Extent of Equilibrium or Disequilibrium Response of Pacific Northwest US Glaciers

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ABSTRACT

The response of Pacific Northwest glaciers to climate change is observed on 15 glaciers in each of three ranges; Wind River Range, Wyoming, Glacier National Park, Montana and North Cascade Range, Washington. Examination of glacier areal extent change, accumulation zone margin change and accumulation zone thickness changes are utilized to identify the equilibrium or disequilibrium response of the glaciers to recent climate change. Comparison of USGS topographic maps from the 1950's and 1960's, and 2005-2007 SPOT satellite imagery identify changes in glacier extent, margins and thickness. All glaciers experiencing sustained negative mass balances retreat, to distinguish those undergoing an equilibrium response compared to a disequilibrium response requires examination of accumulation zone change. Glaciers with an equilibrium response experience small changes in the margins and thickness of the accumulation zone versus glaciers in disequilibrium which experience significant thinning and marginal retreat in the accumulation zone. Thinning and retreating margins in the accumulation zone indicate the lack of consistent retained accumulation, suggesting that there is no location to which the glacier can retreat that has dependable accumulation. Of the 15 North Cascade glaciers observed 9 experienced substantial thinning in the accumulation zone indicating glacier disequilibrium. In the Wind River Range 9 of 15 are in disequilibrium and in Glacier National Park 10 of 15 are in disequilibrium.

Keywords: glacier equilibrium; mass balance; climate change; North Cascades; Wind River Range, Glacier National Park

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INTRODUCTION

Glaciers have been studied as sensitive indicators of climate for more than a century. Observations of alpine glaciers most commonly focus on changes in terminus behavior, to identify glacier response to climate changes (Oerlemans, 1994). Changes in mass balance control a glacier's long term behavior. A glacier with a sustained negative balance is out of equilibrium and will retreat, while one with a sustained positive balance is out of equilibrium and will advance. In either case the response is an attempt to reach a new point of equilibrium. A glacier that cannot retreat to a point of equilibrium is in disequilibrium (Pelto, 2006), a non-steady state response (Paul et. al., 2004). Recent climate change has resulted in ubiquitous retreat in the Pacific Northwest (Pelto, 2006; Key et. al, 2002), hence the focus will be on the equilibrium or disequilibrium response of glaciers undergoing retreat.

Terminus observations have long been the hallmark of glaciologic observations (Oerlemans, 1994). These observations identify the response of the glacier to recent climate changes. However, the response of the terminus does not address the ability of a glacier to survive. A glacier can retreat rapidly, while maintaining a significant accumulation zone, which will allow the glacier to survive. Or a glacier could retreat slowly, but thin considerably along its entire length and then melt away, a disequilibrium response. Only glaciers lacking a significant accumulation will not survive the climate conditions causing the retreat.

Ideally identifying the equilibrium or disequilibrium response would utilize glacier mass balance data and remapping the surface elevation of each glacier, as in the North Cascade Range (Paul et al. al., 2004; Pelto, 2006). This would quantify the specific thinning of the glacier in the accumulation zone. To complete this on all glaciers in a range is a prohibitively costly and time consuming procedure. Recently attention has shifted to assessing changes in areal extent of all glaciers using satellite imagery (Kaab et. al., 2003; Andreasson et. al., 2008). Such inventories have noted widely disparate changes in glacier extent in neighboring glaciers (Paul et. al., 2004). This has prompted an examination of 15 glaciers in each of three ranges in the Pacific Northwest to identify their response to climate and assess the ability of satellite imagery to delineate accumulation zone changes.

DISTINGUISHING EQUILIBRIUM VERSUS DISEQUILIBRIUM RESPONSE

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 of the glacier reduces overall ablation, thereby increasing mass balance and potentially reestablishing equilibrium (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). The result is minimal changes in the thickness and margin in the accumulation zone, and limited reductions in crevassing due to reduced velocity.

Disequilibrium response

Without a substantial consistent accumulation area a glacier cannot survive. If a non-surging alpine glacier is experiencing extensive thinning and marginal retreat in the accumulation zone of the glacier it is in disequilibrium. The result is a more unstable form of retreat with substantial thinning throughout the length and breadth of the glacier. A glacier in this condition is unlikely to be able to survive in anything like its present extent given the current climate. In the Swiss Alps Paul et al., (2004) identify glaciers that are disintegrating due to massive down-wasting, a non-steady state response, as opposed to a dynamic steady state response to a climate change.

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 terminus in the Pacific Northwest. Paul et. al., (2004) utilized satellite imagery to non-uniform changes in glacier geometry, emerging rock outcrops, disintegration and tributary separation to determine collapse versus a dynamic (equilibrium) response to climate change. It has become practical to examine the terminus and areal extent change of all glaciers in the region (Key et. al., 2002; Andreasson et al., 2008; Paul et. al., 2004). This does quantify the extent of the retreat, but not the nature of the equilibrium or disequilibrium response. To identify disequilibrium requires identification of significant thinning in the accumulation zone. Accumulation zone thinning is evidenced by the emergence of rock outcrops in the accumulation zone, changes in the accumulation zone margin and reduced crevassing (Meier and Post, 1962; Paul et. al., 2004)).

In this study we overlay SPOT satellite imagery from 2005 and 2007 on USGS maps based on aerial photography from the 1950's and 1960's to distinguish glacier activity in terms of equilibrium or disequilibrium response. To identify disequilibrium three parameters are observed: 1. Greater than 35% areal extent change. 2. Changes in the glacier margin in the accumulation zone averaging greater than 50 m. 3. Thinning in the accumulation zone of the glacier as revealed by changes in the margin at the head of the glacier and emergence of significant rock outcrops. For North Cascade glacier we compare the results obtained using the aforementioned parameters to results from mass balance and direct glacier surface mapping data to determine the suitability of the method. The method is then extended to Glacier National Park and the Wind River Range.

GLACIER EXTENT CHANGES

Recent climate change has caused ubiquitous retreat of Pacific Northwest glaciers (Pelto, 2001; Key et al., 2002; Hall and Fagre, 2003; Granshaw and Fountain, 2006). Since the maximum advance of the Little Ice Age (LIA) there have been three climate changes in the Pacific Northwest sufficient to substantially alter glacier terminus behavior. During the LIA mean annual temperatures were 1.0-1.5^{o}C cooler than at present (Porter, 1986; Key et al., 2002).

The first substantial climate change was a progressive temperature rise from the 1880's to the 1940's. The warming led to ubiquitous rapid retreat of Pacific Northwest alpine glaciers from 1890 to 1944 (Dyson, 1952; Meier and Post, 1962; Hubley, 1956).

The second substantial change in climate began in 1944 when conditions became cooler and precipitation increased (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 (Pochop et al., 1989). In Glacier National Park the retreat of Sperry Glacier diminished from 1960-1979 (Key et al., 2002).

The third change to warmer and drier conditions began in 1977 (Ebbesmeyer, 1991). The retreat and negative mass balances of the 1977-2007 period have been without exception in the three 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 by NCGCP were retreating (Pelto, 1993). By 2006, four had disappeared Lewis Glacier, David Glacier, Spider Glacier (Figure 1) and Milk Lake Glacier (Pelto, 2006).

Figure 1. Spider Glacier separated into several small snow patches, none larger than .01 km^2 by 2005 and is no longer a glacier.

RESULTS

North Cascades

In the North Cascades repeat longitudinal profiles have been completed on 15 glaciers (Pelto and Hartzell, 2004; Pelto, 2006). Annual mass balance has been measured on ten of these glaciers with a mean annual balance of -0.51 m/a, from 1984-2007 (Pelto, 2008) and on South Cascade Glacier by the USGS (Krimmel, 2001). This represents a 20-40 % loss in glacier volume in this interval for North Cascade glaciers (Pelto, 2008). Ten of the 15 glaciers have experienced significant thinning in the accumulation zone, thinning that is comparable to the terminus region and exceeds 10 m, since 1984 (Table 1).

Table 1. Assessment of equilibrium response based on remapping of centerline longitudinal profiles on 10 glaciers where annual mass balance data has been measured 1984-2007, Sholes and Easton Glacier 1990-2007. Accumulation zone thinning is the mean change in glacier surface elevation in the accumulation zone from 1984-2007, Sholes and Easton Glacier 1991-2007.

Glacier	Cumulative Mass Balance	Accumulation Zone Thinning	Glacier Response
Columbia	-12.7	-17	DEQ
Daniels	-14.4	-12	DEQ
Easton	-10.5	-4	EQ
Daniels	-12.4	-14	DEQ
Ice Worm	-15.8	-13	DEQ
L. Curtis	-13.0	-11	DEQ
Lynch	-10.4	-11	DEQ
Rainbow	-8.8	-3	EQ
Sholes	-11.5	-4	EQ
Yawning	-13.3	-5	EQ

This indicates a disequilibrium response to climate change, based on field observations. Relying simply on SPOT imagery and USGS maps comparison of the same 15 glaciers illustrates the ability to assess disequilibrium using remote sensing (Table 2). On 9 of the 15 glaciers the thinning is evident in the accumulation zone from SPOT imagery indicated by the marginal retreat or exposure of new bedrock islands.

Table 2. The areal extent and change in areal extent of North Cascade glaciers. Identified accumulation zone thinning and accumulation zone marginal retreat. Nature of glacier response: equilibrium (EQ) or disequilibrium (DEQ).

Glacier	Area in 1958	Area in 2005	% Areal Reduction 1958-2005	Accumulation zone thinning	Accumulation zone marginal retreat	Glacier Response
Yawning	0.2	0.16	20%	no	no	EQ
Columbia	1	0.9	10%	no	yes	DEQ
Daniels	0.5	0.35	30%	yes	yes	DEQ
Easton	2.9	2.7	7%	no	no	EQ
Foss	0.5	0.2	60%	yes	yes	DEQ
Honeycomb	3.5	3.1	11%	no	no	EQ
Ice Worm	0.1	0.06	40%	yes	yes	DEQ
Lower Curtis	0.8	0.7	13%	no	no	EQ
Lyman	0.5	0.3	40%	no	yes	DEQ
Lynch	1	0.6	40%	yes	yes	DEQ
Rainbow	1.9	1.7	11%	no	no	EQ
Sholes	0.9	0.8	11%	no	no	EQ
Spider	0.1	0	100%	yes	yes	DEQ
White River	1	0.7	30%	yes	no	DEQ
Whitechuck	1.9	0.6	68%	yes	yes	DEQ

One glacier, Lower Curtis Glacier (Figure 2), is assessed to have a different response than using field observations. On Lower Curtis Glacier the margins are avalanche fans, and it is not evident in SPOT imagery that there is thinning in the accumulation zone; however average thinning in the accumulation zone since 1984 has been 11 m (Pelto, 2006). On Ice Worm, Lyman, Spider and Columbia Glacier retreat of the head of the glacier is comparable to retreat of the terminus indicative of glacier thinning in the accumulation zone. On Foss (Figure 3), Daniels, Spider and Lynch (Figure 4), Whitechuck (Figure 5), and White River Glacier numerous rock islands have been exposed in the accumulation zone illustrating thinning. These changes independently corroborate the longitudinal profile identified thinning of the accumulation zone. This suggests that for smaller alpine glaciers (area < 5 km^2) satellite imagery does provide a reasonably accurate means of assessing accumulation zone changes in glacier thickness, which can be used to determine equilibrium response. The ultimate result of substantial accumulation zone thinning is the loss of the glacier, such as on Lyall Glacier (Figure 6), which disappeared in the mid 1990's.

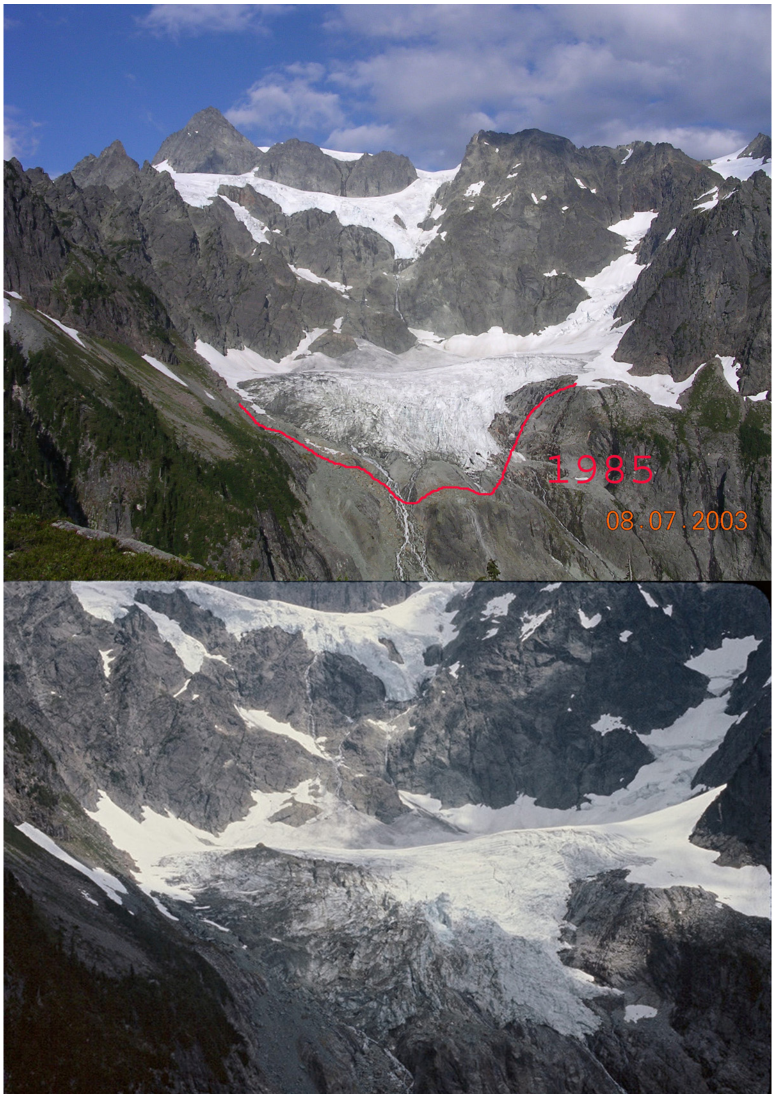

Figure 2. Lower Curtis Glacier, North Cascades 1985 and 2003 illustrating a lack of evident change in the marginal position of the Lower Curtis Glacier or in the appearance of rock outcroppings. This would suggest an equilibrium response. A longitudinal profile up the glacier indicates thinning has occurred in the accumulation zone indicative of a disequilibrium response.

Figure 3. 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, indicating a disequilibrium response.

Figure 4. Whitechuck Glacier, North Cascades 1973 and 2006 from Glacier gap at the head of the north branch of the glacier. A disequilibrium response led to the complete loss of this branch of the glacier by 2003.

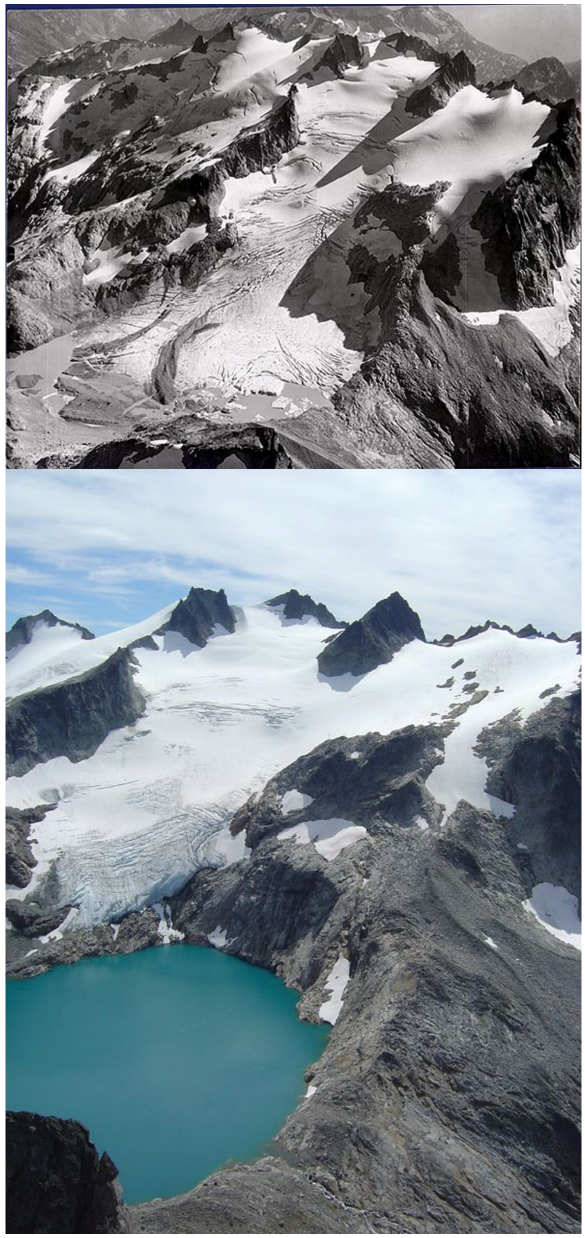

Figure 5. Lynch Glacier, North Cascades in 1960 (Austin Post, USGS) and 2007. There are new rock outcroppings in the accumulation zone on the right side (west side) of the glacier indicating a disequilibrium response.

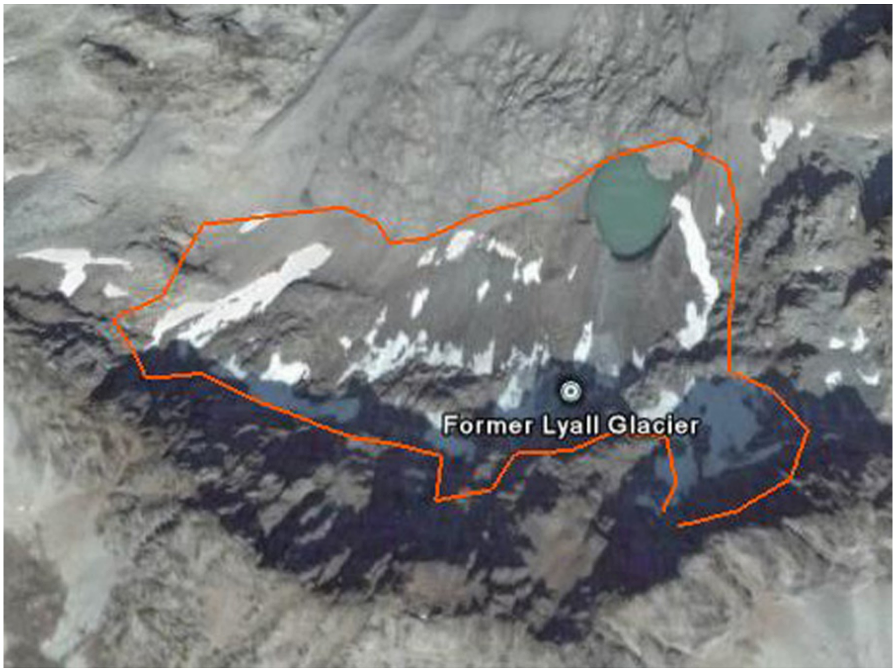

Figure 6. Lyall Glacier, North Cascades with 1966 map outline and SPOT satellite image overlay from 2005. A new lake has formed and the glacier is gone.

Wind River Range

Glaciers in the region have experienced ongoing negative balances and glacier shrinkage (Dyson, 1952; Pochop et al., 1989). Examination of Dinwoody 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. Of the 15 glacier examined six have experienced insignificant change in glacier margin and ice thickness (Table 3). Gannett and Dinwoody Glacier are the two largest glaciers in the range and despite significant terminus retreat, the accumulation zones remain unchanged. On Fremont Glacier (Figure 7) the change in areal extent is 11%. Of the nine glaciers in disequilibrium J, Twins, Grasshopper, Minor, Heap Steep, Mammoth and Lower Fremont Glacier exhibit significant new bedrock exposure within the accumulation zone. Marginal retreat in the accumulation zone is evident on Baby, J, Twins, Grasshopper, Minor (Figure 8), Heap Steep, Helen and Lower Fremont Glacier. 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 has experienced 640 m of retreat and 27% reduction in areal extent, with most of the reduction in the accumulation zone. These examples indicate the difficulty in using only terminus change or areal extent change in determining equilibrium response.

Table 3. The areal extent and change in areal extent of Wind River Range glaciers. Identified accumulation zone thinning and accumulation zone marginal retreat. Nature of glacier response: equilibrium (EQ) or disequilibrium (DEQ).

Glacier	Area in 1966	Area in 2005	% Areal Reduction 1966-2005	Accumulation zone thinning	Accumulation zone marginal retreat	Glacier Response
Baby	0.25	0.18	28%	no	yes	DEQ
Dinwoody	2.76	2.4	13%	no	no	EQ
Fremont	1.55	1.38	11%	no	no	EQ
Gannett	2.69	2.15	20%	no	no	EQ
Gooseneck	0.3	0.25	17%	no	no	EQ
Heap Steep	0.15	0.11	27%	yes	yes	DEQ
Helen	1.04	0.78	25%	no	yes	DEQ
Knife Point	1.02	0.7	31%	no	no	EQ
Mammoth	2.23	1.65	26%	yes	no	DEQ
Minor	0.56	0.27	52%	yes	yes	DEQ
Sphinx	0.16	0.14	13%	no	no	EQ
Twins	0.51	0.16	69%	yes	yes	DEQ
L. Fremont	0.61	0.47	23%	yes	yes	DEQ
J	0.33	0.22	33%	yes	yes	DEQ
Grasshopper	2.94	2.14	27%	yes	yes	DEQ

Figure 7. Fremont Glacier, Wind River Range, the glacier margin in 2005 and orange line showing the region where the margin is not the same from the 1966 map overlay on this SPOT satellite image. No evident change in the accumulation zone indicates an equilibrium response.

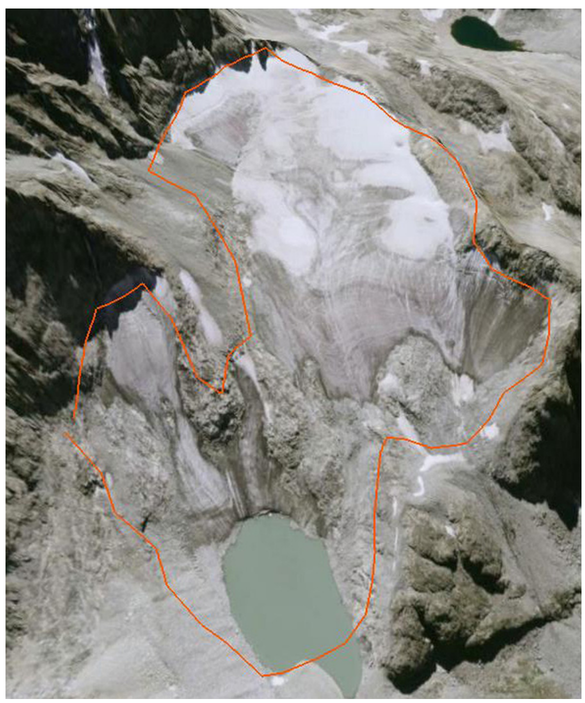

Figure 8. Minor Glacier, Wind River Range, the glacier margin in 2005 and orange line showing the glacier margin from the 1966 map overlay on this SPOT satellite image. Much of the accumulation zone of the glacier is now gone indicating a disequilibrium response.

Glacier National Park

Glacier National Park's glaciers have been the focus of long term mapping changes of Sperry Glacier and Grinnell Glacier (Johnson, 1980) and areal extent change mapping of many of the larger glaciers in the Park (Key et. al., 2002). Mass balance and ice surface elevation mapping have not been completed; hence satellite imagery must be utilized to assess glacier response. Key et al., (2002) noted that by 1980 Glacier National Park glaciers had been confined to high elevation cirques for three decades, and had lower recession rates during the previous three decades, though broad recession continued. They concluded that the glaciers had not reached equilibrium with the present climate. In the current assessment 10 of the 15 glaciers are experiencing a disequilibrium response (Table 4). Blackfoot and Harrison Glacier (Figure 9) are the two largest glaciers and show minimal changes in the accumulation zone. Both glaciers continue to retreat with the main termini retreating approximately 100-120 m since 1966. Three smaller glaciers Ahern, Old Sun and Weasal Collar occupy avalanche fed cirques and continue to maintain significant snowcover even in warm summers such as 2005 and 2007. The result has been minimal changes in these glaciers. Exposure of significant new bed rock in the accumulation zone was evident on Sperry, Baby, Ipasha, Whitecrow and Shepard Glacier (Figure 10). Extensive marginal retreat in the accumulation zone is evident on Grinnell, Sperry, Jackson, Kintla, Baby, Whitecrow, Sexton and Shephard Glacier. Areal extent losses of these glaciers ranged from 20 to 100% during the 1966-2007 period. Dixon, Baby and Whitecrow are no longer glaciers with no evident ice mass more than 0.01 km^2, Shephard Glacier is nearly gone. Many of the 34 glaciers identified on the 1966 USGS maps (Key et al., 2002), have disappeared, yet a number of glaciers have been experiencing an equilibrium response. Hall and Fagre (2003) utilized a model to construct the future of glaciers in the Blackfoot-Jackson watershed, and determined that all would be gone by 2030 with continued substantial warming, but not with limited additional warming. Based on the slow recession and equilibrium response of Blackfoot and Harrison Glacier to recent climate over the last 40 years these two glaciers are not going to disappear within the next 30 years. There are at least five glaciers in the park that have retreated slowly in the last 40 years and still have healthy accumulation zones, indicating they are not on the verge of disappearing. As A. Fountain (pers. comm.) has noted as glaciers shrink to a small size they can be tough to eliminate if they have an accumulation area.

Table 4. The areal extent and change in areal extent of Glacier National Park glaciers. Identified accumulation zone thinning and accumulation zone marginal retreat. Nature of glacier response: equilibrium (EQ) or disequilibrium (DEQ).

Glacier	Area in 1966	Area in 2005	% Areal Reduction 1966-2005	Accumulation zone thinning	Accumulation zone marginal retreat	Glacier Response
Ahern	0.59	0.43	27%	no	no	EQ
Baby	0.12	0	100%	yes	yes	DEQ
Blackfoot	1.74	1.18	32%	no	no	EQ
Dixon	0.29	0	100%	yes	yes	DEQ
Grinnell	1.15	0.72	37%	yes	yes	DEQ
Harrison	1.24	1.11	10%	no	no	EQ
Ipasha	0.31	0.11	65%	yes	no	DEQ
Jackson	0.98	0.79	19%	no	yes	DEQ
Kintla	0.66	0.4	39%	no	yes	DEQ
Old Sun	0.4	0.25	38%	no	no	EQ
Sexton	0.4	0.2	50%	no	yes	DEQ
Shephard	0.2	0.03	85%	yes	yes	DEQ
Sperry	1.4	0.72	49%	yes	yes	DEQ
Weasal Collar	0.56	0.48	14%	no	no	EQ
Whitecrow	0.24	0	100%	yes	yes	DEQ

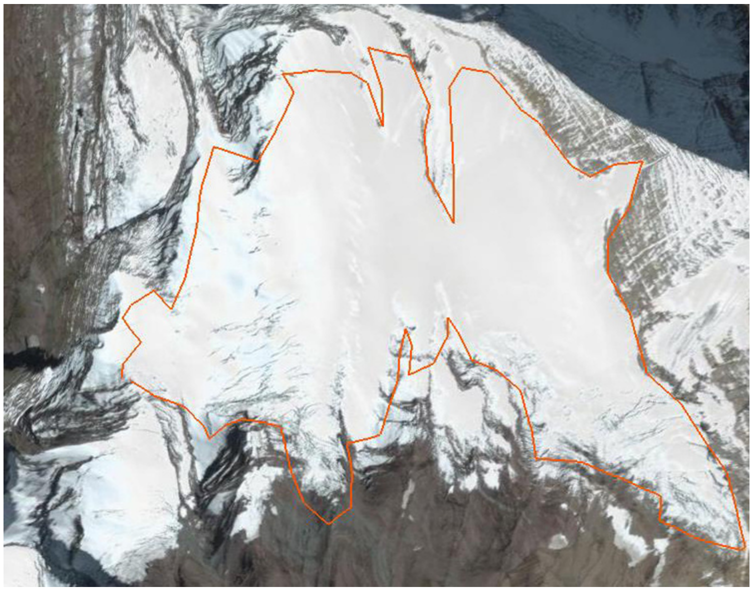

Figure 9. Harrison Glacier, Glacier National Park, the glacier margin in 2005 and orange line showing the 1966 margin map overlay on this SPOT satellite image. No evident change in the accumulation zone indicates an equilibrium response.

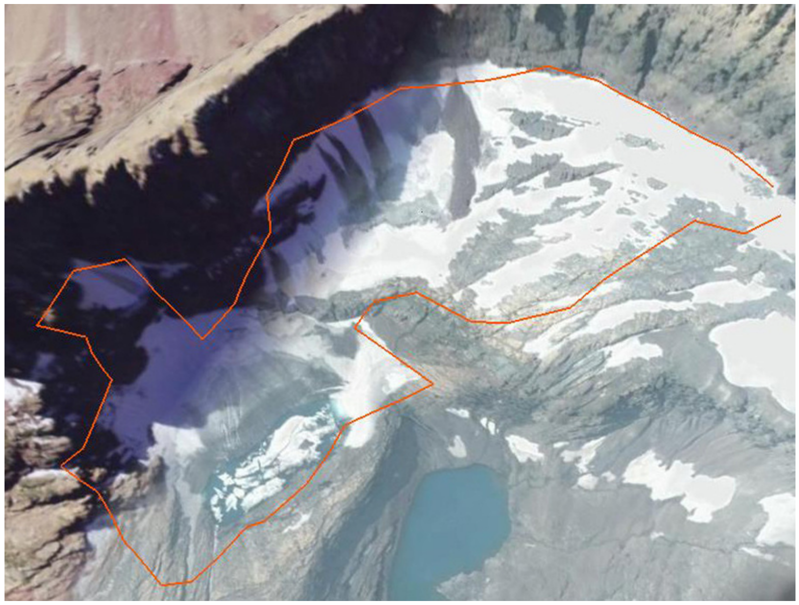

Figure 10. Shephard Glacier, Glacier National Park, the glacier margin in 2005 and orange line showing the 1966 margin map overlay on this SPOT satellite image. Much of the accumulation zone of the glacier is now gone indicating a disequilibrium response.

CONCLUSIONS

It is proposed that accumulation zone thinning observations are key to identifying glacier disequilibrium versus equilibrium response to climate change, as opposed to terminus observations. Accumulation zone thinning can be identified from changes in the accumulation zone margin and the appearance of new rock outcrops in the accumulation zone utilizing satellite imagery.

In each range of the three study areas 30-40% of the glaciers are undergoing an equilibrium response to recent climate change. These glaciers will survive the current climate. The remaining glaciers are thinning substantially even in the accumulation zone and will not survive current climate. The nature of the response is not broken down with respect to geographic characteristics. That will be the goal of an expanded study of 30 glaciers in each range. The extent to which glaciers in the Wind River Range, Wyoming, Glacier National Park, Montana and North Cascade Range, Washington are experiencing an equilibrium or disequilibrium response to current climate is important to determine as it identifies glaciers that are disappearing, impacting summer glacier runoff and alpine streamflow (Pelto, 1993; Bach, 2002; Hall and Fagre, 2003; Granshaw and Fountain, 2006).

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