Rising ELA and Expanding Proglacial Lakes Lead to Initiation of Rapid Retreat of Brady Glacier, Alaska

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ABSTRACT

Brady Glacier, Alaska, is a large tidewater glacier that is beginning a period of substantial retreat. Examination of 27 Landsat and MODIS images from the period 2003–2011 indicates that Brady Glacier has a mean ELA (equilibrium line altitude) of 745 m and AAR (accumulation area ratio) of 0.40. The zero balance ELA is 600 m and equilibrium AAR 0.65. The negative mass balance associated with the increased ELA has triggered thinning of 20–100 m over most of the glacier below the ELA from 1948 to 2010. The thinning has caused substantial retreat of seven calving distributary termini of the glacier. Thinning and retreat have led to an increase in the width of and water depth at the calving fronts. In contrast, the main terminus has undergone only minor retreat since 1948. In 2010 several small proglacial lakes were evident at the terminus. By 2000, a permanent outlet river issuing from Trick Lake had developed along the western glacier margin. Terminus lake development combined with continued mass losses will lead to expansion of the lakes at the main terminus and retreat by calving. The glacier bed is likely below sea level along the main axis of Brady Glacier to the glacier divide. Retreat of the main terminus in the lake will likely lead to a rapid calving retreat similar to Bear, Excelsior, Norris, Portage, and Yakutat glaciers.

Keywords: glacier retreat, Glacier Bay, equilibrium line altitude.

INTRODUCTION

Brady Glacier is the largest glacier in the Fairweather Range of southeast Alaska and northwest British Columbia; it has a length of 51 km and an area of 490 km^2 (Armstrong et al., 2011). The glacier flows south and terminates on a large outwash plain that transitions into a tidal delta complex in Taylor Bay. Brady Glacier, along with Taku and Baird glaciers, are the only land terminating glaciers in southeast Alaska that did not significantly retreat between 1950 and 2010 (Pelto, 1987). Taku Glacier has maintained a generally positive mass balance (Pelto et al., 2008) while Baird Glacier is thinning and appears poised to begin a retreat (Molnia, 2008). Brady Glacier is unique among these glaciers because it presently dams at least 10 proglacial lakes ≥ 1 km^2. The lakes are in different stages of evolution: incipient, stable and non-draining, and periodically draining.

Brady Glacier occupies a deep valley that extends from Taylor Bay on the south to near the north end of Glacier Bay (Figure 1). Ice-penetrating radar measurements near the main axis of the

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glacier indicate a bed at least 200 m below sea level (Barnes and Watts, 1977). Approximately two-thirds of the ice in the valley flows SSE towards Taylor Bay, and one-third flows NNW into Lamplugh and Reid glaciers and Glacier Bay (Bengtson, 1962; Derksen, 1976). The divide between south-and north-flowing ice lies at approximately 820 m, based on the 2000 Shuttle Radar Topography Mission (SRTM) digital elevation model (DEM) (Capps, 2011).

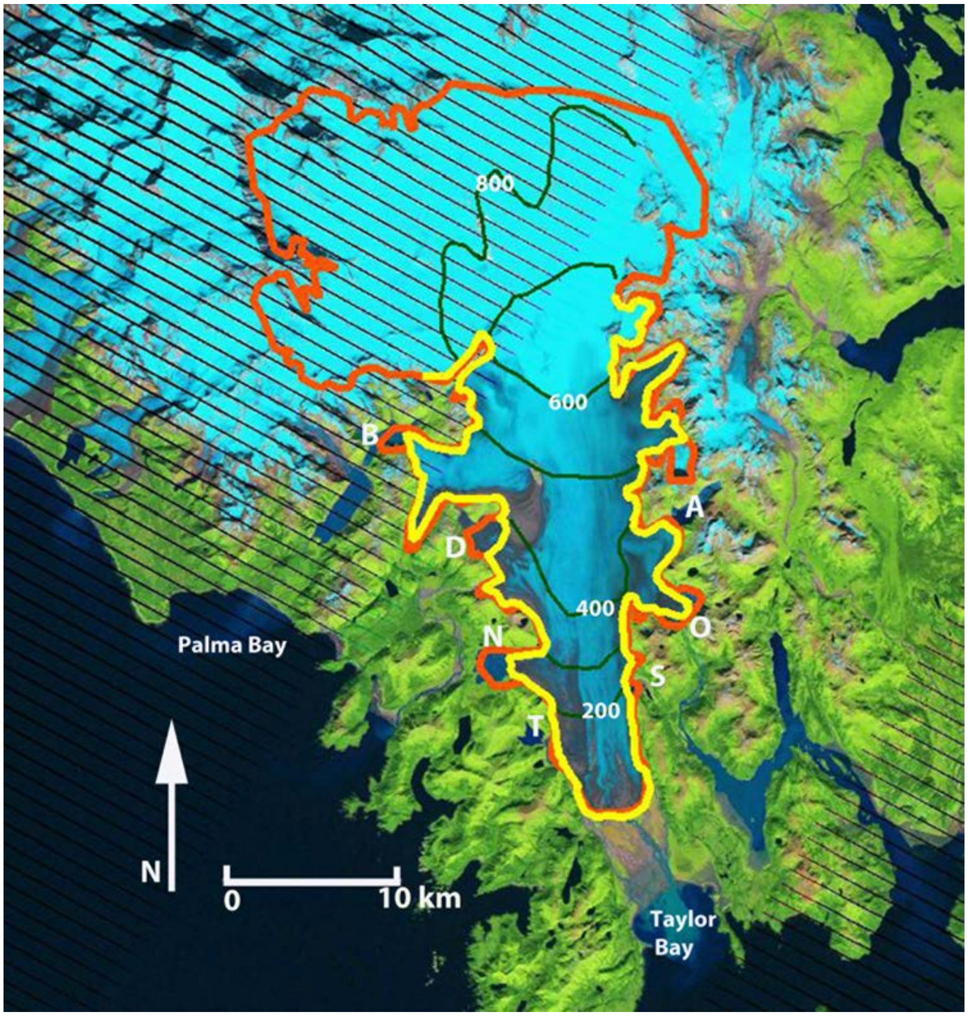

Figure 1. Map of Brady Glacier area showing locations of ten proglacial lakes and glacier elevation contours every 100 meters. The orange outline is the glacier boundary in 1948, the yellow line the 2010 glacier boundary which has changed only below 700 meters. A=Abyss, B=Bearhole, D=Dixon, N=North Deception, O=Oscar, S=Spur, T=Trick.

Brady Glacier was first mapped by Captain Vancouver in 1794; at that time, the glacier was calving icebergs into Taylor Bay (Klotz, 1898). The glacier ceased calving and advanced approximately 8 km during the 19th century (Bengston, 1962). Its secondary distributary termini also achieved their maximum extent at that time (Capps et al., 2011). After 1870, the outwash plain began a rapid expansion and, by 1977, extended more than 6 km (Molnia, 2008). As Bengston (1962) notes, the 20th century advance resulted from a change from calving to non-calving status rather than a more positive mass balance due to climate change. This response is characteristic of the advance stage of the calving tidewater glacier cycle in Alaska (Meier and Post, 1987) and has been documented, for example, at Taku Glacier (Pelto and Miller, 1990). The massive outwash plain at the terminus is primarily responsible for Brady Glacier maintaining an advanced position (Bengston, 1962) while other glaciers in the Glacier Bay region have retreated substantially. In the 1960s, the glacier slowly advanced; and during the 1970s, the terminus was stable (Bengtson, 1962; Molnia, 2008; Capps, 2011). By the late 1980s, the glacier was thinning and some of the distributary termini were retreating (Molnia, 2008; Capps, 2011). By 2010, the main terminus had begun to retreat; but the retreat to date is less than 200 m.

Subsidiary termini ending in proglacial lakes have retreated considerably more than the main terminus, ranging from 300–500 m in Abyss Lake and Trick Lake, to 1300–1800 m in North Deception Lake, Dixon, and Bearhole Lake (Capps, 2011).

The mass balance of southeast Alaskan tidewater glaciers is dictated by the calving rate and the accumulation-area ratio (AAR: percentage of a glacier's area above the equilibrium line altitude). The regimen of a non-surging glacier changes only when AAR equilibrium threshold value or the calving status changes (Mercer, 1961; Pelto, 1987). Threshold values of AAR are 0.67 for a non-calving or low-calving-rate glacier, 0.76 for a moderate-calving-rate (< 200 m/a) glacier; and 0.84 for a high-calving-rate (> 200 m/a) glacier (Pelto, 1987). Only three of 120 glaciers in southeast Alaska and northwest British Columbia examined by Pelto (1987), including Brady Glacier, did not meet these criteria.

Brady Glacier had an AAR of 0.64 in 1973 (Molnia, 2008) and 0.65 in the 1980s (Pelto, 1987). The mean ELA (equilibrium line altitude) of the glacier is about 600 m (Bengston, 1962; Pelto, 1987), one of the lowest in Alaska. During the period 2000–2011, the ELA has been notably higher. The recent snowline rise has led to a significant widespread thinning of the glacier (Larsen et al., 2007). In this paper, we examine two key factors that influence the mass balance of the glacier: 1) its ELA and AAR from 2003 to 2011 and 2) expansion of proglacial lakes, which can lead to changes in calving balance. We then examine the impact of the mass balance losses on the future behavior of the glacier and draw comparisons with the recent response of Bear, Excelsior, Norris, Portage, and Yakutat glaciers to the collapse of their in proglacial lakes.

METHODS

TSL, ELA, AAR, and mass balance

There is a strong relation between glacier ELA and mass balance (Ba), and between AAR and Ba (Hock et al., 2007; Zemp et al., 2009). The World Glacier Monitoring Service produces detailed graphs of Ba versus both ELA and AAR in their mass balance bulletin series for individual glaciers (WGMS, 2011). Østrem (1975) first noted the utility of identifying the ELA and transient snow line (TSL) using remote sensing images in mass balance assessment. The TSL is the location of the transition from bare glacier ice to snowcover at a particular time (Østrem, 1975), whereas the ELA is the altitude of the snowline at the end of melt season. Glacier mass balance at the TSL is zero (Hock et al., 2007), providing an important reference point for the balance gradient curve. On temperate glaciers in southeast Alaska, the TSL coincides with the ELA at the end of the melt season (Østrem, 1975; Williams et al., 1991; Miller and Pelto, 1999). The TSL can be identified near the end of the melt season using satellite imagery (Hall et al., 1989). However, in many years, the time difference between available and usable imagery where the TSL is visible and the end of the melt season occurs can be several weeks. If the rate of TSL rise can be determined and is reasonably constant, the ELA can be reliably estimated from TSL observations several weeks removed from the end of the melt season (Pelto, 2011). The current availability of satellite imagery from many sources ensures coverage late in the melt season for most years. Once the AAR-Ba relation is calibrated for a particular glacier or area, the approach outlined above using TSL-AAR observations enables accurate remote monitoring of glacier mass balance.

Satellite imagery

The TSL on Brady Glacier is readily identifiable on 25 Landsat Thematic Mapper (TM) scenes acquired between 2003 and 2011 and available from the US Geological Survey Globalization Viewer (http://glovis.usgs.gov/) (Table 1). Brady Glacier falls in Path/Row 59/19 for Landsat TM imagery; all images are RGB color composites, bands 5, 4, and 3 from the Landsat 4, 5, and 7

(TM) with a 2% linear stretch applied. The spatial resolution of 30 m, combined with mean surface gradients of 0.022–0.028 m/m, yields an error of less than ±2 m in TSL elevation.

Table 1. Dates of transient snowline identification (m) for Brady Glacier from Landsat 4–7 and MODIS imagery.

Date	TSL	Date	TSL
8/28/2003	750	7/22/2007	525
9/5/2003	775	8/15/2007	600
9/29/2003	800	8/17/2008	520
10/15/2003	800	9/25/2008	640
7/13/2004	550	7/11/2009	500
8/14/2004	725	8/5/2009	560
8/30/2004	800	9/5/2009	650
9/7/2004	825	9/14/2009	700
10/10/2004	875	9/29/2009	700
7/8/2005	580	8/3/2010	550
8/9/2005	680	8/15/2010*	600
9/21/2005	800	9/14/2010*	680
7/3/2006	500	9/16/2010	700
7/11/2006	525	7/10/2011	480
8/28/2006	675	9/11/2011	680
9/13/2006	700	9/27/2011*	750

* Dates with both types of imagery.

We expanded the satellite image coverage using MODIS real-time, true-color, swath imagery provided by the Geographic Institute Network of Alaska (GINA—http://www.gina.alaska.edu/data/gina-modis-images/) (Table 1). The MODIS imagery is Band 1, which has a resolution of 250 m. With an average surface mean gradient of 0.022–0.028 m/m, the error in TSL elevation is less than ± 10 m.

We georeferenced the satellite images in ArcMap 9.3 using five topographically unique reference points. The data frame containing imagery and base map was transformed to NAD_1983_UTM_Zone_8N to ensure spatial accuracy for measurements. TSL estimates for Landsat and MODIS images from the same dates (August 15, 2010, and September 16, 2010) were compared to evaluate potential errors (Figure 2). Overlain images indicated a mean difference of 110 m ± 80 m in horizontal TSL position, which corresponds to a vertical difference of 3–5 m (Figure 3).

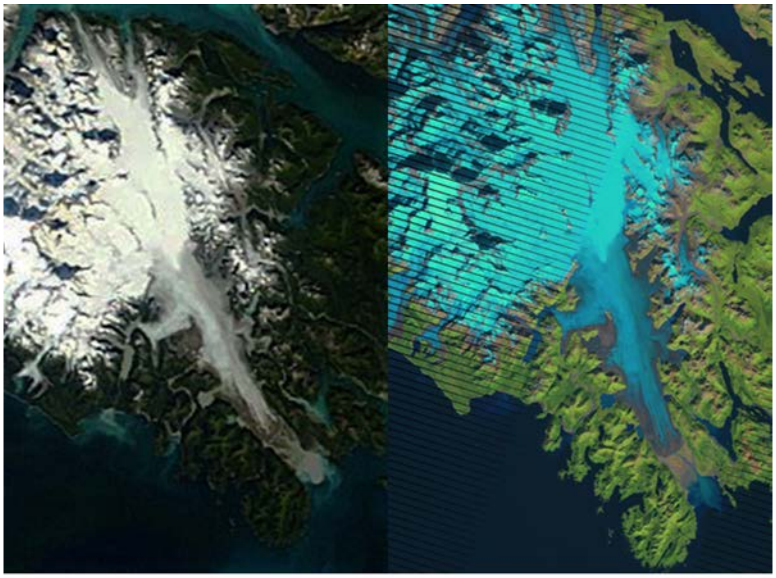

Figure 2. Comparison of MODIS and Landsat images from 9/14/2010 and 9/16/2010. Note the close agreement between the two estimates of the TSL.

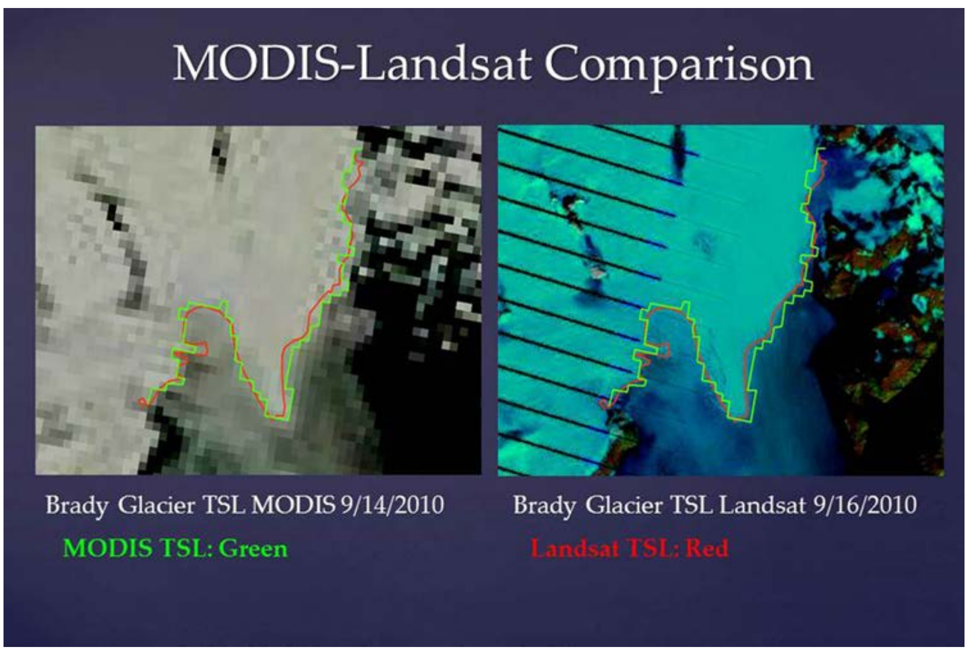

Figure 3. Close-up comparison of MODIS and Landsat on9/14/2010 and 9/16/2010.The mean deviation in horizontal position is +100 m.

RESULTS

TSL, ELA, AAR and mass balance observations

We identified the TSL and rate of TSL rise for Brady Glacier for the end of each ablation season from 2003 until 2011 using multiple satellite images. Periods of at least 15 days were used to reduce the error in the rate of rise that could result from small errors in TSL observations (Pelto, 2011). There are 12 periods after August 15 that provide a measure of late season ablation; the TSL rate of rise for those periods ranges from 2.9 m/day to 4.7 m/day with a mean of 3.6 m/day.

The ELA is valuable for mass balance estimation and is the TSL at the end of the melt season. For seven of the nine years from 2003 to 2011, we identified the TSL after September 15. In those years, the highest observed TSL is assumed to be the ELA. In each of those seven years the last TSL observation was within eight days of the end of the ablation season determined from local weather records. The end of the ablation season is identified as the date the daily mean temperature in nearby Gustavus, AK, dropped below 8°C. Gustavus was chosen because it is has a reliable long-term climate record. Beginning in 2011, MODIS and the Northern Mesoscale Climate model (NAM) were used. The temperature threshold of 8°C was selected based on the modeled NAM surface temperature difference between Gustavus and 600 m elevation on Brady Glacier for the period October 2011 through May 2012. Lowering snowlines evident in MODIS images between 2009 and 2011 provide further validation for the model. MODIS imagery indicates snowline lowering before September 29, 2009; October 3, 2010; and October 2, 2011. In 2006 and 2007, the last usable MODIS or Landsat images were, respectively, 18 and 43 days before the end of the ablation season. In those two cases, the ELA was estimated using the product of the mean migration rate of the TSL, 3.6 m/day, and the number of days to the end of the ablation season.

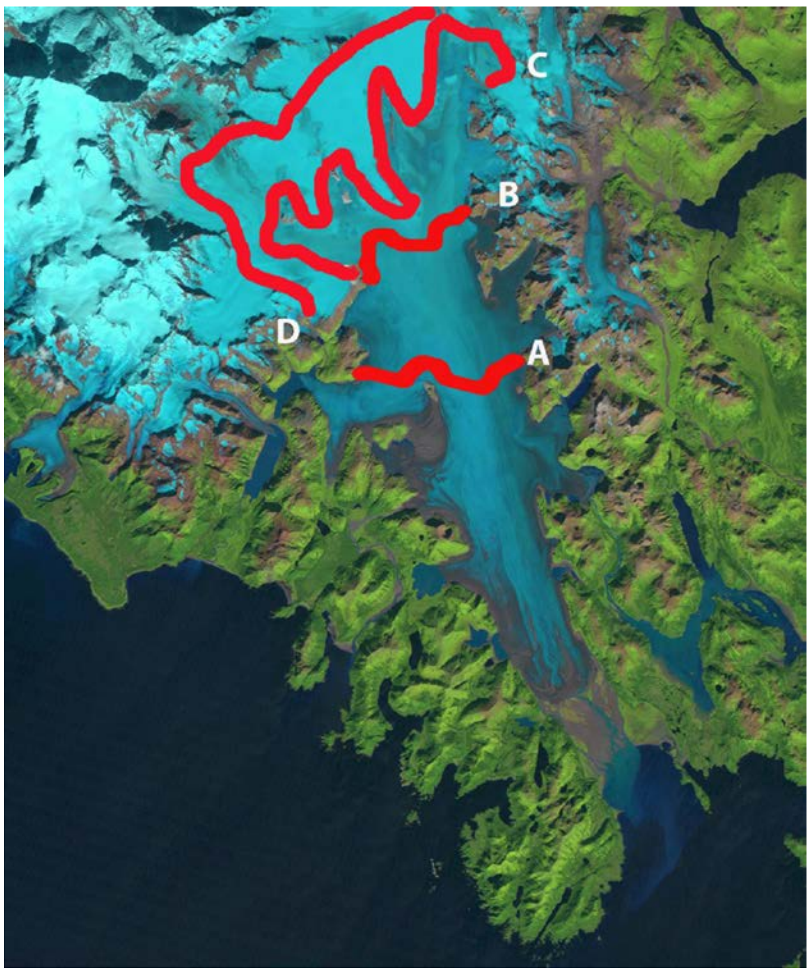

Figure 4. Brady Glacier transient snowline in 2004: A=7/13, B=8/14, C=8/30, and D=10/10. The TSLs are overlain on the August 30, 2004, image.

In 2003, the TSL on Brady Glacier was 800 m on both September 29 and October 15, which are two dates that straddle the end of the ablation season (October 6). In 2004, four satellite images were used to identify the TSL: July 13, 550 m; August 14, 670 m; August 30, 730 m; and October

10, 940 m (Figure 4). In a typical year new snow would have fallen on Brady Glacier by early October, but not in 2004 when the ablation season ended on October 9.

The mean ELA for Brady Glacier for the period 2003–2011 was 745 m (Table 2). Taking into account the hypsometry of the glacier, this ELA yields a mean AAR of 0.40 (Table 2). The AAR value is much lower than the value of 0.65 required for Brady Glacier to be in equilibrium. The values indicate a glacier with a substantial negative surface mass balance.

Table 2. ELA and AAR of Brady Glacier 2003–2011.

	TSL	ELA	AAR	Date*	Day to end*
2003	800	800	36	6-Oct	0
2004	875	875	28	9-Oct	1
2005	800	800	36	28-Sep	7
2006	700	750	39	1-Oct	18
2007	600	740	39	24-Sep	40
2008	640	640	50	23-Sep	2
2009	700	700	45	21-Sep	7
2010	700	700	45	24-Sep	8
2011	720	720	43	28-Sep	1
Mean		747	40	28-Sep	

* Date of the end of the ablation season. For 2006 and 2007, the last TSL observation was more than 10 days from the end of the ablation season; and the ELA has been adjusted.

Our observations of a substantial and persistent negative surface balance are supported by two independent sets of observations. Bethier and Toutin (2008) identified an average thinning of almost 10 m at elevations below 500 m on southeast Alaskan glaciers from 2000 to 2004, with Brady Glacier thinning by up to 40 (± 10) m at its front. Larsen et al. (2007) used repeat laser altimetry to show that, from 1995 to 2000, Brady Glacier thinned more than 2 m/a below 400 m and 0.5 m/a at 600 m. From 2000 to 2005, thinning was at least 1 m/a from the terminus to 1000 m.

Impact on calving of proglacial lakes

In addition to the surface mass balance losses, Brady Glacier is currently experiencing significant calving balance losses in seven proglacial lakes: Abyss Lake, Oscar Lake, and Spur Lake on the east side of the glacier and Bearhole Lake, Dixon Lake, North Deception Lake, and Trick lakes on the west side of the glacier. Dixon, Abyss, and Spur Lake produce periodic jokulhlaups (Capps et al. 2010). Capps et al. (2010) provide detailed descriptions of the evolution of the lakes (Figure 5).

Figure 5. Brady Glacier terminus in 2009 with developing proglacial lakes (yellow arrows) and the major western margin river outlet (red arrow). O=Oscar, S=Spur, T=Trick.

There is a consistent pattern in the change in position of the glacier margin at each of the lakes between 1948 and 2010 (Table 3). The rate of retreat of the glacier margin at all seven lakes accelerated later during this period; the mean retreat rate is 13 m/a from 1948 to 2004 and 42 m/a from 2004 to 2010 (Table 3). The seven lakes have changed dramatically in response to this acceleration in retreat. North Deception illustrates the magnitude of the changes from 1948 to 2010, including a retreat of 1700 m (Figure 6).

Table 3. Comparison of lake area, surface elevation, and retreat for Brady Glacier proglacial lakes.

	1948 area (km^2)	2010 area (km^2)	1948 elevation (m)	2000 elevation (m)	1948–2004 retreat (m)	2004–2010 retreat (m)
Abyss	2.6	2.7	269	230	−125	−150
Bearhole	0.8	3.2	204	165	−200	−1300
North Deception	0.5	3.2	23	18	−350	−1350
Oscar	0.1	2.6	198	198	−400	−250
Spurr	0.8	0.6	133	133	−200	−600
East Trick	x	1	x	30	−200	−300
North Trick	1.8	1	60	30	x	x
South Trick	0.7	0.2	60	30	x	x
Dixon	0.8	4.1	274	170	−700	−600

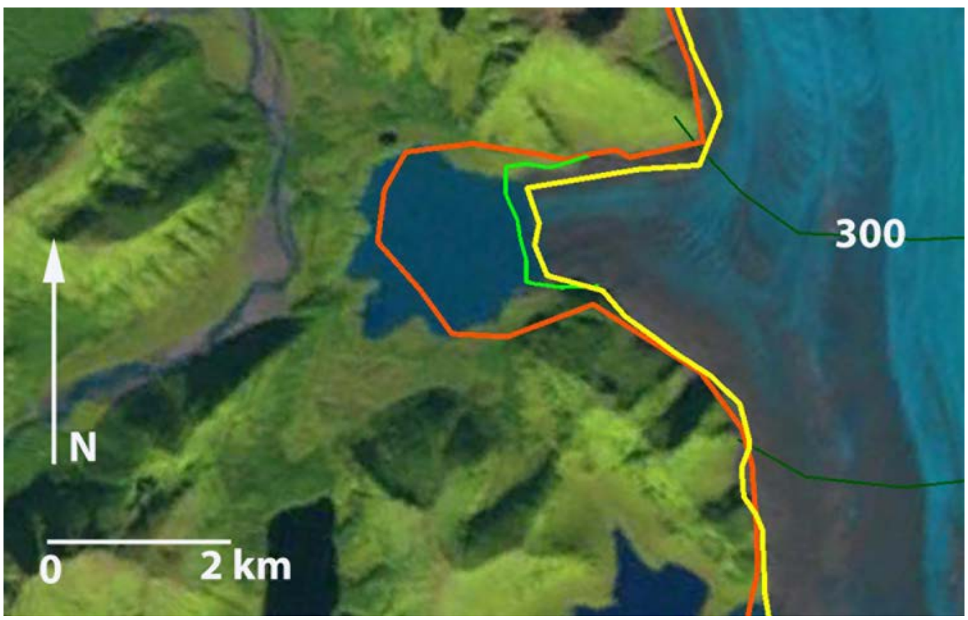

Figure 6. Changes in the Brady Glacier margin from 1948–2010 at North Deception Lake. Orange = 1948, green = 2004 and yellow = 2010.

Lake area and calving fronts were measured for each lake: Spur, Abyss, North Deception, Bearhole, Oscar, and East Trick based on the September 2010 imagery, with earlier measurements from Capps et al. (2010). Lake areas have increased as a result of glacier retreat and can decrease due to declines in surface water levels as previously ice-dammed conduits form to drain the lake. Water levels have fallen in Abyss, Bearhole, Dixon, North Deception, Spur, and Trick lakes since 1948. Only Oscar Lake, the most recent to form, has maintained its surface level. Retreat of the glacier margin has been greatest at Bearhole, North Deception, and Oscar lakes, which as a consequence have expanded substantially in area. Water level falls at Abyss, Spur, and Trick lakes have offset the increase in area resulting from glacier retreat, leading to small changes in lake area (Table 3).Until recently; North Trick and South Trick lakes were adjacent to Brady Glacier. With glacier thinning and retreat, the level of the two lakes has fallen and neither lake is now proglacial, in contact with the glacier. The more recently developed East Trick Lake is the current proglacial Trick Lake.

Key factors in calving balance losses are water depth and the width of the glacier that is calving (Mercer, 1961; Skvarca et al., 2002).Glacier thinning and retreat near the lakes dammed by Brady Glacier have led to changes in the widths of calving fronts between 1948 and 2010, with the largest changes between 2004 and 2010 (Table 4). The combined increase in the width of the six secondary calving fronts is 34% from 1948 to 2004 and 15% from 2004 to 2010 (Table 4). The greatest increases have occurred at Oscar Lake. Continued thinning and retreat will lead to an increase in the calving widths of Abyss and Oscar lakes. Calving widths at Bearhole, Spur, and Trick lakes will not change appreciably. Spur and Trick lakes parallel the margin of the glacier; and although this margin will likely continue to recede, the length of the depression filled by the two lakes probably will not change. Bearhole Lake is retreating up valley, and there are no significant changes in the width of the valley that would suggest a significant increase in calving width could occur in the near future. The width of the glacier margin at North Deception Lake will not change in the short term, but the valley widens 2 km back from the current calving front, thus the lake may grow considerably in the future.

Table 4. Variation of calving width and calving depth of Brady Glacier secondary termini in proglacial lakes.

	Calving width 1948 (m)	Calving width 2004 (m)	Calving width 2010 (m)	Calving depth 1948 (m)	Calving depth 2004 (m)	Calving depth 2010 (m)
Abyss	890	1050	1100	200	160	200
Bearhole	200	1700	1550	30	75	75
North Deception	2150	1600	2000	20	30	20
Oscar	770	2700	4200	20	40	120
Spur	890	1100	1240	x	x	x
Trick	1680	1800	1660	20	10	20
Dixon	940	2800	2800	x	x	x
Total	7520	12750	14550	58	63	87

Water depth is an important factor affecting the calving rate of glaciers in lacustrine environments; velocity and calving rate increase with water depth by a factor of 3.6 (Skvarca et al., 2002). Capps (2011) determined the bathymetry and calving depths of five of the lakes at Brady Glacier. Water depths increase toward the calving fronts at Abyss Lake, Bearhole Lake, Oscar Lake, and Trick Lake; only at North Deception Lake does the water not currently become deeper towards the calving front; however it almost certainly will as the east margin moves into the main Brady Glacier valley (Table 4). It is likely that retreat toward the main valley of the Brady Glacier will lead to increased water depths at Dixon and Spur lakes as well. The observations indicate that mean calving depths, at least in the short term, will increase with continued retreat.

Increases in calving width and depth will lead to increased calving at the secondary termini in the near future. The thickness of the Brady Glacier at calving fronts is not accurately known, preventing direct calculation of calving flux. Instead, we use the formula for lacustrine glacier calving (Skvarca et al., 2002) to estimate the percentage change in calving flux between 2004 and 2010. Over this period the mean calving width increased by 15% and the mean calving depth increased by 38%. Because water depth increases calving by a factor of 3.6, the calving flux in 2010 is at least twice that in 2004.

Several small lakes are now forming at the main terminus of Brady Glacier, possibly the first indication that the glacier will soon retreat from its protective outwash plain. If the glacier retreats, its bed will be much deeper than the adjacent outwash plain and a large lake will develop at the newly calving glacier margin.

DISCUSSION

This sequence of events outlined above at Brady Glacier has been observed at a number of glaciers in the region, each of which has experienced rapid calving retreat. Examples include Yakutat, Excelsior, Norris, Bear, and Portage glaciers. Yakutat Glacier, during the 1894–1895 International Boundary Survey, terminated against a moraine on a flat coastal outwash plain. By 1906, the glacier had retreated from the moraine; and a new lake, Harlequin Lake, was forming. The glacier retreated 5 km between 1906 and 1948, 3.6 km from 1948 to 1958, and another 3–4 km from 1958 to 2008 (Molnia, 2008). Excelsior Glacier, in 1913, terminated on an outwash plain about 1 km from Johnstone Bay. By 1951, the glacier had retreated as much as 4.3 km into a terminal lake. A secondary lake, Excelsior Lake, expanded dramatically upglacier of the terminus; it eventually drained when Excelsior Glacier retreated back to the former location of Excelsior Lake. In 1948 Norris Glacier terminated on Grizzly Bar with very limited calving (Miller, 1964). By 1964, the glacier was retreating into a proglacial lake (Miller, 1964), and by 2010 it had retreated 1.8 km from Grizzly Bar with the proglacial lake expanding by the same amount. Bear Glacier ended as a piedmont lobe on an outwash plain in the early 20th century; this lobe slowly downwasted during the first half of the 20th century, preconditioning the glacier for a rapid retreat. By 1980, the terminus had retreated 1 km, thinned by 150 m, and was calving small icebergs into an ice-marginal lake that was beginning to develop in the still-narrow basin (Molnia, 2008). By 2000, much of the terminus was afloat; and calving increased, leading to a terminus retreat of 3.5 km by 2007 (Hall et al., 2005; Molnia, 2008). In the early 1900s, Portage Glacier terminated on land at the west end of Portage Lake (Kennedy et al., 2006). As the glacier receded, its stable land-based terminus retreated into proglacial Portage Lake and began to calve. Since then, the glacier has receded 5 km in contact with Portage Lake. The most rapid recession (140–160 m/a) occurred between 1939 and 1950 when water depth at the terminus was at its maximum. Recession has now slowed considerably as the glacier has reached a more stable position at the east end of Portage Lake (Kennedy et al., 2006).

CONCLUSION

The tidewater glacier cycle described by Meier and Post (1987) strictly applies to glaciers calving into fjords. Brady Glacier and the other glaciers mentioned above are not calving into the sea, although the considerable depths of the resultant lakes lead to similarities. During the period 2003–2011, the mean ELA of Brady Glacier was 745 m, compared to equilibrium ELA of 600 m. The AAR of Brady Glacier was 0.40, indicative of a significant ongoing negative mass balance that has been verified by surface thinning from altimetry data (Larsen et al., 2007). The negative mass balance has been enhanced by retreat of the seven secondary Brady Glacier termini ending in calving fronts in proglacial lakes. The width of the calving fronts has been increasing and, combined with the increased mean water depth at the calving fronts, has led to increased ice losses by calving. The combined surface lowering and calving losses will lead to further thinning and the development of a proglacial lake at the terminus of Brady Glacier. Based on the behavior of other similar glaciers in southeast Alaska, rapid calving retreat will ensue as a lake develops at the main terminus of Brady Glacier.

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