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Forecasting temperate alpine glacier survival from accumulation zone observations

M. S. Pelto

Nichols College Dudley, MA 01571, USA

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Correspondence to: M. S. Pelto (mspelto@nichols.edu)

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Abstract

For temperate alpine glaciers survival is dependent on the consistent presence of an accumulation zone. The lack of a consistent and persistent accumulation zone leads to substantial thinning of the glacier in the accumulation zone. Accumulation zone thinning is evident in satellite imagery or field observation based the emergence of new rock outcrops or the recession of the margin of the glacier in the accumulation zone along a substantial portion of its perimeter. In either case the accumulation zone is no longer functioning as an accumulation zone and survival is unlikely. In both the North Cascades and Wind River Range nine of the fifteen glaciers examined are forecast not to survive the current climate or future additional warming. The results vary considerably with adjacent glaciers having a different survival forecast. This emphasizes the danger of extrapolating survival from one glacier to the next. This trait also emphasizes the value of a simple forecasting tool that can be applied to all glaciers. The automated remote sensing based glacier classification schemes developed offer the potential for automating this process based on the changes in the glacier outline.

1 Introduction

Glaciers have been studied as sensitive indicators of climate for more than a century and are now part of the Global Climate Observing System (Haeberli et al., 2000). Observations of alpine glaciers most commonly focus on changes in terminus position, to identify glacier response to climate changes (Oerlemans, 1994) and mass balance to assess annual volume change (WGMS, 2008). The worldwide retreat of mountain glaciers is one of the clearest signals of ongoing climate change (Haeberli and Hoelzel, 1995; Oerlemans, 1994). The retreat is a reflection of strongly negative mass balances over the last 30 years (WGMS, 2007). Mass balance is the most sensitive climate parameter for glaciers because it is a direct response to local weather conditions for a year (Haeberli and Hoelzle, 1995; Pelto and Hedlund, 2001). The change in glacier length is a smoothed and delayed response to the mass balance changes (Haeberli and Hoelzle, 1995). The recent rapid retreat has led to glaciers disappearing (Pelto, 2006) and will lead to more highlighting the importance of being able to forecast glacier survival.

Temperate alpine glaciers in the Andes, European Alps, Himalaya, Norway, Iceland, Western Canada and Pacific Northwest, United States are critical to water resources. Alpine glacier runoff is at a maximum during warm, dry period when other sources of contribution are at a minimum. Their disappearance will have large economic and societal impacts, for example on the hydrologic regime, hydropower, tourism, fishing, agriculture, and natural hazards (Post et al., 1971; Hock, 2006). Recent climate change has caused ubiquitous retreat of Pacific Northwest glaciers (Pelto and Hedlund, 2001; Key et al., 2002). In 1992, all 47 glaciers termini observed in the North Cascades were retreating (Pelto and Hedlund, 2001), by 2006 four had disappeared Lewis Glacier, David Glacier, Spider Glacier and Milk Lake Glacier (Pelto, 2006). Long term water resource management than requires forecasts of individual glacier survival, as the impacts are watershed specific and significant.

Terminus change observations identify the response of the glacier to recent climate changes; however, terminus change does not identify the ability of a glacier to survive. A glacier can retreat rapidly and still reestablish equilibrium. Glacier mass balance measurements identify the rate of volume loss on an annual basis, since significant negative balances can accompany a glacier that still has a substantial accumulation zone. Only the lack of a consistent accumulation zone will lead to the failure of a temperate alpine glacier to survive. This requires that glacier survival assessment must focus on the accumulation zone not the terminus.

The goal of this paper is to develop a simple method of forecasting temperate alpine glacier survival utilizing visual examination of satellite images, identifying features indicating substantial glacier accumulation zone thinning. The same method could be applied to glacier photographs, however, there is typically not a comprehensive repeat collection of photographs that is as easily assessed as satellite imagery. Ideally identifying the thinning would utilize long term glacier mass balance data, such data exists for just 30 glaciers worldwide (WGMS, 2007; WGMS 2008). Remapping the surface elevation of each glacier and developing a DEM for each observation period, identifies thickness changes as well, but exist for few glaciers (Paul et al., 2004; Pelto, 2006). To complete repeat mapping on all glaciers in a region has to date been a prohibitively costly and time consuming procedure. Repeat profiling of a longitudinal profile also yields thickness change over time on a glacier based (Arendt et al., 2002; Pelto and Hartzell, 2003). Ground based mapping of profiles is not possible on large glaciers or on numerous glaciers. Airborne laser profiling is also not feasible on small or on a large population of glaciers. Recently attention has shifted to the potential for assessing changes in areal extent and characteristics of all glaciers using satellite imagery (Paul et al., 2004; Kaab et al., 2002; Andreassen et al., 2008).

2 Distinguishing equilibrium versus disequilibrium response

2.1 Equilibrium response

Glacier terminus retreat results in the loss of the low elevation region of the glacier. Since higher elevations are cooler than lower ones, the disappearance of the lowest portion, terminus region of the glacier reduces overall ablation, thereby increasing mass balance and potentially reestablishing equilibrium (Oerlemans, 2001; Pelto, 2006). Typically a glacier's thinning is greatest at the terminus, and at some distance above the terminus, usually in the accumulation zone, the glacier is no longer thinning appreciably even during retreat (Schwitter and Raymond, 1993). This behavior of greatest thinning at the terminus suggests a glacier that will retreat to a new stable position (Schwitter and Raymond, 1993), an equilibrium response. The result is minimal changes in the glacier thickness and marginal position in the accumulation zone, and limited reductions in accumulation zone crevassing due to reduced velocity.

2.2 Disequilibrium response

If a non-surging temperate alpine glacier is experiencing extensive thinning and marginal retreat in the accumulation zone the glacier is in disequilibrium (Pelto, 2006). The thinning is indicative of the lack of a consistent accumulation zone. An inconsistent accumulation zone is identified by the periodic loss of nearly all accumulated snow and firn in the accumulation zone, repeatedly exposing multiple annual firn layers to ablation. This is observed to have occurred in the North Cascades in 1985–1987, 1992–1994, and 2003–2005. There are years where an accumulation zone exists, but this accumulation does not persist through the aforementioned years of extensive negative mass balances. There is no significant region of persistent snow-firn retention resulting in a more unstable form of retreat with substantial thinning throughout the length and breadth of the glacier (Paul et al., 2004; Pelto, 2006). A glacier in this condition is unlikely to survive in anything like its present extent given current climate. In the Swiss Alps Paul et al. (2004) identify glaciers that are disintegrating due to massive down-wasting, as undergoing a non-steady state response.

2.3 Delineating the response

Meier and Post (1962) used oblique areal photography to assess glacier activity using the appearance of the terminus, focusing on the extent of crevassing, convexity of the terminus, extent of recent deglaciated terrain and moraine cover on glacier termini in the Pacific Northwest. They were able to distinguish stagnating glacier termini from slowly retreating termini, the goal at the time was not to assess the potential for survival. It has become practical to examine the terminus and areal extent change of all glaciers in the region using repeat satellite imagery or a comparison of satellite imagery and previous mapping (Key et al., 2002; Andreasson et al., 2008; Paul et al., 2004). This alone does quantify the extent of the retreat and area loss, but not the nature of the equilibrium or disequilibrium response. The rate of loss of glacier area can be extrapolated to determine if a glacier is likely to survive as has been done in

Glacier National Park (Hall and Fagre, 2003). However, this ignores the fundamental viability of a glaciers accumulation zone. Hoffman et al. (2007) has noted that for some small glaciers the retreat rate declines substantially and is less sensitive to climate once the glacier has retreated to its principal accumulation area. The rate of change is a useful measure of glacier change but not diagnostic of glacier disappearance. Paul et al. (2004) and Hoffman et al. (2007) both noted that neighboring glaciers can have vastly different responses to climate change, and thus the forecast for one glacier cannot be extrapolated reliably to other glaciers. This indicates that forecasting glacier survival requires examination of individual glaciers and assessment of the existence of significant widespread thinning in the accumulation zone.

Paul et al. (2004) developed criteria as indicators of glacier down-wasting and glacier areas experiencing rapid disintegration using satellite imagery emergence of rock outcrops in the accumulation zone, disintegration and shrinkage along the entire perimeter, pro-glacial lake formation and separation from tributaries. Pelto (2006) used retreat of the head of the glacier as an indicator of rapid glacier disappearance. The above criteria provide direct quantifiable evidence of glacier thinning. The goal of a simple forecast tool for glacier survival is that it can based simply on visual inspection of satellite imagery in comparison with previous images, photographs or maps. This makes the forecast tool robust and nearly universally applicable

In this study we forecast glacier survival in the North Cascade Range, Washington (NC) and Wind River Range, Wyoming (WR) based on two criteria: 1. Recession of the glacier margin in the accumulation zone. 2. Emergence of significant rock outcrops in the accumulation zone.

3 Recent glacier changes

Recent climate change has caused ubiquitous retreat of Pacific Northwest glaciers (Pelto and Hedlund, 2001; Key et al., 2002; Hall and Fagre, 2003). Three specific period of glacier behavior are evident for the last century. The first is a ubiquitous rapid retreat of Pacific Northwest alpine glaciers from 1890 to 1949 due to progressive temperature rise (Meier and Post, 1962; Hubley, 1956). The second period from 1950–1975 was in response to cooler and wetter conditions (Hubley, 1956). Many North Cascade glaciers began to advance in the early 1950s, after 30 years of rapid retreat (Hubley, 1956). In the Wind River Range no advances were reported, though the rate of retreat decreased from 1950–1975 (Pochop et al., 1989). The third period is the current ongoing rapid retreat due to warmer conditions that began in 1977 (Pelto, 2006). The retreat and negative mass balances of the 1977–2007 period have been without exception in the two study areas. Between 1979 and 1984, 35 of the 47 North Cascade glaciers observed annually had begun retreating (Pelto and Hedlund, 2001). By 1992, all 47 glaciers termini observed in the NC were retreating (Pelto, 1993). By 2006, four had disappeared Lewis Glacier, David Glacier, Spider Glacier and Milk Lake Glacier (Pelto, 2006).

4 Methods

In the North Cascades repeat longitudinal profiles have been completed on 15 glaciers (Pelto and Hartzell, 2004; Pelto, 2006) to compare to profiles from the USGS maps and previous profile surveys. The goal was to remap glacier surface elevation along the profile to identify long term thickening or thinning. This data could then be used to verify the long term mass balance program on these glaciers (Pelto, 2007). Each longitudinal profile began and ended at fixed locations beyond the terminus and head of the glacier. The distance from the endpoints of the profiles to the glacier margin was also measured each year. In addition mass balance measurements along fixed transects across each glacier have been completed each summer on 10 of the glaciers and reported to the World Glacier Monitoring Service (WGMS, 2007). On three of the glaciers mass balance observations were begun, but discontinued due to either glacier loss or forest fires preventing access during several years. Mean annual mass balance has been −0.51 m/a, from 1984–2007 (Pelto, 2008). This represents a 20–40% loss in glacier volume in this interval for North Cascade glaciers (Pelto, 2008). Transects of interest here are those that begin and end at the lateral margin of the glacier in the accumulation zone. Each mass balance transect begins from a fixed point at the glacier margin and the distance between each measurement site is fixed, using a laser ranger with the spacing typically at 50 m. Each year the mass balance transects and centerline longitudinal profiles are repeated. By 1998, it was evident that accumulation zone marginal recession was occurring along the profiles and transects on a number of glaciers. This had not been an expectation in setting up the profiles and transects, but has since become a focus of annual observation along with terminus observation and annual balance.

In the WRR the changes are from 2005 SPOT images compared to USGS maps and aerial photography from the 1950's and 1960's to distinguish glacier changes. A manual delineation of glacier margins in the SPOT imagery is completed. For this purpose images had to be late in the melt season and in a low snow year, 2005 proved to be the ideal year for this purpose. The SPOT satellite images were then overlain on the USGS maps, using the corner coordinates for fitting. For each glacier examined we also had photographs of the glaciers from close to the date of the mapping from Austin Post (USGS) that verified the mapped marginal position was accurate for glacier extent. This guided selection of WRR glaciers. The best practice for identifying glacier changes would be to develop a DEM for the glacier for each time of observation (Paul et al., 2004). This method is intentionally not utilized as the goal is to derive a survival forecast based solely criteria observable in optical satellite imagery. For wider applicability it is important to have a simple forecast tool. This method can then be readily applied to all glaciers in a single satellite scene or aerial photograph.

5 Observations of accumulation zone change

5.1 North cascades

On Columbia Glacier a longitudinal profile has been completed in 20 of the last 25 years, and every year since 2000. Annual balance measurements from 1984–2007 indicate a mean annual balance of $-0.53\,\mathrm{m\,a^{-1}}$, and a mean AAR of 51. The distance from the fixed locations beyond the terminus and above the head of the glacier is 1800 m. From 1984 to 2007 the glacier terminus retreated 95 m, and the head of the glacier has retreated 55 m. The fixed location at the end of the profile which used to be a few meters from the glacier edge is now well up slope from the glacier edge (Fig. 1). This glacier requires an AAR of 0.62 to have an equilibrium balance (Fig. 2). In 1992, 1998, 2001, 2004, and 2005 the AAR was at or below 20. This indicates that there has not been a large persistent accumulation zone on Columbia Glacier in the last 20 years (Fig. 3). In 2005 in the accumulation zone annual firn layers were evident in the upper basin of the glacier (Fig. 3).

On Ice Worm Glacier the centerline longitudinal profile along which mass balance is also measured indicated a glacier length of 607 m in1985, and 475 m in 2007, the length had been reduced by 132 m. The distance from the benchmark beyond the head of the glacier to the glacier was 10 m in 1985 and is now 58 m, a 48 m recession. The terminus has retreated 84 m in the same period. The primary accumulation zone recession has been along the ridge on the southern margin of the glacier. A mass balance transect from the highest point on the glacier, near the southern lateral edge of the glacier was begun on the glacier 25 m below the ridgeline in 1985. By 2007 the glacier margin was 127 m from the ridgeline, indicating marginal recession of at least 102 m since 1985 (Fig. 4). This section of the glacier is its highest elevation section. In 1992, 1993, 1994, 1998, 2001, 2003, 2004, 2005 and 2006 this area retained now accumulation. Bare firn or ice has been exposed each of these years at some point in August.

On Lyman Glacier a centerline profile was begun at the head of the glacier in 1986 from a fixed location. This headwall location was the principal benchmark because the terminus ended in a calving ice face. The glacier terminus has been retreating at a rate of 9 $\mathrm{m\,a^{-1}}$ from 1986–2008; however, the length of the glacier has been declining at 13 m per year due to recession of the upper margin of the glacier. The distance to the edge of the glacier was 15 m in 1986 and 102 m in 2008, indicating a recession of 87 m. A comparison of the upper margin of the glacier in 1986 and 2008 illustrates the considerable new exposures of bedrock that had been at the base of the glacier in 1986 (Fig. 5). Lyman Glacier has had the lowest AAR of the 15 glaciers that have been part of the NCGCP mass balance program.

The White Chuck Glacier on 1984 USGS topographic maps features a northern branch and a southern branch, each with a separate accumulation zone, joining shortly just above the terminus. The USGS topographic maps of Glacier Peak from 1958 show the still large White Chuck Glacier the northern branch extended 2100 m from the terminus to the head of the glacier near Glacier Gap. The terminus retreated 450 m by 1984. By 1995 an additional retreat of 110 m had occurred, the entire northern branch was 1600 m long, and a new lake had formed at the terminus. The northern Branch was all stagnant ice in 1988, and had an AAR below 5 in 1987, 1992, 1993, 1994, and 1998. By 2002, the northern branch of the glacier was entirely gone. Instead of an ice-filled valley extending 1600 m from the lake to Glacier Gap at the former head of the glacier, there was only a boulder-filled basin (Fig. 6). The retreat of the White Chuck glacier has led to the development of five new lakes, three in the last twenty years. The two smallest of these may fill in with sediment.

On Lynch Glacier the upper margin of the accumulation zone has remained fixed and has retained a thick snowpack even in the most negative mass balance years. There is considerable wind drift accumulation at this point. A transect at the mid-point of the accumulation zone, across the glacier has indicated recession on both the east and west margin of the glacier. On its east margin Lynch Glacier in 1985 was connected to the Daniels Glacier across a ridge that now separates the glaciers. On the west margin a transect ended at the narrow bedrock ridge between the glacier and a cliff. This ridge has expanded to a width of over 75 m, additional numerous rock ribs crossing a transect for the first 200 m of the transect. The east ridge is now continuous with no snow connection and has expanded to a width of 30 m since 1985 (Fig. 7). The combined narrowing from ridge to ridge has reduced the transect length by 105 m, versus a terminus retreat of 120 m since 1985.

Foss Glacier has lost 40% of its area since 1979 (Pelto, 2006). The glacier has had an AAR below 10 in 1992, 1998, 2001, 2004 and 2005. The result was rapid recession of the lateral margin of the glacier from the terminus to the head of the glacier and rapid terminus retreat. The glacier width, on a mass balance transect 150 m below the head of the glacier, has been reduced from 1040 m in 1985 to 620 m in 2005 (Fig. 8). Foss Glacier has no significant avalanche or wind drift accumulation locations that have large winter balances. Particularly the southern margin has receded; this section has been exposed firn or glacier ice by mid-August in each of the years with a low AAR.

In the North Cascades accumulation zone margins have been monitored on Rainbow Glacier, Sholes Glacier, Easton Glacier, Honeycomb Glacier and Lower Curtis Glacier with no significant recession observed. Each of these glaciers has retreated at least 100 m since 1980 with Easton, Rainbow and Honeycomb Glacier retreating more than 300 m. The terminus changes have to date represented the full response of the glacier to climate change. Two glaciers where mass balance observations were completed Spider and Lewis Glacier have completely melted away.

5.2 Wind river range

To test the method in a region without detailed field measurements, the Wind River Range, Wyoming is examined. Glaciers in the region have experienced ongoing negative balances and glacier shrinkage (Dyson, 1952; Pochop et al., 1989). Examination of Dinwoody Glacier and Gannett Glacier indicated relatively little change in terminus position or areal extent from 1958–1983 (Pochop et al., 1989). Since 1983 retreat rates have again accelerated on these two glaciers. There is are no recent field observations of mass balance, glacier thickness or glacier extent change in the Wind River Range, and satellite imagery is the only means to assess glacier response in the region to climate change over the last 40 years. USGS maps from 1966 are used to compare with SPOT imagery from 2005.

We chose 15 glaciers to examine from the largest in the range to several small glaciers. Marginal recession in the accumulation zone is evident on Baby Glacier, J Glacier, Twins Glacier, Grasshopper Glacier, Minor Glacier (Fig. 9), Heap Steep Glacier, Mammoth Glacier, Helen Glacier and Lower Fremont Glacier. On Minor Glacier the recession in the accumulation zone is most pronounced along the lateral margins and nearly the entire western portion of the accumulation zone directly above the lake has been lost. Knife Point Glacier has lost 31% of its area since 1966, but all the change is in the terminus area of the glacier, 280 m of retreat, and one small tributary chute on its northern margin. Grasshopper Glacier (Fig. 10) has experienced 640 m of retreat and 27% reduction in areal extent, with much of the reduction in the accumulation zone, marginal recession in the accumulation averaging 60 m (Fig. 10). Of the 15 glacier examined six have experienced insignificant change in accumulation zone glacier margin (Table 2). Gannet Glacier and Dinwoody Glacier are the two largest glaciers in the range and despite significant terminus retreat, the accumulation zones experienced little evident change. On Fremont Glacier (Fig. 11) the change in areal extent is 10%, but almost exclusively at the terminus. These examples indicate the difficulty in using only terminus change or areal extent change in determining survival. This also indicates the difficulty in extrapolating behavior from several glaciers to an entire range of glaciers (Paul et al., 2004; Pelto and Hedlund, 2001).

6 Conclusions

Glacier termini can retreat substantially without causing a glacier to disappear. A glacier cannot survive if it no longer has a consistent accumulation zone. To forecast glacier survival then requires examination of the accumulation zone. In both the North Cascades and Wind River Range two-thirds of the examined glaciers are forecast not to survive the current climate or future additional warming. The assessment is based on accumulation zone thinning as evident by the emergence of new rock outcrops or the recession of the margin of the glacier in the accumulation zone along a substantial portion of it s perimeter. The results vary considerably with adjacent glaciers having different survival forecasts. This trait emphasizes the value of a simple forecasting tool that can be applied to all glaciers in a region. The automated classification schemes developed Andreassen et al. (2008) and Paul et al. (2004) offer the potential for automating this process based on the changes in the glacier outline. If the perimeter change is substantial for the majority of the glacier, its accumulation zone is no longer functioning as an accumulation zone and survival is unlikely.

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References

Andreassen, L. M., Paul, F., Kb, A., and Hausberg, J. E.: Landsat-derived glacier inventory for Jotunheimen, Norway, and deduced glacier changes since the 1930s, The Cryosphere, 2, 131–145, 2008,
http://www.the-cryosphere-discuss.net/2/131/2008/.

Arendt, A. A., Echelmeyer, K. A., Harrison, W. D., Lingle, C. S., and Valentine, V. B.: Rapid wastage of Alaska glaciers and their contribution to rising sea level, Science, 297, 382–386, 2002.

Bidlake, W. R., Josberger, E. G., and Savoca, M. E.: Water, Ice, and Meteorological Measurements at South Cascade Glacier, Washington, Balance Years 2004 and 2005: US Geological Survey Scientific Investigations Report 2007–5055, 2007.

Haeberli, W. and Hoelzle, M.: Application for inventory data for estimating characteristics of and regional climate-change effects on mountain glaciers: a pilot study with the European Alps, Ann. Glaciol., 21, 206–212, 1995.

Haeberli, W., Cihlar, J., and Barry, R.: Glacier monitoring within the Global Climate Observing System, Ann. Glaciol., 31, 241–246, 2000.

Hall, M. P. and Fagre, D. B.: Modeled climate-induced glacier change in Glacier National Park, 1850–2100, Bioscience, 53(2), 131–140, 2003.

Hock, R.: Glacier melt – A review on processes and their modelling, Prog. Phys. Geogr., 29(3), 362–391, 2005.

Hoffman, M. J. Fountain, A. G., and Achuff, J. M.: 20th-century variations in area of cirque glaciers and glacierets, Rocky Mountain National Park, Rocky Mountains, Colorado, USA, Ann. Glaciol., 46, 349–354, 2007.

Hubley, R. C.: Glaciers of Washington's Cascades and Olympic Mountains: Their present activity and its relation to local climatic trends, J. Glaciol., 2(19), 669–674, 1956.

Kaab, A., Paul, F., Maisch, M., Hoelzle, M., and Haeberli, W.: The new remote-sensing-derived Swiss glacier inventory: II. First results, Ann. Glaciol., 34, 362–366, 2002

Key, C. H., Fagre D. B., and Menicke, R. K.: Glacier retreat in Glacier National Park, Montana, in: Satellite image atlas of glaciers of the world, Williams Jr., R. S. and Ferrigno, J. G., USGS Prof. Pap. 1386-J, 365–375, 2002.

Meier, M. F. and Post, A.: Recent variations in mass net budgets of glaciers western North America, IUGG/IAHS Pub., 58, 63–77, 1962.

Oerlemans, J.: Quantifying global warming from the retreat of glaciers, Science, 264, 243–245, 1994.

Oerlemans, J.: Glaciers and climate change, A. A. Balkena Publishers. 2001.

Paul, F., Kääb, A., Maisch, M., Kellenberger, T. W., and Haeberli, W.: The new remote-sensing-derived Swiss glacier inventory: I. Methods, Ann. Glaciol., 34, 355–361, 2002.

Paul, F., Kääb, A., Maisch, M., Kellenberger, T. W., and Haeberli, W.: Rapid disintegration of Alpine glaciers observed with satellite data, Geophys. Res. Lett., 31, L21402, doi:10.1029/2004GL020816, 2004.

Pelto, M. S.: The current disequilibrium of North Cascade Glaciers, Hydrol. Process., 20, 769–779, 2006.

Pelto, M. S.: Glacier annual balance measurement, forecasting and climate correlations, North Cascades, Washington 1984–2006, The Cryosphere, 2, 13–21, 2008, http://www.the-cryosphere-discuss.net/2/13/2008/.

Pelto, M. S. and Hedlund, C.: Terminus behavior and response time of North Cascade glaciers, Washington USA, J. Glaciol., 47, 497–506, 2001.

Pelto, M. S. and Riedel, J.: Spatial and temporal variations in annual balance of North Cascade glaciers, Washington 1984–2000, Hydrol. Process., 15, 3461–3472, 2001.

Pelto, M. S. and Hartzell, P. L.: Change in longitudinal profile on three North Cascades glaciers during the last 100 years, Hydrol. Process., 18, 1139–1146, 2004.

Pochop, L., Marston, R., Kerr, G., and Varuska, M.: Long-term trends in glacier and snowmelt runoff Wind River Range, Wyoming, Wyoming Water Research Council 89-05, 1989.

Post, A., Richardson, D., Tangborn W. V., and Rosselot, F. L.: Inventory of glaciers in The North Cascades,Washington, US Geological Survey Prof. Paper, 705-A, 1971.

Schwitter, M. P. and Raymond, C.: Changes in the longitudinal profile of glaciers during advance and retreat, J. Glaciol, 39(133), 582–590, 1993.

WGMS: Glacier Mass Balance Bulletin No. 9 (2004–2005). edited by: Haeberli, W., Zemp, M. and Hoelzle, M., ICSU (FAGS)/IUGG (IACS)/UNEP/UNESCO/WMO, World Glacier Monitoring Service, Zurich, Switzerland, 2007.

WGMS: Global Glacier Changes: facts and figures, edited by: Zemp, M., Roer, I., Kääb, A., Hoelzle, M., Paul, F., and Haeberli, W., UNEP, World Glacier Monitoring Service, Zurich, Switzerland, 2008.

Table 1. The areal extent and change in areal extent of North Cascade glaciers 1958–2003. Identified rock emergence (RE) and accumulation zone marginal retreat (MR), survival forecast, measured accumulation zone thinning in the field and resulting survival forecast.

Glacier	Area 1958 km^2	Area 2005 km^2	% Change 1958–2005	AZ Thinning (m)	Field Based SF	RE	MR
Yawning	0.2	0.16	20%	−5	Yes	no	no
Columbia	1	0.9	10%	−12	No	no	yes
Daniels	0.5	0.35	30%	−14	No	yes	yes
Easton	2.9	2.7	7%	−4	Yes	no	no
Foss	0.5	0.2	60%	−14	No	yes	yes
Honeycomb	3.5	3.1	11%	−5	Yes	no	no
Ice Worm	0.1	0.06	40%	−13	No	yes	yes
Lower Curtis	0.8	0.7	13%	−11	Yes	no	no
Lyman	0.5	0.3	40%	−15	No	no	yes
Lynch	1	0.6	40%	−11	No	yes	yes
Rainbow	1.9	1.7	11%	−3	Yes	no	no
Sholes	0.9	0.8	11%	−4	Yes	no	no
Spider	0.1	0	100%	−10	No	yes	yes
White River	1	0.7	30%	−24	No	yes	no
Whitechuck	1.9	0.6	68%	−18	No	yes	yes

Table 2. Identified rock emergence (RE) and accumulation zone marginal retreat (MR), and survival forecast for Wind River Range glaciers.

Glacier	RE	MR	Survival Forecast
Baby	no	yes	No
Dinwoody	no	no	Yes
Fremont	no	no	Yes
Gannett	no	no	Yes
Gooseneck	no	no	Yes
Heap Steep	yes	yes	No
Helen	no	yes	No
Knife Point	no	no	Yes
Mammoth	no	yes	No
Minor	yes	yes	No
Sphinx	no	no	Yes
Twins	yes	yes	No
L. Fremont	yes	yes	No
J	yes	yes	No
Grasshopper	yes	yes	No

Fig. 1. Columbia Glacier 1985 (above) and 2006 (below). The black line in the 2006 image indicates the upper margin of the glacier in 1986.

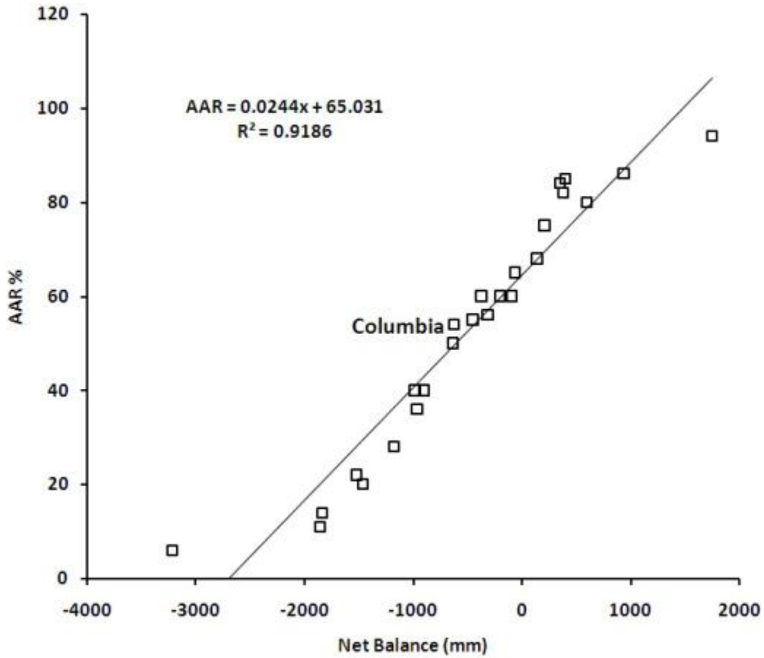

Fig. 2. A comparison of AAR and annual balance on Columbia Glacier from 1984–2007 indicates that an AAR of of 62 is required for equilibrium balances.

Fig. 3. Accumulation zone of the Columbia Glacier from the headwall. Notice the number of annual horizons exposed on 1 August 2005. This is the third consecutive year of significant negative annual balances, and follows 2004 when the AAR dropped below 20.

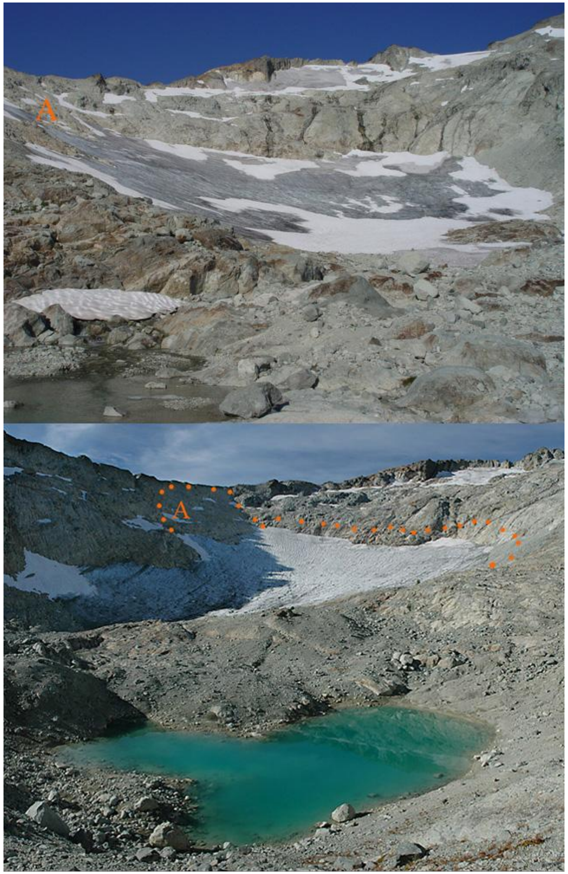

Fig. 4. Ice Worm Glacier in 2004 (above) and 2006 (below). The dotted line in the 2006 image indicates the margin of the glacier in 1984. Even in the two years separating these photographs the loss of ice at the upper margin of the glacier is evident near A.

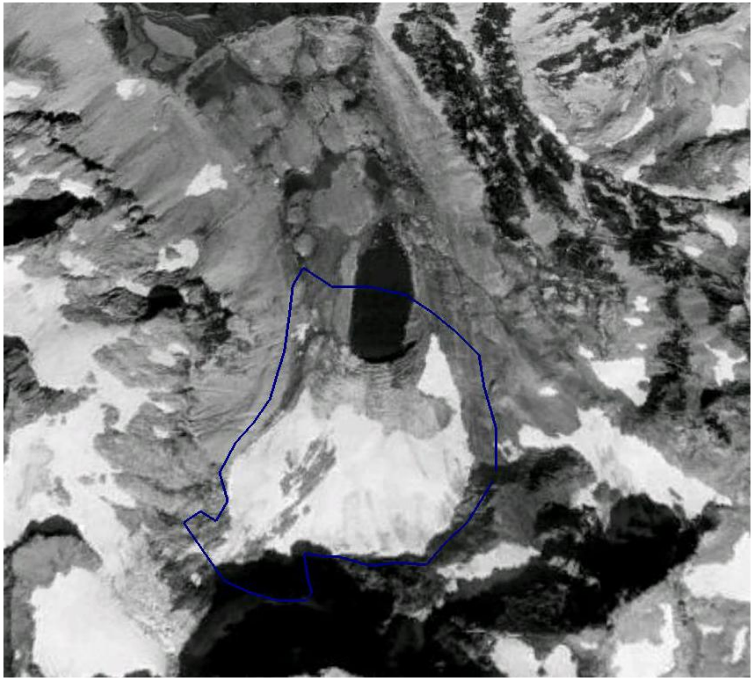

Fig. 5. Lyman Glacier, North Cascades with 1979 map outline and 2005 SPOT satellite image. Recession along the entire perimeter of the glacier has occurred.

Fig. 6. Whitechuck Glacier viewed from the head of the glacier in 1973 (above) and in 2006 (below). The north branch of the glacier which was km long in 1973 has melted away completely. This glacier had an AAR of less than 5 in 1987, 1988, 1992, 1993, 1994 and 1995. By 2002 it had melted away.

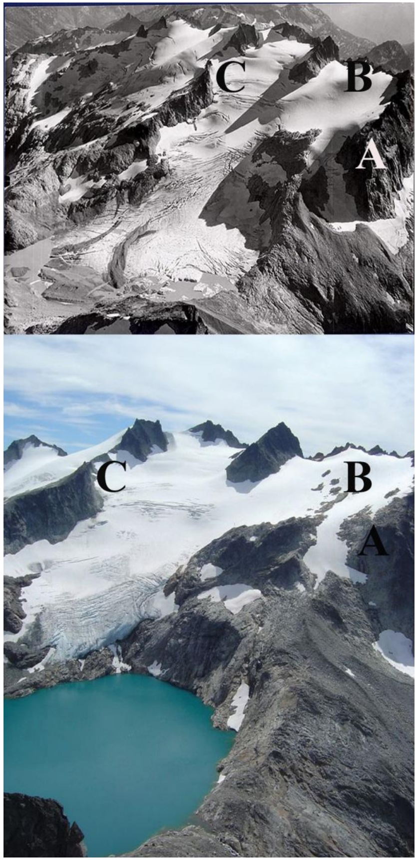

Fig. 7. Lynch Glacier, North Cascades in 1960 (Austin Post, USGS) and 2007 (below). There are new rock outcroppings in the accumulation zone on the right side (west side) of the glacier, the width of exposed rock on the ridge on the right side of the glacier has expanded (A and B). On the left side of the glacier the snow connection to the Daniels Glacier which existed up through 1987, is now an exposed ridge (C).

Fig. 8. Foss Glacier, North Cascades 1988 and 2005 indicating the change in the extent of the glacier. There is substantial marginal retreat in the accumulation zone and new rock outcroppings in the accumulation zone.

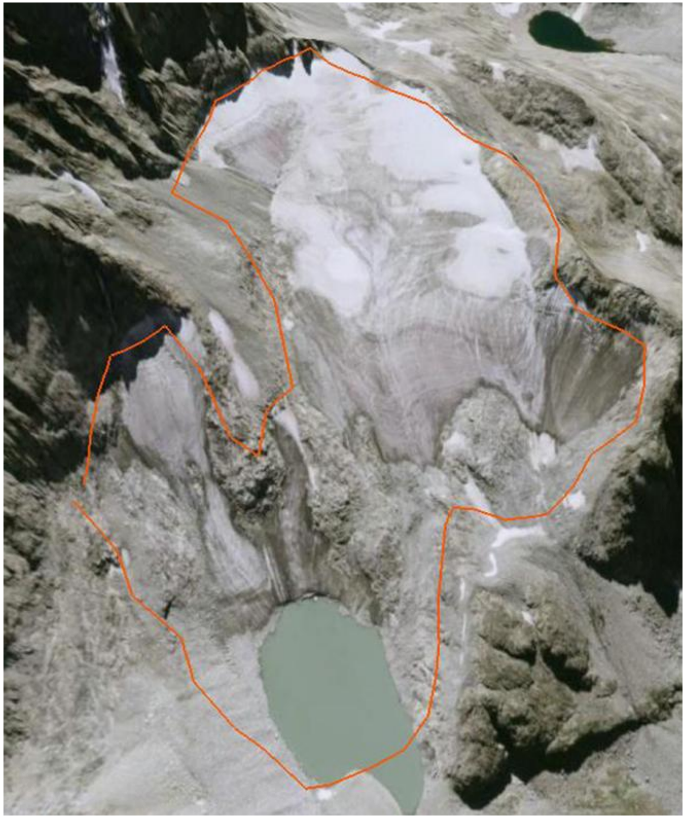

Fig. 9. Minor Glacier, Wind River Range, the glacier margin in 2005 and orange line showing the glacier margin from the 1966 map overlay on this SPOT satellite image. More than 50% of the accumulation zone margin has experienced recession.

Fig. 10. Grasshopper Glacier, Wind River Range, WY. Outline is the 1966 USGS topographic map boundary, confirmed with aerial photographs. The glacier has two termini one ending in the lake the other at the top of the glacier. There has been substantial expansion of new bedrock exposed in the upper elevations of the glacier. The image is a 2005 SPOT image.

Fig. 11. Fremont Glacier showing the marginal change from 1966 to 2005. There is no change above the end of the orange line in the accumulation zone of the glacier.