The Current Disequilibrium of North Cascade Glaciers

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ABSTRACT

Three lines of evidence indicate that North Cascade glaciers are currently in a state of disequilibrium. Annual balance measured on nine glaciers yields a mean cumulative annual balance for the 1984–2004 period of –8.58 m 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, 18–32% of their entire volume lost in two decades.

Longitudinal profiles completed in 1984 and 2002 on nine glaciers 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 cumulative mean annual balance of –5.52 m w.e for that period. The change in glacier thickness on several glaciers has been equally substantial in the accumulation zone and the ablation zone, indicating no point to which the glacier can retreat to achieve equilibrium.

North Cascade glacier retreat is rapid and ubiquitous. All 47 monitored glaciers are currently undergoing a significant retreat or have disappeared in the case of three of them. Two of the glacier where mass balance observations were begun, Spider Glacier and Lewis Glacier, have disappeared. This retreat on eight Mount Baker glaciers since 1984, that were all advancing in 1975, averages 297 m. The data indicate broad regional continuity in glacial response to climate.

Keywords: Glacier retreat, climate change, North Cascades, Mass balance

INTRODUCTION

Glaciers have been studied as sensitive indicators of climate for more than a century. Glacier behavior integrates water and energy balance factors to exhibit a maximum climate change signaling effect (IPCC, 1996). In the North Cascades, approximately 50% of the landscape is above 1100m elevation, but the highest long term weather station is at Stampede Pass at 1170 m. This same region contains more than 700 glaciers, which cover 250 km^2 and range in elevation from 1500–2500 m (Post et. al., 1971).

The North Cascade Glacier Climate Project (NCGCP) was founded in 1983 to monitor glaciers throughout the range and identify the response of North Cascade, Washington glaciers to regional climate change. In particular annual balance measurements on 8–10 glaciers, periodic terminus surveys on 47 glaciers and longitudinal profile mapping on nine glaciers over a 20-year period have been completed. This has enabled the identification of consistent trends from glacier to glacier.

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 (Pelto and Hedlund, 2001). The current climate change favors glacier

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retreat. A glacier will retreat in an attempt to reach a new point of equilibrium. In the North Cascades can most of the glacier reach a new point of equilibrium with the current climate?

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.

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. Climate east of the Cascade Crest is more continental, creating a sharp contrast to the maritime climate of the west of the crest.

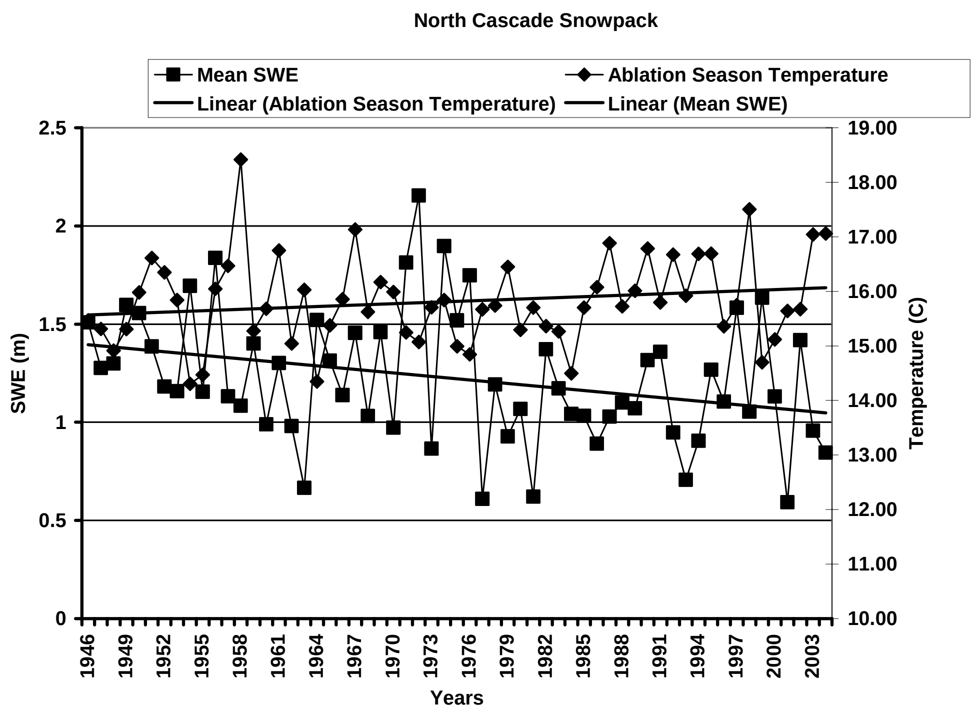

Figure 1 Ablation season temperature (June–September) at , and April 1 SWE at five USDA snotel sites (Rainy Pass, Stevens Pass, Harts Pass, Miners Ridge and Fish Lake).

North Cascade temperatures have increased during the 20th century. On average, the region warmed about 0.6°C; warming was largest west of the Cascades during winter and spring (Kovanen, 2003). The North Cascades region experienced a substantial climate change in 1976, to generally warmer-drier conditions (Ebbesmeyer et al., 1991). The long terms trends that in particular affect glaciers are the mean ablation season temperature and winter season snowfall.

Winter season snowfall is directly measured by the USDA at a series of USDA Snotel sites, and the April 1 SWE provides an excellent measure of winter season snowfall. The April 1 SWE is from five long terms Snotel stations (Rainy Pass, Lyman Lake, Stevens Pass, Miners Ridge, Fish Lake). In Figure 1, April 1 SWE has declined by 25% at these stations since 1946, while winter season precipitation has declined only slightly 3% at these stations and at Diablo Dam. Thus, most of the loss 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 same interval summer temperatures have risen 0.6o C in the region (Kovanen, 2003) and at Diablo Dam (Figure 1). 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 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 behavior over short time periods because it is a direct measure of annual climate conditions, whereas terminus behavior is determined by the cumulative impact of climate and other glaciologic factors over many years. 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, beginning October 1 and ending September 30. 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). The glaciers represent a wide range of characteristics and span the range (Table 1). NCGCP methods emphasize surface mass balance measurements with a comparatively high measurement density on each glacier, consistent measurement methods, and fixed measurement locations. The methods are reviewed in detail by Pelto (1996, 1997) and, Pelto and Riedel (2001). The average density of measurements by the NCGCP in the accumulation zone of each glacier ranges from 180–300 points km^2 (Pelto, 1996; Pelto and Riedel, 2001).

Table 1. The geographic characteristics of the nine glaciers where annual balance has been monitored annually.

GLACIER	ASPECT	AREA (km2)	ACCUMULATION[1]	TO DIVIDE [2]	ELEVATION (m)
Columbia	SSE	0.9	DS, DW, AV	15km west	1750–1450
Daniels	E	0.4	DS, WD	1km east	2230–1970
Easton	SSE	2.9	DS	75km 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
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
Accumulation sources: wind drifting = WD, avalanche accumulation = AV, direct snowfall = DS.					

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 program 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 shapes, without multiple accumulation areas and ice divides.

RESULTS

Glaciers in the North Cascades exhibit a consistent response to climate from year to year. Figure 2 illustrates the closely correlated pattern of mass balance fluctuations. In most years, all glaciers respond in step with each other to variation in winter precipitation and summer temperature. There is an annual range of 0.8 m in the specific annual balances, but the inter-annual trend is always the same.

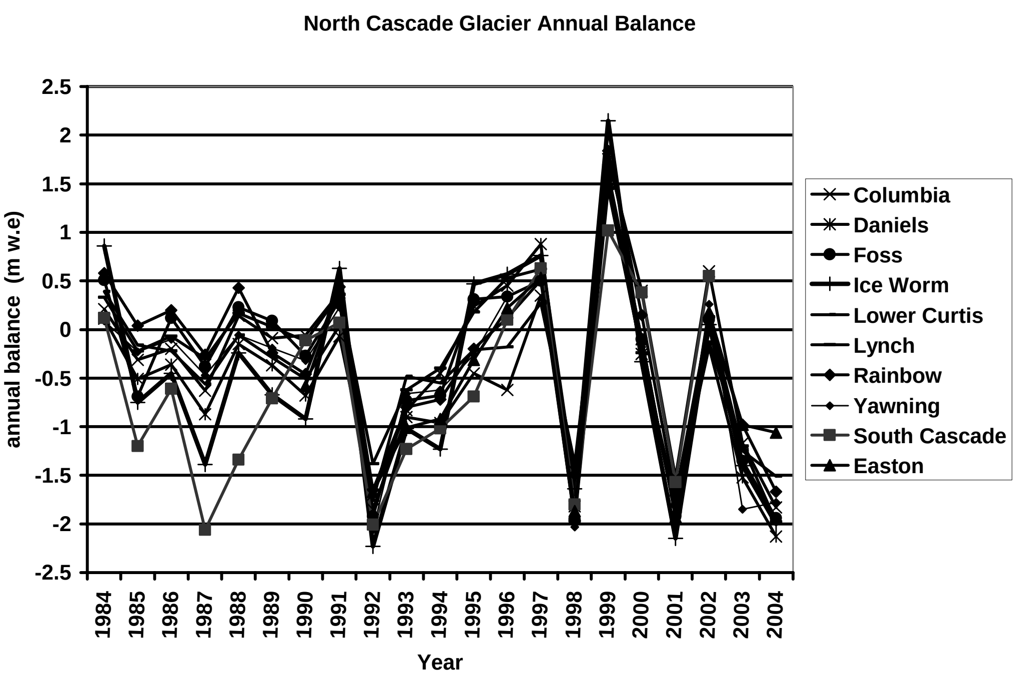

Figure 2: Annual balance records on ten North Cascade glaciers. South Cascade Glacier data from the USGS (Krimmel, 2001).

Regional response to climate is also indicated by the high cross correlation values of mass balance between glaciers that range from $r^2 = 0.75$ to 0.99. The South Cascade Glacier monitored by the USGS is also included and likewise has a high correlation coefficient (Krimmel, 1998).

Table 2. The annual and mean mass balance of the 9 North Cascade glaciers in this study by the NCGCP. USGS data for South Cascade Glacier (Krimmel, 2001).

Year	Columbia NCGCP	Daniels NCGCP	Easton NCGCP	Foss NCGCP	Ice Worm NCGCP	Lower Curtis NCGCP	Lynch NCGCP	Rainbow NCGCP	Yawning NCGCP	South Cascade USGS	Cumu-lative
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		–6.82
2004	–1.83	–2.13	–1.06	–1.94	–2.00	–1.51	–1.98	–1.67	–1.78		–8.58

The mean annual balance has been –0.41 m/a for the 1984–2004 period on the eight glaciers monitored annually. The mean cumulative mass balance loss has been –8.5 m w.e, which is a minimum of 9.5 m of glacier thickness lost. North Cascade glacier average thickness ranges from 30–60 m (Post et al, 1971; Pelto and Hedlund, 2001). Thus, 18–32% of the volume of these glaciers has been lost since 1984. Observations by the USGS at South Cascade Glacier indicate that since the mid-1950s, South Cascade Glacier's cumulative mass balance was –25m, mean annual balance from 1956–1975 averaged –0.15 m/a, and from 1976–2003 averaged –1.00 m (Krimmel, 2001). The cumulative mass balance is trending more negatively, indicating that instead of approaching equilibrium as the glaciers retreat they are experiencing increasing disequilibrium with current climate (Figure 3). The mean April 1 SWE in the North Cascades in 2005 at USDA Snotel locations is the lowest since 1984 indicating that a negative annual balance will be experienced this year as well.

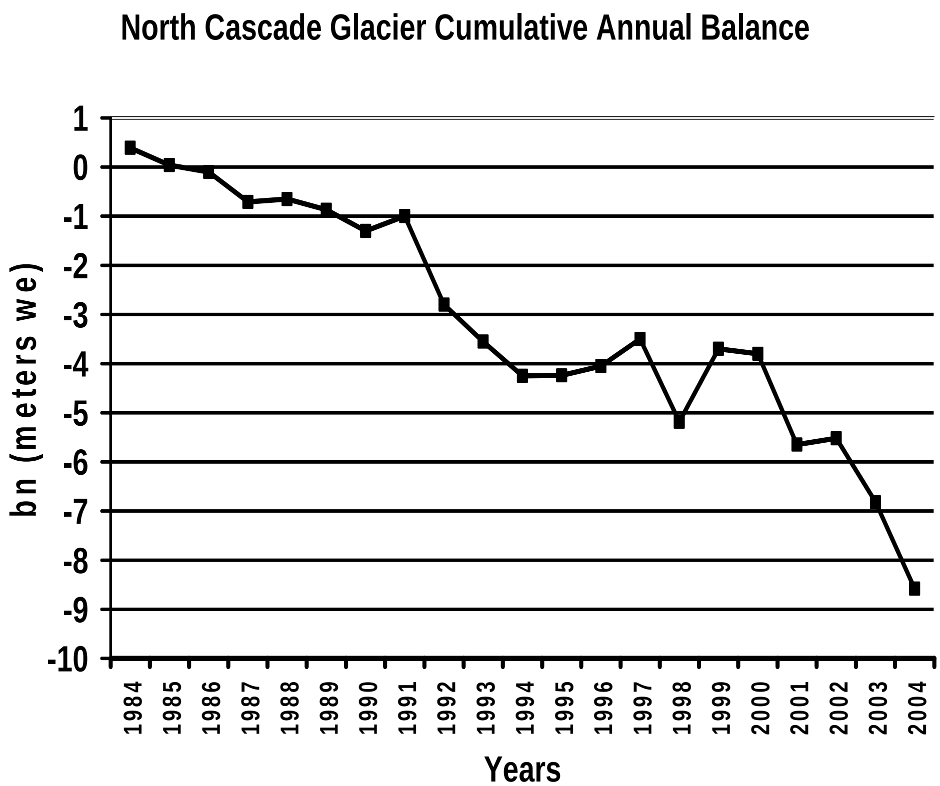

Figure 3. Cumulative mass balance record of North Cascade glaciers in meters of water equivalent. The high degree of correlation between glaciers is evident in the close tracking of each record.

TERMINUS BEHAVIOR

Since the maximum advance of the Little Ice Age (LIA) there have been three climate changes in the North Cascades sufficient to substantially alter glacier terminus behavior. During the LIA 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 (Porter, 1986; Burbank, 1981). North Cascade glaciers maintained advanced terminal positions from 1650–1890, emplacing one or several Little Ice Age terminal moraines.

This first substantial climate change was a progressive temperature rise from the 1880's to the 1940's. The warming led to ubiquitous rapid retreat of North Cascade Range alpine glaciers from 1890 to 1944 (Rusk, 1924; Burbank, 1981; Long, 1955; Hubley, 1956). Average retreat of glaciers on Mt. Baker was 1440 m from LIAM to 1950, and of 38 North Cascade glaciers monitored across the range, 1215 m (Pelto and Hedlund, 2001).

The second substantial change in climate 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, after 30 years of rapid retreat. All 11 Mount Baker glaciers advanced during this period.

The retreat and negative mass balances of the 1977–1998 period have been noted by Harper (1993), Krimmel (1994 and 1999), and Pelto (1993 and 2001). By 1984, all the Mount Baker glaciers, which were advancing in 1975, were again retreating (Pelto, 1993). The average retreat from 1984–2004 of Mount Baker glaciers is 297 m, and of all North Cascade glaciers it has been 137 m. Between 1979 and 1984, 35 of the 47 North Cascade glaciers observed annually by NCGCP had begun retreating. By 1992 all 47 glaciers termini observed by NCGCP were retreating (Pelto, 1993). By 2004, three had disappeared Lewis Glacier, David Glacier and Milk Lake Glacier.

The time between the onset of a mass balance change and the onset of a significant change in terminus behavior is called the initial terminus response time or reaction time (*Ts*) (Johannesson and others, 1989). Ts is determined from observed terminus response to the relative cooler and wetter weather beginning in 1944 (Hubley, 1956; Long 1955 and 1956; Tangborn, 1980), and to the subsequent warmer and drier conditions beginning in 1977 (Ebbesmeyer and others, 1991). Focusing on 21 North Cascade glaciers that responded to these two climate shifts, all having an area under 10 km^2, the initial terminus response invariably is less than 16 years (Pelto, 1993; Hubley, 1956; Harper, 1993). Thus, all North Cascade glaciers terminus behavior in 2004 has moved beyond the initial response to the 1976 climate change (Figure 4).

Figure 4. Terminus of the Easton Glacier in 2003, 1985 position indicated.

The 38 North Cascade glaciers, where the terminus history has been determined for the 1890–1998 period exhibit three distinct patterns (Pelto and Hedlund, 2001: 1) Retreat from 1890 to 1950 then a period of advance from 1950–1976, followed by retreat since 1976. 2) Rapid retreat from 1890 to approximately 1950, slow retreat or equilibrium from 1950–1976 and moderate to rapid retreat since 1976. 3) Continuous retreat from the 1890 to the present. Today regardless of glacier type rapid retreat is underway indicating disequilibrium with current climate.

LONGITUDINAL PROFILES

Centerline surface elevation longitudinal profiles have been completed for three different moments in time from historic photographs (~1900), USGS maps (1964 and 1985), and our own field measurements (1984 to present) for three North Cascade glaciers (Pelto and Hartzell, 2004)

Columbia Glacier has retreated 134 m since 1984. 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 since 1989 when retreat began. The Lower Curtis terminus remains vigorously active, but has retreated 184 m since the onset of retreat in 1986.

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

The 1984–2002 profile change shows the greatest thinning for Lower Curtis and Columbia Glacier to be in middle of the cirque basin, in the accumulation zone, where slope is at a minimum and glacier thickness a maximum (Figure 5). The thinning in the cirque basin for Columbia Glacier since 1984 has been 13–16 m, versus a glacier average thinning of 8 m. On Lower Curtis Glacier the thinning in the cirque basin has averaged 10 m, versus 6 for the entire glacier. In both cases this location is in the accumulation zone (Pelto and Hartzell, 2004).

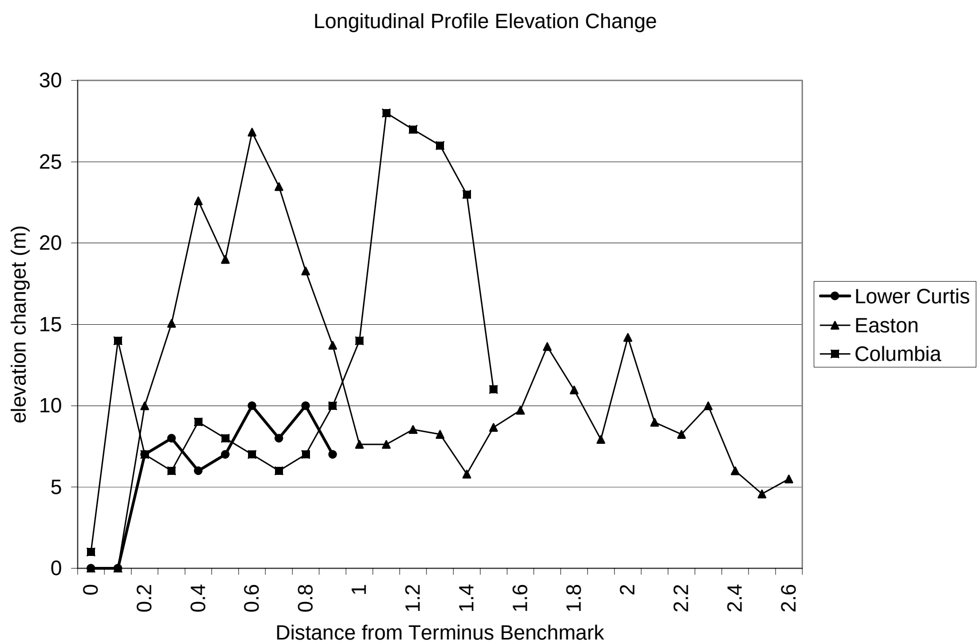

Figure 5. Longitudinal profile height changes on three glaciers from the terminus benchmark proceeding upglacier.

Typically a glaciers thinning is greatest at the terminus, and at some distance above the terminus, usually in the accumulation zone, the glacier is no longer thinning appreciably even during a retreat (Schwitter and Raymond, 1993). Easton Glacier exhibits a 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 ELA. This latter behavior of greatest thinning at the terminus suggests a glacier that will retreat to a new stable position. The reduction in thinning with elevation indicates that at some point in the accumulation zone the glacier is not appreciably thinning. Lower Curtis and Columbia Glacier indicate a more unstable form of retreat, where the accumulation zone itself is a location for substantial thinning. This in conjunction with terminus retreat suggests that, the entire glacier is out of equilibrium. A glacier in this condition seems unlikely to be able to survive in anything like its present extent given the current climate.

Cumulative mass balance change obtained from annual balance records for Columbia Glacier is –6.09 meters water equivalent (mwe), and a change of –6.26 mwe for the Lower Curtis, 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, thus corroborating the annual surface balance records. The surface balance record for Easton Glacier, which has been slightly more negative than the other two glaciers since 1990, cannot be directly compared in this fashion, as the longitudinal profile does not extend to the head of the glacier, while the surface annual balance record incorporates data from the entire extent of the glacier.

CONCLUSIONS

The recent 0.6°C temperature rise and 25 % reduction in mean April 1 SWE in the North Cascades have resulted in evident disequilibrium of North Cascade glaciers**.** Mean annual balances of North Cascade glaciers have average –0.41 m/a over the past 21 years. The net loss, –8.58 m w.e. is a significant portion of the total glacier volume, 18–32%, resulting in substantial retreat and thinning. 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, than no point of equilibrium can be achieved with present climate and the glacier is unlikely to survive.

The coherent response of all the glaciers to climate change was noted for the Pacific Northwest as a whole by Hodge and others (1997). This is born out by the annual balance and terminus records. The trend in mass balance is becoming more negative and terminus retreat rates are rising. With a warm phase PDO and an El Nino for the 2005 hydrologic year, mass balance will be negative for this year as well.

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