HYDROLOGICAL PROCESSES
Hydrol. Process. **26**, 2601–2607 (2012)
Published online 17 July 2012 in Wiley Online Library
(wileyonlinelibrary.com) DOI: 10.1002/hyp.9453

Mass balance loss of Mount Baker, Washington glaciers 1990–2010

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Abstract:

Mount Baker, North Cascades, WA, has a current glacierized area of 38.6 km^2. From 1984 to 2010, the North Cascade Glacier Climate Project has monitored the annual mass balance (Ba), accumulation area ratio (AAR), terminus behaviour and longitudinal profiles of Mount Baker glaciers. The Ba on Rainbow, Easton and Sholes Glaciers from 1990 to 2010 averaged -0.52 m w.e. a^{-1}(m a^{-1}). Terminus observations on nine principal Mount Baker glaciers, 1984–2009, indicate retreat ranging from 240 to 520 m, with a mean of 370 m or 14 m a^{-1}. AAR observations on Rainbow, Sholes and Easton Glaciers for 1990–2010 indicate a mean AAR of 0.55 and a steady state AAR of 0.65.

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 7 years to assess Mount Baker glacier mass balance. Utilizing the AAR–Ba relationship for the three glaciers yields a mean Ba of -0.55 m a^{-1} for the 1990–2010 period, 0.03 m a^{-1} higher than the measured mean Ba. The mean Ba based on the AAR–Ba relationship for the entire mountain from 1990 to 2010 is -0.57 m a^{-1}. The product of the mean observed mass balance gradient determined from 11 000 surface mass balance measurements and glacier area in each 100-m elevation band on Mount Baker yields a Ba of -0.50 m a^{-1} from 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 Ba of -0.77 m a^{-1} from 1990 to 2010. All but one estimate converge on a loss of -0.5 m a^{-1} for Mount Baker from 1990 to 2010. This equates to an 11-m loss in glacier thickness, 12–20% of the entire 1990 volume of glaciers on Mount Baker.

KEY WORDS glacier mass balance; North Cascades; accumulation area ratio; balance gradient

Received 24 August 2011; Accepted 17 April 2012

INTRODUCTION

Glaciers have been studied as sensitive indicators of climate for more than a century (Forel, 1895). Annual mass balance measurements are the most accurate 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 number of benchmark glaciers around the world were chosen where mass balance would be monitored. This network has proven valuable, but in many areas, the number of glacier is limited; for example, there is just one benchmark glacier in the conterminous United States South Cascade Glacier (Figure 1) (Fountain *et al*., 1991). Glacier mass balance varies because of geographic characteristics such as aspect, elevation and location with respect to prevailing winds. Because 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 covered 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, WA, glaciers to regional climate change (Pelto, 1988). The annual observations include mass balance, terminus behaviour, glacier surface area and accumulation area ratio (AAR). Annual mass balance (Ba) measurements have been continued on the eight original glaciers that still exist. Two glaciers have disappeared: the Lewis Glacier and Spider Glacier (Pelto, 2008). In 1990, Easton and Sholes Glaciers were added to the annual balance programme to offset the loss. The AAR is the fraction of a glacier that is in the accumulation area at the end of the melt season; an AAR of 0.90 indicates that 90% of the glacier has retained firn at summer's end.

Three of the glaciers currently monitored by the NCGCP, Easton, Rainbow and Sholes Glaciers, are on Mount Baker. A stratovolcano, Mount Baker is the highest peak in the North Cascades at 3286 m. Mount Baker has the largest contiguous network of glaciers in the mountain range with 12 significant glaciers covering 38.6 km^2 and ranging in elevation from 3250 m to 1320 m a.s.l. (Figure 1).

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 AAR observations and annual balance measurements on Mount Baker glaciers

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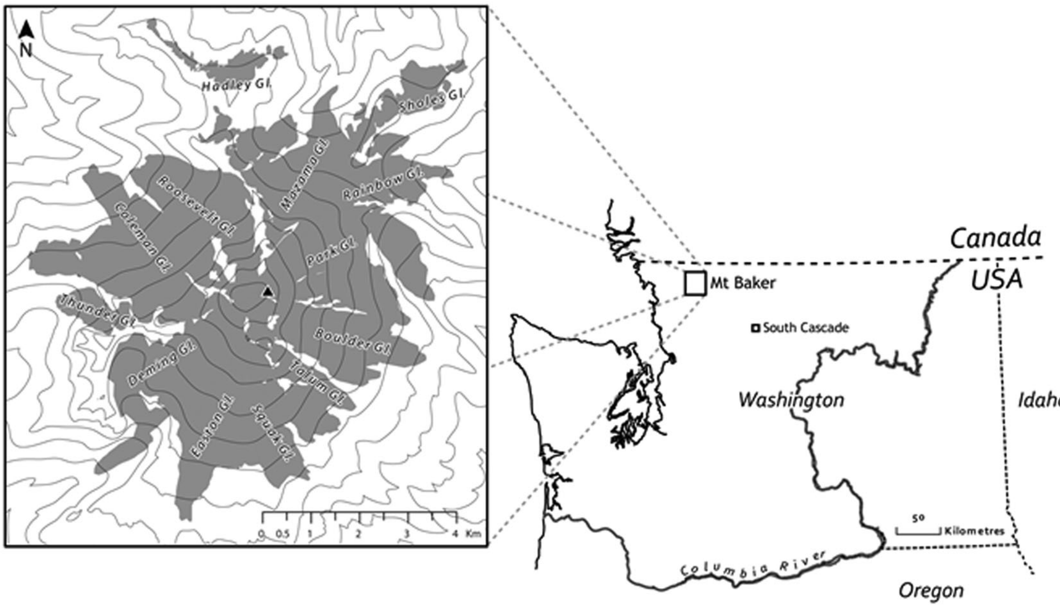

Figure 1. Base map delineating the glaciers of Mount Baker

provides an opportunity to assess the mass balance of the entire glacier complex from 1990 to 2010 using several methods for comparison and validation. The validation can identify the best regional method for mass balance assessment that can be widely applied to glaciers without detailed mass balance records (Khalsa *et al*., 2004).

At regional scales and on specific glaciers, there are two common proxies for assessing mass balance without detailed observations. They are the AAR and equilibrium line altitude (ELA) that can be derived from satellite imagery (Østrem, 1975; Racoviteanu *et al*., 2008). 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 glaciers because of variability of snow accumulation from impacts of wind and avalanche redistribution. Ascribing the ELA is also difficult when a recent digital elevation model (DEM) is not available, particularly when glacier surface elevation is changing rapidly. AAR is a more accurately determined parameter and a better proxy in this case. Rabatel *et al*. (2008) and Dyurgerov (1996) developed methods to derive mass balance from long-term AAR observations. The AAR–Ba method has proven reliable (Hock *et al*., 2007; Racoviteanu *et al*., 2008; Pelto, 2010). The World Glacier Monitoring Service (WGMS) has adopted the reporting of AAR with all mass balance values (WGMS, 2007, 2009) and plotting the relationship for each glacier. AAR is a parameter that can be evaluated using satellite imagery, providing an efficient mechanism for utilization of AAR-based mass balance determination on numerous glaciers (Kulkarni, 1992).

MOUNT BAKER GLACIER BEHAVIOUR

From 1920 to 1945, Mount Baker glaciers were all retreating (Hubley, 1956; Harper, 1993; Pelto, 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 (Long, 1955; Hubley, 1956; Burbank, 1981).

Hubley (1956) and Long (1956) noted that North Cascade glaciers began to advance in the early 1950s. This change was reflected in the mass balance of North Cascade glaciers. From 1944 to 1976, conditions became cooler, and precipitation increased (Hubley, 1956; Tangborn, 1980; Pelto, 1993; Kovanen, 2003). Approximately half the North Cascade glaciers advanced during the 1950–1979 period, while the remaining glaciers continued to retreat at varying rates (Pelto and Hedlund, 2001). Advances of Mount Baker glaciers ranged from 120 to 750 m, an average of 480 m, and ended in 1978 (Heikkinen, 1984; Harper, 1993; Pelto, 1993). From 1977 to 2009, mass balance has been negative (Pelto, 2009) driven initially by a drier–warmer climate in the Pacific Northwest from 1978 to 1998 (Ebbesmeyer *et al*., 1991) and by warmer conditions despite above-average precipitation from 1999 to 2010 (Casola *et al*., 2009). The impact on North Cascade glacier mass balance is evident from the US Geological Survey long-term record of South Cascade Glacier (1958–2009) and Place Glacier, British Columbia. On South Cascade Glacier, mean annual balance was $-0.15\,\mathrm{m\,a^{-1}}$ from 1958 to 1976, in contrast to $-1.15\,\mathrm{m\,a^{-1}}$ from 1977 to 1998 (Krimmel, 2001) and $-0.88\,\mathrm{m\,a^{-1}}$ from 1999 to 2009.

The retreat and negative mass balances from 1977 to 2009 have been noted by Bidlake *et al*. (2007) and Pelto (2008, 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 1970s–early 1980s). In each case, a maximum advance moraine had been emplaced. By 1997–1998, the average retreat had been

−197 m (Pelto and Hedlund, 2001). The retreat has continued to 2010 with the average retreat of 370 m for the nine principal glaciers (Table I).

METHODS

Annual mass balance is the difference of accumulation and ablation over the balance year (Cogley *et al*., 2011). NCGCP essentially measures conditions on a glacier near the time of minimal mass balance at the end of the water year by using a fixed date method. 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.

The 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; the error range has been observed at ±0.10–0.15 m a^{-1} (Pelto, 2000). Rainbow, Sholes and Easton Glaciers 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 to 2750 m. On Rainbow Glacier, there are 160 sites from 1400 to 2200 m. On Sholes Glacier, the network extends from 1600 to 2000 m with 80 sites. This provides approximately 480 point measurements of mass balance each year from 1400 to 2900 m. The best fit regression line through this data for 1990–2010 provides the average balance gradient for Mount Baker used to directly calculate mass balance (Table II).

Accumulation area ratio observations are completed each year on Rainbow, Sholes and Easton Glaciers. The snowline is delineated using photographs and GPS measurement on the glacier surface. The ELA is plotted on the mass balance map of the glacier completed annually and the fraction of the glacier above the ELA determined. 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 error in AAR assessment from aerial photography is 1–3% (Racoviteanu *et al*., 2008).

The area covered by glaciers and the elevation distribution were determined from the 2009 NAIP (National Agriculture Imagery Program) 1-m resolution, 1:40 000-scale orthoimage, acquired in late August, combined with the National Elevation Dataset 10-m DEM of the Mount Baker area (vertical resolution ±7 m), based on based on scans of 1974–1975 topographic maps.

Mass balance is assessed in four ways: (1) a simple mean of the observed field mass balance, (2) a regression of mass balance and AAR (Kulkarni, 1992), (3) an overall mass balance assessed as the summation of the products of the mean mass balance for each elevation band and the glacier area in that elevation band and (4) a median elevation approach adjusting the balance gradient based on glacier median elevation (Kuhn *et al*., 2009).

RESULTS

Annual mass balance observations

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} (m a^{-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 Glaciers has been −0.58 m a^{-1} from 1990 to 2009 (Figure 2) and −0.51 m a^{-1} from 1990 to 2010. This is comparable with the mean annual balance on South Cascade Glacier of −0.78 m a^{-1} from 1990 to 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 (Post *et al*., 1971; Harper, 1993). The increase in negative mass balance during a period of substantial

Table I. 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

Table II. 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 (m)	Area (m^2)	ba (m)	Ba total (m^3)	ba-adj. (m)	Ba total adj. (m^3)
1400	629 087	−5	−3 145 435	−5	−3 145 435
1500	851 245	−4.5	−3 830 601	−4.75	−4 043 412
1600	1 164 077	−4.2	−4 889 125	−4.35	−5 063 736
1700	1 888 341	−3.9	−7 364 529	−4.05	−7 647 780
1800	2 958 575	−3	−8 875 726	−3.45	−10 207 085
1900	4 331 234	−1.8	−7 796 220	−2.4	−10 394 961
2000	4 826 824	−0.9	−4 344 142	−1.35	−6 516 212
2100	4 475 067	−0.2	−895 013	−0.5	−2 237 533
2200	4 221 042	0.6	2 532 625	0.3	1 266 312
2300	3 252 556	1.1	3 577 812	0.9	2 927 300
2400	2 565 231	1.3	3 334 800	1.2	3 078 277
2500	1 850 184	1.6	2 960 294	1.5	2 775 275
2600	1 515 297	1.6	2 424 475	1.6	2 424 475
2700	1 259 183	1.8	2 266 529	1.7	2 140 610
2800	896 353	1.8	1 613 435	1.8	1 613 435
2900	788 306	1.7	1 340 120	1.75	1 379 534
3000	458 884	1.8	825 992	1.75	803 047
3100	282 234	1.9	536 245	1.85	522 133
3200	318 752	1.9	605 629	1.9	605 628
Total	38 618 705		−19 122 836		−29 720 124
Mean Ba		−0.50		−0.77	

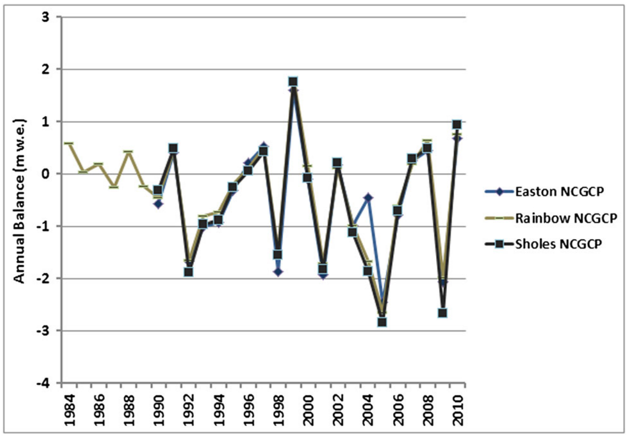

Figure 2. The annual balance of Rainbow, Sholes and Easton Glaciers

retreat suggests that the current retreat is insufficient for the glaciers to approach equilibrium.

AAR–Ba relationship

A comparison of annual AAR and Ba observations in WGMS (2006; 2008) indicates correlation coefficients ranging from 0.70 to 0.92 for 15 glaciers with at least 10 years of records. The AAR0 value is the AAR for a glacier with an equilibrium mass balance (Meier and Post, 1962). Muller and Braithwaite (1980) noted that the AAR0 for an alpine glacier with an equilibrium balance was 0.67. The mean AAR0 reported for 89 temperate alpine glaciers is 0.57 (WGMS, 2008, 2009). The regression line from the plot of the AAR and Ba for Rainbow, Sholes and Easton Glaciers indicates an AAR0 of 0.64 and a correlation coefficient of 0.89 (Figure 3). A comparison of the observed AAR in 2009 of these three glaciers of 0.34 *versus* that for the entire mountain of 0.39 indicates the slightly higher AAR of Mount Baker glaciers overall than the three index glaciers (Figure 4). In years where the AAR is 0.50 or less for the index glaciers, the AAR of all Mount Baker glacier is greater on average by 0.03. During years when the AAR on the index glaciers is greater than the ELA0 of 0.67, there is not a significant difference in the AAR between the two groups. This suggests a slightly different slope to the Ba–AAR relationship but too few data points to construct with confidence. In this study, we assume the same mass

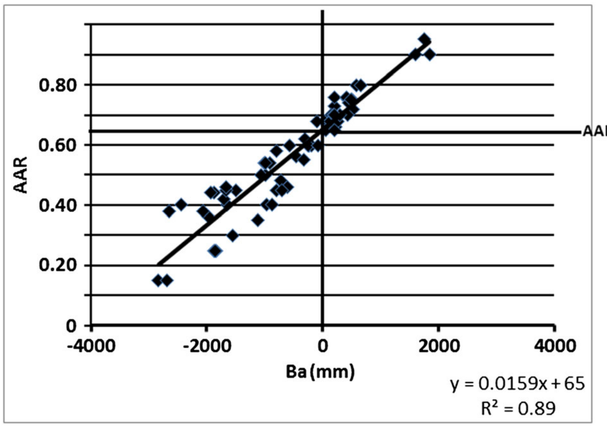

Figure 3. The relationship of annual balance (Ba) and accumulation area ratio (AAR) of Sholes, Easton and Rainbow Glaciers. The *y*-intercept of 0.65 indicates the equilibrium balance AAR. The correlation coefficient of 0.89 indicates the usefulness of the measure

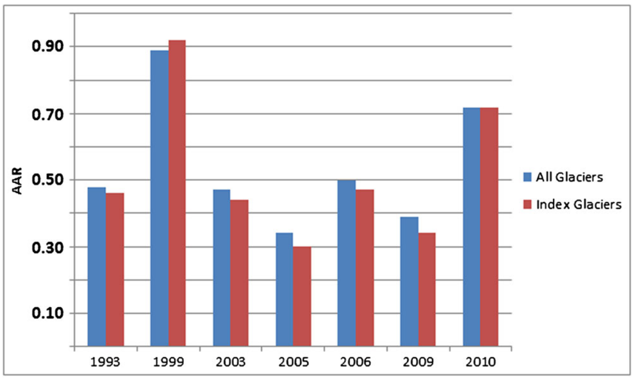

Figure 4. Relationship between the AAR of the index glaciers and all 12 glaciers in selected years. The index glaciers have a lower AAR during negative balance years

balance–AAR relationship for the entire mountain as for the three index glaciers but adjust the AAR by 0.03 for years when the AAR is below 0.50. The mean Ba derived from the AAR relationship for the index glaciers from 1990 to 2010 is 0.55 m a^{-1} and Ba for the entire mountain of 0.57 m a^{-1}.

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 Glaciers. The area elevation distributions for each glacier were obtained by combining mapped glacier limits from the analysis of the 2009 NAIP orthoimage with elevation data from the 10-m DEM (Figure 6). Glacier polygons were then separated into 100-m elevations bands, such that each subdivision contains the total glacier area that falls within that elevation range (Table II). The mean Ba derived from this balance gradient method is −0.50 m a^{-1} for the 1990–2010 period.

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 Ba. 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 inputted into Table II, the mean Ba is −0.77 m a^{-1} (Table III). This Ba value is significantly more negative than that determined from the other methods. The small change in the median elevation from the index glaciers to all Mount Baker glaciers and the steep balance gradient suggests that this balance gradient transfer should yield reasonable results. The result is not as accurate as the direct measurement-based methods because of the extrapolation required.

DISCUSSION

Mass balance assessment of all glaciers has been made using several methods (Table III): (1) direct observations of the annual balance on three glaciers, −0.51 m a^{-1}; (2) from the observed Ba–AAR relationship on the three index glaciers −0.55 m a^{-1}and 0.57 m a^{-1} for the entire mountain; (3) calculated from the observed balance gradient on three glaciers and the observed glacier covered area, −0.50 m a^{-1}; and (4) adjusting the balance gradient for the different median elevation of all Mount Baker glaciers compared with the three index glaciers, −0.77 m a^{-1}. The first three methods all yield mean Ba of −0.50 m a^{-1} to −0.55 m a^{-1}, indicating that each provides a reasonable assessment. The fourth method yielded a mean Ba of −0.77 m a^{-1}, significantly more negative, suggesting that this is not the best approach.

Deriving Ba from AAR observation or from balance gradient information provided accurate measures of mass balance compared with detailed field observations. The balance gradient method is dependent on detailed mass balance records from a glacier in the specific region, limiting its applicability. The latter method allows for calculation of mass balance of North Cascade glaciers from end of the year observations of the snowline position, which is the only observation needed to determine AAR along with a recent glacier DEM.

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

Direct measurement method	AAR method	Balance gradient method	Median Elevation Adjustment method
−0.51 m a^{-1}	−0.55 m a^{-1}	−0.51 m a^{-1}	−0.77 m a^{-1}

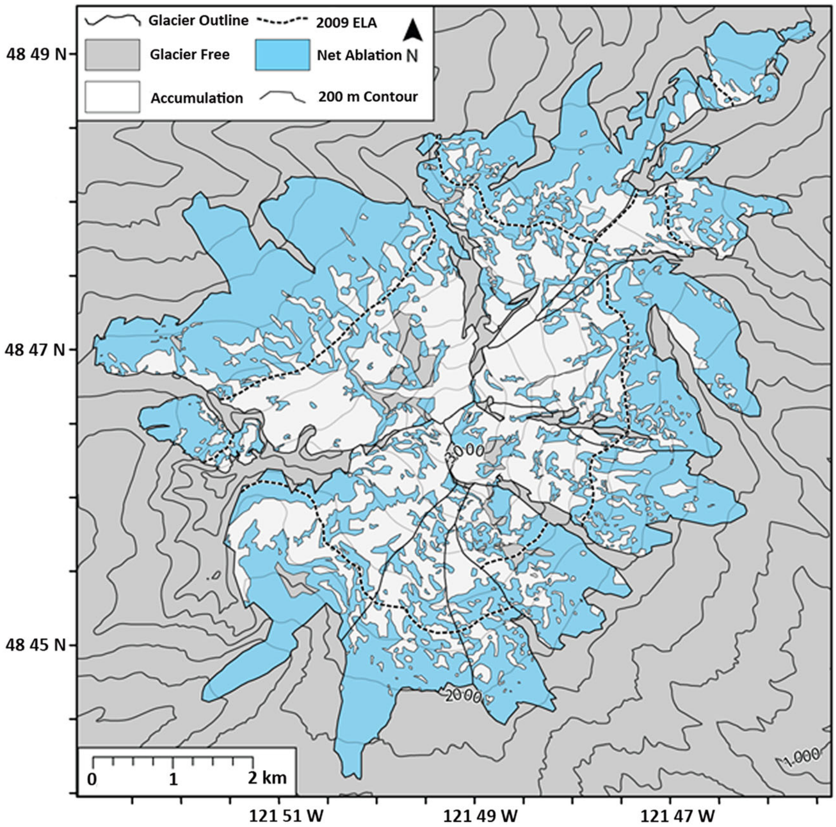

Figure 5. The 2009 AAR assessment from aerial photography. White is snow cover and blue is exposed glacier ice

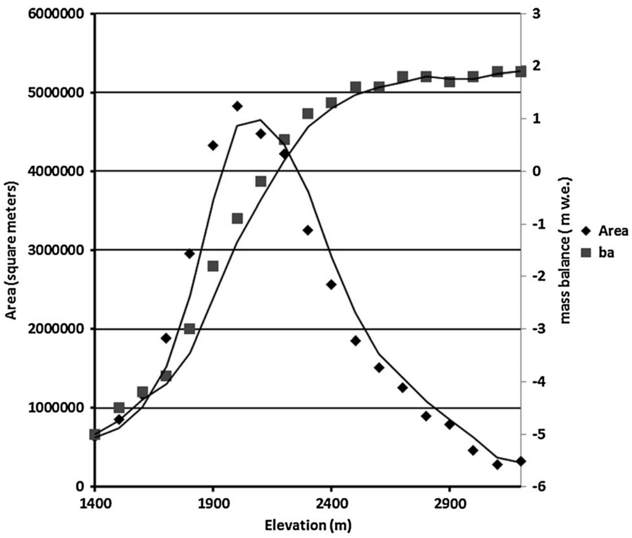

Figure 6. Mean balance gradient for the 1990-2010 period and hypsometry of Mount Baker glaciers from 2009

CONCLUSION

The mass balance of glaciers on Mount Baker from 1990 to 2010 have been significantly negative. The cumulative loss of 10–11 m w.e. from Mount Baker glaciers from 1990 to 2010 is 12–20% of their entire volume. This mass balance loss had led to significant retreat of all of the glaciers and will lead to continued retreat.

Assessment of the Ba of Mount Baker glaciers can be reasonably completed from AAR observations alone, for the current climate and general glacier configuration. Significant changes in either area or climate may require a recalibration of the AAR–Ba relationship. The results support the concept that reliable Ba assessment can be derived from AAR observations when detailed Ba observations from one glacier in the region can provide a baseline for both the balance gradient and the AAR–Ba relationship.

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