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MASS BALANCE OF "VESPER" GLACIER, WASHINGTON, U.S.A.

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ABSTRACT. During 1974–75 glaciologic and geologic studies were conducted on a small (0.17 km^2) avalanche-nourished glacier in the North Cascade Range of Washington. The approximate equilibrium-line altitude (ELA) for this ice body, informally called "Vesper" glacier, lies at 1 475 m, some 300 m below the regional ELA value. Estimated annual accumulation was 6 100±675 mm during the two years of study; 15 to 30% of this flux resulted from avalanche and wind-transported snow. Average annual ablation during the period was 5 350 mm, giving a total net balance of +1 600 mm for the two-year study period. "Vesper" glacier persists well below the regional snow-line because of excessive local precipitation, substantial avalanche contributions, and a favourable north-facing aspect.

Neoglacial moraines indicate that maximum ELA lowering in this period was approximately 165 m and occurred prior to A.D. 1670. Minor re-advances occurred during the nineteenth century. These reconnaissance measurements are consistent with the sparse geologic data reported from other glaciers in the Cascade Range. While the relationship between regional lowering of snow-line and avalanche activity is uncertain at present, these data suggest that avalanche-nourished glaciers provide a useful record of climatic fluctuations.

RÉSUMÉ. *Bilan de masse du "Vesper" glacier, Washington, U.S.A.* En 1974–75, des études glaciologiques et géologiques ont été conduites sur un petit glacier (0,17 km^2) nourri par les avalanches dans la North Cascade Range, Washington. L'altitude approximative de la ligne d'équilibre (ELA) pour cet appareil glaciaire, officieusement baptisé "Vesper" glacier, se situe à 1 475 m, quelques 300 m en-dessous de la valeur de l'ELA dans cette région. L'accumulation annuelle estimée était de 6 100±675 mm pendant les deux ans de l'étude; 15 à 30% de cet apport résulte de l'avalanche et de la neige transportée par le vent. L'ablation annuelle moyenne durant cette période a été de 5 350 mm, donnant un bilan net total de plus de 1 600 mm pour la période de deux ans étudiée. Le "Vesper" glacier subsiste bien en dessous de la ligne de névé de la région à cause d'un excès local de précipitations, de contributions substantielles des avalanches et d'une exposition Nord favorable.

Les moraines néoglaciaires indiquent que le maximum d'abaissement de l'ELA dans cette période était approximativement de 165 m et survint avant A.D. 1670. De faibles avancées survinrent au cours du 19e siècle. Ces mesures d'identification sont cohérentes avec les données géologiques dispersées rapportées de l'observation d'autres glaciers de la Cascade Range. Bien que la relation entre l'abaissement local de la ligne des neiges et l'activité des avalanches soit pour le moment incertaine, ces données font penser que les glaciers nourris par les avalanches peuvent être un utile enregistreur des fluctuations climatiques.

ZUSAMMENFASSUNG. *Massenbilanz des "Vesper" Gletscher, Washington, U.S.A.* An einem kleinen (0,17 km^2), lawinengespeisten Gletscher in der North Cascade Range von Washington wurden in den Jahren 1974 und 75 glaziologische und geologische Untersuchungen durchgeführt. Die ungefähre Höhe der Gleichgewichtslinie auf diesem Eiskörper, der informell "Vesper" Gletscher heisst, liegt bei 1 475 m, etwa 300 m unter der regionalen Gleichgewichtslinie. Die jährliche Akkumulation während der beiden Studienjahre lässt sich auf 6 100±675 mm abschätzen; 15 bis 30% dieses Zuwachses stammen von Lawinen und Schneedrift. Die mittlere Jahresablation während der Untersuchungsperiode betrugt 5 350 mm, was auf eine Netto-Gesamtbilanz von +1 600 mm für die Zweijahresperiode führt. Der "Vesper" Gletscher erhält sich sehr gut unterhalb der regionalen Schneegrenze infolge des übermässigen lokalen Niederschlages, des wesentlichen Zutrages durch Lawinen und seiner günstigen Exposition nach Norden.

Jungglaziale Moränen weisen darauf hin, dass die Gleichgewichtslinie maximal um 165 m abgesunken ist, und zwar vor A.D. 1670. Kleinere Vorstösse erfolgten im 19. Jahrhundert. Die Erkundungsmessungen stimmen gut mit den spärlichen geologischen Daten von anderen Gletschern in der Cascade Range überein. Obwohl die Beziehung zwischen dem regionalen Absinken der Schneegrenze und der Lawinenhäufigkeit derzeit noch unbekannt ist, lassen diese Daten vermuten, dass lawinengespeiste Gletscher nützliche Indikatoren von Klimaschwankungen sind.

INTRODUCTION

Small alpine glaciers in temperate regions respond rapidly to climate change. Geologic features such as moraines, trimlines, and outwash trains result from the response of glaciers to climatic fluctuations, but there is no simple relationship between climate and the formation of these persistent geologic features (Meier, 1965). Mass-balance measurements on a glacier

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provide useful indications of climate change long before response at the glacier terminus, and are essential to research on the dynamics of glaciers. These dynamics must be understood before geologic evidence can be safely used to infer past climates.

A reconnaissance study of small alpine glaciers can provide substantial information on the response of these ice bodies to changes in mass balance. Many of these small glaciers are nourished in part or entirely by avalanches (Meier, 1973), complicating the measurement of mass balance. Thus, it is important to understand the limitations on climate interpretation imposed by measurements from such glaciers. We report data collected during 1974 and 1975 on "Vesper" glacier (informal name), a small avalanche-nourished glacier located in the North Cascade Range of Washington. The locations of moraines are utilized to infer local and regional snow-line lowering which resulted in more positive mass balance and Neoglacial advances of the glacier.

LOCATION

"Vesper" glacier is the larger of two small ice bodies located immediately north of Vesper Peak (1 894 m), in the southern part of Washington's North Cascade Range (Fig. 1). Figure 2 indicates local relationships; the glacier covers approximately 0.17 km² of the 5.2 km² Copper Lake basin, and has a mean altitude of 1 475 m. The terminus of this small valley glacier, located at an elevation of 1 110 m, is among the lowest in the conterminous United States (Post and others, 1971). Field observations, discussed below, suggest that active ice extends only to 1 250 m. Below this elevation, the "glacier" is largely a snow-field.

"Vesper" glacier lies in a narrow slot cut into quartz diorite of early Oligocene age; its orientation coincides with the principal joint set in the area (Dungan, unpublished). Topography in the area is rugged; local relief approaches 1 000 m. The lake and glacier are surrounded by cliffs and gullies which shed snow and debris onto the glacier and cirque floor. More than 85% of the area is affected by avalanches; as a result, vegetation is generally sparse in this sub-alpine and alpine basin. Copper Lake occupies the floor of a cirque last filled with

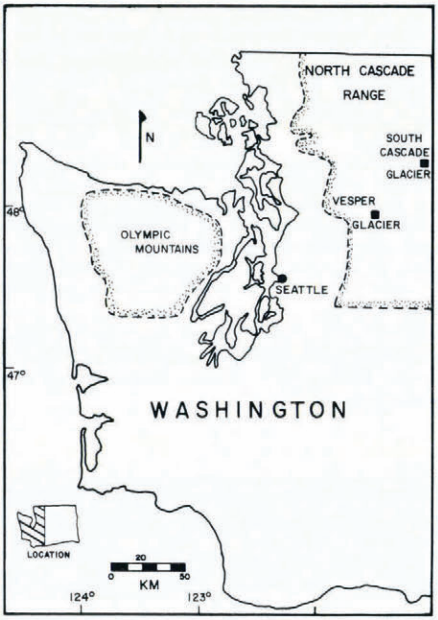

Fig. 1. Location map of the North Cascade Range, Washington.

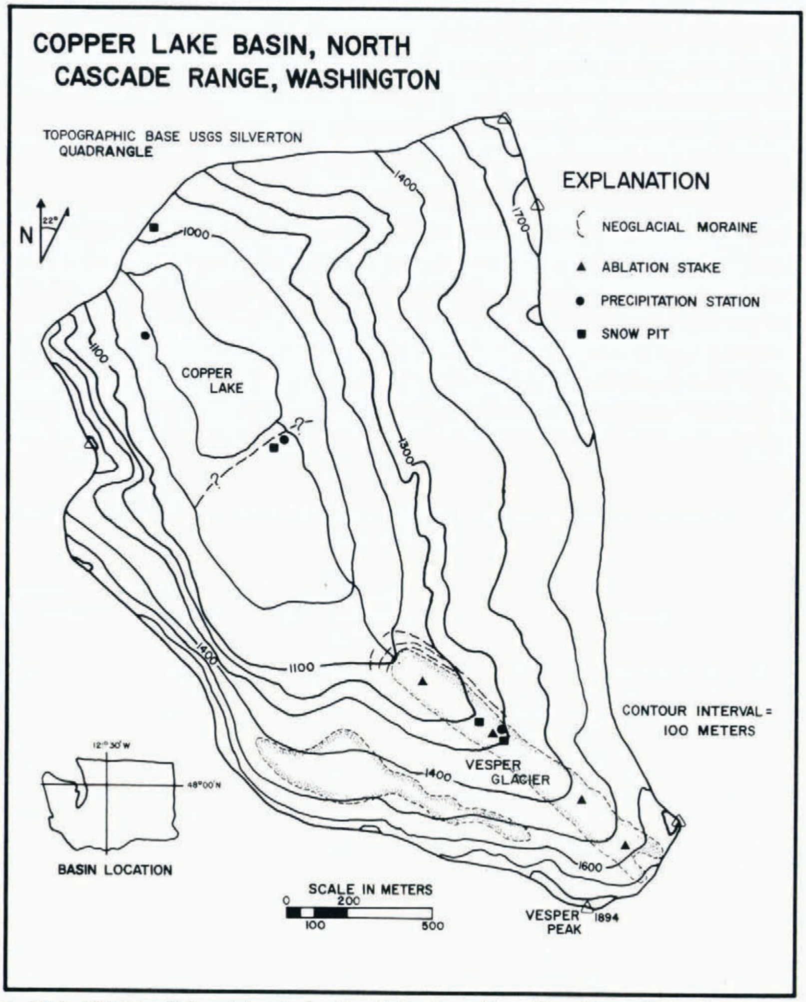

Fig. 2. Map of Copper Lake catchment showing the location of sampling sites and Neoglacial moraines.

ice during late stages of the Fraser (latest Wisconsinan) Glaciation. The lake forms the headwaters of Williamson Creek, which flows 10 km down-stream to Spada Lake, drinking-water supply for some 250 000 residents of nearby Snohomish and King Counties. Moraines flanking "Vesper" glacier (Fig. 2), numerous nivation hollows, and several moraine-like features attest to extensive Neoglacial activity.

Field studies commenced in April 1974 and continued until early November, encompassing the ablation season; data were collected from late May until late October during the 1975 ablation season as well. Results and interpretation of our mass-balance studies are discussed in the following sections.

DETERMINATION OF MASS BALANCE

Field studies were primarily concerned with defining the water budget for "Vesper" glacier and the Copper Lake basin. Conservation of mass for glaciers on an annual basis may be stated as (Mayo and others, 1972):

$$\Delta S = \bar{C}_{\mathrm{a}} - \bar{A}_{\mathrm{a}} \tag{1}$$

where ΔS is the change in glacier storage, $\bar{C}_{\mathrm{a}}$ the total measured accumulation from direct precipitation and snow transported by avalanche or wind, and $\bar{A}_{\mathrm{a}}$ the total ablation, including snow melt and evaporation, all expressed in water equivalent.

For the entire Copper Lake basin, re-arranging and expanding Equation (1) gives:

$$R = P - E \pm \Delta S \tag{2}$$

where R is the annual run-off averaged over the basin, P the annual precipitation averaged over the basin, E the annual evapotranspiration averaged over the basin, and ΔS the annual change in ice and ground-water storage averaged over the basin, all expressed as an equivalent thickness of water.

Calculation of water balance for the glacier and catchment requires data for: precipitation influx, ablation on the glacier, run-off from Copper Lake, evapotranspiration, and changes in water storage. Mass-balance data collected during 1974 and 1975 are summarized in Table I. Measurement techniques, measurements, and estimated values for these parameters are discussed below.

TABLE I. SUMMARY OF MASS BALANCE FOR COPPER LAKE BASIN AND "VESPER" GLACIER FOR 1974 AND 1975

Period	*Total precipitation (snow and rain)* mm	*Run-off* mm	*Ablation ("Vesper" glacier)* mm
1 October 1973–30 April 1974	4 700*	1 200†	560‡
1 May 1974–20 June 1974	520*	1 510†	1 100‡
21 June 1974–30 June 1974	60	370	230
1 July 1974–31 July 1974	260	1 090	1 250
1 August 1974–31 August 1974	80	760	1 450
1 September 1974–30 September 1974	120	470	850
1 October 1973–30 September 1974	5 740	5 400	5 440
1 October 1974–31 October 1974	155	35†	310
1 November 1974–30 April 1975	3 285*	2 120†	610‡
1 May 1975–23 May 1975	285	530†	255‡
24 May 1975–6 July 1975	305	725†	1 110
7 July 1975–19 July 1975	70	90†	400
20 July 1975–22 August 1975	70	190†	1 500
23 August 1975–13 September 1975	275	80†	650
14 September 1975–30 September 1975	35	10†	450
1 October 1974–30 September 1975	4 480	3 790	5 285

* Estimated after Schermerhorn (1967) and from the 1974–75 relation between Olney Pass and Copper Lake area precipitation.

† Estimated from Wallace River run-off; run-off from 13 September 1975 to 25 October 1975 is estimated from ablation and precipitation during the period.

‡ Estimated from detailed snow-course measurements (Soil Conservation Service) at Stevens Pass (1 300 m), Washington (45 km south-east of "Vesper" glacier).

Precipitation

At elevations above 900 m in the North Cascades, more than 80% of annual precipitation falls as snow; amounts range from 2 000 to more than 4 000 mm (Rasmussen and Tangborn, 1976). In the study area, winter (1 October to 30 April) precipitation accounts for 80% of the annual total. Precipitation influx to the Copper Lake area was measured by several non-recording gages and one continuous-recording gage during the summer and fall of 1974; during 1975 the recording gage was moved to lower elevations along Williamson Creek. Water content of the snow-pack at 1 000 m was determined in early April 1974, and in late May 1975.

The Everett Water Department maintains a weather station at Olney Pass, located some 15 km west of Copper Lake; additional nearby weather stations are shown in Figure 3. Monthly precipitation measured at Copper Lake during the study period was highly correlated with, and averaged 1.3 times, precipitation amounts measured at Olney Pass. Measurements were made only during the summer and fall, so this relationship is based on less than 20% of annual precipitation. Yearly precipitation can also be estimated using the effective-elevation technique suggested by Schermerhorn (1967). Figure 4 shows the relationship for precipitation stations near Copper Lake; the Copper Lake value, calculated from 1974–75 measurements, appears consistent with the other data, and with the regional gradient shown by Rasmussen and Tangborn (1976).

Precipitation at Olney Pass from 1 October to 30 September in 1974 and 1975 amounted to 4 335 and 3 380 mm, respectively; mean annual precipitation (1965–75) is 3 700 mm. Utilizing these values and Figure 4, annual precipitation on "Vesper" glacier is calculated as 4 700 mm; influx in 1974 was 5 635 mm, while in 1975 it was 4 395 mm.

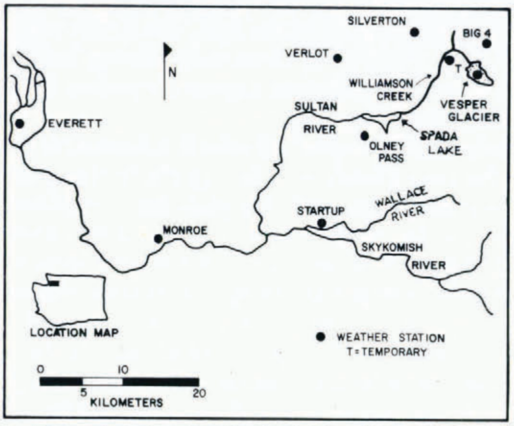

Fig. 3. Meteorological stations in the vicinity of Copper Lake basin.

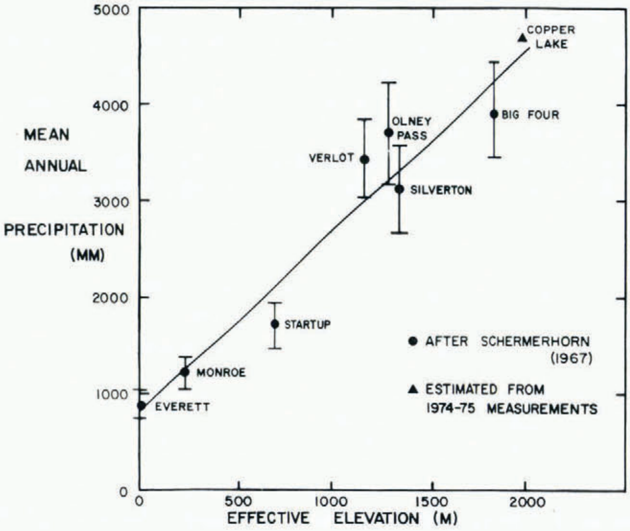

Fig. 4. Effective elevation/precipitation gradient in the vicinity of Copper Lake basin (after Schermerhorn, 1967). The mean and 1σ value for each point were calculated from precipitation records for the stations: Everett (1916–75); Monroe (1938–75); Startup (1952–75); Verlot (1947–78); Silverton (1953–68); Big Four (1928–42, missing months); Olney Pass (1965–75); and Copper Lake (1974–75, partial records).

Ablation

Ablation, the loss of snow and ice, primarily by melt, occurs at significant rates from late April or early May until October on glaciers in the North Cascades. Meier (1962) has termed this the "ablation season". Melt was measured during most of this period on "Vesper" glacier in 1974 and 1975. However, snow melt also takes place during the accumulation season when warm storms sweep off the Pacific Ocean, and during infrequent sunny, warm periods of early spring. These "losses" occur while the Copper Lake area is inaccessible. Estimation of this ablation requires data from a nearby snow course.

Ablation on "Vesper" glacier was measured from 20 June to 2 November 1974, and from 23 May to 25 October 1975 by means of wooden snow stakes at elevations of 1 140, 1 260, 1 430, and 1 560 m. Considering the size of the glacier, our array is thought to be adequate. Stakes were read at three-day intervals in the summer of 1974, and less frequently during the fall of that year and in 1975. Snow density, measured in snow pits, averaged 0.55 Mg m^{-3} during the summer of both years; values were slightly higher in the fall, and lower ($\approx$0.40) in the spring months. Measured ablation in 1974 was 3 780 mm, while a loss of 4 420 mm was recorded in 1975. Losses recorded at each stake during individual periods were erratic, but summer ablation at the stake with the highest elevation (1 560 m) was approximately 20% lower than that recorded at 1 140 m.

Ablation during periods when "Vesper" glacier is inaccessible can be estimated from snow-course measurements at Stevens Pass (1 300 m), 45 km to the south-east of the glacier.

Ablation before the measurement period equals the cumulative precipitation before the measurement period, minus the water content of the snow pack at the beginning of the measurement period. Calculation of pre-measurement ablation at Stevens Pass during the two study years suggests that substantial ablation occurred during the early spring of each year. It is also likely that a series of very warm storms resulted in winter ablation during January 1974. Ablation estimates for "Vesper" glacier during the spring of 1974 appear high (Table II), but the weather was unusually sunny and warm during late May and early June. The ablation estimate from 30 April to 20 June 1974 agrees well with the 1 200 mm of ablation measured at a snow pit immediately north of Copper Lake from 13 April to 20 June 1974 (Fig. 2). It is more difficult to evaluate the accuracy of estimates for the other two periods (Table II). If most of this estimated ablation occurred between March and June of each year, an ablation rate of approximately 10 mm d^{-1} is required. Estimated rates averaged 10 to 15 mm d^{-1} during April 1974 and nearly 20 mm d^{-1} in May at the Copper Lake snow pit. W. V. Tangborn (personal communication in 1978) has measured comparable rates for two-week periods at higher altitude on the South Cascade Glacier during early May. Thus, use of snow-course data from Stevens Pass to estimate unmeasured ablation on "Vesper" glacier seems reasonable.

TABLE II. ESTIMATED ABLATION DURING PERIODS WHEN "VESPER" GLACIER WAS INACCESSIBLE

Period	*Ablation* mm
1 October 1973–29 April 1974	560
30 April 1974–20 June 1974	1 100
1 November 1974–23 May 1975	865

Taking the estimates in Table II plus the measured values (Table I) gives total ablation of 5 440 mm in 1974 and 5 285 mm in 1975. The accuracy of these figures is difficult to evaluate; direct ablation measurements are subject to a variety of errors (see Meier and Tangborn, 1965; Müller and Keeler, 1969), but they are not likely to introduce errors of more than 5 to 10% in measured figures. Estimated ablation for each year may be in error by as much as 200 to 300 mm. Finally, integration of point measurements over the surface of the glacier doubtless introduces some error, but the density of stakes (1 per 0.04 km²) seems adequate.

The yearly pattern of ablation rates is similar to temperature patterns recorded at Olney Pass (Fig. 5) where July and early August temperatures average 14°C. On "Vesper" glacier, temperatures during peak ablation periods averaged 8.5°C, and were closely related to temperatures recorded at Olney Pass. Five-day ablation rates measured on the glacier during 1974 are highly correlated ($N = 15$, $r^2 = 0.84$) with Olney Pass temperature during the summer and fall; highest measured rates occurred in the warmest period of the summer, and averaged 79 mm d^{-1} over a five-day period. During sunny, warm periods, ablation is primarily a function of the net radiation balance, which is highly correlated with mean air temperature. A reasonable estimate of summer ablation on "Vesper" glacier can thus be obtained from temperature measured some 15 km away.

Ablation rates and total ablation are remarkably high on "Vesper" glacier; comparable snow melt has been reported at the Blue Glacier and in other maritime zones (LaChapelle, 1959).

Run-off

Snow melt is the principal component of run-off from alpine and sub-alpine zones; highest flows in the Cascades generally occur during the summer months. Discharge from Copper Lake basin was monitored in 1974 from mid-June to early November by a continuous recording gage installed at the north-west end of the lake. The lake gage was destroyed by an avalanche in early 1975, and discharge measurements were made on a reconnaissance basis during the 1975 ablation season.

Monthly run-off for the 1975 water year was estimated from discharge measured on the Wallace River, located 20 km south of Copper Lake. The Wallace catchment receives about 30% less precipitation than the Copper Lake area. However, Dethier (unpublished) has demonstrated that daily and monthly discharge on the Wallace River is highly correlated with that measured on Williamson Creek, which drains Copper Lake. Monthly run-off from Copper Lake catchment was taken as 1.4 times Wallace River run-off. As a rough check on these estimates, measured ablation rates were applied to the average monthly snow cover in the basin. Monthly run-off then equalled this volume plus precipitation during the period. Run-off calculated by this method was within 15% of that estimated from Wallace River run-off.

Discharge measurements during 1974 are thought to be accurate to within 10 to 15% for most periods. Estimated run-off before June in 1974 and during 1975 is dependent on correlation with Wallace River records, precipitation amount, area snow cover, and snow-melt rates. Listed values are probably accurate within 25% and may be substantially better, but the error is difficult to evaluate. Run-off in 1973–74 was approximately 5 400 mm, while in 1974–75 it was about 3 800 mm; measured peak discharge was 5.2 $m^3 s^{-1}$. Mean annual run-off from the entire Sultan River basin (193 km²) down-stream from Copper Lake is 3 700 mm (Rasmussen and Tangborn, 1976). This basin includes considerable forested low-land area, so it is reasonable to calculate upland contributions as more than four meters.

Storage

Water may be stored in alpine catchments as ground water, as snow or ice, or as liquid water within glaciers. Ground-water storage in the study area is minor because thin surficial deposits and impermeable bedrock dominate the basin, run-off is rapid, and there is little available storage. Annual ΔS for ground water can be considered equal to zero. Net evaporation from Copper Lake basin is probably close to 100 mm (Puget Sound Task Force, 1970); thus we can assume $E \approx 0$, also.

At the close of the ablation season, the volume of the new firn covering older firn or ice (minus the measured ice ablation where ice is exposed) provides an accurate measure of ΔS

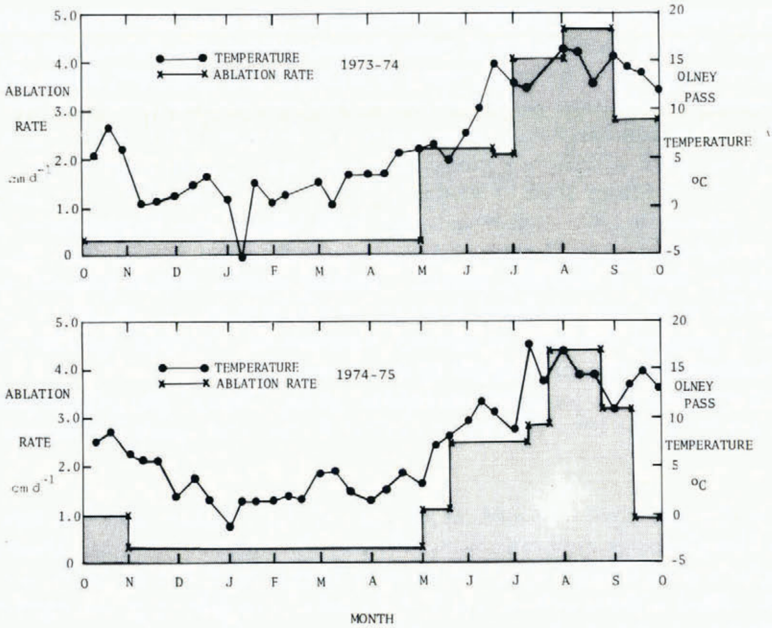

Fig. 5. Graph showing the relationship between average ablation rate on "Vesper" glacier and temperature measured at Olney Pass for 1974 and 1975.

for the glacier and for the basin. We made a detailed snow probe and crevasse survey in 1974 and a reconnaissance study in 1975 to measure "net" accumulation on "Vesper" glacier. In 1974, net accumulation was equivalent to 1 200 mm of water, whilst net accumulation for 1975 was estimated as 400 mm. Newly fallen snow mantled the fall surface to depths of 500 mm when the final snow surveys of each year were made. Ablation rates decrease to near zero by early October, and the sun never strikes the glacier after mid-September; thus 1 October is considered as the beginning of the accumulation season, even though significant accumulation may not occur until mid-November.

DISCUSSION

Annual ablation, precipitation as rain, plus net storage at the end of the ablation season must equal the total water influx to the surface of a glacier. However, the budget for "Vesper" glacier during the study years (Table III) suggests that accumulation exceeded precipitation by some 15 to 30%. Figure 6 portrays the relationship between total and net accumulation patterns on "Vesper" glacier for 1974 and 1975. While our measurements and estimates include some inaccurate figures, effects are likely to compensate, and discrepancies of 1 000 mm are extremely unlikely. Results are also reasonably consistent with a net balance of 1 050 mm (1974) and ≈0 mm (1975) measured on South Cascade Glacier, located 40 km to the north-east (Tangborn, 1980). Precipitation in the Copper Lake area is approximately 1.5 times that measured at the South Cascade site.

TABLE III. ANNUAL WATER AND ICE BALANCES FOR "VESPER" GLACIER IN 1974 AND 1975

Period	*Precipitation* mm	*Accumulation* mm	*Glacier storage change* mm
1973–74	5 740±575	6 640±690	1 200±120
1974–75	4 480±450	5 685±660	400± 60

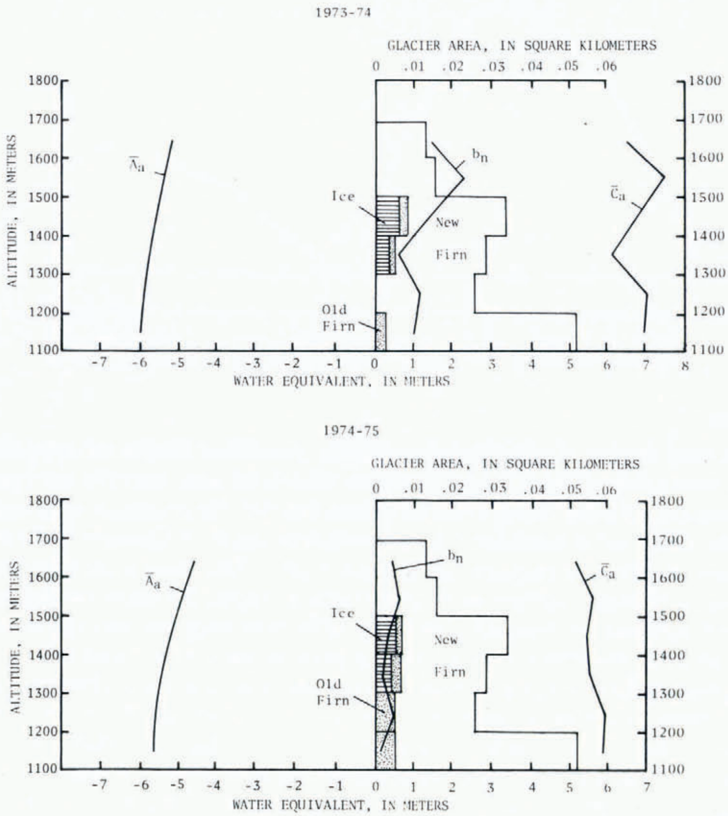

Fig. 6. Net balance b_n total accumulation $\bar{C}_a$ and total ablation $\bar{A}_a$ as functions of altitude and glacier and basin area–altitude distribution.

Two sources of the "excess" accumulation are wind-blown snow and avalanche-transported snow. It is likely that the lower 300 m of the glacier is actually a permanent snow-field fed by avalanches that travel down the glacier. A lack of crevasses below 1 250 m supports this observation. While the upper three ablation stakes displayed as much as 40 m of down-slope motion, the lowest snow stake did not move in 1974 or 1975, and the stake installed in 1974 melted out of avalanche debris in early fall 1975 within a few meters of the position in which it was first placed in 1974. Avalanches (and perhaps wind-blown snow) thus play a central role in the pattern of accumulation on "Vesper" glacier and contribute 15 to 30% of the total mass influx to the glacier. Tangborn and others (1977) suggest that these processes contribute as much as 35% of the yearly accumulation on South Cascade Glacier.

The mass balance for the Copper Lake catchment, neglecting the minor effects of evapotranspiration and storage changes, suggest that run-off was approximately equal to precipitation in 1974. Figure 7 shows the water balance for the Copper Lake catchment during 1974 and 1975. The two years are separated because run-off data for 1975 are only approximate. Estimated run-off in 1975 is about 700 mm less than the precipitation for that period, an error of some 17%. The error is likely to be a result of yearly differences in precipitation for the Copper Lake and Wallace River areas, inaccurate estimates of snow cover, and difficulties inherent in applying ablation rates measured on the glacier to the entire basin. Given these uncertainties, the error does not seem unreasonable.

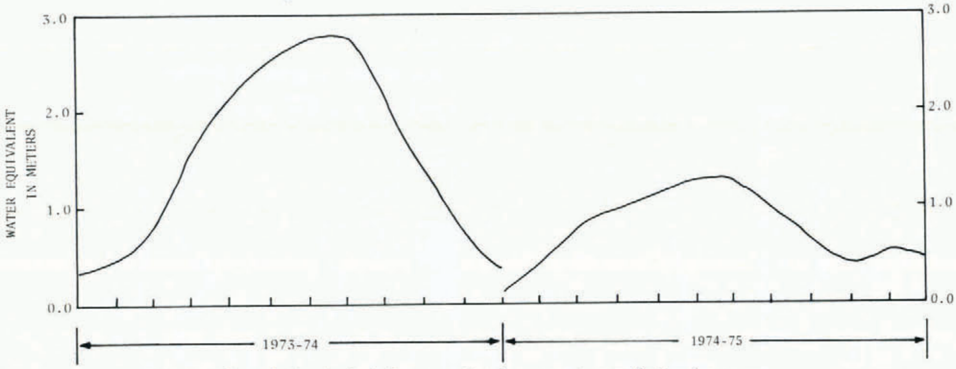

Fig. 7. Cumulative basin balance 1 October 1973 to 30 September 1975.

Neoglacial features

Distribution and dating of Neoglacial moraines provide a means of estimating past ELAs and changes in elevation of the glacier terminus which in turn permits an approximation of glacier mass balance. Nested Neoglacial moraines border the terminus and north-east side of "Vesper" glacier (Fig. 2); a moraine (?) immediately south of Copper Lake may be a rock-avalanche deposit in part and requires additional study. Moraines near the glacier are nearly symmetrical, sharp-crested, and rise one to four meters above the surrounding terrain. Dating of these features is difficult; reconnaissance study of lichens suggests that the record is adversely affected by winter kill. Weathering rinds are not present on the majority of exposed clasts, and various techniques useful in dating deposits east of the Cascade crest (Porter, 1975, 1976) are not appropriate here. Coring of trees provides minimum age estimates for the moraines, as tree survival may relate to avalanche frequency, and ecesis time is unknown. It is interesting to note that a U.S. Geological Survey topographic mapping team found the hanging glacier and "Vesper" glacier to be continuous in 1898; they plotted the terminus of this glacier near the innermost pair of moraines. St Helens "Yn" tephra (*c.* 3400 B.P.) does not appear to be present on the moraines, but more detailed investigation is required.

"Vesper" glacier is not forming a moraine at present and it is likely that active ice does not extend below 1 250 m. Because the accumulation pattern on the glacier is strongly modified by avalanche activity, a snow-line does not form, or was not observed during 1973–76. The boundary between areas of net accumulation and net ablation on a glacier can also be expressed as an equilibrium-line altitude (ELA). For small alpine glaciers, the mean altitude of the glacier provides a baseline useful in measuring changes in ELA over time (Paterson, 1969; personal communication from S. C. Porter in 1978). We have calculated present and Neoglacial ELA values by this technique (Table IV).

TABLE IV. NEOGLACIAL FEATURES IN THE "VESPER" GLACIER AREA

Description	*Approximate date of formation*	*Glacier elevation*		*Calculated ELA§* m	*Lowering of ELA from present* m	*Change in elevation of glacier terminus* m
		Head m	*Toe* m			
Present glacier	—	1 700	1 250	1 475	0	0
Innermost pair of moraines	<1900*	1 700	1 100	1 400	75	−150
Outer moraine near glacier	<1865†	1 700	1 050	1 375	100	−200
Moraine (?) near Copper Lake	<1670‡	1 700	920	1 310	165	−330

* Scrub vegetation, no lichens.
† Age of oldest cored tree *c.* 110 years.
‡ Age of oldest cored tree *c.* 305 years.
§ Mean altitude of glacier, or former glacier.

The current ELA for "Vesper" glacier is approximately 1 475 m (regional value *c.* 1 800 m), and moraines formed in the last 150 years suggest an ELA depression of approximately 100 m. If the pre-1700 feature is a moraine, it was formed by "Vesper" glacier, the hanging glacier, and smaller contributing ice bodies. The area of the glacier is thus uncertain, and the calculated ELA depression of 165 m must be regarded as tentative. Limited data from other North Cascade sites (Miller, 1969; Crandell, 1969; Crandell and Miller, 1974; Porter, 1976) indicate that regional ELA depression amounted to 100 to 200 m (personal communication from S. C. Porter in 1978), and these figures are consistent with observations by Scott (1977) for the Cascades of Oregon.

"Excess" accumulation from avalanches and substantial local precipitation result in the persistence of "Vesper" glacier at an elevation 250 to 400 m below that of other North Cascade ice bodies. Preliminary data indicate that the pattern of Holocene fluctuations on "Vesper" glacier is compatible with measurements made on other North Cascade glaciers. Thus glaciers which receive a substantial proportion of their accumulation from wind-blown or avalanche-transported snow may be useful as climatic indicators. This hypothesis implies that the accumulation of avalanche deposits and drifted snow are functions of total precipitation; increased precipitation apparently results in increased accumulation on the glacier surface and surrounding slopes. However, the processes which link total snow-fall and avalanche activity are not well-documented at present and observations must remain qualitative. The depressed regional snow-line which characterized the mid- to late-nineteenth century resulted in positive net balances on "Vesper" glacier; additional investigation of the dynamics of small glaciers may help to separate the effects of decreased ablation from increases in total accumulation (Tangborn, 1980).

SUMMARY

"Vesper" glacier persists 300 m below the regional threshold of glaciation (Porter, 1977) as a result of excessive local precipitation and the accumulation of transported snow on the glacier surface. Precipitation amounted to 5 635 and 4 480 m in 1974 and 1975 (estimated average, 4 700 mm), respectively, while ablation in these years averaged 5 350 mm. Accumulation in excess of precipitation, largely from avalanches, resulted in net accumulation equal to 1 200 mm in 1974, and 400 mm in 1975; net balance figures compare favorably with those measured at nearby South Cascade Glacier.

Moraines near the terminus of "Vesper" glacier reflect advances in the past 3 400 years, probably in the last 500 years. Snow-line lowering of approximately 165 m apparently occurred during the most extensive advance. The Neoglacial chronology and relative ELA depression at "Vesper" glacier correspond with sparse data from other glaciers in the North Cascade Range. Changes in the position of the terminus and moraine formation are apparently systematic, which suggests that avalanche-nourished bodies like "Vesper" glacier are useful for climatic reconstruction.

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