a slope of 13 m/km.

The normal geographic variation in glacier mean altitudes is large; in the area shown on Figure 3 glacier mean altitudes range from less than 500 m to more than 4,000 m. The steady state ELA can be expected to show a similarly large variation. The year-to-year variation for individual glaciers, on the other hand, is comparatively small, generally amounting to a few hundred meters or less. Consequently the distinctive peculiarities of the 1961 glacier budgets cannot be discerned in Figure 3. One could measure the 1961 shifts of the ELA's from the steady-state ELA's, and these data would show accurately the distinctive characteristics of the season. However, this type of analysis could not be done for lack of knowledge of the steady-state ELA's and lack of accurate, large scale topographic maps. We therefore searched for another method of extracting net budget information directly from reconnaissance aerial photography.

## 5. Accumulation area ratios

The accumulation area ratio (AAR) is the amount of area above the equilibrium line (the accumulation area) divided by the total area (Meier, 1962). Detailed studies on South Cascade Glacier have shown that the AAR is directly related to the specific net budget (Figure 4). Yearly variations in net budget-altitude curves for individual glaciers also indicate that this relation is generally true. In the case of South Cascade Glacier, an AAR of 0.58 corresponds to a specific net budget of zero (a balanced regime). For a glacier with a linear increase of net budget with altitude and a symmetrical distribution of area about the median altitude, an AAR 0.5 will correspond with a balanced budget. The increase of net budget with altitude is usually steeper

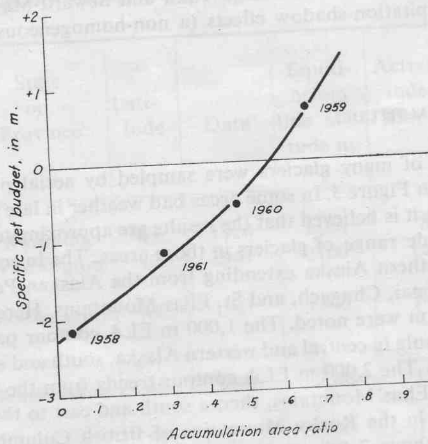


Fig. 4 — Specific net budget as a function of accumulation area ratio, South Cascade Glacier, Wash. Data taken from Meier and Tangborn (1962).

at low altitudes than at high altitudes (Figure 2). Thus most glaciers will have balanced regimes at AAR's greater than 0.5; generally they will be between 0.5 and 8.0. Piedmont glaciers and ice caps have very asymmetric area-altitude distributions, and are exceptions to this rule. Accumulation area ratios can be readily determined from oblique or vertical aerial photography.

Accumulation area ratios were measured for 475 glaciers at 17 principal locations, and were estimated from scanty data for 3 other regions. At each glacier the position of the transient snowline was first recorded from the aerial photography. These photographic observations were made at various times from mid-July to late September. The percentage of the total area which was snow covered at the time of the aerial photography (the transient-AAR) was then estimated in reference to maps or directly from aerial photographs. The character of the snow cover was also noted. In many cases it was possible to tell whether the snow cover was thick or thin as revealed by transparency, patchiness, and other indications (Fig. 5). The transient-AAR data were then adjusted to the end of the ablation season in order to determine AAR's. This involved knowledge of the approximate time of the end of the ablation season (obtained through knowledge of local weather conditions) and a subjective appraisal as to the rate at which the snowline had retreated based on weather records and the apparent thickness of the snowpack. The transient-AAR's, date of photography, adjusted AAR's, and numbers of glaciers sampled are listed in Table 2. It will be noted

TABLE 2

*Accumulation area ratios (AAR) and condition of glacier termini in 1961*

| Number listed on Fig 5 | Mountain Range | State or Province | Accumulation area ratios: Transient AAR | Date | Final AAR | Nº. of glaciers observed | Condition of glacier termini: Advancing % | Active % | Retreating % | Stagnant % | Nº of glaciers observed |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Wind River | Wyoming | 0.12 | July 28 | 0.08 | 13 | 0 | 0 | 90 | 10 | 20 |
| 2 | Sawtooth | Idaho | .06 | July 27 | .04 | 9 | | | | | |
| 3 | Rocky | Northwest Montana | .73 | Aug. 7 | .40 | 14 | 10 | 30 | 60 | 0 | 37 |
| 4a | Rocky | Alberta-B.C. | .46 | Aug. 7 | .30 | 7 | 0 | 43 | 52 | 5 | 61 |
| b | Rocky | Alberta-B.C. | .48 | Aug. 7-8 | .31 | 26 | | | | | |
| 5a | Purcell-Selkirk | British Columbia | .52 | Aug. 7 | .40 | 22 | 10 | 43 | 46 | 1 | 61 |
| b | Monashee | British Columbia | .74 | July 29 | .50 | 6 | | | | | |
| 6 | Cascade | Oregon-California | | | .40? | | 0 | 14 | 86 | 0 | 21 |
| 7 | Cascade | Washington | .71 | July 27-Aug. 7 | .45 | 10 | 2 | 46 | 48 | 4 | 137 |
| 8 | Olympic | Washington | .70 | Aug. 16 | .45 | 3 | 0 | 17 | 83 | 0 | 12 |
| a | South Coast | British Columbia | .58 | Sept. 29 | .56 | 50 | 18 | 25 | 53 | 4 | 134 |
| 10 | North Coast | B. C.-Alaska | .81 | Aug. 8-9 | .63 | 115 | 12 | 40 | 47 | 1 | 146 |
| 11 | Glacier Bay | Alaska | .86 | Aug. 16 | .65 | 60 | 5 | 37 | 45 | 13 | 97 |
| 12a | South St. Elias | Alaska | .89 | Aug. 14-15 | .65 | 21 | 0 | 19 | 81 | 0 | 54 |
| b | North St. Elias | Yukon | .74 | Aug. 10 | .45 | 32 | | | | | |
| 13a | South Chugach | Alaska | .78 | Aug. 12 | .60 | 59 | 3 | 37 | 59 | 1 | 65 |
| b | North Chugach | Alaska | .69 | Aug. 12 | .50 | 11 | | | | | |
| 14 | Kenai | Alaska | .88 | Aug. 12 | .68 | 17 | 2 | 53 | 45 | 0 | 57 |
| 15 | West Alaska | Alaska | | | .10? | | 0 | 6 | 94 | 0 | 18 |
| 16 | East Alaska | Alaska | | | .57? | | 0 | 0 | 92 | 8 | 40 |

Fig. 5 — Oblique aerial photograph of Helen Glacier, Wind River Mountains, Wyoming, taken July 28, 1961. The snow cover is relatively thin and patchy. This photograph shows a low transient AAR (0.20). It is assumed that by late August the snow cover on this glacier had retreated so high that the final AAR was less than 0.1. The terminus of this glacier is classified as retreating. Photography by A. S. Post.

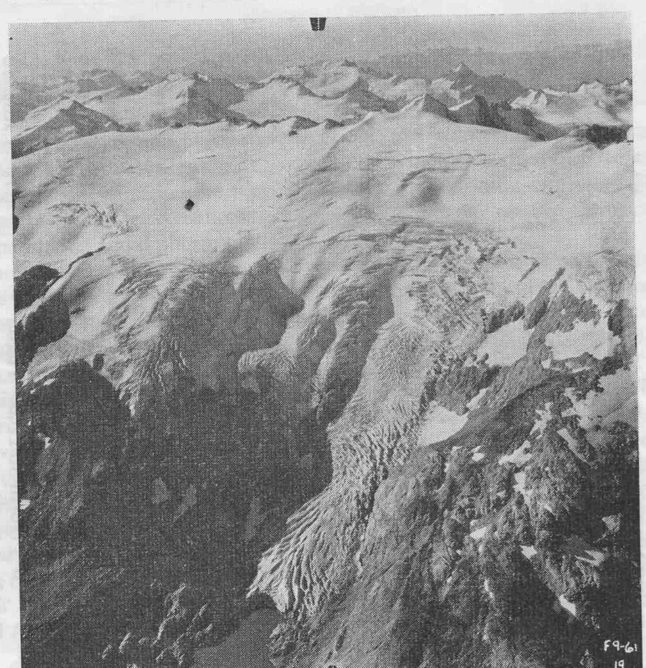


Fig. 6 — "Snow Cap Glacier" at the head of Snow Cap Lake, Coast Range, British Columbia, about 80 km north of Vancouver. This photograph was taken on September 29, 1961, almost at the end of the ablation season, and shows a transient AAR of about 0.60. The terminus of this glacier is classified as active. Photography by A. S. Post.

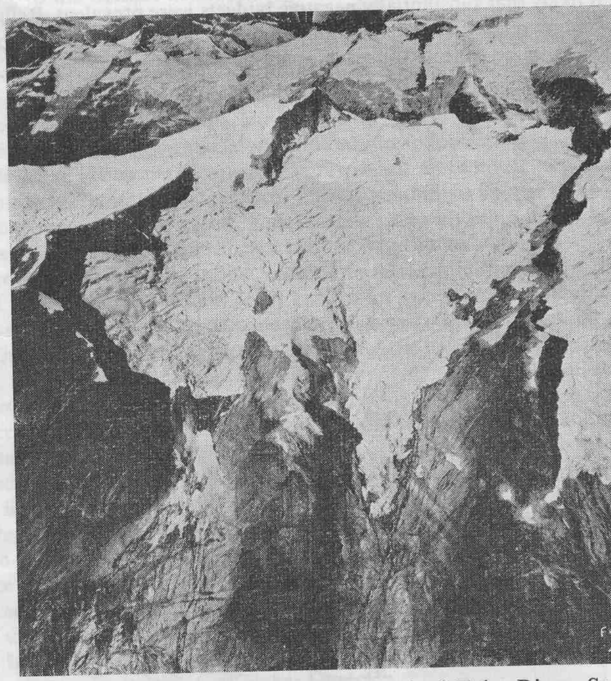

Fig. 7 — Small, advancing glacier near the head of Toba River, Southern Coast Range, British Columbia. The glacier in the center of the photograph advanced more than 460 m between 1952 and 1961. The glaciers on the left and right also advanced between 1952 and 1961, but were classified as only "active" in 1961. The accumulation area ratios for these glaciers are high but difficult to determine exactly because of the highly fractured glacier surface. Photograph taken September 29, 1961, by A. S. Post.

that in only a few cases was the adjustment very large. Typical oblique aerial photographs of glaciers having low or high AAR's are presented in Figures 5, 6 and 7.

The results (Table 2 and Figure 8) show a consistent pattern. The area along Pacific Coast from the Kenai Mountains in Alaska to latitude 53° in British Columbia had average AAR's greater than 0.60. This area has been shaded in Figure 8. One would expect that in this area positive net budgets were common during the 1960-61 budget year and that many of the glaciers were "healthy". Over a larger area, including eastern Alaska, the southern Coast Range in British Columbia, and the Monashee Mountains, the AAR's ranged between 0.5 and 0.6. It is believed that the eastern Alaska Range and Wrangell Mountains also had AAR's in this range; however, the weather conditions were poor for aerial photography throughout much of the summer so that very little data were obtained in these regions. In the larger area where the AAR's fell between 0.5 and 0.6, one would expect that, although a substantial number of glaciers experienced positive budgets, most of the glaciers had deficit budgets.

The glaciers of the Rocky Mountains in Canada and northwestern Montana, and in the Cascade Range of Washington showed AAR's ranging between 0.25 and 0.5. In this area positive budgets must have been very rare and negative budgets the rule. In the western Alaska Range, the Rocky Mountains of Wyoming, and on the remnant glaciers in Idaho, AAR's less than 0.2 were found consistently. This means that virtually none of the glaciers in these areas were healthy during the 1960-61 budget year, and it is likely that substantially negative budgets were prevalent. Refined studies might allow more quantitative estimation of the exact percentage of positive and negative budgets to be expected in each zone.

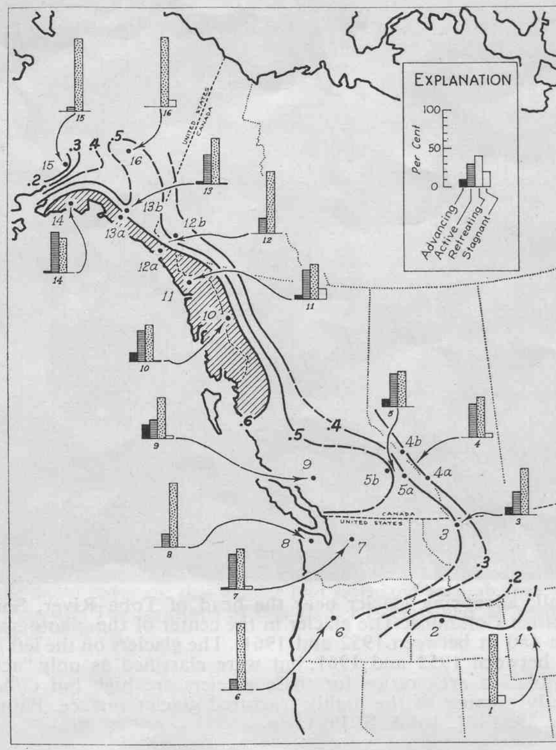


Fig. 8 — Map of Western North America showing 1961 accumulation area ratios (AAR's) and activity of glacier termini. Heavy lines are drawn through points of equal AAR; the area where average AAR's exceeded 0.6 is shaded. The lines are dashed where the data are few or uncertain. Solid dots indicate regions where many AAR's were measured and the results averaged, and are numbered to agree with Table 2. The bar graphs indicate the activity of glacier termini; arrows point to locations where data were obtained.

## 6. Activity of glacier termini

The condition of the terminus of many glaciers could be readily ascertained from the oblique aerial photographs. In order to obtain a valid consensus of glacier activity over a large area, it appears to be far more important to have a large statistical sample of many glaciers than to have accurate and detailed information from only a few. In most areas it was possible to find some glaciers which were obviously advancing and others which were obviously stagnant or retreating. Only relative percentages appear to be significant and usable for conclusions about the geographical extent of glacier activity.

A total of 960 glacier termini were studied and classified, and the results summarized for each of 15 principal regions. The termini were classified on the basis of appearance, not actual comparison of terminus positions from year to year. Although it is possible to use oblique aerial photography to actually relate changes in terminus position in different years, it is laborious to get a large statistical sample. Confidence in the use of appearance only has come from extensive experience in comparing terminus appearances with known data on advance and retreat, and it is believed that the results are approximately correct.

Glaciers were classified into four categories. These categories and some of the more important criteria used in classification are as follows :

1. *Advancing glaciers*. These are characterized by convex, crevassed termini, with sharp-edged, recently-fractured ice. The terminal areas appear to be encroaching on areas not recently ice covered, and in some cases invading brush or timber. In Figure 7 is illustrated a glacier which is advancing at its terminus.

2. *Active glaciers*. These show convex termini with many crevasses present. When the glacier ends on a cliff, fresh broken ice is present at the base of the cliff but not in sufficient quantity to indicate that an increase in mass is taking place below the cliff. One cannot tell from appearance whether the terminus is actually advancing, retreating, or stable. An active glacier terminus is illustrated in Figure 6.

3. *Retreating glaciers*. Retreating glaciers ending on land are generally characterized by ice with few, if any, crevasses present at the terminus, and if ablation moraine is not present the ice frequently terminates in a thin feather edge. Barren, recently deglaciated land is exposed along the margins of the ice. A glacier with a retreating terminus is illustrated in Figure 5.

4. *Stagnant glaciers*. Somewhat different criteria were used for large and small glaciers in this category. A small stagnant glacier shows no crevasses and a concave ice surface more or less covered with ablation moraine. A large stagnant glacier terminus is covered with ablation moraine with many kettles, and entrenched stream channels divide the ice into masses more or less separated from the active glacier upvalley. In the case of large glaciers the term stagnant applies only to the terminus; the glacier may be quite active at higher levels.

In some exceptional cases the appearance of the glacier and its activity do not coincide. For instance, the Carbon Glacier on Mount Rainier had a long, ablation moraine-covered terminus in 1961 which appeared to be retreating. However, from actual measurement it is known that this terminus was actually advancing. Another complication is the fact that in some areas (especially the Coast Range in British Columbia and southeastern Alaska) the small high-altitude and high-gradient glaciers were generally behaving in a different way from the low-gradient valley glaciers. For instance, the large, low-gradient Toba Glacier in British Columbia (Lat. 51°N, Long. 125°W) retreated 150 m from 1952 to 1961. During the same interval a small, steep, high-altitude cirque glacier (Fig. 7) immediately to the south advanced more than 460 m. Thus there are several complications which may cast doubt on the quantitative validity of this sampling program. However, it is believed that the sampling is in general unbiased from a geographic point of view, and that the results should be indicative if not an exact measure of glacier activity.

The results of this study are shown in Table 2 plotted as bar graphs in Figure 5. One may note that in most areas glaciers were found that fell into at least three different categories. In general, within the area in which the 1961 AAR's were greater than 0.5, at least half of the glaciers sampled were either active or advancing. In those areas in which the 1961 AAR's were less than 0.2, the glacier termini were predominantly retreating or stagnant. Therefore, the distribution of glacier net budgets in 1961 cannot be considered as unusual. Glacier AAR's must have been high for several years within the area shaded on Figure 5 in order for the positive regimes to have caused activity and advance at the glacier termini.

In several areas the snow cover at the time of the aerial photography had retreated far upglacier revealing the character of previous years' accumulation. In this case it is relatively easy to determine if the several previous years' budgets have been characterized by high accumulation or excessive ablation. This information, coupled with observations on the ground and from the air in 1957 to 1960, indicate that strongly negative mass budgets had been the rule, not the exception, in the Brooks and Alaska Ranges in Alaska and the Wind River Range in Wyoming. This explains the fact that the Eastern Alaska Range glaciers apparently experienced healthy AAR's in 1961 but showed glacier termini which were predominantly retreating or stagnant.

In 1956, Hubley reported many advancing glaciers in the Northern Cascade Range of Washington. Some evidence indicated a concurrent rejuvenation of glaciers in the Southern Coast Range of British Columbia. There were few reports at that time of large numbers of advancing glaciers further north. In 1961, we found that glaciers in the Cascade Range of Washington generally experienced slightly negative budgets and more than half of them were retreating or stagnant. However, positive budgets and vigorous glacier termini are now common in southeastern Alaska. Therefore, it might be true that the locus of strong glacier rejuvenation has moved north and west, but further data are needed to form any firm conclusions. Only time will tell as to whether this apparent rejuvenation of glaciers along the north Pacific Coast will progress inland to effect those areas where the glaciers are now in a general state of recession. A more complete analysis of the results of the reconnaissance program will appear in a later paper by A. S. Post.

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