MASS BALANCES OF SOME NORTH CASCADE GLACIERS AS DETERMINED BY HYDROLOGIC PARAMETERS, 1920-65

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ABSTRACT

Ice and snow storage changes in the glaciers of the Thunder Creek drainage basin for the period 1920-65 were calculated by using hydrologic and meteorologic data from low elevation stations. The basis for these computations was the difference between streamflow in glacierized and non-glacierized drainage basins, combined with precipitation data from nearby valley stations.

A significant correlation was found between balances measured for South Cascade Glacier (14 km south of the Thunder Creek basin) and balances calculated for Thunder Creek glaciers for the period 1958-65. The balance history of South Cascade Glacier for the period 1928-57 was estimated on the basis of this statistical relationship.

The significant findings of this study are:

1. The balance trend for the higher altitude Thunder Creek glaciers shows a major change occurring about 1944, from generally negative balances between 1920-44 to a gain in glacier mass between 1945-65;
2. The balance trend for the lower elevation South Cascade Glacier shows a consistent loss of mass at the rate of 1.7 metres of water per year for the period 1928-44, and a loss rate of 0.6 metres per year for the period 1945-65.

As a check on these long-term estimated balances, the total mass changes of South Cascade Glacier and of the North and South Klawatti Glaciers in the Thunder Creek basin were calculated on the basis of detailed topographic maps and aerial photographs. The results show close agreement between these independent calculations.

RÉSUMÉ

Les variations de la masse de glace et neige accumulée dans les glaciers du bassin hydrologique de « Thunder Creek » pendant la période 1920-65 ont été calculées d'après des relevés hydrologiques et météorologiques effectuées dans des stations de basse altitude. La base de ces calculs était la différence de l'écoulement dans les vallées avec et sans glaciers, étudiée en relation avec les indications pluviométriques des stations avoisinantes.

On découvrit une corrélation significative entre les oscillations de volume mesurées pour le « South Cascade Glacier » (14 km au sud du bassin de « Thunder Creek ») et celles calculées pour les glaciers de « Thunder Creek » pendant la période 1958-65. L'histoire des variations de volume de « South Cascade Glacier » pendant la période 1928-57 fut établie à partir de cette relation statistique.

Les découvertes significatives faites à l'occasion de cette étude sont les suivantes:

1. L'évolution du bilan des glaciers à haute altitude de « Thunder Creek » fait apparaître un important changement qui se produit vers 1944: à un recul presque constant entre 1920 et 1944 succède une augmentation de la masse glaciaire entre 1945 et 1965;
2. L'évolution du bilan du « South Cascade Glacier » situé à plus basse altitude montre pour la période 1928-44 une notable diminution de la masse glaciaire à raison de 1,7 m d'eau par an, et pour la periode 1945-65 une fonte de l'ordre de 0,6 m par an.

Pour vérifier ces estimations à long terme, on a calculé, à partir de cartes topographiques et de photographies aériennes détaillées, le changement de masse total du « South Cascade Glacier » ainsi que des glaciers « North Klawatti » et « South Klawatti » dans le bassin de « Thunder Creek ». La concordance de ces calculs indépendants est satisfaisante.

Runoff from glacierized areas is highly variable on a daily, seasonal, and annual basis. These variations reflect the differences in melt rates of the ice and snow within the basin and, in part, the differences in snow cover and amounts. The total annual runoff is indicative of the annual ice and snow storage changes of the glaciers present in the drainage area and suggests that the mass balance of these glaciers could be calculated by employing runoff data.

Several attempts have been made in the past to measure glacier mass changes by using runoff data (Rogstad, 1941, 1942, 1951; Kasser, 1959). The greatest problem in accomplishing this with confidence in accuracy is the lack of reliable and complete precipitation data. Evaporation and transpiration losses are also seldom known in these areas and in many cases cannot be neglected. The purpose of this paper is to present a technique whereby accumulation, ablation, and mass balances of glaciers can be estimated using existing long-term records of runoff and precipitation in glacierized areas. To illustrate this hydrologic technique, the mass changes of glaciers in the Thunder Creek basin of the Cascade Range in Washington are estimated. As a check on the method, the calculated changes of nearby glaciers are compared with the changes determined by the hydrologic technique.

SETTING

The Thunder Creek drainage basin, located in the North Cascades in Washington (fig. 1), has an area of about 275 km^2. There are 14 glaciers in this basin ranging in size from 0.5 to 6.7 km^2. The total glacierized area, about 47 km^2, covers atout 17 percent of the total drainage area. The basin ranges in altitude from 370 to over 2,800 m and has a mean altitude of 1,600 m. Average annual runoff during the period 1920-65 was

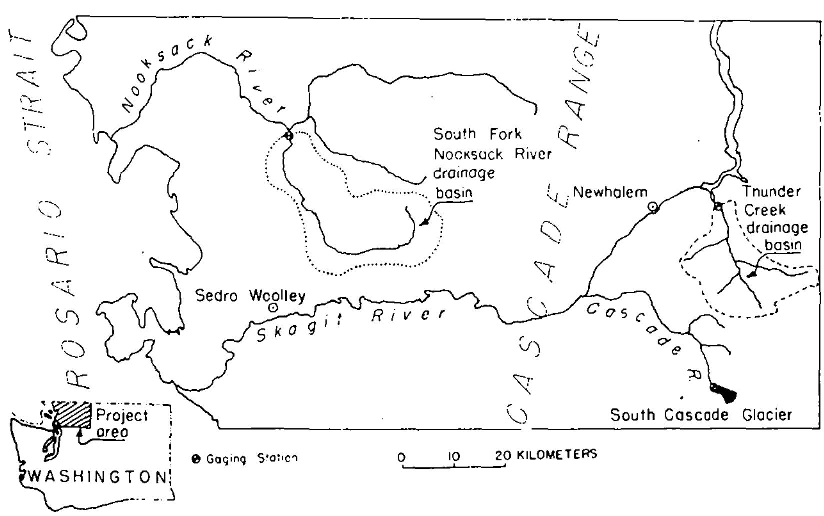

Fig. 1 — Location of the Thunder Creek drainage basin, the South Fork Nooksack River basin, South Cascade Glacier, and two U.S. Weather Bureau precipitation stations, Sedro Woolley, and Newhalem Washington.

210 cm. About 80 percent of the annual runoff is derived from melting snow and ice; the remaining 20 percent is direct runoff from rainfall and release of ground-water storage.

A non-glacierized drainage basin, that of the South Fork Booksack River, was also used in this analysis. This basin, located in the western foothills of the Cascade Range, has an area of about 285 km^2, ranges in altitude from 150 to 1,800 m, and has a mean altitude of 880 m. The average annual runoff for the period 1934-65 was 244 cm*. Several other non-glacierized basins were used for short periods to estimate the annual runoff of the South Fork Nooksach River for the period 1920-33. Mass balance measurements made on South Cascade Glacier during the period 1958-65 were used in this analysis. Also included was the total mass change of two glaciers in the Thunder Creek basin during the period 1947-61.

Precipitation data used in the analysis were from the U.S. Weather Bureau stations at Newhalem, Washington (altitude 160 m) and near Sedro Woolley, Washington (altitude 17 m). A monthly average of these two stations closely represents valley precipitation in the lower Skagit and Nooksack River basins. The average annual precipitation for the period 1920-65 at these two stations was 155 cm.

Method

For any time period the equation for the water balance of a glacierized area is:

$$R_g = P_g - E_g - \Delta G_g - \Delta S_g \tag{1}$$

where R = runoff from basin, P = average precipitation (all forms) in the basin, E = evaporation and transpiration losses, ΔG = change in ground-water storage, and ΔS = change in snow and ice storage, and the subscript g denotes a glacierized basin.

A similar equation applies to a basin without glaciers, designated by the subscript n:

$$R_n = P_n - E_n - \Delta G_n - \Delta S_n \tag{2}$$

The significant difference between (1) and (2) is that ΔS_n is usually zero for a water year the period from October 1 to September 30. For some non-glacierized basins this may not be true during those years when all the snow does not melt by September 30. Care must be taken to consider the annual value of ΔS_n. Due to changes in the annual mass balance of glaciers in the basin, the factor ΔS_g is seldom equal to zero on an annual basis.

Subtracting (2) from (1) results in the following expression:

$$\Delta S_g - \Delta S_n = (R_n - R_g) - (P_n - P_g) - (E_g - E_n) - (\Delta G_g - \Delta G_n) \tag{3}$$

As both basins are affected by nearly the same climatological variations, the physical significance of (3) would seem to be valid. There is, however, a limit to the distance between basins that should be selected for this type of analysis.

Evaporation and transpiration losses, E_g and E_n, have not been measured in either basin. Such losses are assumed to be small and of the same order of magnitude in the two basins during any period, and therefore can be cancelled in equation (3) without too

(*) It appears anomalous that the much higher elevation, glacierized Thunder Creek basin produced less runoff, even with a sizable contribution to runoff from the glaciers which were losing mass during this period. This can be explained by a rain shadow effect caused by a high (2,800 m) ridge extending along the western edge of the basin.

great an error. Ground-water storage changes are undoubtedly very small in both basins, and are assumed to be equal for any period and can also be cancelled.

Equation (3) then reduces to :

$$\Delta S_g - \Delta S_n = (R_n - R_g) - (P_n - P_g) \tag{4}$$

Precipitation values, P_n and P_g, are unmeasured in the two basins and are difficult to assess. Nearby valley stations are no more than an index of basin-wide precipitation. On a monthly or annual basis, basin-wide precipitation can be assumed to be proportional to precipitation measured at valley stations, so that $P_n = MP_v$ and $P_g = NP_v$ (where M and N are coefficients, and P is average valley-station precipitation described earlier). That a simple proportionality exists between valley and basin precipitation may be questioned. However, a comparison of several years of snow accumulation measurements on South Cascade Glacier with precipitation at those valley stations indicates that the assumption of a linear relationship is valid.

Equation (4) then becomes

$$\Delta S_g - \Delta S_q = (R_n - R_g) - (M - N)\, P_v \tag{5}$$

The only unknown on the right side of the equation is the quantity (M-N).

Integrating equation (5) over a specific time of several months or years, t_1-t_2, results in

$$\int_{t_1}^{t_2} (\Delta S_g - \Delta S_n)\, dt = \int_{t_1}^{t_2} (R_n - R_g)\, dt - (M - N) \int_{t_1}^{t_2} (P_v)\, dt$$

If t_1 and t_2 are the dates on which the glacier balance year ends, approximately September 30, ΔS_m is zero and ΔS_g is the water storage change, in the form of ice and snow, of the glacierized basin. Determining (M-N) is possible, therefore, if a period can be defined when $\int(\Delta S_g\text{-}\Delta S_n)dt = 0$.

As the quantity ΔS_n is zero at the end of each glacier balance year, it is necessary to find a period of time when the quantity ΔS_g is equal to zero. An ideal solution would be to determine the volume change of the basin's glaciers, as measured by maps or other means, over a specific time period. Rogstad (1942) defined a period with no mass change in a glacier's volume as one that begins and ends with the terminus of the glacier in the same position, having receded several hundred meters and then advanced to the same position. Contrary to Rogstad's definition, however, it is very doubtful that the volume of an advancing glacier is equal to the volume of a receding glacier, even though the areas are equal. Certainly the longitudinal profiles would differ significantly.

The quantity (M-N), which was assumed to remain constant over the time period under study, was determined with reasonable accuracy as described below.

Aerial photographs of the Thunder Creek basin glaciers were available for nearly every year since 1947. La Chapelle (1962) has described methods where by such photographs can be used for assessing glacier mass balances. With the aid of the Thunder Creek basin photographs, consecutive years were selected when the temporary snowline elevations, or Accumulation Area Ratios (Meier and Post, 1962, p. 70), were very nearly the same although occurring at different times during the ablation season. The volume change of the glaciers between these two years was therefore assumed to be approximately zero. The method would only be valid when the temporary snowline positions are near the equilibrium line of the glacier and only for consecutive years.

Another method by which (M-N) may be found is to determine, also by the inspection of snowline positions on aerial photographs, those years when the mass balance of the glaciers is approximately zero at the end of the balance year.

Based on these two methods the value of (M-N) was calculated to be approximately 0.23 for the Thunder Creek and South Fork Nooksack River basins. Taking into account all the possible sources of error in determining (M-N) a probable error of 25 percent was assigned to this value. The significance of a value of 0.23 for this coefficient is that the difference in annual precipitation in these basins represents about 23 percent of the valley station precipitation or an average of 36 cm per year for the period 1920-65. The resulting probable error of 9 cm for (P_n-P_g) is then much less than the average storage change, ΔS_g, and the probable error for ΔS_g would be considerably less than 25 percent.

The snow storage on the non-glacierized basin, ΔS^n, must be substracted from the term $\int(\Delta S_g$-$\Delta S_n)$ for the period of each year when snow is present in that basin. Iti s quite simple to determine when all the snow has melted from the South Fork Nooksack basin (usually by about July 15) by inspection of the gaging station record. The very pronounced diurnal fluctuations in stage and discharge due to snow melt are very obvious during the spring melt season, and disappear by early summer. The value for ΔS_n is determined as

$$\Delta S_n = P_n - R_n$$

or

$$\Delta S_n = M P_n - R_n$$

Annual periods are selected to start when snow deposition begins in the fall, and end when all snow is depleted. M is then approximated by R_n/P_v, and ΔS_n can be determined for this period, usually October 1 to July 15. In figure 2 the annual cumulative values, beginning on October 1, for ΔS_g, ΔS_n, and ΔS_g-ΔS_n are shown for the period 1958-64. Monthly values of R_n, R_g, and P_v for this period were averaged and used to calculate the snow storage changes throughout the year.

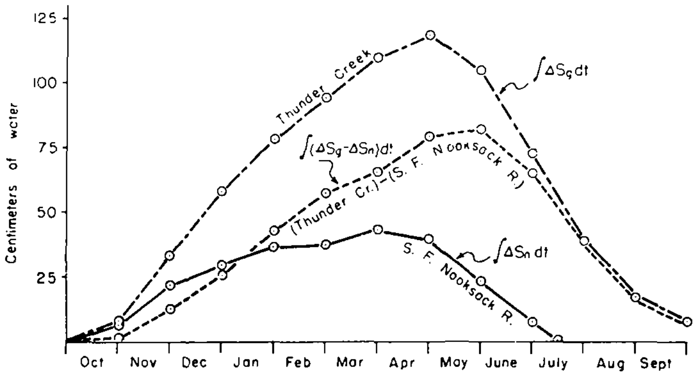

Fig. 2 — The annual change in snow and ice storage of the Thunder Creek basin, ΔS_g; the South Fork Nooksack River basin, ΔS_n; and the difference between the two basins, $\Delta S_g - \Delta S_n$; values are averaged for the period 1958-64.

Results and conclusions

A fair statistical correlation was found between the mass balance (ΔS_g) for the Thunder Creek glaciers and South Cascade Glacier (14 km south of Thunder Creek

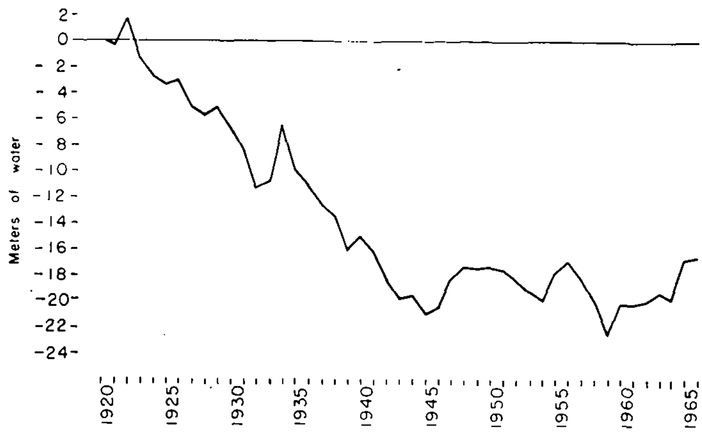

Fig. 3 — The cumulative mass balances of the Thunder Creek glaciers, 1920-65.

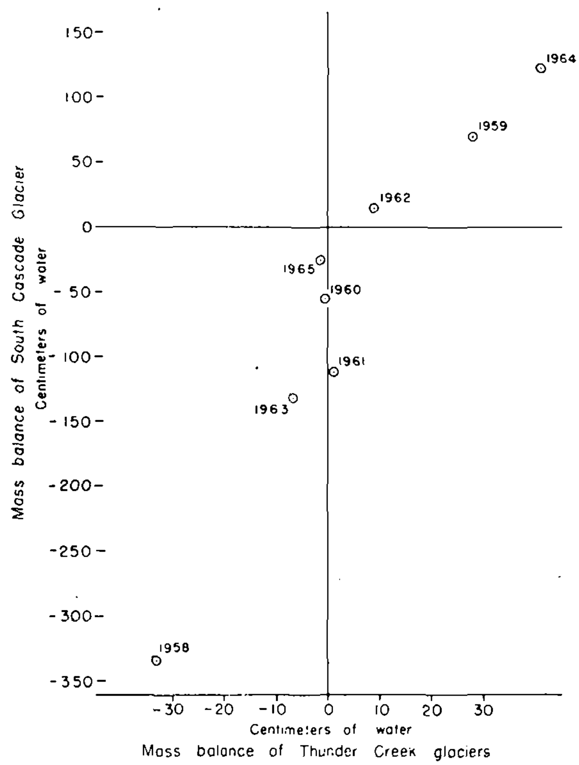

Fig. 4 — Annual mass balances of South Cascade Glacier as a function of the mass balances, ΔS_g, of the Thunder Creek glaciers, averaged over the drainage area, 1958-65.

basin) for the period 1958-65 (fig. 3). Mass balances were measured directly on South Cascade Glacier during this period by glaciological methods. The relationship shows that a zero balance at South Cascade Glacier corresponds to a positive balance on the Thunder Creek glaciers, and the Thunder Creek glacier balances are always considerably more positive than those on South Cascade Glacier. An obvious explanation for this is that the average elecvation of the Thunder Creek glaciers is about 300 m higher than that of South Cascade Glacier.

On the basis of the relationship between the mass balances of glaciers in the two basins, the total mass loss of South Cascade Glacier for the period 1928-65 was found to be about 39 m of water. The rate of loss was 1.7 m per year for the period 1928-44 and 0.6 m per year for the period 1945-65. By comparison, on the basis of recent maps and a 1928 photograph of South Cascade Glacier, the volume loss from 1928 to 1965 was calculated to be about 36 m of water.

The mass loss from North and South Klawatti Glaciers between 1947 and 1961 was calculated on the basis of precise maps made for those years. Both glaciers are in the Thunder Creek basin and are reasonably representative of most glaciers in the basin with respect to area-altitude distribution, size, and orientation. The total mass llss from these glaciers during the period 1947-61 was determined to be 1.6 m of water; during the same period all the Thunder Creek glaciers lost approximately 2.0 m, as calculated by the hydrologic method.

The glaciers in the Thunder Creek basin lost mass steadily during the period 1920-44 at an average rate of 0.9 m of water per year. During the period 1945-65 a gain in glacier mass occurred at the rate of 0.2 m per year (fig. 4).

Several pronounced advances of glaciers in the North Cascades have been observed since the late 1940's and early 1950's. Most high elevation glaciers have been unusually active and many have advanced or increased in size (Bengson, 1956; Harrison, 1956; Hubley, 1956; Johnson, 1954). A distinct change in climate, which was conducive to glacier growth, undoubtedly occurred in the Pacific Northwest in the mid-forties. On the basis of this rather approximate hydrologic method of determining glacier mass balances, a significant change from a negative to positive trend in the mass balances of the high elevation Thunder Creek glaciers occurred at the same time. The reliability of the hydrologic method of measuring approximate glacier mass balances is supported, therefore, by this recent evidence of glacier growth.

The accuracy of this method appears relatively good; the probable error is approximately 15 percent on an annual basis and somewhat less for longer periods. Additional precipitation measurements, particularly at higher elevations, would undoubtedly increase the accuracy.

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DISCUSSION

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It would be most desirable to use this method on a glacier for which detailed mass balance measurements are available. This would provide a most valuable check of validity of a method which is potentially very useful. I imagine you have not done this because run-off data are not available for the drainage basin including South Cascade Glacier.