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Change in Longitudinal Profile on Three North Cascade Glaciers During the Last 100 Years

MAURI S. PELTO[1]
PAULA HARTZELL[2]

ABSTRACT

A centerline surface elevation longitudinal profile has been determined for three North Cascade glaciers, where surface mass balance data is also available. Construction of the longitudinal profile for each glacier has been completed from historic photographs, USGS maps and North Cascade Glacier Climate Project field measurements. This data enabled surface elevation profiles to be constructed for three different points in time for each of the three North Cascade glaciers. A comparison indicates substantial overall volume loss this century on each glacier.

Easton Glacier has lost 46 m of ice thickness since 1916, and 13 m from 1984-2002. Lower Curtis Glacier ice thickness losses from 1908-1984 averaged 45 m, from 1984-2002 to the present 6 m. On Columbia Glacier the ice thickness loss from 1911-1984 was 57 m, 11 m from 1965-2002, and –8 m from 1984-2002. During the 1984-2002 period surface mass balance measurements indicate a thinning of – 7 m and –7 m on Lower Curtis and Columbia Glacier respectively. The ongoing thinning of the last twenty years, indicates that none of these three glaciers is close to equilibrium and will continue to retreat for the foreseeable future.

The changes on each glacier, which today average less than 75 m in thickness, represent the loss of 35-50 % of their volume since the turn of the century and 10-15 % of their volume since 1984.

Keywords: glacier, longitudinal profile, terminus behavior, mass balance

INTRODUCTION

Glaciers are one of the world's best climate monitors and are a critical water resource in many glaciated populated regions. This is particularly true in the North Cascades of Washington where 700 glaciers yield 900 million m^3 of runoff each summer, and where the glaciers have lost 35-50% of their volume and 30 % of their area in the last century, resulting in a similar decline in mid-late summer glacier runoff (Pelto and Hedlund, 2001). Changes in surface elevation along a longitudinal profile are key to understanding current and future glacier behavior (Schwitter and Raymond, 1993). The longitudinal profile reflects the adjustment of the glacier to the current climate conditions not just at the terminus, but along the entire length of the glacier. A glacier adjusting to a new equilibrium position will feature little surface elevation change in the accumulation zone (Schwitter and Raymond, 1993).

[1]Dept. of Environmental Science, Nichols College, Dudley MA 01571 **peltoms@nichols.edu**
[2]Dept. of Biology, Clark University, Worcester MA 01610 **phartzell@clarku.edu**

A glacier that is experiencing a significant period of disequilibrium will be losing considerable surface elevation in the accumulation zone and the ablation zone. The longitudinal profile is a direct measure of long-term mass balance change of the glacier. On the North Cascade glaciers examined in this study this long term mass balance change provides an independent check of the ongoing annual surface mass balance program (Pelto and Riedel, 2001).

The North Cascade Glacier Climate Project (NCGCP) was founded in 1983 to identify the response of North Cascade glaciers to regional climate change, particularly changes in mass balance, glacier runoff and terminus behavior. Annual mass balance measurements on nine glaciers since 1984, including all three in this study, indicate a cumulative mass balance of -5.7 m, or -6.3 m (Figure 1). This is approximately 10-15% of the entire volume of North Cascade glaciers, gone in fifteen years (Pelto and Riedel, 2001).

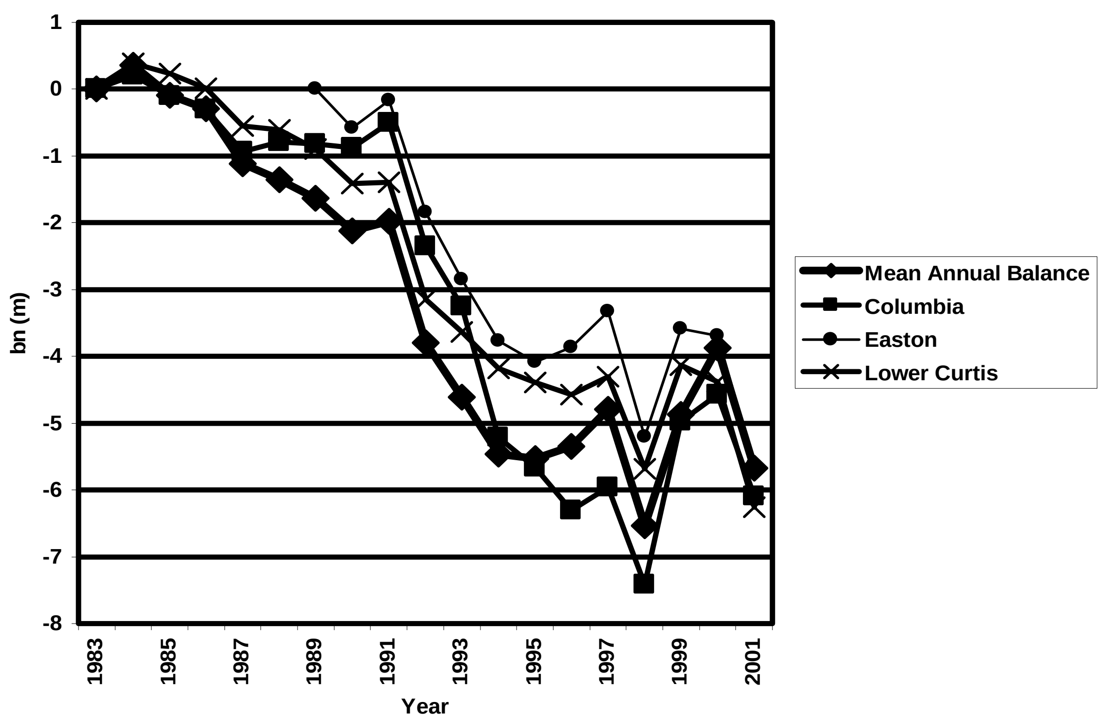

Figure 1: The cumulative annual balance of North Cascade glaciers 1984-2001.

Observation of the terminus behavior of 38 North Cascade glaciers since 1890 illustrates three different types of glacier response (Pelto and Hedlund, 2001) 1) Continuous retreat from the Little Ice Age advanced positions, from 1890 to approximately 1950, followed by a period of advance from 1950-1976, and then 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 1890 LIA to the present. Thus, the changes in surface elevation along a longitudinal profile of each glacier will be dominated by the extensive retreat covering approximately 80 of the last 110 years. The Lower Curtis and Easton Glacier are the first glacier type and Columbia Glacier the second glacier type.

Lower Curtis Glacier (0.8 km^2) is a south facing cirque glacier that is fed by avalanches from the Upper Curtis Glacier and direct snowfall accumulation. The accumulation zone is relatively flat ranging from 1615 m to1730 m. The glacier then flows out of the cirque and down a steep headwall terminating part way down the slope. The overall slope of the glacier is 0.36. Columbia Glacier (0.9 km^2) is the lowest elevation large glacier in the North Cascade. It is a south facing cirque glacier fed by avalanching off of Kyes Peak on the east and Columbia Peak on the west, and direct snowfall accumulation. The accumulation zone is a combination of a relatively flat cirque basin extending from 1585 m to 1700 m and several large avalanche cones. Overall Columbia Glacier has the shallowest slope of any of the North Cascade glaciers monitored by NCGCP at 0.18. Easton Glacier (2.8 km^2) is a valley glacier on the south side of Mount Baker a stratovolanco. The glacier descends from 2800 m to 1670 m. The glacier is fed primarily be direct snowfall accumulation and the mean equilibrium line altitude of 2050 m. The width of the glacier declines from 1060 m at 2100 m to a width of 450 m at 1800 m. Easton Glacier descends a series of steps, and has an overall slope of 0.35.

Data Sources:

Historic photographs from Asahel Curtis of the Lower Curtis Glacier, of the Easton Glacier and from of the Columbia Glacier indicate the location of the glaciers with respect to prominent and still existing lateral moraines near the beginning of the century. In each case the glaciers were still in contact with and near the crest of these moraines. Schwitter and Rayomd (1993) illustrated the utility of using Neoglacial trimlines and moraine crests for determining previous glacier surface levels in the ablation zone and current lower accumulation zone of each glacier. They restricted their choice of glaciers to those with easily identifiable lateral moraines on topographic maps, as have we. Longitudinal profiles of each of the lateral moraines were completed using the TOPO! Program. In addition a surface survey was completed along each lateral moraine crest, establishing specific benchmark locations using the GPS to corroborate the USGS maps in TOPO!. The USGS topographic maps in TOPO! for each location provide one of the longitudinal profiles, the dates for each are:1984 for the Easton Glacier, 1984 for the Lower Curtis Glacier and 1965 for the Columbia Glacier. Lateral moraines are not generally created and preserved above the equilibrium line. Thus, the surface elevation profile for the Easton Glacier extends only to the equilibrium line. Above this point there is no reference location. On both the Lower Curtis and Columbia Glacier the steep valley sidewalls provide unique prominences identifiable in both historic and current photographs that allows the profiles to be completed to the head of the glacier. This profile is further corroborated by the presence of lichen trimlines, which are also a reliable indicator (Schwitter and Raymond, 1983). Thus, the elevation profiles on both glaciers extend to the head of the glacier.

In 2001 and 2002 each glacier was resurveyed starting and ending at known fixed prominent locations that could be pinpointed on the map and in the field using GPS. A laser ranger was used in combination with an inclinometer to complete profiles up glacier, with stations every 100 m. Each profile was resurveyed going down glacier, reoccupying each station. Errors in the laser ranger are less than 1 m and in the inclinometer 1^o. The combination yields errors in surface elevation of 1-2 m along the profile.

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^{o}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.

Retreat from the LIAM was modest prior to a still stand in the 1880’s (Burbank, 1981, Long, 1956). Long (1953) noted that retreat on Lyman Glacier and Easton Glacier became substantial only after 1890. Photographs of Columbia and Lower Curtis Glacier used in this study indicate both glaciers still in contact with their terminal and lateral moraines in 1908-1910. Thus, changes in glacier profiles of each of the observed glaciers from their Little Ice Age maximum moraines were not significant before this period.

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). Each North Cascade glacier retreated significantly from its LIAM. Average retreat of glaciers on Mt. Baker was 1440 m from the LIAM to 1950 (Pelto, 1993). Easton Glacier retreated 2420 m, Columbia Glacier retreated 580 m and Lower Curtis Glacier retreated 645 m during this period (Table 1), This represent a reduction in overall glacier length of 38%, 26% and 26% for Easton, Columbia and Lower Curtis Glacier respectively. The greater length reduction of the Easton Glacier is probably a reflection of the substantial narrowing of the terminus reach of the glacier, which is not apparent on Columbia or Lower Curtis Glacier. The percentage change in glacier area from the Little Ice Age maximum to 1950 for each glacier was a nearly uniform 29%, 26% and 28% for Easton, Columbia and Lower Curtis Glacier respectively (Table 1).

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 North Cascade glaciers began to advance in the early 1950s, after 30 years of rapid retreat. Approximately half the North Cascade glaciers advanced during the 1950-1979 period (Hubley, 1956; Meier and Post, 1962). Advances of Mount Baker glaciers ranged from 120 m to 750 m, an average of 480 m, and ended in 1978 (Heikkinnen, 1984; Harper, 1993; Pelto, 1993). Of the 47 glaciers that NCGCP has observed during the 1984-1998 period, 15 advanced during the 1950-1978 period. Easton Glacier began advancing in 1955 and advanced a total of 608 m by 1979. Lower Curtis Glacier began advancing in 1951 (Hubley, 1957) and advanced 245 m by 1979. Columbia Glacier retreated slightly, 15 m during this same period.

Table 1. The characteristics and terminus behavior of three North Cascade glaciers.

Glacier	LIAM-1950	1950-1979	1979-1997	1979-2002	Slope	Glacier Size (km2)
Columbia	-560	-15	-70	-65	0.18	0.9
Easton	-2420	608	-165	-315	0.35	2.9
Lower Curtis	-645	225	-82	-102	0.36	0.8

Glacier	Mean Altitude (m)	Latitude	Longitude
Columbia	1600	47 56	121 21
Easton	2250	48 45	121 50
Lower Curtis	1650	48 50	121 37

The final climate change was a step change in 1977 to a drier-warmer climate in the Pacific Northwest (Ebbesmeyer and others, 1991). 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 1996). By 1984, all the Mount Baker glaciers, which were advancing in 1975, were again retreating (Pelto, 1993). In 2001-2002, NCGCP measured the retreat of eight Mount Baker glaciers from their recent maximum position (late 1970's-early 1980's). The average retreat had been -305 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), and two had disappeared, Lewis Glacier and Milk Lake Glacier. Easton Glacier was slow to begin its retreat, remaining in contact with the advance terminal moraine until 1989, by 2002 the terminus had retreated 315 m. The glacier is still in advance of its 1950 position but the lower section of the glacier is stagnant and should retreat quickly past that point. Columbia Glacier has retreated 134 m since 1984, however, the lateral reduction in glacier width, 95 m in the lower section of the glacier, and the reduction in glacier thickness are even more substantial as a percentage.

The Lower Curtis Glacier terminus remains vigorous, but has retreated 184 m since 1985 when retreat began. The steep slope that the glacier ends on has led to substantial avalanching off of the glacier front, which has enhanced retreat beyond what would be expected from the observed glacier thinning.

CHANGES IN LONGITUDINAL PROFILES

The changes in each glacier (Figures 2-4) indicate Easton Glacier has lost 46 m of ice thickness since 1916, and 13 m from 1984-2002. Lower Curtis Glacier ice thickness losses from 1908-1984 averaged 45 m, from 1984-2002 to the present 6 m. On Columbia Glacier the ice thickness loss from 1911-1984 was 57 m, 11 m from 1965-2002, and 8 m from 1984-2002.

Typically one can observe crests of lateral moraines or trimlines marking Neoglacial maxima converging up-glacier with the glacier surface (Schwitter and Raymond, 1993). This characteristic indicates that glacier thinning is most pronounced in the lower reaches of glaciers for a particular climate change. This is the case for Easton Glacier (Figure2) for changes from 1908-1983. For Columbia Glacier the thinning is more uniform from 1910-1984, but still greatest near the terminus. Lower Curtis Glacier has the greatest thinning from 1908-1984 in the accumulation zone.

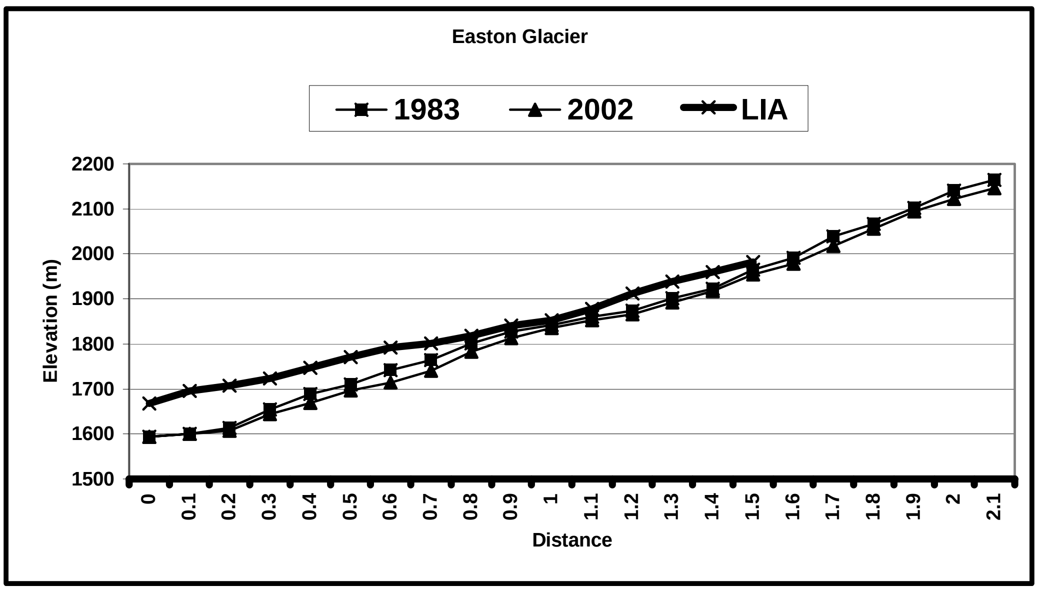

Figure 2. The longitudinal profile of the Easton Glacier

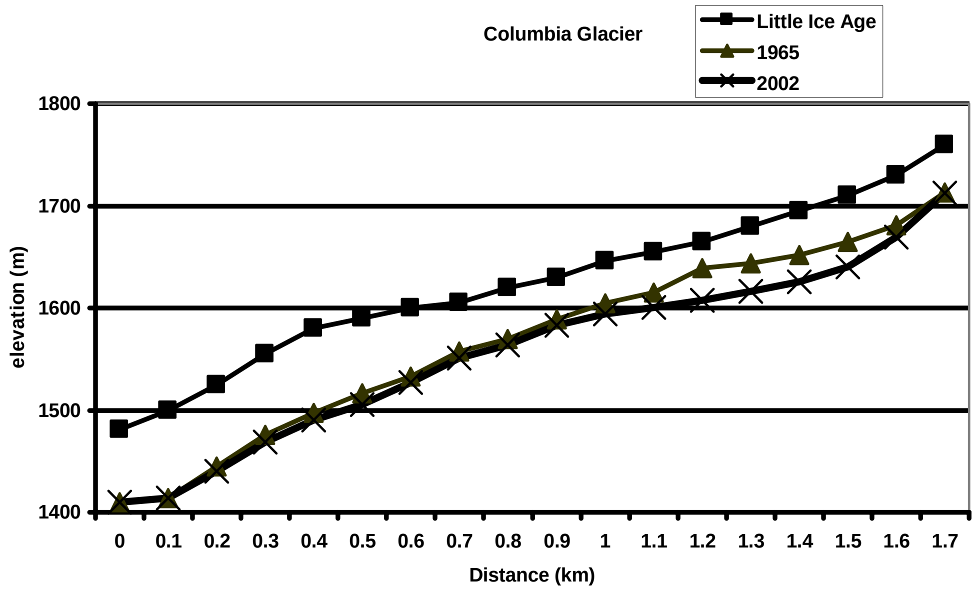

Figure 3. The longitudinal profile of the Columbia Glacier.

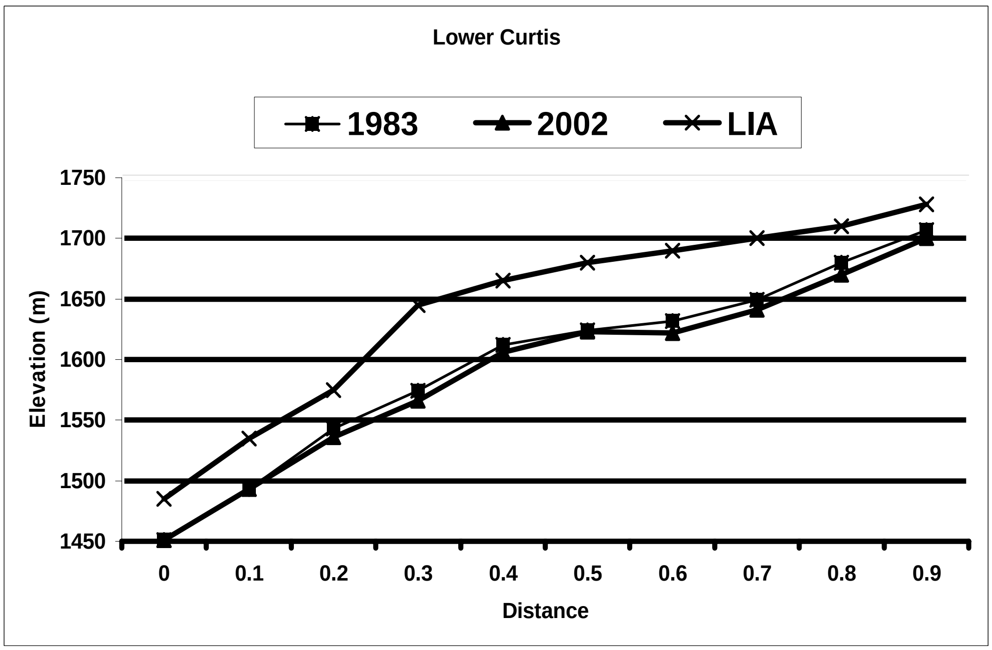

Figure 4. The longitudinal profile of the lower curtis glacier.

The 1984-2002 thinning shows the greatest thinning for Lower Curtis and Columbia Glacier to be in middle of the cirque basin where slope is at a minimum and glacier thickness a maximum. In both cases this location is in the accumulation zone. Easton Glacier exhibits a more typical thinning with the greatest elevation change at the terminus. 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 would not be appreciably thinning. Lower Curtis and Columbia Glacier indicate a more unstable form of retreat, where the accumulation zone itself is a location for thinning. This in conjunction with terminus retreat suggests that, neither the accumulation zone or the ablation zone is in equilibrium. A glacier in this condition seems unlikely to be able to survive in anything like its present extent given the current climate.

LONG TERM MASS BALANCE CHANGE

Cumulative mass balance change from annual balance records for Columbia Glacier is –6.09 m.w.e., for Lower Curtis Glacier –6.26 m.w.e. These correspond to actual thickness changes of 7 m on both Columbia and Lower Curtis Glacier. Contrasted with the observed thickness changes of 8 m on Columbia Glacier and 6 m on Lower Curtis Glacier. The long term mass balance change indicated by the surface elevation changes, thus, corroborating the annual surface balance records. The surface balance record for Easton Glacier, which is slightly more negative than the other two glaciers cannot be directly compared, because the longitudinal profile does not extend to the head of the glacier and thus, provides a an incomplete measure of surface balance change for the entire glacier, while the surface annual balance record incorporates data from the entire elevation extent of the glacier.

Figure 5. Easton Glacier in 1999. The lack of crevassing near the terminus indicates retreat. The 1980's terminal moraine is visible on the lower right crossing the snow slope with a convex shape.

CONCLUSION

The ongoing thinning of the last twenty years, indicates that none of these three glaciers is close to equilibrium and will continue to retreat for the near future. The thinning being at a maximum in the accumulation zone for the Lower Curtis Glacier and Columbia Glacier suggests that both glaciers are far from equilibrium in the current climate and may melt away. In both cases the rate of thinning is less approximately –0.35 m/a, given their overall thickness of 50-80 m these two glaciers will endure in the current climate for many decades. The annual surface balance records agree closely with the long term surface change record provided by the longitudinal profiles.

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