

## **Satellite Identification of Transient Snowline Variation During the Melt Season for Mass Balance Assessment Taku and Brady Glacier, Alaska**

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### **ABSTRACT:**

A key measure of mass balance on large Alaskan glaciers is the Equilibrium line altitude (ELA) at the end of the melt season, which can during most years be observed in satellite imagery. Observations of the transient snowline position (TSL) during the course of the melt season also are useful for defining ablation in a significant region of the glacier. On Taku Glacier we combine field observations of snow depth from snowpits and probing, with satellite TSL observations to quantify ablation and the balance gradient. The balance gradient determined from the difference in elevation and snow water equivalent (SWE) from the TSL elevation to the snowpits at 1000 m from 1998-2009 is 2.8-3.7 mm/m. Probing transects from 900 m-1200 m yield a slightly higher balance gradient of 3.3-3.9 mm/m. In 2004 the snowline rose from 850 m on July 15, to 950 m on Aug. 16, to 1030 m on Sept. 1. The observed balance gradient was 3.4 mm/m and snowline rise was 3.75 m/day, yielding an ablation rate of 12.75 mm/day on Taku Glacier in 2004. Mean ablation determined from the TSL rise and the observed balance gradient varied from 8 to 13 mm/day on Taku Glacier during the 1998-2009 period. A comparison of the TSL rise for Brady Glacier and Taku Glacier based on seven different periods of more than 24 days during the ablation season with repeat imagery indicate a respective mean snowline rise of 4.2 m/day on Brady Glacier and 3.8 m/day on Taku Glacier. Assuming the observed balance gradient near the snowline on Brady Glacier is the same as Taku Glacier of 3.4 mm/m, a daily ablation rate of 14.3 mm/m is estimated. This is somewhat higher than the 12.9 mm/day observed on Taku Glacier where the ELA is 200-250 meters higher.

**Keywords:** glacier runoff, glacier retreat, snowpack, stream discharge, North Cascades

### **INTRODUCTION**

Ostrem (1975) first noted the utility of identifying the 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 any particular time (Ostrem, 1975). Williams et al., (1991) found that during the melt season the TSL is easily identifiable in satellite imagery dividing the regions of snow melt and snow accumulation areas. 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 (Ostrem, 1975; Williams et al., 1991; Pelto and Miller, 1999). Using satellite imagery the TSL

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can be identified close to the end of the melt season, but in many seasons the time difference can be several weeks between available usable imagery where the TSL is visible and the end of the melt season. This emphasizes the need to understand the behavior of the TSL and the relationship between mass balance and the TSL. If the rate of TSL rise can be determined and it is reasonably consistent at the end of the melt season than the ELA can be reliably estimated from TSL observations several weeks removed from the end of the melt season. The current availability of satellite imagery from many sources ensures coverage late in the melt season for the majority of years.

Dyurgerov (1996) developed a method to compute a transient mass balance ( $b_{nt}$ ), the mass balance ( $b_n$ ) at a particular time for a glacier, based on observation of the TSL, which was used to determine the transient accumulation area ratio (AAR) associated with each TSL and transient  $b_{nt}$  value. This relationship can be utilized to determine the annual mass balance if the relationship between transient  $b_{nt}$  and TSL is identical to the relationship between  $b_n$  and ELA over many years (Dyurgerov, 1996). Hock et al., (2007) identified the TSL to calculate the accumulation area ratio (AAR) during the course of an ablation season on Storglaciaren, Sweden. They found the relationship between the TSL, derived AAR and  $b_n$  to be robust when the AAR was below 0.60. It has been well established that most glaciers have a strong relationship between their AAR and  $b_n$  (Zemp et al., 2009; Hock et al., 2007). The observations of Hock et al., (2007) indicate that the AAR-  $b_n$  relationship can also be identified by examination of the TSL and the transient AAR and  $b_{nt}$  values during a single summer. This indicates that once the AAR-  $b_n$  relationship is calibrated for a particular glacier or area the approach from TSL-AAR observations provides a powerful and efficient method for widely monitoring glacier mass balance given the increased availability of remote sensing products.

A third potential utility of TSL variations is identification of ablation rates in the vicinity of the TSL. Variations in the TSL through the course of the melt season identify ablation in the vicinity of the TSL and near the end of the ablation season the ELA (Miller and Pelto, 1999). This application of the TSL to glacier mass balance depends on the calibration of the TSL to ablation for specific regions on specific glaciers. In this study the TSL elevation rise, TSL derived balance gradient and TSL derived ablation is completed from satellite TSL observations with field measurement identification of the balance gradient on Taku Glacier, Alaska by the Juneau Icefield Research Program (JIRP). The method is then extended to Brady Glacier, Alaska which occupies the same climate setting as Taku Glacier. The goal being to simply observe if the rate of TSL rise is similar.

## **TAKU AND BRADY GLACIER**

Taku Glacier is selected because of the long mass balance record measured by the Juneau Icefield Research Program (JIRP) extends from 1946-2006 (Pelto and Miller, 1990; Pelto, et. al., 2008). Taku Glacier is a temperate, maritime valley glacier in the Coast Mountains of Alaska. With an area of 671 km<sup>2</sup>, it is the principal outlet glacier of the Juneau Icefield (Fig. 1). The mean ELA is at 925 m. The glacier slope ranges from 0.021 to 0.028 to in the section of the glacier from 200 m below to 200 m above the ELA. It attracts special attention because of its continuing, century-long advance (Pelto and Miller, 1990; Post and Motyka, 1995), while all other outlet glaciers of the Juneau Icefield are retreating. Taku Glacier is also noteworthy for its positive mass balance from 1946-1988, which has resulted from the cessation of calving around 1950. The positive mass balance resulting from this dynamic change which gives the glacier an unusually high AAR for a non-calving glacier makes the glacier relatively insensitive to climate change (Pelto et al, 2008; Criscitiello, et al., 2010). The positive mass balance is continuing to drive the advance (Pelto and Miller, 1990; Pelto et al., 2008), during a period when alpine glacier mass balances have been dominantly negative (Zemp et al., 2009). Taku Glacier is significantly correlated with ablation season temperatures in Juneau, Alaska and Whitehorse, Yukon (Criscitiello et al., 2010).

JIRP has relied on applying consistent mass balance methods at standard measurement sites (Pelto and Miller, 1990; Miller and Pelto, 1999). On the Taku Glacier the key annual inputs are 17 test pits at fixed sites ranging from 950 m to 1800 m directly measuring the snow water equivalent (SWE), ablation measurements along survey profiles, and observations of the TSL and ELA (Pelto and Miller, 1990; Pelto et al., 2009). Six of the snowpits are near the ELA 950-1200 m, two are at approximately 1000 m (Figure 1). The migration of the TSL is monitored from field observation and remote sensing images and the final ELA position at the end of the balance year is located. Ablation during the field season is observed along survey lines where repeat surveys are completed and the final ELA position at the end of the balance year is located (Pelto and Miller, 1990; Pelto et al., 2008). Measurements of retained accumulation in the snowpits are completed during late July and August and are adjusted to end of the balance year values, based on the variations of the TSL, observed ablation and the measured balance gradient (Pelto and Miller, 1990; Miller and Pelto, 1999).

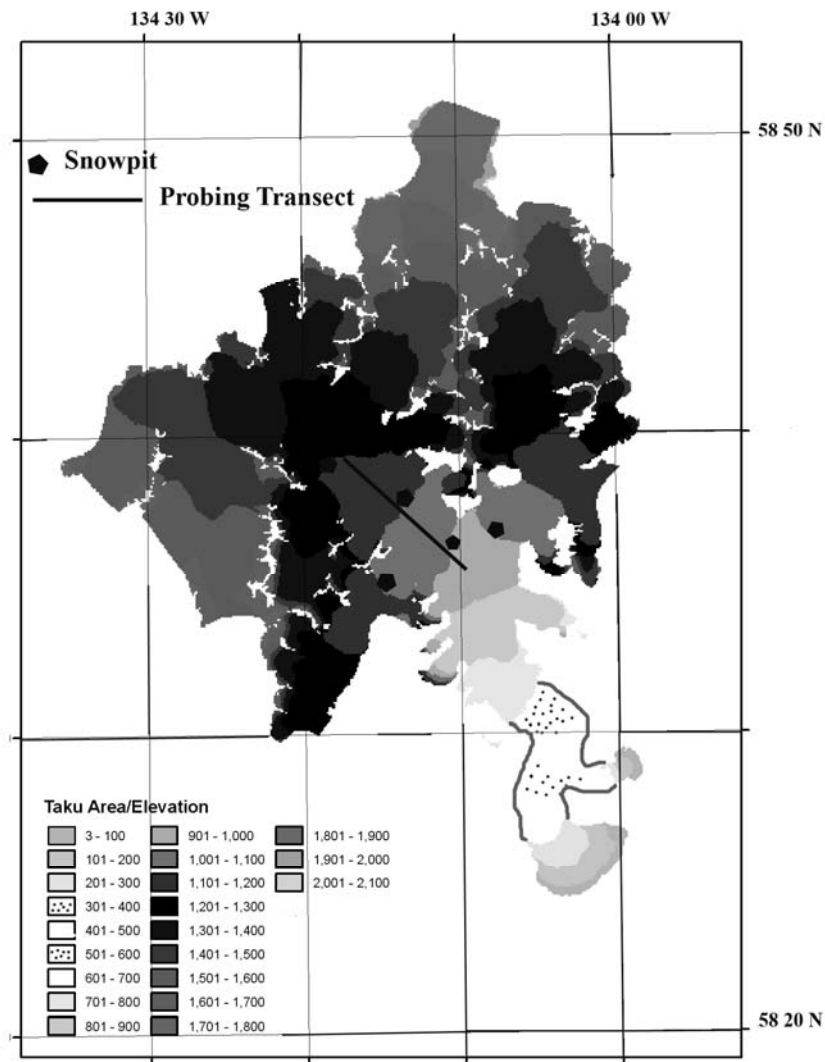


Figure 1. Location map for Taku Glacier indicating the snowpit locations, black pentagon. Probing transects is also noted.

The Taku Glacier mass balance record has been confirmed by observation of glacier surface elevation change using the ongoing laser altimetry by the University of Alaska, Fairbanks (Echelmeyer et al., 1996), indicating a mean  $b_n$  of -0.21 m/a for the 1993-2007 period, compared to the JIRP mean  $b_n$  of -0.16 m/a. A comparison of the surface elevation from the 2000 Shuttle Radar Topography Mission and a DEM from the 1948 USGS mapping indicates a mean  $b_n$  of 0.45 m/a versus the JIRP record of +0.27 m/a for the 1948-2000 period (Larsen et al., 2007).

Brady Glacier is 150 km west of Taku Glacier has an area of 478 km<sup>2</sup> and is 45 km long. Brady Glacier ceased calving and advanced approximately 8 km during the 19th century (Bengston, 1962). As Bengston (1962) notes, the advance is like the Taku Glacier an example of an advance following a change from tidal to non-tidal status rather than that of a more positive mass balance due to climate change. Bengston (1962) further notes that the massive outwash plain at the terminus is primarily responsible for Brady Glacier maintaining an advanced position while other glaciers in the Glacier Bay region retreated substantially. The mean ELA on this glacier is 800 m in the last 10 years, but had been noted as 600 m (Bengston, 1962; Pelto, 1987), this is one of the lowest in Alaska. The recent snowline rise has led to a notable thinning of the glacier of nearly 3 m from 1995-2005 in the vicinity of 600 m (Larsen et al., 2007). The main terminus was still advancing in the 1960's and 1970's but has begun to retreat, the retreat to date is less than 200 meters. Subsidiary termini ending in several proglacial lakes indicate considerably more retreat. The retreat ranges from 200 m in Abyss Lake, 200 m in Trick Lake to 1200 meters in North Deception Lake. These also suggest the glacier currently has a negative surface mass balance. The glacier slope ranges from 0.022 to 0.028 between 500 and 1000 m, the TSL observation zone.

## **BALANCE GRADIENT**

Prior to the availability of satellite imagery the TSL was mapped in early July, late July, mid-August and in early September, this last observation was assumed to be the ELA. In 1998 (Mauri Pelto), 2004 and 2005 (Matt Beedle, UNBC) JIRP measured the mass balance along transects from the TSL to at least 1150 m in late July using probing measurements at 200 meter intervals. Three measurements within 25 m were averaged to determine the snowpack depth at each probing location. SWE is then determined from the snowpack depth and mean snow density observed in the snowpits along the probing transect in at least three locations. This directly identifies the mass balance gradient (Figure 2). The balance gradient from probing above the TSL ranges from 3.3-3.9 mm/m, mean 3.5 mm/m.

Two snowpits TKGTP5 and DGTP1 (Figure 1) completed at 1000 m identify snowpack depth and SWE directly. The difference in SWE between the snowpits and TSL, where SWE is by definition zero, and the difference in elevation between the TSL and the snowpits provides a second and independent direct measure of the balance gradient (Figure 3). The Taku Glacier balance gradient from TSL to snowpits at 1000 m from 1998 to 2009 range from 2.8-3.7 mm/m, mean 3.3 mm/m. The gradient is slightly lower than the mean observed from probing above the TSL.

## **SATELLITE IMAGE IDENTIFICATION OF TSL**

Examination of available Landsat imagery from the USGS Globalization Viewer (<http://glovis.usgs.gov/>) identified 29 scenes from 1984-2009 where the TSL could be readily identified during the ablation season on Taku Glacier (Table 1). On Brady Glacier 15 scenes were identified for the 1999-2009 period. For Landsat imagery Taku Glacier is Row/Path 58/19 and Brady Glacier 59/19. For years with multiple images, the rate of rise of the TSL is determined. This rate of rise is only calculated for period of more than 24 days. For example in 2006 the ELA was identified in four Landsat images on Taku Glacier. The ELA rose from 370 m on May 26, to 730 m on July 5, to 800 m on July 29, and to 980 m on Sept. 15 (Figure 4). For Taku Glacier

there are eight periods where the TSL was observed for more than 24 days. The mean rise of the TSL averages 3.8 meters/day during the July-September period, for the elevation range between

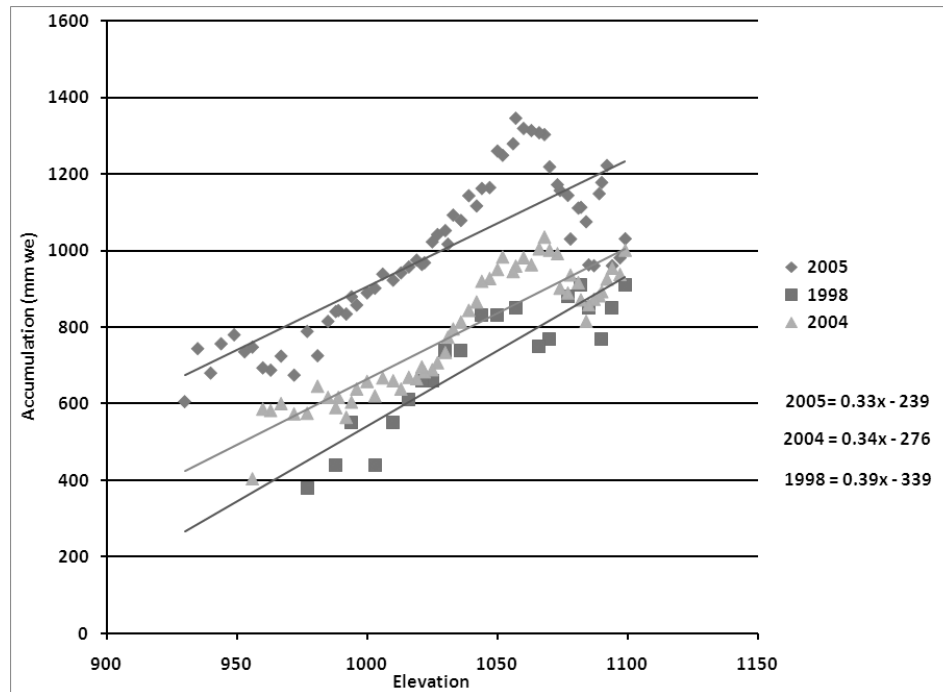


Figure 2. Balance gradient determined from probing transects extending upglacier from the transient snowline on Taku Glacier in 1998, 2004 and 2005. Matt Beedle from the University of Northern British Columbia supplied to the 2004 and 2005 JIRP probing data.

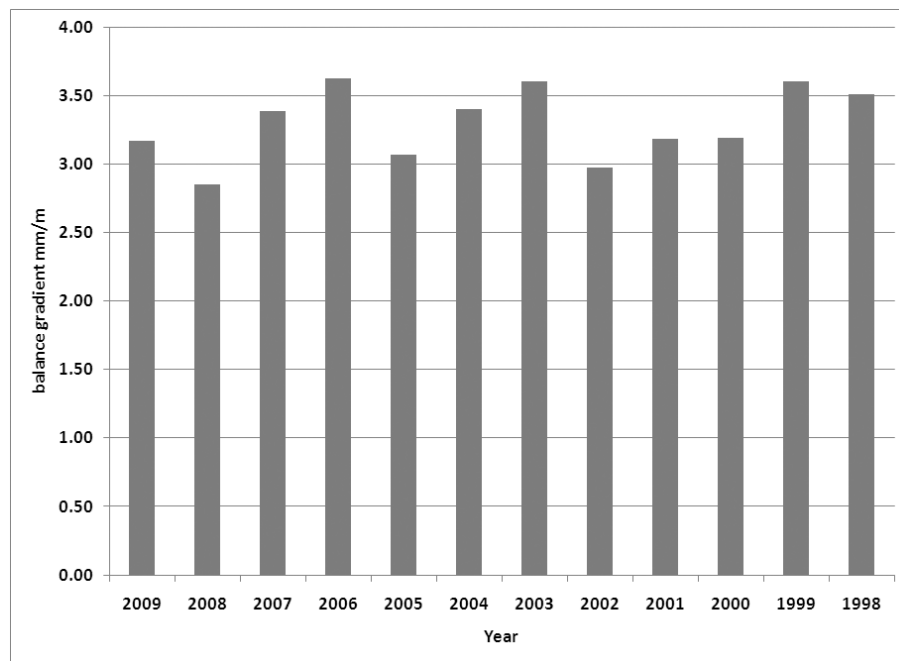


Figure 3. Balance gradient on Taku Glacier between the snowpits and the transient snowline.

## 700 AND 1100 M

If we extend the observation earlier in the summer and to lower elevations not only do we lack the field data to corroborate the balance gradient, but the rate of rise is markedly faster.

Mean daily ablation can be determined from the rate of rise of the TSL and the mean balance gradient. This illustrates the usefulness of the shift in position of the TSL for assessing ablation. Given the mean observed balance gradient near the snowline on Taku Glacier is 3.3-3.5 mm/m and daily TSL rise is 3.8 m/day. The mean daily ablation is then 12.5-13.3 mm water equivalent for the July-September period. This compares to direct measurement of ablation on Taku Glacier at 1000-1100 m of 17.7 mm/day for the mid-July to early-August period, and of 10.7 mm/day after early August.

On Brady Glacier in 2004 four satellite images provided TSL identification: July 13, 550 m, Aug. 14 670 m, Aug. 30 730 m, and Oct., 10, 940 m (Figure 5). In a typical year by early October new snow would have fallen on Brady Glacier as is evident in several other years where the TSL has begun to drop, but not in 2004. The rise of the TSL averages 4.2 meters/day (Figure 6) during the July-September period, assuming the balance gradient of 3.3-3.5 mm/m from Taku Glacier yields a daily ablation rate of 13.9-14.7 mm/day is estimated for Brady Glacier. This is somewhat higher than the 12.6 mm/day observed on Taku Glacier where the snowline is 200 meters higher. The number of multiple TSL observations over an extended period of the latter half of the same ablation season are insufficient to have great confidence in the above TSL rate of rise determination. It is encouraging that for two low slope large southeast Alaskan glaciers, both glaciers have slopes of approximately 0.025 the TSL rise rate is quite similar and encourages further examination of additional glaciers and additional remote sensing sources.



Figure 4. Transient snowline on the Taku Glacier during 2006: A=5/26, B=7/5 C=7/29 and D=9/16



Figure 5. Brady Glacier transient snowline in 2004: A=7/13, B=8/14, C=8/30 and D=10/10. Usually new snow would have fallen by 10/10, but not in 2004.

## CONCLUSIONS

Multiple observations of the TSL during the course of a melt season provide a measure of ablation that can be quantified if the balance gradient of a glacier in the area of the TSL is known. Due to the availability of satellite imagery from even one source (Landsat), the TSL has been identified late in the ablation season on Taku Glacier in 9 of the last 12 years. On Taku Glacier the balance gradient assessed in the field using snowpits and probing transects is 3.3 mm/m compared to 3.5 mm/m from field measurements. This combined with the observed rate of TSL rise of 3.8 mm/day yields a mean daily ablation rate in the latter half of the ablation season of 13 mm/day. On Brady Glacier TSL rise is 4.2 m/day, from July through the latter part of the ablation season, yielding an ablation rate of 14 mm/day. Multiple observations of TSL during a single balance year provide a means to better establish annual balance-ELA and annual balance-AAR relationships for Alaskan glaciers. The next step will be to identify how consistent the TSL rise is on southeast Alaskan glaciers.

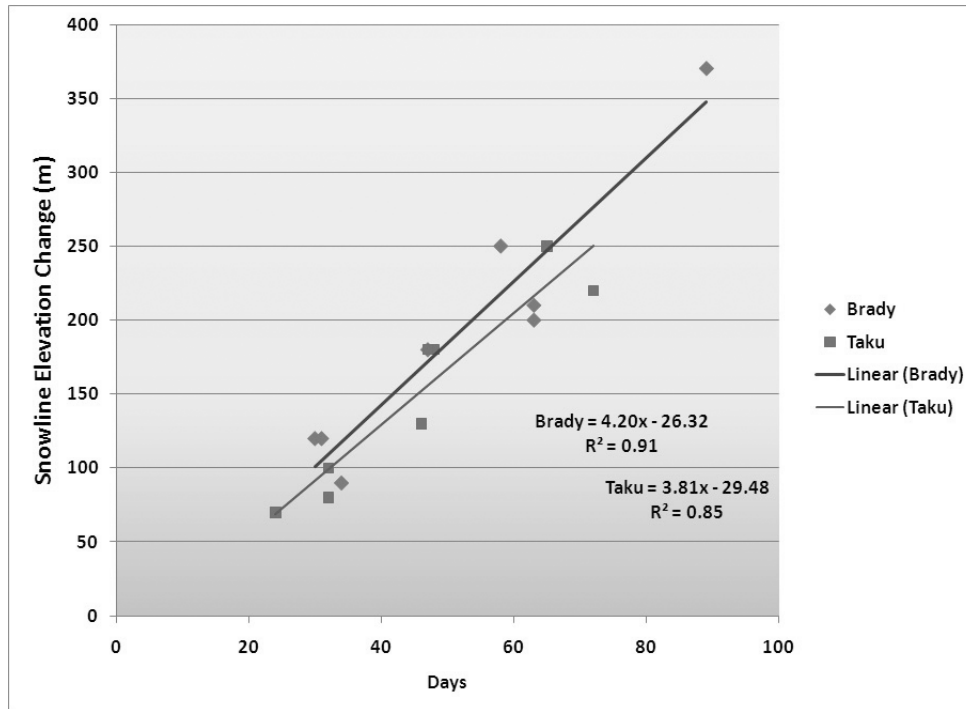


Figure 6. Daily rate of rise of the transient snowline on Brady and Taku Glacier for periods of greater than 24 days.

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