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Please refer to the corresponding final paper in TC if available.

Utility of late summer transient snowline migration rate on Taku Glacier, Alaska

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Received: 31 December 2010 – Accepted: 24 February 2011 – Published: 6 May 2011

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Published by Copernicus Publications on behalf of the European Geosciences Union.

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Abstract

On Taku Glacier, Alaska a combination of field observations of snow water equivalent (SWE) from snowpits and probing in the vicinity of the transient snowline (TSL) are used to quantify the mass balance gradient. The balance gradient is determined from the difference in elevation and SWE from the TSL to snowpits at 1000 m from 1998–2010 and ranges from 2.6–3.8 mm m⁻¹. Probing transects from 950 m–1100 m directly measure SWE and yield a slightly higher balance gradient of 3.3–3.8 mm m⁻¹. TSL is identified in MODIS and Landsat 4 and 7 Thematic Mapper imagery for 31 dates during the 2004–2010 period on Taku Glacier to assess the consistency of its rate of rise and usefulness in assessing mass balance. In 2010, the TSL rose from 750 m on 28 July, 800 m on 5 August, 875 m on 14 August, 925 m on 30 August, and to 975 m on 20 September. The mean observed probing balance gradient was 3.3 mm m⁻¹ and TSL rise was 3.7 m day⁻¹, yielding an ablation rate of 12.2 mm day⁻¹ on Taku Glacier from mid-July to mid-September. A comparison of the TSL rise in the region from 750–1100 m on Taku Glacier during eleven different periods of more than 14 days during the ablation season with repeat imagery indicates a mean TSL rise of 3.7 m day⁻¹ on Taku Glacier, the rate of rise is relatively consistent ranging from 3.0 to 4.8 m day⁻¹. This is useful for ascertaining the final ELA if imagery or observations are not available within a week or two of the end of the ablation season. From mid-July-mid-September the mean ablation from 750–1100 m determined from the TSL rise and the observed balance gradient varied from 11 to 18 mm day⁻¹ on Taku Glacier during the 2004–2010 period.

1 Introduction

Ostrem (1975) first noted the utility of identifying the transient snow line (TSL) using remote sensing images in mass balance assessment. A glacier consists of two primary glacier facies an ice and a snow facies, with the transition between the two describing

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the TSL (Ostrem, 1975). Late in the hydrologic year, the TSL approximates the glacier equilibrium line on most temperate glaciers including southeast Alaskan glaciers which lack superimposed ice (Hall et al., 1989). Ostrem (1975), Hall et al. (1989) and Williams et al. (1991) found that during the melt season the TSL is easily identifiable in satellite imagery. For the specific date of TSL observation annual mass balance at the TSL is zero (Hock et al., 2007), providing an important reference point for the balance gradient curve. Meier and Tangborn (1965) and Dyugorov and Meier (1999) noted that the balance gradient, the change in mass balance with elevation, for temperate glacier varied little from year to year. We combine TSL observations with field snow depth measurements on Taku Glacier, Alaska to examine the consistency of the rate of TSL rise, and the potential for using TSL variations from satellite imagery in assessing the balance gradient and ablation. Prior to the availability of daily MODIS (Moderate Resolution Imaging Spectroradiometer) imagery the number of useful Landsat images for TSL observations was insufficient to provide reliable multiple annual observations late in the ablation season.

2 Study area

Taku Glacier was selected because of the long mass balance record measured by the Juneau Icefield Research Program (JIRP) which extends from 1946–2010 (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 km², it is the principal outlet glacier of the Juneau Icefield (Fig. 1). The mean ELA from 1998–2010 is at 950 m. In the region of the glacier within 200 m of the ELA glacier surface slope ranges from 2.1 to 2.8%. This region on the Taku Glacier encompasses 131 km², approximately 20% of the glacier.

Taku Glacier is noteworthy for its positive mass balance from 1946–1988, which resulted from the cessation of calving around 1950 (Pelto and Miller, 1990). The positive mass balance resulting from this dynamic change gives the glacier an unusually high

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AAR for a non-calving glacier and 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; Post and Motyka, 1995; Pelto et al., 2008), while all other outlet glaciers of the Juneau Icefield are retreating and during a period when alpine glacier mass balance globally has been dominantly negative (Zemp et al., 2009).

JIRP has relied on applying consistent mass balance methods at standard measurement sites (Pelto and Miller, 1990; Miller and Pelto, 1999). On Taku Glacier the key annual measurements are: (1) 17 test pits at fixed locations ranging in elevation from 950 m to 1800 m directly measuring the snow water equivalent (SWE) through the entire snowpack profile, (2) ablation measurements at survey stakes along survey profiles, (3) observations of the TSL and ELA (Pelto and Miller, 1990; Pelto et al., 2008). Ed LaChapelle (1956) first noted that the density of the snowpack is consistent and fixed after early July on the Taku Glacier (Pelto and Miller, 1990). For this study our goal is not further assessment of the overall mass balance of the glacier, but variations of mass balance during the ablation season near the TSL. I utilize data from two snowpits near the ELA at 1000 m (Fig. 1). 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). Ablation during the field season is observed at survey stakes along survey lines where repeat surveys are completed and through migration of the TSL (Pelto and Miller, 1990; Pelto et al., 2008). Prior to the availability of satellite imagery in 1984 the TSL was determined by field observations by JIRP in early July, late July, mid-August and in early September, this last observation was assumed to be the ELA. From 1984–1997 remote sensing images supplemented the field observations. After 1998 remote sensing imagery has provided many of the TSL and ELA observations and since 2004 the majority.

The Taku Glacier mass balance record has been confirmed by independent observation of glacier surface elevation change using the ongoing laser altimetry by the

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University of Alaska, Fairbanks (Echelmeyer et al., 1996), indicating a mean net balance (b_n) of -0.21 m a^{-1} for the 1993–2007 period, compared to the JIRP mean b_n of -0.16 m a^{-1} . A comparison of the surface elevation from the 2000 Shuttle Radar Topography Mission and a DEM derived from the 1948 USGS mapping indicates a mean b_n of $+0.45 \text{ m a}^{-1}$ versus the JIRP record of $+0.27 \text{ m a}^{-1}$ for the 1948–2000 period (Larsen et al., 2007).

3 Methods

Three lines of evidence are used in to identify the TSL, balance gradient and ablation rate. Remote sensing imagery is used to identify the TSL. Examination of available Landsat Thematic Mapper (TM) imagery from the USGS Globalization Viewer (<http://glovis.usgs.gov/>) identified 21 scenes from 2004–2010 where the TSL could be readily identified during the ablation season on Taku Glacier (Table 1). For Landsat (TM) imagery Taku Glacier falls in Row/Path 58/19, all images provided are RGB color composites, bands 5, 4, and 3 from the Landsat 7 (TM) and from Landsat 4–5 (TM), with a 2 % linear stretch applied. In addition MODIS real time true color swath imagery from the Geographic Institute Network of Alaska (GINA-<http://www.gina.alaska.edu/data/gina-modis-images/>) has been utilized on 10 occasions (Table 1). All images are overlain on a USGS Topographic map Digital Elevation Model and the elevation of the TSL determined.

Probing transects in late July have been utilized to determine the balance gradient in more detail in the vicinity of the ELA. In 1998 (Mauri Pelto), 2004 and 2005 (Matt Beedle) and 2010 (Chris McNeil), as part of JIRP, measured the mass balance along transects from near the TSL at 900 m to 1150 m in late July using probing at a horizontal interval of 200 m. Three measurements made 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 three locations.

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Two snowpits TKGTP5 and DGTP1 (Fig. 1) are completed annually at 1000 m within several days of July 20th each year since 1998. At each test pit the SWE is directly identified along with the snowpack depth. SWE varied from 300 mm in 2003 to 1920 mm in 2000, with a mean of 1200 mm (Fig. 2). The mean difference between the two snowpits is 65 mm. The two snowpits, TKTP5 and DGTP1, have been completed within a few days of 20 July each year since 1998. 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 direct measure of the balance gradient in late July. For the average year on 20 July SWE is 1200 mm at the testpits at 1000 m and 0 mm at the TSL. If the TSL is 800 m on 20 July than the balance gradient is 1200 mm/200 m, or 6 mm m⁻¹. In some years the TSL is lower than region where probing transects reach, and the balance gradient is not as well established from field observations at elevations below 800 m.

4 Balance gradient observations near the TSL

Probing transects conducted in 1998, 2004, 2005 and 2010 utilize the same measurement transect to assess SWE at 200 m intervals from near the TSL during late July to 1150 m. This directly identifies the mass balance gradient at this elevation for late July (Fig. 3). The balance gradient determined from probing above the TSL ranges from 3.3–3.8 mm m⁻¹, with a mean of 3.5 mm m⁻¹. The balance gradient has been consistent on Taku Glacier for each year observed regardless of the respective mass balance or ELA for that year (Fig. 3).

The SWE at the two test pits provides a direct measure of the balance gradient from the TSL to the snowpits at 1000 m in late July (Fig. 4). The Taku Glacier balance gradient from the TSL to the snowpits at 1000 m from 1998 to 2009 ranged from 2.8 to 3.7 mm m⁻¹, with a mean of 3.3 mm m⁻¹. The gradient is slightly lower than the mean 3.5 mm m⁻¹ observed from probing above the TSL. The 2003 balance gradient was not determined as the TSL was too close to the snowpits on 20 July for a reliable gradient to be determined.

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The TSL is identified in Landsat and MODIS imagery by overlaying the images on the USGS DEM. For years with multiple images, the rate of rise of the TSL is determined. This rate of rise is only calculated for periods of longer than 14 days. For example in 2006 the ELA was identified in five Landsat images on Taku Glacier. The mean rise of the TSL for 11 periods averages 3.7 m day^{-1} during the July-September period, for the elevation range between 750–1100 m (Table 2). The ELA rose from 370 m on May 26, to 575 m on June 10, 730 m on 5 July, 800 m on 29 July, and finally 980 m on 14 September (Fig. 5). For Taku Glacier there are sixteen periods since 2004 where the TSL was observed for more than 14 days (Table 2). As evidenced in Table 2 earlier in the summer and or at lower elevations we lack the field data to corroborate the balance gradient, and the rate of TSL rise is markedly faster. For the five periods for elevations from 450–800 m the mean rate of rise was 7.9 m day^{-1} .

5 Ablation determination from TSL observations and the balance gradient

Ablation at the TSL is the product of the observed balance gradient and the TSL rate of rise. In 2006, the TSL rate of rise was 3.6 m day^{-1} from 5 July 2006 to 14 September 2006 (Fig. 5). The balance gradient from snowpits was 3.0 mm m^{-1} and from probing is 3.5 mm m^{-1} . For 2006 the mean ablation rate at the TSL from 5 July to 14 September is 10.8 mm day^{-1} from the snowpit balance gradient and 12.6 mm m^{-1} from the probing balance gradient. In 2010, the TSL rose from 750 m on 28 July, to 800 m on 5 August, 875 m on 14 August, 925 m on 30 August, and 975 m on 20 September (Fig. 6). The mean observed probing balance gradient was 3.3 mm m^{-1} and TSL rise was 3.7 m day^{-1} , yielding an ablation rate of 12.2 mm day^{-1} on Taku Glacier from 28 July to 20 September 2010.

Mean daily ablation at the TSL can be determined from the rate of rise of the TSL and the balance gradient. Given the mean observed balance gradient near the TSL when it is between 750 and 1000 m on Taku Glacier is 3.5 mm m^{-1} from probing and 3.0 mm m^{-1} from snowpits, and daily TSL rise is 3.7 m day^{-1} , then the computed mean

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daily ablation is 11–13 mm water equivalent for the July–September period in the vicinity of the ELA. This illustrates the usefulness of the shift in position of the TSL for assessing ablation. 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 in the vicinity of 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. The consistency of the rate of rise of TSL on Taku Glacier from 750–1050 m over periods of several weeks or more suggests it can be reliably used in conjunction with a known balance gradient to assess mass balance characteristics near the ELA.

A further potential value is comparison of the rate of rise of the TSL on Taku Glacier to that of other nearby glaciers. The ratio of the rise in TSL on Taku Glacier to a nearby glacier in combination with the known balance gradient on Taku Glacier would allow derivation of the balance gradient on the nearby glacier. The glaciers would have to be observed simultaneously and be in close enough proximity to experience the same climate conditions at the TSL. The MODIS imagery is generally clear for the Taku Glacier is generally clear for most nearby glaciers. The daily availability of the MODIS images would provide ample simultaneous observations of the TSL on glaciers in the region.

6 Conclusions

Multiple observations of the TSL during the course of several melt seasons allowed determination of the consistency of the rate of rise. If there is consistency in the rate and pattern of TSL rise then multiple TSL observations in the same melt season can 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 Landsat TM and MODIS the TSL has been identified late in the ablation season on Taku Glacier in each of the past 7 years. On Taku Glacier the balance gradient assessed annually in the field using probing transects is 3.5 mm m^{-1} compared to 3.0 mm m^{-1} from snowpit measurements. This combined with the observed rate of TSL rise of

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3.7 mm day⁻¹ yields a mean daily ablation rate in the latter half of the ablation season of 11–13 mm day⁻¹. Multiple observations of TSL during a single balance year provide a means to better establish annual balance-ELA relationship, the balance gradient of a glacier and ablation near the TSL during the period of observation. 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). The existence of imagery allowing frequent TSL observation and local balance gradient observations raises the possibility of extending TSL observations to other glaciers on the Juneau Icefield for annual balance assessment or balance gradient determination.

Acknowledgements. The dedication of two individuals to the study of Alaskan glaciers led to the development of two data sets that are invaluable for assessing mass balance of Alaskan glacier over the last 50 years, Keith Echelmeyer, University of Alaska, Fairbanks and Maynard Miller, University of Idaho. The commitment of Scott McGee, Matt Beedle and Chris McNeil in coordinating and replicating the 1998 probing profiles was also essential.

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

Date	Taku TSL	Date	Taku TSL
7/15/2004	850	7/3/2008	400
8/16/2004	950	7/22/2008	550
9/1/2004	1030	8/5/2008*	750
6/7/2005	475	8/19/2008	800
8/10/2005	870	9/26/08*	800
9/11/2005	975	7/2/2009	500
5/26/2006	370	7/29/2009	800
6/10/2006	575	8/5/2009	850
7/5/2006	730	8/31/2009*	925
7/28/2006	800	9/14/09*	950
9/14/2006	980	7/8/2010*	580
7/15/2007	550	8/5/2010*	800
7/25/2007*	675	8/14/2010*	875
8/16/2007	875	8/29/2010	915
9/2/2007	930	9/20/2010*	975
7/25/2007*	675		

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Table 2. Periods between TSL observations separated by at least 14 days. For each period the rate of rise is determined. The group of observations for lower elevations is for periods where the TSL on the start date was below 750 m.

Start Date	End Date	Days	Rise (m)	Rate of Rise
7/15/2004	9/1/2004	47	180	3.83
7/15/2004	8/16/2004	32	100	3.13
8/10/2005	9/11/2005	31	125	4.03
7/5/2006	9/14/2006	70	250	3.57
7/5/2006	7/28/2006	23	70	3.04
8/16/2007	9/2/2007	16	55	3.44
8/5/2008	8/19/2008	14	50	3.57
7/29/2009	8/31/2009	33	125	3.79
7/29/2009	9/14/2009	46	150	3.26
8/5/2010	8/29/2010	24	115	4.79
8/5/2010	9/20/2010	45	175	3.89
Mean				3.65
Lower Elevations				
6/10/2006	7/5/2006	25	180	7.20
7/25/2007	9/2/2007	38	275	7.24
7/3/2008	8/5/2008	33	250	7.58
7/2/2009	7/29/2009	27	300	11.11
7/8/2010	8/5/2010	27	170	6.30
Mean				7.88

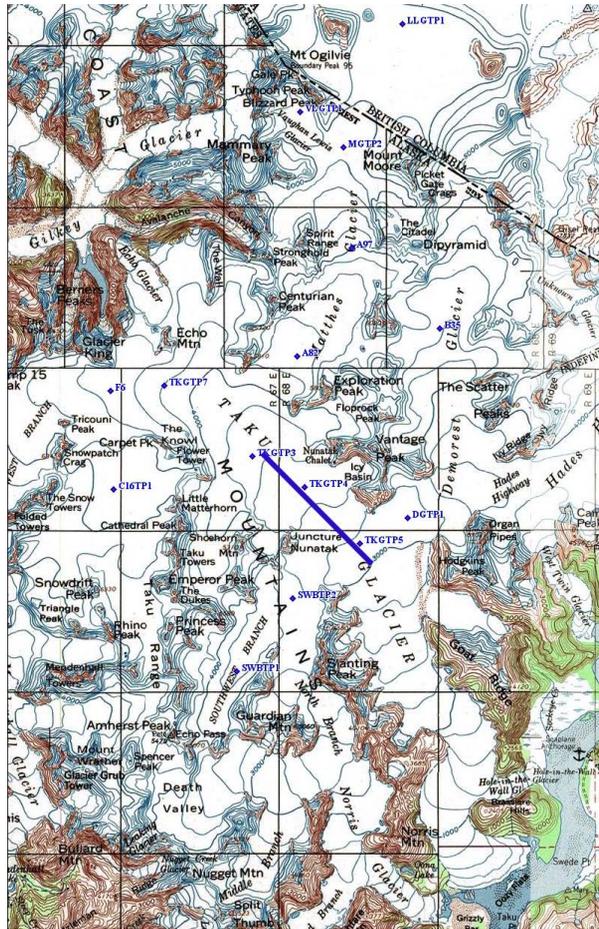


Fig. 1. Location map for Taku Glacier indicating the snowpit locations and probing transect noted.

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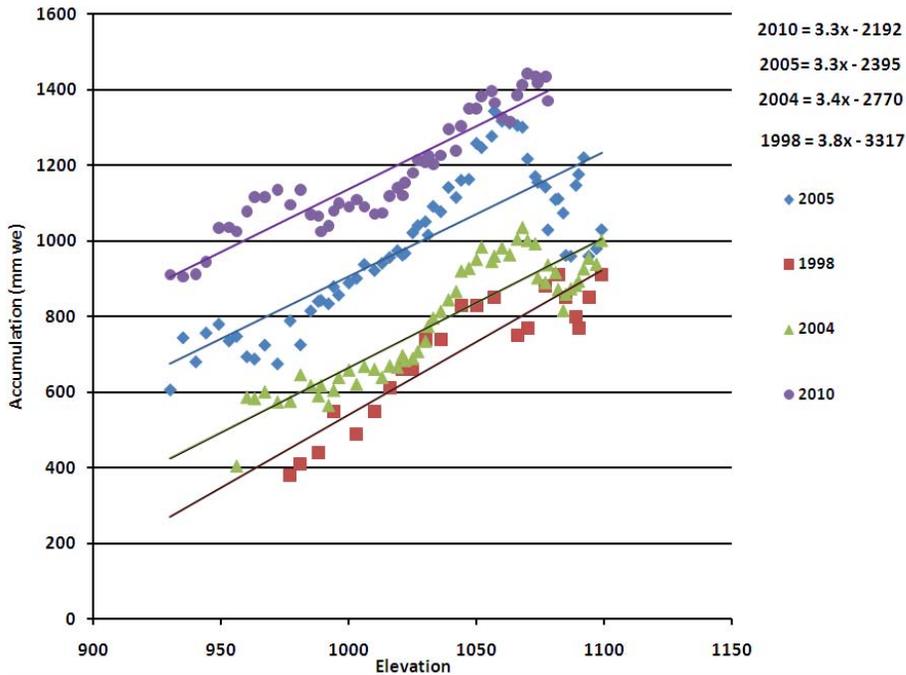


Fig. 2. TKTP5 and DGTP1 testpit SWE 1998–2010 at 1000 m on Taku Glacier.

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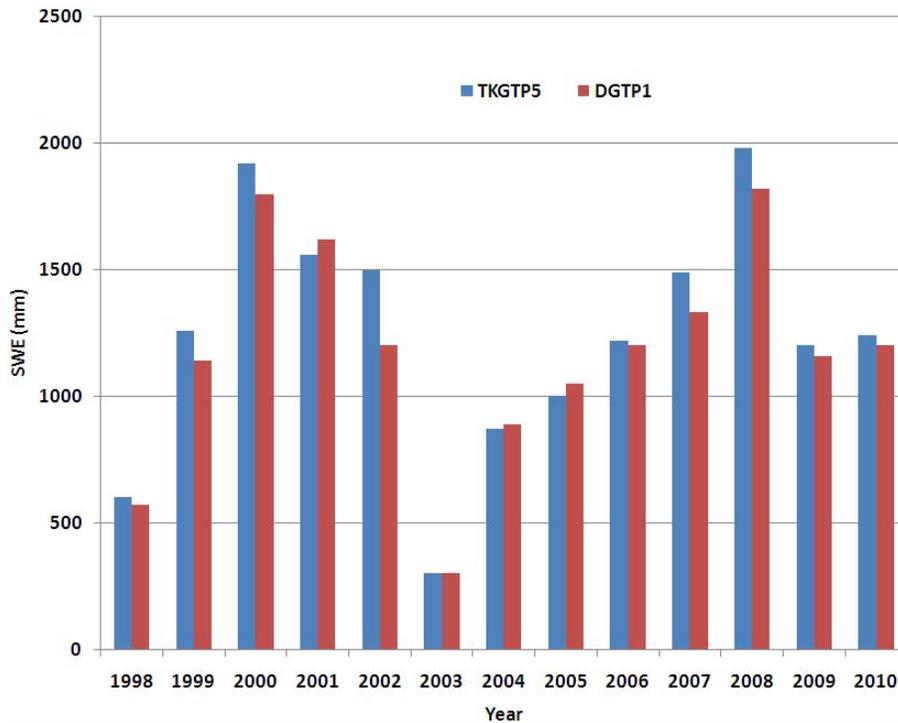


Fig. 3. Should be Juneau Icefield annual snow pit measurements near the ELA on Taku Glacier from 1998–2010 in mm of SWE.

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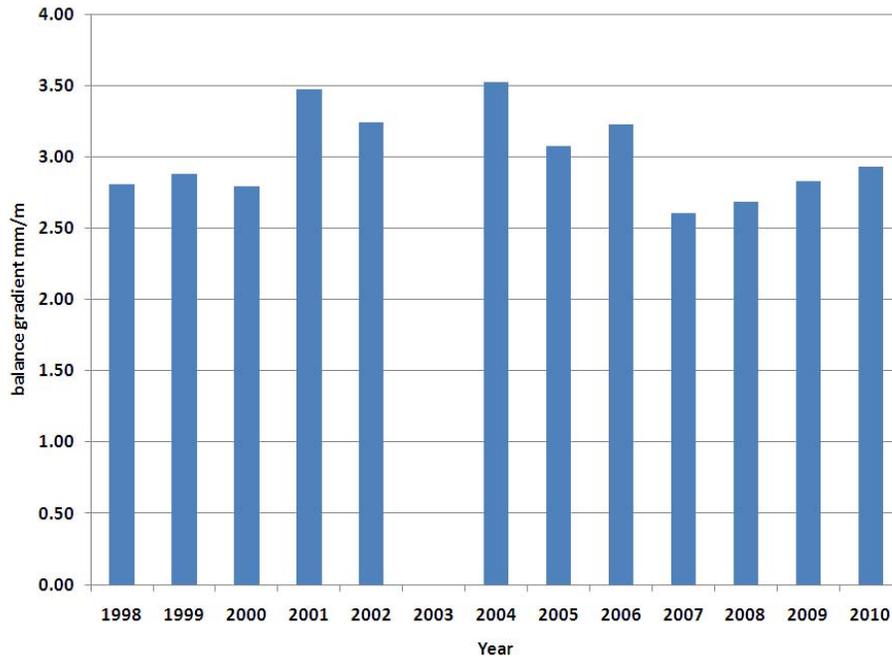


Fig. 4. Balance gradient on Taku Glacier between the snowpits and the transient snowline, based on snowpit data 1998–2010, except 2003 when the TSL was nearly at the snowpits.

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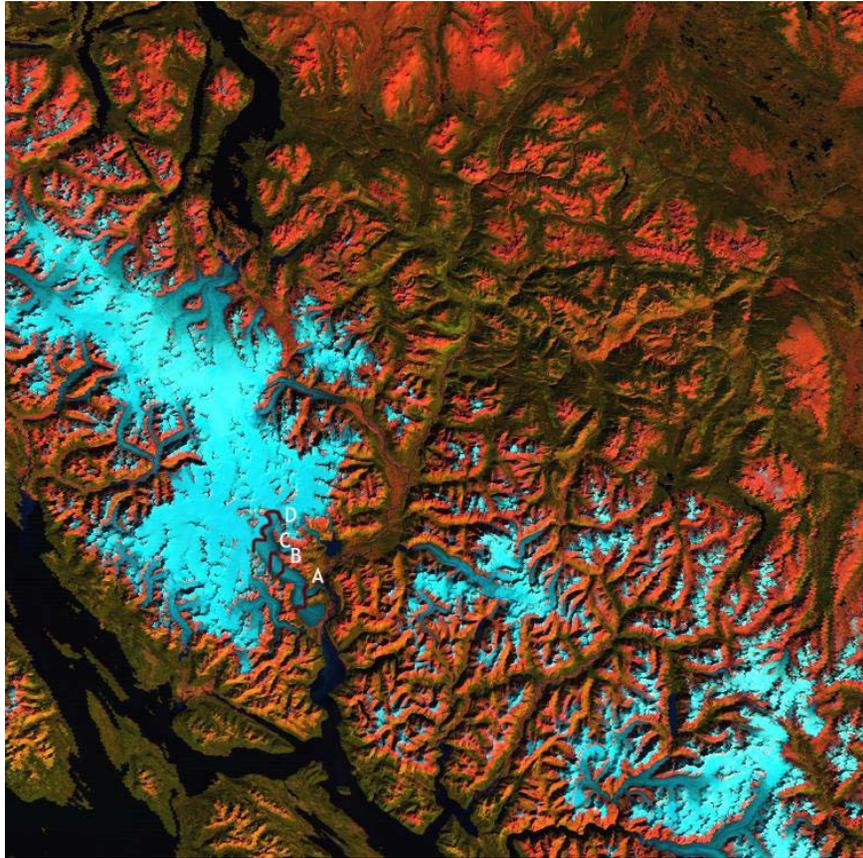


Fig. 5. TSL identification on Taku Glacier in 2006 Landsat image from 9/14/2006. A = 5/26/2006, B = 7/5/2006, C = 7/28/2006, D = 9/14/2006.

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Fig. 6. MODIS image from 9/20/2010, with the TSL indicated.

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