Mass Balance Loss of Mount Baker, Washington, glaciers 1990−2010

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ABSTRACT

Mount Baker, North Cascades, WA, has a current glaciated area of 38.6 km^2. From 1984-2010 the North Cascade Glacier Climate Project has monitored the annual balance (ba), accumulation area ratio (AAR), terminus behavior and longitudinal profiles of Mount Baker glaciers. The ba has been assessed on Rainbow Glacier 1984-2010, and from 1990-2010 on Sholes and Easton Glacier, averaging -0.52 m.w.e a^{-1}(ma-1) on Rainbow, Easton and Sholes Glacier from 1990-2010. Terminus observations 1984-2009 on nine principal Mount Baker glaciers indicate retreat ranged from 240 m to 520 m, mean 370 m, or 14 ma^{-1}. The AAR is the percentage of a glacier in the accumulation zone at the end of the melt season. AAR observations on Rainbow, Sholes and Easton Glacier 1990-2010 indicate a mean AAR of 0.55, and a steady state AAR of 0.65.

Plotting the annual AAR and ba provides an AAR-ba relationship for the three glaciers yielding a mean ba of -0.55 ma^{-1} for the 1990-2010 period, 0.03 m/a higher than the measured mean annual balance. A comparison of ba and AAR on these three glaciers yields a relationship that is used in combination with AAR observations made on all Mount Baker glaciers during seven years to assess Mount Baker glacier mass balance. The mean ba based on the AAR-ba relationship for the entire mountain for the 1990-2010 period is assessed at -0.57 ma^{-1}. The product of the mean observed mass balance gradient determined from the 11,000 surface mass balance measurements combined with glacier area in each 100 m elevation band on Mount Baker, yields a ba of -0.50 ma^{-1} for 1990-2010 for the entire mountain. The median altitude of the three index glaciers is lower than that of all Mount Baker glaciers. Adjusting the balance gradient for this difference yields a mean annual balance of -0.77 ma^{-1} from 1990-2010 All but one estimate converge on a loss of -0.5 ma^{-1} for the entire mountain for the 1990-2010 period this equates to a 10 m loss in glacier thickness represents 12-20 % of the entire 1990 volume of glaciers on Mount Baker.

Keywords: Mount Baker, glacier mass balance, glacier retreat, North Cascades

INTRODUCTION

Glaciers have been studied as sensitive indicators of climate for more than a century. Annual mass balance measurements are the most reliable indicator of short-term glacier response to climate change (Haeberli, 1995). The importance of monitoring glacier mass balance was recognized during the International Geophysical Year (IGY) in 1957. For the IGY a series of benchmark glaciers around the world were chosen where mass balance would be monitored. This

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network has proven valuable, but in many areas the number of glacier is limited, for example, there is just one benchmark glacier in the North Cascades and in the lower 48 United States, South Cascade Glacier (Fig. 1), with ongoing measurements (Fountain et al, 1991). Glacier mass balance varies due to geographic characteristics such as aspect, elevation and location with respect to prevailing winds. Since no single glacier is representative of all others to understand the causes and nature of changes in glacier surface mass balance throughout a mountain range, it is necessary to monitor a significant number of glaciers (Fountain et al, 1991).

The North Cascade region contains more than 700 glaciers, which cover 250 km^2 (Post et. al., 1971; Granshaw and Fountain, 2006). The North Cascade Glacier Climate Project (NCGCP) was founded in 1983 to monitor 10 glaciers throughout the range and identify the response of North Cascade Range, Washington glaciers to regional climate change (Pelto, 1988). The annual observations include of mass balance, terminus behavior, glacier surface area and accumulation area ratio (AAR). Annual balance (ba) has been continued on the 8 original glaciers that still exist, two have disappeared, Lewis and Spider Glacier (Pelto, 2008). In 1990, Easton Glacier and Sholes Glacier were added to the annual balance program to offset the loss.

Three of the glaciers currently monitored, Easton, Rainbow and Sholes Glacier are on Mount Baker. Mount Baker a stratovolcano is the highest peak in the range at 3286 m. Mount Baker has the largest contiguous network of glaciers in the mountain range with twelve significant glaciers covering 38.6 km^2 reaching from 3250 m to 1320 m (Fig. 1).

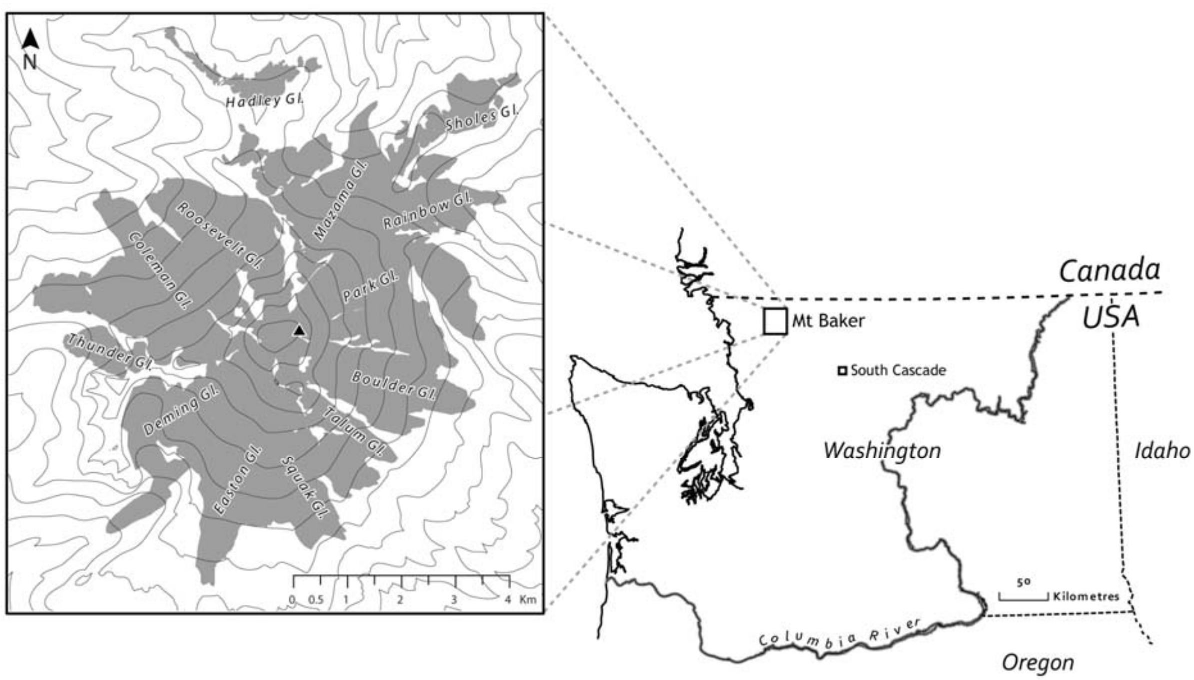

Figure 1. Base map delineating the glaciers of Mount Baker and indicating South Cascade Glacier

That there are three glaciers on this single mountain with long term mass balance records of at least 20 years is unique globally. A combination of accumulation area ratio (AAR) observations and annual balance measurements on Mount Baker glaciers provide an opportunity to assess the mass balance of the entire glacier complex since 1990 using several methods for comparison. There are two common proxies for assessing mass balance indirectly, AAR and equilibrium line altitude (ELA). AAR is defined as the ratio of accumulation area at the end of the melt season to total glacier area. The ELA is the elevation at which ablation equals accumulation, on temperate alpine glaciers this is coincident with the snowline at the end of the melt season. The ELA is not typically an easily discernible line or elevation on Mount Baker. AAR is a more accurately determined parameter and a better proxy in this case. Dyurgerov (1996) developed a method to derive mass balance from long term AAR observations. This method has proven reliable (Hock and Koostra, 2007; Pelto, 2010) and the World Glacier Monitoring Service (WGMS) has adopted the reporting of AAR with all mass balance values (WGMS, 2006, 2008) and plotting the relationship for each glacier.

FIELD AREA GLACIER BEHAVIOR

From 1920-1945 Mount Baker glaciers were all retreating (Hubley, 1957; Pelto, 1993; Harper, 1993; Pelto and Hedlund, 2001). This was a warm dry period that has been noted around the world and in the North Cascades as a period of rapid glacier retreat (Burbank, 1981; Long, 1955; 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. From 1944-1976 conditions became cooler and precipitation increased (Hubley 1956; Tangborn, 1980; Pelto, 1993; Kovanen, 2001). 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 (Heikkinen, 1984; Harper, 1993; Pelto, 1993). From 1977-2009 mass balance has been negative driven initially by a drier-warmer climate in the Pacific Northwest from 1978-1998 (Ebbesmeyer and others, 1991) and by warmer conditions despite above average precipitation from 1999-2010 (Casola et al. 2009). The impact on North Cascade glacier mass balance is evident from the USGS long-term record of South Cascade Glacier (1958-2009), where mean annual balance was –0.15 ma-1 from 1958-1976, in contrast to –1.15 ma-1 from 1977-1998 (Krimmel, 1999) and –0.88 ma-1 from 1999-2009.

The retreat and negative mass balances beginning in 1977-2009 have been noted by Bidlake et al, (2009) and Pelto (2008 and 2009). By 1984, all the Mount Baker glaciers, which were advancing in 1975, were again retreating (Harper, 1993; Pelto, 1993). The retreat was measured in the field from benchmarks established in 1984 or 1985 at their recent maximum position (late 1970's-early 1980's), in each case a maximum advance moraine had been emplaced. By 1997-1998, the average retreat had been -197 m. The retreat has continued to 2010 with the average retreat of 370 m for the nine principal glaciers (Table 1).

Table 1 Characteristics of individual Mount Baker glaciers including retreat from 1979 to 2009.

Name	*Area km^2*	*Terminus (m)*	*Top (m)*	*Orientation*	*Retreat m)*
Deming	4.79	1350	3200	215	-360
Easton	2.87	1680	2900	195	-320
Squak	1.55	1700	3000	155	-300
Talum	2.15	1800	3000	140	-240
Boulder	3.46	1530	3270	110	-520
Park	5.17	1385	3270	110	-360
Rainbow	2.03	1340	2200	90	-480
Sholes	0.94	1610	2110	330	NA
Mazama	4.96	1480	2970	10	-410
Coleman-Roosevelt	9.85	1380	3270	320	-340
Thunder	0.81	1870	2490	295	NA

METHODS

Annual mass balance is the difference between accumulation of snow and ice in winter and loss of snow and ice by ablation in summer. NCGCP essentially measures conditions on a glacier near the time of minimal mass balance at the end of the water year, using a fixed date method. This is known as annual balance (ba) (Mayo et al, 1972; Pelto and Riedel, 2001). Measurements are made at the same time each year in July-August and again in late September near the end of the ablation season. Any additional ablation that occurs after the last visit to a glacier is measured during the subsequent hydrologic year. Net balance in contrast (bn) is defined as the change observed on a glacier's surface between successive balance minimums (Mayo et al., 1972).

NCGCP methods emphasize surface mass balance measurements with a relatively high density of sites on each glacier (>100 sites km-2), consistent measurement methods, applied on fixed dates, and at fixed measurement locations (Pelto, 1996; Pelto and Riedel, 2001; Pelto, 2009). The use of a high measurement density and consistent methods generates errors resulting from an imperfectly representative measurement network that are largely consistent and correctable (Pelto, 2000). Rainbow, Sholes and Easton Glacier do not lose significant mass by calving or avalanching, thus changes observed are primarily a function of winter accumulation and summer ablation on the glacier's surface.

On Easton Glacier the measurement network consists of 240 measurement locations ranging from 1650 m to 2750 m. On Rainbow Glacier there are 160 sites from 1400 m to 2200 m. On Sholes Glacier the network extends from 1600 m to 2000 m with 80 sites. This provides approximately 480 point measurements of mass balance each year from 1400 m to 2900 m. The best fit regression line through this data for the 1990-2010 provides the average balance gradient for Mount Baker used to directly calculate mass balance.

AAR observations are completed each year on Rainbow, Sholes and Easton Glacier. In addition AAR observations have been made on all Mount Baker glaciers during selected years from photographs and satellite imagery 1993, 1999, 2003, 2005, 2006, 2009 and 2010.

The area covered by glaciers and the elevation distribution were determined from the 2009 NAIP (National Agriculture Imagery Program) 1-m orthoimage, acquired in late August, combined with the National Elevation Dataset 10 m DEM of the Mount Baker area.

Mass balance is assessed in four ways. 1) A simple mean of the observed field mass balance. 2) From the regression of mass balance and AAR. 3) Overall mass balance is assessed as the summation of the products of the mean mass balance for each elevation band and the glaciated area in that elevation band. 4) A median elevation approach adjusting the balance gradient based on glacier median elevation.

RESULTS AND DISCUSSION

Annual Balance

The cumulative balance trend for North Cascade glaciers indicates an increasing trend of negative mass balance. The mean annual balance from 1984 to 2010 on North Cascade glaciers is reported in water equivalence -0.51 m.w.e a^{-1} (ma^{-1}). The cumulative balance is -13.20 m, equal to an ice thickness loss of nearly 15 m. The mean annual balance of Rainbow, Sholes and Easton Glacier has been –0.58 ma^{-1} from 1990-2009 (Fig. 2), and -0.51 ma^{-1} 1990-2010. This is comparable to the mean annual balance on South Cascade Glacier of -0.78 $ma^{-}1$, 1990-2009 (Bidlake et. al, 2007). Given a mean thickness of 50-75 m the mass loss is a 12-20% loss in total glacier volume. The increase in negative mass balance during a period of substantial retreat, suggests that the current retreat maybe insufficient for the glaciers to approach equilibrium.

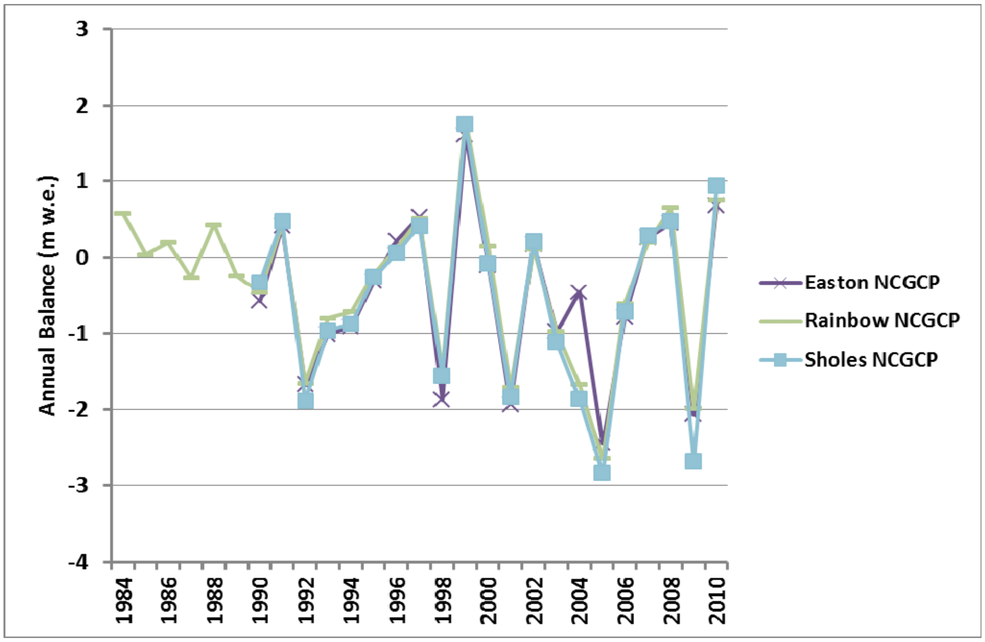

Figure 2. The annual balance of Rainbow, Sholes and Easton Glacier

AAR-Mass balance relationship

A comparison of annual AAR, and bn or ba observations in WGMS (2006; 2008) indicate correlation coefficients ranging from 0.70-0.92 for fifteen glaciers with at least 10 years of records. Muller and Braithwaite (1980) noted that the average AAR for an alpine glacier with an equilibrium balance was 0.67. The AAR0 value is the AAR for a glacier with an equilibrium mass balance. The mean AAR0 reported for 89 glaciers temperate alpine glaciers is 0.57 (WGMS, 2008: WGMS, 2010). A plot of the AAR versus annual balance for Rainbow, Sholes and Easton Glacier indicate an AAR0 of 0.64 of and a correlation coefficient between annual balance and AAR of 0.88 (Fig. 3). A comparison of the observed AAR of these three glaciers 0.34 versus that for the entire mountain 0.39 from 2009 indicates the higher AAR of Mount Baker glaciers overall than the three index glaciers (Fig. 4 and Fig. 5). In other years where the AAR is 0.50 or less for the index glaciers the AAR of all Mount Baker glacier is higher on average by 0.03. When the AAR on the index glaciers is greater than the ELA0 of 0.67 there is not a significant difference between the two groups. This indicates a slightly different slope to the mass balance-AAR relationship, but too few data points to construct with confidence. In this study we assume the same mass balance-AAR relationship for the entire mountain as for the three index glacier, but adjust the AAR by 0.03 for years when the AAR is below 0.50. The mean AAR for the index glaciers from 1990-2010 is 0.55 ma-1, indicating a mean AAR for the entire mountain of 0.57.

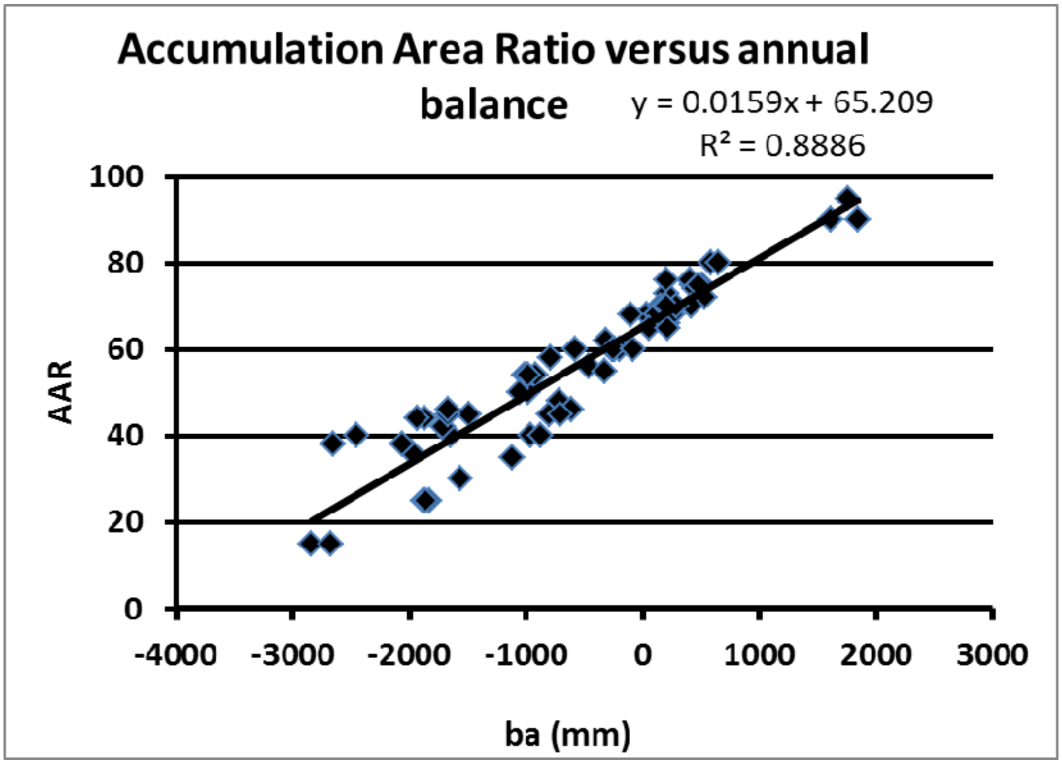

Figure 3. The relationship of annual balance (ba) and accumulation area ratio (AAR) of Sholes, Easton and Rainbow Glacier. The y-intercept of 65 indicates the equilibrium balance AAR. The correlation coefficient of .89 indicates the usefulness of the measure.

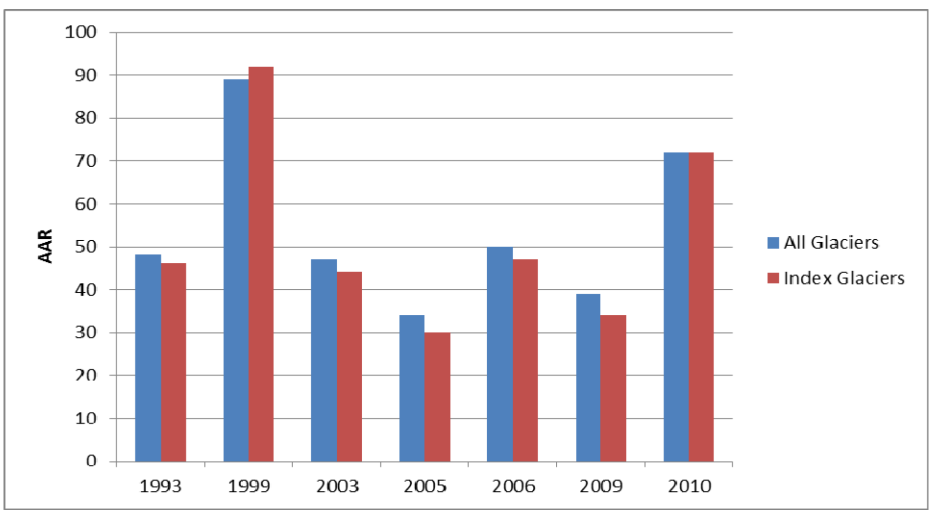

Figure 4. Relationship between the AAR of the index glaciers and all 12 glaciers in selected years. The index glaciers have a lower AAR during negative balance years

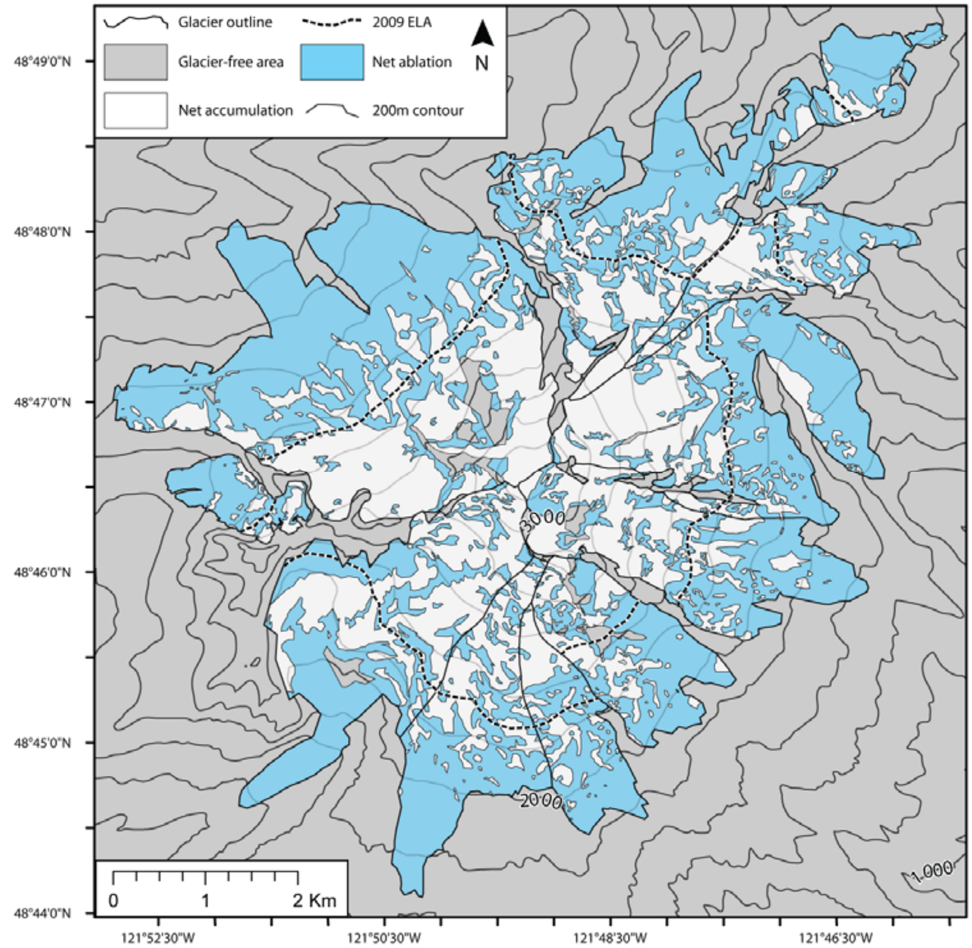

Figure 5. 2009 AAR assessment from aerial photography. White is snow cover, blue is exposed glacier ice

Balance Gradient Based Mass Balance Assessment

A third approach to assessing the mass balance of Mount Baker is to sum the product of mass balance and glacier area at each 100 m elevation interval. The balance gradient is constructed from the 11,000 point measurements of mass balance on Easton, Rainbow and Sholes Glacier. The area elevation distributions are taken from the analysis of the 2009 NAIP orthoimage and 10 m DEM for each 100 meter contour band of the entire mountain (Table 2and Figure 6). The mean ba is -0.50 ma^{-1} for the 1990-2010 period.

Table 2 The directly measured mass balance (ba), glacier area, and total mass balance (Ba) in each 100 m elevation band on Mount Baker. After adjusting the balance gradient by 50 m for the difference in median elevation of the index glaciers and all glaciers on Mount Baker the mass balance is reassessed.

Elevation Band	*Area*	*ba*	*Ba total*	*ba-adj.*	*Ba total adj.*
1400	629087	-5	-3145435	-5	-3145435.3
1500	851245	-4.5	-3830601	-4.75	-4043412
1600	1164077	-4.2	-4889125	-4.35	-5063736.5
1700	1888341	-3.9	-7364529	-4.05	-7647780.1
1800	2958575	-3	-8875726	-3.45	-10207085
1900	4331234	-1.8	-7796220	-2.4	-10394961
2000	4826824	-0.9	-4344142	-1.35	-6516212.4
2100	4475067	-0.2	-895013	-0.5	-2237533.5
2200	4221042	0.6	2532625	0.3	1266312.6
2300	3252556	1.1	3577812	0.9	2927300.5
2400	2565231	1.3	3334800	1.2	3078277.2
2500	1850184	1.6	2960294	1.5	2775275.6
2600	1515297	1.6	2424475	1.6	2424475.4
2700	1259183	1.8	2266529	1.7	2140610.5
2800	896353	1.8	1613435	1.8	1613435.2
2900	788306	1.7	1340120	1.75	1379534.8
3000	458884	1.8	825992	1.75	803047.72
3100	282234	1.9	536245	1.85	522133.19
3200	318752	1.9	605629	1.9	605628.68
Total	38618705		-19122836		-29720124
Mean ba		-0.50		-0.77	

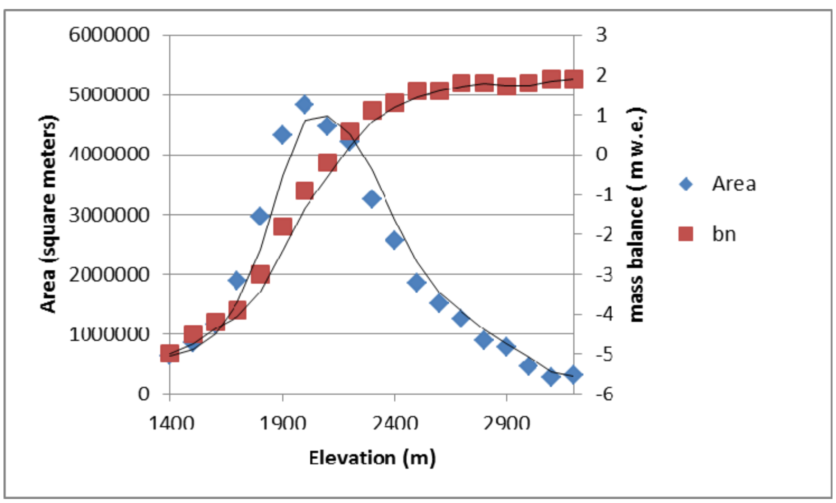

Figure 6. Mean balance gradient for the 1990-2010 period and hypsometry of Mount Baker glaciers from 2009.

Median Elevation Mass Balance Assessment

Kuhn et al (2009) developed a means to transfer the balance gradient from a measured to an unmeasured glacier to determine mass balance. The method is based on the change in median elevation of the glacier. The balance gradient is transferred along the axis of elevation with the median elevations having equivalent mass balances at that point. The median elevation for the index glaciers is 1950 m and for all Mount Baker glaciers is 2000 m. This difference leads to an elevation shift of the balance gradient of 50 m. With the adjusted values of mass balance than inputted into Table 3, the mean ba is -0.77 ma^{-1} (Table 3). This mass balance value is significantly more negative than that determined from the other methods. The small change in the median elevation from the index glaciers to the entire Mount Baker and the steep balance gradient suggest that this balance gradient transfer yields reasonable results, but not as accurate as the direct measurement based methods.

Table 3 Mean annual balance of Mount Baker glaciers assessed using four different methods.

Direct measurement method	*AAR method*	*Balance gradient method*	*Median Elevation Adjustment method*
-0.51 ma^{-1}	-0.55 ma^{-1}	-0.51 ma^{-1}	-0.77 ma^{-1}

CONCLUSIONS

The mass balance of glaciers on Mount Baker from 1990-2010 have been significantly negative. Mass balance assessment of the mass balance of all glaciers has been made using several methods (Table 3) 1) direct observations of the annual balance on three glaciers, -0.51 ma^{-1} 2) from the observed ba-AAR relationship on the three index glaciers -0.55 ma^{-1} 3) calculated from the observed balance gradient on three glaciers and the observed glacier covered area -0.50 ma^{-1} , 4) adjusting the balance gradient for the different median elevation of all Mount Baker glaciers compared to the three index glaciers, -0.77 ma^{-1}. The first three methods all yield mean ba of -0.50 ma^{-1} to -0.55 ma^{-1}, indicating each is a reasonable means of assessment. The fourth method yielded a mean ba of -0.77 ma^{-1}, significantly more negative, suggesting this is not the best approach. The cumulative loss of 10 m.w.e. from Mount Baker glaciers from 1990-2010 is 12-20% of their entire volume. This mass loss had led to significant retreat of all of the glaciers and will lead to continued retreat.

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