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Mass balance and a glacier surge of Guliya ice cap in the western Kunlun Shan between 2005 and 2015

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ABSTRACT

Contemporary estimates of glacier changes are necessary to assess the impact of climate change, associated hazards and water resources management. Glaciers in High Mountain Asia (HMA) are mostly retreating except the Karakoram and western Kunlun Shan, confirmed by remote sensing measurements. However, ground validation with precise measurements of these mass balance estimates are scarce. This study selected Guliya ice cap in the western Kunlun Shan to observe its recent changes regarding surface dynamics and mass balance using ASTER DEM of 2005 and 2015. Our findings indicate that one of the north-facing glaciers surged (with no previous surging history) during July and early November 2015, advancing at about 8 m per day on average. The mass balance shows a balance condition +0.01 ± 0.02 m w.e. a^{-1}. The ICESat data (2004–2008) at selected locations compared to dGPS data collected in the field during 2015, indicating a minute difference of 0.03 ± 0.05 m a^{-1} with ASTER data in the same area. Our findings suggest that Guliya ice cap in the western Kunlun Shan is in equilibrium state following a similar pattern (mass gain or stable conditions) as observed previously.

1. Introduction

Glaciers in the High Mountain Asia (HMA) are sensitive to climate change (Bach et al., 2018; Yao et al., 2012) and significantly crucial for sustainable future of the downstream population (Kaser et al., 2010). The glaciers variability makes downstream human society significantly vulnerable to associated hazards and therefore urged immediate adaptation and mitigation measures (Milner et al., 2017). Mass balance is the most suitable indicator of climate change and glacier health (Oerlemans, 2001). Although remote sensing data can explore large spatial coverage and regional glacier mass balance (Brun et al., 2017; Kääb et al., 2012), the uncertainty estimates can be significantly high (Gardelle et al., 2013). On the other hand, in-situ measurements can potentially produce precise, high-temporal resolution estimates of mass balance but for a limited number of glaciers (Mayer et al., 2006; Muhammad and Tian, 2016; Tshering and Fujita, 2016).

Most glaciers studies in HMA have used remote sensing data owing to the difficulty of conducting fieldwork in remote, challenging areas (Kääb et al., 2015; Pieczonka and Bolch, 2015). Glaciers in the HMA are widely retreating (Brun et al., 2017; Gardner et al., 2013; Yao et al., 2012) whereas, some glaciers are in balance in the Karakoram (Bolch et al., 2017; Zhou et al., 2017) and even growing in the western Kunlun Shan as observed in the recent years (Kääb et al., 2015; Lin et al., 2017). The present remote sensing observations are also constrained to limited temporal coverage (Gardelle et al., 2013; Muhammad et al., 2019a) and provide regional mass balance (Brun et al., 2017). It is indeed necessary to derive vigorous estimates for future glacier-related water resources planning and management (Immerzeel et al., 2010; Kaser et al., 2010; Kehrwald et al., 2008; Latif et al., 2020).

Currently, ground-based glacier measurements in the HMA are limited to spatio-temporal coverage (Hewitt, 2005; Mayer et al., 2006; Muhammad and Tian, 2016; Yao et al., 2012) which requires continuous monitoring. However, it is usually challenging due to logistic and financial limitations, making long time series glacier dynamics difficult to obtain (Zhu et al., 2019). Re-measurement of remote sensing data (e.g., from Ice, Cloud, and land Elevation Satellite (ICESat)) by

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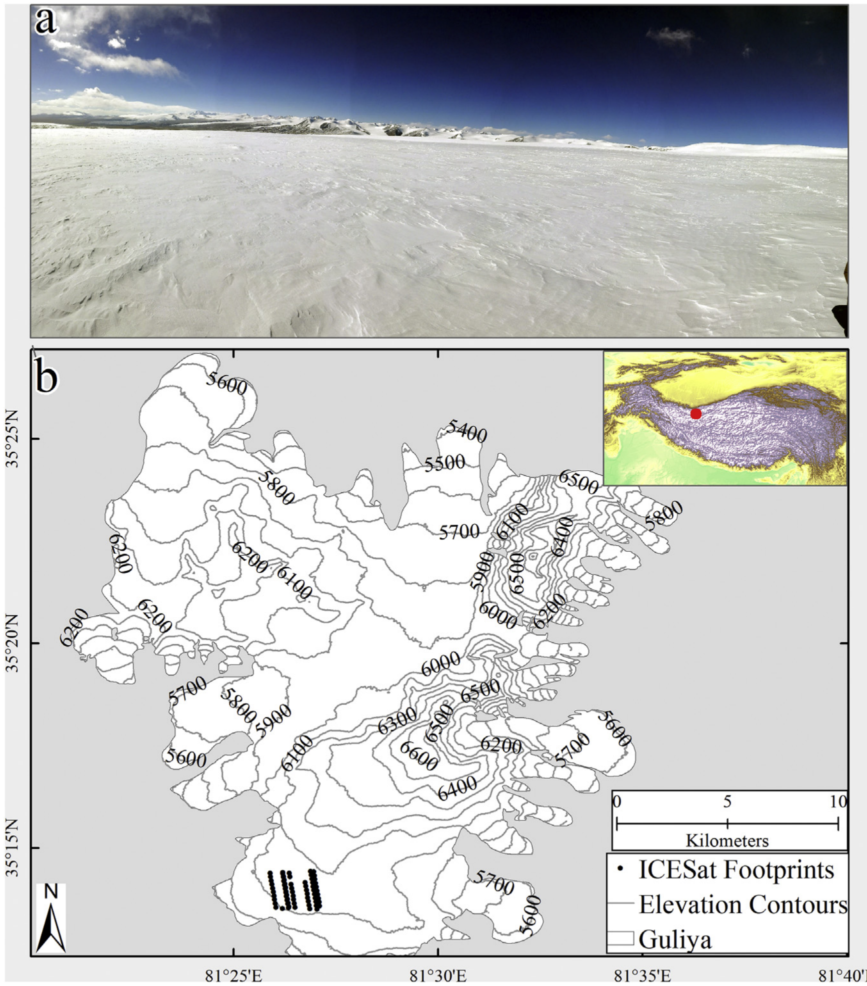

Fig. 1. Panel a is a photograph taken by Lide Tian in a field survey in October 2015 showing the topography of the Guliya ice cap, Panel b is the study area (Guliya ice cap) and the ICESat footprints remeasured by dGPS shown in black circles.

differential global positioning system (dGPS) can potentially extend the observation period (Muhammad and Tian, 2016; Zhu et al., 2014) and also increase the accuracy of recent estimates of glacier thickness changes (Muhammad et al., 2019b). Such observations, in addition to remote sensing data, are also crucial for studies of abrupt glacier dynamics (e.g., surging and the collapse of twin (Aru) glacier in 2016 in western Tibet) (Kääb et al., 2018; Tian et al., 2017). Therefore, this study is attempting to compare both ground-based and remote sensing measurements, in order to better constrain glacier changes in this region.

This study uses ASTER 30 m DEM data generated from 15 m resolution stereo data acquired in 2005 and 2015 to estimate the mass balance and surges dynamics of Guliya ice cap. ICESat footprints were re-measured by dGPS in the field by direct measurements to confirm the mass balance and investigate its recent dynamics. Our study helps to increase the knowledge and understanding of contemporary glacier dynamics and mass balance, of Guliya ice cap (western Kunlun Shan) using ASTER DEM 30 m and dGPS with high quality.

1.1. Study area

Guliya is a polar-type ice cap in central Asia (western Kunlun Shan), lying in the driest Tibetan Plateau (TP) region (Yao et al., 2012). Guliya ice cap is a major ice reserve in TP with largest (> 370 km^2), and thickest (308.6 m) ice among all the ice caps in middle-low latitude regions (Thompson et al., 1995; Yao et al., 1997). The region is mainly influenced by westerlies and partly by Indian monsoon (Yao et al., 2012). The annual precipitation is 185 mm, with 84% coming in the summer month from June–September, based on one-year observation from an automatic weather station installed in front of the Guliya ice cap (5500 m a.s.l.) during 2015–2016. The meteorological data imply that most of the accumulation at Guliya Ice Cap comes during summer months. Field-based dGPS measurements were carried out around the geographic location at latitude 35.23° N, longitude 81.44° E in this study to remeasure the center of the ICESat footprints as shown in Fig. 1(b). The mean elevations of the measured positions were approximately 6000 m a.s.l., located near the equilibrium line altitude (Bao et al., 2015). The Guliya Ice Cap is well known for ice core investigations, previously the lowest and nearest (to the current field-based dGPS measurements) ice cores drilling site was about 6200 m a.s.l. (Thompson et al., 1995; Wang et al., 2002; Yao et al., 1997). The study area with ICESat and dGPS measurement locations and a photo of the Guliya ice cap taken during the field survey are shown in Fig. 1.

2. Methodology

2.1. ASTER DEM processing

ASTER data of October 31, 2005, and November 12, 2015, representing the late ablation season (preferred for mass balance estimates) was acquired from www.earthdata.nasa.gov. A relative DEM of 30 m resolution was generated from the stereo data using MicMac ASTER (MMASTER) (Girod et al., 2017). The tool helps to overcome

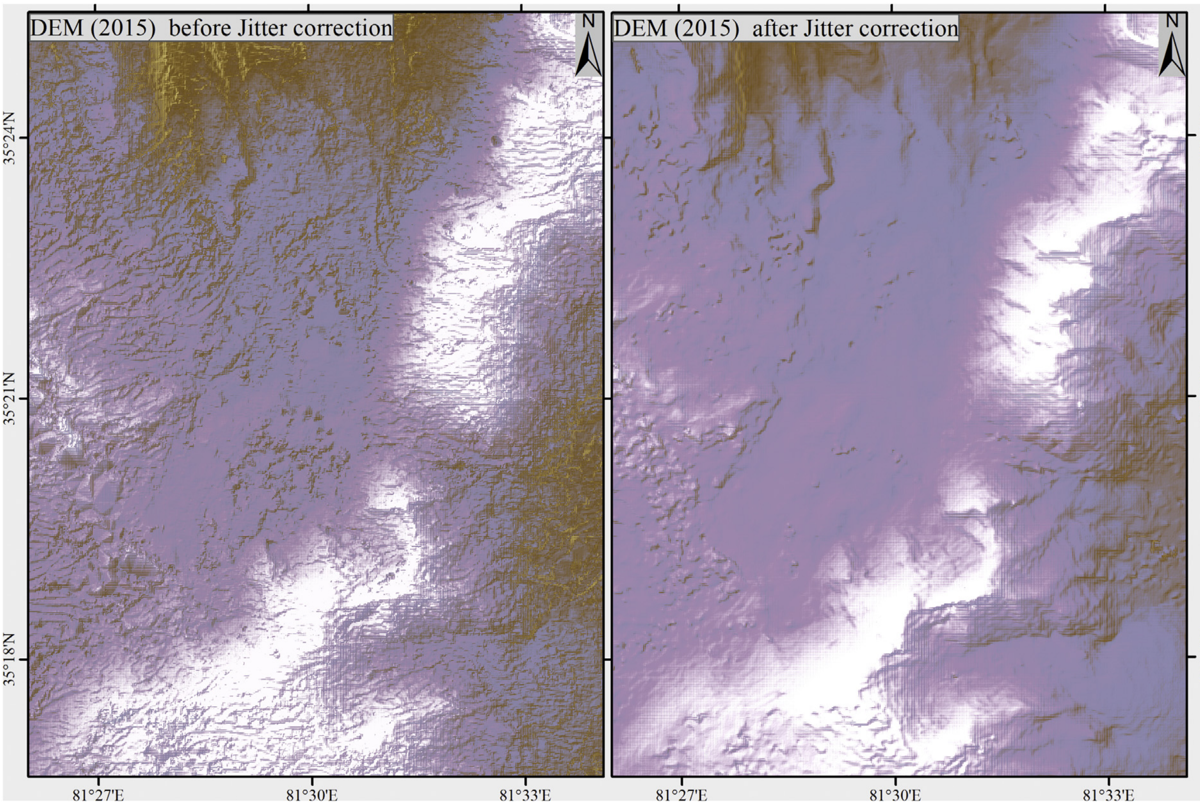

Fig. 2. DEM before (left) and after (right) jitter correction. DEM before jitter correction shows significant noises.

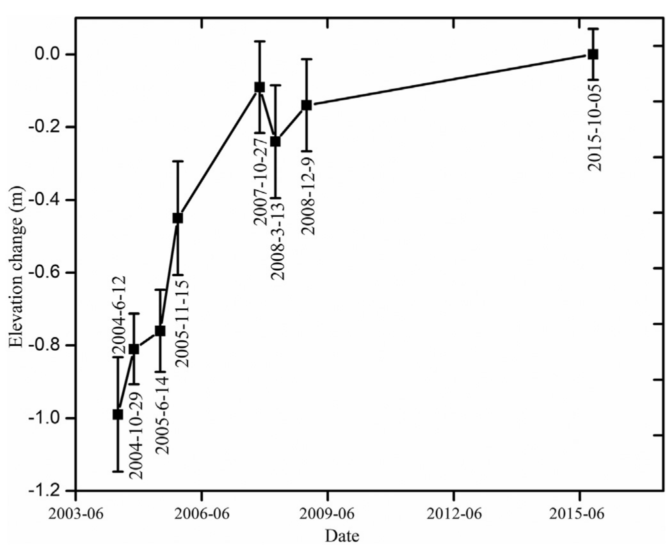

Fig. 3. Comparison of ICESat and dGPS elevation changes at locations shown in the study area between 2004 and 2015.

cross-track (roll) jitter in the ASTER stereo pair. Across-track jitter produces a large offset in the epipolar line and cannot be matched using the correlation algorithm. Whereas, along-track jitter (pitch) produces systematic bias and can be corrected in the DEMs differencing over stable terrain. The effect of nadir-axis jitter (yaw) is insignificant (millimeter-level) (Girod et al., 2017). The generated DEM requires further corrections to reduce the along-track jitter which mainly causes a horizontal shift and altitudinal bias. For the purpose, we used the approach suggested by Nuth and Kääb (2011). The altitude dependent biases were corrected for each 100 m elevation bin by removing elevation differences larger than 3δ. After cross-track parallax error correction, the standard deviation of the DEMs difference over off-glacier terrain (which is very rough and mountainous) was reduced from 22.47 m to 14.01 m, which was further reduced to 6.07 m after along-track correction. The effect of jitters (comparing DEMs generated before and after jitter correction) are shown in Fig. 2. The DEM generated before jitter correction contains significant noises, clearly visible in the figure. An average thickness change was calculated for the region after correction. After the processing, off-glacier elevation change was calculated to estimate the accuracy of the thickness change estimates. The error estimates (root mean square error of ± 0.02 m w.e.a^{-1}) also include uncertainty due to density assumptions 850 ± 60 kgm^{-3} and possible uncertainty (negligible) due to the glacier area changes (based on comparison of our estimated glacier outlines and second Chinese glacier inventory) because of the negligible retreat/advance of the ice cap. Our thickness change results were also validated with ICESat footprints re-measured by dGPS at selected locations.

2.2. ICESat data processing

This paper uses GLAH14 product release-34 of ICESat data. The product is the latest release of ICESat data which includes several corrections, i.e., removing range determination error from transmit-pulse reference-point selection (Centroid vs. Gaussian), dry troposphere correction jitter, corrections of invalid GLAH14 parameters, and addition of atmosphere confidence flag from the GLAH09 (Zwally et al., 2015). The saturation elevation correction (d_satElevCorr) includes rectifications up to 1 m that needs to be added to the elevation estimates (Zwally et al., 2015). The saturation correction flag (sat_corr_flg) value of 3 or higher are likely to have uncorrectable errors, and these results were excluded from analyses (Zwally et al., 2015). In addition, the use of different semi-major axis of an ellipsoid, the dataset also has a constant difference (d_ellipsoid) with the WGS84 ellipsoid height of about 70 to 71.37 cm at the equator and poles, respectively (Bhang et al., 2007). The values of the d_ellipsoid were subtracted, and

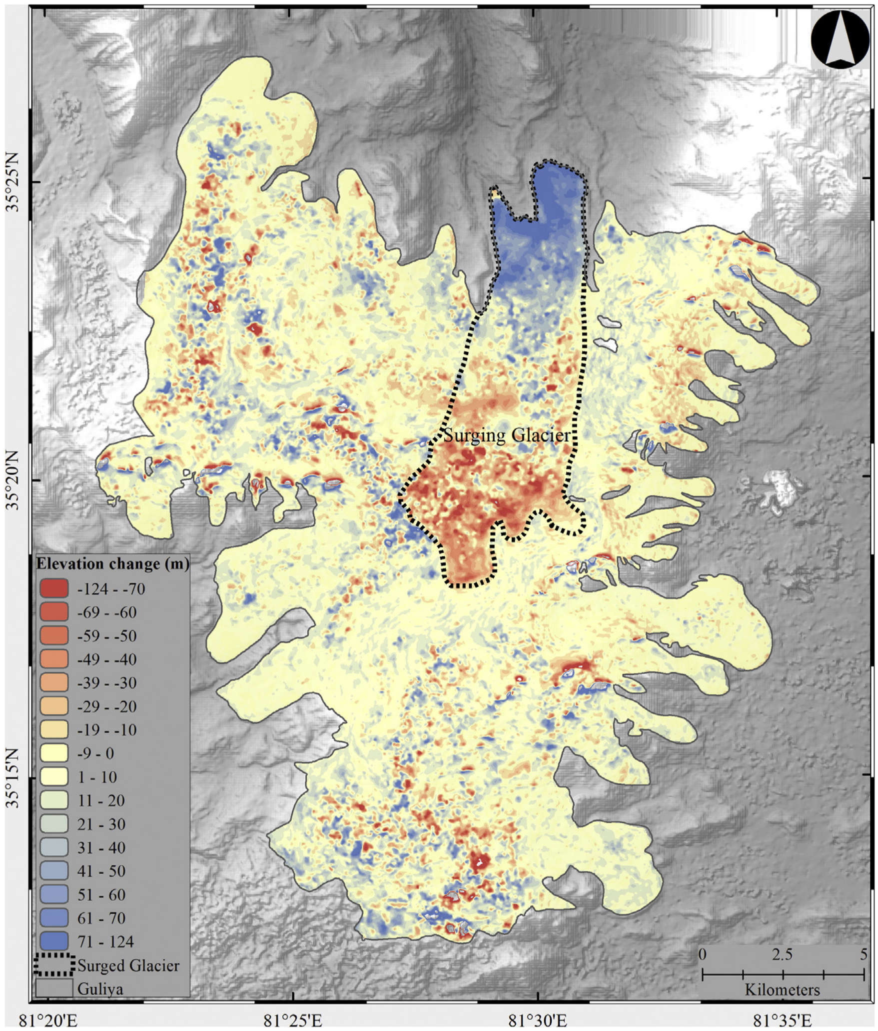

Fig. 4. Map showing surface elevation changes of Guliya ice cap between 2005 and 2015 using ASTER DEMs data.

d_satElevCorr were added to the ICESat elevations for making it comparable/compatible with dGPS survey data. The processing and comparison of ICESat and dGPS data were carried out similarly as in previous studies (Muhammad and Tian, 2016).

2.3. DGPS data processing

ICESat data acquired from 2004 to 2008 were compared with the remeasured dGPS data in 2015. A Flat surface was selected for DGPS measurement of the ICESat footprint on both glacier surface and land surface to eliminate uncertainty in the remeasurement of large ICESat footprint (70 m diameter) at the centre of the footprint by dGPS. The dGPS data were surveyed on the 4th and 5th of October 2015 (Fig. 1). The ICESat center footprints data were stored in dGPS before the field survey and traced by geo-locating for re-measurement. The primary error sources in GPS survey are from the ionosphere weather and multipath in addition to other errors including dilution of Precision (DOP), local terrain, satellite outages, and interference. A NavCom Starfire (SF-3040) dGPS receiver was employed for the field survey. Integrated StarFire receiver is capable to achieve up to 5 cm vertical precision with careful measurement. The centres of ICESat footprints acquired between 2004 and 2008 were re-measured by dGPS. These remeasured dGPS data with a vertical accuracy of 0.10 m or better were compared with the ICESat footprint centre elevation to give a precise result of the glacier surface elevation change in the specific region in the recent years. The estimated vertical error was used to calculate the uncertainty in thickness changes estimates similarly as in previous studies (Bolch et al., 2017; Muhammad et al., 2019a, 2019b).

3. Results

3.1. Surface elevation change by DGPS remeasurement

Fig. 1a shows a photo of the flat surface of the Guliya ice cap where dGPS remeasurement was carried out. Validation of ICESat vs dGPS at a flat surface near the glacier showed a difference (root mean square error) of ± 0.33 m (which is equal to uncertainty of ± 0.03 m a^{-1} in the annual elevation changes) based on re-surveying of thirty ICESat footpoints. The slightly higher difference is due to the roughness of the off-glacier land surface and a few individual higher errors with the bulged surface near the mountain ridges. In total 68 ICESat footprints acquired during the years 2004, 2005, 2007 and 2008 were re-measured in 2015 on the glacier surface. At least ten footprints were remeasured in each acquisition year of the ICESat data and averaged for annual changes compared to dGPS data. The annual surface elevation changes based on dGPS and ICESat with error bars derived from the uncertainty (Fig. 3) similarly as in the earlier studies (e.g. Muhammad et al., 2019b). All the ICESat data, re-measured in the field by dGPS is shown in Fig. 1b. For ICESat data in an individual year, dGPS give consistent results for the surface elevation change. The overall results showed a slight thicking on the glacier surface during 2004–2015 on the measured area, with an increase of 1.0 m at selected locations

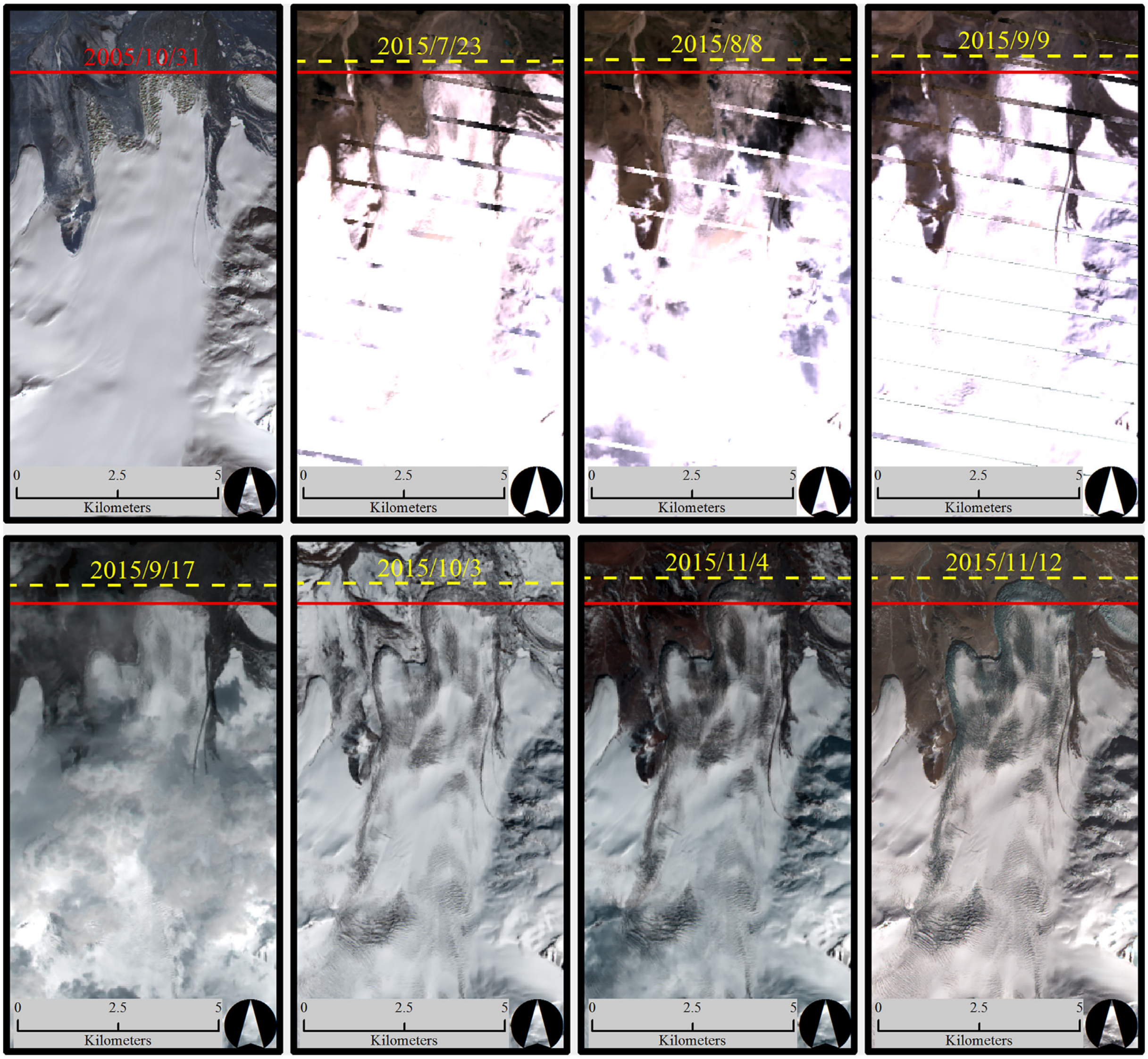

Fig. 5. Temporal change of surge event between July 2015 to early November 2015 assessed using ASTER, Landsat 7 (gap-filled) and Landsat 8 cloud-free data. The Landsat images in the figure were acquired from Earth Resources Observation and Science (EROS) Center, USGS (http://earthexplorer.usgs.gov/).

where ICESat data was observed. Most of the slight thickening at the ICESat footprints is in the periods of 2004–2008 (Fig. 3). The field-based results in comparison to ICESat provide annual elevation changes at selected locations with centimeter-level accuracy.

3.2. Glacier surface mass balance

The map in Fig. 4 shows the spatial thickness changes derived from the comparison of October 31, 2005, and November 12, 2015, DEMs with 30 m resolution generated from ASTER 15 m stereo images, validated through ICESat (2004–2008) compared to dGPS data at selected locations near the equilibrium line altitude. The selection of ASTER data is subject to the availability in the late–ablation season and coverage close to the ground observation period. Mass balance of the Guliya ice cap is almost in equilibrium i.e. $+0.01 \pm 0.02$ m w.e. a^{-1} on average derived from the estimated thickness change in the observed decadal study period using ASTER DEMs data. Our results also indicate that one of the northern outlet glaciers of the ice cap surged, with positive elevation changes up to 110 m observed, as shown in Fig. 4. All other data with thickness changes > 124 m were discarded from our analysis. The surge event started approximately in early July 2015 based on the available Landsat 7, 8 and ASTER cloud-free images (EarthExplorer, 2018). The glacier reached its maximum extent until the early November 2015 causing a terminus advance of about 650 m at approximately 8 m per day. The temporal variation of the surge event is shown in Figs. 5 and 6. The rough glacier surface/crevasses in Figs. 5 and 6 also confirm the surge event.

The thickness change results were validated through ICESat re-measured in the field by dGPS. All the ICESat data re-measured were around 6000 m a.s.l., below the altitude (6200–6700 m a.s.l.) where ice cores were drilled previously (Huss, 2013; Thompson et al., 1995; Wang et al., 2002; Yao et al., 1997). The observed average equilibrium line altitude in the Guliya ice cap was 6000 ± 19 m a.s.l. (Li et al., 2019). While the ground measurements conducted in this study are in the vicinity of 6000 m a.s.l. which is well at the equilibrium line altitude as observed in the study period.

4. Discussion

The recent spatially inhomogeneous glacier mass balance in the western Tibetan Plateau (Brun et al., 2017; Cao et al., 2017; Kääb et al., 2015) attracted us to assess these changes using ASTER DEM data of 2005 and 2015. These results were compared with dGPS ground observations in comparison to ICESat data near the equilibrium line

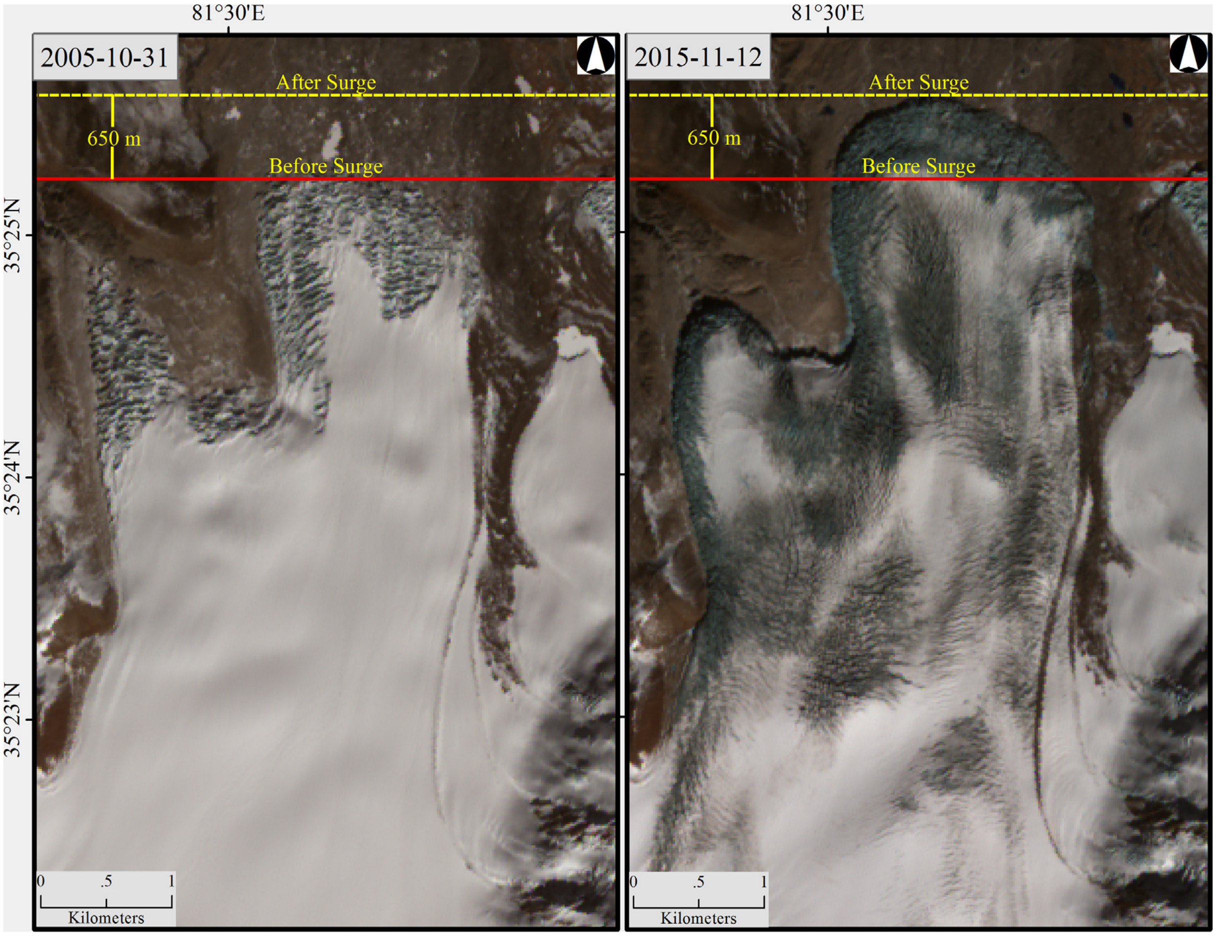

Fig. 6. Map showing the maximum advance of the terminus position of approximately 650 *m* with an average rate of about 8 m per day. The satellite images shown on this map are the same as used for mass balance in this study. The Landsat images in the figure were acquired from Earth Resources Observation and Science (EROS) Center, USGS (http://earthexplorer.usgs.gov/).

altitude to validate our findings. To the best of our knowledge, it is the first time remote sensing-based glacier mass balance of Guliya ice cap, validated by field-based precise dGPS data covering the same period.

This mass balance derived from ASTER stereo images showed -0.01 ± 0.02 m w.e. a^{-1}, indicates an equilibrium state by Guliya ice cap. These results were confirmed by comparing ICESat data between 2004 and 2008 with dGPS data of 2015. The validation results indicated a difference of 0.03 ± 0.05 m a^{-1} derived from dGPS and ICESat data differencing in comparison to the ASTER based results at selected locations (by averaging the pixels within the extent where dGPS data ICESat data exist similarly as in (Muhammad and Tian, 2016)) near the equilibrium line altitude. This difference of dGPS and ICESat compared to ASTER DEM differencing agree well within the uncertainty limit. We did not compare the dGPS observations with ASTER pixel by pixel elevations because of the irregular distribution of dGPS data compared to the ASTER DEMs pixels. The dGPS data were only collected at the centre of ICESat footprints to represent the ICESat measurements. The ground-based observations will help to reduce the uncertainty in glacier changes. The high temporal resolution of elevation changes will be useful for validating long-term observations and simulations of glacier dynamics. Earlier findings of the mass balance in the western Kunlun Shan also suggest a minute loss of -0.06 ± 0.13 m w.e. a^{-1} from 1970 to 1999 (Wang et al., 2018). In addition, one of the north-facing glaciers surged between July and early November 2015 (as shown in Figs. 5 and 6). Before the surging, Yasuda and Furuya (2015) indicated, no glacier surged in the region selected in this study between 1972 and 2013. This event in the western Tibetan Plateau is one year before the massive twin (Aru) glacier collapses in the nearby mountains, caused by climate and weather-driven forcings (Kääb et al., 2018; Tian et al., 2017). These results suggest that the conditions causing a surge–like instability exist in the nearby region at least since 2015 and stresses regular monitoring of glaciers in the future to reduce the impacts of glacier-related disasters. Future monitoring could not only help to understand the glaciers mass balance but also the glacier dynamics in the region.

The elevation changes from ASTER DEMs are sensitive to the spatial resolution, sensor jitter, cloud cover, and seasonality because of the difference in time of data acquisition. Except for the spatial resolution, the rest of the uncertainty was reduced by selecting cloud-free images of almost the same time (end of October and early November) and using MMASTER to minimize the jitter. In addition to the spatial resolution, the poorly contrasted areas cause numerous outliers which were removed using a 3δ threshold. Also, the decadal and long-term mass balance minimizes the uncertainty due to the spatial resolution of the DEMs.

Earlier estimates of glaciers mass balance in the High Mountain Asia based on dGPS measurements, the only and first decadal (2003–2014) mass balance of a small glacier in the Bhutan Himalaya reveals the change from -1.12 to -2.04 m w.e. a^{-1} (Tshering and Fujita, 2016) comparatively the most negative than glaciers in the rest of the Himalaya estimated by remote sensing data (Brun et al., 2017; Kääb et al., 2015). In contrast to the most negative mass balance of Bhutan Himalaya by direct measurements (Tshering and Fujita, 2016), remote sensing data suggest the same in Nyainqentanglha followed by Bhutan Himalaya (Brun et al., 2017; Kääb et al., 2015). Most of the direct dGPS measurements for glaciers thickness change and mass balance are in the

Tibetan Plateau (Cao et al., 2014; Tian et al., 2014; Zhang et al., 2012; Zhu et al., 2014). All these direct measurements suggest thinning and retreat in the observed glaciers of Tibetan Plateau. Moreover, Chhota Shigri is the only glacier in Spiti–Lahaul/western Himalaya, India measured by dGPS having a mass balance of -0.17 ± 0.09 m w.e. a^{-1} covering the period of 1988 to 2012 (Azam et al., 2014). In the debris–cover part of the Changri Nup Glacier in the Nepal Himalaya derived from dGPS data between 2011 and 2014 was -0.6 m a^{-1} (Vincent et al., 2016). Similarly, the debris cover part of two glaciers in the western Himalaya and Karakoram observed using dGPS data in comparison to ICESat data during 2003–2015 show comparatively insignificant surface lowering of -0.15 to -0.26 m a^{-1} (Muhammad and Tian, 2016).

Most of the remote sensing studies agree on the slight mass gain/loss or balance condition in the Karakoram, Pamir, and western Kunlun Shan. Also, our findings suggest that the western Kunlun Shan is in a stable state (at least in the Guliya ice cap) following the earlier findings of mass gain or stable conditions (Brun et al., 2017; Kääb et al., 2015). Whereas, the area changes in the western Kunlun Shan for the period 1970 to 2001 indicate a slight retreat of 0.4% of the total area (Shangguan et al., 2007) which agree to our findings of negative changes, specifically for the Guliya ice cap. This study not only extends the observation period to 2005–2015 but also validate the remote sensing results by the same observation period with precise dGPS and ICESat data.

5. Conclusion

This study suggests that mass balance of the Guliya ice cap in the western Kunlun Shan is in equilibrium state i.e. -0.01 ± 0.02 m w.e.a^{-1} between 2005 and 2015. The surface elevation change was validated by comparing ICESat data between 2004 and 2008 with dGPS data surveyed in 2015 indicating a difference of $+0.03 \pm 0.05$ m a^{-1} at selected locations near the equilibrium line altitude. The ASTER based results at the same locations are in good agreement with the field-based results within the uncertainty limit. In addition to the mass balance, one of the striking findings was the surge of a north-facing glacier in the Guliya ice cap. The surge occurred in summer 2015 (with no previous surging history of this or any other glacier in the study area), 1 year before the twin (Aru) glacier collapses (summer 2016) in the western Tibet indicating the instability to cause the surge existing in the nearby region at least since 2015. However, further field-based validation of remote sensing estimates is necessary to reduce the uncertainty of mass balance estimates in the areas where there are disagreements by various studies. Similarly, access to high–resolution remote sensing can provide better estimates of abrupt (surge/collapse) and mass balance/glacier changes on a large scale.

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Author contributions

L. T. and S.M. designed the study. L. T. collected all the dGPS data in the field. S. M. processed all the data. Both the authors contributed to preparing maps and writing the paper.

Declaration of competing interest

Both authors declare no competing financial and non-financial interests.

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