Temperature-Ablation Relationships on Glaciers and in Alpine Areas, North Cascades, Washington

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ABSTRACT

In the North Cascade Range, Washington snowpack accumulation and the resultant ablation provide critical summer water resources. Utilizing SWE data from 10 USDA Snotel sites and nine glaciers in the North Cascades, the variation in ablation rates with location and temperature are analyzed. How variable is ablation of alpine snowpack during the principal melt season (May and June) and on glaciers during their principal melt season (July and August)?

Ablation peaks in May at low-elevation Snotel sites, in June at high-elevation Snotel sites, and in August on glaciers Snotel sites have onsite temperature record and daily SWE. The derived relationship between temperature and ablation from May 1 to July 1 at Snotel sites in the sub-alpine or alpine zone (<1500m) yielded an $r^2 = 0.70$, indicating that given onsite temperature ablation can be accurately ascertained. There is not a significant correlation between temperature and ablation at Snotel sites at elevations low enough to be forested (>1500m). Glacier dominate runoff from the alpine zones from July to August, and during this interval temperature provides an accurate estimate of ablation. That glacier dominate is due to the maximum SWE at the glacier locations being 299% and 212% of that at the low elevation and high elevation Snotel sites. Ablation rate on glaciers from July 1 to October 1 yielded an $r^2 = 0.69$. From 1948 to 2003 April 1 SWE has declined at eight North Cascade Snotel sites by 21%. The decline in snowpack by early spring reduces the endpoint of the snowpack ablation season.

The regional nature of both the ablation-temperature relationship, SWE and glacier annual balance indicates that ablation is not particularly dependent on microclimates.

Keywords: glacier, ablation, snowpack, North Cascades

INTRODUCTION

In the North Cascades, approximately 50% of the landscape is above 1100-m elevation, but the highest long-term weather station is at Stampede Pass at 1170 m. This same region contains more than 700 glaciers, which cover 250 km^2 and range in elevation from 1500 to 2500 m (Post et. al., 1971). Climate in the Cascade Mountains is characterized by mild year-round temperatures, abundant winter snow, and comparatively dry summers. There is a strong gradient in precipitation from the west to the east side of the Cascades. Average annual precipitation in the mountains west of the Cascade Crest and at the crest is 3–4 m declining to 2 m in the Cascade Mountains 20 km east of the crest.

Approximately three quarters of the region's precipitation occurs from October to April when the Cascades are on the receiving end of the Pacific storm track. The greatest amount of this precipitation is captured in the region's mountains as snow, influencing hydrology particularly in the release of this runoff in the spring and summer. From May into early October high pressure to the west generally keeps the Northwest fairly dry. These seasonal variations are related to changes in large-scale atmospheric circulation occurring over the Pacific Ocean, including the Gulf of Alaska. The Pacific Decadal Oscillation (PDO) is one key measure of internannual changes in this circulation system. The PDO typically persists for 20 to 30 years, and its impacts are most significant in the North Pacific and the Pacific Northwest (Mantua et al. 1997, Minobe 1997).

The cool phase PDO regimes are associated with cold water off the Pacific Northwest Coast and wetter weather. The warm phase regime has warm water immediately offshore and drier, warmer weather conditions. Several independent studies find evidence for two full PDO cycles in the past century: “cool” PDO regimes prevailed from 1890 to 1924 and again from 1947 to 1976, while “warm” PDO regimes dominated from 1925 to 1946 and from 1977 through (at least) the mid-1990s (Mantua et al. 1997, Minobe 1997). Since the mid-1990s it has been postulated that we might be returning to a cool phase PDO (Mantua, 1999), but no consistent pattern has emerged; we seem to be in neither a warm or a cool phase.

The spatial and temporal variation of snowpack accumulation, snowpack ablation, and consequent alpine runoff is crucial to determining regional summer water resources in the North Cascades Range, Washington. Glaciers alone provide 750 million m^3 of runoff each summer (Fountain and Tangborn, 1985). What is the spatial and temporal variability of accumulation and ablation across the North Cascades?

Rasmussen and Tangborn (1976) noted a poor relationship between observed annual precipitation and annual runoff. They also noted, in plotting mean annual runoff versus basin mean altitude in 36 basins in the North Cascades, that there was a poor relation between runoff and basin altitude. Is this due to variations in snowpack accumulation, ablation rates or both? This paper focuses on identifying whether a consistent ablation temperature relationship exists that can be used to calculate runoff from snow and glacier melt.

DATA SETS

The following data sets are used (Table 1): 1) Annual glacier mass balance measurements from 10 North Cascade glaciers (NCGCP on nine; USGS on one). 2) Daily snow water equivalent and temperature data from 10 USDA Snotel sites. 3) Climate data from local North Cascade Weather stations from the Wester Regional Climate Center.

The Natural Resources Conservation Service (NRCS) of the U.S. Department of Agriculture (USDA) operates an extensive automated Snotel system to collect snowpack and climatic data in the western United States. Snotel sites have at a minimum a pressure sensing snow pillow, storage precipitation gage, and air temperature sensor. The snow pillows are envelopes of stainless steel or synthetic rubber containing an antifreeze solution. As snow accumulates on the pillow it exerts a pressure that is measured and converted to a reading of snow water equivalent and telemetered to two NRCS master stations. Each site measures snow water equivalent (SWE) maximum, minimum, and average daily temperature.

From 1000 to 1900 m the USDA Snotel network provides an excellent network of snowpack and temperature data recorders in the North Cascades, but no sites are found on or adjacent to the highest accumulation areas, which are glaciers. The necessity of using Snotel sites and glaciers to adequately identify snowpack water resources in the North Cascades is emphasized by the difference in mean maximum winter accumulation in SWE from 1.17 m at the 10 USDA Snotel sites, ranging in altitude from 1000 to 1900 m, and 2.93 m at nine glacier locations ranging from 1650 to 2200 m.

Table 1. Location of USDA Snotel, USGS and NCGCP glacier measurements sites.

	Elevation	Latitude	Longitude	Source
Lyman Lake	1805	48 12	120 55	USDA
Harts Pass	1980	48.72	120.65	USDA
Rainy Pass	1460	48 33	120 43	USDA
Thunder Basin	1285	48 31	120 59	USDA
Stevens Pass	1245	47 44	121 05	USDA
Stampede Pass	1190	47 17	121 20	USDA
Wells Creek	1280	48 51	121 47	USDA
Park Creek Ridge	1405	48 27	120 55	USDA
Fish Lake	1030	47 31	121 04	USDA
Miners Ridge	1890	48 10	120 59	USDA
Columbia Glacier	1450–1750	47 58	121 21	NCGCP
Daniels Glacier	2000–2250	47 34	121 10	NCGCP
Ice Worm Glacier	1900–2050	47 34	121 10	NCGCP
Lynch Glacier	1950–2250	47 34	121 11	NCGCP
Rainbow Glacier	1350–2250	48 48	121 40	NCGCP
Easton Glacier	1700–2900	48 44	121 50	NCGCP
S.Cascade Glacier	1645–2100	48 21	121 03	USGS
L.Curtis Glacier	1650–1950	48 50	121 37	NCGCP
Cache Col Glacier	1880–2100	48 22	121 03	NCGCP

At the ten Snotel sites from November 1 to February 15 snowpack development is rapid, reaching 68–80% of the maximum (SWE). The average maximum SWE for sites above 1500 m is May 5, and for sites below 1500 m is April 10, and for glaciers by May 10 (Table 2). The actual maximum accumulation varies with elevation ranging from 0.8 m to 1.6 m, with a mean of 0.98 m for the six sites below 1500 m, and a mean of 1.38 m above 1500 m (Figure 2). The maximum glacier snowpack SWE is distinctly larger with an average accumulation of 2.93 m, this is 299% and 212% of that at the low elevation and high elevation Snotel sites, respectively. This indicates just how crucial glaciers are as a natural reservoir releasing runoff during the driest, warmest period of the year.

The correlation between annual maximum snowpack and total winter precipitation at Diablo Dam is highest for Snotel sites above 1500 m (0.75–0.81). For sites below 1500 m the correlation drops to (0.63–0.75). This is expected since a higher proportion of total precipitation falls as snow at the higher sites. Comparison of annual maximum SWE on glaciers yields cross correlations of 0.82–0.99, indicating the strong regional control of accumulation.

The mean correlation between low elevation sites and individual glacier maximum SWE ranges from 0.37–0.82, and for Lyman Lake the best Snotel site from 0.72–0.95. The mean and maximum SWE depth is variable from site to site; however, the annual pattern of development and relative amount is consistent in response to specific annual climate conditions for each elevation band. Figure 2 indicates the decline in April 1 SWE at eight long-term North Cascade USDA snow course/Snotel sites. The 21% decline is substantial, and exceeds the decline in winter snowfall, indicating greater winter ablation of the snowpack.

By July 15 the nine glacier locations average 1.3 m SWE remaining in the snowpack from the previous winter, while the Snotel sites have no snowpack remaining. Thus, Snotel sites provide a good indicator of late spring and early summer runoff, and glaciers a better measure of mid and late summer runoff. Ablation has been measured for periods of at least two weeks with on site temperature measurement at the Snotel and glacier sites. Ablation peaks in May at low elevation Snotel sites, in June at high elevation Snotel sites, and in August on glaciers. Glaciers dominate runoff from the alpine zones from July to August.

Mass balance measurements have been made using the same methods at the same time of the year on nine North Cascade glaciers by NCGCP (Pelto, 1996; Pelto and Riedel, 2001). The USGS has maintained a mass balance record and weather records at South Cascade Glacier since 1958 (Krimmel, 1993–1999). Each program monitors ablation during specific time periods using stakes emplaced in the glacier surface. Revisiting each site through the ablation season and measuring the emergence of each stake identifies the ablation rate. The maximum snowpack depth and water equivalent is also determined at specific locations at approximately the same time each year in early to mid-May utilizing probes driven through the snowpack on the glacier.

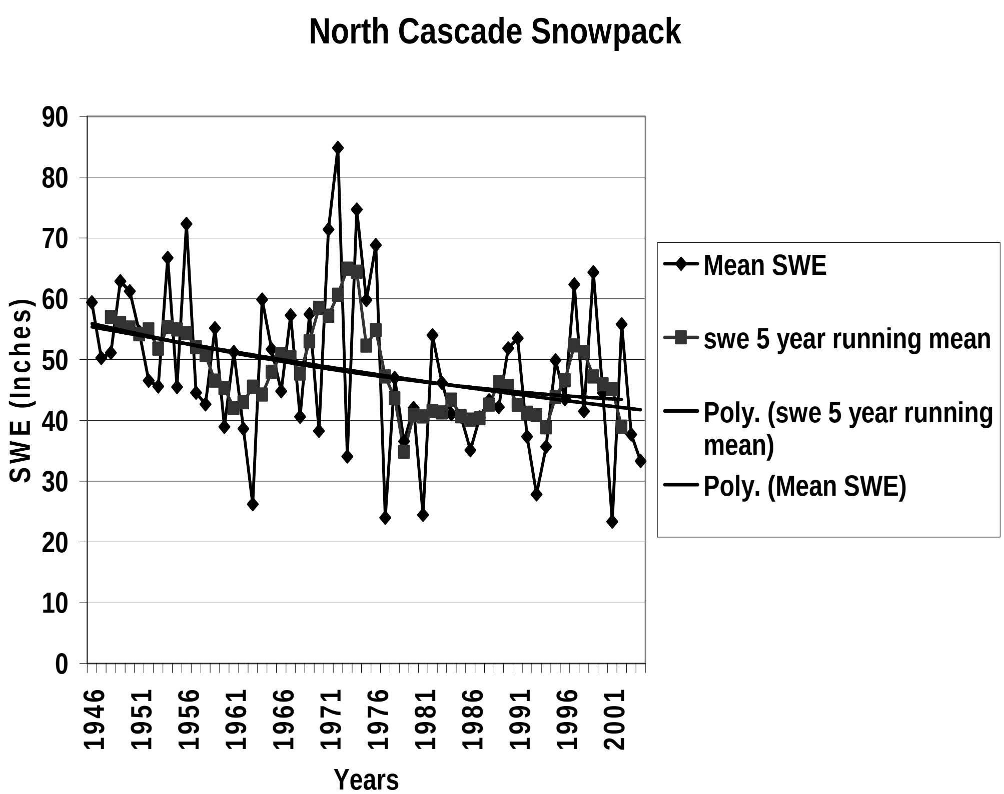

Figure 1. April 1 SWE at eight North Cascade USDA snow course/Snotel sites.
Trendlines indicate the declining nature of April 1 SWE.

MAXIMUM SNOWPACK ACCUMULATION

SNOWPACK ABLATION

Ablation is determined by the reduction in SWE at USDA Snotel sites. Early in the melt season (April–June 15), ablation is dominated by melt at the lower elevation range (>1500m) in alpine basins (Pelto, 1996; Fountain and Tangborn, 1985). Ablation during May at Snotel sites from 1000 to 1500 m averages 0.018 m/day, while at sites from 1500 to 1900 m average ablation is 0.012 m/day, and above 1600 m on glaciers average ablation is 0.08 m/day (Table 2). Snowpack ablation is reduced somewhat, for the Snotel sites are that more protected by surrounding forest (Wells Creek and Thunder Basin).

Table 2. The average maximum SWE, average date of maximum SWE, and mean daily ablation in May at Snotel sites.

Site	Maximum SWE	Maximum Date	May Ablation	June Ablation
Fish Lake	0.83	4/5	0.019	
Harts Pass	1.17	5/1	0.014	
Lyman Lake	1.63	5/10	0.012	0.028
Miners Ridge	1.38	5/10	0.012	0.027
Park Creek	1.12	4/10	0.023	
Rainy Pass	1.04	4/15	0.018	0.032
Stampede Pass	1.19	4/10	0.021	
Stevens Pass	1.07	4/5	0.019	
Thunder Basin	0.84	4/15	0.014	
Wells Creek	0.79	4/15	0.015	

Snowpack is lost from the lower sites in May or early June. The early ablation season is marked by freezing levels that frequently result in snowfall at Lyman Lake and rainfall at the lower elevation Snotel sites. Cross correlation of May monthly ablation rates between Snotel sites as a result is poor, as are the daily ablation rates, correlation coefficients ranging from 0.43 to 0.76. The early season monthly correlation between the high elevation Snotel sites and glacier sites is modest at 0.72.

Average ablation after June 1 is limited to data from Snotel sites above 1500 m and glaciers. At the three stations (Lyman Lake, Miners Ridge, Rainy Pass), when snowpack endured throughout all of June, ablation ranged from 0.027 to 0.032 m/day. June ablation on South Cascade, Easton, and Columbia Glacier during these same June periods ranged from 0.23 to 0.29 m/day, averaging 0.027 m/day. The correlation from glacier to glacier for the same time periods is 0.86–0.99, indicating that ablation conditions are becoming increasingly consistent on glaciers as the summer melt season develops. Correlation in daily ablation rates for the three Snotel sites is 0.79–0.92, indicating that in the elevation zone from 1500 to 2000 m across the North Cascades, ablation after June 1 has a comparatively low degree of variability.

Each of the Snotel sites measures air temperature onsite. A comparison of daily temperature and ablation yield insignificant correlation coefficients for each site. If we examine ablation over a week- to one-month period and correlate with onsite observed air temperature, a significant relationship emerges for Snotel sites in the sub-alpine to alpine zone. No significant relationship exists at the sites in the forested zone, Stevens Pass, Thunder Basin, Wells Creek, Stampede Pass, Park Creek Pass, Fish Lake, and Harts Pass. The linear regression equations that best fit Lyman Lake, Miners Ridge, and Rainy Pass are quite similar, and a plot of all of the sites yields a significant and robust ablation versus temperature relationship for spring snowpack ablation in the alpine zone in the North Cascades (Figure 2-5).

By early July, snowpack beyond the glacier margins is limited, and streamflow is heavily dependent on snow and ice melt from glaciers (Fountain and Tangborn, 1985; Pelto, 1996). From July to September glaciers are the primary area of residual snow and ice ablation. This region has the highest melt rates during this period, while other inputs are at an annual low (Rasmussen and Tangborn, 1976). Thus, glaciers ameliorate low-flow conditions (Fountain and Tangborn, 1985; Pelto, 1993).

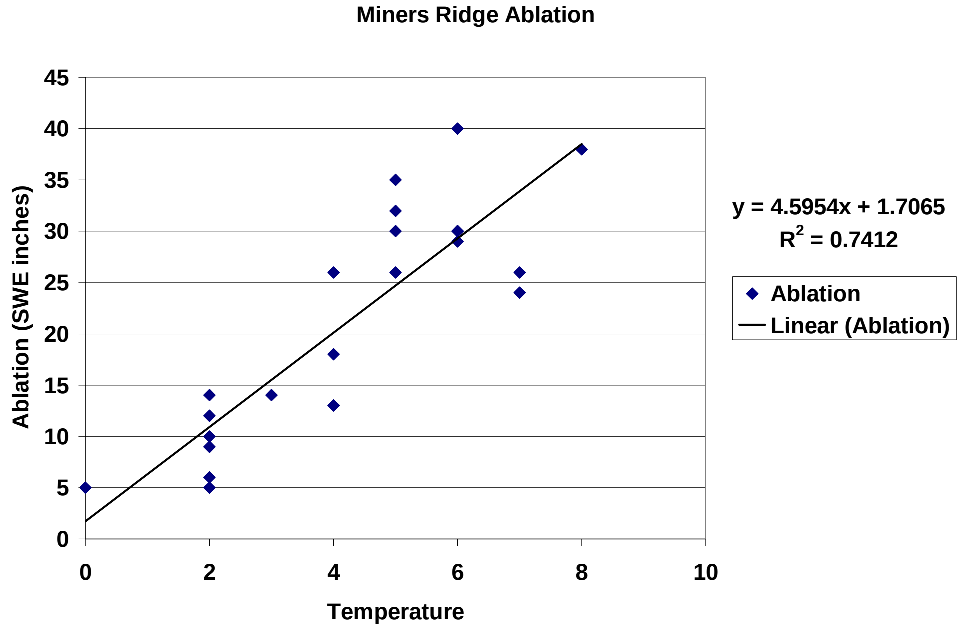

Figure 2. Ablation rate temperature relationship for Miners Ridge USDA Snotel site.

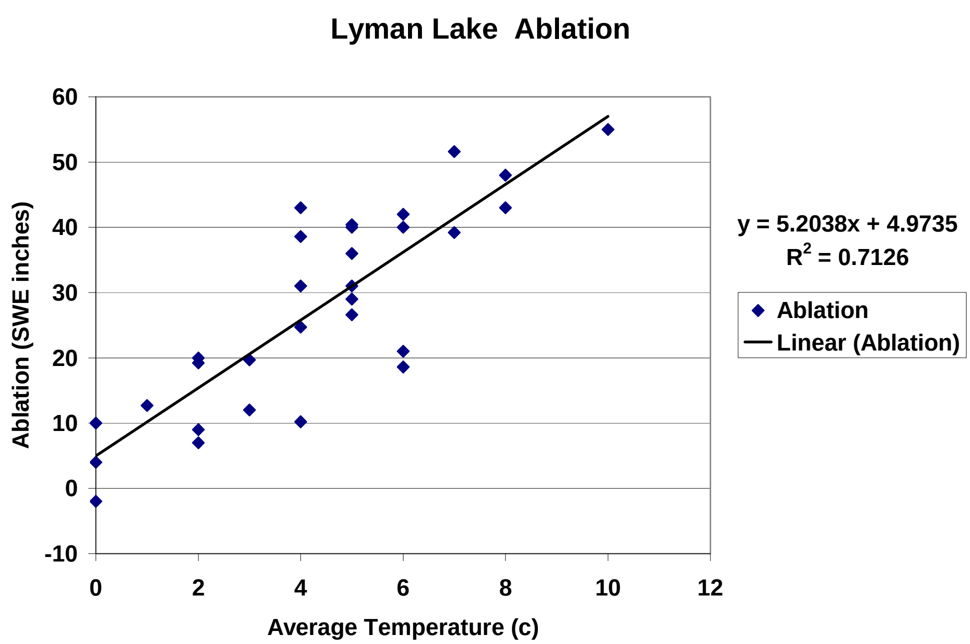

Figure 3. Ablation rate temperature relationship for Lyman Lake USDA Snotel site

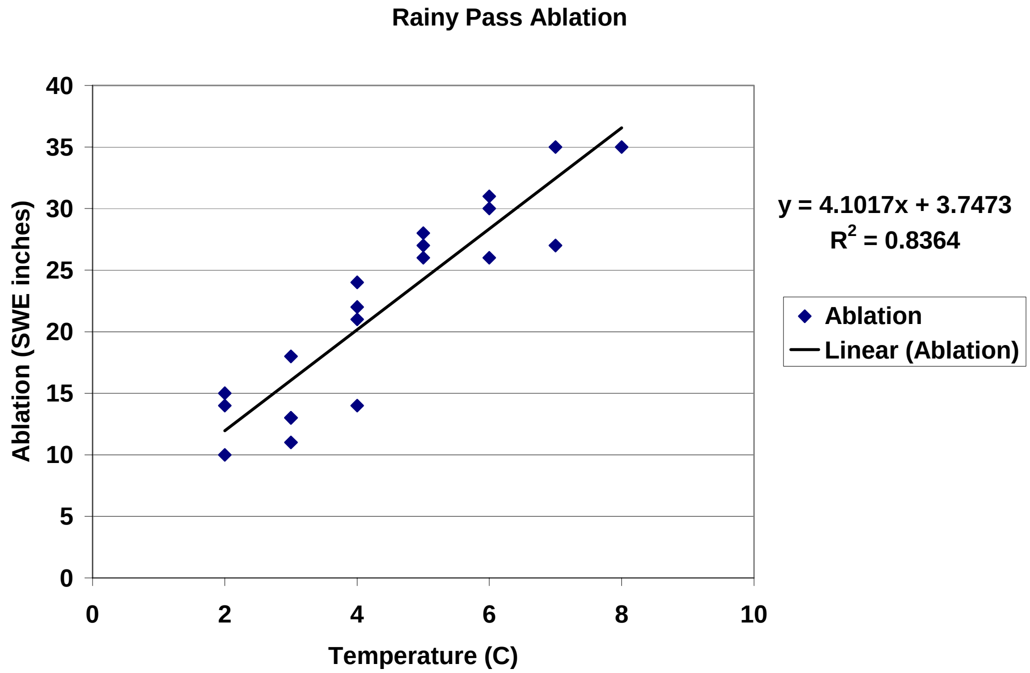

Figure 4. Ablation rate temperature relationship for Rainy Pass USDA Snotel site.

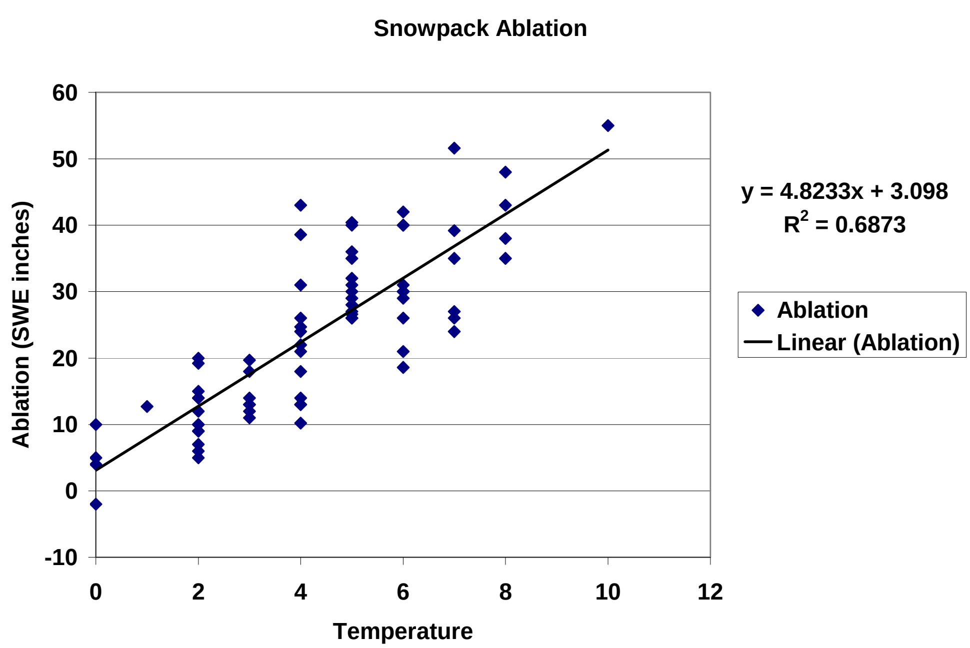

Figure 5. Ablation rate temperature relationship of all thre sites.

In heavily glaciated basins such as Baker River, from 20 to 45% of the total input is from glacier melt during the latter part of the summer (Pelto, 1996; Post et al; 1971). This glacier runoff is best determined by direct measurement of ablation on glaciers. NCGCP (Pelto, 1996; Pelto and Riedel, 2001) and the USGS (Krimmel, 1998) measurements on glaciers do provide a direct measure of ablation in this elevation band at multiple locations over the last 20 years. Stakes drilled into the snow and ice of the glaciers are measured several weeks and/or months after emplacement. This provides the ablation rate.

Ablation measurement on nine North Cascade glaciers for 29 discrete two- to six-week periods during this part of the ablation season yields mean ablation rates of 0.036 m/day, 0.038 m/day, and 0.028 m/day for July, August, and September, respectively. The correlation in mid and late season ablation between each glacier exceeds 0.95, indicating the degree to which the regional summer climate is consistent across the North Cascades.

Comparison of ablation rates and onsite temperature records in the case of the South Cascade Glacier, Easton Glacier, Ice Worm Glacier, and Columbia Glacier yield a relationship between air temperature and daily ablation for snow and ice in SWE (Figure 6).

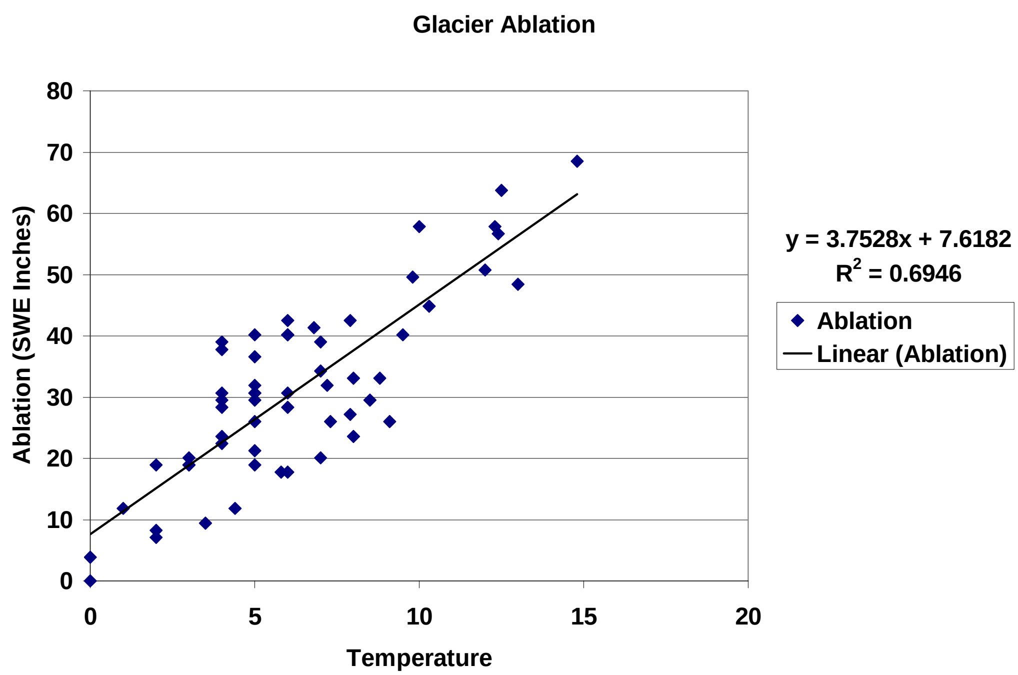

Figure 6. Ablation rate temperature relationship on North Cascade glaciers for snow and ice.

Of greatest interest is the insignificant variation in the temperature-ablation relationship between glaciers that are scattered across the mountain range. The temperature-ablation relationship is also very similar to that for the Snotel sites. The temperatures are all on site and thus do not reflect similar daily ablation rates, just similar ablation rates given the same temperatures, which should not be surprising. With a robust temperature relationship when compared to on-site multi-day temperature records, the next step will be to contrast ablation with temperatures from a few selected weather stations, which would allow time-efficient calculation of glacier ablation.

For glaciers, overall July–August ablation has been increasing: 1998, 2001, 2003, and 2004 all had exceptionally high summer ablation. The result has been an increasingly negative cumulative annual balance on North Cascade glaciers resulting from both decreasing annual snowpack as noted above and from enhanced ablation (Figure 7). The loss of more than 6.5 m of water equivalence and 7 m of glacier thickness represents more than 10% of the volume of these glaciers gone.

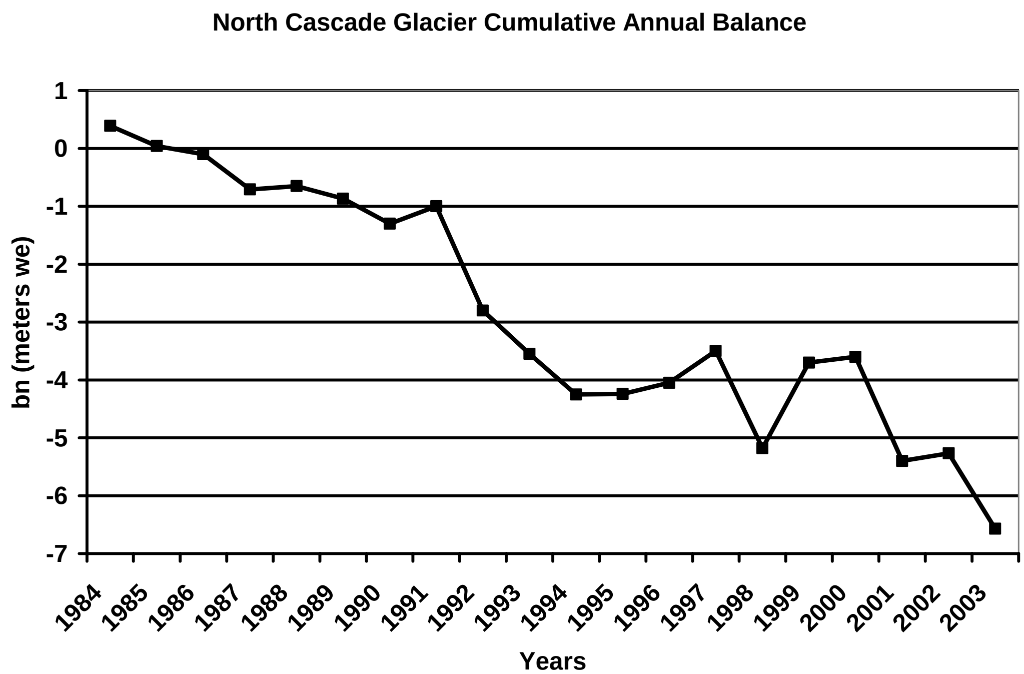

Figure 7. Cumulative annual balance on eight North Cascade glaciers observed by the NCGCP (Pelto, 1996; Pelto and Riedel, 2001).

CONCLUSIONS

Ablation rates in May at the start of the melt season are widely variable from Snotel site to site, but fit within specific mean ranges based on elevation. Ablation rates after June 1 are similar in the summer season, and can be extrapolated from primary to secondary Snotel sites in regions above 1500 m, without substantial baseline data. By mid-summer, ablation rates do not vary substantially within the 1600-m–2400-m elevation band, which is the primary elevation zone for glaciers. The most important ramification is that if the distribution and depth of the snowpack is known on June 1, then summer water resources can be estimated for a wide range of basins from a limited number of primary ablation measurement sites.

With declining April 1 SWE observed on glaciers and Snotel sites, and increased recent summer ablation, late summer alpine streamflow in the North Cascades is reduced. The PDO is not in a mode that delineates a climate mode toward wetter/cooler conditions at present (Figure 8), which would ameliorate this trend. Figure 8 indicates a PDO that has been ambivalent in its trend and phase since 1996.

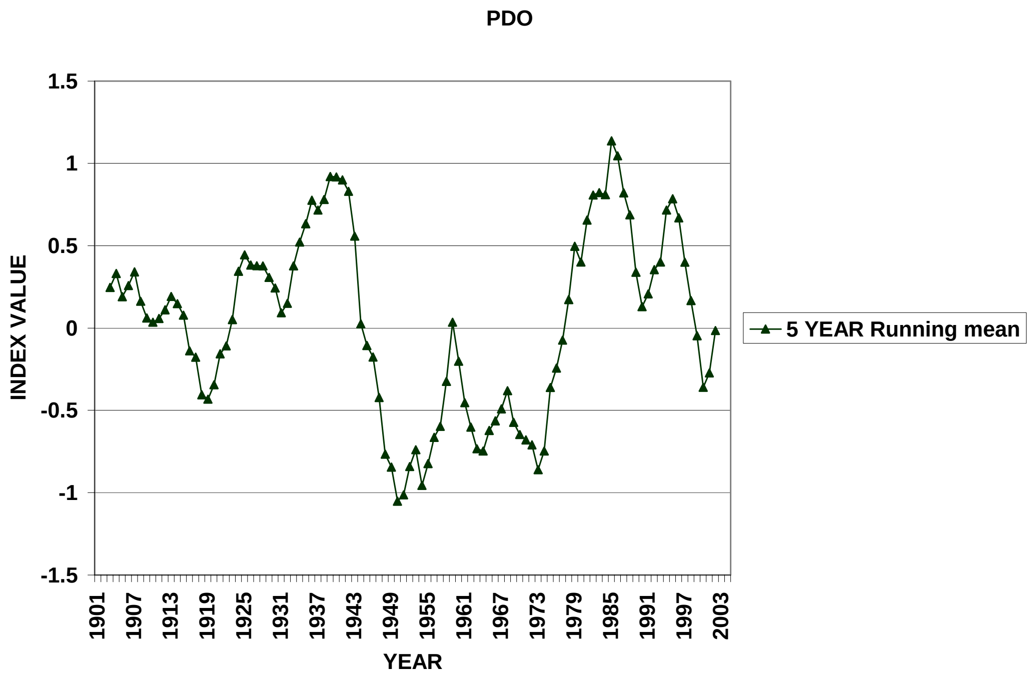

Figure 8. Variation in PDO over the last 100 years. Positive periods are associated with warm/ dry conditions, lower streamflow, snowpacks, and glacier retreat. Negative valuesare associated with wetter/cooler conditions, high snowpacks, positive glacier balances, and higher streamflow. At present, after seeming to be entering a negative phase, the PDO trend is ambivalent.

To model or directly calculate the timing and magnitude of water resource storage, it is essential to collect baseline data on accumulation at numerous secondary sites. Once the relationship of these secondary sites can be related to long-term records at primary measurement sites, then the secondary sites measurements can be discontinued. This also applies to early season, April–May ablation. Ablation rates and consequent runoff can be assessed from a few primary sites at glaciated levels from June 1–September 31. It is also evident that the Snotel system provides an excellent and cost-effective means of collecting data on snowpack development from 1000 to 1900 m in the North Cascades, but does not well represent snowpack accumulation at the average glacier accumulation zones of 2000 m. Making accurate summer streamflow estimates is impossible without data from glacier sites.

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