TESTING THE VERACITY OF SATELLITE-DERIVED END-OF-SEASON SNOWLINE ALTITUDES AS A PROXY FOR THE GLACIER ELA

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① Background

Extensive databases of satellite imagery are now available and can be used to undertake large-scale assessments of the mass balance of glaciers and icecaps without in-situ measurements. Some previous studies have mapped the end-of-season snowlines (ESS) on glaciers from satellite imagery to find their snowline altitudes (SLA) and used these as proxies for the glacier equilibrium-line altitudes (ELA)[1][2]. This approach is advantageous because it can be implemented at scale and may employ automated methods. The veracity of using remotely measured SLAs as a proxy for in-situ measured ELAs however, has not yet been robustly demonstrated[1][2][3]. We present in-situ measured ELAs vs. SLAs for 14 glaciers covering time series of $\geq$ 20 years. Figure 1 shows the locations of selected glaciers.

Figure 1: Locations of selected glaciers shown by red dots.

② Methodology

1. A dataset of glaciers with a multi-year time series of mass balance records was compiled from the World Glacier Monitoring Service (WGMS) fluctuations of glaciers (FoG) database[4]. Glacier records classified as 'calving', 'surging', or 'debris-covered' were removed to limit the glaciers selected for study to those with budgets determined by surface mass balance[4].
2. Two datasets of satellite imagery for the glaciers identified in objective 1 were compiled from 30 m resolution Landsat 4-9 data[5]. For each ELA record, we identify the Landsat image closest in date to the recorded ELA measurement (where cloud cover is minimal), this is the 'closest date' dataset. For each ELA record, we identify the image with the highest visible snowline by visual assessment of snow coverage between July and October (the snowline may be recorded significantly before or after the ELA measurement date), this is the 'highest snowline' dataset. The 'highest snowline 2' dataset excludes years where the only image available is completely covered by snow.
3. End-of-season snowlines were generated from each of the datasets compiled in objective 2, for the glaciers identified in objective 1. The snowline is manually mapped, and its corresponding SLA is extracted from the ASTER Global Digital Elevation Map version 3 (ASTERGDEM V3)[6].

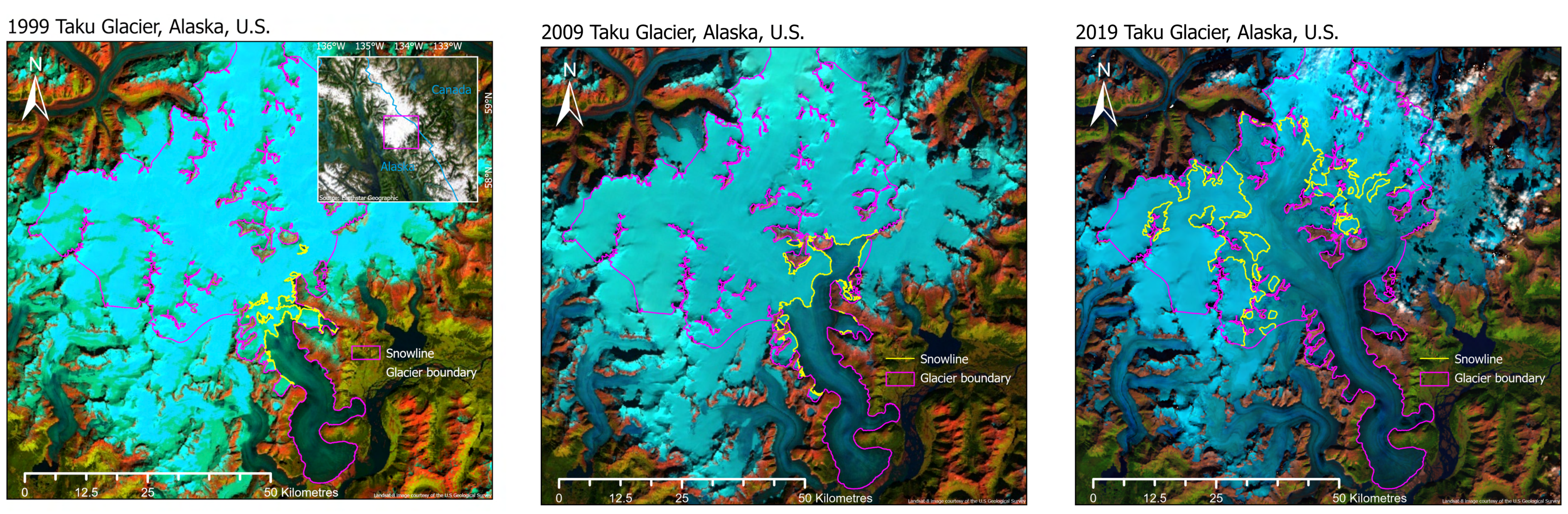

Figure 2: Taku glacier, Juneau Icefield, Alaska, U.S., on 02/08/1999 (left), 14/09/2009 (centre), and 10/09/2019 (right). SWIR, NIR, and red false colour composites[7]. Glacier boundary shown in magenta, snowline shown in yellow. Landsat-5 and Landsat-8 images courtesy of U.S. Geological Survey[5]

③ SLA ELA differences

Median differences

The median differences between the SLAs and ELAs are shown in Figure 3. The median was selected to represent the difference between the SLAs and ELAs as the distribution of residuals is moderately negatively-skewed.

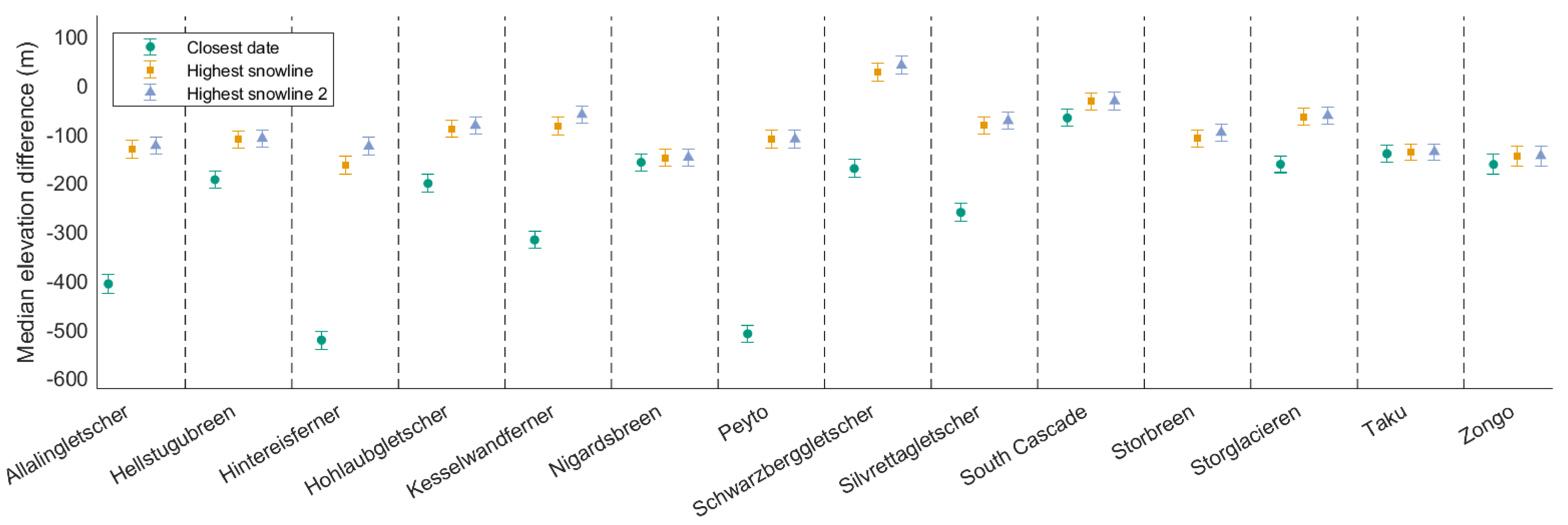

Figure 3: The median differences between the SLAs and ELAs for each glacier are shown by the green dots, orange squares, and blue triangles for the closest date, highest snowline, and highest snowline 2 (excluding full snow cover) methods respectively, with corresponding uncertainty bars.

Largest differences

- The maximum positive difference for the closest date method is 166.11 ± 17.56 m (Schwarzberggletscher).
- The maximum positive difference for the highest snowline and highest snowline (excluding full snow cover) methods is 270 ± 17.63 m (Hohlaubgletscher).
- The maximum negative difference for the closest date method is −810.30±17.65 m (Hohlaubgletscher).
- The maximum negative difference for the highest snowline and highest snowline (excluding full snow cover) methods is −667.47 ± 18.73 m (Allalingletscher).

Associated uncertainties

The elevation uncertainty of the SLA measurements was found by error propogation (adding in quadrature) of the vertical uncertainty sources:

- Landsat 4-9 have a resolution of 30 m for the relevent bands and an RMSE $\leq$ 12 m for tier 1 imagery[5][8]. The horizontal uncertainty, ε_h, is the error propogation (adding in quadrature) of these values. The resulting vertical uncertainty is $\varepsilon_v = \tan\theta \cdot \varepsilon_h$, where θ is the slope of the glacier vicinity of the SLA (approximated from median ASTERGDEM V3 slope angle at SLA).
- The vertical uncertainty of ASTERGDEM V3 $\approx$ 16.7 m[6].
- Note that we do not account for DEM uncertainty due to glacier thinning.

④ ELAs vs. SLAs

Figure 4 presents 3 examples for the highest snowline 2 method (excluding years with full snow cover). Figures 4(a), 4(b), and 4(c) show the ELAs and SLAs time series, and Figures 4(d), 4(e), and 4(f) show the ELAs vs. SLAs for Hellstugubreen, Hohlaubgletscher, and Taku, respectively.

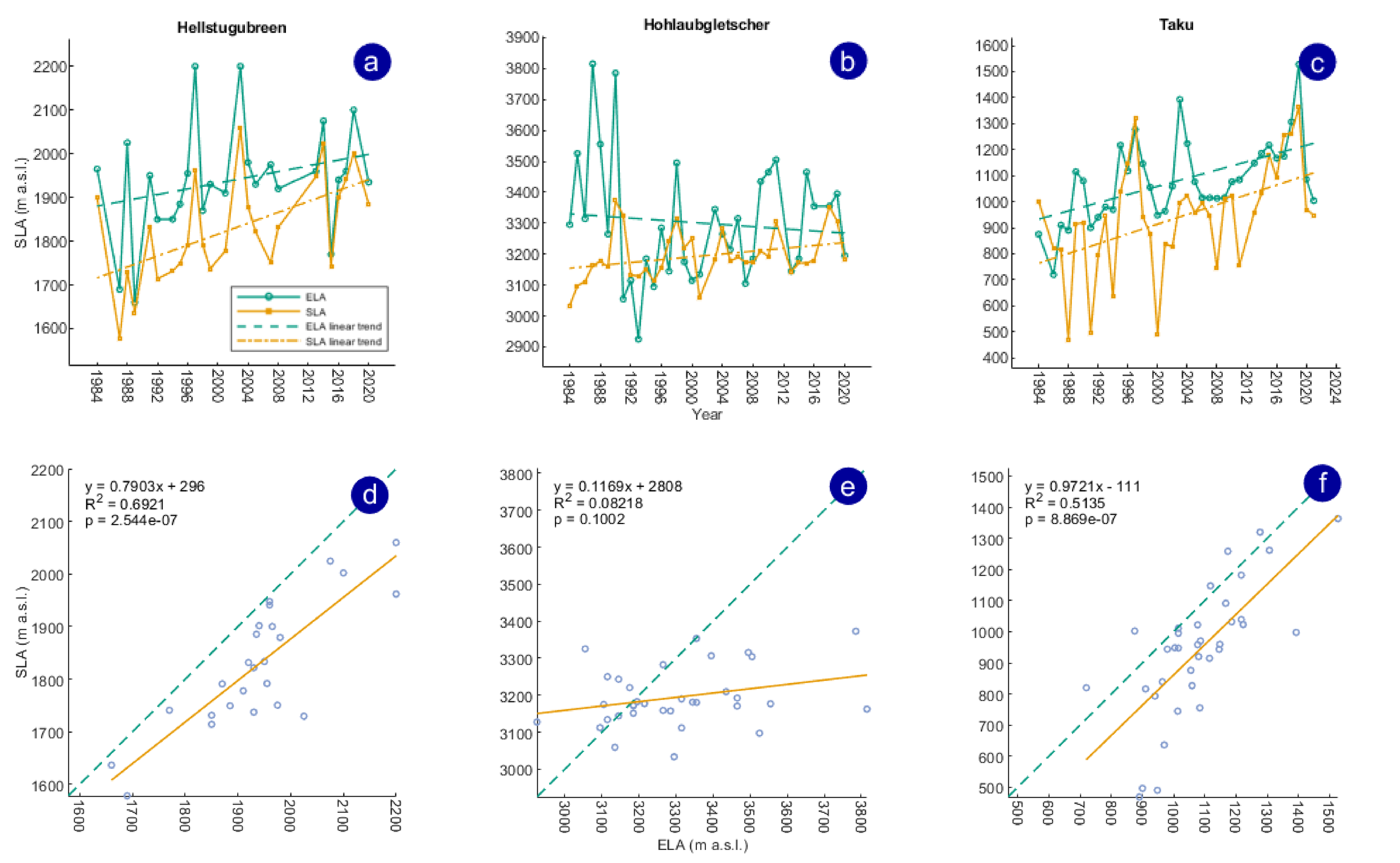

Figure 4: (a), (b), and (c) show the ELA and SLA time series for Hellstugubreen (left), Hohlaubgletscher (centre), and Taku (right). ELAs are shown in green, SLAs are shown in orange, linear trends are shown by dashed lines. (d), (e), and (f) show ELAs vs. SLAs for Hellstugubreen (left), Hohlaubgletscher (centre), and Taku (right). Linear fitting is shown in orange, 1:1 reference line is shown in dashed green, each point represents a year of measurement.

Table 1: R^2 values for each glacier for closest date (C.D.), highest snowline (H.S.), and highest snowline 2 excluding full snow cover (H.S. 2) methods.

	R^2		
Glacier	C.D.	H.S.	H.S. 2
Allalingletscher	0.0053	0.3004	0.3919
Hellstugubreen	0.2753	0.5436	0.6921
Hintereisferner	0.2442	0.2703	0.4289
Hohlaubgletscher	0.0149	0.0962	0.0822
Kesselwandferner	0.2176	0.1210	0.3101
Nigardsbreen	0.0007	0.0014	0.2065
Peyto	0.4079	0.3653	0.3653
Schwarzberggletscher	0.0016	0.2525	0.3746
Silvrettagletscher	0.0936	0.0586	0.2488
South Cascade	0.0216	0.0195	0.4165
Storbreen	0.0030	0.2617	0.6106
Storglaciären	0.1673	0.1391	0.3172
Taku	0.3429	0.5135	0.5135
Zongo	0.2285	0.2663	0.2752

Table 1 shows R^2 values for each glacier:

- $R^2 \approx 0.0007$ to $R^2 \approx 0.4079$ for the closest date method,
- $R^2 \approx 0.0014$ to $R^2 \approx 0.5436$ for the highest snowline method,
- $R^2 \approx 0.0822$ to $R^2 \approx 0.6921$ for the highest snowline 2 method (excluding years with full snow cover),

showing weak to moderate agreement between ELAs and SLAs, with the highest snowline 2 method (excluding years with full snow cover) performing best.

⑤ Limitations

Satellite revisit times Landsat revisit times are 16 days (8 days where 2 satellites are in orbit simultaneously)[9].

Cloud cover The most extreme case was 86 days between the ELA measurement date and the collection date of a cloud-free image (Taku).

Snowfall events Early snowfall events may occur close to the date of the highest snowline, Figure 5 shows how snow cover changes throughout September 2018 on South Cascade glacier, Washington, U.S..

Firn Exposure In years where the snowline is higher than the previous year, firn may be exposed. It can be difficult to distinguish the snowline and firnline from satellite imagery in this case[3][10].

Non-Guassian distribution of snowline elevations Where the elevation points extracted from the snowline are not distributed normally, the median elevation should be taken rather than the mean.

ASTERGDEM V3 uncertainty ASTERGDEM V3 is based on data from 2000 to 2013. Elevation uncertainties are likely greater outside these years due to glacier thinning rates[11].

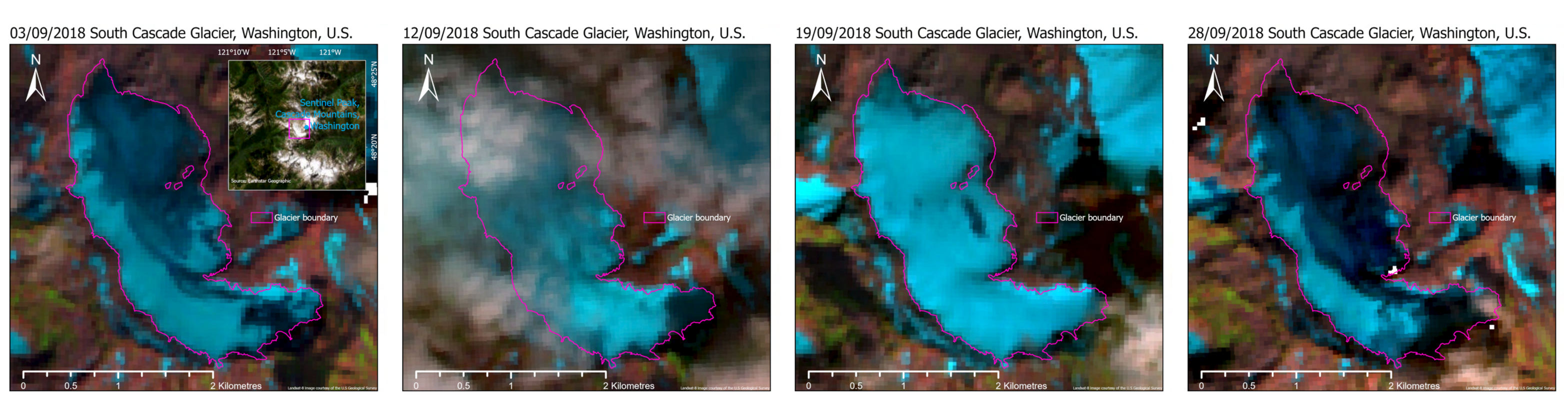

Figure 5: South Cascade glacier, Washtington, U.S., on 03/09/2018 (left), 12/09/2018 (centre left), 19/09/2018 (centre right), and 28/09/2018 (right). SWIR, NIR, and red false colour composites[7]. Glacier boundary shown in magenta. Landsat-8 images courtesy of U.S. Geological Survey[5].

⑥ Conclusions

- The highest snowline SLAs show a better correlation with in-situ measured ELAs than closest date SLAs, especially when years with full snow cover are excluded.
- The closest date method is highly susceptible to influence from snowfall events near the ELA measurement date.
- The closest date SLAs and highest snowline SLAs both underestimate the ELAs, though less so for the latter.
- The SLAs and ELA differences are greater when the ELA is at a higher elevation.

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