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Spatial and temporal variations in annual balance of North Cascade glaciers, Washington 1984–2000

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Abstract:

Since 1984, annual glacier mass balance measurements have been conducted on eight glaciers by the North Cascades Glacier Climate Project (NCGCP). Since 1993 the National Park Service (NPS) has monitored the mass balance of four glaciers, and the NCGCP an additional two glaciers. This 14 glacier monitoring network, covering an area of 14 000 km^2, represents the most extensive network of mass balance measurements for alpine glaciated areas in the world. The breadth of the record allows determination of the annual variability of annual balance from glacier to glacier, and from year to year.

Data indicate a broad regional continuity in the response of these glaciers to climate. All cross-correlation values between any pair of the 14 glaciers ranged from 0·80 to 0·98. This strong degree of correlation indicates that regional-scale climate conditions, not local microclimates, are the primary control of glacier annual balance in the North Cascades.

Data also indicate that the annual mass balance trend for glaciers was strongly negative from 1984 to 1994 and slightly positive from 1995 to 2000. The cumulative annual mass balance for eight glaciers between 1984 and 1994 was −0·39 m year^{-1}. From 1995 to 2000 the cumulative annual mass balance of the same eight glaciers was +0·10 m year^{-1}, and +0·15 m year^{-1} for all 14 glaciers in this study.

The correlation coefficients indicate the strongly similar response, not that the specific magnitude of the annual mass balance for each glacier is the same. There is a significant annual range in the individual glacier balances, averaging 1·01 m, and in the mean annual mass balance between glaciers. All of the glaciers with more positive annual mass balances since 1995 had either significant accumulation areas extending above 2300 m, and/or are east of the zone of maximum precipitation. The glaciers with the most negative annual mass balance are those with the lowest mean elevation. The record is, as yet, too short to explain the variability of mass balance fully using climate data and seasonal mass balance data. Copyright © 2001 John Wiley & Sons, Ltd.

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INTRODUCTION

The annual mass balance is the most sensitive glacier indicator of glacier response to climate change. Annual mass balance is the difference between total annual snow and ice accumulation on a glacier, and total annual snow and ice loss from a glacier during a given year. The importance of annual glacier mass balance monitoring was recognized during the International Geophysical Year in 1957. A series of benchmark glaciers around the world was chosen where annual mass balance would be monitored. This network has proven valuable, though too sparse in its coverage, with just two index glaciers in the USA with ongoing measurements: Lemon Creek Glacier, Alaska, and South Cascade Glacier, North Cascades, Washington (Fountain *et al.*, 1991).

A glacier's mass balance, and hence its response to climate, is complicated by its geographic characteristics. No single glacier is representative of all others; thus, to understand the causes and nature of changes in glacier mass balance throughout a mountain range it is necessary to monitor a significant number of glaciers (Fountain

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et al., 1991). Even in areas where the correlation in annual mass balance is high, the range in annual mass balance and consequent glacier terminus response can still be significantly different (Tangborn, 1980; Pelto, 1996).

Currently, in the USA there are four ongoing mass balance programs. (1) The USGS measures annual balance on three US glaciers: Gulkana and Wolverine Glaciers in Alaska, and South Cascade Glacier in Washington (Krimmel, 1999). (2) The Juneau Icefield Research Program measures annual balance on Lemon Creek Glacier, Alaska (Pelto and Miller, 1999)•. (3) The North Cascades National Park Service (NPS) monitors the annual balance of four glaciers in the North Cascades. (4) The North Cascade Glacier Climate Project (NCGCP) measures annual balance on ten glaciers in the North Cascades, Washington (Pelto, 1996, 1997, 2000). Q1

This paper focuses on the latter two programs, which together provide the most extensive regional network of glacier annual mass balance measurements in the world (Figure 1). The characteristics of the 14 selected glaciers in the NCGCP and NPS study vary considerably, and represent the range of conditions found in the North Cascades (Table I). This record provides an opportunity to answer several key questions. (1) How variable is annual mass balance from glacier to glacier? (2) What factors determine the variability from glacier to glacier? (3) What is the recent mass balance record of North Cascade glaciers?

There are approximately 750 glaciers in the North Cascades (Post *et al*., 1971). These glaciers are vital for regional water resources (Tangborn, 1980; Pelto, 1993). Thus, measurement of mass balance is of more than academic interest. The study interval 1984–2000 began in a period of negative glacier mass balance• that dominated the 1975–94 interval (Pelto, 1996; Krimmel, 1994). The latter portion of the study period 1995–2000 has been more favourable, but very inconsistent, and cannot yet be identified as a period of more favourable mass balance. Q2

METHODS

Annual mass balance changes can only be accurately assessed through field measurement, this has been the goal of the NPS and NCGCP programs. Mayo (1972) estimates• that surface measurements on temperate glaciers can account for approximately 95% of annual changes in glacier mass. Long-term changes in mass balance, which can verify the accuracy of the annual balance measurements, can be made using geodetic methods, such as airborne surface profiling using laser altimetry or surface remapping. Glacier balance data are collected with somewhat different approaches by the NCGCP and NPS programs. Despite the different approaches, however, we are confident that the data collected by the two programs can be compared at the end of the hydrologic year. Q3

NPS, USGS and NCGCP methods emphasize surface mass balance measurements with a relatively high density of sites on each glacier, consistent measurement methods, and fixed measurement locations. Glaciers monitored in these programs do not lose significant mass by calving or avalanching, so that the changes observed are primarily a function of winter accumulation and summer ablation on the glaciers' surfaces. Glaciers monitored in these programs also have relatively simple shapes, without multiple accumulation areas and ice divides.

Glacier surface mass balance data is collected with different approaches by the USGS, NCGCP and NPS programs. NCGCP essentially measures conditions on a glacier at the time of minimal mass balance near the end of the water year. NCGCP measures the change in snow, firn and ice storage between fixed dates t_0 and t_1 at the end of consecutive hydrologic years. The fixed dates are in the last 10 days of September. This is known as annual balance b_a (Mayo *et al*., 1972; Pelto, 1997). The annual balance can be calculated with this approach because winter and summer balance quantities, not measured prior to the NGCP field season, cancel each other out. The NCGCP measurements allow for analysis of a glacier's response to climate for the preceding water year, but do not account for total winter or total summer balance, and cannot be used to estimate total annual runoff from a glacier. It is critical that the glaciers in the NCGCP be visited before any part of the glacier loses its snow cover from the previous winter.

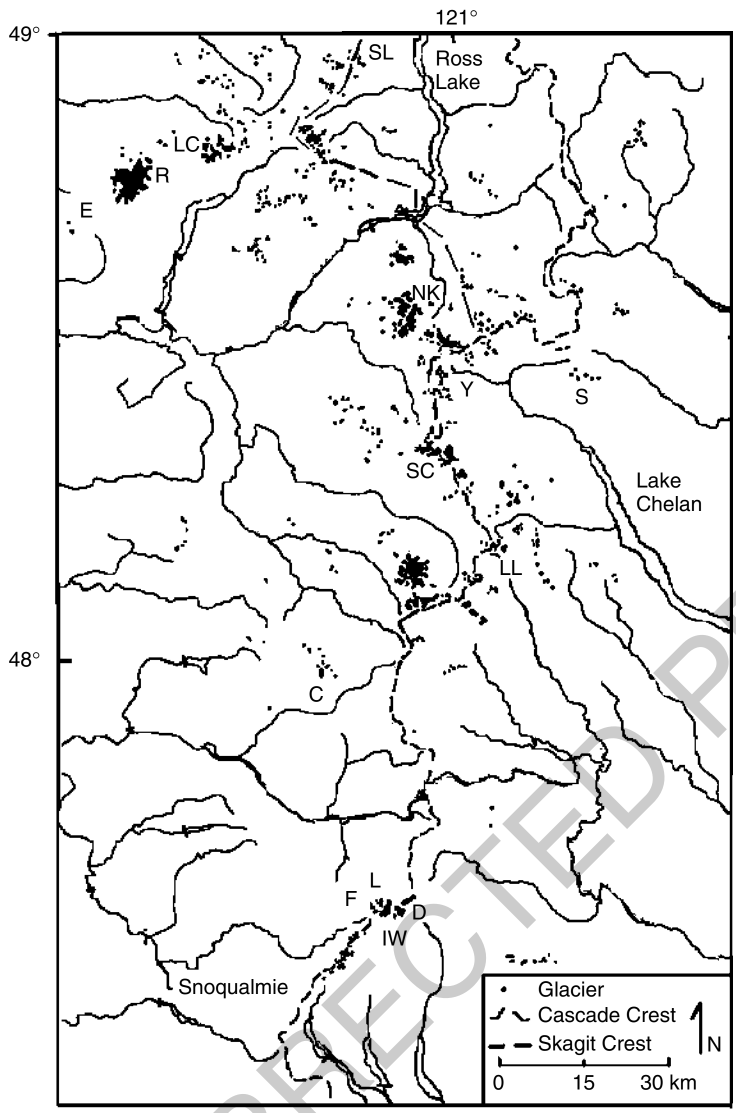


Figure 1. Map of North Cascade glaciers indicating weather stations at● the Skagit Crest and Cascade Crest. Glaciers where annual mass balance measurements are completed are labelled as follows B = Bacon, C = Columbia, D = Daniels, E = Easton, F = Foss, IW = Ice Worm, L = Lynch, LL = Lyman Glacier, LC = Lower Curtis, NC = Noisy, NK = North Klawatti, R = Rainbow, S = Sandalee, SC = South Cascade, Y = Yawning Q6

The NPS uses a two-season approach, developed by the USGS and others, with measurements at the mid (spring) and end (fall) points of the water year (Ostrem and Bruggman, 1991). These measurements allow for calculation of total winter (accumulation) balance, total summer (ablation) balance, net balance, and for determination of net melt-season runoff from a given glacier. The NPS measures the change in annual balance from one balance minimum to the next; this does not occur on a consistent date, this is a stratigraphic method and yields the net balance b_n for the glacier (Mayo *et al.*, 1972). The balance minimum in the North Cascades identified by the NPS varies from late September to the start of October, not on a fixed date.

The only difference between the end result of the mass balance measurement programs is the difference in timing between the fixed date method and the end of the hydrologic year method. In this instance the

Table I. The geographic characteristics of the 14 glaciers where annual mass balance has been monitored annually. Accumulation sources: wind drifting = WD, avalanche accumulation = AV, direct snowfall = DS

Glacier	Aspect	Area (km^2)	•Accumulation*	•To divide*	Elevation (m)
Columbia	SSE	0·9	DS, DW, AV	15 km west	1750–1450
Daniels	E	0·4	DS, WD	1 km east	2230–1970
Easton	SSE	2·9	DS	75 km west	2900–1700
Foss	NE	0·4	DS	At divide	2100–1840
Ice Worm	SE	0·1	DS, AV	1 km east	2100–1900
Lower Curtis	S	0·8	DS, WD	West 55 km	1850–1460
Lyman	N	0·5	DS, AV	2 km east	2100–1850
Lynch	N	0·7	DS, WD	At divide	2200–1950
Rainbow	ENE	1·6	DS, AV	70 km west SC	2040–1310
Yawning	N	0·3	DS	At divide PC	2100–1880
Noisy	N	0·5	DS, WD, AV		1850–1700
N. Klawatti	SE	1·5	DS, AV		2315–1820
Sandalee	N	0·2	DS, WD, AV		2510–2130
Silver	N	0·5	DS, WD, AV		2698–2088

Q8

timing of the measurements is a 5–10 days difference at the end of the water year, a period of minimal ablation, 0·01 m day^{-1}. Any accumulation during this interval is measured during the next year's accumulation measurements by both programs. Paterson (1967) noted the comparability; since the hydrologic measurement year is unlikely to coincide with the balance year, annual balance and net balance are not equal in a given year, and so differences in measurement timing of a few days can be ignored. Paterson (1967) further notes that the average values of annual balance and net balance over a span of years would be equal. The stratigraphic system is usually used on the South Cascade Glacier, because it is more field compatible, but the fixed-date results are readily incorporated (Krimmel, 1998).

For the purposes of this study, annual balance and net balance can be directly compared at the end of each water year to assess spatial variation of glacier response to climate. In this paper, we use the term 'annual mass balance' to refer to both annual balance and net balance. Cross-correlation of net balance and annual balance data from these programs supports the comparison of the two data sets. Correlation coefficients between glaciers using the different methods range from $r^2 = 0 \cdot 80$ to $0 \cdot 97$ (Table II).

NCGCP program

Since 1984, NCGCP has monitored the annual balance of eight glaciers, and since 1994 an additional two glaciers (Pelto, 1996, 1997). Measurements are made at the same time each year in early summer, late July and again in late September near the end of the ablation season. Any additional ablation that occurs after the last measurement is measured during the subsequent hydrologic year.

The average density of measurements by the NCGCP in the accumulation zone of each glacier ranges from 180 to 300 points km^{-2}• (Pelto, 1996, 2000). Measurement of accumulation is accomplished using probing and crevasse stratigraphy. Probing has proved successful in most temperate glaciers (Ostrem and Bruggman, 1991). LaChapelle (1954) noted that a dense snow-cover surface develops during the summer• due to repeated surface refreezing. This results in a marked increase in probe ram resistance, which allows for determination of the thickness of the previous winter snowpack. Crevasses also provide an opportunity to assess accumulation, as they are a natural incision that provides a vertical view of snowpack thickness. Crevasse stratigraphic measurements are conducted only in vertically walled crevasses with distinguishable annual layer dirt bands. In extensive tests, NCGCP found crevasse measurements had a lower standard error in duplicate measurements than probing (Pelto, 1996, 1997). Q4 Q5

In the North Cascades at the end of summer, the density of the previous winter's snowpack that remains on a glacier is remarkably consistent (Pelto, 1996; Krimmel, 1998). NCGCP dug more than 100 snow pits to

Table II. The annual mass balance in metres of water equivalent for the 14 North Cascade glaciers in this study, and the South Cascade Glacier. The Columbia Glacier through Lyman Glacier are monitored by NCGCP. The Noisy Glacier through N. Klawatti Glacier are monitored by the NPS. The South Cascade glacier is monitored by the USGS

Glacier	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
Columbia	0·21	−0·31	−0·2	−0·63	0·14	−0·09	−0·06	0·38	−1·85	−0·9	−0·96	−0·45	−0·62	0·35	−1·46	1·75	0·4
Daniels	0·11	−0·51	−0·36	−0·87	−0·15	−0·37	−0·68	−0·07	−1·7	−0·83	−0·45	0·24	0·45	0·88	−1·82	1·52	−0·25
Foss	0·51	−0·69	0·12	−0·38	0·23	0·09	−0·27	0·3	−1·92	−0·73	−0·68	0·31	0·34	0·5	−1·95	1·56	−0·1
Ice Worm	0·86	−0·75	−0·45	−1·39	−0·24	−0·67	−0·92	0·63	−2·23	−1·02	−1·23	0·47	0·57	0·76	−1·64	2·15	−0·33
L. Curtis	0·39	−0·16	−0·22	−0·56	−0·06	−0·29	−0·51	0·04	−1·76	−0·48	−0·55	−0·21	−0·18	0·27	−1·38	1·55	−0·25
Lynch	0·33	−0·22	−0·07	−0·3	0·17	0·03	−0·12	0·36	−1·38	−0·62	−0·4	0·18	0·53	0·62	−1·97	1·45	−0·24
Rainbow	0·58	0·04	0·2	−0·26	0·43	−0·24	−0·46	0·44	−1·65	−0·8	−0·72	−0·2	0·12	0·51	−1·49	1·84	0·15
Yawning	0·09	−0·23	−0·1	−0·47	−0·06	−0·19	−0·32	0·23	−2·06	−0·66	−0·62	−0·26	0·34	0·5	−2·03	1·63	−0·18
Easton							−0·58	0·41	−1·67	−1·01	−0·92	−0·31	0·22	0·53	−1·87	1·61	−0·1
Lyman			−0·64	−1·15	−0·53	−0·58	−0·9	0·55		−0·98	−0·71	−0·48	−0·41	0·43	−1·66	0·58	−0·28
Noisy										−0·95	−1·16	−0·11	0·22	0·1	−1·54	1·45	0·34
Sandalee											−0·19	0·37	0·81	0·87	−1·1	1·45	0·7
Silver										−0·04	−0·11	0·46	0·87	0·63	−0·07	1·49	1·01
N. Klawatti										−1·09	−1·93	−0·47	0·33	0·88	−1·49	1·57	0·8
S. Cascade	0·12	−1·2	−0·71	−2·56	−1·64	−0·71	−0·73	−0·2	−2·01	−1·23	−1·02	−0·69	0·1	0·63	−1·8	1·02	

measure bulk density between 1984 and 1986, and found that it ranged from 0·59 to 0·63 Mg m^{-3}. Owing to this consistency, snow pits are no longer used, and bulk density at the end of the ablation season is assumed to be 0·60 Mg m^{-3}.

In the ablation zone, ablation stakes are emplaced in a sequence from areas that lose their snow cover early in the summer to those that lose it late in the summer and not at all. Ablation measurements are made at a minimum of six stakes on each glacier• at 20–50 points km^{-2}. Measurements are made in late July and early August, recording the ablation during the first 3 months of the ablation season, for water resource assessment purposes and redrilling of the stakes when necessary. Ablation measurements are repeated in late September at the designated conclusion of the hydrologic year. Q2

The use of a high measurement density and consistent methods ensures that errors resulting from an imperfectly representative measurement network are largely consistent and correctable (Pelto, 1996, 1997, 2000).

NPS program

Since 1993 the NPS has monitored the net balance of three glaciers, and a fourth glacier has been monitored since 1994. Methods generally follow those established by the USGS during 45 years of monitoring South Cascade Glacier (Krimmel, 1994). These methods employ a two-season stratigraphic approach to calculate mass gained (accumulation) and mass lost (ablation) on a seasonal basis. Summation of these measurements allows for calculating the net balance of a given glacier for a given hydrologic year.

Measurements of accumulation are made in late April–early May as conditions allow. The thickness of the previous winter's snowpack is measured using probes at various points on the glacier. Measurement density ranges from 40 points km^{-2} on North Klawatti Glacier to 100 points km^{-2} on Noisy Glacier. The density of the snowpack at this time of year is assumed to be 0·5 Mg m^{-3}; this again reflects the observed consistency of density even early in the melt season. The actual bulk density, measured annually on South Cascade Glacier and from 1993 to 1995 on these glaciers, supports this assumption.

Measurements of ablation are made in mid-summer and in late September–early October on each glacier. Ablation stakes are used to measure the amount of firn and ice lost beneath the previous winter's snowpack. At least four stakes are placed on a longitudinal profile at fixed locations down the centreline of each glacier.

Winter accumulation and summer ablation balance maps are constructed annually for each glacier using large-scale digital elevation models for each glacier. Data from point measurements are used to develop statistical relationships between accumulation and ablation and elevation. These relationships are then used to integrate point data across the entire surface of the glacier within each 10 m contour. The net annual mass balance for a given year is then determined by summing the values for each 10 m contour for the entire glacier surface.

Assessment of actual error in mass balance measurement is difficult (Paterson, 1967; Pelto, 2000). In an examination of the error in mass balance measurements using different sampling densities, it was noted on the Columbia Glacier that the total number of measurements necessary to achieve consistent accuracy within $\pm$0·10 m $year^{-1}$ was 40 points (Pelto, 2000). The results confirm the Fountain and Vecchia (1999) conclusion that the number of measurements necessary to determine mass balance on small alpine glaciers is scale invariant; in this case, that 40 points satisfactorily minimized errors on both glaciers.

The error range for NCGCP glaciers where independent surface mapping and redundant measurements have been completed indicates a range of $\pm$0·1–0·20 m $year^{-1}$ (Pelto, 1996, 2000). Both NCGCP and NPS rely on a higher number of field measurements than any other programs in the USA, and hence the error should be reduced. The comparatively complete and uniform distribution of measurement locations and high-density network allows for avoiding the use of statistical tests that are applied to compensate for lower measurement densities (Pelto, 2000).

ANNUAL MASS BALANCE RECORD

The annual mass balance record is shown in Table II and Figure 2. The emphasis of Figure 2 is to illustrate the parallel nature of the trendlines for annual mass balance for each glacier, indicating the degree of similarity in annual response, which makes it difficult to distinguish the balance record of a single glacier. There is a significant average range in annual mass balance: 1·01 m year^{-1} from the most positive to most negative glacier for each year. This emphasizes that though the annual mass balance response to annual climate conditions is similar there is significant variation. The standard deviation of annual mass balance for individual years from 1995 to 2000 for all 14 glaciers ranged from 0·24 m in 1997 to 0·48 m in 1998. The standard deviation is highest in years with higher negative balances.

The annual mass balance record of North Cascade glaciers indicates a significant negative balance from 1984 to 1994 on all nine glaciers observed annually during this entire interval: −0·39 m year^{-1} for an average loss in mean glacier thickness of 4–4·5 m. The mean annual mass balance from l995 to 2000 for the same eight glaciers is 0·10 m year^{-1}, and 0·15 m year^{-1} for all 14 glaciers in this study, indicating a significant change to a slightly positive annual mass balance regime. Mean annual mass balances since 1995 have been particularly variable, making it difficult to establish this period as any type of specific climate interval; this is distinct from the previous period, which featured nearly continuous dry winter conditions (Bitz and Battisti 1999)●. Q6

That the mass balance is dominated by a regional climate signal is clear in a comparison of the annual mass balance records from these 14 glaciers in this study and the South Cascade Glacier (Krimmel, 1999) monitored by the USGS (Table II and Figure 2).

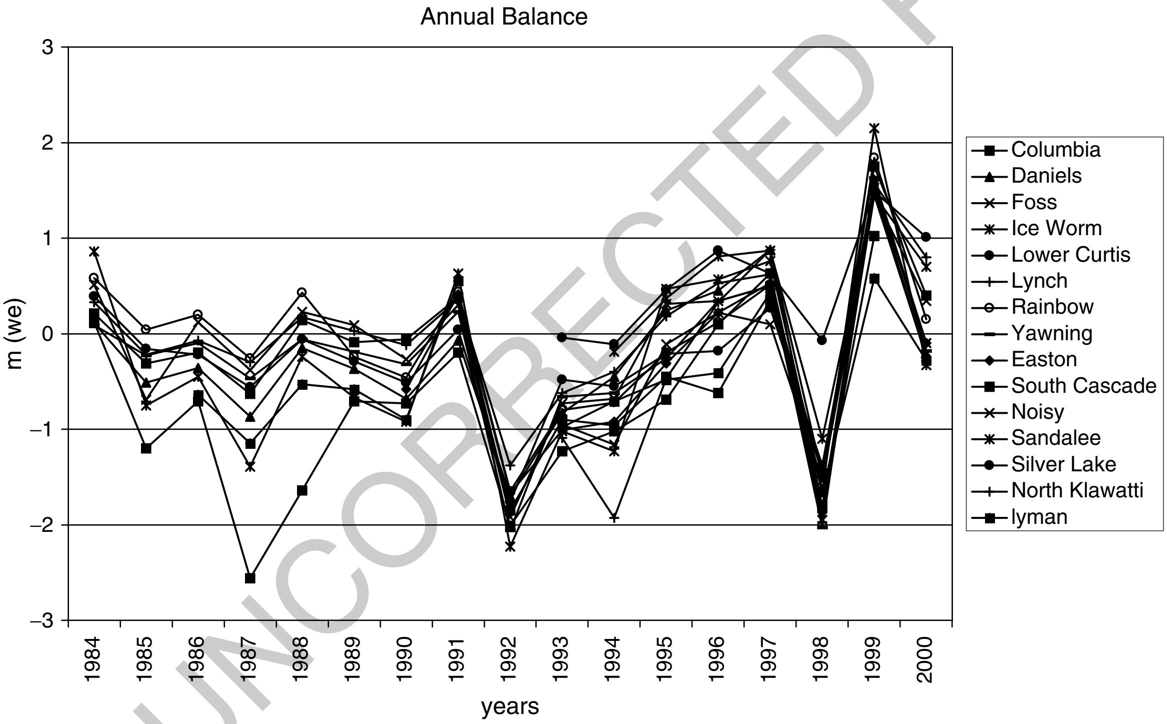
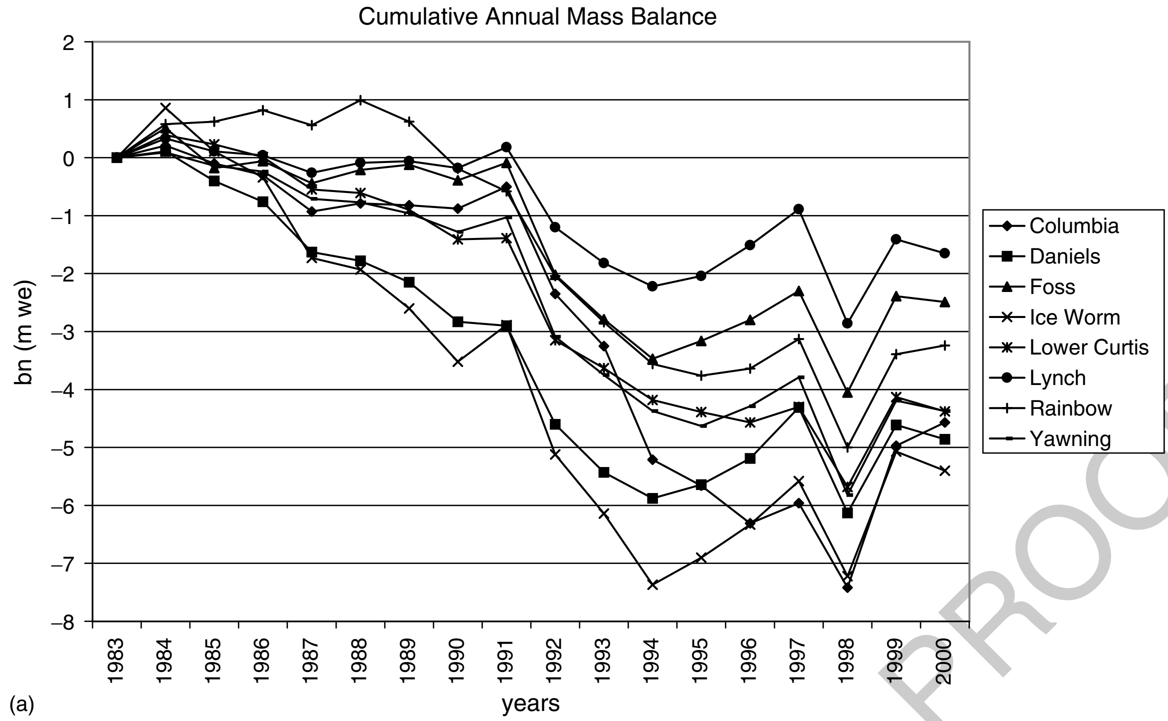


Figure 2. Annual mass balance record of North Cascade glaciers in metres of water equivalent. The high degree of correlation between glaciers is evident in the close tracking of each record. The annual balance of 14 North Cascade glaciers in this study, and the South Cascade Glacier. The Columbia Glacier through Lyman Glacier are monitored by NCGCP and the reported values are for b_a. The Noisy Glacier through N. Klawatti Glacier are monitored by the NPS and the reported values are the net balance b_n. The South Cascade glacier is monitored by the USGS and is the net balance b_n

Table III. Cross-correlation of annual mass balance on North Cascade glaciers

	Columbia	Daniels	Foss	Ice Worm	Lower Curtis	Lynch	Rainbow	Yawning	Easton	Noisy Creek	Silver Lake	Sandalee	North Klawatti	South Cascade
Columbia	1													
Daniels	0·83	1												
Foss	0·91	0·94	1											
Ice Worm	0·89	0·94	0·91	1										
Lower Curtis	0·93	0·92	0·94	0·92	1									
Lynch	0·86	0·96	0·98	0·9	0·93	1								
Rainbow	0·95	0·9	0·94	0·9	0·97	0·93	1							
Yawning	0·91	0·95	0·97	0·89	0·96	0·98	0·96	1						
Easton	0·93	0·96	0·97	0·96	0·95	0·97	0·99	0·98	1					
Noisy Creek	0·83	0·87	0·84	0·89	0·85	0·85	0·85	0·87	0·93	1				
Silver Lake	0·93	0·9	0·94	0·94	0·91	0·89	0·97	0·93	0·96	0·88	1			
Sandalee	0·87	0·95	0·97	0·92	0·9	0·96	0·95	0·97	0·97	0·94	0·96	1		
North Klawatti	0·9	0·8	0·85	0·88	0·82	0·8	0·92	0·84	0·9	0·8	0·98	0·9	1	
South Cascade	0·89	0·81	0·83	0·86	0·81	0·79	0·9	0·84	0·9	0·85	0·94	0·9	0·95	1



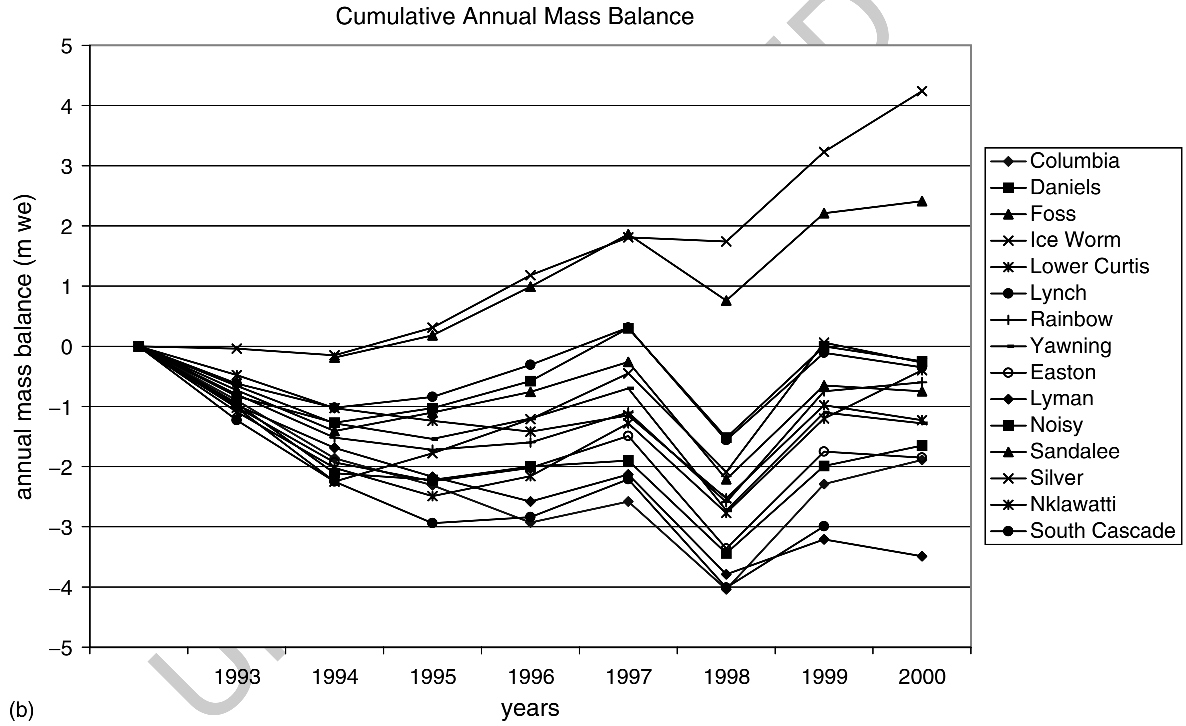


Figure 3. (a) Cumulative annual mass balance of eight North Cascade glaciers, 1984–2000. (b) Cumulative balance of 14• North Cascade glaciers, 1993–2000 plus South Cascade Glacier Q10

From a statistical standpoint the records of some of the glaciers are still short and the best measure of their similarity is cross-correlation of annual mass balance between each glacier (Table III). In most years, as indicated by Figure 2, a glacier's annual mass balance is similar regardless of regional setting. The lowest correlation coefficient between glaciers in this study is 0·80, with a mean correlation coefficient of 0·91. This demonstrates the degree to which annual mass balance in the North Cascades is a function of the regional climate for a given year. If we include the South Cascade Glacier measured by the USGS, the lowest correlation is 0·79. This glacier is retreating more rapidly than any other in the study, as a result of its generally more negative annual mass balance; hence its lower correlation is not a surprise.

Figure 3a shows, the long-term cumulative balance of the eight NCGCP glaciers form 1984 to 2000, and Figure 3b shows the cumulative balance of all 15 glaciers in the North Cascades (1993–2000) where mass balance measurements have been made. The trends in Figure 3a are parallel, but represent a substantial range in the magnitude of the cumulative balance.● Q7

Regional variations

The glaciers in this study can be broken into two broad regional groups based on cumulative balance and annual mass balance records. In most years, the agreement between all of the glaciers is excellent. However, in a few years, particularly 1995 and 1996, regional variations are evident. In both cases glaciers further east with respect to the climate divide had more positive mass balances; Figure 4. Owing to the short length of the record and the high correlation between all of the glaciers, the changes in variance and coefficient of variation between regions is not significant. The best measured at this point is the change in the mean for the groups as a whole.

From 1985 to 1994 Ice Worm Glacier and Daniels Glacier had the most negative balances; both of these glaciers are on Mt Daniels, just east of the Cascade Crest. From 1995 to 2000 Columbia Glacier and Lower

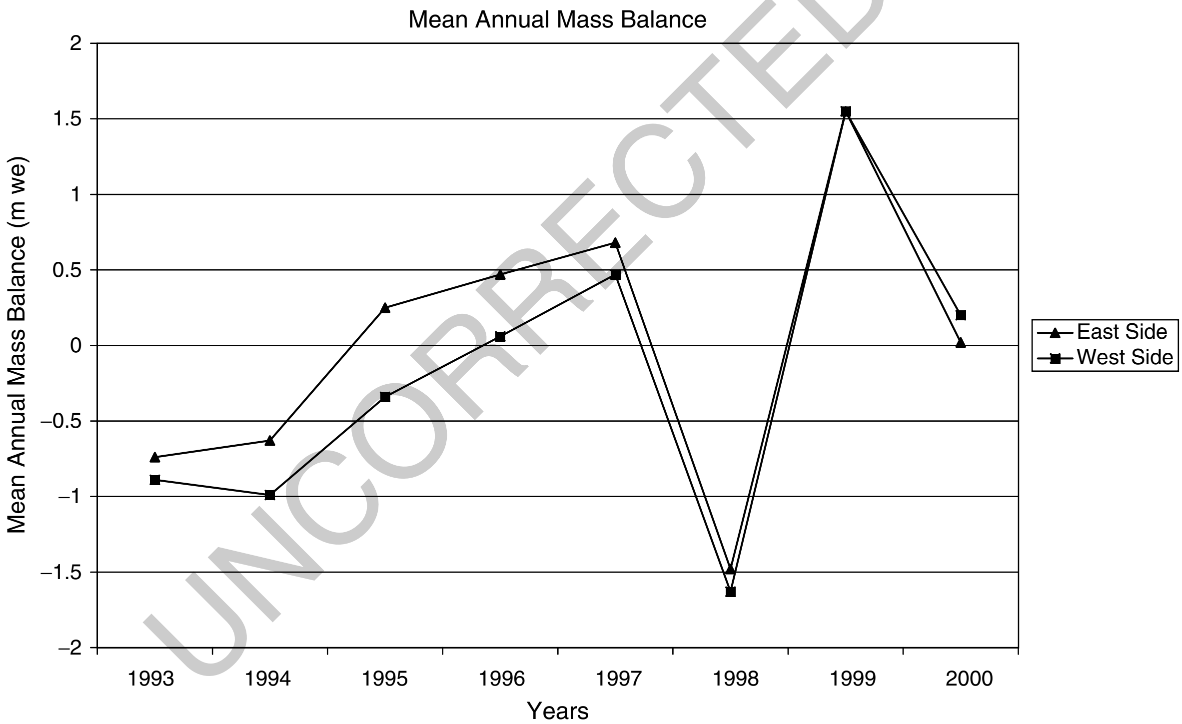


Figure 4. Mean annual mass balance of the eastern and western regions

Curtis Glacier had the most negative balances, these being the two lowest elevation glaciers. In Figure 3b, Silver Lake and Sandalee Glacier have had noticeably more positive balances. The next three most positive are Lynch Glacier, Daniels Glacier and Ice Worm Glacier. Each of these five glaciers is in the drier region of the range, with annual precipitation of 150–200 cm. The Cascade Crest and West Side glaciers all have annual precipitation exceeding 200 cm.

Glaciers that are east of the precipitation divide have a less maritime climate and share a similar history. Within the east-side group Silver Glacier tends to have the highest mean annual mass balance and Lyman Glacier the lowest (Figure 4). Lyman Glacier has the lowest mean altitude of any glacier in this group. Silver Glacier has the highest mean altitude. This group includes the glaciers of Mt Daniels, which have a distinct record. Mt Daniels is on the Cascade Crest and has two glaciers on either side of the crest. These glaciers have a very similar record and, as a group, fit the east-side pattern better than the Cascade Crest pattern.

The second group encompasses the more maritime or western region of the range. This includes the large volcanoes of Mt Baker and Glacier Peak, outlying peaks east of the Cascade Crest, and glaciers along the Cascade Crest between Glacier Peak and the Skagit River. Within this group the Lower Curtis and Columbia Glacier are low elevation, avalanche-fed glaciers that are less consistent in their annual mass balance. The west-side glaciers had a more positive year in 1999 than the east-side glaciers (Figure 4).

In the east-side group the glacier that has the poorest fit is the lowest elevation glacier, the Lyman Glacier. In the west-side glacier group the poorest fits are for Columbia Glacier and Lower Curtis Glacier, both low-altitude glaciers. Grouping these glaciers together not as a regional group•, as a topographic group, yields a good agreement. Q2

IMPACT ON TERMINUS BEHAVIOUR

How significant were the recent negative mass balances? The negative mass balance of the 1977–94 period led to the retreat of all North Cascade glaciers observed (Pelto, 1993; Krimmel, 1999). By 1984, all the Mt Baker glaciers, which were advancing in 1975, were again retreating (Pelto, 1993). The mean retreat of eight Mt Baker glaciers from 1979 to 1998 was 197 m. Between 1979 and 1984, 35 of the 47 North Cascade glaciers observed annually by NCGCP had retreated. By 1991 all 47 glaciers' termini observed by NCGCP were retreating (Pelto, 1993). As these 47 glaciers have retreated the NCGCP has observed the development of nine new alpine lakes, occupying basins formerly filled by ice. The less negative balances of the last-5 years have not had a substantial impact on terminus behaviour yet. With the 2000–01 winter season having the lowest snowpack at the USDA Snotel system in the North Cascades, it is evident that the upcoming year will be one of negative annual mass balances.

CONCLUSION

All glaciers in the North Cascades of Washington have similar mass balance histories. The mean annual range between the most positive and negative annual mass balance for a glacier is significant at 1·1 m, but the degree of similarity in response to annual climate conditions is even more striking, as indicated by the high correlation coefficients. There are some regional patterns evident within the range, but the dominant signal is the overall climate regime of the entire North Cascade region. The regional signals separate the glaciers in the western (more maritime) and eastern (less maritime) regions of the North Cascades. The difference in the mean annual balance of glaciers in each region is evident in some (1994–97) but not all of the years. Altitude is also a key factor in determining recent mean annual mass balance, with low-elevation glaciers having higher negative balances.

An equally important conclusion is that the annual mass balance field methods utilized by both NPS and NCGCP, though different, are yielding consistent and comparable results. This is not surprising, since both are measuring the same two variables, residual snowpack and surface ablation; the only differences are the

7–10 days change in the timing of the fall measurements, and the use of a higher density of measurements on NCGCP glaciers. This network represents an important record for understanding the long-term impact of climate change on the glaciers of the entire North Cascades.

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