Change in longitudinal profile on three North Cascade glaciers during the last 100 years.

Mauri S. Pelto, Dept. of Environmental Science,
Nichols College, Dudley MA 01571 peltoms@nichols.edu
Paula Hartzell, Dept. Biology, Clark University, Worcester MA 01610
phartzell@clarku.edu

Abstract

We constructed centerline surface elevation longitudinal profiles for three different points in time from historic photographs (~1900), USGS maps (1964 and 1985), and our own field measurements (annually between 1984 to present) for three North Cascade glaciers. Comparison of thinning and terminus behavior over this time period indicates substantial overall volume loss during this century for each glacier.

Easton Glacier has lost 46 m of ice thickness between 1916 and 1984, and 13 m between 1984 and 2002. Its terminus has retreated a net distance of 2123 m. Lower Curtis Glacier lost an average of 45 m thickness from 1908 to 1984, and 6 m from 1984 to 2002, with a net terminus retreat of 522 m. On Columbia Glacier, ice thickness loss was 57 m from 1911 to 1984, and 8 m from 1984 to 2002. The net terminus retreat for Columbia was 640 m.

The changes on each glacier, which today average less than 75 m in thickness, represent the loss of 35-50% in their volume since the turn of the century, and 10-15% of this volume since 1984. There is no evidence that these glaciers are close to equilibrium. Their ongoing thinning indicates that these three glaciers will continue to retreat in the foreseeable future. Long-term monitoring of these glaciers should continue in order to assess the impact to downstream flow.

Introduction

Glaciers hold approximately 75% of the world's freshwater, and glacially-generated water provides a critical water resource for many parts of the world, contributing to population- and ecosystem-dependent rivers. At the same time these glaciers are especially sensitive to small changes in temperature, and their decline may be vastly accelerated by climate change. This is particularly true in the Pacific Northwest of North America. In the North Cascades of Washington, for example, 700 glaciers yield 900 million m^3 of runoff each summer; in this area, glaciers have lost 35-50% of their volume in the last century, resulting in a similar decline in mid- to late-summer glacier runoff (Pelto and Hedlund, 2001).

Changes in surface elevation along a longitudinal profile are particularly useful in understanding current and future glacier behavior (Schwitter and Raymond, 1993). A longitudinal profile is a direct measure of long-term mass balance change of the glacier; it reflects the adjustment of the glacier not only at the terminus, but along the entire length of the glacier. A glacier adjusting to a new equilibrium will typically feature little surface elevation change in the accumulation zone (Schwitter and Raymond, 1993), and considerable terminus thinning, while a glacier that is experiencing a significant period of nonequilibrium will be exhibit significant surface elevation change in both the accumulation zone and ablation zone. 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 longitudinal profiles on nine glaciers, including the three focal glaciers in this study, indicate a loss of -5.7 to -6.3 m in thickness between 1984 and 2002 (Figure 1). This represents a loss of approximately 10-15% of the entire volume of North Cascade glaciers in fifteen years (Pelto and Riedel, 2001).

Lower Curtis Glacier (with current surface area of 0.8 km^2) is a south-facing cirque glacier that is fed by avalanches from Upper Curtis Glacier and direct snowfall accumulation. The accumulation zone is relatively flat area ranging from 1615 m to 1730 m in elevation. The glacier then flows out of the cirque and down a steep headwall, terminating midway down the slope. The average slope of the glacier is 36%.

Columbia Glacier (with current surface area of 0.9 km^2) is the lowest elevation glacier of significant size in the North Cascade. It is a south facing cirque glacier fed by avalanches from Kyes Peak on the east and Columbia Peak on the west, and direct snowfall accumulation. The accumulation zone includes a relatively flat cirque basin extending from 1585 m to 1700 m in elevation, and several large avalanche cones. Columbia Glacier, with an average slope of 18%, has the least slope of any of the North Cascade glaciers monitored by NCGCP.

Easton Glacier (with a current surface area of 2.8 km^2) is a valley glacier on the south side of Mount Baker, a stratovolanco located in Northwestern Washington. The glacier descends from 2800 m to 1670 m elevation. The glacier is fed primarily by direct snowfall accumulation, with a mean equilibrium line at 2050 m elevation. Easton Glacier descends a series of steps, and has an average slope of 35%. The width of the glacier constricts longitudinally from 1060 m at 2100 m elevation, to a width of 450 m at 1800 m elevation.

Methods

Schwitter and Raymond (1993) demonstrated 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. Using similar methods, we have identified the positions of Lower Curtis, Easton and Columbia Glaciers near the beginning of the century from historic photographs by Asahel Curtis. In each case, the glaciers were still in contact with and near the crest of large lateral moraines, which are visible at present. Longitudinal profiles of each of the lateral moraines were completed using the TOPO! Program. A surface survey was completed along each lateral moraine crest, establishing specific benchmark locations using the GPS to corroborate with the USGS maps in TOPO. The USGS maps dates were 1984 for Easton Glacier, 1984 for Lower Curtis, and 1965 for Columbia Glacier. Because lateral moraines are not generally created above the equilibrium line, the surface elevation profile for Easton Glacier extends only to the equilibrium line. Lower Curtis and Columbia Glaciers are bound by steep valley sidewalls, exhibit lichen trimlines in the accumulation zone, allowing profiles to be completed to the head of these glaciers. Lichen trimlines are reliable indicators (Schwitter and Raymond, 1983).

In 2001 and 2002, each glacier was surveyed between known fixed points. A laser ranger and inclinometer were used to complete profiles moving up glacier, with stations every 100 m. Each longitudinal survey was repeated going down glacier for increased data reliability. Laser ranger measurements are accurate within <1 m, and inclinometer readings within 1^{o}. These methods limit error in surface elevation to <2 m along a given profile.

Results and Discussion

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). Lower temperatures in the North Cascades led to a snowline lowering of 100 to 150 m during the LIA. North Cascade glaciers maintained advanced terminal positions from 1650 to 1890, emplacing one to 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 and Easton Glaciers became substantial only after 1890. Photographs of Columbia and Lower Curtis Glaciers show both glaciers still in contact with their terminal and lateral moraines in 1908-1910. Changes in glacier profiles from their Little Ice Age maximum moraines were probably not significant before the study period (~1900).

The 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). All North Cascade glaciers retreated significantly from their LIAM positions. 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 560 m, and Lower Curtis Glacier retreated 645 m during this period (Table 1). These represent reduction in overall glacier length by 38% for Easton, and 26% for Columbia and Lower Curtis Glaciers. The substantial narrowing of the lower part of Easton Glacier probably contributed to its greater abatement.

The second substantial change in climate began in 1944 when conditions became cooler and precipitation increased (Hubley 1956; Tangborn, 1980). Hubley 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 in Mount Baker glaciers ranged from 120 m to 750 m, with 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, 15 were advancing between 1950-1978. Easton Glacier began advancing in 1955, for 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.

The final climate change began in 1977, with a drier-warmer climate in the Pacific Northwest (Ebbesmeyer et al., 1991). Between 1979 and 1984, 35 of the 47 North Cascade glaciers observed annually by NCGCP had begun retreating. By 1984, all the Mount Baker glaciers, which were advancing in 1975, were again retreating (Pelto, 1993). Harper (1993), Krimmel (1994 and 1999), and Pelto (1993 and 1996) all report retreat and negative mass balances during 1977-1998. By 1992, 47 glaciers termini observed by NCGCP were retreating (Pelto, 1993), and two glaciers (Lewis and Milk

Lake) had disappeared. 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 was 305 m.

Easton Glacier was slow to begin its retreat during this period, remaining in contact with the advance terminal moraine until 1989. By 2002, however, 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 in the near future.

Columbia Glacier has retreated 134 m since 1984. 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 terminus remains vigorously active, but has retreated 184 m since 1985 when retreat began. The steep slope at the terminus substantial avalanching off 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 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.

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. 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.

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.

Long Term Mass Balance Change

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

Thinning is at a maximum in the accumulation zone for Lower Curtis Glacier and Columbia Glacier, suggesting that both glaciers are far from equilibrium in the current climatic conditions. In both cases the rate of thinning is 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, but complete melting may be possible in the future.

Easton Glacier will retreat quickly to a new equilibrium position. Easton shows a slower retreat relative to Lower Curtis and Columbia, probably because of its higher elevation (snowfall) accumulation zone.

The ongoing thinning of the last twenty years indicates that these three glaciers are not close to equilibrium and will continue to retreat for the near future. The annual surface balance records agree closely with the long-term surface change record provided by the longitudinal profiles. Continued long-term monitoring will assess changes in downstream water availability in the future.

References

Burbank, D.W. 1981. A chronology of late Holocene glacier fluctuations on Mt. Rainier. *Arctic and Alpine Res.*, 13, 369-386.

Driedger, C.L., and P.M. Kennard. 1986. Ice volumes on Cascade Volcanoes. *USGS Prof. Paper*, 1365.

Ebbesmeyer, C.C., D.R. Cayan, D.R. McLain, F.H. Nichols, D.H. Peterson, and K.T. Redmond. 1991. 1976 step in the Pacific Climate: Forty environmental changes between 1968-1975 and 1976-1984. *In Betancourt, J.L. and Tharp, V.L., Proc. On the 7th Annual Pacific Climate Workshop*, 129-141.

Harper, J.T. 1993. Glacier terminus fluctuations on Mt. Baker, Washington, USA, 1940-1980, and climate variations. *Arctic and Alpine Res*, 25, 332-340.

Heikkinen, A. 1984. Dendrochronological evidence of variation of Coleman Glacier, Mt. Baker. Washington. *Arctic and Alpine Res*., 16, 53-54.

Hubley, R.C. 1956. Glaciers of Washington's Cascades and Olympic Mountains: Their present activity and iTs relation to local climatic trends. *J. Glaciol*., 2(19), 669-674.

Johannesson, T., C. Raymond, and E. Waddington. 1989. Time-scale for adjustment of glacier to changes in mass balance. *J. Glaciol.*, 35(121), 355-369.

Krimmel, R.M. 1994. “Water, ice and meteorological measurements at South Cascade Glacier, WA 1993 balance year. *USGS OFR*-94-4139.

Krimmel, R.M. 1999. Mass balance and volume of South Cascade Glacier, Washington. *Geografiska Annaler*, 81A, 653-658.

Long, W.A. 1953. Recession of Easton and Deming Glaciers. *The Scientific Monthly*, 76, 241-245.

Long, W.A. 1955. What’s happening to our glaciers. *The Scientific Monthly*, 81, 57-64.

Long, W.A. 1956. Present growth and advance of Boulder Glacier, Mt. Baker. *The Scientific Monthly*, 83, 1-2.

Miller, C.D. 1971. Chronology of neoglacial moraines in the Dome Peak Area, North Cascade Range, Washington. *Arctic and Alpine Research* 1, 49-66.

Pelto, M.S. 1993. Current behavior of glaciers in the North Cascades and iTs effect on regional water supply. *Washington Geology*, 21(2), 3-10.

Pelto, M.S. 1996. Annual balance of North Cascade glaciers 1984-1994. *J. Glaciol*., 41, 3-9.

Pelto, M.S. and J.Riedel 2001: The spatial and temporal variation of mass balance on North Cascade glaciers., *Hydrological Processes*, 15, 3461-3472

Pelto, M.S. and Cliff Hedlund, 2001: The terminus behavior and response time of North Cascade glaciers. *Journal of Glaciology* 47, 497-506

Porter, S.C. 1986. Pattern and forcing of Northern Hemisphere glacier variations during the last millenimum. *Quaternary Res*., 26, 27-48.

Post, A., D. Richardson, W.V. Tangborn, and F.L. Rosselot. 1971. Inventory of glaciers in the North Cascades,Washington. *USGS Prof. Paper*, 705-A

Rusk, C.E. 1924. *Tales of a Western Mountaineer*. Houghton Mifflin Co., New York.

Schwitter, M.P., and C. Raymond. 1993. Changes in the longitudinal profile of glaciers during advance and retreat. *J. Glaciol*, 39(133), 582-590.

Tangborn, W. V. 1980. Two models for estimating climate-glacier relationships in the North Cascades, Washington, USA. *J.Glaciol*., 25, 3-21.

Table 1. Change in terminus and other characteristics of three North Cascade glaciers.

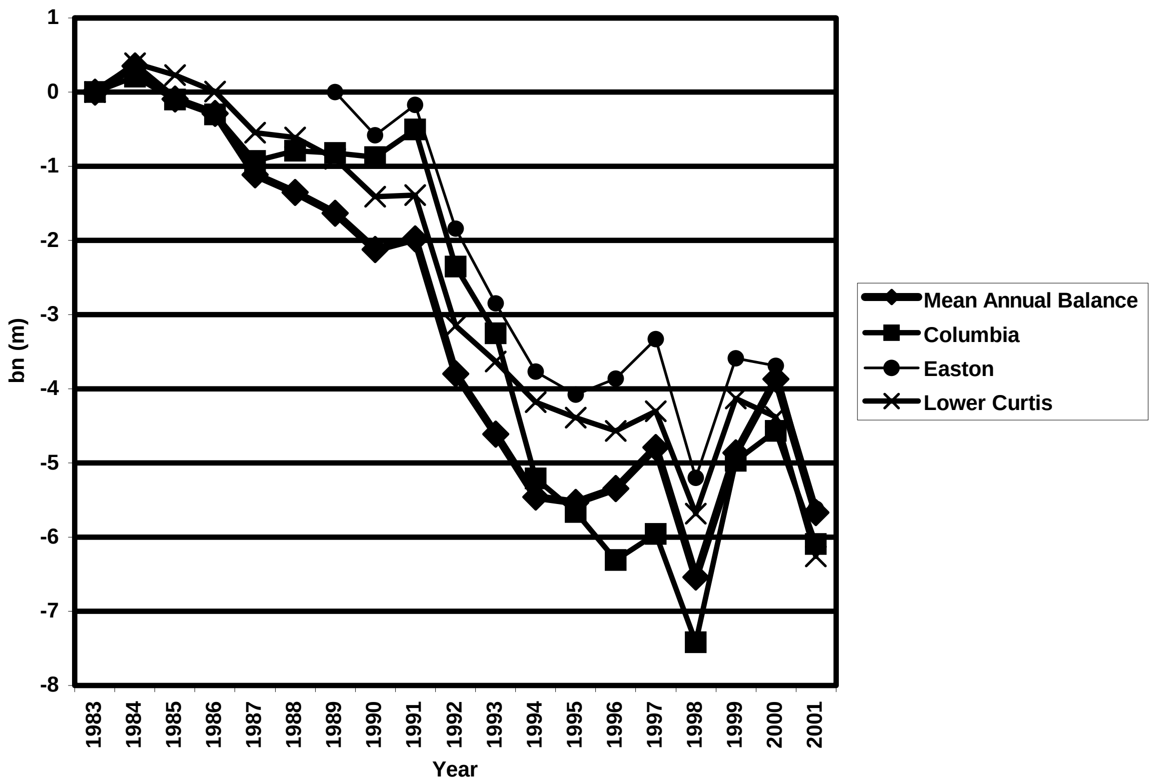
Glacier	LIA Max to 1950	1950 to 1979	1979 to 1997	1979 to 2002	Slope (%)	Glacier Size (km2)	Mean Altitude (m)	Latitude	Longitude
Columbia	-560	-15	-70	-65	0.18	0.9	1600	47 56	121 21
Easton	-2420	608	-165	-315	0.35	2.9	2250	48 45	121 50
Lower Curtis	-645	225	-82	-102	0.36	0.8	1650	48 50	121 37

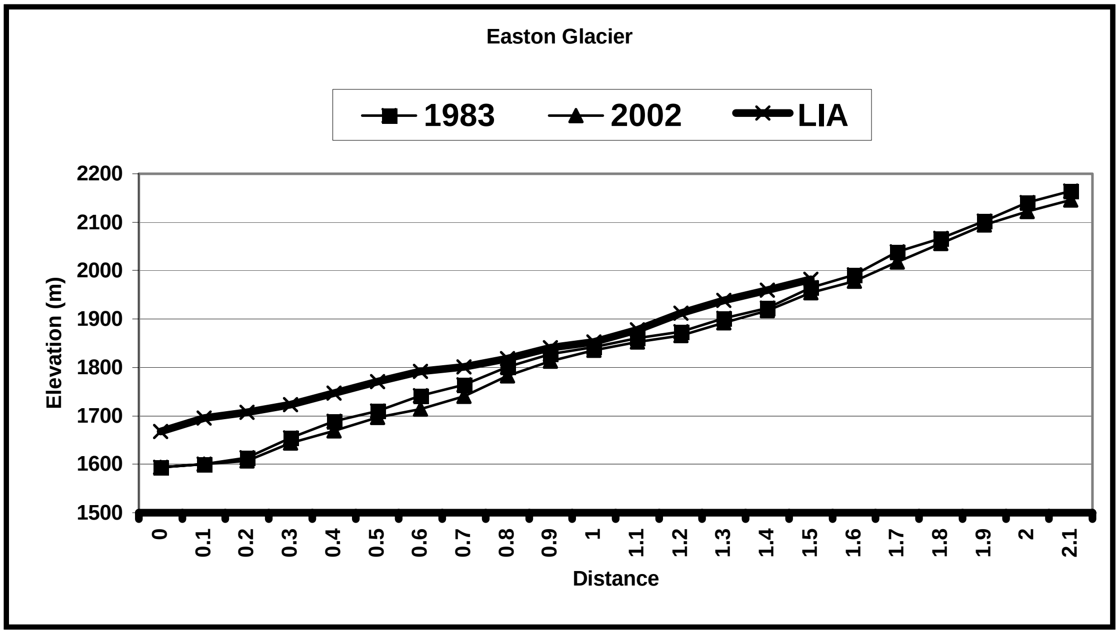
Figure 1. Cumulative and mean annual balance of Easton, Lower Curtis and Columbia Glaciers, North Cascades, Washington, observed by NCGCP between 1984 and 2002.

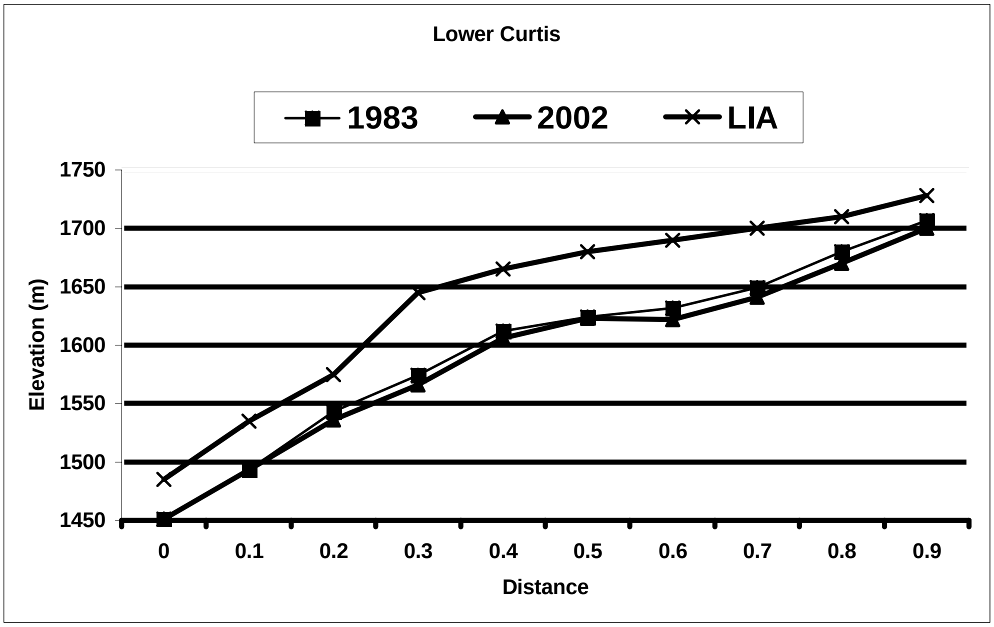
Figure 2. Change in longitudinal profile of Easton Glacier, North Cascades, Washington. The profile does not extend to the head of this glacier. Note the reduced thinning at higher elevations.

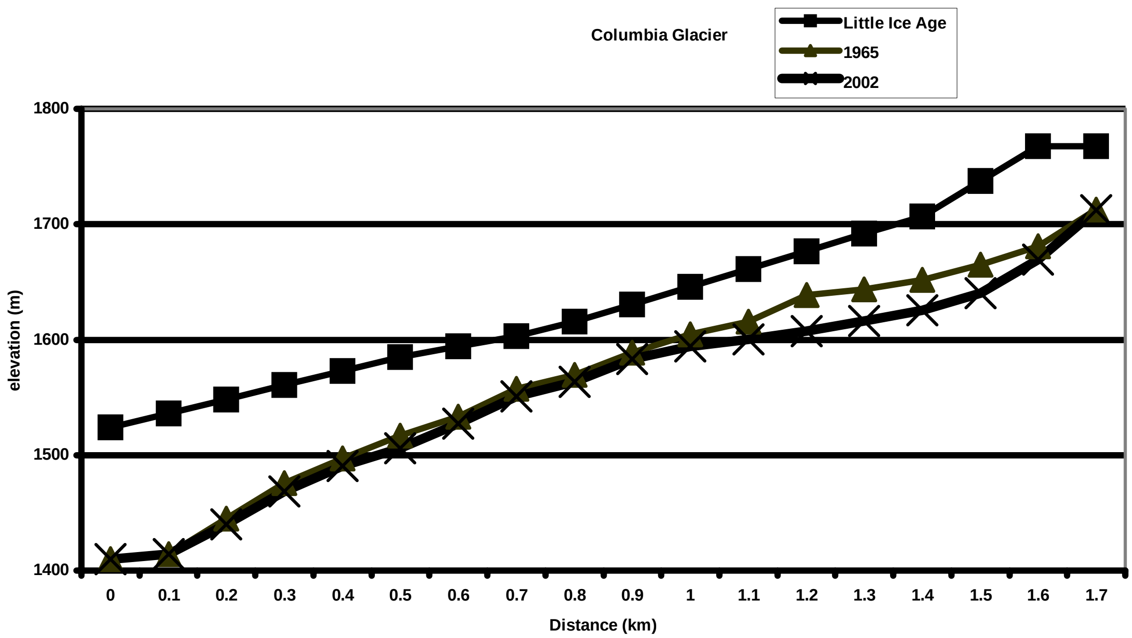
Figure 3. Change in longitudinal profile, Columbia Glacier, North Cascades, Washington. The greatest thinning occurred near the terminus in the early part of the century, but in the cirque basin more recently.

Figure 4. Change in longitudinal profiles of Lower Curtis Glacier, North Cascades, Washington. Thinning is greatest in the cirque basin accumulation zone.


1
0
-1
-2
-3
-4
-5
-6
-7
-8
bn (m)
1983
1984
1985
1986
1987
1988
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
Year
Mean Annual Balance
Columbia
Easton
Lower Curtis


Easton Glacier
1983
2002
LIA
2200
2100
2000
1900
1800
1700
1600
1500
Elevation (m)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
1.9
2
2.1
Distance


Lower Curtis
1983
2002
LIA
1750
1700
1650
1600
1550
1500
1450
Elevation (m)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
Distance



Columbia Glacier
Little Ice Age
1965
2002
1800
1700
1600
1500
1400
elevation (m)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
1.4
1.5
1.6
1.7
Distance (km)