# THE ANNUAL BALANCE AND CLIMATIC SENSITIVITY OF NORTH CASCADE, WASHINGTON GLACIERS

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## ABSTRACT

The annual balance has been directly measured on 10 North Cascade glaciers in 1984, 1985, 1986 and 1987. Based on these data an annual balance prediction method was designed and tested. Comparison of measured versus predicted annual balances indicates an error in annual balance determination of +0.20-0.28 m of water equivalent. The method is based on annual measurement of the accumulation area ratio (AAR), and determination of the perennially constant activity index and area/altitude distribution on each glacier. The activity index method was used to calculate the annual balance of forty seven North Cascade glaciers in 1984-1987. The mean balance during the four year period was - 0.33 m.

From the mass balance records, it is apparent that North Cascade glaciers can be divided into 6 climatic sensitivity types. Each glacier type responds differently to specific climatic conditions. The climatic sensitivity type of a glacier is a result of its geographic location and topographic position and can be determined from analysis of topographic position and geographic location. Since 1977 warmer, drier climatic conditions have prevailed in the North Cascades, resulting in the retreat of 42 of the 47 glaciers examined.

## INTRODUCTION

There are 756 glaciers with a total area of 267 km02 in the North Cascades (Post et al., 1971)(Figure 1). Glaciers for this study are defined as perennial bodies of snow and ice with an area ¼0.1 km02.

The North Cascades exhibit a system of peaks and ridges separated by deep glaciated valleys. The altitutde range of valley floors are from 600 to 1000 m. Ridge crests are from 1900 to 2700 m and trend east-west with the exception of the North Cascade divide. The region is densely forested up to 1400 m. The tree line which varies from 1500 to 2100 m, is commonly above the accumulation zone of the glaciers.

Annual precipitation ranges from 2.0 m to 4.0 m on the west side of the range, and from 1.0 to 2.0 m on the east or dry side side of the range. Annual temperatures are moderated by the strong maritime air flow. The mean annual temperature at the glaciation threshold ranges from 0.0 to 2.0 C, decreasing with increasing distance from the ocean (Porter, 1977).

The weather of the North Cascades is controlled by the atmospheric pressure distribution over the northeast Pacific Ocean. From October until May, the weather of Washington is dependent on the position and relative strength of the Aleutian Low and Pacific High (Yarnal, 1984). The Aleutian Low strengthens and moves south during the fall. Simultaneously, the Pacific High weakens and shifts south. The result is a southwesterly to westerly airflow across the region. Embedded in this flow are cyclonic disturbances originating over the northeast Pacific Ocean that are the

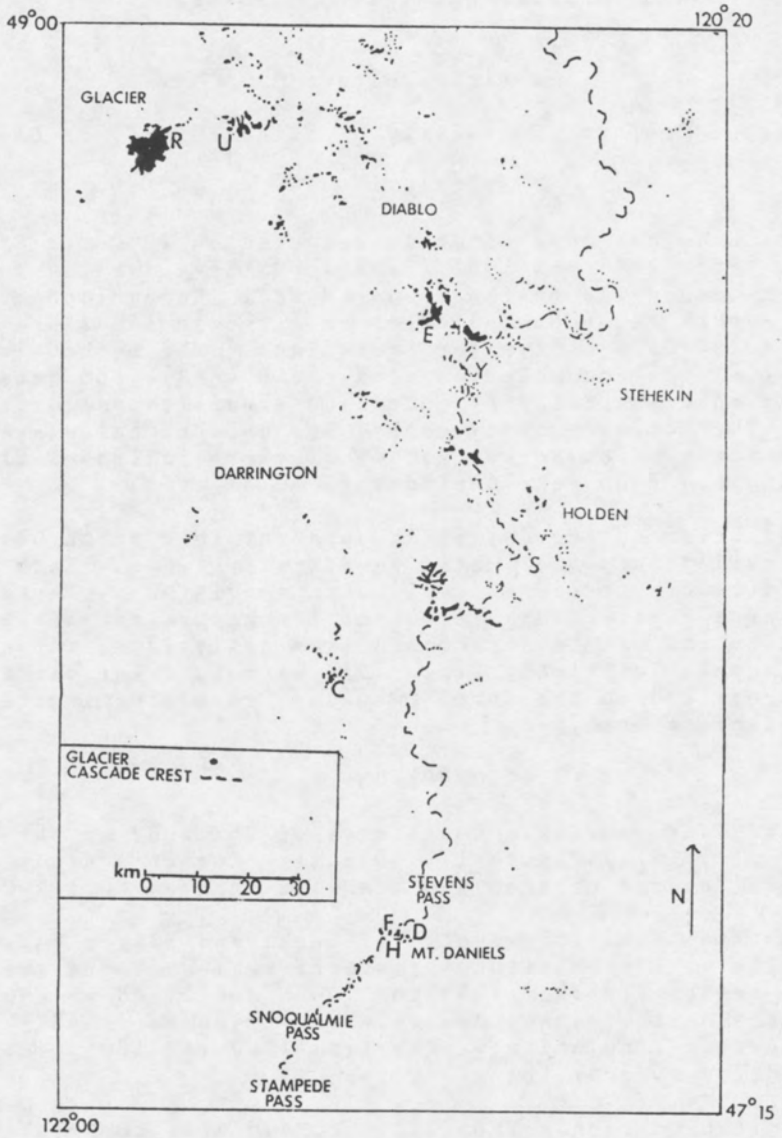

Figure 1. Location of glaciers where annual balance measurements are completed. C=Columbia, D=Daniels, E=Eldorado, F=Foss, H=Lynch, L=Lewis, R=Rainbow, S=Spider, U=Lower Curtis, Y=Yawning.

primary precipitation source for the North Cascades (Yarnal, 1984). The heaviest precipitation occurs in the months of October-December. In the spring, the Aleutian Low moves northwest and weakens. The Pacific High expands and strengthens, causing a west to northwest flow of generally dry stable air from the Pacific High pressure region. The July-September period is noted for a lack of precipitation. The changing influence of the Aleutian Low is apparent in the cloud cover decrease from 75% during the winter to 30% during the summer (Tangborn, 1980).

The United States Geological Survey (USGS) has monitored the mass balance of South Cascade Glacier since 1955. The extensive hydrologic and mass balance measurements have greatly increased the understanding of glacier hydrology, the annual variation of mass balance, and of the climatic parameters controlling mass balance on North Cascade glaciers (Meier and Tangborn, 1965; Tangborn et al. 1975; Tangborn, 1980). North Cascade glaciers fall into several different categories based on their sensitivity to specific climatic conditions. South Cascade Glacier is representative of only one climatic sensitivity group. Thus, no quantitative climatic or hydrologic conclusions can be drawn for the bulk of North Cascade glaciers, based on data from South Cascade Glacier alone. For this reason the Foundation for Glacier and Environmental Research (FGER) in 1984 founded the North Cascade Glacier-Climate Project. The North Cascade Glacier-Climate Project has established a system for annually monitoring the annual balance and terminus activity of 47 North Cascade glaciers. The annual balance of 10 glaciers is directly measured. Based on these data an annual balance prediction model was developed, tested and used to calculate the annual balance of the remaining 37 glaciers under investigation.

## ANNUAL BALANCE METHODS

The goal of the North Cascade Glacier-Climate Project is to determine the annual balance with reasonable accuracy on numerous glaciers, rather than strict accuracy on a few. Mass balance measurements are conducted during the later portion of each ablation season. Thus, only annual balance is measured. Techniques of mass balance measurement used in this study are discussed in greater detail by Pelto (in press).

In the accumulation zone, annual accumulation layer thickness is determined at the end of the ablation season using crevasse stratigraphy, snowpits, and probing with a density of 200 points/km02. Techniques used are those of Ostrem and Stanley (1969), who stated that for the best accuracy an acceptable density of measurements was 100 points/km02. Crevasse stratigraphic measurements are conducted only in narrow, vertically walled crevasses that have distinguishable dirt bands. A measuring tape is lowered to the ablation surface of the past summer, marked by a 2 to 5 cm thick band of dirty firn or glacier ice, in several spots on each crevasse wall within a space of several meters. The average thickness is taken to be the accumulation layer thickness at that point.

Two to four snowpits are completed on each glacier. The density and water equivalent of the snow-firnpack is measured in two vertical profiles in each snowpit. Probing is an accurate method of measuring accumulation layer thickness in the North Cascades, since ice lenses indicative of internal accumulation are rarely present (Meier and Tangborn, 1965; Pelto, 1987). Probing transects are started from bare glacier ice and then continued across the glacier in zones of limited crevassing. Probing is used in snow depths of less than 2 m because of the difficulty in identifying the previous ablation surface at greater depths.

Comparison of results obtained from snowpits, crevasse stratigraphy and probing, indicates that the error in measurement of accumulation layer thickness is smallest using crevasse stratigraphy (Pelto, 1988). The narrow vertically walled crevasses are approached on skis, and the skis are not removed during measurements.

All annual balances and annual balance errors are in meters of water equivalent, reported errors are the standard deviation of the observed data values. Standard maximum errors in depth measurment at any point are +0.05 m, and in density determination +0.04 g/cm03. The resulting error in annual balance assessment for the accumulation zone is +0.10 m. The density of measurements in the accumulation area is considerably greater than is typical, causing a smaller error.

Below the snowline, ablation triangles are used to determine annual ablation. An ablation triangle consists of three stakes drilled into the glacier at 3 m intervals, forming an equilateral triangle. Two to four triangles are emplaced on each glacier. Each stake is a 3.3 m long white fiberglass pole. Ablation triangles are placed in a sequence from regions that first lose their snowcover, to regions where snowcover persists late into the ablation season. Each triangle is considered representative of annual ablation for portions of the ablation zone that are exposed at the same time. This method helps distinguish the changes in ablation rate as the summer progresses. Ablation measurements are made at nine points on the triangle periphery in late July and early August, identifying the ablation during the first three months of the ablation season. Ablation measurements are repeated at the end of the ablation season, identifying total annual ablation. The stakes are drilled into the ice at the end of the ablation season, and again after the initial late July and early August ablation measurement.

The error in annual ablation measurement at a point is +0.30 m, due to ice density variations, low sampling density and stake settling. In contrast to the accumulation zone, measurements in the ablation are sparser than typical; hence, errors are greater. A mass balance map is then compiled for each glacier. The error in annual balance calculation for an entire glacier is +0.12-0.20 m, except during years of extreme ablation, when the error is probably higher. The annual balance in 1984, 1985, 1986, and 1987 for ten North Cascade glaciers is shown in Table 1, and glacier locations are noted in Figure 1.

## AAR-ACTIVITY INDEX METHOD

The accumulation area ratio (AAR) is the percentage of a glaciers total area above the equilibrium line altitude (Meier and Post, 1962). The activity index is the change in annual balance with elevation (balance gradient), in the vicinity of the equilibrium line (Meier and Post, 1962).

Knowing the mass balance of 10 North Cascade glaciers still does not satisfactorily identify the mass balance of North Cascade glaciers as a whole or their varying sensitivity to climatic conditions. For this reason a simpler method of mass balance determination was developed. The mass balance (Bn) of a glacier is calculated using:

$$Bn = \int_{z_t}^{z_u} b(z)\ a(z)\ dz \qquad (1)$$

where a(z) is the area/altitude distribution, b(z) is the balance gradient, $z_t$ is the terminus elevation, and $z_u$ is the highest elevation of the glacier. The area/altitude distribution is determined using standard planimetric techniques. The only unknown is the balance gradient.

| Glacier | (km$^2$) Area | 1984 | 1985 | 1986 | 1987 | n |
|---|---|---|---|---|---|---|
| Columbia | 0.9 | +0.21 | -0.31 | -0.20 | -0.63 | 163 |
| Daniels | 0.5 | +0.11 | -0.51 | -0.36 | -0.87 | 97 |
| Eldorado | 1.4 | +0.25 | -0.14 | -0.02 | -0.45 | 204 |
| Foss | 0.7 | +0.42 | -0.69 | +0.12 | -0.20 | 146 |
| Lewis | 0.1 | +0.67 | -1.16 | -0.34 | -0.48 | 78 |
| Lower Curtis | 0.9 | +0.39 | -0.16 | -0.22 | -0.56 | 188 |
| Lynch | 0.8 | +0.33 | -0.22 | -0.07 | -0.30 | 112 |
| Rainbow | 1.5 | +0.58 | +0.04 | +0.20 | -0.26 | 159 |
| Spider | 0.1 | +1.12 | -0.63 | +0.30 | -1.15 | 38 |
| Yawning | 0.2 | +0.09 | -0.23 | -0.14 | -0.47 | 71 |

Table 1. The annual balance of ten North Cascade glaciers, from direct field measurements, in meters of water equivalent. The minimum number of annual measurement sites used during the 1984-1987 period is n.

Because of the small size of North Cascades glaciers the activity index actually represents the entire balance gradient. The activity index of North Cascade glaciers varies only slightly from year to year, as noted on South Cascade Glacier (Meier and Tangborn, 1965), and on each of the ten glaciers examined in this study (Pelto, 1987). This indicates that spatially there is little annual variation in the pattern of annual balance isolines for a given glacier. The annual balance at each isoline is annually variable but the difference in annual balance between isolines is constant. This attribute has been noted on many other alpine glacier systems Pamirs, Rocky Mountains, Alps and Norway (Kotlyakov and Krenke, 1982; Ostrem 1973 and 1975; Hoinkes, 1971). This attribute would allow calculation of annual balance from measurement at a single representative point (Konovalov, 1987). Unfortunately there is no single representative point. However, AAR observations can provide a representative network of mass balance values, along the snowline.

The AAR is determined from ground and aerial photographs taken at the end of the ablation season, and keyed to topographic maps of the glacier. The AAR has been observed annually on 47 North Cascade glaciers, during the 1984-1987 period. The activity index is determined for each of the 47 glaciers by observing the rate of rise with time of the snow line, during the ablation season, in comparison with measured snow depth above the snow line (Pelto, in press).

The balance gradient used in equation (1) to calculate mass balance is then the observed activity index, referenced with respect to the altitude and mass balance axes at the snow line, using AAR observations. On 43 of the 47 glaciers the acitivity index has varied less than 10%. from minimum to maximum values during the four-year period. Since, the activity index is demonstrated to be approximately constant, then only observation of the AAR will be necessary to calculate annual balance.

The annual balance (bn) is calculated for each glacier using:

$$bn = Bn/At \qquad (2)$$

where At is the total area of the glacier.

This method is tested against the annual balance of the 10 glaciers, where annual balance is directly measured. Comparison of the results indicates an error of +0.20 to 0.28 m of water equivalent (Figure 2), and that the error is random.

## RECENT GLACIER BEHAVIOR

North Cascade glaciers retreated rapidly during the first half of this century (Hubley, 1957). The retreat ended and a general advance began in the 1950's, due to an increase in winter precipitation and a decrease in ablation season temperature beginning in 1944 (Hubley, 1957). The majority of North Cascade glaciers advanced during the 1955-1965 period and mantained an advanced position until 1976. Between 1944 and 1974 North Cascade glaciers were near mass balance equilibrium (Tangborn, 1980). Since 1977, ablation season temperature has been 1.1 C above, and winter precipitation 15 % below, the 1920-1980 mean in the North Cascade region. The result has been moderate negative mass balances and retreat of 42 of the 47 glaciers observed in this study.

## CLIMATIC CONTROLS OF MASS BALANCE

The mass balance of North Cascade glaciers is primarily determined by winter precipitation (October 1-April 30), ablation season temperature (May 1-September 30), and summer cloud cover (July 1-September 1)(Tangborn,

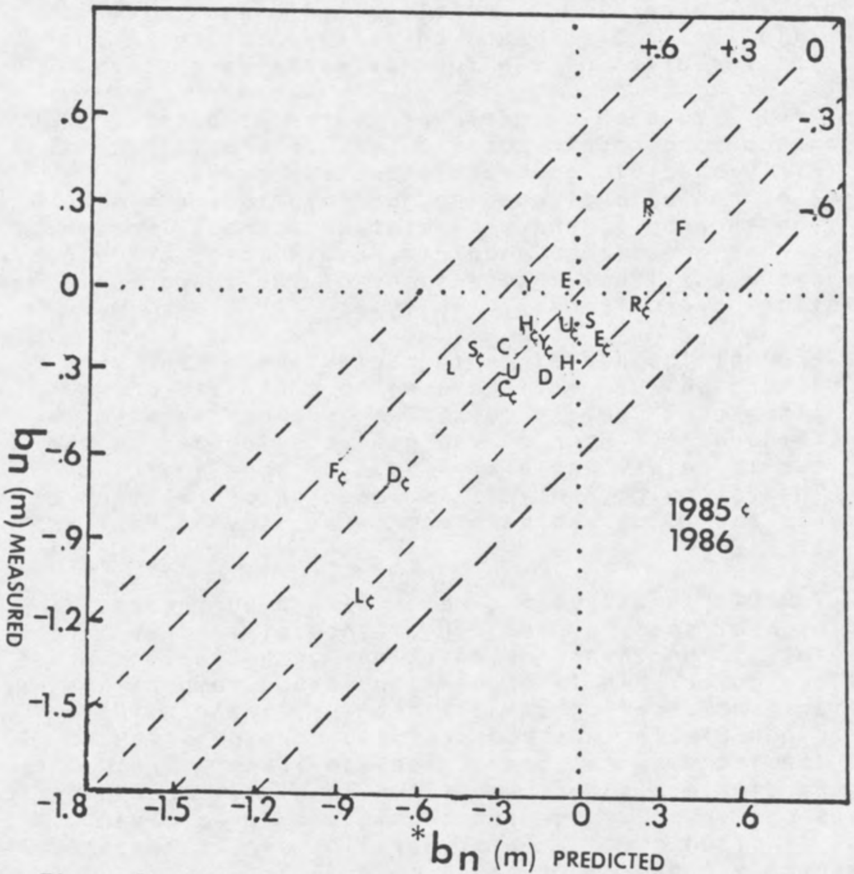

Figure 2. The measured annual balance ($b_n$) of ten North Cascade glaciers in 1985 and 1986, compared to the predicted annual balance. The predicted annual balance was obtained using an activity index method. C=Columbia, D=Daniels, E=Eldorado, F=Foss, H=Lynch, L=Lewis, R=Rainbow, S=Spider, U=Lower Curtis, Y=Yawning.

1980). The freezing level during precipitation events in May and October has a significant effect on winter accumulation for many glaciers. The freezing level is the line above which precipitation falls as snow during each precipitation event.

Observation of the mass balance records obtained from the 47 glaciers indicates that North Cascade glaciers presently fall into six distinct climatic sensitivity types , based on their differing sensitivity to four controlling climatic parameters (Table 2). The annual balance record of each glacier can be accurately explained by only one ranking scheme of the four climatic parameters. The ranking of sensitivity to each climatic parameter is still qualitative, and is based on analysis of the annual balance record versus the variation of the four climatic parameters.

A glacier's sensitivity to each climatic parameter is determined by its geographic location and topographic position. Each sensitivity type is then associated with fairly specific geographic and topographic characteristics; degree of radiational shading, orientation, altitude with respect to the glaciation threshold, and accumulation sources (Porter, 1977). Accumulation sources are direct snowfall, avalanching and wind drifting . Table 3 shows a qualitative assessment of the topographic and geographic characteristics of each sensitivity type.

Mass balance measurements completed on four glaciers on the same mountain massif in 1984 through 1987 will be used to emphasize changes in climatic sensitivity. The Mount Daniels massif is located twelve miles south of Stevens Pass (Figure 1). Four of the glaciers located on the massif have been examined in detail Daniels, Foss, Ice Worm and Lynch Glaciers (Figure 3). The following analysis is based on correlation of mass balance measurements and local weather records at Stevens Pass and Stampede Pass (Table 4).

Lynch Glacier (0.7 km02) is a type 5 glacier with a northward orientation, good radiational shading, and direct snowfall and avalanche accumulation. Because of its northward orientation Lynch Glacier is not sensitive to summer cloud cover. In 1986 ablation season temperature was 0.4 C higher, and winter precipitation was 11% greater, than in 1985. The annual balance of the Lynch Glacier was considerably more positive in 1986 than in 1985, despite the increase in ablation season temperature. This indicates that the Lynch Glacier is most sensitive to winter precipitation. Measured ablation rates on Lynch Glacier are consistent for a given temperature regardless of cloud cover. Thus, ablation season temperature is a more important variable than summer cloud cover.

Type 3 glaciers, which are the most common glacier type in the North Cascades, share the same climatic sensitivity as type 5 glaciers but have lower winter balances since only direct snowfall accumulation occurs.

Daniels Glacier (0.5 km02) is a type 1 glacier with an eastward orientation, poor radiational shading, and only direct snowfall accumulation. The upper portion of the accumulation zone achieves an equilibrium surface profile in mid-winter. After mid-winter wind erosion offsets deposition on the upper portion of Daniels Glacier. This is an important attribute of approximately 13 of the 47 glaciers examined in this study and appears to be a common attribute of many large semi-permanent snow patches. The result is that Daniels Glacier is not as sensitive to changes in winter precipitation. Ablation on 6 clear days in 1987 with maximum temperatures between 11 and 13 C, was 6.5 cm/day. In 1984 the ablation on five cloudy days with maximum temperature of 10 to 12 C was 3.9

| Group | Primary------ |  | ------Secondary |  | Example |
|---|---|---|---|---|---|
| 1 | SC | WP | AT | FL | Daniels |
| 2 | WP | SC | AT |  | Eldorado |
| 3 | WP | AT | SC |  | Yawning |
| 4 | WP | AT | FL | SC | Columbia |
| 5 | WP | AT | SC | FL | Rainbow |
| 6 | AT | WP | SC | FL | Lewis |

Table 2: Ranking of importance of climatic parameters affecting glacier mass balance for each climatic sensitivity group. Winter precipitation (WP), ablation season temperature (AT), summer cloud cover (SC), and freezing level during precipiation events in May and October (FL).

| Group | Orientation | Shading | Altitude | Accumulation Sources | Annual Balance |
|---|---|---|---|---|---|
| 1 | 75 - 285 | Poor | Average | DS | -0.60 |
| 2 | Any | Poor | High | DS | -0.40 |
| 3 | 285 - 75 | Good | Average+ | DS | -0.20 |
| 4 | 300 - 60 | Good | Low | DS & WD or AV | -0.35 |
| 5 | Any | Fair | Average+ | DS & WD or AV | -0.15 |
| 6 | 270 - 90 | Fair | Average- | DS & AV | -0.75 |

Table 3: A classification of the climatic sensitivity groups by the orientation in degrees (reading clockwise from left N=0 , S=180); degree of radiational shading; altitude with respect to the glaciation threshold; accumulation sources (AV=avalanching, DS=direct snowfall, WD=wind drifting), and mean annual mass balance from 1977 to 1986.

| Glacier | 1984 | 1985 | 1986 | 1987 |
|---|---|---|---|---|
| Daniels | +0.11 | -0.51 | -0.36 | -0.87 |
| Foss | +0.42 | -0.69 | +0.12 | -0.20 |
| Ice Worm |  | -0.75 | -0.45 | -1.39 |
| Lynch | +0.33 | -0.22 | -0.07 | -0.30 |
| WP (cm) | 196 | 161 | 176 | 172 |
| AST (°C) | 53.3 | 55.6 | 55.9 | 57.4 |
| SCC (%) | 68 | 32 | 38 | 30 |

Table 4. Annual balance of Mt. Daniels glaciers, winter precipitation (WP), ablation season temperature (AST), and summer cloud cover (SCC) at Stampede Pass.

| Sensitivity Type | Number | Mean Balance | Area | Mass Balance |
|---|---|---|---|---|
| 1 | 84 | -0.60 m | 25.2 $km^2$ | -15.1 $m^3$ |
| 2 | 98 | -0.40 | 34.3 | -13.7 |
| 3 | 268 | -0.25 | 80.4 | -20.1 |
| 4 | 102 | -0.35 | 40.8 | -14.3 |
| 5 | 69 | -0.15 | 59.1 | - 8.9 |
| 6 | 97 | -0.75 | 19.4 | -14.6 |
| total | 718 | -0.38 | 259.2 | -86.7 |

Table 5. Calculation of the overall mass balance of North Cascade glaciers, using the AAR-Activity index method for the 1977-1986 period.

Figure 3a. Lynch Glacier from northeast.

Figure 3b. Daniels Glacier from east.

Figure 3c. Foss Glacier from east.

Figure 3d. Ice Worm Glacier from east.

cm/day. Thus, summer cloud cover is the primary climatic control of ablation and annual balance on Daniels Glacier.

Foss Glacier (0.7 km02) is a type 2 glacier, having a northeast orientation, poor radiational shading, and only direct snowfall accumulation. In 1987 ablation season temperature was 1.7 C higher and summer cloud cover 8% less than in 1985; yet, mass balance increased on Foss Glacier. The increased mass balance was due to a 10% increase in winter precipitation, demonstrating that winter precipitation is the dominant control of mass balance on Foss Glacier. As is the case on Daniels Glacier ablation is much higher on clear days then on cloudy days of similar temperature. Hence, summer cloud cover has a greater impact on annual balance than ablation season temperature on Foss Glacier.

Ice Worm Glacier is a type 6 glacier, with an eastward orientation, fair radiational shading, direct snowfall and avalanche accumulation, and a lower elevation than the neighboring glaciers. A comparison of 1986 and 1987 annual balance and weather records indicates that an 11% decrease in winter accumulation and a 1.5 C rise in ablation season temperature caused an annual balance decrease of -0.60 m. The large change in mass balance can not be accounted for by the small change of +0.20 m in winter precipitation. Thus, Ice Worm Glacier is primarily sensitive to ablation season temperature. Because of its low altitude the Ice Worm Glacier is sensitive to May and October freezing levels. In May most precipitation events result in snowfall on the Foss, Lynch, and Daniels Glacier, but not the Ice Worm Glacier. In 1985 a series of May snowfalls blanketed the Ice Worm Glacier. As a result the Ice Worm Glacier's July direct snowfall snowpack was 6% above normal, while the neighboring glaciers had direct snowfall totals 9% below normal.

Type 4 glaciers differ from type 6 glaciers only in that they have greater radiational shading, as a result freezing levels during May and October precipitation events are of greater importance than summer cloud cover in determining annual balance.

Identification of the sensitivity type of a North Cascade glacier should provide a framework for determining the regimen of each North Cascade glacier, without examining each glacier in detail. The observed behavior could then be understood in a climatic context. Table 5 displays the annual balance for each climatic sensitivity type, during the 1984-1987 period.

During the past decade in the North Cascades the larger a glacier's mean winter balance, the healthier the glacier. High altitude accumulation zones, multiple accumulation sources and a northward orientation are all associated with larger winter balances.

The glaciers showing the greatest mass balance response to the recent climatic fluctuations are those most sensitive to changes in winter snowfall. These glaciers have none or one of the large winter balance factors. The rise in ablation season temperature has had a lesser affect on glacier mass balance. Mass balance and snowpack measurements indicate a greater reduction in snowfall at lower altitudes than at higher altitudes. The greatest reduction in snowfall has been south of Holden and east of the Cascade Crest (Figure 1).

## CONCLUSIONS

The primary goal of this project was to establish a system for annually monitoring the mass balance and determining the climatic sensitivity on numerous North Cascade glaciers. This task has been completed on a total of 47 glaciers.

It is evident that the annual balance of a North Cascade glacier can be determined with an accuracy of +0.20-0.28 m by observation of the annual AAR, of the activity index and area-altitude distribution. The AAR can be quickly determined from aerial and ground photographs at the end of the ablation season (Meier and Post, 1962).

Four primary climatic parameters determine annual balance on North Cascade Glaciers; winter precipitation, ablation season temperature, summer cloud cover, and freezing levels during May and October precipitation events. Examination of a glacier's sensitivity to the primary climatic controls of annual balance indicates that six different glacier climatic sensitivity types exist in the North Cascades. Annual mass balances are similar for each sensitivity type member in a specific region. The sensitivity type of a North Cascade glacier can be determined from analysis of its topographic position and geographic location. The next goal of the North Cascade Glacier-Climate Project is to quantify the climatic sensitivity of numerous North Cascade glaciers

The mean annual balance of North Cascade glaciers during the 1984 through 1987 period was -0.33 m/a. Since 1976 there has been a strong negative mass balance regime in the North Cascades. This trend is due to an increase in persistence of anticyclonic conditions throughout the year (Pelto, 1987).

Braithwaite (1984) posed the question, "can the mass balance of a glacier be estimated from its equilibrium line position?" The activity index method of annual balance calculation relies on annual identification of the AAR, which is determined by the equilibrium line position. The accuracy of this method indicates that the mass balance of North Cascade glaciers can be determined from the equilibrium line position.

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