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The current disequilibrium of North Cascade glaciers

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Abstract:

Three lines of evidence indicate that North Cascade (Washington, USA) glaciers are currently in a state of disequilibrium. First, annual balance measured on nine glaciers yields a mean cumulative balance for the 1984–2004 period of −8·58 m water equivalent (w.e.), a net loss of ice thickness exceeding 9·5 m. This is a significant loss for glaciers that average 30–50 m in thickness, representing 18–32% of their entire volume.

Second, longitudinal profiles completed in 1984 and 2002 on 12 North Cascade glaciers confirm this volume change indicating a loss of −5·7 to −6·3 m in thickness (5·0–5·6 m w.e.) between 1984 and 2002, agreeing well with the measured cumulative balance of −5·52 m w.e. for the same period. The change in thickness on several glaciers has been equally substantial in the accumulation zone and the ablation zone, indicating that there is no point to which the glacier can retreat to achieve equilibrium. Substantial thinning along the entire length of a glacier is the key indicator that a glacier is in disequilibrium.

Third, North Cascade glacier retreat is rapid and ubiquitous. All 47 glaciers monitored are currently undergoing significant retreat or, in the case of four, have disappeared. Two of the glaciers where mass balance observations were begun, Spider Glacier and Lewis Glacier, have disappeared. The retreat since 1984 of eight Mount Baker glaciers that were all advancing in 1975 has averaged 297 m. These observations indicate broad regional continuity in glacial response to climate. Copyright © 2006 John Wiley & Sons, Ltd.

KEY WORDS glacier; mass balance; terminus retreat; climate change; North Cascades

INTRODUCTION

Glaciers respond to climate in an attempt to achieve equilibrium, advancing with a climate cooling/snowfall increase and retreating with climate warming. If a glacier cannot achieve a point of equilibrium through retreat, it is in disequilibrium with the climate system. A glacier that is in disequilibrium with the present climate will melt away with a continuation of this climate.

The North Cascade Glacier Climate Project (NCGCP) was founded in 1983 to monitor glaciers throughout the range and to identify the response of North Cascade (Washington) glaciers to regional climate change. This task requires monitoring a large number of glaciers. In particular, annual balance measurements on 8–10 glaciers (Figure 1), periodic terminus surveys (every 1–5 years) on 47 glaciers and longitudinal profile mapping on 12 glaciers over a 20 year period have been completed.

This data set is unique in western North America, both in the number of glaciers monitored annually and in the temporal length of the record. This has enabled the identification of consistent trends from glacier to glacier across this mountain range. In the western USA, continuous long-term (>20 years) mass balance records exist on only one other glacier, the South Cascade Glacier monitored by the United States Geological Survey (USGS; Krimmel, 2001). Blue Glacier, in the Olympic Mountains of Washington, also has a long mass balance record, but substantial portions are not based on annual field measurements. Mapping of changes in glacier area have been conducted in both Mount Rainier and Glacier National Parks (Driedger and Kennard,

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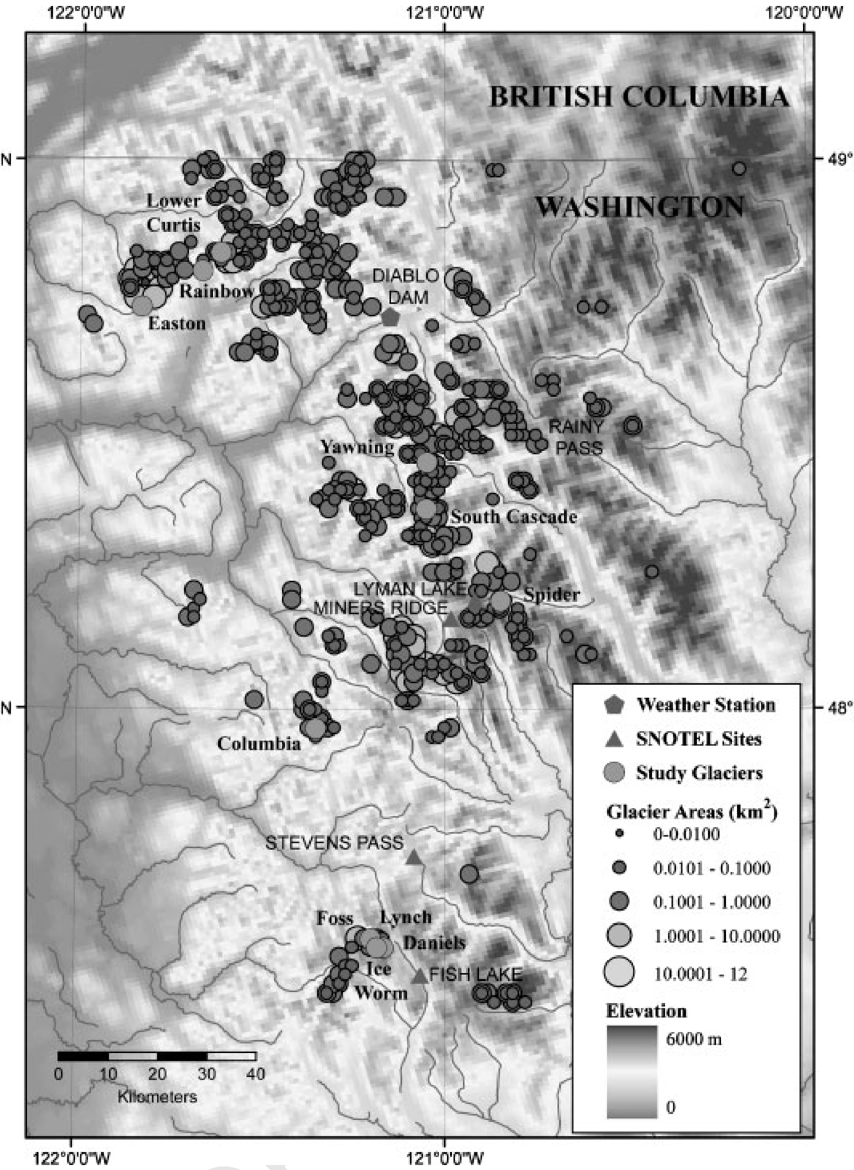

Figure 1. Location map of the North Cascade glaciers

1986; Hall and Fagre, 2003). Changes in longitudinal profile have been completed on the Klawatti and South Cascade glaciers (Tangborn *et al.*, 1990; Krimmel, 2001).

The response time of North Cascade glaciers to climate change is comparatively short: 5–20 years for the initial response to a climate change, and 30–100 years for a response that begins to approach equilibrium (Schwitter and Raymond, 1993; Pelto and Hedlund, 2001). The current climate change favours glacier retreat. A glacier will retreat in an attempt to reach a new point of equilibrium. In the North Cascades, the recent loss of several glaciers (Pelto and Hedlund, 2001) raises the question as to whether these glaciers can reach a new point of equilibrium with the current climate. The marked retreat and expected melting away of a majority of glaciers in a mountain range, which indicates regional disequilibrium, has been noted in Glacier

National Park (Hall and Fagre, 2003) and on many tropical glaciers, including on Mount Kenya and Mount Kilimanjaro (Kaser *et al*., 2004).

CLIMATE

The North Cascade region has a temperate maritime climate. Approximately 80% of the region's precipitation occurs during the accumulation season (October–April), when the North Cascades are on the receiving end of the Pacific storm track. From late spring to early fall, high pressure to the west keeps the Pacific Northwest comparatively dry. These seasonal variations are related to changes in large-scale atmospheric circulation occurring over the Pacific Ocean, including the Gulf of Alaska.

The climate west of the Cascade Crest is temperate with mild year-round temperatures, abundant winter precipitation, and dry summers. Average annual precipitation in the North Cascades typically exceeds 200 cm west of the divide. The climate east of the Cascade Crest is more continental, creating a sharp contrast to the maritime climate of the west of the crest.

North Cascade temperatures have increased during the 20th century. On average, the region warmed about 0·6 °C; warming has been largest west of the Cascades during winter and spring (Kovanen, 2003). Beginning in 1976, the North Cascades region experienced a substantial climate change to generally warmer and drier conditions (Ebbesmeyer *et al*., 1991).

The long-term trends that in particular affect glaciers are changes in mean ablation-season temperature and winter-season snowfall. Winter-season snowfall across the western USA is directly measured by the United States Department of Agriculture (USDA) at a series of USDA snowpack telemetry (SNOTEL) sites. The 1 April snow water equivalent (SWE) provides an excellent measure of winter-season snowfall in the North Cascades. The 1 April SWE record from five long-term SNOTEL stations (Rainy Pass, Lyman Lake, Stevens Pass, Miners Ridge, Fish Lake) indicates 1 April SWE has declined by 25% at these stations since 1946, whereas winter-season precipitation has declined only slightly by 3% at these stations and at Diablo Dam (a National Weather Service cooperative station). Thus, most of the loss in winter SWE reflects increased melting of the snowpack or rain events during the winter season. This decline in snowpack has been noted throughout the Pacific Northwest (Mote *et al*., 2005). During the 1946–2005 interval, summer temperatures have risen 0·6 °C at Diablo Dam (Figure 2), and this change is consistent throughout this part of the range (Kovanen, 2003).

Figure 2 illustrates the two long-term climatic trends that have been impacting glaciers negatively, namely the decline in 1 April SWE and the rise in ablation-season temperature (May–September). As can be seen in Figure 2, the annual variability has been high and will remain so; however, what is striking is the number of recent years, nine during 1984–2005 versus four during 1946–1983, with summer temperatures exceeding 16 °C. Equally noteworthy is the paucity of recent years with SWE reaching 1·5 m water equivalent (w.e.), i.e. two from 1984–2005 compared with 10 from 1946–1983. Several climate models agree that the Pacific Northwest will likely experience a 1·7–2·8 °C temperature increase and 1–10 cm increase in winter precipitation during the early 21st century (Parson, 2001). A portion of this warming has already placed glaciers in jeopardy.

ANNUAL BALANCE

Methods

Mass balance measurements are the most sensitive indicator of short-term glacier response to climate change. Mass balance is a more valuable indicator of climate than terminus behaviour over short time periods because it is a direct measure of annual climate conditions, whereas terminus behaviour is determined by the cumulative impact of climate and other glaciologic factors over many years (Johannesson *et al*., 1989).

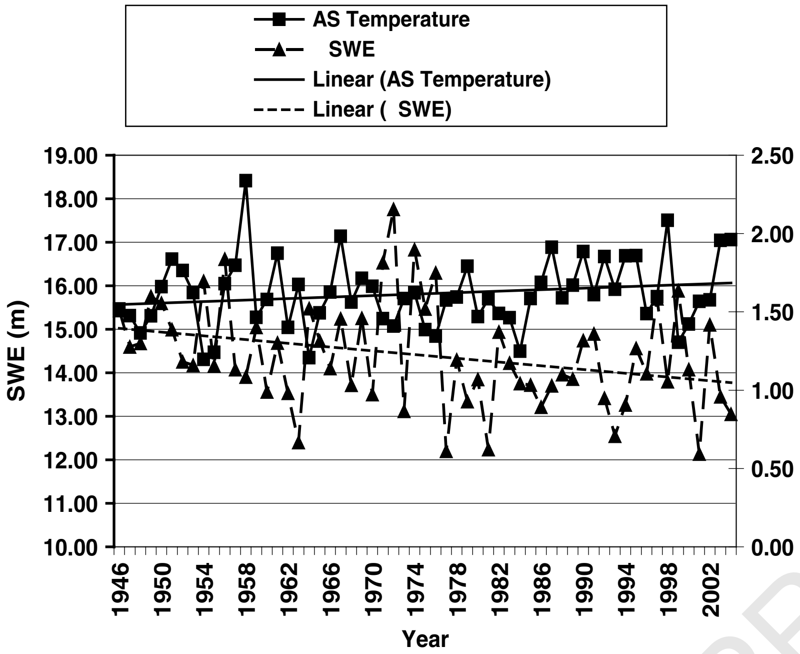

Figure 2. Ablation-season temperature (June–September), and 1 April SWE at five USDA SNOTEL sites (Rainy Pass, Stevens Pass, Harts Pass, Miners Ridge and Fish●Lake)

AQ1

Surface mass balance is the difference between accumulation of water in winter and loss of water by ablation in summer. It is typically measured on a water-year basis, which in the North Cascades begins on 1 October and ends 30 September of the following calendar year. Annual balance is defined as the change observed on a glacier's surface between successive balance minimums (Mayo *et al*., 1972).

Since 1984, NCGCP has monitored the annual balance of eight glaciers, adding one additional glacier in 1990 (Pelto, 1996, 1997). These glaciers represent a wide range of characteristics and span the North Cascade Range (Table I). NCGCP methods emphasize measuring surface mass balance measurements with a high measurement density on each glacier compared with standard methods, with consistent measurement methods, and at fixed measurement locations. The NCGCP methods are reviewed in detail by Pelto (1996, 1997; Pelto and Riedel, 2001). The average density of measurement points by the NCGCP in the accumulation zone of each glacier ranges from 180 to 300 km^{-2} (Pelto, 1996; Pelto and Riedel, 2001). Measurements are made at the same time each year, in late July and again in late September near the end of the ablation season. Any additional ablation that occurs after the last visit to a glacier is measured during the subsequent hydrologic year. Glaciers monitored in this programme do not lose significant mass by calving or avalanching, so that changes observed are primarily a function of winter accumulation and summer ablation on the glacier's surface. The glaciers monitored also have relatively simple geometries, without multiple accumulation areas and ice divides.

Annual balance results

Glaciers in the North Cascades exhibit a consistent response to year-to-year climate variations (Table II). Figure 3 illustrates the closely correlated pattern of annual balance fluctuations on the nine glaciers measured. In most years, all glaciers respond in step with each other to variations in winter precipitation and summer temperature; hence the frequency of overlain lines in Figure 3. There is an annual range of 0·8 m w.e. in the individual annual balances, but the interannual trend remains the same.

Table I. The geographic characteristics of the nine glaciers where annual balance has been monitored annually. Accumulation sources:

Glacier	Aspect	Area (km^2)	Location	Accumulation sources[a]	Distance to climate divide	Elevation range (m)
Columbia	SSE	0·9	47°58′N, 121°21′W	DS, DW, AV	15 km west	1750–1450
Daniels	E	0·4	47°34′N, 121°10′W	DS, WD	1 km east	2230–1970
Easton	SSE	2·9	48°44′N, 121°50′W	DS	75 km west	2900–1700
Foss	NE	0·4	47°35′N, 121°12′W	DS	At divide	2100–1840
Ice Worm	SE	0·1	47°34′N, 121°10′W	DS, AV	1 km east	2100–1900
Lower Curtis	S	0·8	48°50’N, 121°37′W	DS, WD	West 55 km	1850–1460
Lynch	N	0·7	47°34′N, 121°11′W	DS, WD	At divide	2200–1950
Rainbow	ENE	1·6	48°48′N, 121°40′W	DS, AV	70 km west	2040–1310
Yawning	N	0·3	48°27′N, 121°03′W	DS	At divide	2100–1880

[a] WD: wind drifting; AV: avalanche accumulation; DS: direct snowfall.

Table II. The annual balance of nine North Cascade glaciers observed in this study (NCGCP) and for South Cascade Glacier, measured by the USGS (Krimmel, 2001)

Year	Columbia	Daniels	Easton	Foss	Ice Worm	Lower Curtis	Lynch	Rainbow	Yawning	South Cascade	Cumulative balance[a]
1984	0·21	0·11		0·51	0·86	0·39	0·33	0·58	0·09	0·12	0·39
1985	−0·31	−0·51		−0·69	−0·75	−0·16	−0·22	0·04	−0·23	−1·20	0·04
1986	−0·20	−0·36		0·12	−0·45	−0·22	−0·07	0·20	−0·10	−0·71	−0·10
1987	−0·63	−0·87		−0·38	−1·39	−0·56	−0·30	−0·26	−0·47	−2·56	−0·71
1988	0·14	−0·15		0·23	−0·24	−0·06	0·17	0·43	−0·06	−1·64	−0·65
1989	−0·09	−0·37		0·09	−0·67	−0·29	0·03	−0·24	−0·19	−0·71	−0·87
1990	−0·06	−0·68	−0·58	−0·27	−0·92	−0·51	−0·12	−0·46	−0·32	−0·73	−1·30
1991	0·38	−0·07	0·41	0·30	0·63	0·04	0·36	0·44	0·23	−0·20	−1·00
1992	−1·85	−1·70	−1·67	−1·92	−2·23	−1·76	−1·38	−1·65	−2·06	−2·01	−2·80
1993	−0·90	−0·83	−1·01	−0·73	−1·02	−0·48	−0·62	−0·80	−0·66	−1·23	−3·55
1994	−0·96	−0·45	−0·92	−0·68	−1·23	−0·55	−0·40	−0·72	−0·62	−1·02	−4·25
1995	−0·45	0·24	−0·31	0·31	0·47	−0·21	0·18	−0·20	−0·26	−0·69	−4·24
1996	−0·62	0·45	0·22	0·34	0·57	−0·18	0·53	0·12	0·34	0·10	−4·05
1997	0·35	0·88	0·53	0·50	0·76	0·27	0·62	0·51	0·50	0·63	−3·50
1998	−1·46	−1·82	−1·87	−1·95	−1·64	−1·38	−1·97	−1·49	−2·03	−1·80	−5·18
1999	1·75	1·52	1·61	1·56	2·15	1·55	1·45	1·84	1·63	1·02	−3·70
2000	0·40	−0·25	−0·10	−0·10	−0·33	−0·25	−0·24	0·15	−0·18	0·38	−3·80
2001	−1·52	−1·75	−1·93	−1·92	−2·15	−1·88	−1·82	−1·71	−1·94	−1·57	−5·65
2002	0·60	−0·18	0·18	0·10	0·05	0·13	−0·13	0·12	0·26	0·55	−5·52
2003	−1·17	−1·52	−0·98	−1·35	−1·40	−1·25	−1·20	−0·98	−1·85	−2·01	−6·82
2004	−1·83	−2·13	−1·06	−1·94	−2·00	−1·51	−1·98	−1·67	−1·78		−8·58

[a] Does not include Easton Glacier due to its shorter record or South Cascade● Glacier.

AQ2

Regional response to climate is also indicated by the high correlation values of annual mass balance between glaciers that range from $r^2 = 0{\cdot}75$ to 0·99 (Table III). The South Cascade Glacier, located approximately 10 km south of Yawning Glacier, in the midst of the NCGCP network, and monitored by the USGS, is also included and is seen to be highly correlated with the NCGCP-surveyed glaciers (Krimmel, 1998).

The mean annual balance for the 1984–2004 period was −0·41 m on the eight glaciers monitored annually. The mean cumulative mass balance loss was −8·5 m w.e., which represents a minimum of 9·5 m of glacier thickness lost. North Cascade glaciers have average thicknesses ranging from 30 to 60 m (Post *et al.*, 1971;

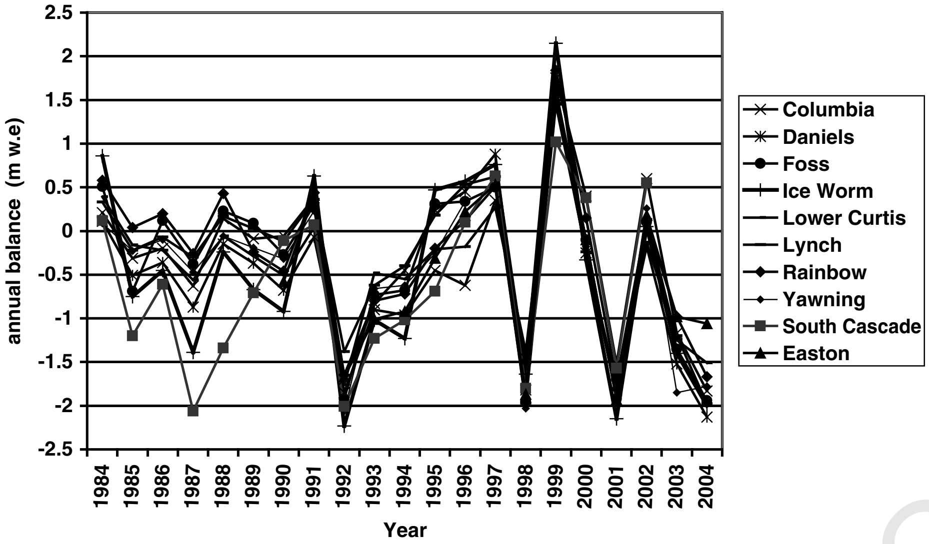

Figure 3. Annual balance records for 10 North Cascade glaciers. South Cascade Glacier data from the USGS (Krimmel, 2001)

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

	Columbia	Daniels	Foss	Ice Worm	LCurtis	Lynch	Rainbow	Yawning	Easton	South Cascade
Columbia	1	0·85	0·9	0·86	0·93	0·86	0·94	0·92	0·93	0·84
Daniels	0·85	1	0·95	0·95	0·93	0·96	0·92	0·95	0·98	0·97
Foss	0·9	0·95	1	0·93	0·95	0·98	0·95	0·97	0·98	0·78
Ice Worm	0·86	0·95	0·93	1	0·93	0·91	0·92	0·9	0·97	0·84
Lower Curtis	0·93	0·93	0·95	0·93	1	0·94	0·97	0·97	0·97	0·78
Lynch	0·86	0·96	0·98	0·91	0·94	1	0·94	0·97	0·97	0·75
Rainbow	0·94	0·92	0·95	0·92	0·97	0·94	1	0·95	0·99	0·76
Yawning	0·92	0·95	0·97	0·9	0·97	0·97	0·95	1	0·99	0·81
Easton	0·93	0·98	0·98	0·97	0·97	0·97	0·99	0·99	1	0·94
South Cascade	0·83	0·97	0·78	0·84	0·78	0·75	0·76	0·81	0·94	1
Mean correlation	0·9	0·95	0·94	0·92	0·94	0·93	0·93	0·94	0·97	0·85

Pelto and Hedlund, 2001). Thus, 18–32% of the volume of these glaciers has been lost since 1984. This finding is consistent with observations by the USGS at South Cascade Glacier. Since the mid 1950s, South Cascade Glacier's cumulative mass balance has been −25 m. Its mean annual balance from 1956–75 averaged −0·15 m; but this decreased substantially from 1976 to 2003, during which time the mean annual balance averaged −1·00 m (Krimmel, 2001). The cumulative mass balance of the North Cascade glaciers is becoming increasingly negative, indicating that, instead of approaching equilibrium as the glaciers retreat, they are experiencing increasing disequilibrium with current climate (Figure 4). The mean 1 April SWE in the North Cascades in 2005 at USDA SNOTEL locations in the Northern Cascades is the lowest since 1984, indicating that a negative annual balance will be experienced this year as well.

TERMINUS BEHAVIOUR

Since the maximum glacier advance during the Little Ice Age (LIA) there have been three climate changes in the North Cascades sufficiently large to alter glacier terminus behaviour substantially. During the LIA the

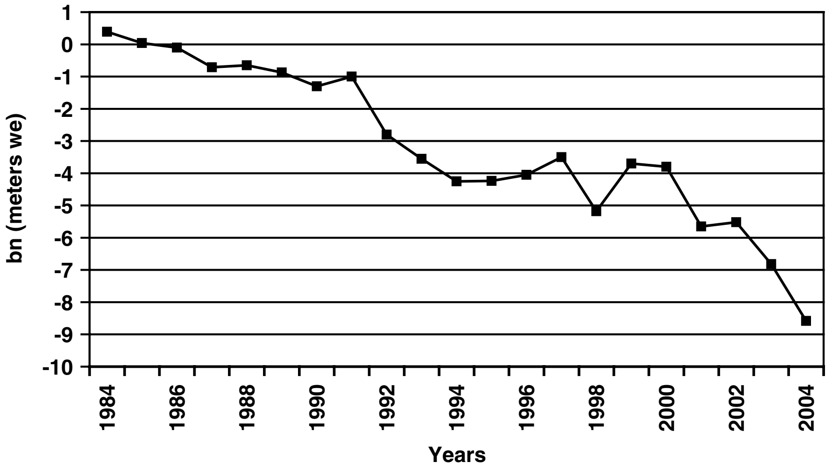

Figure 4. Cumulative mass balance record of North Cascade glaciers in metres of water equivalent. The high degree of correlation between glaciers is evident in the close tracking of each record

mean annual temperatures were 1·0–1·5 °C cooler than at present (Burbank, 1981; Porter, 1986). The lower temperatures in the North Cascades led to a snowline lowering of 100 to 150 m during the LIA (Burbank, 1981; Porter, 1986). North Cascade glaciers maintained advanced terminal positions from 1650 to 1890, emplacing from one to several terminal moraines.

This first substantial climate change following the LIA was a progressive temperature rise from the 1880s to the 1940s. The warming led to ubiquitous rapid retreat of North Cascade Range alpine glaciers from 1890 to 1944 (Rusk, 1924; Long, 1955; •Hubley, 1956; Burbank, 1981). The average terminus retreat of glaciers on Mount Baker from their LIA moraines to their 1950 positions was 1440 m. For the 38 North Cascade glaciers monitored across the range, the retreat over the same period was 1215 m (Pelto and Hedlund, 2001).

AQ3

The second substantial change in climate in the Northern Cascades began in 1944, when conditions became cooler and precipitation increased (•Hubley 1956; Tangborn, 1980). •Hubley (1956) and Long (1956) noted that many North Cascade glaciers began to advance in the early 1950s, following 30 years of rapid retreat. All 11 Mount Baker glaciers advanced during this 1945–75 period.

AQ4
AQ5

The retreat and negative mass balances of the 1977–98 period have been noted by Harper (1993), •Krimmel (1994, 1999), and •Pelto (1993, 2001). By 1984, all Mount Baker glaciers, which were advancing in 1975, were again retreating (Pelto, 1993). The average retreat of Mount Baker glaciers from 1984 to 2004 was 297 m, ranging from 260 to 430 m. The average retreat measured 137 m for all 47 North Cascade glaciers. This is less retreat than on Mount Baker glaciers; but, given the small size of many of the glaciers, it represents a greater percentage of overall length. Between 1979 and 1984, 35 of the 47 North Cascade glaciers observed annually by NCGCP had begun retreating. By 1992, all 47 glacier termini observed by NCGCP were retreating (Pelto, 1993). By 2004, four glaciers had disappeared: David Glacier, Lewis Glacier, Spider Glacier and Milk Lake Glacier. The NCGCP had been monitoring the terminus position of the four glaciers that disappeared and in each case no glacier ice mass exceeding 0·01 km^2 was observed.

AQ6
AQ7

The time between the onset of a mass balance change and the onset of a significant change in terminus behaviour is called the initial terminus response time or reaction time Ts (Johannesson *et al.*, 1989). For the Northern Cascade glaciers, Ts was determined from the time it took for an observed change in terminus response to the relative cooler and wetter weather that began in 1944 (Long 1955, 1956; •Hubley, 1956; Tangborn, 1980), and to the subsequent warmer and drier conditions beginning in 1977 (Ebbesmeyer *et al.*, 1991). Focusing on 21 North Cascade glaciers that responded to these two climate shifts, all having areas under 10 km^2, the initial terminus response was invariably less than 16 years (•Hubley, 1956; Harper, 1993;

AQ8
AQ9

Pelto, 1993). Thus, by 2004, the termini of all North Cascade glaciers had completed their initial response to the 1976 climate change. The current climate change is significant enough that equilibrium is not being approached yet.

The 38 North Cascade glaciers where the terminus history has been determined for the 1890–1998 period exhibit one of three distinct patterns (Pelto and Hedlund, 2001):

1. Retreat from 1890 to 1950, then a period of advance from 1950 to 1976, followed by retreat since 1976.
2. Rapid retreat from 1890 to approximately 1950, followed by slow retreat or equilibrium from 1950 to 1976 and moderate to rapid retreat since 1976.
3. Continuous retreat from 1890 to 2005.

Today, regardless of the initial pattern of glacier retreat, rapid retreat is under way, indicating that the Northern Cascade glaciers are in disequilibrium with current climate.

Longitudinal profiles

Centreline surface elevation longitudinal profiles have been completed for three different moments in time from historic photographs (ca 1900), USGS maps (1964 and 1985), and our own field measurements (1984 to present) on 12 glaciers. This paper focuses on results from Columbia, Easton, and Lower Curtis Glaciers (Pelto and Hartzell, 2004). Each profile begins at a fixed bedrock location below the terminus and ends at the head of the glacier. Easton Glacier lacks a fixed bedrock feature at its head; thus, the profile extends over only 80% of its length.

Since 1984, Columbia Glacier has retreated 134 m. Lateral reduction in glacier width of 95 m in the lower section of the glacier and the reduction in glacier thickness are even more substantial as a percentage. Easton Glacier has retreated 315 m from 1989 to 2005. In 1989, the glacier was in contact with a terminal moraine emplaced during the glacier's advance in the 1950–75 period (Figure 5). The Lower Curtis terminus remains vigorously active, but has retreated 184 m since the onset of its retreat in 1986.

The changes in each glacier indicate that Easton Glacier has lost 46 m of ice thickness since 1916, and 13 m from 1984 to 2002. Lower Curtis Glacier lost 45 m of ice thickness from 1908 to 1984, and an additional 6 m from 1984 to 2002. On Columbia Glacier, the ice thickness loss from 1911 to 1984 was 57 m, 11 m from 1965 to 2002, and 8 m from 1984 to 2002 (Pelto and Hartzell, 2004).

The 1984–2002 profile change shows that the greatest thinning for Lower Curtis and Columbia Glacier has occurred in the middle of their cirque basins, in the accumulation zone, where slope is at a minimum and glacier thickness a maximum (Figure 6). The thinning in the cirque basin for Columbia Glacier since 1984 has been 13–16 m, versus a glacier-wide average thinning of 8 m. On Lower Curtis Glacier, the thinning in the cirque basin has averaged 10 m, versus 6 m for the entire glacier. In both cases, this location of maximum thinning is in the accumulation zone (Pelto and Hartzell, 2004).

Typically, a glacier's thinning is greatest at the terminus. At some distance above the terminus, usually in the accumulation zone, the glacier no longer thins appreciably even during a retreat (Schwitter and Raymond, 1993). The observed profile change exhibited by Easton Glacier from 1984 to 2002 is more typical thinning, with the greatest elevation change at the terminus. Recent thickness change averages 18 m in the vicinity of the terminus and 8 m at the equilibrium line altitude. The reduction in thinning with elevation indicates that, at some point in the accumulation zone, the glacier is not thinning appreciably. This behaviour of greatest thinning at the terminus suggests the Easton Glacier is capable of retreating to a new stable position. However, Lower Curtis and Columbia Glaciers exhibit a more unstable form of retreat, where the accumulation zone itself experiences substantial thinning. This observation, in conjunction with the observed terminus retreat, suggests that the entire glacier is out of equilibrium. The two glaciers in this condition seem unlikely to be able to survive in anything like their present extent, given the current climate.

The 1984–2002 cumulative mass balance change obtained from annual balance records for Columbia Glacier is −6·09 m w.e., and a change of −6·26 m w.e. has been measured for the Lower Curtis Glacier,

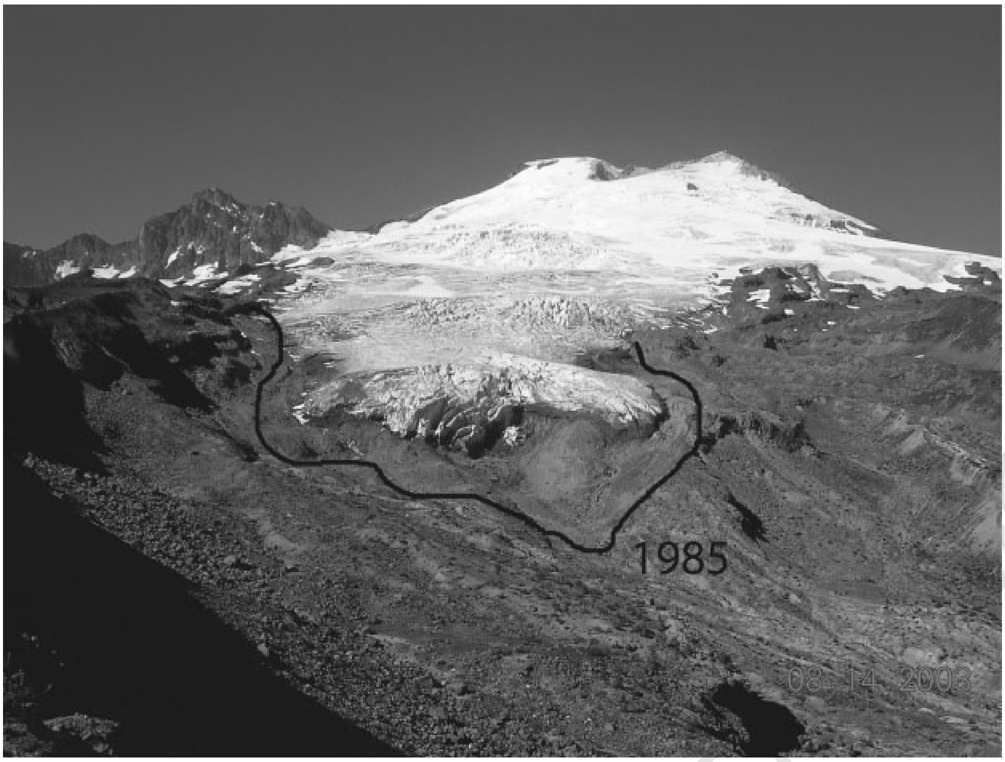

Figure 5. Terminus of the Easton Glacier in 2003; 1985 position indicated by black line

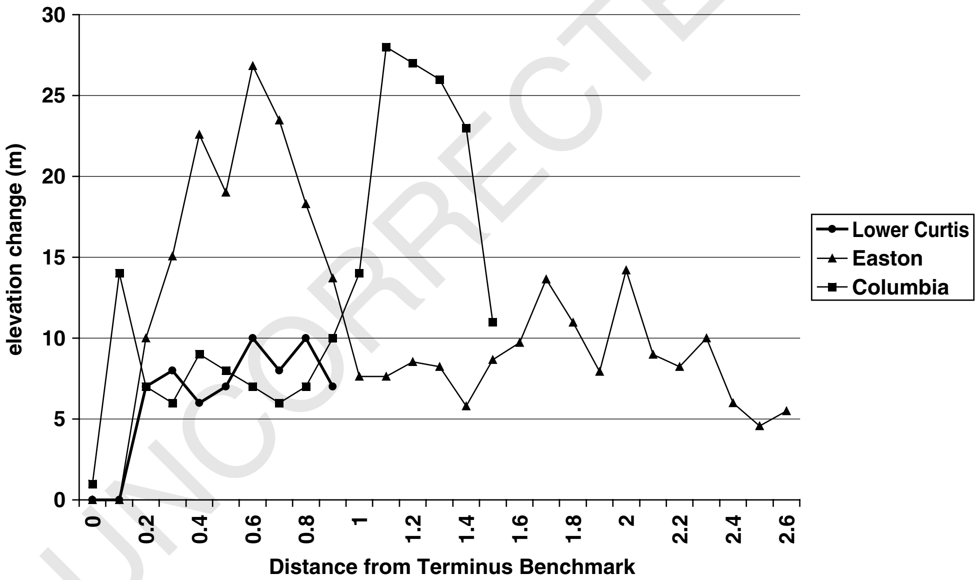

Figure 6. Longitudinal profile height changes on the Lower Curtis, Easton and Columbia Glaciers as measured from the terminus benchmark and proceeding upglacier

both corresponding to a change of 7 m in ice thickness. Field measurements recorded ice thickness reductions of 8 m on Columbia Glacier and 6 m on Lower Curtis Glacier, corroborating the annual surface balance records. The surface balance record for Easton Glacier has been slightly more negative than the other two glaciers since 1990. However, the surface balance and longitudinal profile cannot be compared directly in this fashion, as the longitudinal profile does not extend to the head of the glacier and the surface annual balance record incorporates measurements from the entire extent of the glacier.

CONCLUSIONS

The recent 0·6 °C temperature rise in summer temperature and the 25% reduction in mean 1 April SWE from 1946 to 2004 in the North Cascades have resulted in evident disequilibrium of North Cascade glaciers. The 1990s were the warmest decade by 0·5 °C of the 20th century in the Pacific Northwest (Mote *et al*., 2005). The mean annual balances of North Cascade glaciers averaged −0·41 m from 1984 to 2004. The net loss, −8·58 m w.e., represents a significant portion (18–32%) of the total glacier volume and has resulted in substantial retreat and thinning. The annual balance pattern is quite similar from glacier to glacier in the North Cascades from 1984 to 2004, indicating that morphometric and geographic characteristics of the glaciers are much less important than the regional climate in determining glacier mass balance. This has not been viewed to be the case in research focusing on just two or three glaciers (Tangborn *et al*., 1990; Kovanen, 2003). The retreat is ubiquitous, rapid and increasing. There is no evidence that North Cascade glaciers are close to equilibrium. Their ongoing thinning indicates that all of the glaciers will continue to retreat in the foreseeable future.

In cases where the thinning is substantial along the entire length of the glacier, no point of equilibrium can be achieved with present climate and the glacier is unlikely to survive. This has already occurred on the David, Lewis, Spider and Milk Lake Glaciers. In 2005, 10 of 12 glaciers where longitudinal profiles were completed are thinning dramatically along their entire length. The majority of North Cascade glaciers are hence in a state of disequilibrium with current climate. A glacier in disequilibrium cannot achieve equilibrium via retreat and will melt away with the current climate. This is a rule that should apply to temperate alpine glaciers regardless of location.

The coherent response of all the glaciers to climate change has been noted for the Pacific Northwest as a whole by •Hodge *et al*. (1997). This is emphasized by the annual balance and terminus records described in this paper. The trend in mass balance of the glaciers of the North Cascades is becoming more negative and terminus retreat rates are rising. With a warm-phase Pacific decadal oscillation and an El Niño for the 2005 hydrologic year, the mass balance will be negative for this year as well.

AQ10

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