Annual Balance of North Cascade, Washington Glaciers Predicted From Climatic Records

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ABSTRACT

North Cascade glaciers supply 25% of the regions total summer water supply. The magnitude and timing of glacier runoff is determined by mass balance. From 1984-1989 the North Cascade Glacier Climate Project has monitored the annual balance of 10 North Cascade glaciers, using an efficient reconnaissance technique emphasizing probing, crevasse stratigraphy and ablation stakes. These 10 glaciers have a wide range of geographic characteristics (orientation, altitude, etc.), and provide a geographically representative group.

Three climatic variables are used to obtain a best fit equation of mass balance calculation mean ablation season temperature (AST), winter precipitation (WP), and ablation season length (ASL). Comparison of measured and calculated annual balance yields annual balance (bn) results with a correlation coefficient of 0.98, and a standard error of ±0.08 m/a of water equivalent. The degree of demonstrates that the overall annual balance of North Cascade glaciers can be accurately determined from local weather records. It must be cautioned that the mass balance of a specific glacier cannot be reliably calculated using the above equation. The mean annual balance of North Cascade glaciers from 1984 through 1989 is measured to be -0.20 m/a, and calculated to be -0.22 m/a.

INTRODUCTION

North Cascade glaciers supply 25% of the regions total summer water supply, hence, it is impossible to intelligently manage the regions water resources without understanding changes in glacier runoff. Glacier runoff from alpine glaciers is determined by the mass balance during the past several years (Bazhev, 1986). Thus, it is crucial to water resources management that glacier mass balance be determined in a timely fashion. Direct measurement is the standard method, however measurements are typically limited to an individual glacier, because of the financial costs and time required to complete measurements using traditional methods. Traditional methods emphasize determination of both winter and summer balances, requiring two field seasons (Ostrem and Stanley, 1969). Traditional methods often rely on runoff records to determine ablation, and time consuming snowpit digging to ascertain snowpack depth. In this study emphasis is placed on more expeditious measurement techniques, such as probing, crevasse stratigraphy, and ablation stakes. The only practical way to monitor the annual balance of a large number of glaciers is utilization of time efficient methods or an army of assistants. A question that arises is, can mass balance be determined in a more timely fashion using climate records. This would provide cheaper and more timely data.

One of the primary objectives of the North Cascade Glacier Climate Project is to develop an accurate model for calculating the mass balance of North Cascade glaciers based on climate data. Two different approaches have been explored. The first, relating mass balance to daily classification of atmospheric circulation, using the techniques of Yarnal (1984). The second method utilizes climate data from eight weather stations in the North Cascades.

MEASUREMENT OF MASS BALANCE

The goal of the NCGCP mass balance study is determination of annual balance with reasonable accuracy on a number of glaciers rather than strict accuracy on a few glaciers. In this study, the annual balance is determined using direct field measurements late in the ablation season. Thus, only annual balance is measured; winter and summer balances are not determined.

In the fixed date method mass balance measurements are made on the same date each year, close to the end of the ablation season. Some ablation will probably occur after this date, but this ablation is measured as mass loss for the next hydrologic year. Thus, errors do not result from completing measurements prior to the end of the ablation season.

In the accumulation zone, annual accumulation layer thickness is determined using crevasse stratigraphy, and probing. The average density of measurements utilized in this study is 280 points/km^2, while the average density of measurements used in assessing the mass balance in the accumulation zone of Norwegian and other United States glaciers is 33 points/km^2 (Meier et al., 1971; Pytte, 1969). A comparison of the density of measurements used by the NCGCP, the U.S. Geological Survey (USGS), and Norges Vassdrags-Og Elektristetsvesen (NVE) are shown in Table 1.

The mean accumulation layer density observed in over 100 snowpits on ten different North Cascade glaciers from 1984 through 1987 is 0.58 g/cm^3, with a standard deviation of 0.01 g/cm^3. This narrow range indicates that late in the ablation season the density of snowpack on North Cascade glaciers is uniform, and need not be measured to determine mass balance. The lack of variation in snowpack density has also been noted on the South Cascade Glacier (Meier and Tangborn, 1965) and on the Blue Glacier in the Olympic Range of Washington (Armstrong, 1989). The uniformity of the density in the North Cascades results in part because ice lenses do not occur late in the summer.

Accumulation measurements are made using probing and crevasse stratigraphy; because both methods are quick and accurate. These two methods allow an unusually high density of measurements to be completed. At least 25% of the accumulation area on each glacier is a zone of overlap where both probing and

Table 1. The number of measurement sites used in mass balance studies by the United States Geological Survey (U) (Meier et al., 1971), Norges Vassdrags-Elektrissen (N) (Pytte, 1969), and by the North Cascade Glacier Climate Project (P).

Glacier	Ablation area		Accumulation area		Source
	Sites	Density pts./km^2	Sites	Density pts./km^2	
Gulkana	20	3	68	6	U
South Cascade	20	17	81	50	U
Wolverine	15	1	105	6	U
Alfotbreen	5	4	126	35	N
Austre Memurubre	8	3	316	52	N
Grasubreen	9	8	125	50	N
Hellstugubreen	13	7	216	144	N
Nigardsbreen	10	4	237	5	N
Vestre Memurubre	6	4	88	10	N
Columbia	3	10	165	250	P
Daniels	4	12	115	280	P
Eldorado	3	9	240	220	P
Foss	3	15	110	240	P
Lewis	2	30	31	310	P
Lower Curtis	3	10	185	280	P
Lynch	3	10	125	250	P
Rainbow	3	6	200	180	P
Spider	2	30	30	450	P
Yawning	2	20	40	260	P

crevasse stratigraphy are used to ensure unreliable data is not used. The standard deviation obtained in replicate measurements is smallest for crevasse stratigraphy, ±0.02 m and is ±0.03 m for probing.

The accumulation layer thickness is measured at each point to the nearest 0.01 m. Crevasse stratigraphy measurements are conducted only in vertically walled crevasses with distinguishable dirt bands. Crevasses lacking vertical walls yield inaccurate depth measurements. In the North Cascades the ablation surface of the previous year is always marked by a 2-5 cm thick band of dirty firn or glacier ice. The depth to the top of this dirty band is measured at several spots on each crevasse wall within a space of several meters. The average thickness is the accumulation layer thickness at that point. Crevasses have been avoided previously because of obvious dangers and the false density readings that can occur due to the snowpack having a free air face. Density readings from crevasse walls are not used and crevasses are approached on skis, which are not removed during measurement.

Since North Cascade glaciers rarely have ice lenses, probing is also an accurate method for measuring accumulation layer thickness. The probe is driven through the snowpack until the previous year's ablation surface is reached. This surface of glacier ice or hard dirty firn cannot be penetrated. The probing instrument is a 2.5 m long, 1/2 inch thick copper tube which is driven through the snowpack using a two pound weight. Probing transects are used in regions with few crevasses and are used to check the accuracy of crevasse stratigraphic measurements. Probing transects are started from bare glacier ice and continued across the glacier to a snow depth of 2.5 m. At depths greater than 2.5 m, it becomes difficult to accurately distinguish the previous ablation surface. In the North Cascades, snowpack in excess of 2.5 m at the conclusion of the ablation season is rare. Where snowpack depth does exceed 2.5 m, glacier flow is typically extending, resulting in numerous open crevasses.

To ensure that mass balance measurements are consistent from year to year, measurements are made at a fixed network of points. The network is fixed spatially with respect to the surrounding bedrock walls.

Annual balance measurements are reported in meters of water equivalent, the product of the accumulation layer thickness and density of the snow pack (0.58 g/cm^3). Internal accumulation and superimposed ice are insignificant components in the mass balance of North Cascade glaciers (Meier and Tangborn, 1965). Errors in depth measurement are +0.05 m and the standard deviation in density is $\pm$0.01 g/cm^3. The resulting error in annual assessment for the accumulation zone is $\pm$0.08 m. All errors in this study are for one standard deviation of the three observed data values for each measurement site. The density of measurements in the accumulation zone is considerably greater than is typical for glacier mass balance surveys (Table 1), which results in smaller errors.

Ablation triangles are used to determine annual ablation down glacier of the snowline. An ablation triangle consists of three 3.3 m long fiberglass poles driven or drilled into the glacier at 3 m spacing forming an equilateral triangle. Three to four triangles are emplaced on each glacier. Longer stakes are too cumbersome to transport and emplace. Ablation measurements are made at nine points along the edge of the triangle at the conclusion of the ablation season.

Ablation triangles are placed in a sequence on areas of the glacier that first lose their snow cover to areas where snow cover persists for a significant portion of the ablation season. Each ablation triangle is then representative of ablation for other portions of the glacier that lose snowpack simultaneously. In the fixed-date method of mass balance measurement, the ablation season is assumed to end at the same time each year, this date marks the end of the hydrologic year for that glacier. Mass balance measurements are completed on the same dates each year. In some years, such as in 1987, the ablation season extends beyond the fixed date. Ablation occurring after this date will be measured as part of the mass balance of the next hydrologic year. Snow ablation occurring after mass balance measurement is completed and before the accumulation season begins is monitored by placing a single ablation triangle in the accumulation zone after measurements have been completed. This ablation triangle is checked the next year to determine the amount of snow ablation that occurred during the previous fall.

The stakes are drilled into the ice at the end of the ablation season and after the initial late July-early August measurement. Redrilling of the stakes is necessary to prevent melting out. Drill hole settling averages less than 0.05 m/a. The error in annual ablation measurements is $\pm$0.18 to 0.22 m, due to ice density variations, low sampling density, and stake settling.

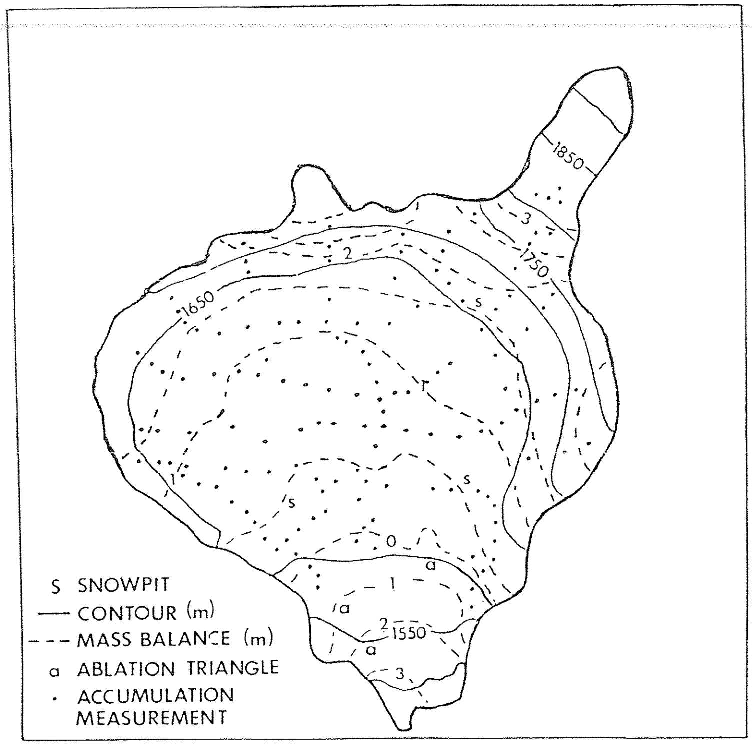

Figure 1. Mass balance map of the Lower Curtis Glacier in 1986. Mass balance is contoured in meters of water equivalent.

Because each measurement is the mean of nine measurements in a 25 m^3 area, the error of individual measurements is small. There are three to four measurement sites on each glacier. The sampling density is low at 10-30 points/km^2, but is comparable to the density used by the USGS and NVE noted in Table 1 (Meier et al., 1971; Pytte, 1969). On South Cascade Glacier a measurement density of 3 or 4 points/km^2 was used between 1973 and 1982 with a reported error of ±0.12 m (Krimmel, 1989). On Blue Glacier a density of 4 point/km^2 has been used (Armstrong, 1989). Measurement error in the ablation zone is larger than for other studies, despite a higher density of measurements, because the total number of measurements is small.

A mass balance map is then compiled for each glacier (Fig. 1). The mass balance for the entire glacier is calculated by summation of the product of glacier area within each 0.10 m mass balance contour, and the net balance in that interval. The error in mass balance calculation for North Cascade glaciers is ±0.12 to 0.15 m, except during years of extreme ablation when the error is higher. Errors increase as the ablation area increases and the accumulation zone, where better accuracy is possible, shrinks. The annual balance of 10 North Cascade glaciers is shown in Table 2.

Table 2. The annual balance of ten North Cascade glaciers, from direct measurements, in meters of water equivalent. See Figure 2 for glacier locations.

Glacier	Area km^2	1984	1985	1986	1987	1988	1989
Columbia	0.9	+0.21	-0.31	-0.20	-0.63	+0.14	-0.09
Daniels	0.5	+0.11	-0.51	-0.36	-0.87	-0.15	-0.37
Eldorado	1.4	+0.25	-0.14	-0.02	-0.45	+0.19	-0.06
Foss	0.7	+0.51	-0.69	+0.12	-0.38	+0.23	+0.09
Lewis	0.1	+0.67	-1.16	-0.34	-0.48	-0.31	-0.60
Lower Curtis	0.9	+0.39	-0.16	-0.22	-0.56	-0.06	-0.29
Lynch	0.8	+0.33	-0.22	-0.07	-0.30	+0.17	+0.03
Rainbow	1.5	+0.58	+0.04	+0.20	-0.26	+0.43	-0.24
Spider	0.1	+1.12	-0.63	+0.30	-1.15	+0.73	-0.15
Yawning	0.2	+0.09	-0.23	-0.14	-0.47	-0.06	-0.19

MASS BALANCE CALCULATION

The 8 North Cascade weather stations are at elevations 700-1800 m lower than the mean elevation of the glaciers (Fig. 2). Stevens Pass is the highest station at 1245 m, 700 meters below the mean elevation of North Cascade glaciers. The other seven stations are Stampede Pass 1210 m, Stehekin 388 m, Concrete 46 m, Holden 970 m, Diablo Dam 272 m, Upper Baker Dam 210 m, Ross Dam 379 m. It has previously been demonstrated that the four climatic variables controlling glacier mass balance are winter precipitation (November-April), ablation season temperature (May-September), summer cloud cover (June-August) and freezing levels during May and October precipitation events (Tangborn, 1980: Pelto, 1988). The two prime variables being winter precipitation and ablation season temperature, these two variables account for 81% of the variation in annual balance on the 11 glaciers where mass balance has been measured (Tangborn , 1980; Pelto, 1989). In southern British Columbia and in Washington winter precipitation is the dominant factor.

The importance of freezing level, is that snows falls above the freezing line, which may intersect the glaciers during October and May. From November through April North Cascade glaciers are above the freezing line except on rare occasions. May and October precipitation that falls when the temperature is below 5°C at Stevens Pass will fall as snow on North Cascade glaciers, and is included as winter precipitation. Thus, freezing levels are accounted for but not as a separate variable.

At present no cloud cover observations are being made in the North Cascades. Tangborn (1980) demonstrated that the correlation coefficient for summer cloud cover and summer temperature is approximately 0.90 in the North Cascade region. Thus, major errors will not result from not considering summer cloud cover separately from ablation season temperature.

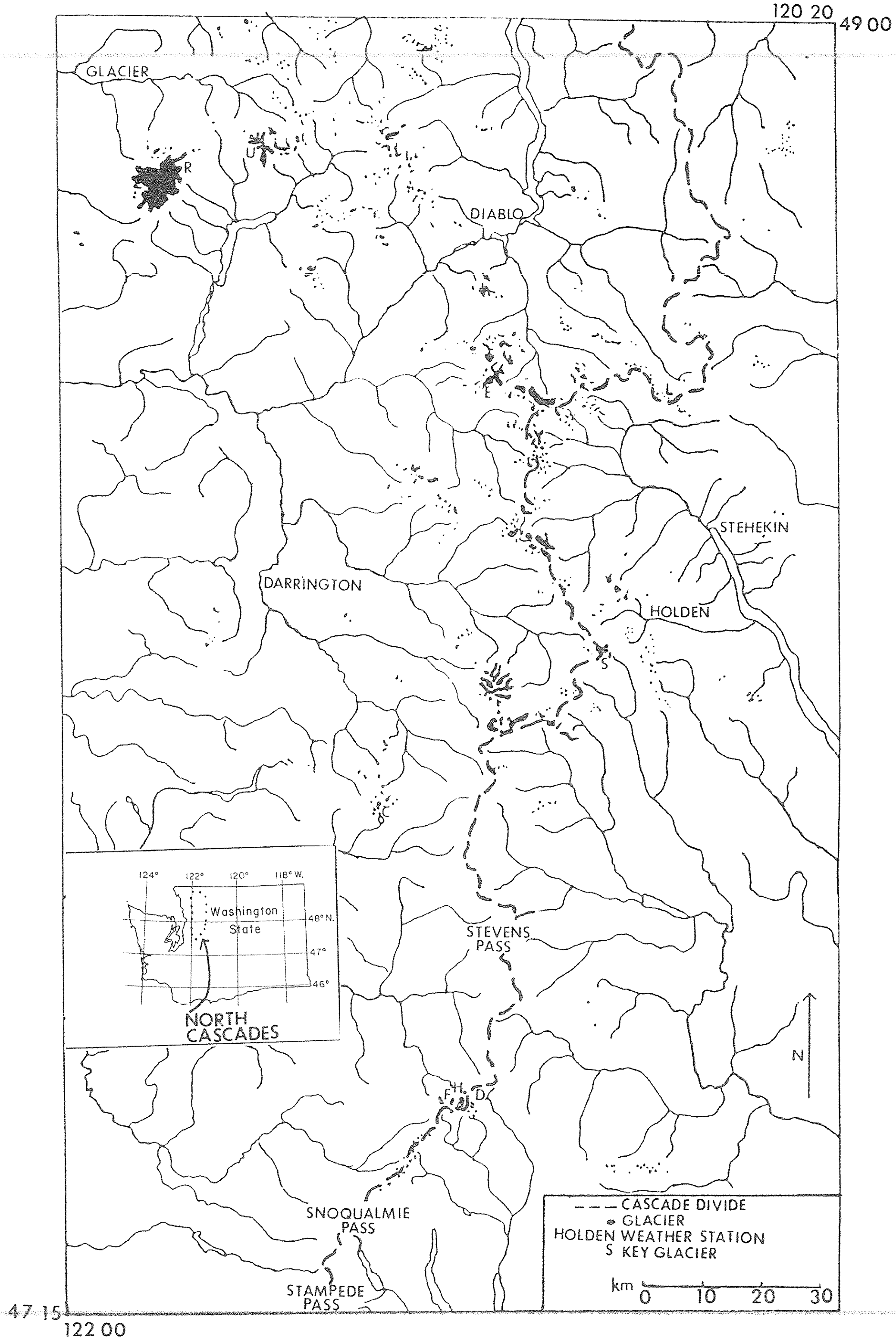

Figure 2. Location of glaciers and weather stations in the North Cascades.

Table 3. Climatic conditions in the North Cascades 1984-1988 compared to the long term mean. The data is the mean for eight North Cascade stations. This data is used in equation 1 and 2. Accumulation season precipitation is all precipitation occurring between October 1 and May 31 when the temperature at Stampede Pass is below 5°C. Ablation season temperature is the mean temperature from May 1 to September 30. Ablation season length is the period in days from the first occurrence of three consecutive days with mean temperature above 7°C at Stampede Pass to the last occurrence.

Year	Accumulation season precipitation (m)	Ablation season temperature (°C)	Ablation season length (days)
1984	1.95	12.7	136
1985	1.34	13.8	146
1986	1.54	13.4	156
1987	1.58	14.2	184
1988	1.69	13.5	151
1989	1.76	13.2	176
Mean	1.62	13.5	155
Mean 1920-1980	1.87	12.8	144

Multiple linear regression produced a best fit equation using ablation season temperature and winter precipitation data shown in Table 3. Input data are the mean temperature and mean precipitation for the eight stations. The climate input data are entered without units, as there is no clear method to change temperature into m.

$$bn = WP - [(AST-5)(21.5)] \quad (1)$$

Annual balance (bn) is in cm of water equivalent, Winter precipitation (WP) is entered in cm, and ablation season temperature (AST) is entered in degrees Celsius. Equation 1 is reasonably accurate when compared to the directly measured mass balance having a standard deviation of ±0.18 m/a, but in 1987 it is apparent the equation failed to yield a reasonable result (Table 4). The reason was the unusually early start of the ablation season in mid-April. An ablation season length variable is needed to account for the fact that the ablation season may begin before May 1 or extend beyond October 1. The resulting increase in ablation due to an extended ablation season cannot be addressed by using a mean temperature for the entire ablation period because the temperatures during the early and latter part of the ablation season are lower than the mean, and would reduce the mean AST. Ablation season length (ASL) is the interval between the first two consecutive days when the mean temperature at Stevens Pass exceeds 7°C and the last such occurrence. This temperature marks the boundary below which negligible ablation occurs on North Cascade glaciers. The multiple linear regression best fit equation utilizing ablation season length, winter precipitation and ablation season temperature proved more accurate and reliable than equation 1 (Table 4).

Table 4. Measured annual balance of ten North Cascade glaciers, and calculated annual balance of North Cascade glaciers using Equations 1 and 2.

Year	Mass balance measured(10)	Mass balance predicted Eq. 2	Eq. 1
1984	+0.45	+0.48	+0.30
1985	-0.54	-0.46	-0.56
1986	-0.19	-0.29	-0.27
1987	-0.72	-0.79	-0.39
1988	-0.02	-0.11	-0.13
1989	-0.18	-0.10	0.00

$$bn = WP - [(AST-5)(21)(ASL/150)] \quad (2)$$

The standard deviation for predicted versus measured annual balance is ±0.09 m/a. The derived relationship is based on six years of record. This is a short time span and undoubtedly minor adjustments will result with a longer record. A six year period of record would be insufficient to determine an accurate relationship between a single dependent and independent variable. However, predicting the mass balance, from three independent variables with a six year period of record yields an equation that is significant and accurate.

Equations 1 and 2 cannot be applied with any accuracy to a single glacier. Table 2 indicated that considerable fluctuations occur between glaciers for a given year. Calculating the correlation coefficient for winter precipitation and ablation season temperature and annual balance indicates considerable variation as well. The reason for the variation in climate sensitivity and hence annual balance is the difference in geographic and topographic characteristics of the glacier.

Why is a simple equation based on three climatic variables sufficient to accurately predict mass balance in the North Cascades? Applying the same methods to large Alaskan glaciers has proved inaccurate. It is likely that the small size of North Cascade glaciers is the key. Because of their small size the entire area of a North Cascade glacier experiences the same regional and local weather systems. True the microclimate varies across the surface of North Cascade glaciers, but these fluctuations are due to topographic setting which is constant from year to year. On larger Alaskan glaciers different portions of the glacier will experience significantly different weather conditions.

The second method tested to predict glacier mass balance uses synoptic scale 500 millibar atmospheric circulation data to predict glacier mass balance using techniques developed by Yarnal (1984). This method utilized the NOAA Daily Weather Map series, classifying each day as one of 18 potential

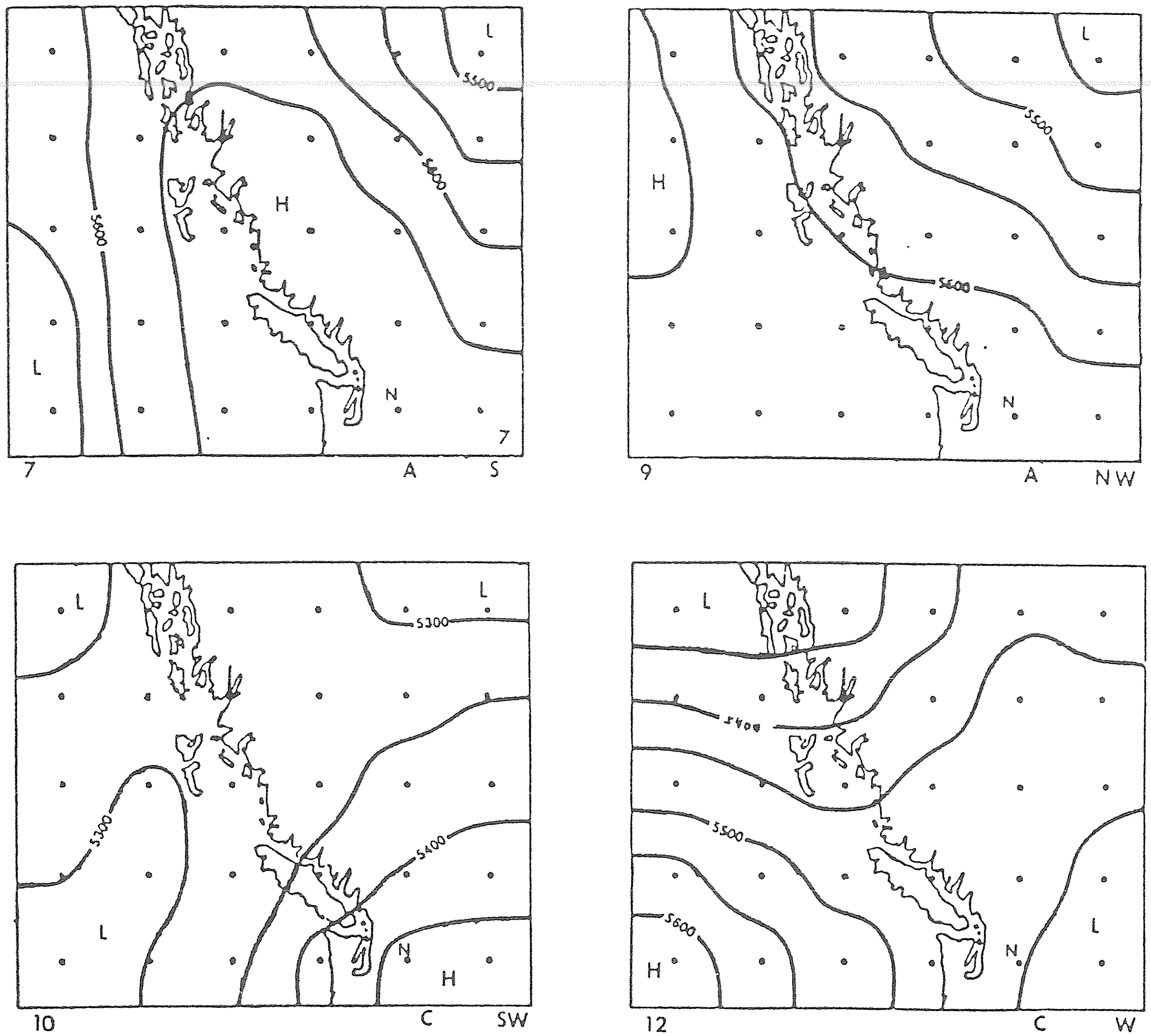

Figure 3. 500 mb pressure distribution maps used in classifying daily atmospheric circulation (Yarnal, 1984). These are four of the eighteen circulation types that account for 91% of all the days in the North Cacades. Circulation types are designated as anticyclonic(A), cyclonic (C) or intermediate (S). N=North Cascades, H=high pressure center, L=low pressure center.

circulation types. This task was completed in the Pacific Northwest for the 1982-1988 period, and 93% of the days could be classified into of the 18 circulation types (Fig. 3). The idea being that each circulation type would yield fairly specific weather conditions in the North Cascades and hence would have a predictable impact on North Cascade glacier mass balance. However, though the general climatic conditions for a given circulation type such as cool and wet or cool and dry, were seasonally consistent, the actual amount of precipitation or actual temperature proved to be to wide ranging for each circulation type to provide an accurate equation. Thus, atmospheric circulation records cannot yet be used to accurately predict North Cascade glacier mass balance. This conclusion is supported by Walters and Meier (in press), who noted that the primary changes in atmospheric circulation explain

62% of the annual variation in mass balance on Pacific Northwest glaciers. This is a correlation coefficient of 0.79 not bad, but far short of the 0.98 achieved using local weather records.

CONCLUSIONS

A method has been developed to efficiently monitor the mass balance of North Cascade glaciers with an accuracy of ±0.12-0.15 m/a. An equation to accurately predict the annual balance of North Cascade glaciers from climate records has also been developed. The mean error is ±0.09 m/a for North Cascade glaciers as a whole. The equation is not reliable for application to a specific glacier. From 1984 through 1989 the mean annual balance on North Cascade glaciers was -0.20 m/a. The cause of the negative mass balance is primarily due to the decrease in winter precipitation from the long term mean (Table 3).

The next step in this study is to test a model for predicting the annual mass balance for a single watershed, so as to improve forecasts of streamflow in glaciated drainage basins.

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