

## 4. Glaciers

### Abstract

On a global scale, many glaciers have been retreating since the end of the Little Ice Age (~1550-1850) while some glaciers have advanced during intervening relatively cool and wet periods. Recent studies have demonstrated that widespread negative mass balance and the resulting accelerated glacier retreat over the last two or three decades is largely a response to increasing anthropogenic greenhouse gases which has caused accelerated global warming since the 1970s. Following trends for the North Cascades as a whole, the Skagit's 394 glaciers (which provide 12-18 % of May-September summer flow--120-180 B gallons) have been retreating in response to observed warming and changes in precipitation. Estimates of total loss of glacial area in the Skagit Basin since 1900 are on the order of 50%. Glacial retreat has been more rapid on the wetter western side of the Skagit River Basin than on the more arid eastern side. Projected warming for the 21<sup>st</sup> century is likely to accelerate glacier retreat, resulting in exacerbated summer low flows (particularly during droughts) and higher summer water temperature in watersheds with significant glacial coverage.

### 4.1 Background

Globally, glaciers are an important natural water resource, providing water for agriculture, water supply, hydropower generation, recreation, and fish flow augmentation, particularly during warm and dry periods (Barry, 2006; Moore et al., 2009; Pelto, 2010). Glaciers fluctuate depending on the amount of snowfall (accumulation) and the amount of snow and ice lost by melting and sublimation (called ablation) (Myrna et al., 2003). When the ablation exceeds accumulation, a glacier is said to have negative mass balance and the glacier decreases in mass and volume. Changes in atmospheric conditions such as precipitation, wind, temperature, radiation fluxes, and cloud cover affect the surface energy, mass balance, and terminus (or end) location of a glacier (Zemp et al., 2006 & 2009). Glacial ice also gradually moves downslope to the terminus of the glacier. Below the terminus, all snow and transported ice mass from higher elevations melts

each year. Unlike animals and plants, glaciers are not capable of adaptation to mitigate the impacts of climate change; they react physically to the surrounding conditions (Hall and Fagre, 2003). Thus, mountain glaciers provide some of the most tangible evidence of climate change and are essential variables for early detection strategies in global climate related observation (Hall and Fagre, 2003; WGMS, 2008; Barry, 2006).

The mass balance of a number of glaciers has been monitored since the mid-20<sup>th</sup> century. These observations provide direct evidence of climate change effects without any time lag (Josberger et al., 2007; Pelto and Riedel, 2001; Krimmel, 1999; Moore et al., 2009; WGMS, 2008; Zemp et al., 2006; Pelto, 2010). However, most of the mass balance observations do not have long records available. Only about 20% of world's glacial mass balance observations have continuous records more than 20 years long (Dyurgerov and Meier, 1997; Barry, 2006). The longest continuous record of glacial mass balance is for the period from 1946 to present for Storglaciären, Sweden (Dyurgerov and Meier, 1997). Several glaciers in the North Cascades have relatively long mass balance records, and long-term monitoring in the region has provided a rich data resource for the Pacific North West. Sound Cascade Glacier has been monitored by the USGS since 1957 (55 years at the time of this writing), for example, and the North Cascade Glacier Climate Project (NCGCP) has monitored 3 glaciers for 31 years. The National Park Service has monitored three glaciers for 19 years.

The terminus behavior of glaciers (i.e. changes in the location of the lower end of the glacier), by comparison, is an indirect and delayed proxy for climate change signals but generally has much longer records available (Barry, 2006). In comparison with mass change measurements (reported in cubic meters of water lost or as thickness averaged over the entire area of the glacier), the location of the terminus of the glacier is relatively easy to monitor. So, changes in the length of the glacier are most commonly used to monitor the response to climate change (Pelto and Hedlund, 2001; Oerlemans, 1994).

Glaciers are influenced not only by climate variables such as temperature and precipitation but also by regional factors such as topography and geography (Huybers and Roe, 2009). Therefore,

it is important to review how glaciers have historically responded to climate change at both global and regional scales.

## 4.2 Global glacier changes

Worldwide collection of information about ongoing glacier changes was initiated as early as 1894, in some cases (WGMS, 2008). International glacier monitoring has produced some 36,000 length change observations for 1,800 glaciers and about 3,400 mass balance measurements for about 300 glaciers (IPCC, 2007; WGMS, 2008). The observations are located around the world but most (90%) are located in the Northern Hemisphere (NH) and many of these (40% of the NH observations) are in Europe (Zemp et al., 2009). Figure 4.1 shows glacier length changes since the late 19<sup>th</sup> century for about 1800 glaciers worldwide (WGMS, 2008).

The length change observations show that glaciers have been retreating since the end of the Little Ice Age that lasted from about 1550 to 1850 in North America (Mann, 2002; Hall and Fagre, 2003). Within this general trend, glacial extent has fluctuated in response to climate variability; strong glacier retreats were observed in the 1940s and 1950s, followed by stable or advancing conditions until the end of the 1970s, followed by rapid rates of ice loss since the mid-1980s (WGMS, 2008). Though there are some deviations from these global trends such as the advance of glaciers in coastal Scandinavia (in Atlantic) and the New Zealand (in the Southern Hemisphere) during the 1990s (See Figures 4.1 and 4.2), smoothed mean terminus data averaged over large regions back to 1700, based on 169 glacier length records compiled by Oerlemans (2005) shows unambiguous declines since about 1850 as shown in Figure 4.2 (IPCC, 2007).

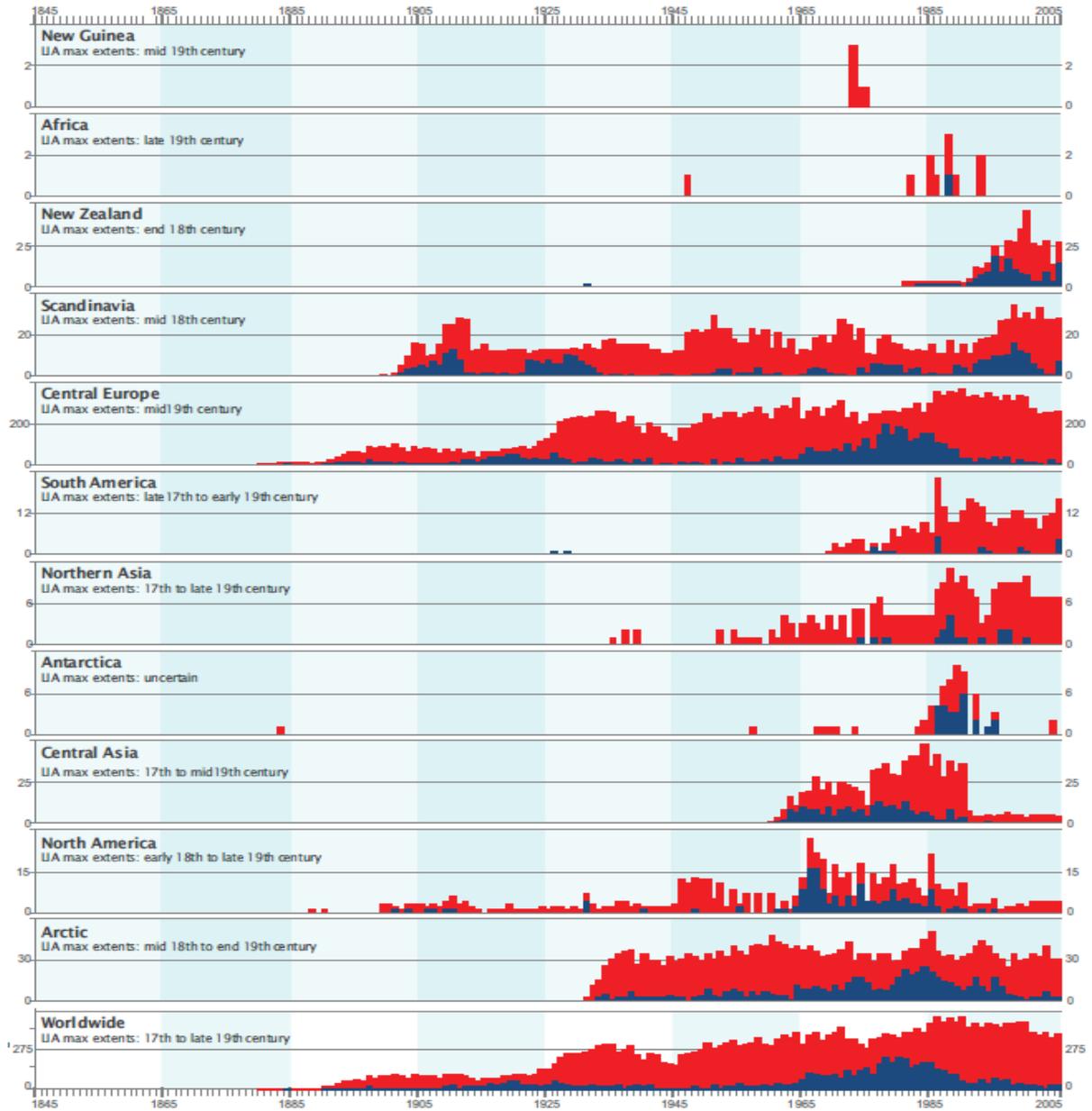


Figure 4.1 Glacier length changes - Temporal overview on short-term glacier length changes. The number of advancing (blue) and retreating (red) glaciers are plotted as stacked columns in the corresponding survey year. Note that the scaling of the number of glaciers on the y-axis changes between the regions (Source: WGMS, 2008).

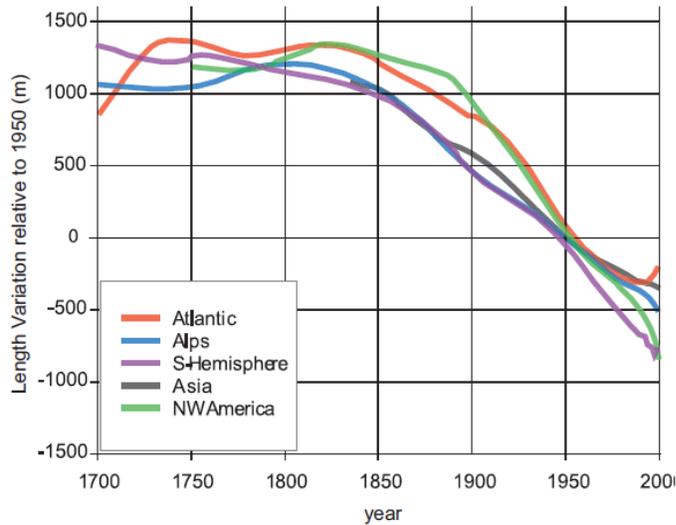


Figure 4.2 Large-scale regional mean length variations of glacier tongues. Glaciers are grouped into the following regional classes: SH (tropics, New Zealand, Patagonia), Northwest America (mainly Canadian Rockies), Atlantic (South Greenland, Iceland, Jan Mayen, Svalbard, Scandinavia), European Alps and Asia (Caucasus and central Asia) (Source: IPCC, 2007).

Seasonal and annual mass balance data from 228 glaciers around the globe have been collected since 1946 by the World Glacier Monitoring Service (WGMS) (IPCC, 2007; WGMS, 2008). Of these glaciers, only 30 which have ongoing and continuous date series since 1976 were used for reference glaciers by the WGMS (WGMS, 2008; Zemp et al., 2009). Glaciologists often express the change in a glacier’s mass in terms of the “specific mass balance”, which is the total change in ice mass divided by the surface area of the glacier (units in  $\text{kg m}^{-2}$ ) or meters of water equivalent (m w.e.) (Note 1 m w.e. =  $1000 \text{ kg m}^{-2}$ ) (WGMS, 2008). Thus, the mass changes in different glaciers of any size and elevation range can be directly compared using the specific mass balance, and runoff can be easily calculated by multiplying the specific mass balance with the corresponding glacier area (WGMS, 2008).

The cumulative specific mass balance curves for the mean of all glaciers and 30 ‘reference’ glaciers show that the mean specific mass balance was close to zero (near equilibration condition) around 1970, supporting the argument that the glacier mass loss in the late 20<sup>th</sup> century is related most strongly to post-1970 global warming (see Figure 4.3) (Rignot et al., 2003; Arendt et al., 2003; Meier et al., 2003; Greene, 2005; Haeberli et al. 2005; Barry, 2006; Zemp et al., 2006; Kaser et al., 2006; Pelto, 2006; IPCC, 2007).

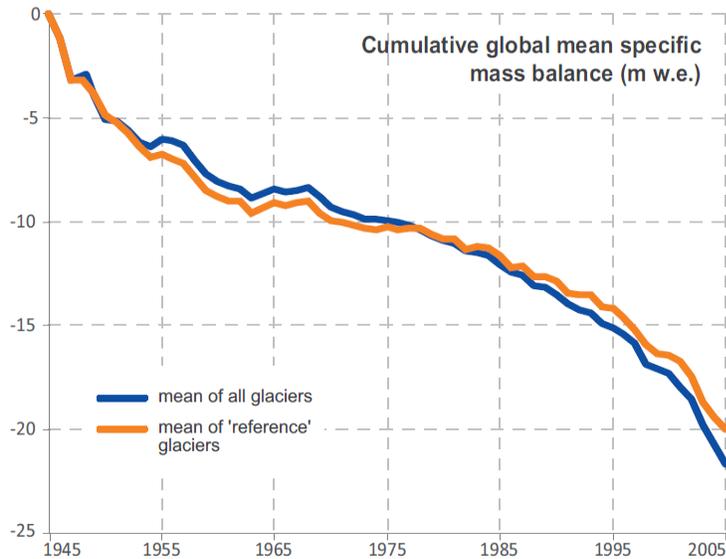


Figure 4.3 The cumulative specific mass balance curves are shown for the mean of all glaciers and 30 'reference' glaciers with (almost) continuous series since 1976 (Source: WGMS, 2008).

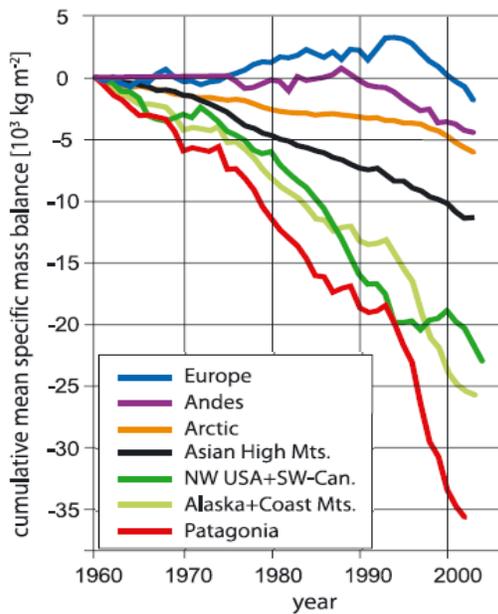


Figure 4.4 Cumulative specific mass balances of glaciers and ice caps since 1960, calculated for large regions [Dyurgerov and Meier, 2005]. Specific mass balances signalize the strength of the glacier response to climatic change in each region (Source: Kaser et al., 2006).

Dyurgerov and Meier (2005) combined individual mass balance values into averages for large regions which were weighted by the surface area of each glacier (Figure 4.4). Generally,

negative trends in area-weighted specific mass balance were observed for all of the regions except Europe. The most markedly negative mass balance values were observed for Patagonia, Alaska and Northwest U.S. and Southwest Canada until the early 1990s (Kaser et al., 2006; IPCC, 2007). Thereafter, greatly accelerated loss rates in Patagonia and Alaska were observed, while modest mass gain was observed for Northwest U.S. and Southwest Canada in the late 1990s to early 2000s (Dyurgerov and Meier, 2005; Kaser et al., 2006; IPCC, 2007). For glaciers in the European Alps regional mass gains were observed in the late 1970s to early 1980s and the early 1990s (Figure 4.4).

### 4.3 Glacial changes in the Skagit Basin and North Cascades

Since the importance of monitoring glacier behavior was acknowledged during the International Geophysical Year in 1957 (Pelto, 2008a), the U.S. Geological Survey has been studying South Cascade Glacier as one of several benchmark glaciers (Krimmel, 1999; Bidlake et al., 2005; Moore et al., 2009). Because a single glacier cannot represent the behavior of all glaciers in response to climate change (Fountain et al., 1991 & 2009), the North Cascade Glacier Climate Project (NCGCP) has been monitoring more than 10 representative glaciers in the North Cascade Range since 1983 (see Figure 4.5) (Pelto, 2006 & 2008a). Beginning in 1993, the National Park Service (NPS) began long-term monitoring of seasonal mass balance on four glaciers in North Cascades National Park Complex (NOCA), which is the crest of the northern section of the North Cascade Range and includes parts of the Skagit River Basin (see Figure 4.6) (Pelto and Riedel, 2001; Granshaw and Fountain, 2006; Riedel et. al., 2008; Riedel and Larrabee, 2011). NPS mass balance monitoring focuses on representative four glaciers out of 394 glaciers in the Skagit River Basin (Granshaw and Fountain, 2006; Riedel et. al., 2008; Post et al., 1971) and follows typical methods in estimating annual net mass balance by summing winter accumulation (mass gained) and summer ablation (mass lost) (discussed below). On the other hand, the study of glaciers by NCGCP measures the residual snow left on a glacier at the end of summer to assess mass balance. This approach is somewhat different from the method discussed above, but is valuable because it covers spatially wider range in the region and temporally longer data set. Therefore we introduce both glacial studies conducted by NCGCP and NPS.

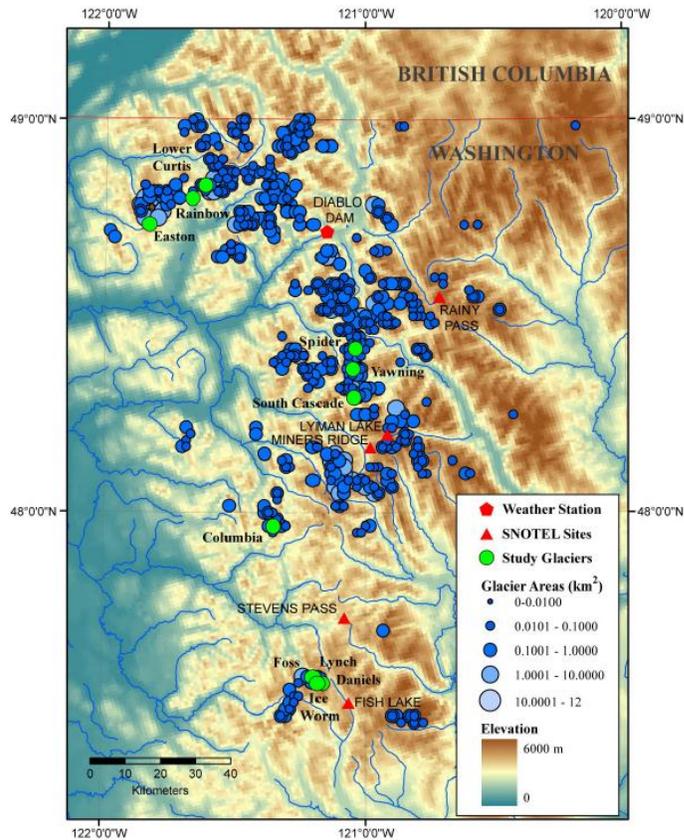


Figure 4.5 Location map of North Cascade glaciers (Source: Pelto, 2006)

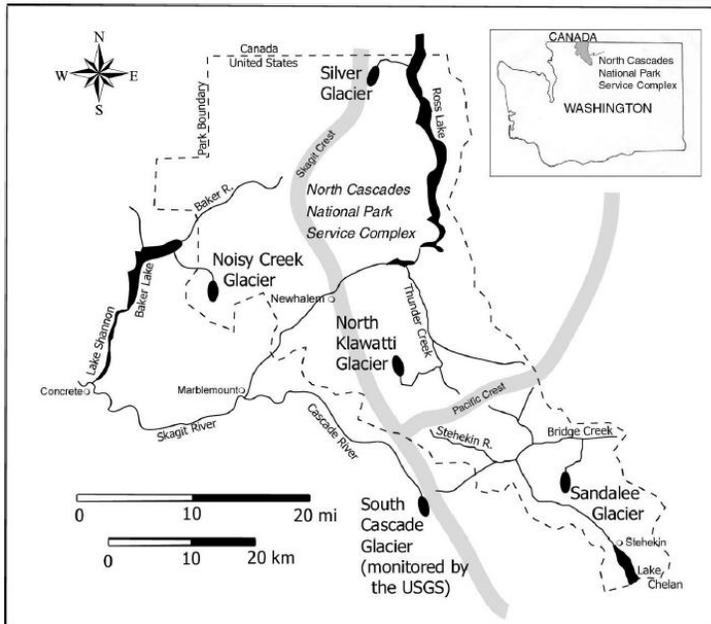


Figure 4.6 Locations of monitored glaciers and major hydrologic crests in the North Cascades National Park Complex (Source: Riedel et. al., 2008)

### 4.3.1 Glaciers monitored by NCGCP

Following the global patterns discussed above, North Cascade glaciers have generally retreated since the end of the Little Ice Age, though glacier retreat has also fluctuated from decade to decade in response to climate variability (Pelto and Hedlund, 2001). Based on monitoring of the terminus location, three distinctive periods have been identified. Rapid retreat of North Cascade glaciers occurred between 1890 and 1944 due to a progressive temperature rise (Pelto and Hedlund, 2001; Burbank, 1981; Pelto, 2010). The average retreat of the 38 North Cascade glaciers monitored by NCGCP was 1215 m (Pelto and Hedlund, 2001). During the second period which began in 1945, many North Cascade glaciers and all 11 Mount Baker glaciers advanced in response to cooler and wetter weather (Pelto and Hedlund, 2001; Meier and Post, 1962; Pelto, 2006). The third period began in 1977, and rapid retreat from that date forward continues, due to a drier, warmer climate (Pelto and Hedlund, 2001; Pelto, 2010). For example, all 11 Mount Baker glaciers had receded by an average of 197 m by 1984 (Pelto and Hedlund, 2001). Thirty-five of the 47 North Cascade glaciers observed by NCGCP had retreated during 1979-1984 (Pelto and Hedlund, 2001) and, by 1992, a retreat was observed for all 47 glaciers (Pelto, 1993). A dramatic retreat was observed in the White Chuck glacier as shown in Figure 4.7. By 2003, the north branch of the White Chuck glacier was entirely gone. Since 1958, the White Chuck glacier has lost approximately 70% of its area (Pelto, 2009). By 2006, four of the monitored glaciers had disappeared entirely: David, Lewis, Spider and Milk Lake glaciers (Pelto, 2006). Milk Lake glacier in the North Cascades had melted away between 1988 and 1996, creating Milk Lake (see Figure 4.8).



Figure 4.7 White Chuck glacier, the North Cascades 1973 (left) and 2006 (right) from Glacier gap at the head of the north branch of the glacier. The north arm of White Chuck glacier was completely gone by 2003 (Source: Pelto, 2008b).



Figure 4.8 a) Milk Lake glacier in 1988 and b) Milk Lake in 2009 (Source: URL 1).

Table 4.1 Cumulative mass balance measured during 1984-2007 (Easton and Sholes glaciers during 1990-2007) and change in area extent of the 10 North Cascade glaciers monitored by NCGCP (data adapted from Pelto, 2008b).

Glacier	Cumulative Mass Balance (in meters in water equivalent)	Area in 1958 (km <sup>2</sup> )	Area in 2005 (km <sup>2</sup> )	% Areal Reduction 1958- 2005
Columbia	-12.7	1	0.9	10
Daniels	-14.4	0.5	0.35	30
Easton	-10.5	2.9	2.7	7
Foss	-12.4	0.5	0.2	60
Ice Worm	-15.8	0.1	0.06	40
Lower Curtis	-13.0	0.8	0.7	13
Lynch	-10.4	1	0.6	40
Rainbow	-8.8	1.9	1.7	11
Sholes	-11.5	0.9	0.8	11
Yawning	-13.3	0.2	0.16	20

Table 4.1 shows cumulative mass balance for the 10 North Cascade glaciers monitored by NCGCP. Substantial mass loss has occurred in Ice Worm glacier since 1984. The largest area reduction since 1958 was observed in Foss glacier. These two glaciers are recognized as endangered and are not expected to survive long in the current climate (Pelto, 2008a). As shown in Figure 4.9, the cumulative mean mass balance of the 10 glaciers from 1984-2006 was -12.28 m w.e., which is equal to a minimum of 14 m of glacier thickness lost. Considering that the

average thicknesses of North Cascade glaciers are between 30 and 60 m (Pelto and Hedlund, 2001), North Cascade glaciers have lost 20-40 % of their volume since 1984 (Pelto, 2008a). Some caution should be used in interpreting these results because this volume loss estimate is based on surface mass balance measurements which tend to underestimate overall changes in glacier mass and volume (personal communication with Jon Riedel).

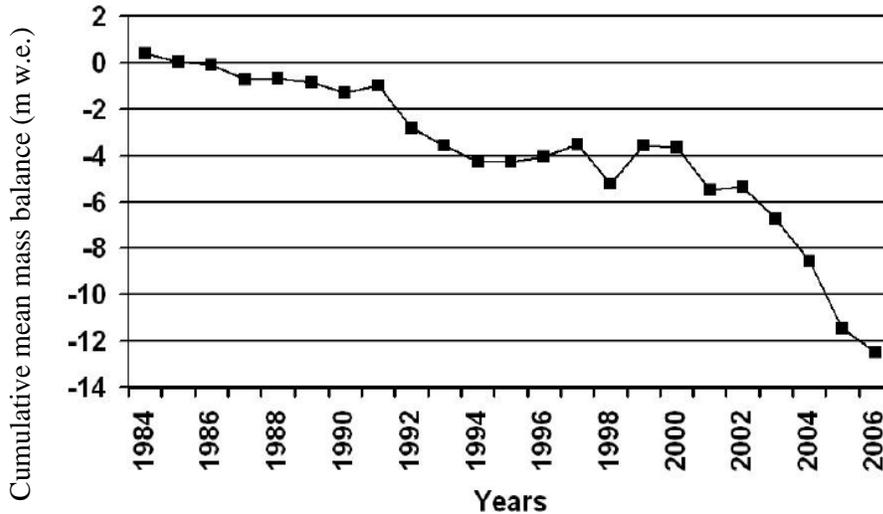


Figure 4.9 Cumulative mass balance record of North Cascade glaciers, 1984–2006, in meters of water equivalent. The increasingly negative trend is evident (Source: Pelto, 2008a).

Pelto (2010) also examined 12 glaciers in the North Cascades to forecast glacier survival based on accumulation zone observations. Based on this analysis, most of the glaciers except Easton, Rainbow and Yawning glaciers are out of equilibrium with current climate. Without a consistent accumulation zone these glaciers are predicted not to survive current climate or future warmer climate.

#### 4.3.2 Glaciers monitored by the National Park Service

In 1958, the North Cascades National Park Complex (NOCA) had 321 glaciers which covered approximately  $117.3 \pm 1.1 \text{ km}^2$ . By 1998, the total glacier population had decreased to 316 (loss of 5) and the total glacier area had reduced to  $109.1 \pm 1.1 \text{ km}^2$ , a reduction of  $8.2 \pm 0.1 \text{ km}^2$  (7 %) (Granshaw and Fountain, 2006), and unpublished estimates of total loss of glacial area in the

Skagit Basin since 1900 are on the order of 50% (personal communication Jon Riedel). The volume of melt water from the net glacier mass loss over the 40 years was estimated to  $0.8 \pm 0.1$  km<sup>3</sup> of ice which contributes up to 6 % of the late summer (August –September) streamflow of the four watersheds in NOCA such as Thunder Creek, Stehekin River, Cascade River and Newhalem Creek (Granshaw, 2002; Granshaw and Fountain, 2006).

Four representative glaciers in NOCA were monitored by the National Park Service since 1993: Noisy Creek, Silver Creek, and North Klawatti Glaciers in the Skagit River Basin and one glacier outside of the Skagit Basin, Sandalee Glacier as shown in Figure 4.6. The National Park Service has estimated annual net mass balance of four NOCA glaciers (see Figure 4.10) (Riedel et al., 2008; Riedel and Larrabee, 2011). Generally, the four NOCA glaciers have shown a negative long-term trend in response to climate change, although the glacier net mass balance at NOCA has fluctuated in response to climate variability. For example, 5 out of 7 water years had positive mass balance between water years 1996 and 2002 in response to the last cool phase of the Pacific Decadal Oscillation (PDO), although the volume gains were modest and glaciers did not advance (Riedel and Larrabee, 2011). After a short period of positive mass balance, all four NOCA glaciers have resumed a consecutive negative net mass balance (Figure 4.10).

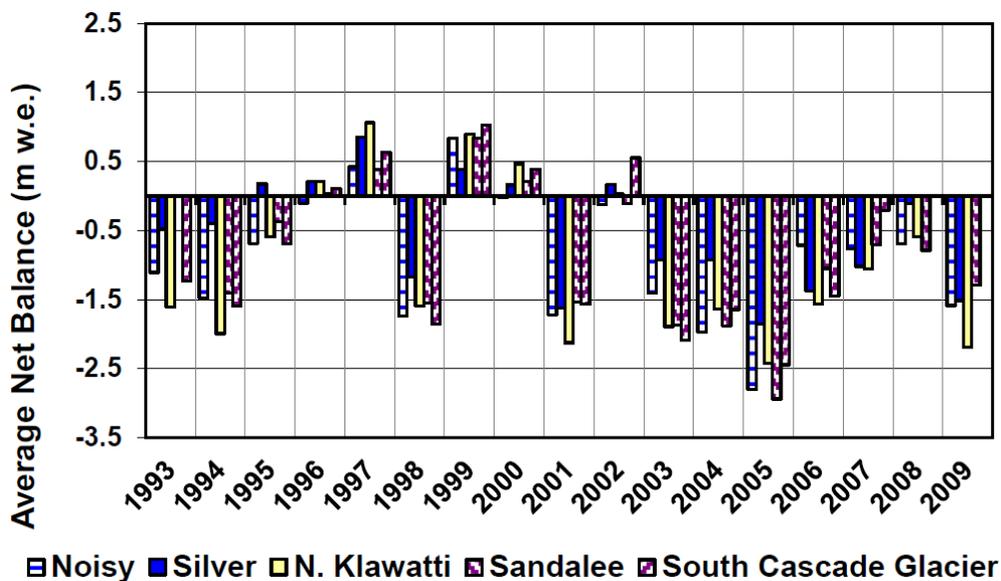


Figure 4.10 Net annual mass balances comparison for four glaciers monitored by NPS and South Cascade Glacier monitored by USGS (Source: Riedel and Larrabee, 2011).

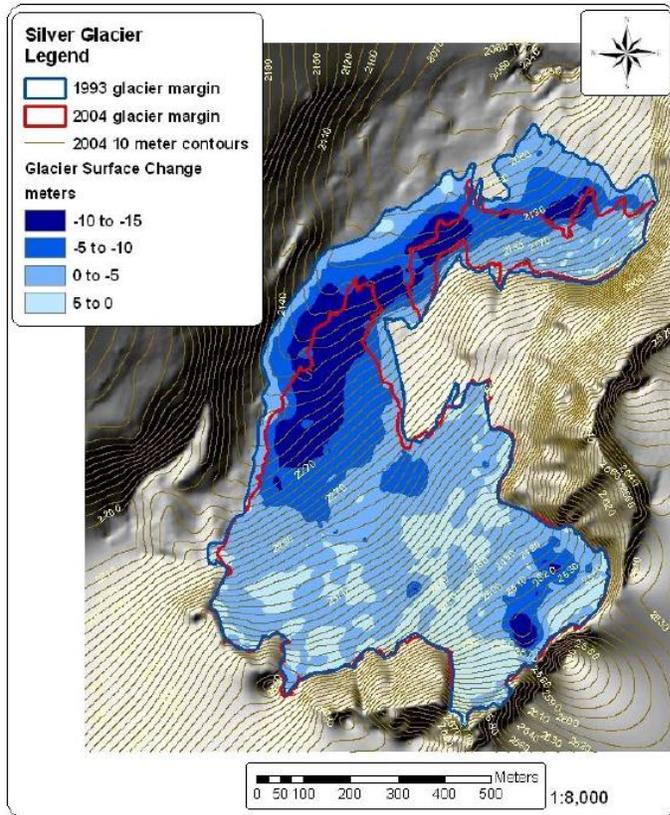


Figure 4.11 Silver Glacier comparison of 1993 adjusted reference map and 2004/2005 balance map. Glacier surface elevation change is the difference between the 1993 surface (photogrammetry) and 2004/2005 surfaces from photogrammetry and GPS (Source: Riedel and Larrabee, 2011).

National Park Service has been remapping the NOCA glaciers after ~10 years to assess area changes, advance/retreat of termini, surface elevation/volume changes and recalculated mass balance based on updated maps to provide more accurate and consistent mass balance results (Riedel and Larrabee, 2011). Updated maps were created for Silver and Sandalee glaciers in 2009 (Figure 4.11) and used to adjust mass balance of Silver and Sundalee glaciers for water years 2001-2009 (Figure 4.12). New maps for North Klawatti and Noisy glaciers will be finalized in 2011 (Riedel and Larrabee, 2011). Comparison of old and new maps (or photos) illustrates that the glacial area in NOCA has declined due to observed warming and precipitation change and that most of the loss occurred in the ablation zone (Riedel and Larrabee, 2011). For instance, comparison of 1993 adjusted reference map and 2004/2005 balance map for Silver Glacier illustrated that the area of Silver Glacier decreased 16 % and Silver Glacier has lost as

much as 15 m in depth near its terminus (Figure 4.11) (Riedel and Larrabee, 2011). Photos of Silver Glacier taken in 1958 and 2006 (Figure 4.12) show extensive loss of ice mass on the slopes feeding the lake and an enlargement of the lake area. Furthermore, comparison with an earlier map from 1913 shows that ice that completely covered the current location of the lake in the early 20<sup>th</sup> century had essentially disappeared by 1958 (Jon Riedel, personal communication).



Figure 4.12 View to the west of Silver Glacier in 1958 (left, by Post) and 2006 (right, by Scurlock) (Source: URL 2).

The cumulative balance for the four NOCA glaciers has been negative although there were slight volume increases between 1996 and 2002 (Figure 4.13) (Riedel and Larrabee, 2011). After a short period of slight volume increase, the negative cumulative balance trend was strengthened due to the seven consecutive years of negative net mass balance for all four glaciers. In general, large glaciers on the wetter west side of NOCA such as Noisy and North Klawatti Glaciers show more negative cumulative balance in comparison with those on the more arid eastern part of the park such as Silver and Sandalee Glaciers (Riedel and Larrabee, 2011). This is due to the fact that the eastern glaciers are relatively small, exist at higher elevations and receive solar shading from nearby mountains (Riedel and Larrabee, 2011). In water year 2009, cumulative net mass balance was most negative for North Klawatti Glacier ( $-16.7$  m w.e.) and least for Silver Glacier ( $-9.5$  m w.e.) (see Figure 4.13). Between water years 1993 to 2009, the average annual melt rate

for all four NOCA glaciers has increased by about 12 % (1 m w.e.) (Figure 4.14), increasing glacial contribution to summer (May – September) runoff (Granshaw and Fountain, 2006). In the Thunder Creek watershed, the most heavily glaciated basin in the North Cascades (Chennault, 2004), North Klawatti Glacier contributed about 32 % of total summer (May-September) streamflow, while in the more arid, less glaciated Ross Lake basin Silver Glacier provided about 6 % of total summer streamflow (Riedel and Larrabee, 2011). Glacier contribution to summer runoff on the Skagit River Basin is about 12-18 % (120-180 B gallons) (personal communication Jon Riedel).

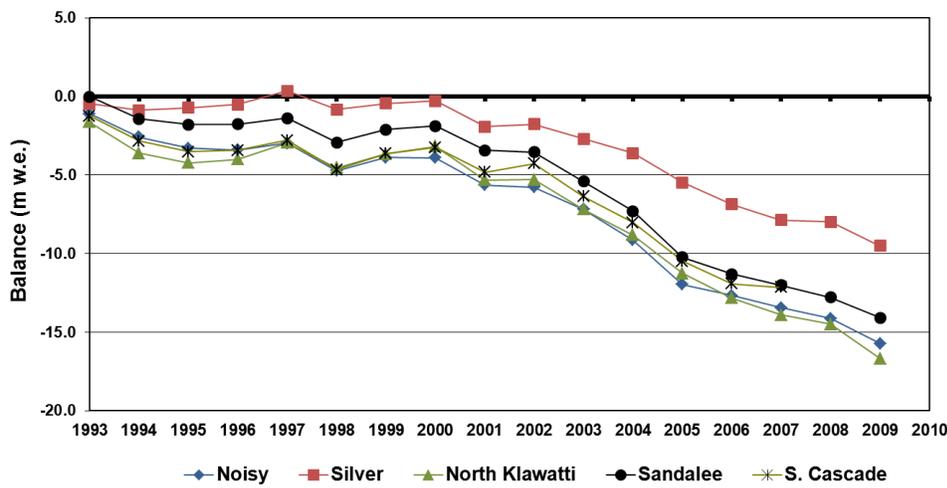


Figure 4.13 Cumulative mass balances for four glaciers monitored by NPS and South Cascade Glacier monitored by USGS. Silver and Sundalee glacier curves are map-adjusted (Source: Riedel and Larrabee, 2011).

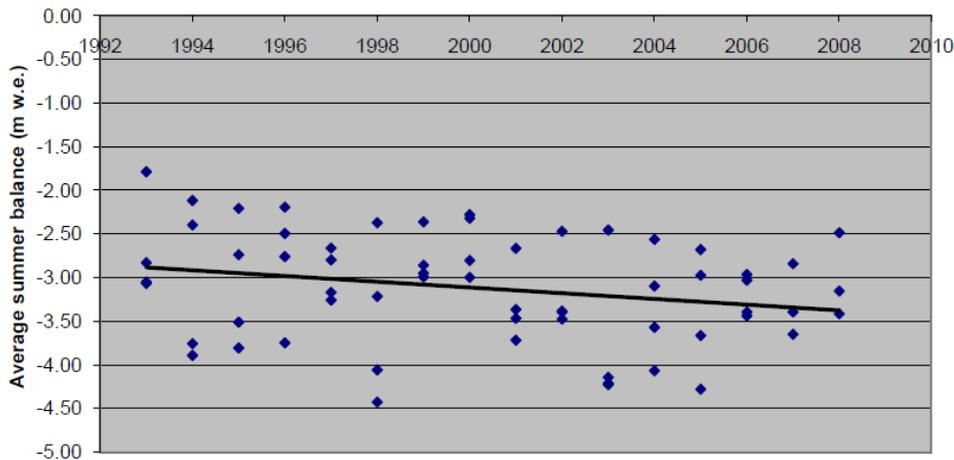


Figure 4.14 Average summer balance (ablation) from 1993 to 2009 (Source: URL 2).

Chennault (2004) evaluated the impact of projected future climate change on glacial hydrology in Thunder Creek using the Distributed Hydrology Soils Vegetation Model (DHSVM). The glacier coverage of Thunder Creek watershed had dropped from about 22.5 % to 12.8 % between the Little Ice Age (1850) and 1998 (Figure 4.15) (Chennault, 2004). Based on the glacier retreat rate from the Little Ice Age to 1998, a decrease to 7.1 % glacier coverage is expected by 2100 and could result in a 31% decline in late summer streamflow in Thunder Creek (Chennault, 2004).

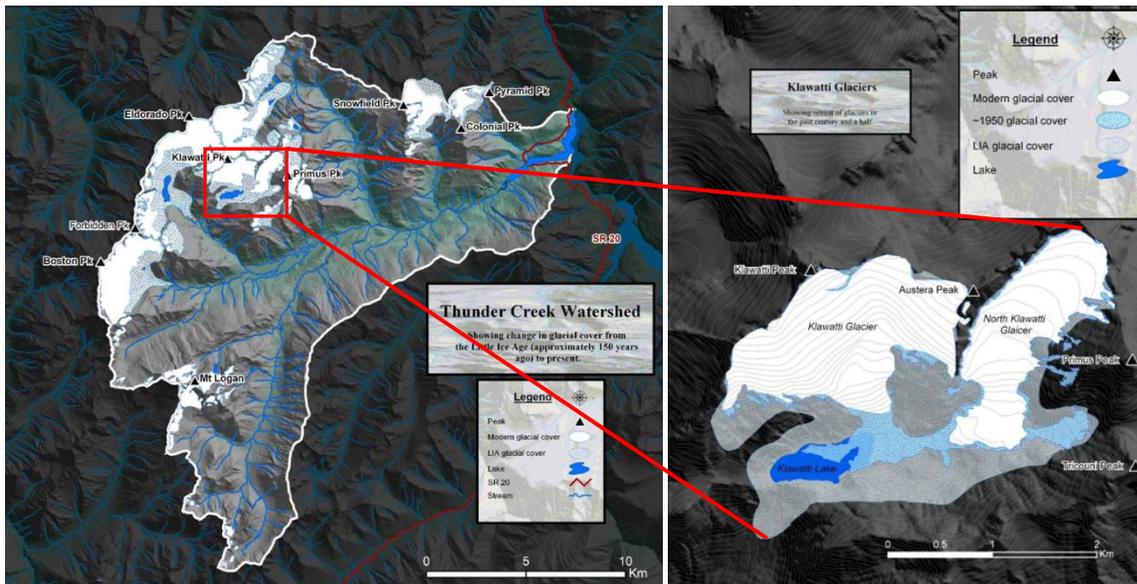


Figure 4.15 Glacier area changes in Thunder Creek watershed (left) and in the Klawatti glaciers since the Little Ice Age (Source: URL 2)

The shrinking or disappearance of glaciers and the resulting decrease in glacial contribution to summer runoff influence hydropower generation, instream flow augmentation in late summer, sediment and nutrient loadings, and water temperature. These impacts may in turn create socioeconomic impacts related to municipal and industrial water supply, agriculture, energy supply, fluvial and marine ecosystems, recreation, and tourism (Fountain and Tangborn, 1985; Granshaw and Fountain, 2006; Mantua et al., 2010). The disappearance or shrinkage of glaciers is expected to exacerbate reductions in annual minimum flows and projected increases in water temperature due to warmer air temperature, impacting cold water fish such as salmon and bull trout (Mantua et al., 2010).

## 4.4 Summary and Conclusions

Glacier retreat and mass losses occurred locally, as well as globally and regionally have accelerated in response to post-1970 global warming and are projected to continue in response to global climate change. The changes in summer melt in the Skagit Basin are likely to influence water resources management of hydropower generation, agriculture, and instream flow augmentation in the region during the summer months. The disappearance or shrinkage of glaciers is expected to exacerbate summer low flow and result in warmer water temperatures, impacting cold-water fish in the Skagit basin such as salmon and bull trout in headwater streams. Key findings are summarized below:

- Worldwide records of glacier length changes and mass balance measurements show that glaciers have been generally retreating since the end of the Little Ice Age (~1550-1850) but rates of glacier changes have fluctuated corresponding to climate variability; strong glacier retreats were observed in the 1940s and 1950s, followed by stable or advancing conditions until the end of the 1970s, and then rapid rates of ice loss since the mid 1980s.
- Glacier recession rates have increased due to rapid global warming since the 1970s, although different regions have shown somewhat different rates of change. Mass losses per unit area were strongest for Patagonia, followed by Alaska and U.S. and Canada. Unlike the other regions, glaciers in the European Alps showed small regional mass gains mostly due to increased precipitation. Similar effects were observed for glaciers in coastal Scandinavia and New Zealand.
- Following global trends, North Cascades glaciers have been retreating, although glaciers in the North Cascades have also fluctuated in response to the 20<sup>th</sup> century climate variability. Rapid retreat occurred between 1890 and 1944, glaciers slightly advanced from 1945 to 1976 and then have again retreated rapidly since about 1977.
- Based on 1958 and 1998 inventories, reductions of the glacier population (loss of 5) and area ( $8.2 \pm 0.1 \text{ km}^2$ ) were observed in the North Cascades National Park Complex (NOCA). The estimated volume loss for the same periods was  $0.8 \pm 0.1 \text{ km}^3$  of ice which contributes up to 6 % of the late summer (August –September) runoff.

- Glaciers in the Skagit River Basin have also shown a strongly negative long-term trend corresponding to climate change since monitoring began in 1957 on South Cascade Glacier. This trend was slowed by cool-wet periods in 1970-76 and 1996-2002 in response to climate variability (the cool phase of the PDO). Estimates of total loss of glacial area in the Skagit Basin since 1900 are on the order of 50%.
- More rapid losses of glacial resources were observed on the wetter west side of the Skagit Basin such as Noisy and North Klawatti Glaciers than on the more arid east side of the park such as Silver Glacier: cumulative net mass balance was most negative for North Klawatti Glacier (– 16.7 m w.e.) and least for Silver Glacier (-9.5 m w.e.). This is due to the fact that the eastern glaciers are relatively small, exist at higher elevations and receive solar shading from nearby mountains.
- Glacier contribution to summer (May-September) runoff on the Skagit River Basin is about 12-18 % (120-180 B gallons).
- All glaciers in the Skagit River Basin are expected to continue to decrease rapidly in volume. Ongoing losses of glacial ice and ice caps are projected to continue in response to the regional expressions of global climate change. Some glaciers in the North Cascades are already in disequilibrium with the current climate, and are expected not to survive either the current climate or future (warmer) climate.

URL1: [http://www.nichols.edu/departments/glacier/glacier\\_retreat.htm](http://www.nichols.edu/departments/glacier/glacier_retreat.htm)

URL2: <http://www.nps.gov/noca/naturescience/glacial-mass-balance8.htm>

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