

ASSESSING GLACIER MASS BUDGETS BY RECONNAISSANCE AERIAL PHOTOGRAPHY*

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ABSTRACT. Glacier reconnaissance in North America depends largely on aerial photography. Qualitative interpretation of such photography presently yields information on extent and yearly variations of existing glaciers, vigor of their activity, formation of kinematic waves, snow-line altitudes, residual annual snow accumulation, and recent climatic changes. Methods are proposed whereby such data can be combined with limited ground observations to obtain quantitative mass budget data.

RÉSUMÉ. La reconnaissance des glaciers en Amérique du Nord dépend en grande partie de la photographie aérienne. L'interprétation qualitative de telles photographies fournit immédiatement des renseignements sur l'étendue et les variations annuelles des glaciers existants, l'intensité de leur activité, la formation de vagues cinématiques, les altitudes de "ligne de neige", l'accumulation annuelle résiduelle de neige, et les changements climatiques récents. On propose des méthodes où de telles données peuvent être combinées à des observations limitées au sol, pour obtenir des données quantitatives de budget de masse.

ZUSAMMENFASSUNG. Die Gletscher-Beobachtung in Nordamerika beruht weitgehend auf Luftaufnahmen. Die qualitative Interpretation solcher Aufnahmen liefert gegenwärtig Daten über die Grösse und die jährlichen Schwankungen bestehender Gletscher, über den Grad ihrer Aktivität, die Bildung kinematischer Wellen, die Höhe der Schneegrenze, den jährlichen Überschuss an Schneeauftrag und rezente Klimaänderungen. Es werden Methoden vorgeschlagen, nach denen aus der Verbindung solcher Daten mit beschränkten Bodenbeobachtungen der Massenhaushalt quantitativ bestimmt werden kann.

INTRODUCTION

The present major glaciation of western North America is distributed along the sparsely populated North Pacific Coast of Canada and Alaska. A comprehensive view of the present status, past history and current variations in these glaciers can practically be obtained only from reconnaissance aerial photography. Glacier observations made in this fashion necessarily must sacrifice precise quantitative data on a few glaciers in favor of less accurate information on many glaciers representative of a large geographical area. North American glaciology in the past decade has relied heavily on the aerial camera to provide much of its general information on current glaciation. Repeated annual glacier photography of a given region was initiated early in the 1950's in the Juneau Ice Field area of Alaska by the American Geographical Society. In 1955 Hubley (1956) began a similar program in the mountains of western Washington State which has been continued to the present day (LaChapelle, unpublished). More recently, Meier and Post (1962) have prepared a report on an extensive aerial photographic survey covering most of the major existing glaciation in western North America. Though the initial results of these surveys by the Department of Meteorology and Climatology, University of Washington, have been largely qualitative, they have provided much useful information on the current glacier advances and retreats and the general effects of weather variations from year to year.

This paper discusses present methods of evaluating glacier aerial photography and proposes methods of recovering quantitative mass budget data from such reconnaissance.

QUALITATIVE METHODS

(1) The simplest and most obvious glacier information obtainable from aerial photography is extent of ice coverage and position of termini. Once the extent of glaciers in a given region has been established, either by special glacier photography or in the course of routine regional mapping photography by government agencies, repeated photography in subsequent years readily reveals the patterns of advance or recession. Comparison of photos taken in different years shows the changes in terminus position or ice level along the glacier margins in reference to fixed bedrock or other features. Magnitudes of these changes can be approximated

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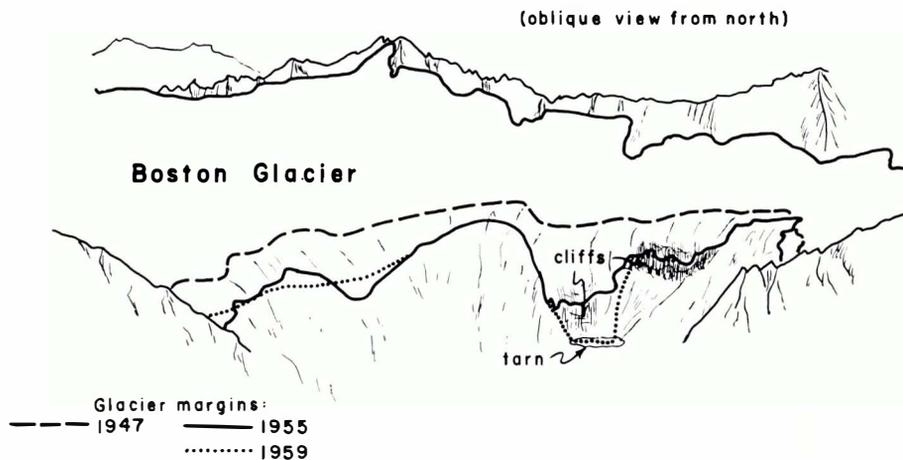


Fig. 1. Sketch of the Boston Glacier, Northern Cascade Range, Washington State, showing marginal changes recorded by oblique aerial photography



Fig. 2. The "Three Congruent Glacier", St. Elias Range, Alaska. An example of advancing, retreating and active glaciers whose states are readily recognizable in an aerial photograph. Photograph by Austin S. Post

by visual estimate, often within 10 per cent where good maps exist. The immediate yield from such comparisons is a catalogue of glacier variations throughout a region, itemized in terms of advance, retreat or equilibrium stand, and the year-to-year changes of glacier membership in these categories. In order to simplify data presentation, the yearly sequence of terminal positions changes on a given glacier can be reduced from a series of photographs to a single sketch (Fig. 1).

(2) The vigor of glacier activity as revealed by effects of ice motion provide an index of glacier health even when marginal positions do not change or when a series of pictures is not available for comparison. The degree of crevassing is one such evidence of active ice motion. Another is the character of the terminus, which may be gently sloping smooth ice in the case of stagnation, or may exhibit a steep, crevassed front where active or actually advancing. Profile of the glacier tongue in cross-section is also much more strongly convex in the case of an active or advancing glacier, a marked contrast with the gradually sloping margins of stagnant ice. All of the above situations are shown in Figure 2. A developing kinematic wave often strikingly changes the surface character of a glacier in its lower reaches long before any reaction is felt at the terminus. These changes are particularly noticeable when invigorated ice invades or overrides a stagnant, moraine-covered valley tongue. Though such observations from aerial photography are subjectively dependent in part on the experience of the interpreter, they nevertheless can provide valuable data on the general vigor of glaciation and may indicate effects of climatic change before these are reflected in actual changes in glacier extent.

(3) One of the obvious glacier features revealed by aerial photography is the snow line. Less obvious but also detectable in the case of some high-latitude glaciers is the lower limit of superimposed ice. When pictures are taken late in the ablation season (usually late August or early September on the North Pacific Coast), the snow line is close to its limiting position at the annual firn limit. Relative areas of accumulation and ablation can be quickly estimated, especially if adequate maps exist. Seasons of heavy accumulation are revealed by snow lines at low elevations which exhibit a sharply defined boundary with bare ice. Those of light accumulation are revealed by higher snow lines separated from bare ice by zones of older firn (Fig. 3). Years of strongly positive or negative mass budget in a given region stand clearly revealed from even a cursory inspection of snow lines on aerial photographs. If maps are available, the ratio of snow-covered area to total glacier area at the end of each ablation season can be computed and this ratio used to deduce approximate changes in the mass budget (Meier, 1962). Mercer (1961) has also pointed out how this information can be utilized to analyze mass budget changes.

(4) Longer-term climatic conditions are also revealed by the character of the line between snow and ice. Prolonged periods of glacier melt can remove firn entirely from the upper glacier, leaving only solid ice, part of which may carry a small blanket of annual snow. In this case a *high* snow line exhibits a sharp transition from snow to solid ice. Stratigraphic evidence of climatic change is also found in the sudden transition from blue ice to white firn in fracture-exposed faces in the accumulation zone, indicating that a period of heavy melt has been followed by a period of accumulation. In some cases the glacier equivalent of a geological unconformity may reveal the same climatic sequence.

(5) There are a number of photographic clues to the thickness of residual snow accumulation in any given year. High-quality oblique aerial photography often exhibits sufficient detail in enlarged prints to permit identification and thickness estimation of annual accumulation horizons exposed in the walls of crevasses and bergschrunds or on the sides of freshly formed seracs. Reasonable deductions can then be made concerning water content in maritime climates where snow tends to reach quite a uniform density ($0.55-0.60$ g./cm.³) by the end of the ablation season. The degree to which crevassing on the upper glacier is obscured by a heavy accumulation blanket offers a more qualitative indication of relative accumulation.



Fig. 3. The Whitechuck Glacier, Northern Cascade Range, Washington State. A high snow line, exposing old firn between snow line and ice, gives evidence of a negative budget year. Photograph by Austin S. Post

The status of transient or semi-perennial snow patches on surrounding peaks also indicates relative magnitude of residual snow accumulation. Interpreting such features as snow lines and residual accumulation calls for care in avoiding confusion due to recent falls of new snow. Careful timing is necessary in planning the photographic flights in order to collect the photographic records as late in the season as possible, but still prior to the first snowfalls of autumn.

The fragmentary information provided by any one of the principles described above is rather limited. When all such data are assembled for many glaciers in a selected region, a comprehensive view of current glacier behavior emerges. Spatial and temporal variations in climate become apparent, as do their effects on the glaciers, especially the smaller ones. Qualitative records alone may thus provide useful glaciological information over wide regions where it is available by no other means than reconnaissance aerial photography, and such records do in fact offer a synoptic view of glacier behavior which is lacking from individual ground studies.

QUANTITATIVE METHODS

In this section methods are proposed whereby quantitative information on glacier mass budgets can be approximated from aerial photographs. These methods presuppose at least a

limited amount of past or current information on regional climate and glacier characteristics obtained from ground observations. Reference is made to the analysis of mass budget variables by Meier (1962), whose terminology is adopted here.

First, a simple sequence of aerial photographs of a glacier snow line obtained during the melt season can provide quantitative information on the net ablation term of the annual mass budget. The residual accumulation cannot be directly determined in this instance because it depends on an unknown initial accumulation. Ice ablation, on the other hand, begins each season at the known value of zero (assuming winter snow entirely blankets the glacier), and can be deduced at any subsequent time during the ablation season from the expression often used for mass budget computations:

$$B_a = \iint_{S_{as}} \dot{b} dS dt \quad (1)$$

where \dot{b} is the budget rate, in this case effectively the specific ice melt rate $\rho dW_i/dt$, where W_i is the ice surface wastage, and B_a is the total water equivalent volume of ice ablated by time t , a relation generally better suited to graphic than to formal integration. This expression becomes applicable to aerial photography when a sequence of photographs establish successive values for areas of exposed ice and these values are combined with ice surface melt rates, $\rho dW_i/dt$, to give the successive volume melt rates. For maximum accuracy, the ice wastage, dW_i/dt , should be obtained from ground measurements on selected representative glaciers, but it is suggested that mean values of this quantity over intervals of several days may reasonably be approximated if general weather conditions are known and past records of ice wastage observations on the ground are available for the region in question. This approximation is permissible because total ice melt is much more dependent on the rate at which exposed ice area increases than on day-to-day variations in surface wastage rate.

A more general application of aerial photography to glacier mass budget measurement is suggested by the concept of the *vertical gradient of net annual specific mass budget*, introduced by Shumskiy (1946) as the *energy of glacierization*, and restated by Meier (1961) as the *activity index*. Both authors defined these respective terms as the *steady-state* budget gradient at the equilibrium firn limit, $E = (db_o/dz)_{z_o}$. In the present discussion the more general term db/dz , applicable to the entire glacier, will be used. db/dz is positive when ice ablation decreases and net accumulation increases with increasing altitude, and negative in the converse instances. Initially it will be assumed that db/dz in a given glacier region is constant with time and altitude, though it may have different values (db_c/dz) above and (db_a/dz) below the firn limit.

Consider the element of map area, δS , between two successive contour lines, altitudes z and $z + \delta z$, on a glacier surface. In general this area is some complex function of z

$$\delta S = f(z).$$

The vertical thickness of net annual accumulation above the firn limit (in water equivalent) on this element of area is given by

$$b_c = \frac{db_c}{dz} (z - z_o), \quad (1a)$$

and the vertical thickness of ice ablation on a similar element below by

$$b_a = \frac{db_a}{dz} (z - z_o) \quad (1b)$$

where z_o is the altitude of annual firn limit, db_c/dz is the budget gradient above z_o , and db_a/dz is the budget gradient below z_o . The volume elements of accumulation and ablation are thus respectively

$$\delta B_c = \frac{db_c}{dz} (z - z_o) \delta S \quad (2a)$$

and

$$\delta B_a = \frac{db_a}{dz} (z - z_0) \delta S, \quad (2b)$$

and the net mass budget is

$$B = \frac{db_c}{dz} \int_{z_0}^{z_2} (z - z_0) f(z) dz + \frac{db_a}{dz} \int_{z_1}^{z_0} (z - z_0) f(z) dz \quad (3)$$

where z_1 is the altitude of the terminus and z_2 is the maximum altitude of the accumulation zone. The slope and width of a glacier normally being dependent on altitude in a complex fashion, this expression for B does not readily lend itself to formal integration, but it may be approximated by summing increments of area (and accumulation volume) between conveniently spaced contour intervals. In theory at least, the mass budget of a glacier can thus be obtained if the position of the annual firn limit, determinable from a single aerial photograph, is known, a reasonable accurate topographic map exists, and approximate regional values of db/dz can be estimated.

The initial assumption that db/dz is constant in time and independent of altitude requires closer examination, for often it is not. As Shumskiy has shown, the energy of glacierization ought to be characteristic of a given area, and thus it might be expected to exhibit the same stability, or lack of it, as the climate. Mercer (1961) has described the budget-altitude relations of several Alaskan glaciers, and cites figures for, among others, the Taku Glacier, where net ablation varies linearly with altitude below the firn limit as does net accumulation over middle reaches of the accumulation zone. In a different season, LaChapelle (1954) found a constant value for db/dz throughout the Taku accumulation zone, and this value was 33 per cent higher than that mentioned by Mercer. A fixed value of db/dz thus does not appear to be a feature of the Taku accumulation zone.

Blue Glacier mass budget records since 1958 allow average values of db/dz above and below the firn limit to be computed for four successive years:

TABLE I. BLUE GLACIER BUDGET GRADIENTS

Year	Ablation zone	Accumulation zone	Mean specific budget m. water equivalent
	mm./m.	mm./m.	
1958	10	3	-1.7
1959	8	5	-0.1
1960	8	5.5	-0.1
1961	10	8	0.7

Here the average budget gradient in the ablation zone is reasonably constant from year to year, but that in the accumulation zone varies with the character of the annual mass budget. In each of these cases cited the variation of net accumulation or ablation is taken along a *line* running up the glacier. To be strictly applicable in equation (3), db/dz ought to be calculated from average values of b across the entire glacier for successive altitude increments. In this manner local variations due to wind drift, and difference of exposure can be taken into account. Figure 4 plots db/dz as a function of 25 m. altitude increments for the Blue Glacier in 1960, a year of nearly equilibrium budget. Here it is readily apparent that *average* values of the budget gradient fluctuate widely with altitude, reflecting irregularities of the glacier topography.

Thus the application of equation (3) to quantitative glacier regimen studies is limited to the more favorable circumstances. Nevertheless, it can prove useful if the following limitations are recognized. On the average for a number of adjacent glaciers over a number of years, mean regional values of db_c/dz and db_a/dz for glaciers of similar firn limit elevations might be

applicable, but not for individual glaciers in individual years. Where regular reconnaissance aerial photography can be maintained over a number of years, mean values of the budget gradient obtained from ground observations may give useful mass budget information via equation (3). If specific quantitative data are required in a given year, the aerial photograph

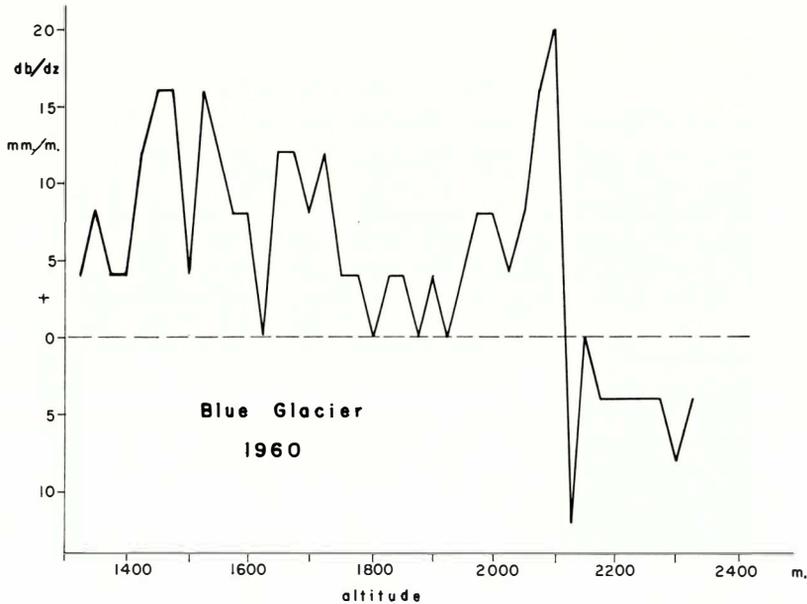


Fig. 4. The energy of glacierization as a function of altitude for the Blue Glacier, Olympic Mountains, Washington State

method must be supplemented with annual ground observations. Extension each year of such field-determined values from selected representative glaciers to others in a region appears feasible, thus permitting much wider collection of quantitative regimen data than would be practical by ground observations alone.

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DISCUSSION OF MR. E. R. LACHAPELLE'S PAPER

MR. W. CAMPBELL: Has anyone determined the mass budget using aerial photographic means and this technique for a glacier whose budget had also been exactly determined by ground measurements?

MR. LACHAPELLE: I started out to do that on the Blue Glacier, but when I ran into that fluctuating vertical gradient (Fig. 4) I found it was not as simple as it might at first seem; one has to be very careful what one assumes.

M. M. BAUSSART: Expédition Glaciologique Internationale au Groenland have attempted to determine mass balance in this way, but the problem is that aerial photography only gives the surface area of the glacier, and I consider that the difficulty of passing from this areal measurement to mass balance is extremely difficult without some measurements on the ground.

MR. LACHAPELLE: This is precisely the limitation of aerial photography, it gives us only the surface, and it is in an attempt to circumvent this that I introduced the vertical gradient of net accumulation; this then gives us theoretically the thickness of accumulation or ablation at various points up and down from the firn limit.

MR. B. FRISTRUP: How did you determine this gradient? It is not just a function of altitude, for example it would vary with latitude.

MR. LACHAPELLE: Yes, this is what causes the variations I showed in Figure 4. Horizontal variations, for instance that due to differences in wind drift, make it difficult to obtain the averages. In theory the method is very simple and appealing, but its application is fraught with many difficulties.