

**TERMINUS BEHAVIOR AND RESPONSE TIME OF NORTH CASCADE,  
WASHINGTON GLACIERS**  
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**ABSTRACT**

Observation of the terminus behavior of 38 North Cascade glaciers since 1890 illustrates three different types of glacier response 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.

Type 1 glaciers are notable for steeper slopes, extensive crevassing, and higher terminus region velocities. Type 2 glaciers have intermediate velocities, moderate crevassing and intermediate slopes. Type 3 glaciers have low slopes, modest crevassing and low terminus region velocities. This indicates that the observed differences in the response time and terminus behavior of North Cascade glaciers to climate change are related to variations in specific characteristics of the glaciers. The response time of North Cascade glaciers approximately 20-30 years on Type 1 glaciers, 40-60 years on Type 2 glaciers, and a minimum of 60-100 years on Type 3 glaciers.

The high correlation in annual balance of North Cascade glaciers indicate that microclimates are not the key to differences in behavior. Instead it is the physical characteristics slope, terminus velocity, thickness, and accumulation rate of the glacier that determines  $T_s$  recent terminus behavior and response time.

The delay between the onset of a mass balance change and initiation of a noticeable change in terminus behavior has been observed on 21 glaciers to be 4-16 years. This initial response time of North Cascade glaciers applies to both positive and negative changes in mass balance.

**INTRODUCTION**

Observation of the differing terminus behavior of North Cascade glaciers in response to the same

climate changes during the last century (Tangborn and others, 1990), has prompted the evaluation of the terminus behavior of 38 glaciers in the North Cascades for the 1890-1990's period. The objective is to determine the characteristics that lead to differential terminus behavior among North Cascade glaciers.

To complete this task requires examination of the response time of glaciers to climate change. For any glacier there is a lag time ( $T_s$ ) between a significant climate change and the initial observed terminus response (Paterson, 1994), this is also referred to as the reaction time of the glacier. It should be noted that  $T_s$  cannot be considered a physical property of a glacier and is expected to depend on the mass balance history and physical characteristics of the glacier. In this paper  $T_s$  is simply defined as the time lag from an observed climate shift to the initial observed change from an advancing to a retreating terminus or from a retreating to an advancing terminus.

In addition, for each glacier there is a response time to approach a new steady state for a given climate driven mass balance change ( $T_m$ ), referred to as length of memory by Johannesson and others (1989). Johannesson and others (1989) defined  $T_m$  as the time-scale for exponential asymptotic approach to a final steady state (approximately 63% of a full response), resulting from a sudden change in climate to a new constant climate. The magnitudes of  $T_s$  and  $T_m$  are crucial to interpreting past and current glacier fluctuations and predicting future changes (Paterson, 1994; Johannesson and others, 1989).

In nature a step change in climate causing an evolution from an initial to a final steady state never happens (Schwitter and Raymond, 1993). The variability of climate forcing and the continuous changes in the glacier superimpose new disturbances on the response of the glaciers to previous climate. This leads to the conclusion that  $T_m$  cannot be defined directly from observations in nature. However,  $T_m$  cannot be accurately defined from models alone either.

In this study we recognize that the response of the terminus is influenced by ongoing changes in forcing, limiting the accuracy of determination of  $T_m$  from terminus observations. We use terminus observations to establish limits on the range of  $T_m$ , rather than attempting direct calculation of  $T_m$  from observations. We use terminus observations to establish time limits on the range of  $T_m$ . Our estimates of  $T_m$  are based on the understanding that, during a period of relatively constant climate, the glacier should advance to about 2/3 of its final adjustment in its terminus positions and the rate of advance/retreat of the terminus should be reduced to approximately 1/3 over a time period of length  $T_m$ . The difficulty of

examining terminus response to a specific step change is minimized with respect to the post Little Ice Age warming, because the climate change and associated terminus response is large compared to climate changes and resulting terminus changes that have occurred in the last half-century (Schwitter and Raymond, 1993; Burbank, 1981; Porter, 1986).

In the North Cascades the disparate terminus behavior of glaciers has been noted by Hubley (1956), Post and others (1971), Tangborn and others (1990) and Pelto (1993). The primary goal of this paper is to examine the observed terminus behavior and glacier geographic characteristics of 38 North Cascade glaciers to determine why the terminus behavior history varies. The secondary goal is to identify the ranges of  $T_s$  and  $T_m$  for the response of North Cascade glaciers to climate changes.

#### DATA USED

The North Cascade Glacier Climate Project (NCGCP) has been observing terminus behavior on 47 North Cascade glaciers and measuring annual balance on 9 glaciers since 1984 (Pelto, 1993; 1996). The primary objective of this glacier research has been to identify the magnitude and timing of glacier response to a climate change. This NCGCP data set is extensive in its breadth, but not in its length of record, extensive USGS aerial photographic collections and the ongoing research by the USGS on South Cascade Glacier have been indispensable to this research in providing long-term records.

#### Terminus Observations

The magnitude of terminus changes from the Little Ice Age Maximum (LIAM) has been measured on 38 glaciers by utilizing 720 USGS vertical aerial photographs, taken by Austin Post between 1962 and 1979, 150 aerial photographs taken by Richard Hubley at the University of Washington from 1950 to 1955, and 120 photographs taken by J.B. Richardson and William Long of the US Forest Service from 1940 to 1960 (all of these photographs have been donated to NCGCP by William Long, Austin Post, and the USGS).

Schwitter and Raymond (1993) noted the ease of identification and utility of the well-preserved Little Ice Age moraines for reconstructing former glacier profiles in the North Cascades and elsewhere. The distance from the typically well preserved, fresh LIA moraines and trimlines to the current glacier front has been measured in each case using a laser ranging device ( $\pm 1\text{m}$ ). Additionally on each of the 38 glaciers field measurements from the same LIA moraines to the current glacier front was completed on at least two

occasions between 1984 and 1998. The goal being to verify both the LIAM and the actual terminus position changes from 1984-1998. In cases where the field measurements and photographic measurements differed by more than 20 m the glacier is not used in this analysis. This was the case on two glaciers.

Terminus change from 1850-1950 is the distance from the aforementioned LIAM and the position of the glacier terminus as in 1950 noted by Hubley (1956). Terminus change from 1950-1979 is the change between the position noted by Hubley (1956) and the USGS aerial observations in 1979. Neither, 1950 or 1979 perfectly match the timing of climate changes noted in the following section; however, they are closest to the climate shifts, beginning in 1944 and 1976 respectively, for which adequate aerial photographic observations were made. Terminus change from 1979 to the present is based on comparison of the USGS aerial observations and repeated field measurements of the North Cascade Glacier Climate Project from 1984-1998 (Pelto, 1993; 1996).

To determine  $T_s$  a group of 21 North Cascade was observed to switch from retreat to advance shortly after 1944, and from advance to retreat shortly after 1976. Observations of the initial post-1944 glacier advances were made by Long (1955 and 1956) and Hubley (1956). Observations of the onset of retreat after 1976 are from Heikinen (1984), NCGCP field observations (Pelto, 1993) and USGS aerial photographs from 1979.

#### Glacier Characteristics

On seventeen of the aforementioned 38 glaciers more detailed observations are used to calculate theoretical estimates of  $T_m$  for comparison with observations of terminus behavior. Each of these 17 glaciers had at least five terminus observations during the 1850 to 1998 period (Table 1)(Hubley, 1956; Long, 1955; Meier and Post, 1962; Pelto, 1993; Post and others, 1971). To be able to calculate  $T_m$  terminus velocity  $u(t)$ , mass balance near the terminus  $b(t)$ , ice thickness ( $h$ ) and glacier length ( $l$ ) have to be determined. Nine of the 17 glaciers have had annual balance measurements over a span of more than 10 years (Table 1)(Pelto, 1996; Krimmel, 1996). Krimmel (1999) has observed  $b(t)$  and  $u(t)$  on South Cascade Glacier. On the other 16 glaciers  $b(t)$  and  $u(t)$  have been directly observed for at least two hydrologic years using stakes drilled into the glacier terminus area by NCGCP (Pelto, 1996; Krimmel, 1999). Measurement of  $u(t)$  relied on at least three points, in the lower 25% of the glacier's length, which is within

200 m of the terminus in each case. The longer term annual balance measured on nine of these glaciers indicates that the period of record for terminus mass balance measurement (1994-1996) was close to the 1984-1997 mean.

In 1998, Krimmel (1999) observed the length of the South Cascade Glacier. Glacier length on the other 16 glaciers length has been taken from the most recent USGS maps compiled from aerial photographs between 1982 and 1984, and adjusted for the observed retreat up 1998.

Glacier thickness ( $h$ ) has been measured on three North Cascade glaciers South Cascade Glacier (Krimmel, 1970), Easton Glacier (Harper, 1993) and Lewis Glacier. The first two are both comparatively large glaciers for the area. Each had a maximum mean profile depth of 60-80 m. These measurements along with those of Driedger and Kennard (1986) on Cascade volcanoes, which yielded a mean thickness of 50 m on Mt. Rainier, and 35 m on Mt. Hood, illustrate that these glaciers are comparatively thin. On Lewis Glacier the thickness was measured in a moulin that reached the base of the glacier in 1985, 1986 and 1987. The thickness of each of the other 14 glaciers where direct measurement has not been made is assumed to be 50 m on thin concave or slope glaciers and 100 m on thicker convex or valley glaciers. In both cases the resulting  $h$  is a maximum value, thus the  $Tm$  would be a maximum value too (Post and others, 1971).

#### Climate Data

A good single climate indicator for North Cascade glaciers behavior is the Pacific Northwest Index (PNI), developed by Ebbesmeyer and others (1991). Figure 1 is a graph of the PNI during this century. The index is based on March 15 snowpack depth at Paradise on Mt. Rainier, WA, mean annual temperature at Olga, WA., and total annual precipitation at Cedar Lake, WA. Positive values reflect negative glacier mass balances.

#### TERMINUS OBSERVATIONS

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). Depending on the glacier, the maximum advance occurred in the 16th, 18th, or 19th century (Miller, 1971; Long, 1956). 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). Miller (1971) mapped the age of terminal moraines in front of Chickamin and South Cascade Glacier and found in each case that a late-19<sup>th</sup> century moraine was emplaced within 100 m of the LIAM. On Mt. Rainier, just south of the study area, mapping of terminus changes by (Burbank, 1981) indicate that rapid and continuous retreat of Mt. Rainier glaciers from their LIAM began after the 1880-1885 still stand. Long (1953) noted that retreat on Lyman Glacier and Easton Glacier became substantial only after 1890. Long (1955) noted that the Lyman Glacier has been retreating steadily since the 1890's. Climate warming and retreat began about 1850, but because of the modest retreat and subsequent stillstand or advance of North Cascade glaciers around 1880, 1890 is used as the approximate time for the climate change that initiated a continuous substantial retreat from the LIA advanced positions in the North Cascades.

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. It must be emphasized that the entire retreat noted from the LIAM to 1944 did not occur in the 1890-1944 interval, observations do not exist on most glaciers to distinguish the exact timing of the initial post LIAM retreat, though retreat was minor before 1890 on glacier where observations exist. Average retreat of glaciers on Mt. Baker was 1440 m from LIAM to 1950 (Pelto, 1993). Average retreat of the 38 North Cascade glaciers in this study was 1215 m.

The PNI from 1895-1923 is rising, but has a comparatively low mean (-0.34), that is still capable of generating retreat on North Cascade glaciers, that are all still in advanced positions from the LIA. The PNI average during the 1924 –1944 was the high at 0.44. This warm dry period has been noted around the world and in the North Cascades as a period of rapid glacier retreat (Burbank, 1981; Long, 1955; Hubley, 1956). The second substantial change in climate began in 1944 when conditions became cooler and precipitation increased (Hubley 1956; Tangborn, 1980). The climate change in 1944 is evident in the PNI record (Figure 1). The mean PNI from 1945-1976 was -0.37. This drop in the PNI average of 0.76 from the previous interval marks the climate change that initiated the advance of some North Cascade glaciers and the more positive mass balance for that period (Tangborn, 1980; Hubley, 1956).

Hubley (1956) and Long (1956) noted that North Cascade glaciers began to advance in the early 1950s, after 30 years of rapid retreat. This change was reflected in the mass balance of North Cascade glaciers. A Runoff-Precipitation model constructed for South Cascade Glacier (Tangborn, 1980) yielded a mean annual balance of  $-1.15$  m/a from 1924-1944, compared to  $-0.15$  m/a from 1945-1976.

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). All 11 Glacier Peak glaciers that advanced during the 1950-1979 period emplaced an identifiable maximum advance terminal moraine, the mean advance was 295 m. Of the 47 glaciers that NCGCP has observed during the 1984-1998 period, 15 advanced during the 1950-1978 period.

The final climate change was a step change in 1977 to a drier-warmer climate in the Pacific Northwest (Ebbesmeyer and others, 1991). The mean PNI from 1977-1998 was 0.53, even higher than the 1924-1944 period, indicating a warmer drier period that reestablished the ubiquitous retreat of North Cascade glaciers (Pelto, 1993). This change impacted glacier mass balance, alpine streamflow, and alpine snowpack (Ebbesmeyer and others, 1991). The impact on North Cascade glacier mass balance is evident from the USGS long-term record of South Cascade Glacier (1958-1998), where mean annual balance was  $-0.15$  m/a from 1958-1976, in contrast to  $-1.00$  m/a from 1977-1998 (Krimmel, 1999).

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 1997-98, 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  $-197$  m. All of the Mt. Baker termini are still in advance of their 1940 position as observed in photographs from J.B. Richardson, and observations by Austin Post (pers. comm.). However, the glacier region between the current terminus and 1940 terminus is nearly stagnant on each of the glaciers. 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.

INITIAL TERMINUS RESPONSE

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 ( $T_s$ ). As indicated previously  $T_s$  is a descriptive quantity that quantifies the time lag between climate forcing and terminus response for a particular climate event, rather than a physical property of a glacier.  $T_s$  in this study is based solely on the first observed terminus change from retreat to advance after 1944, and from advance to retreat after 1976.  $T_s$  has been identified from the response of North Cascade glaciers 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; Pelto, 1988; Pelto, 1993; Krimmel, 1994; Harper, 1993).

Focusing on 21 North Cascade glaciers that responded to these two climate shifts, all having an area under 10 km<sup>2</sup>, the initial terminus response invariably is less than 16 years (Pelto, 1993; Hubley, 1956; Harper, 1993). Table 2 is a list of 21 North Cascade glaciers where  $T_s$  has been noted for both advance and retreat for the post-1944 period by Hubley (1956), or Long (1955 and 1956). In each case the glaciers were observed to be in retreat during the 1940's, and subsequently each advanced within 16 years of the climate change. Table 2 also notes the response of the same glaciers from a period of advance by each glacier in the early 1970's to retreat by 1988, 12 years after the climate change (Pelto, 1988 and 1993; Harper, 1993). The observed  $T_s$  is not significantly different on individual glaciers for initiation of advance, versus initiation of retreat.

Many North Cascade glaciers did not respond to these two climatic changes. This may be the result of a longer  $T_s$ , or as more likely is either due to an ongoing retreat caused by continuing negative mass balances, or that climate change was insufficient to substantially alter mass balance on these glaciers.

#### ANALYSIS AND CLASSIFICATION OF THE RESPONSE OF THE GLACIERS

The 38 North Cascade glaciers, where the terminus history has been determined for the 1890-1998 period exhibit three distinct patterns (Table 3): 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. Distinction of a glacier's Type is based solely on its terminus behavior in this analysis.



## TYPE 1 GLACIERS

From 1890-1946 a retreat of at least 1000 m occurred on each of the significant glaciers (over 1.0km<sup>2</sup>) on Mt. Baker and Glacier Peak. Each of these glaciers is a Type 1 glacier: Mazama, Rainbow, Easton, Squak, Talum and Boulder Glacier on Mt. Baker and, Ermine, Dusty, N. Guardian, Kennedy, Scimitar, Ptarmigan and Vista Glacier on Glacier Peak are used in this study. The two strato-volcanoes, Glacier Peak and Mt. Baker are the highest peaks in the North Cascades. The ability to advance was not limited to the high elevation glaciers of the two large volcanoes, as this advance was also noted on other North Cascade glaciers Ladder Creek, Challenger, Quien Sabe, Lower Curtis, Sulphide and N. Klawatti Glacier (Hubley, 1956).

Even in 1940 at the height of retreat Type 1 glaciers were extensively crevassed and quite active in the photographs taken by William Long and J.B. Richardson of the National Forest Service (Figure 2). Today despite moderate to rapid retreat rates of 10-30m/a, all Type 1 glaciers remain extensively crevassed.

Each Type 1 glacier was still retreating appreciably in 1940 but had approached close enough to equilibrium that the climate shift beginning in 1944, indicated by a decrease of the mean PNI of approximately 1, brought about a rapid change from retreating to advancing conditions (Hubley, 1956). The 50 years of continuous retreat reflects Type 1 glacier response to the initial climate shift in approximately 1890, the progressive warming during the 1895-1923 period, and the warmth of the 1924-1944 period (Long, 1955 and Burbank, 1981). None of the glaciers had achieved a full adjustment by 1940, but certainly seemed to be approaching it, suggesting that  $T_m$  is in the 20-30 year range for Type 1 glaciers.

Similarly by 1976 advance had brought these glaciers close enough to equilibrium, as evidenced by the slow rate of terminus change (Harper, 1993), that the modest (10%) recent decline in winter precipitation and rise in summer temperature (1.1°C) resulted in glacier retreat (Pelto, 1993 and 1996; Harper, 1993). This again indicates that  $T_m$  is in the range of 20-30 years. It must be acknowledged that these glaciers became smaller since the post Little Ice Age warming, and  $T_m$  should therefore be shorter.

## TYPE 2 GLACIERS

Each of these glaciers retreated substantially from 1890-1950, followed by nearly stable terminus positions between 1955 and 1979, and an increasing retreat rate since 1984. Type 2 glaciers in this study

are Columbia, Watson, Cache Col, Yawning, Sahale, Neve, Ice Worm and Suiattle Glacier. The maximum retreat or advance of this group was less than 30 m from 1955-1984. Since 1984 the retreat rate has been increasing for this group of glaciers, average retreat for the 1992-1998 period was 8 m/a. In 1998 the retreat rate remains modest as the glaciers still seem to be adjusting slowly to climate change.

An increase in crevassing was noted on the Neve, Yawning and Suiattle Glacier in 1955, but little or no advance occurred, though the retreat did end in the early 1970's on these three glaciers. This suggests that the climate change was insufficient to generate an advance, but did manage to halt the ongoing retreat.

After continuously retreating from 1890-1950 the Type 2 glaciers had not approached close enough to equilibrium for the 1944 climate shift to stop retreat initially. This suggests that  $T_m$  for Type 2 glaciers is on the order of 40-60 years, since each glacier termini was close to equilibrium after the 1944 climate change, but had not yet attained equilibrium due to the 1890 climate change. Exponential filtering of the PNI index also indicates that a response time in this range is required to approximately halt the retreat in the period 1944-1976 (Johannesson, personal communication).

### TYPE 3 GLACIERS

This group includes South Cascade, Honeycomb, Foss, Hinman, Milk Lake, Lyman, Whitechuck, White River, Lewis, Sholes and Colonial Glacier. Each of these glaciers has retreated continuously throughout this century. The most rapid retreat period has varied; however, each glacier retreated more than 100 m between 1950 and 1979 and thinned appreciably, when many North Cascade glaciers were advancing or in equilibrium (Hubley, 1956; Meier and Post, 1962).

Type 3 glaciers all have a low slope, limited crevassing and in general low velocities for their respective size. South Cascade Glacier is a typical Type 3 glacier. Lyman, Hinman, Foss and Colonial Glacier have each lost more than 50% of their area in the last 50 years (Figure 4). Of these four only Lyman Glacier is still moving at a detectable rate. The others three had continuously negative mass balances and will disappear with our current climate. None of the Type 3 glaciers has neared a post LIA equilibrium.

The disappearance of two glaciers in this group, Lewis Glacier in 1989 and Milk Lake Glacier in 1993, illustrates that after nearly 150 years of adjustment these glaciers still had failed and did fail to

achieve a new equilibrium. That none of the glaciers had achieved equilibrium by 1975, after 85 years of retreat, indicates a  $T_m$  of at least 60-100 years for Type 3 glaciers. The complete melting away of Hinman and Foss Glacier may take another 50 years despite their small size.

South Cascade Glacier is the most studied glacier in the North Cascades. The USGS has monitored the mass balance since 1952. The mass balance trend through time indicates that from 1958-1976 mean annual balance was  $-0.15$  m/a (Krimmel, 1999). The 1945-1975 period of more positive mass balance that generated advance for many North Cascade glaciers, resulted only in smaller negative balances, but a significant ongoing retreat (Krimmel, 1996). From 1977-1998 mean annual balance on South Cascade Glacier was  $-1.0$  m/a (Krimmel, 1999), and retreat has been rapid. During the 1940-1998 period for which terminus observations exist, South Cascade Glacier has not approached equilibrium.

None of the Type 3 glaciers has approached a steady state since the end of the LIA regardless of the fluctuations in mass balance and the low values of the proxy forcing function PNI from 1945-1976. Type 3 glaciers are still adjusting in part to the post Little Ice Age climate change, which has been reinforced by recent warming. It therefore, seems likely that Type 3 glaciers and South Cascade Glacier are still adjusting to the post LIA warming after a century of retreat and that  $T_m$  is at least 75 years.

#### CHARACTERISTICS OF GLACIER TYPES

Each of the three glacier types was established based solely on terminus behavior history; however, it is apparent that each type has specific characteristics (Figure 2-5). Figure 6 illustrates the different terminus behavior history of North Cascade glaciers. The slower initial response to climate change of Type 3 glaciers is evident. The long-term result of the slow start is a more persistent retreat. Table 3, lists the mean slope, mean altitude and area of each glacier of the 38 glaciers. Mass balance measurements in the accumulation zone exist for 12 of the glaciers in this study. Type 1 glaciers have the highest mean elevations (2200 m), largest mean slope ( $0.42, \pm 0.07$ ), highest measured mean accumulation (Pelto, 1988; 1996), most extensive crevassing and highest measured terminus region velocity ( $20$  m/a,  $\pm 3$  m/a). Type 3 glaciers have the lowest slopes ( $0.23, \pm 0.06$ ), least crevassing, and lowest mean terminus velocity ( $5$  m/a,  $\pm 3$  m/a) of any of the glacier types. Type 2 glaciers have on average, a lower slope ( $0.35, \pm 0.08$ ), a lower terminus region velocity ( $7$  m/a,  $\pm 4$  m/a), less crevassing, and a lower mean accumulation rate than Type 1 glaciers (Figure 3).

There is no significant relation between aspect and glacier type. A larger mean slope, higher accumulation rates, more extensive and higher velocity either reflect or lead to increased glaciers velocities and longitudinal strain rates. The greater the longitudinal strain rate the faster the glacier can adjust to changing climate conditions (Paterson, 1994). The terminus region velocities on large alpine glaciers may be quite independent of glacier velocity as a whole. On the smaller North Cascade glaciers the terminus region velocity is, on the other hand, a good indicator of mean glacier velocity.

The three glacier types illustrate that persistent differences in glacier behavior are explainable based on the basic characteristics of the glacier which in turn determine response time, and not unique to specific glaciers. This is reinforced by the exceptionally high degree of correlation in annual balance between North Cascade glaciers (Pelto, 1997). The lowest cross correlation value for annual balance, between any pair of nine glaciers observed by the USGS and NCGCP, is 0.79.

The different behavior of adjacent glacier termini based on differing topographic characteristics in the North Cascades was observed on S. Klawatti and N. Klawatti Glacier (Tangborn and others, 1990). From 1947-1961 N. Klawatti Glacier lost a volume equivalent to a mean thickness of 8.3m, continuing its ongoing retreat. S. Klawatti Glacier gained a thickness equivalent to a mean thickening of 5.8 m (Tangborn and others, 1990). This is not an unusual case in the North Cascades. Based on the classification of glacier type in this study S. Klawatti is a Type 1 glacier and N. Klawatti a Type 3 glacier. The difference in the degree of crevassing alone indicates a notable difference in flow. The adjacent glaciers differing responses fit the overall pattern for glaciers of their respective types in the North Cascades, and are not an anomalous case. We identified no important microclimatic effects that created differing mass balance conditions on glaciers across the North Cascades (Pelto, 1996 and 1997).

An even more poignant example is that of the Neve and Ladder Creek Glacier, which share the same accumulation zone and have termini that both end at approximately 1680 m. The shared accumulation zone between 2000 m and 2400 m flows into a pass at 2000 m where the glacier turns both east and west. The Ladder Creek Glacier flows northwest and is a Type 1 glacier and has a steep, shorter terminus, 1200 m to terminus from the pass, comparatively rapid velocity, and was noted to advance by Hubley (1956). Neve Glacier is a Type 2 glacier, it is slightly larger than the Ladder Creek Glacier and has a longer terminus region, 1920 m from the pass. This results in a gentler slope and consequently slower

velocity. This glacier did not advance, though crevassing did increase within 500 m of the terminus slowing the retreat to a standstill.

Observation of different responses of glacier types to a climate change is not unique to the North Cascades. In Switzerland a sample of 38 glaciers with 150 year long terminus records was classified into, four different classes, with different types of terminus responses for each glacier class (Herren and others, 1999): 1) Large valley glacier such as the Gornergletscher which has retreated rapidly and continuously. 2) Small mountain glaciers such as the Saleina, which has advanced twice during this century, though retreat has been more pronounced. 3) Large mountain glaciers, such as the Tschierva, which follow the same pattern as Saleina except with more significant retreat. 4) Small cirque glaciers, such as the Gran Plan Neve, which has retreated slowly throughout the century.

#### THEORETICAL ESTIMATES OF RESPONSE TIME

A primary difficulty in the identification of  $T_m$  is that after a climate change climate conditions do not reach a new steady state for periods comparable to the  $T_m$  of glaciers. Each glacier is then adjusting to the continually changing climate conditions and never achieves a steady state, due to the non-steady state climate (Schwittter and Raymond, 1993). Schwittter and Raymond (1993) noted that these difficulties are minimized with regard to changes from the LIAM to the present, since the basic climate change since the late 1800's has been from a LIA climate favorable to glaciers and a post LIA climate unfavorable for glaciers. Changes in North Cascade terminus behavior and glacier thickness from the LIAM to the present are large compared to changes in response to more recent climate changes (Schwittter and Raymond, 1993).

The observed terminus record of North Cascade glaciers indicates a range of  $T_m$  from 20 to 30 years on Type 1 glaciers, approximately 40-60 years on Type 2 glaciers, and a minimum of 60-100 years on Type 3 glaciers. How do these values compare to those calculated from the equations of Johannesson and others (1989).

Johannesson and others (1989), compared two means of calculating  $T_m$ :

$$T_m = fL / u(t) \quad (1)$$

and

$$T_m = h / -b(t) \quad (2)$$

$T_m$  in these equations is potentially dependent on four variables:  $L$  the glacier length,  $u(t)$  velocity of the glacier at the terminus,  $h$  the thickness of the glacier, and  $b(t)$  the net annual balance at the terminus. The former equation, which was proposed by Nye (1960), produces longer full response times of 100 to 1000 years, the latter full response times of 10 to 100 years (Johannesson and others, 1989). The variable  $f$  is a shape factor that is the ratio between the changes in thickness at the terminus to the changes in the thickness at the glacier head (Schwitter and Raymond, 1993). Similar changes in ice thickness will yield a value of  $f=1$ ,  $f=0.5$  corresponds to a linear decrease of thickness change from a maximum at the terminus to zero at the head. The mean value of  $f$  has been determined as 0.3 (Schwitter and Raymond, 1993), and this value of  $f$  is applied. This equation is quite sensitive to terminus velocity, which is often spatially inconsistent.

Table 4 displays the variables used in determining  $T_m$  for 17 North Cascade glaciers, the calculated  $T_m$  from equation 1, and  $T_m$  from equation 2. Each variable, except  $h$ , has been observed on each glacier by the USGS (South Cascade Glacier) or NCGCP.

It is evident that equation 2 yields values that are lower than the estimates of  $T_m$  for North Cascade glaciers of Types 2 and 3 glaciers, but the difference is smaller for Type 1 glaciers. Equation 1 overestimates  $T_m$  and because of the wide spatial variability of  $u(t)$ , it is not expected to yield a consistently accurate result on alpine glaciers.

South Cascade Glacier, like all Type 3 glaciers, is still adjusting to post LIA warming and the discontinuous but progressive warming of this century. This is not unique to the North Cascades, many alpine glaciers have not yet fully adjusted to post LIA warming. The Ptarmigan and Lemon Creek Glacier, Alaska; Gornergletscher and Rhonegletscher in Switzerland; Athabasca Glacier, Canada, and in the Darwin Cordillera, Chile several glaciers have retreated continuously during this century (Marcus and others, 1995; Herren and others, 1999; Holmund and Fuenzalida, 1995).

## CONCLUSIONS

North Cascade glaciers had a varied terminal response to the 1944 climate change, with only Type 1 glaciers advancing. Based on this study, the failure of Type 2 and Type 3 glaciers to advance is a function of their incomplete adjustment to the post LIA progressive warming. Thus, they were still significantly out of equilibrium in 1944, after approximately a half-century of retreat (Burbank, 1981), and

the modest positive mass balances did not trigger a glacier advance. Peltó (1996) noted the high cross correlation in observed annual balance on North Cascade glaciers (Figure 7). This similarity is true regardless of glacier type. This is evidence that microclimates are not the key to differences in behavior. Instead it is the physical characteristics slope, terminus velocity, thickness, and accumulation rate of the glacier that determines its recent terminus behavior and response time.

An example is the adjacent N, Klawatti and S. Klawatti Glaciers. S. Klawatti advanced in the 1950-1975 interval and N. Klawatti continued to retreat. The glaciers have different area-altitude distributions, to which Tangborn and others (1990) attributed the differential terminus response. However, the different area-altitude distribution is both a result of slower response and a reflection of the differing topographic setting.

Porter (1986) noted that many alpine glaciers experienced nearly synchronous reversals in terminus behavior around 1950. This change in glacier terminus behavior prompted Johannesson and others (1989) to suggest that, alpine glacier behavior is dominated by short-term climate effects. In the North Cascades, this synchronous reversal to advance and later to retreat of only Type 1 glaciers indicates that in the North Cascades only glaciers close to equilibrium had a reversal in terminus behavior due to the short-term climate effects. Glacier termini such as the Honeycomb, Lyman, Columbia, Milk Lake, and South Cascade Glacier were only modestly affected by the recent short-term climate changes in the North Cascades.

North Cascade glaciers occupy an exceptionally temperate maritime climate for glaciers.  $T_s$  on North Cascade glaciers are short (Hubley, 1956), ranging from 4-16 years in response to both positive negative mass balance changes.

$T_m$  varies considerably even between similarly sized glaciers in this region. The key variables that decrease  $T_m$  are factors that increase mean glacier velocity, accumulation rates and glacier slopes in particular. The response times of 30-100 years for most of these small glaciers indicates that with a substantial climate change the initial response may be rapid, but full adjustment is not rapid in the North Cascade Range.

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TYPE 1	LIAM-1950	1950-1979	1979-1997	Slope	Glacier Size (km <sup>2</sup> )	Altitude (m)	Latitude	Longitude
Mazama	-2350	450	-125	0.44	3.9	2200	48 48	121 48
Rainbow	-1370	512	-225	0.37	1.6	1850	48 48	121 46
Easton	-2420	608	-165	0.35	2.9	2250	48 45	121 50
Squak	-2500	305	-160	0.45	2.1	2350	48 45	121 49
Talum	-1975	275	-161	0.55	1.8	2400	48 45	121 48
Boulder	-2560	743	-290	0.50	3.4	2350	48 46	121 47
Ermine	-1800	170	-108	0.46	1.4	2400	48 09	121 07
Dusty	-1800	280	-218	0.42	1.2	2350	48 07	121 06
N. Guardian	-1550	160	-120	0.43	1.1	2400	48 07	121 05
Kennedy	-1700	330	-151	0.48	1.6	2100	48 07	121 07
Scimitar	-1600	350	-98	0.46	1.0	2100	48 08	121 07
Ptarmigan	-1050	75	-39	0.50	0.6	2250	48 09	121 08
Vista	-1900	105	-105	0.28	1.3	2150	48 09	121 07
Quien Sabe	-1250	55	-89	0.40	0.9	2350	48 30	121 03
Lower Curtis	-645	225	-82	0.36	0.8	1650	48 50	121 37
Ladder Creek	-1230	105	-52	0.31	1.8	2100	48 39	121 09
Sulphide	-1775	210	-101	0.38	2.4	2100	48 49	121 07
TYPE 2								
Cache Col	-360	-25	-46	0.45	0.3	1950	48 22	121 03
Columbia	-560	-15	-70	0.18	0.9	1600	47 56	121 21
WaTson	-320	-21	-55	0.4	0.5	1650	48 41	121 06
Neve	-720	-25	-48	0.24	2.4	2150	48 38	121 07
Sahale	-260	-12	-53	0.5	0.2	2400	48 49	121 02
Sholes	-1170	-57	-50	0.30	0.9	1850	48 49	121 46
Yawning	-310	35	-31	0.39	0.2	1850	48 27	121 02
Lynch	-160	-390	-88	0.36	0.6	2150	47 34	121 11
Ice Worm	-925	0	-55	0.33	0.1	2150	47 34	121 10
Daniels	-960	-20	-121	0.5	0.4	2200	47 34	121 10
White River	-780	-140	-98	0.2	1.0	2200	48 03	121 05
Suiattle	-2400	15	-23	0.3	2.8	2100	48 04	121 05
TYPE 3								
Lewis	-65	-80	-182 *	0.25	0.2	2100	48 31	120 48
Colonial	-230	-81	-52	0.27	0.7	2000	48 40	121 08
Lyman	-1020	-408	-113	0.23	0.4	2000	48 10	120 54
Foss	-975	-86	-112	0.36	0.5	2050	47 34	121 12
Hinman	-410	-300	-711	0.21	0.3	1950	47 35	121 14
S. Cascade	-1800	-350	-295	0.17	2.0	1900	48 21	121 03
White Chuck	-1300	-330	-170	0.22	1.9	2150	48 04	121 07
Honeycomb	-1750	-290	-338	0.17	3.5	2250	48 04	121 04
Milk Lake	-400	-190	-210*	0.17	0.3	1900	48 10	121 11

Table 3. Retreat, in meters, of North Cascade glaciers for three intervals since the LIAM. The longitude and latitude of each glacier is noted in degrees and minutes, the mean slope of the glacier surface, the mean altitude of the glacier, and the surface area of the glacier are also listed.

\*Lewis and Milk Lake Glacier the retreat ended with the loss of the glacier.

Glacier	1950-55	1964-67	1970-72	1979	1984-98	b(t) and u(t)
Colonial	2	1	2	1	5	1992-1996
Columbia	2	1	2	1	15	1984-1998
Daniels	3	1	2	1	15	1984-1998
Easton	4	2	2	1	7	1991-1996
Foss	2	1	2	1	15	1984-1998
Honeycomb	3	2	2	1	3	1994-1996
Ice Worm	3	1	2	1	15	1984-1998
Kennedy	3	2	2	1	4	1994-1996
Ladder Creek	2	1	2	1	4	1992-1996
Lewis	2	1	2	1	15	1984-1989
Lower Curtis	3	1	2	1	15	1984-1998
Lyman	3	1	2	1	6	1994-1996
Lynch	3	1	2	1	15	1984-1998
Neve	2	1	2	1	4	1992-1996
Rainbow	2	1	2	1	15	1984-1998
South Cascade	4	4	3	1	15	1958-1998
Yawning	2	1	2	1	15	1984-1998

Table 1. Number of terminus observations used in this study for each glacier of the 17 glaciers where  $T_m$  has been both derived from field observations and calculated from theoretical equations, and the interval of mass balance and velocity observations at the terminus of each glacier,  $(b(t))$  and  $u(t)$  respectively.

<u>Glacier</u>	<u>Advance Observed</u>	<u>Retreat Observed</u>
Coleman	1949	1979
Easton	1960	1989
Deming	1955	1986
Boulder	1954	1985
Squak	1955	1985
Rainbow	1955	1985
Kennedy	1955	1986
Chocolate	1950	1986
N. Guardian	1955	1986
Dusty	1955	1986
Ptarmigan	1960	1988
Vista	1960	1988
Ermine	1955	1986
Ladder Creek	1955	1987
Eldorado	1955	1984
Quien Sabe	1955	1984
Yawning	1955	1986
Lower Curtis	1955	1987
Challenger	1955	1985
Price	1954	1987
Chimney Rock	1955	1987

Table 2. Date of first observed advance following the 1944 climate change. Date of the first observed retreat following the climate change in 1976-77.

Glacier	Type	L	U(t)	h	b(t)	$\Delta l$	Tm1	Tm2
Colonial	3	1500	.003	50	-4.5	-310	167	11
Columbia	2	1600	.004	100	-4.5	-610	133	22
Daniels	2	800	.009	50	-4	-960	30	12
Easton	1	4000	.024	75	-6.5	-2420	55	11
Foss	3	1000	.004	50	-4.5	-1060	83	16
Honeycomb	3	4400	.006	100	-6	-2360	244	12
Ice Worm	2	500	.002	50	-4	-930	83	16
Kennedy	1	2400	.02	100	-6	-.006	40	16
Ladder Creek.	1	2600	.025	100	-5	-1230	35	20
Lewis	3	300	.001	50	-2	-280	100	12
Lower Curtis	1	1800	.02	100	-5.5	-540	30	18
Lyman	3	600	.005	50	-5	-1430	40	10
Lynch	2	1200	.010	100	-4	-450	33	25
Neve	2	3500	.008	100	-4.5	-800	146	22
Rainbow	1	2700	.018	100	-5	-1370	60	20
South Cascade	3	3100	.008	80	-6	-1500	129	13
Yawning	2	800	.005	50	-4	-310	53	12

Table 4. Variables used in equations 1 and 2 and the calculated and observed  $Tm$ .  $L$ = glacier length (m),  $u(t)$ = terminus region velocity (m/a),  $h$ = ice thickness (m) near terminus,  $b(t)$ =annual balance (m/a) in the terminus region,  $l$ = change in glacier length (m) since Little Ice Age maximum,  $Tm1=Tm$  from equation 1 with  $f=0.3$ ,  $Tm2=Tm$  from equation 2.

Figure Captions:

Figure 1. Five-year running mean of PNI (Ebbesmeyer and others, 1990), note the increasingly high values from 1895-1945, low values from 1945-1975 and high values from 1980-1996.

Figure 2A. Glacier Peak in 1988, North Guardian and Dusty Glacier are typical Type 1 glaciers steep, crevassed and with high accumulation rates. The glacier is undergoing slow retreat at the time of this photograph.

Figure 2B. Dusty and North Guardian Glacier in 1972 indicating increased crevassing during a period of advance.

Figure 3A. Lynch Glacier in 1972 a Type 2 glacier despite being steep it has fewer crevasses, and has not stopped retreating during this century. Foss Glacier on the right is a Type 3 glacier with a lower slope, and less crevassing.

Figure 3B. Lynch Glacier in 1997 having retreated out of the basin in the foreground, which is now occupied by Pea Soup Lake.

Figure 4A. Honeycomb Glacier in 1967, a Type 3 glacier, which has no crevassing or motion in the terminus region. This is still a large glacier, though it did retreat 480 m from 1979-1997.

Figure 4B. Honeycomb Glacier in 1995, picture taken from the 1967 terminus position.

Figure 5. The shared accumulation zone of Neve and Ladder Creek Glacier. The gentle Neve Glacier terminus is in foreground. The top of the steeper Ladder Creek Glacier terminus region is just visible on left with crevassing increasing.

Figure 5 (alternate). Klawatti Glacier from the north. Note the difference in surface slope and crevassing of South Klawatti Glacier (left) and North Klawatti Glacier (right).

Figure 6. Cumulative terminus position change on seven North Cascade glaciers since approximately 1850. Easton, Mazama, Boulder and Rainbow are four Type 1 glaciers and all show a period of advance. Columbia Glacier, a Type 2 glacier, has a moderate but continuous retreat. Lyman and South Cascade Glacier retreated slowly at first, but have now accelerated.

Figure 7. Annual balance of nine North Cascade Glaciers from 1984 to 1998 in meters of water equivalent (Pelto, 1996; Krimmel, 1999).