

Impact of Climate Change on North Cascade Alpine Glaciers, and Alpine Runoff

Abstract

Analysis of key components of the alpine North Cascade hydrologic system indicate significant changes in glacier mass balance, terminus behavior, alpine snowpack, and alpine streamflow from 1950 to 2005. North Cascade glacier retreat is rapid and ubiquitous. All 47 monitored glaciers are currently undergoing a significant retreat and four of them have disappeared. Annual mass balance measured on ten glaciers, averaging 30-50 m in thickness, yields a mean cumulative annual balance for the 1984-2006 period of -12.4 m water equivalent (m we), a net loss of 14 m in glacier thickness and 20-40% loss of their total volume in two decades.

The data indicate broad regional continuity in North Cascades glacial response to climate. The substantial negative annual balances have accompanied significant thinning in the accumulation zone of 75% of North Cascade glaciers monitored. This is indicative of glacier disequilibrium; a glacier in disequilibrium will not survive the current warmer climate trend. Alpine snowpack snow water equivalent (SWE) on April 1 has declined 25% since 1946 at five USDA Snow Course sites. This decline has occurred in spite of a slight increase in winter precipitation. The combination of a decline in winter snowpack and a 0.6° increase in ablation season temperature, during the 1946-2005 period in the North Cascades, has altered alpine streamflow in six North Cascade basins. Observed changes in streamflow are: increased winter streamflow, slightly declining spring streamflow and a 27% decline in summer streamflow. Only in the heavily glaciated Thunder Creek Basin (> 10% glaciated) has summer streamflow declined less than 10%; this is attributable to enhanced glacier melting.

Introduction

Glaciers have been studied as sensitive indicators of climate for more than a century. Glacier behavior integrates water and energy balance factors exhibiting an enhanced climate change signal (IPCC 1996). The North Cascades, Washington extend from Snoqualmie Pass (47° N) north to the Canadian Border (49° N), and are host to 700 glaciers. These 700 glaciers cover 250 km² and yield 800 million m³ of runoff each summer (Post et al. 1971). The North Cascade Glacier Climate Project (NCGCP) was founded in 1983 to monitor glaciers throughout the North Cascade Range and identify the response of North Cascade glaciers to regional climate change. Annual balance measurements on 10 glaciers, periodic terminus surveys on 47 glaciers, and longitudinal profile mapping on twelve glaciers over a twenty-three year period have been completed. This monitoring effort has enabled the identification of consistent trends from glacier to glacier.

The North Cascades region experienced a substantial climate change beginning in 1976, to generally warmer conditions (Ebbesmeyer et al. 1991; Mote 2003). A climate warming of

0.6-0.9°C in mean annual temperature has been observed in the past century in the North Cascades (Kovanen 2003 and Mote 2003). A resultant decline in winter snowpack, due primarily to rising winter temperatures in the Pacific Northwest, has also been observed since 1976; the impact is most pronounced at lower elevations (Figure 1) (Mote 2003). Several climate models indicate that the Pacific Northwest will likely experience a 1.7-2.8°C temperature increase and 1-10 cm increase in winter precipitation during the early 21st century (Parson 2001). A portion of this warming has already placed some glaciers in jeopardy (Pelto and Hedlund 2001), reduced April 1 winter snowpack, and decreased summer alpine streamflow.

Glacier mass balance and terminus data from NCGCP, USDA Snow course, and SNOTEL data from eight stations, and USGS runoff records from six basins are utilized in this study to address the following questions: What is the current condition of North Cascade glaciers, and can most of the glaciers reach a new point of equilibrium with the current and forecasted future climate? How substantial has the change in alpine winter snowpack been? What has been the impact of changes in glacier annual balance and winter snowpack on alpine streamflow?

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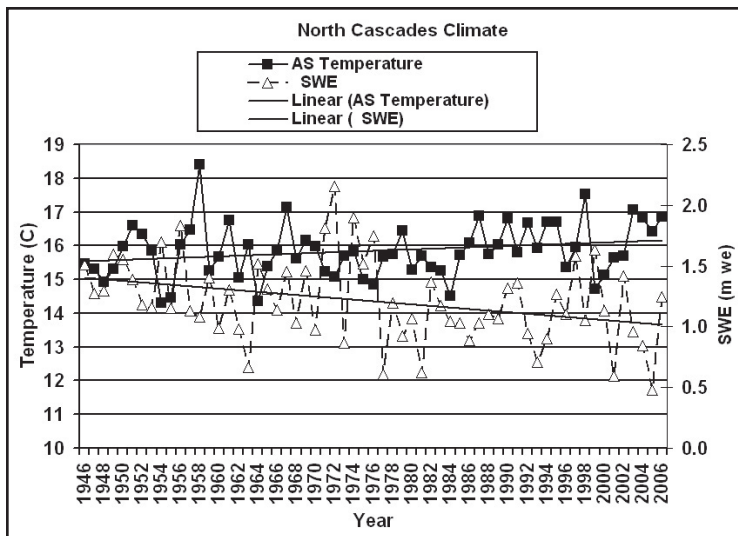


Figure 1. Mean ablation season temperature (June-September) at Diablo Dam (As), and April 1 snow water equivalent (SWE) at five USDA SNOTEL sites (Rainy Pass, Stevens Pass, Harts Pass, Miners Ridge and Fish Lake).

Climate

The North Cascade region has a temperate maritime climate. Approximately 80% of the region's precipitation occurs during the accumulation season (October-April) when the North Cascades are on the receiving end of the Pacific storm track. Moisture-rich Pacific cyclonic systems travel northeasterly into the region; these fronts are slowed by the Cascades and produce low intensity but frequent and lengthy orographic precipitation events (Schermerhorn 1967). Occasionally the warm fronts elevate temperatures, leading to rainfall and rapid snowmelt resulting in potential winter season flooding. From late spring to early fall, high pressure to the west keeps the Pacific Northwest comparatively dry. These seasonal variations in climate are related to changes in large-scale atmospheric circulation occurring over the Pacific Ocean, including the Gulf of Alaska.

Climate west of the Cascade Crest is temperate with mild year-round temperatures, abundant winter precipitation, and dry summers. Average annual precipitation in the North Cascades typically exceeds 200 cm west of the divide. Climate east of the Cascade Crest is more continental, creating a sharp contrast with the maritime climate west of the Cascade Crest (Mote 2003).

Two changes in atmospheric circulation have been noted for the region. In particular, during

winter, southwesterly air flow has been more prevalent since 1977 (Trenberth 1990; Vaccaro 2002). The increased southwesterly flow has produced more frequent warm winter cyclonic air masses and more frequent winter rain events (Moore and McKendry 1995). During summer, more persistent anti-cyclonic systems are associated with a stable high pressure ridge over the Pacific Northwest and weak airflow off the Pacific Ocean (Vaccaro 2002). Both of these changes reflect the general long term trend of a positive Pacific Decadal Oscillation (PDO).

The PDO Index is the leading principal component of North Pacific monthly sea surface temperature variability (poleward of 20N for the 1900-93 period) (Mantua et al. 1997). During the positive PDO phase warm weather is favored in the Pacific along the northwest coast and over the Pacific Northwest. During the negative phase ocean water off the northwest coast is cooler and cooler temperatures prevail across the Pacific Northwest (Mantua et al. 1997). In the past century: "cool" PDO regimes prevailed from 1890-1924 and again from 1947-1976, while "warm" PDO regimes dominated from 1925-1946 and from 1977 through the present (Mantua et al. 1997). It was postulated in the late 1990's that a negative PDO phase may have been starting, however this has not transpired (Gedalof and Smith 2001). We have continued to have a dominantly positive PDO through 2006, which yields warmer conditions in the North Cascades

Glacier Mass Balance

Mass balance is a more valuable indicator of climate than terminus change over short time periods because mass balance is a direct measure of annual climate conditions, while terminus behavior is determined by the cumulative impact of climate and other glaciologic factors over many years. Surface mass balance is the difference between accumulation of water in winter and loss of water by ablation in summer. It is typically measured on a water year basis, beginning October 1 and end-

TABLE 1. The geographic characteristics of the nine glaciers where annual balance has been monitored annually (Figure 2). Accumulation sources: wind drifting = WD, avalanche accumulation = AV, direct snowfall = DS.

Glacier	Aspect	Area (km ²)	Accumulation	To Divide	Elevation (m)
Columbia	SSE	0.9	DS, DW, AV	15 km west	1750-1450
Daniels	E	0.4	DS, WD	1 km east	2230-1970
Easton	SSE	2.9	DS	75 km west	2900-1700
Foss	NE	0.4	DS	At divide	2100-1840
Ice Worm	SE	0.1	DS, AV	1 km east	2100-1900
Lower Curtis	S	0.8	DS,WD	55 km west	1850-1460
Lynch	N	0.7	DS,WD	At divide	2200-1950
Rainbow	ENE	1.6	DS,AV	70 km west	2040-1310
Sholes	N	0.9	DS	70 km west	2070-1630
Yawning	N	0.2	DS	At divide	2100-1880

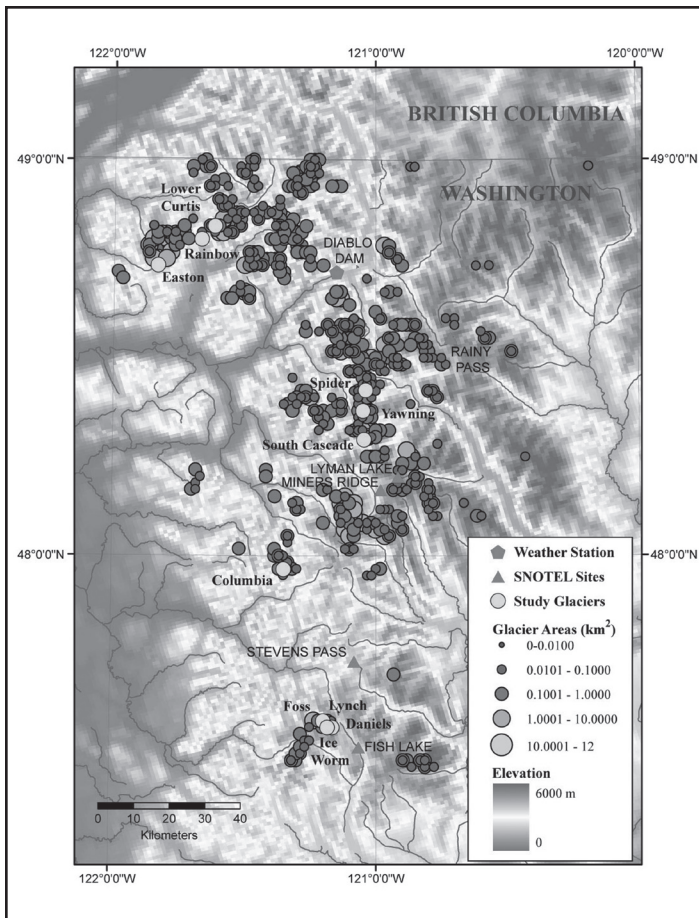


Figure 2. Map of North Cascade glaciers indicating the location of glaciers where mass balance is measured, SNOTEL stations with long term SWE records and weather stations utilized in this study.

ing September 30. Annual balance is defined as the change observed annually on a glacier's surface on a specific date (Mayo et al. 1972).

Since 1984, NCGCP has monitored the annual balance of eight glaciers, with two additional glaciers added in 1990 (Pelto 1996, 1997; Pelto and Riedel 2001). The glaciers represent a range of geographic characteristics and span the North Cascade Range (Table 1 and Figure 2). Key geographic variables are orientation of the glacier, mean elevation, accumulation sources and distance to the mountain ranges watershed and climate divide. NCGCP methods emphasize surface mass balance measurements with a comparatively high measurement density on each glacier, consistent measurement methods, and fixed measurement locations. The methods are reviewed in detail by Pelto (1996, 1997) and Pelto and Riedel (2001). The average density of measurements NCGCP utilizes in the accumulation zone of each glacier ranges from 180-300 points/km² (Pelto 1996; Pelto and Riedel 2001). Measurements are completed at the same time each year in late July and again in late September near the end of the abla-

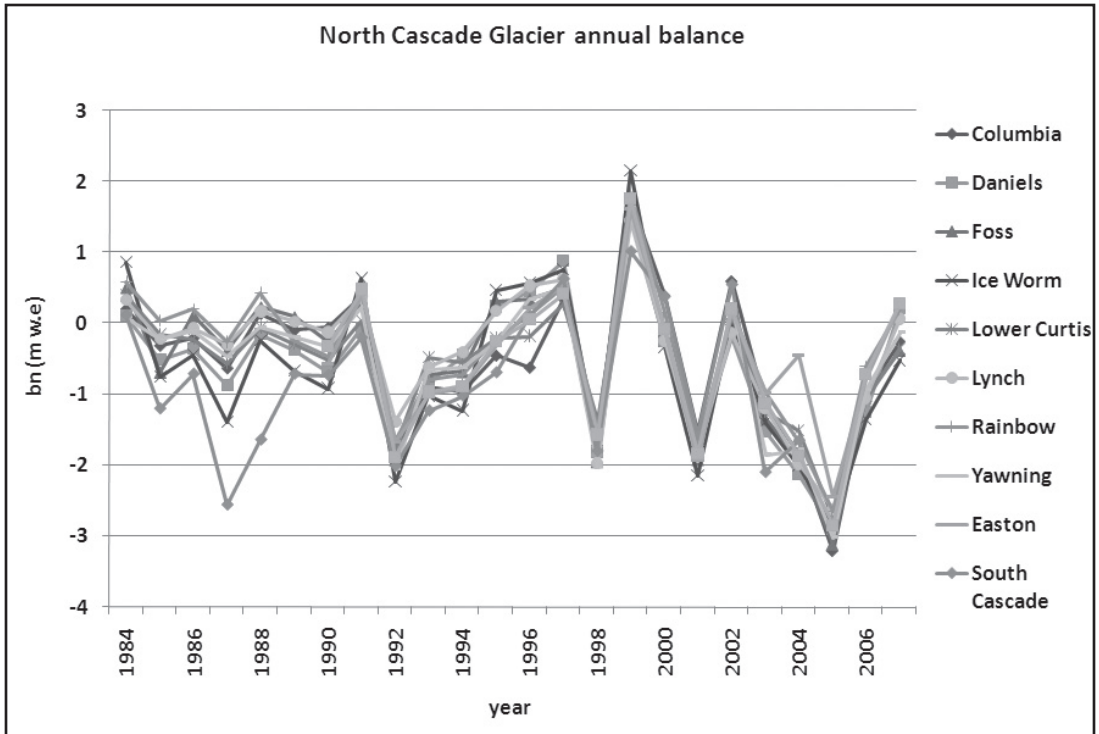


Figure 3. Annual balance records on ten North Cascade glaciers. South Cascade Glacier mass balance data is from the USGS (Bidlake, et al., 2007; Krimmel, 2001). In any given year the mean range from the most negative to the most positive glacier mass balance is 0.8 m. Because the response of each glacier to annual weather conditions is similar the year to year trend of glacier balance is similar causing the lines to overlap.

tion season. Ablation occurring after the last visit to the glacier is measured during the subsequent hydrologic year.

Glaciers in the North Cascades exhibit consistent responses to climate from year to year. Figure 3 illustrates the closely correlated pattern of annual mass balance fluctuations. In most years, all glaciers respond in step with each other to variations in winter precipitation and summer temperature. There is a mean annual range of 0.8 m in annual balance from the highest to the lowest annual balance in a given year, but the inter-annual trend is the same for each glacier. This regional response to climate is also indicated by the high cross correlation values of mass balance between individual glaciers ranging from $r^2 = 0.75$ to 0.99 (Table 2). The South Cascade Glacier monitored by the USGS is included and likewise has a high correlation coefficient (Krimmel 2001).

The mean annual balance has been -0.54 m/a for the 1984-2006 period on the eight glaciers monitored annually (Table 3). The mean cumulative

mass balance loss has been -12.4 m w.e, which is a minimum of 14.0 m of glacier thickness lost. North Cascade glacier average thickness ranges from 30-60 m (Post et al. 1971; Pelto and Hedlund 2001). Thus, 20-40% of the volume of these glaciers has been lost since 1984. Observations by the USGS at South Cascade Glacier indicate that since the mid-1950s, South Cascade Glacier has a cumulative mass balance loss of 25m; mean annual balance averaged -0.15 m/a from 1956-1975, and averaged -1.00 m/a from 1976-2003 (Krimmel 2001). The cumulative mass balance is trending more negatively, indicating that instead of approaching equilibrium as the glaciers retreat they are increasingly in disequilibrium with current climate (Figure 4).

Terminus Behavior

Since the maximum glacier advance during the Little Ice Age (LIA) there have been three climate changes in the North Cascades sufficiently large to substantially alter glacier terminus behavior.

TABLE 2. Cross-correlation of annual balance on North Cascade glaciers 1984-2005, except for Easton Glacier 1990-2005. South Cascade Glacier observed by the USGS, all other glaciers data from NCGCP.

	Columbia	Daniels	Easton	Foss	Ice Worm	Lower Curtis	Lynch	Rainbow	Sholes	Yawning
Daniels	0.90									
Easton	0.90	0.89								
Foss	0.94	0.97	0.93							
Ice Worm	0.89	0.95	0.93	0.94						
Lower Curtis	0.96	0.95	0.94	0.97	0.94					
Lynch	0.93	0.98	0.90	0.98	0.93	0.95				
Rainbow	0.96	0.94	0.95	0.97	0.98	0.98	0.96			
Sholes	0.94	0.96	0.94	0.98	0.97	0.98	0.97	0.97		
Yawning	0.97	0.95	0.94	0.98	0.97	0.98	0.96	0.99	0.98	
S.Cascade	0.85	0.84	0.89	0.82	0.87	0.81	0.79	0.81	0.85	0.92

TABLE 3. The annual and mean cumulative annual balance of the 10 North Cascade glaciers examined by the NCGCP and of the South Cascade Glacier observed by USGS (Bidlake et.al., 2007; Krimmel, 2001).

Glacier Year	Columbia NCGCP	Daniels NCGCP	Easton NCGCP	Foss NCGCP	I. Worm NCGCP	L. Curtis NCGCP	Lynch NCGCP	Rainbow NCGCP	Sholes NCGCP	Yawning NCGCP	SCascade NCGCP
1984	0.21	0.11		0.51	0.86	0.39	0.33	0.58		0.09	0.12
1985	-0.31	-0.51		-0.69	-0.75	-0.16	-0.22	0.04		-0.23	-1.20
1986	-0.20	-0.36		0.12	-0.45	-0.22	-0.07	0.20		-0.10	-0.61
1987	-0.63	-0.87		-0.38	-1.39	-0.56	-0.30	-0.26		-0.47	-2.06
1988	0.14	-0.15		0.23	-0.24	-0.06	0.17	0.43		-0.06	-1.34
1989	-0.09	-0.37		0.09	-0.67	-0.29	0.03	-0.24		-0.19	-0.91
1990	-0.06	-0.68	-0.58	-0.27	-0.92	-0.51	-0.12	-0.46	-0.32	-0.32	-0.11
1991	0.38	-0.07	0.41	0.30	0.63	0.04	0.36	0.44	0.48	0.23	0.07
1992	-1.85	-1.70	-1.67	-1.92	-2.23	-1.76	-1.38	-1.65	-1.88	-2.06	-2.01
1993	-0.90	-0.38	-1.01	-0.73	-1.02	-0.48	-0.62	-0.80	-0.96	-0.66	-1.23
1994	-0.96	-0.45	-0.92	-0.68	-1.23	-0.55	-0.40	-0.72	-0.88	-0.62	-1.60
1995	-0.45	0.24	-0.31	0.31	0.47	-0.21	0.18	-0.20	-0.25	-0.26	-0.69
1996	-0.62	0.45	0.22	0.34	0.57	-0.18	0.53	0.12	0.06	0.34	0.10
1997	0.35	0.88	0.53	0.50	0.76	0.27	0.62	0.51	0.42	0.50	0.63
1998	-1.46	-1.82	-1.87	-1.95	-1.64	-1.38	-1.97	-1.49	-1.56	-2.03	-1.60
1999	1.75	1.52	1.61	1.56	2.15	1.55	1.45	1.84	1.76	1.63	1.02
2000	0.40	-0.25	-0.10	-0.10	-0.33	-0.25	-0.24	0.15	-0.08	-0.18	0.38
2001	-1.52	-1.75	-1.93	-1.92	-2.15	-1.88	-1.82	-1.71	-1.83	-1.94	-1.57
2002	0.60	-0.18	0.18	0.10	0.05	0.13	-0.13	0.12	0.21	0.26	0.55
2003	-1.17	-1.52	-0.98	-1.35	-1.40	-1.25	-1.20	-0.98	-1.12	-1.85	-2.10
2004	-1.83	-2.13	-1.06	-1.94	-2.00	-1.51	-1.98	-1.67	-1.86	-1.78	-1.65
2005	-3.21	-2.90	-2.45	-3.12	-2.85	-2.75	-2.62	-2.65	-2.84	-3.02	-2.45
2006	-0.98	-1.25	-0.79	-1.02	-1.35	-1.06	-1.05	-0.61	-0.71	-0.93	

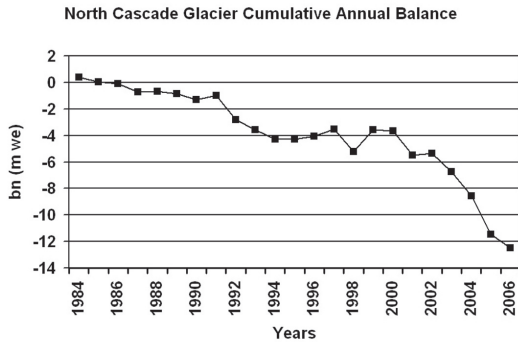


Figure 4. Cumulative annual balance record of North Cascade glaciers in meters of water equivalent, the trend is continuing to become more negative.

During the LIA mean annual temperatures were 1.0-1.5°C cooler than at present (Burbank 1981; Porter 1986). The lower temperatures in the North Cascades led to a snowline lowering of 100 to 150 m during the LIA (Porter 1986; Burbank 1981). North Cascade glaciers maintained advanced terminal positions from 1650-1890, emplacing one or several terminal moraines.

This first substantial climate change following the LIA 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). The average terminus retreat of glaciers on Mt. Baker from their LIA moraines to their 1950 positions was 1440 m. For 38 North Cascade glaciers monitored across the range the retreat over the same period was 1215 m (Pelto and Hedlund 2001).

The second substantial change in climate in the Northern Cascades began in 1944 when conditions became cooler and precipitation increased (Hubley 1956; Tangborn 1980). Hubley (1956) and Long (1956) noted that many North Cascade glaciers began to advance in the early 1950s, following 30 years of rapid retreat. All 11 Mount Baker glaciers advanced during this 1944-1975 period (Pelto 1993; Harper 1993).

The third climate change was towards warmer conditions that reduced April 1 snowpack, led to glacier retreat and prompted negative mass balances (Harper 1993; Krimmel 1994; Pelto 1993 and 2001). By 1984, all Mount Baker glaciers, which were advancing in 1975, were again retreating (Pelto 1993). The average retreat from 1984 to 2007 of Mount Baker glaciers is 340 m, and

ranges from 290-460 m. The NCGCP had been monitoring the terminus position of 47 glaciers from 1984-2007, all have retreated substantially. By 2004, four had disappeared: David Glacier, Lewis Glacier, Spider Glacier and Milk Lake Glacier; in each case no glacier ice mass exceeding 0.01 km² remains.

The 38 North Cascade glaciers where the terminus history has been determined for the 1890-1998 period exhibit one of three distinct behavior patterns (Pelto and Hedlund 2001): 1) Retreat from 1890 to 1950 that was followed by a period of advance from 1950-1976, followed by another retreat after 1976, 2) Rapid retreat from 1890 to approximately 1950, followed by slow retreat or equilibrium from 1950-1976 and moderate to rapid retreat since 1976, 3) Continuous retreat from 1890 to 2006. Today, regardless of glacier type rapid retreat is underway.

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) (Johannesson and others 1989). For the Northern Cascade glaciers initial observed terminus response time to climate change is invariably less than 16 years (Pelto 1993; Hubley 1956; Harper 1993). Thus, by 1993, the termini of all North Cascade glaciers had begun their initial response to the 1976 climate change. The current climate change is of sufficient magnitude that equilibrium is not being approached, even after two decades of retreat.

The glacier margin retreat has been as significant at the head of many glaciers as at the terminus. This indicates thinning in the upper reaches of the glacier. From 1984-2005 Ice Worm Glacier has retreated 165 m at its head and 144 m at its terminus. Columbia Glacier has retreated 72 m at its head and 119 m at its terminus from 1984-2005. If a glacier is thinning not just at its terminus, but also at its head then there is no point to which the glacier can retreat to achieve equilibrium (Pelto 2006). That thinning is occurring in the accumulation zone of the glacier indicates that it no longer has a substantial consistent accumulation zone. The accumulation zone is the region of the glacier that even at the end of summer melt season still retains snowpack from the winter season. To be in equilibrium a glacier during the average year needs approximately 65% of its area to be in the accumulation zone at the end of the

summer melt season. If the upper reaches of the glacier, where the accumulation zone is located, the glacier is thinning significantly, then it is no longer consistently an accumulation zone. Of the 12 glaciers where the change in glacier surface elevation through time has been mapped 9 are experiencing substantial thinning, at least 10 m since 1984, in the accumulation zone at the head of the glacier. Thus, 75% of the North Cascade glaciers observed are thinning appreciably in the accumulation zone and are in disequilibrium with current climate. Foss Glacier (Figure 5) is an example of a glacier that is in disequilibrium and rapidly melting away.

Snowpack Changes

The decline in snow pack since 1950 has been noted throughout the Pacific Northwest (Mote et al. 2005; Pelto 2006). This has been shown to be the result of rising temperatures not declining precipitation (Mote 2003; Mote et al. 2005). Further, Mote et al. (2005) noted that the snow water equivalent (SWE) record was well correlated with temperature. Winter season snowfall is directly measured by the USDA at a series of SNOTEL sites, and the April 1 SWE provides an excellent measure of winter season snow accumulation on glaciers (Pelto 2006). The April 1 SWE record is summarized from five long-term Snow Course and now SNOTEL stations; Rainy Pass, Lyman Lake, Stevens Pass, Miners Ridge and Fish Lake (Table 4). These are the only North Cascade snowpack records that exist for the entire interval. The snowpack maximum for most of the SNOTEL sites is reached near April 1 at most SNOTEL sites (Pelto 1993; Mote 2004). If March 1 or April 15 data are used the results are similar for the sites. The April 1 date is also the date for which longer term snow course measurements were completed prior to the SNOTEL continuous measurement program started in 1980. In

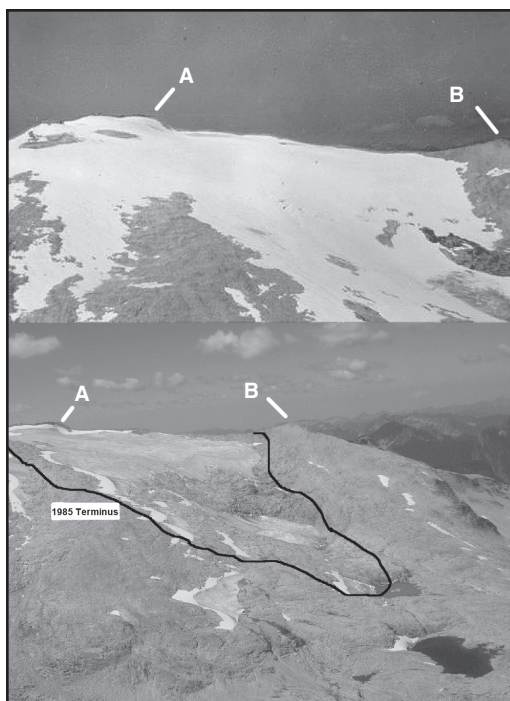


Figure 5. Foss Glacier in 1988 and 2005 viewed from the east. This glacier has lost 40% of its total area since 1984. This glacier feeds the Skykomish River. The decreased area results in less summer glacier runoff released to the river. Note reference points A and B.

Figure 1, April 1 mean SWE has declined by 25% at these stations since 1946, while winter season precipitation (November–March) has increased 3% at Concrete and at Diablo Dam, the most reliable long term weather stations. Kovanen (2003) noted the strong link in precipitation between weather stations with a correlation coefficient of 0.93, indicating the strong regional nature of the precipitation events.

Mote (2003) in examining 40 stations in the Washington and British Columbia noted that

TABLE 4. Location of USDA SNOTEL (Snowpack Telemetry) measurements sites utilized for April 1 SWE data.

	Elevation	Latitude	Longitude	Source	Mean April 1 SWE	Change 1946-2005
Lyman Lake	1805	48 12	120 55	USDA	1.62 m	-.37 m
Rainy Pass	1460	48 33	120 43	USDA	1.01	-.29
Stevens Pass	1245	47 44	121 05	USDA	1.20	-.75
Fish Lake	1030	47 31	121 04	USDA	0.89	-.40
Miners Ridge	1890	48 10	120 59	USDA	1.32	-.29

substantial declines in SWE coincide with significant increases in temperature, and occur in spite of increases in precipitation. Mote (2003) also identified that the lower elevation SNOTEL sites generally experienced the most significant decline in SWE, as would be expected with a moderate rise in the mean snow line. A key ratio that can be used to identify the relationship between the snowpack and precipitation is the ratio between winter precipitation (November-March) and April 1 SWE. An increasing ratio indicates a greater percentage of precipitation is falling and remaining as snow. A declining ratio indicates that greater percentages of precipitation occur as rain instead of snow and/or that melt of winter snowpack is increasing. The declining ratio is evident in Figure 6, demonstrating that reduced April 1 SWE is not due to precipitation decline, but to reduced accumulation of snowpack and winter ablation of existing snowpack.

Alpine Streamflow

Glaciers are key sources of alpine summer streamflow and a critical water supply source in the North Cascades (Bach 2002). Comparison of 1963-2003 USGS runoff records for six alpine North Cascades basins with varying percentages of glacier cover reveal the impact of the climate change and changing glacier extent (Table 5). The seasonal changes in flow, the slope of the linear trend in discharge, and the percent of change annually for the winter, spring and ablation period are all noted in Table 5 for six alpine basins in the North Cascades. The basins have a differing percentage of glacier cover, causing a difference in dependence on glacier runoff (Table 5). The

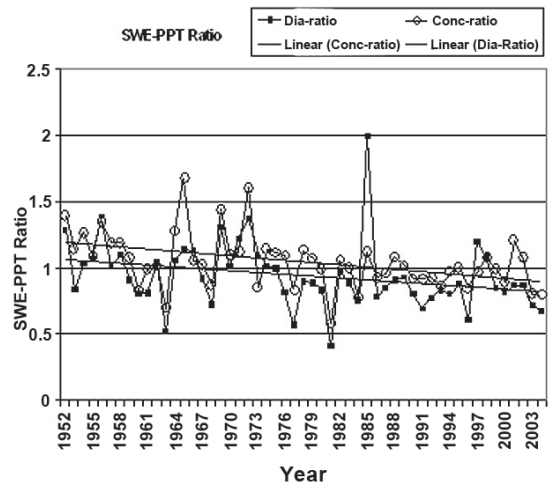


Figure 6. The annual ratio between winter precipitation measured at Diablo Dam and Concrete and April 1 SWE at five USDA SNOTEL stations. The decline in the ratio indicates that a greater percentage of the total precipitation falling at the low elevations station's, is not accumulating in the snowpack at the higher elevations SNOTEL sites. This can be due to more rainfall or to greater snowpack melting during the winter.

discharge response is consistent with all basins having increased streamflow during the winter, declining streamflow in the summer and nearly unchanged streamflow in the spring. Comparison of changing streamflow in two adjacent basins, Thunder Creek and Newhalem Creek, the former with 14% glacier cover the latter with 0% glacier cover, allow determination of the impact of glaciers on streamflow.

Alpine runoff throughout the mountain range increases in the winter (November-March) as more frequent rain on snow events enhance melting and

TABLE 5. Runoff data from six USGS monitored basins in the North Cascades. Change in flow is in percent per year for the 1963-2003 period. Bold numbers indicate reductions in flow. Winter flow increased in all six basins. Summer flow decreased in all six basins.

	USGS Station ID	Mean Elevation	% Glaciation	Winter % change/year	Spring % change/year	Summer % change/year
Thunder	12175500	1755	13.6	0.50	0.31	-0.04
Newhalem	12178100	1320	0.2	0.43	0.09	-0.73
Stehekin	12451000	1561	3.1	0.27	-0.06	-0.37
Nooksack	12210500	1141	2.1	0.01	-0.20	-0.66
NF Nooksack	12205000	1311	6.1	0.55	0.01	-0.52
Skykomish	12134500	1127	0.3	0.30	-0.01	-1.11
Mean				0.344	0.0233	-0.48

reduce snow storage (Mote 2003). The streamflow increase rises substantially in Newhalem Creek (17%), and Thunder Creek (20%), with a mean of 13.8% in all six basins examined. The increased streamflow occurred in part due to a precipitation increase of 3% at Diablo Dam, within 5 km of both basins, but mostly is due to increased winter snowmelt and increased winter rain (Table 5).

The earlier release of meltwater in the North Cascades due to warmer spring conditions and reduced winter snowpack has become more pronounced since 1990 when first documented by Pelto (1993). This trend is seen throughout the western United States (Stewart et al. 2004). However, total spring runoff (April-June) has changed little in each basin. Earlier snowpack melting leading to greater contributions to runoff from higher altitudes, and by reduced contribution from lower altitudes due to the reduced snowpack depth, duration and extent. The two factors largely counteract each other and the net change in spring streamflow is small. Stewart et al., (2004) noted an earlier peak runoff ranges from 10-30 days in the Pacific Northwest.

Summer runoff has decreased markedly, 28%, in the non-glacier Newhalem Creek due to the earlier melt and the reduced winter snowpack. In Thunder Creek runoff has, in contrast, decreased just 3%. The difference is accounted for in part by enhanced glacier melting. Glaciers contribute 35-45% of Thunder Creek's summer streamflow (Tangborn 1980). The observed net loss of -0.54 m a^{-1} in glacier mass spread over the melt season is equivalent to $2.45 \text{ m}^3 \text{ s}^{-1}$ of discharge in Thunder Creek, which is 9% of the mean summer streamflow. The increased glacier melting resulting in reduced glacier volume has enhanced summer streamflow. The increased glacier runoff due to glacier volume loss from 1984-2004 has offset a significant portion of the summer streamflow reduction observed in non-glacier basins. At some point the reduction in glacier area will exceed the increase in melting per unit area. This results in glacier runoff declines even with higher melt rates. For example, Ice Worm Glacier, which is the headwaters of Hyas Creek, has lost 30% of its area since 1984, while during the same period August streamflow has declined 25%. Glaciers act as natural frozen reservoirs in a watershed. In the North Cascades these natural reservoirs are shrinking rapidly, as is the summer runoff they

can provide. The observed seasonal changes in streamflow are summarized in Figure 7.

There has been a significant change in the timing of peak spring streamflow events from alpine streams since 1950. During the period of glacier equilibrium from 1950-1975 summer melt events in Thunder Creek accounted for 17 of the 26 highest peak flows. From 1984-2004 the peak streamflow events dominantly resulted from winter rain on snow melt events accounting for eight of the thirteen yearly peak flow events, the other five occurring in the summer.

Conclusions

The climate drivers for the hydrologic changes in North Cascade alpine regions are: a 0.6°C summer temperature rise, a 0.9°C rise in winter temperature and a minor increase in precipitation (Mote 2003).

The increase in winter temperature has led to a 25% decline in April 1 Snow water equivalent at eight USDA snow course sites since 1946. This decline has occurred despite an increase in winter precipitation. A comparison of April SWE and winter precipitation indicates a decline in this ratio reflecting warmer conditions, yielding more rainfall events, leading to more winter melt and less snowpack accumulation.

The impact of the warmer temperatures and reduced winter snowpack on North Cascade glaciers has been an average annual balance of -0.54 m a^{-1} over the past 23 years. The net loss, -12.4 m w.e. , represents a significant portion of the total glacier volume, 20-40%, that has resulted in substantial retreat and thinning. The resultant retreat is ubiquitous, rapid and increasing. There is no evidence that North Cascade glaciers are close to equilibrium. Their ongoing thinning indicates that all of the glaciers will continue to retreat in the foreseeable future. In cases where the thinning is substantial along the entire length of the glacier, then no point of equilibrium can be achieved with present climate and the glacier is unlikely to survive (Pelto 2006). Of the 12 North Cascade glaciers where longitudinal thinning has been examined, nine are in disequilibrium with current climate.

North Cascades alpine streamflow has increased 18% in the winter from 1963-2003 due to the increased snow melt and the extent and frequency

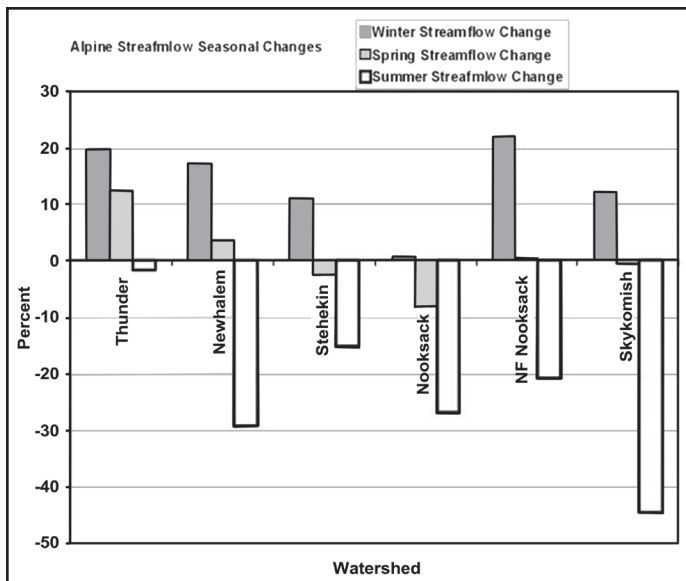


Figure 7. Seasonal changes in alpine streamflow in six North Cascade basins. The consistent increase in winter streamflow and decrease in summer streamflow, regardless of basin is evident. The reduction in summer streamflow is least pronounced in the most heavily glaciated basin, Thunder Creek.

of rain events in the alpine zone. Mean spring streamflow has increased by only 1% in the alpine basins. Mean summer streamflow declined 20%. In Thunder Creek Basin with 10% glacier cover, streamflow declined 3%; it is the only alpine

basin where summer streamflow did not decline more than 15%. The smaller reduction in Thunder Creek discharge is in large part attributable to the enhanced glacier melting that occurred. As North Cascade glaciers continue to retreat and the area available for melting declines, overall glacier runoff will decline, providing less of a buffer during low summer streamflow. Peak streamflow events in glacier dominated Thunder Creek have shifted from summer snowmelt primarily during the 1950-1975 period to winter rain-melt dominated events 1984-2004. The observed changes represent significant shifts in the annual hydrologic cycle in the alpine zone and alpine fed watersheds in the North Cascades.

Continued glacier retreat is inevitable, 75% of the North Cascade glaciers we observe are in disequilibrium and will melt away during this century with the current climate. The loss of glacier area will lead to further declines in summer runoff in glacier-fed rivers as the glacier area available for melting in the summer declines.

Literature Cited

- Bach, A. 2002. Snowshed contributions to the Nooksack River watershed, North Cascades Range, Washington. *Geographical Review* 92 (2):192-213.
- Bidlake, W.R., E.G. Josberger and M.E. Savoca. 2007. Water, Ice, and Meteorological Measurements at South Cascade Glacier, Washington, Balance Years 2004 and 2005. U.S. Geological Survey Scientific Investigations Report 2007-5055, 2007. Washington, D.C.
- Burbank, D.W. 1981. A chronology of late Holocene glacier fluctuations on Mt. Rainier, WA. *Arctic and Alpine Research* 13:369-386.
- Ebbesmeyer, C.C., D.R. Cayán, 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., (editors) *Proc. On the 7th Annual Pacific Climate Workshop*. Pacific Grove, CA. Pp. 129-141
- Gedalof, Z.M and D.J. Smith. 2001. Interdecadal climate variability and regime-scale shifts in Pacific North America. *Geophysical Research Letters* 28:1515-1518.
- Harper, J.T. 1993. Glacier terminus fluctuations on Mt. Baker, Washington, USA, 1940-1980, and climate variations. *Arctic and Alpine Research* 25:332-340.
- Hubley, R.C. 1957. Glaciers of Washington's Cascades and Olympic Mountains: Their present activity and its relation to local climatic trends. *Journal of Glaciology* 2(19):669-674.
- IPCC. 1996. *Climate Change 1995—Contributions of working group I to the second assessment of the Intergovernmental Panel on Climate Change*. Cambridge University Press. Cambridge, UK.
- Kovanen, D.J. 2003. Decadal variability in climate and glacier fluctuations on Mt. Baker, Washington, U.S.A. *Geografiska Annaler: Series A*, 85: 43–55.
- Krimmel, R.M. 1994. *Water, Ice and Meteorological Measurements at South Cascade Glacier, Washington, 1993 Balance Year*. USGS WRI-94-4139. Washington, D.C.
- Krimmel, R.M. 2001. *Water, Ice, Meteorological and Speed Measurements at South Cascade Glacier, Washington, 1999 Balance Year*. USGS WRI-00-4265. Washington D.C.
- 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.
- Mayo, L.R., Meier, M.F. and Tangborn, W.V. 1972: A system to combine stratigraphic and annual mass balance systems. *Journal of Glaciology* 11(61):3-14.
- Mote, P.W. 2003. Trends in snow water equivalent in the Pacific Northwest and their climatic causes. *Geophysical Research Letters* 30: DOI 10.1029/2003GL017258
- Mote, P.W., Hamlet, A.F., Clark, M.P., and Lettenmaier, D.P. 2005. Declining mountain snowpack in western North America. *Bulletin American Meteorological Society* 86:39-48.
- Parson, E.A. 2001. Potential Consequences of Climate Variability and Change for the Pacific Northwest. *In* *Climate Change Impacts on the United States: The Potential Consequences of Climate Variability and Change, Report for the US Global Research Program.*, Cambridge University Press, Cambridge, UK. Pp. 247-280
- 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 net balance of North Cascade glaciers, 1984-1994. *Journal of Glaciology* 42(140):3-9.
- Pelto, M.S. 1997. Reply to comments of Meier and others on "Annual net balance of North Cascade glaciers 1984-1994" by M. S. Pelto. *Journal of Glaciology* 43(143):193-196.
- Pelto, M.S. 2006. The current disequilibrium of North Cascade glaciers. *Hydrological Processes* 20:769-779.
- 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 C. 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 millennium. *Quaternary Research* 26:27-48.
- Post, A., D. Richardson, W.V. Tangborn and F.L. Rosselot. 1971. Inventory of glaciers in The North Cascades, Washington. US Geological Survey Prof. Paper, 705-A. Washington, D.C.
- Rusk, C.E. 1924. *Tales of a Western Mountaineer.* Houghton Mifflin Co., New York.
- Schermerhorn, V. 1967. Terrain effects on precipitation in Washington State. *Weatherwise* 19:204-207.
- Stewart, I.T., D.R. Cayan and M.D. Dettinger. 2004. Changes in snowmelt runoff timing in western North America under a business as usual climate change scenario. *Climatic Change* 62:217-232.
- Tangborn, W. V. 1980. Two models for estimating climate-glacier relationships in the North Cascades, Washington, USA. *Journal of Glaciology* 25:3-21.
- Trenberth, K.E. 1990. Recent observed interdecadal climate changes in the northern hemisphere. *Bulletin American Meteorological Society* 71:988-993.
- Vaccarro, J.J. 2002. Interdecadal Changes in the Hydro-meteorological Regime of the Pacific Northwest and in the Regional-to-Hemispheric Climate Regimes, and Their Linkages. USGS Water-Resources Investigations Report 02-4176. Washington, D.C.

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