Long-range terrestrial laser scanning measurements of summer and annual mass balances for Urumqi Glacier No.1, eastern Tien Shan, China

Chunhai Xu et al.

We would like to thank the referee for the constructive and detailed comments. Reviewer comments are copied in normal font, and our point-by-point reply to each comment is provided after the comments and given in bold font.

Summary

I have reviewed the manuscript "Long-range terrestrial laser scanning measurements of summer and annual mass balances for Urumqi Glacier No.1, eastern Tien Shan, China" submitted to The Cryosphere by Xu et al. The article describes using terrestrial laser scanning to look at annual and intra-annual mass balance for Urumqi Glacier No. 1 over a two-year period, and compares the geodetic results with the glaciological mass balance.

Reply: Thanks!

The article presents some interesting results, but there is not much new material compared with the articles from 2017 and 2018. It is not clear (apart for the obvious reasons) why the authors are publishing these results in several papers. It is suggested that further analysis is done of the results by incorporating velocity measurements, and going into more detail of the thickening or balance at higher elevations, and thinning at lower elevations.

Reply: Thank you for the constructive suggestions. For the published paper in 2017, we used the TLS to implement two measurements one month apart (25 April-28 May 2015) to monitor the monthly net mass balance of UG1 Urumqi Glacier No.1 at the monthly scale (25 April-28 May 2015), however the result of this paper are preliminary. What's more, we have not compared the glacier-wide mass balance between the two methods by considering many factors (e.g. density, data quality, internal and basal mass balance, glacier vertical velocity). The article published in 2018 mainly reanalysis the mass balance of Urumqi Glacier No.1 and evaluate the quality of mass balance records according to the proposal of WGMS. China contains the large number of glaciers around the world, and most of these glaciers are summer-accumulation type, now only several glaciers have discontinuous glaciological mass balance records. The aim of this study is thus to established an optimization scheme of volume-to-mass conversion to realize the calculation of TLS-derived geodetic mass changes, to investigate the possible causes of the differences between glaciological and geodetic mass balance. The potential of such long-range TLS to measure mass balance of glaciers in western China is evaluated and several main considerations for a wide application of the TLS in glaciology are put forward. So publishing results of this paper is prerequisite for a wide

application.

Now we have added a section (6.4) to further analysis as suggested:

"6.4. Glacier vertical velocity component

Geodetic measurements of glacier surface elevation changes include glacier surface mass balance and vertical velocity component (Kaser et al., 2003; Geist et al., 2005). Vertical velocity (w_s) is downward (submergence) and makes dynamic thinning of Urumqi Glacier No.1 in the accumulation area, and in the ablation area, vertical velocity is upward (emergence) and makes dynamic thickening of the glacier. This dynamic process results in the general difference between the elevation-distributed mass changes stated above (Fig. 8). To discuss the influences of vertical velocity component, here w_s depends on the kinematic boundary condition at Urumqi Glacier No.1 surface as basal sliding and bed deformation of the glacier are negligible (cf. Petterson et al., 2007; Cuffey and Paterson 2010)

$$\dot{h} = \frac{\dot{b}}{\rho} + w_s - u_s\frac{\partial S}{\partial x} - v_s\frac{\partial S}{\partial y} \quad (13)$$

in which $\dot{h}$ is the rate of glacier surface elevation changes, u_s and v_s are the components of horizontal ice velocity at the glacier surface s, respectively (Cuffey and Paterson 2010). We neglect the advection of the glacier surface topography induced by horizontal ice flux since the low reduced horizontal velocity (Wang et al., 2017) and short time span of this study. Then changes in $\dot{h}$ equals the sum of $\frac{\dot{b}}{\rho}$ and w_s, can be expressed as (Beedle et al., 2014)

$$\dot{h}\rho - \dot{b} = w_s\rho \quad (14)$$

Glacier dynamic thinning and thickening can be detected by subtracting the glaciological mass balances from the geodetic ones. For most of the study periods, positive difference values (thickening) dominate in the lower elevations, especially the glacier tongue, and negative difference values (thinning) mainly occur in the higher parts (Fig. 7a, d, g and j). Positive values across the east branch in summer

2015 may be related to different survey dates between the geodetic and glaciological methods.

Now applying reciprocal density conversion to the mass balance differences estimate the submergence and emergence velocities. Here we defined the term submergence is negative vertical velocity and emergence is positive vertical velocity. Variation tendency of the estimated velocities at ablation stakes were found to match from in situ measured ones, especially for east branch (Fig. 8). Relative bigger differences of west branch were detected in the mass balance years 2016-17 (Fig. 8b and d), which may duo to an avalanche in the upper part during the summer 2017. The firn basin terrain of west branch is very steep and is adverse to mass accumulation, which can also be validated in terms of TLS-derived glacier surface elevation changes (Fig. 4g). Thus pronounced misalign of mass balance elevation distribution curves between the two methods occurred. Considering the errors of estimate and in situ measurements, submergence and emergence velocities can be estimated using the TLS-derived DEMs and glaciological mass balance. The difference in mass balance elevation distribution can be largely explained by glacier dynamic thinning at higher elevations and dynamic thickening at lower elevations.

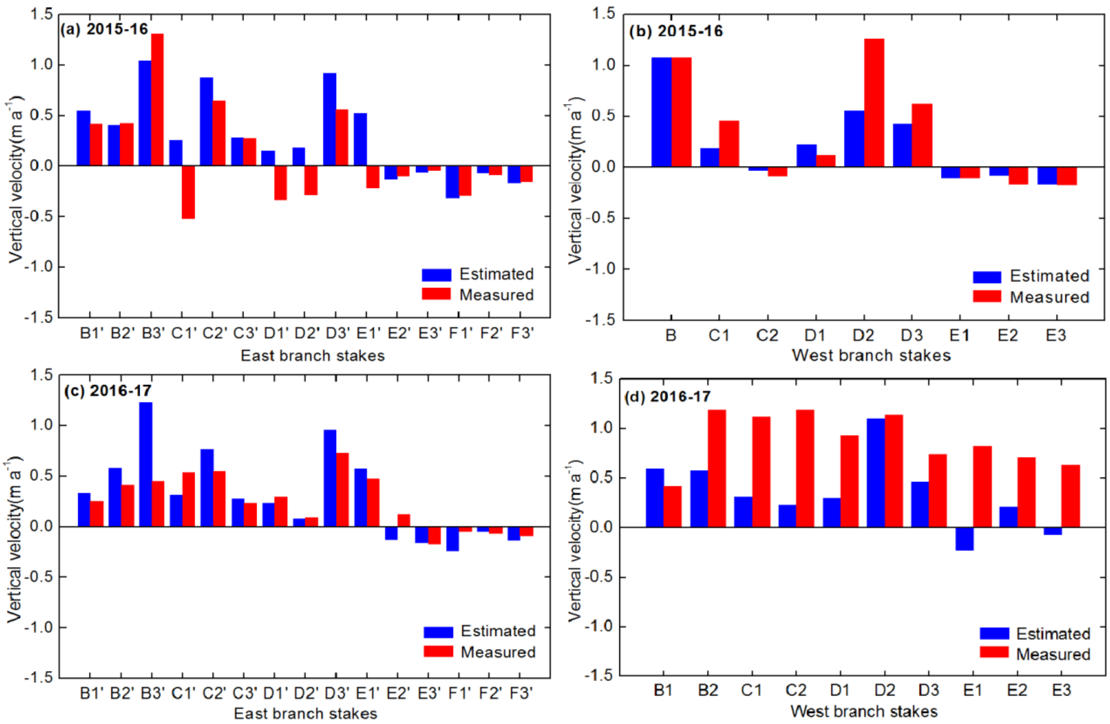

Figure 8. Comparison between estimated and in situ measured vertical velocity for the mass

balance year 2015-16 and 2016-17; the letters represent ablation stakes. Note than the summer periods and stakes in the higher elevations were not selected for comparisons due to snow cover reduced the quality of in situ measured vertical velocity.

In fact, the vertical velocity of Urumqi Glacier No.1 is small (Fig. 8), we now discuss the errors of glacier surface elevation changes versus dynamic thinning and thickening. Differences in glacier surface elevation changes derived from the TLS and glaciological measurements were close to zero for the vast majority of the ablation stakes, and corresponding errors in the differences were mostly larger than the difference themselves (Fig. 9). Compared with the errors of measurements, dynamic thinning and thickening of the glacier were minor and negligible. So Riegl VZ®-6000 TLS can be considered as an effective tool to measure the mass balance of Urumqi Glacier No.1.

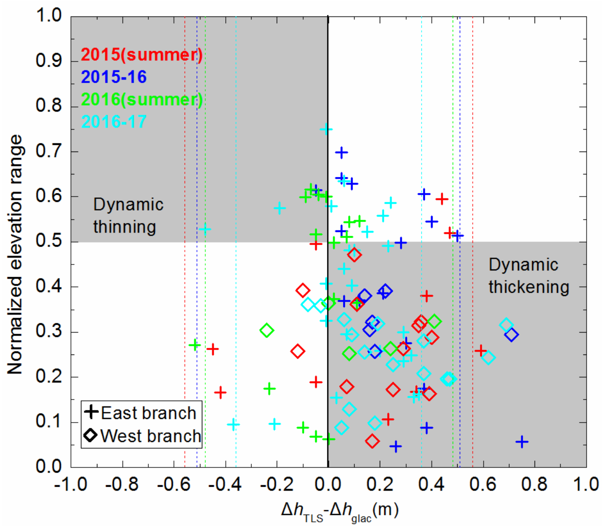

Figure 9. Changing differences between TLS-derived (Δh_{TLS}) and glaciological (Δh_{glac}) annual and summer surface elevation changes at individual stakes versus normalized glacier elevation range of east branch and west for the four investigated periods. Note than dash vertical lines represents the uncertainty ranges ($\sqrt{\sigma^2_{\Delta hTLS} + (\sigma_a^{ice})^2 + (\sigma_a^{firn})^2}$) of the changing differences ($\Delta h_{TLS} - \Delta h_{glac}$), and grey quadrants indicate theoretical areas for Urumqi Glacier No.1 in equilibrium."

Generally, the article is difficult to read for several reasons. The English needs to be considerably improved, there is an overabundance of acronyms and the order in which topics are dealt with is not always logical.

Reply: We have already corrected syntactic problems and improved English in the whole manuscript accordingly. For acronyms, we have written out many, such as: "ICP" is replaced by "iterative closest point"; "DMS" is replaced by "Daxigou Meteorological Station", UG1, EB and WB are written out Urumqi Glacier No.1, east

branch and west branch, respectively. Organizational order of the manuscript has also been changed.

Acronyms should be avoided where possible. E.g. ICP is used only twice, so should be written out. Write out what the acronym means on first use, even for terms such as “w.e.”. DMS should be replaced by “the meteorological station” or “the met. station”. Use of this acronym every time the met station is referred to is confusing.

Reply: Thanks for the carful and detailed comments. Now we have already checked everywhere else in the manuscript and write out acronyms. ICP means iterative closest point and is written out accordingly. “w.e.” indicates “water equivalent” and now we write out it means on first use. DMS has been replaced by the full name as suggested.

Comments on the text and grammar

p. 1, line15-16. Change to “…. well-suited for repeated glacier mapping, and thus determination of annual and seasonal geodetic mass balance.”

Reply: Now corrected accordingly

line 18. Change to “for two consecutive mass balance years …….”

Reply: We added as suggested

Line 24. Change “satisfying” to “satisfactory”

Reply: Corrected

Line 28. Change “function known as” to “concept of”

Reply: Corrected

Line 34. Change “Ongoing” to “Continuous”

Reply: Corrected

p.2 line 9. The geodetic method doesn’t “measure” all mass balance processes as such. Change the sentence to “The method includes all processes that affect the surface ……….”

Reply: We fully agree. The sentence has been rewritten as suggested.

Line 15. Change “burgeoning” to “emerging”

Reply: Corrected

Line 17. Change to “to calculate geodetic mass balance and changes in glacier volume …”

Reply: Corrected

Lines 17-19. It is unnecessary to have to many references. Several of these had no new techniques, merely applying the same technique to different areas. Also, add the first studies of intra-annual changes in mass balance from laser scanning, Pellikka, P. and W.G. Rees, eds. 2010. Remote sensing of glaciers: techniques for topographic, spatial, and thematic mapping of glaciers. Boca Raton, FL, CRC Press/Taylor & Francis. 330pp. ISBN-10: 0-415401-66-6, ISBN-13: 978-0- 415-40166-1 (or Vetter et al, 2009 article) and Geist et al (2005), Investigations on Intra-annual elevation changes using multi-temporal airborne laser scanning data: Case study Engabreen, Norway.

Reply: As suggested by the referee, we have deleted some of the listed references and cited the first studies of intra-annual changes in mass balance from laser scanning mentioned above.

Line 19. Replace “advantageous” with “effective”. Replace “wide” with “extensive”.

Reply: Done

Lines 19-21 require more explanation – “what is meant by “the difficulty of studying small-scale processes”? Small-scale processes are not the focus here. In addition, why is the presence of rock outcrops a problem for airborne observations, rather than ground-based? Usually the opposite would be assumed.

Reply: Thanks for the detailed reviews. For the first sentence: we want to clarify TLS system can more easily capture glacier changes with high time resolution than ALS since the high cost of aircraft. For the second sentence: most ALS instruments have limited operating flight altitude, such as the novel RIEGL VQ-780i ALS has a maximum fighting altitude of 5600 m a.s.l., Leica ALS70 with a maximum altitude of 5000 m a.s.l., Optech ALTM Gemini with a maximum altitude of 5000 m a.s.l., etc. However, the maximum altitude of most glaciers (78.6% of the total number) in western China exceeds 5000 m a.s.l. according to the second Chinese glacier inventory, hence great topographic relief and high altitude of rock outcrops around glaciers usually increase the difficulty of aircraft flight. In order to be more reasonable, these sentences were rephrased as follows:
“but the difficulty of studying glacial changing processes with high temporal resolution since the high costs of ALS and the presence of great topographic relief and high-altitude rock outcrops around glaciers reduce the capacity of observations by aircraft as most ALS instruments have limited operating flight altitude, so we need ground-based surveys (Piermattei et al., 2015).”

Line 22. Change “evolutions of” to “changes in”.

Reply: Corrected

Line 23. Delete “reference glaciers in particular”, as this is irrelevant. Change “-resolution” to “high.resolution”.

Reply: Done

Lines 25-26. From “Being” change to “The scanner is a Laser Class 3B, with laser wavelength in the near-infrared (~1064 nm), and thus well.suited for measuring snow- and ice-covered terrain in…..”

Reply: Done

Line 27. “Some recent studies” – is it some or one? The reference is to Gabbud et al, 2015, which describes a study on one glacier.

Reply: Now we rephrased the sentence as “One study has…...”

Lines 28-32. From “however”, change to “however, only the middle and lower elevations were measured as the glacier is relatively big. Another study reports the performance of the Riegl VZ®-6000 in monitoring 30 the mass balance of five glaciers in the European Alps; the surface terrain of each glacier can be almost entirely detected using one scan position since these glaciers are very small and have steep terrain (Fischer et al., 2016). For medium-sized and large glaciers with flat terrain, however, a single scan position cannot capture the whole glacier surface.”

Reply: These sentences were rephrased as suggested.

Line 35. Delete “-term”

Reply: Done

Line 36. Delete “Riegl VZ® 6000”

Reply: Done

p.3. Line 1. Break the sentence up, e.g. full-stop after results, and start the next sentence “An accurate ….”

Reply: Now changed accordingly

Line 2. Change “received attention” to “been performed”

Reply: Corrected

Line 3. Was the study done at a monthly scale, or were two measurements made one month apart to get net mass balance over one month? This needs to be clearer.

Reply: Thanks for the detailed review. Actually, the sentence wants to mean that two measurements made one month apart to get net mass balance over one month. Now the sentence was rephrased to be clearer:

"Our previous study has used the TLS to implement two measurements one month apart (25 April-28 May 2015) to get monthly net mass balance of UG1"

Lines 6-7. "besides we only considered snow/firn densities in the geodetic mass balance calculations" etc. – this sentence doesn't make sense.

Reply: Now the sentence was rewritten as:
"besides we only considered snow/firn densities in the determination of a density conversion, which was used to convert monthly volume change to geodetic mass changes, as an abundance of fresh snow covered the entire glacier surface at the time of the TLS surveys (Xu et al., 2017)."

Line 8. Change "mass balance" to "mass changes".

Reply: Corrected

Line 9. What is meant by "Meteorological influences on the elevation changes" from Huss (2013)? Is this referring to changing mass balance gradients? Generally, this whole paragraph down to line 24 on page 3 needs to be rewritten. Bader (1954) is referenced later in the text, but could be introduced here, in lines 13-14.

Reply: Yes, this refers to changing mass balance gradients. Bader (1954) is referred in lines 13-14. We now rewrite the whole paragraph down to line 24 as suggested:
Urumqi Glacier No.1 (hereafter known as UG1) has the most detailed annual and seasonal surface mass balance measurements in China. It is also one of the reference glaciers in the World Glacier Monitoring Service (WGMS) network due to its long data series, important location and significant local water supply (Li et al., 2011; Zemp et al., 2009). TLS surveys of UG1 were initiated on 25 April 2015 for four scan positions (Fig. 1a), and the subsequent measurements were nearly coincident with days of glaciological mass-balance measurements. Multi-temporal high-resolution and -precision TLS-derived DEMs are therefore available. To date, comparison of glaciological and geodetic mass balances of UG1 was reported for the period 1981-2009 at intervals of several years (Wang et al., 2014) and for the period 1981-2015 (Xu et al., 2018), but these studies used a series of low-quality topographic maps to calculate sub-decadal and decadal geodetic results. An accurate reanalysis of seasonal and annual glaciological mass balance of UG1 using high-resolution and -precision DEMs has not been performed. Our previous study has used the TLS to implement two measurements one month apart (25 April-28 May 2015) to get monthly net mass balance of UG1, whereas we simply compared glaciological and TLS-derived geodetic elevation changes of individual stakes, whether agreement between the glaciological and TLS-derived glacier-wide mass balance was pending, potential of such technology applied in seasonal and annual glacier mass-balance measurements in western China had not been discussed; besides we only considered snow/firn densities in the determination of a density conversion, which was used to convert monthly volume change to geodetic mass

changes, as an abundance of fresh snow covered the entire glacier surface at the time of the TLS surveys (Xu et al., 2017). In fact, the volume-to-mass conversion becomes more challenging over short time periods as meteorological factors change mass balance gradients (Huss, 2013). Several recent studies have used an area-weighting method to calculate the annual density conversion by classifying a glacier surface into bare ice and firn (Fischer et al., 2016; Klug et al., 2018). But the volume changes in ice and firn/snow usually take place at the same vertical layer for summer-accumulation-type glaciers (accumulation and ablation take part simultaneously in summer months) from our field observations, it is therefore inappropriate for this study to adopt the area-weighting method. Besides, compaction and metamorphosis imply a shift in the vertical firn profile as well as changes in firn thickness and density (Cuffey and Paterson, 2010; Ligtenberg et al., 2011),so assuming no change occurs in the vertical firn density profile over time in the accumulation area is unrealistic (Bader, 1954).

This study takes UG1 as a case and describes the use of the TLS to monitor annual and seasonal geodetic mass balances for two consecutive mass balance years (2015-17). The aim of this study is thus to established an optimization scheme of volume-to-mass conversion to realize the calculation of TLS-derived mass changes, to investigate the potential of such long-range TLS to measure mass balance of glaciers in western China and to put forward some main considerations for a wide application of the TLS.

Line 17. Change “consecutive years” to “consecutive mass balance years”.

Reply: Corrected

Line 30. Why “accelerated” recessions? Do you mean just recessions?

Reply: Yes we mean recessions. Three time periods with different melting rates have been identified according the slope of the accumulative mass balance curve (Figure R1). This indicates that there were two accelerations in the melting processes. In order to clarify clearly, we replace “recessions” with “mass loss”.

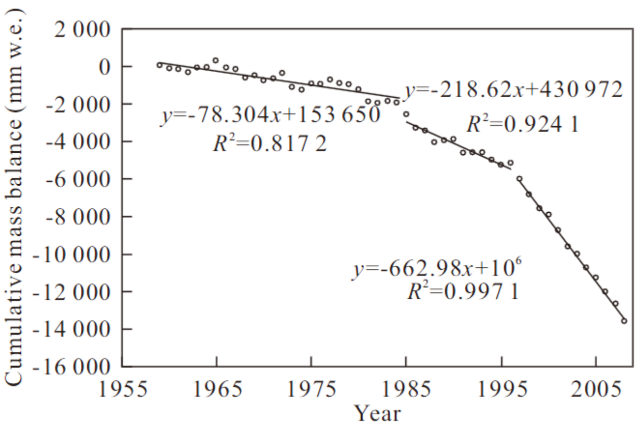

Figure R1 Cumulative mass balance of UG1 with linear regressions (Li et al., 2011)

Line 30. Delete “was” – this was a natural occurrence.

Reply: Corrected

Line 31. Why “enhanced”? Do you mean “increased”? If increased, over which period?

Reply: The air temperature rises during melting season, the ice temperature augment of the glacier and the albedo reduction on the glacier surface induce enhanced melting (Li et al., 2011). Here “enhanced” is same as “increased”. But the increased melting only observed in recent 50 years, we cannot subjectively attribute the separation to the observed result. So we delete “due to enhanced melting” to write as precise as possible.

p. 4, line 3. Change “accumulation rate is quicker” to “accumulation is higher”.

Reply: Corrected

Line 17. Change “-precision” to “high-precision”.

Reply: Corrected

Lines 24-25. Change to “point. The four scan positions were surveyed using real-time kinematic ……..”

Reply: Corrected

Line 26. Change “facilitate” to “give”.

Reply: Corrected

Line 27. Change “RTK surveys” to “survey”.

Reply: Corrected

Line 32. Delete “As to UG1”

Reply: Deleted

Line 35 to p. 5 line 1 Change “no less than” to “at least”

Reply: Corrected

p. 5. Line 19. “advantageous” – compared with what?

Reply: “the direct georeferencing technique in TLS using global navigation satellite systems (GNSS) is advantageous compare with total stations and the inclination sensors (Paffenholz et al., 2010; Mukupa et al., 2016)”
Reference:

Paffenholz, J. A., Alkhatib, H., and Kutterer, H.: Direct geo-referencing of a static terrestrial laser scanner, J. Appl. Geod., 4, 115-126, http://dx.doi.org/10.1515/JAG.2010.011, 2010.
Mukupa, W., Roberts, G. W., Hancock, C. M., and Almanasir, K.: A review of the use of terrestrial laser scanning application for change detection and deformation monitoring of structures, Surv. Rev., 1-18, http://dx.doi.org/10.1080/00396265.2015.1133039, 2016.

p. 6, line 20. Changes "researches" to "researchers"

Reply: Corrected

Line 22. State Sorge's Law, rather than just referencing Bader (1954).

Reply: Done

p. 7, line 1. Delete "3-D"

Reply: Done

Line 4 – insert «descriptive» in front of «free water content». This is in the original article, otherwise you are suggesting that free water content can be calculated merely by digging a snowpit.

Reply: We agree and insert accordingly

Line 10. Change to "………….observed using stakes and snow pits, since 1959 …….."

Reply: Corrected

Line 15. Change "where snow has accumulated" to "in the accumulation area".

Reply: snow pits were not always dug in the accumulation area, fresh snow usually covers the whole glacier at the begin of the ablation season, we should dig snow pits at each ablation stakes

Line 27. After respectively, insert "and the different between these two, i.e."

Reply: Corrected

p. 8, line 4. "probably led to an overestimate of the glacier extent" – when?

Reply: Now we revised the sentence as "Fresh snow cover probably led to an overestimate of glacier extent at the beginning of the ablation season"

Line 11. Change "assessments" to "assessment".

Reply: Corrected

Line 20. Why “finish”? replace with “perform”?

Reply: We agree “perform” is better than “finish”, now replaced accordingly

Line 22. Change “stabilized” to “established”.

Reply: Corrected

p. 9, line 1. “quantitatively”. Should this be “qualitatively”? Otherwise the sentence doesn’t make sense.

Reply: Now changed accordingly

Lines 5-6 – This sentence regarding the supraglacial river doesn’t make sense and needs to be rewritten.

Reply: We have rewritten as suggested

Line 34. Change beginning of this paragraph to “There are additional sources of error for …….”

Reply: Now changed accordingly

P. 10, line 11. Change “glaciers” to “glacier”.

Reply: Corrected

Lines 11-12 – the figures given here from Andreassen et al (2016) differ from the values given in the article.

Reply: We have checked the reference Andreassen et al (2016) and corrected the figures. Now we revised as:
“For Nigardsbreen (Norway) glacier, Andreassen et al. (2016) calculated a point measurement of ±0.25 m w.e. a^{-1} by summing false determination of the summer surface (±15 m w.e. a^{-1}), subsidence of stakes (0.20 m w.e. a^{-1}), errors in snow (0.05 m w.e. a^{-1}) and firn (0.02 m w.e. a^{-1}) density measurements.”

Line 34. Why “remarkable”? What is remarkable about it? Or do you mean significant?

Reply: here, relative bigger difference (ΔB) between glaciological and geodetic mass balances was seen. We now rephrased the sentences in order to be clear:

“In 2016-17, the difference ($\Delta B = B_{\text{glac}} - B_{\text{geod}}$) in glacier-wide mass balances of UG1 between the glaciological and geodetic methods was close to zero. Significant differences between the two mehods were detected in summer 2015 for UG1 and EB, with ΔB = -0.24 m w.e. and ΔB = -0.27 m w.e., respectively. In other three periods, the differences were much less the uncertainties of ΔB, which were

calculated based on the law of error propagation ($\pm\sqrt{\sigma_{\mathrm{geod}}^2+\sigma_{\mathrm{glac}}^2}$)."

p. 12. Line 6. Replace "satisfying" by "satisfactory".

Reply: Corrected

Line 8. Replace "know" by "give"

Reply: Corrected

Line 10. Change "at the steep elevations" to "on steep slopes".

Reply: Corrected

Lines 13-15. These two sentences need to be further clarified. Where are the annual vertical ice velocities reported? The geodetic results were more positive in lower-elevation regions – does this not contradict results for the Western Branch given on page 11?

Reply: Thanks for the careful review. Wang et al (2017) has not studied the vertical ice velocities, an early study reported the annual vertical ice velocities (Sun et al., 1985). The observed annual vertical ice velocities were in the range of -1.14--0.07 m a^{-1} (with a mean value of -0.48 m a^{-1}) and -1.17~-0.08 m a^{-1} (with a mean value of -0.49 m a^{-1}) for mass balance year 2015-16 and 2016-17, respectively (TGS, 2016, 2018). For UG1, both the glaciological and geodetic mass balances were negative in lower elevations and slight positive in higher parts. Here we want to write the geodetic results were more positive in lower-elevation regions compare with the glaciological mass balance. Now we added analysis about vertical velocity, related contents in this part were deleted.

Reference：

Sun, Z., Chen, Y., You, G., and Han, J.: Flow characteristics of Glacier No.1 at the headwater of Urumqi River, Journal of Glaciology and Geocryology, 1, 27–40, 1985 (in Chinese with English summary).

TGS (Tianshan Glaciological Station): The Annual Report Vol. 23 (2015-2016), Cold and arid regions environmental and engineering research institute, Chinese Academy of Sciences, Lanzhou, China, 2016 (in Chinese).

TGS (Tianshan Glaciological Station): The Annual Report Vol. 24 (2017-2018), Cold and arid regions environmental and engineering research institute, Chinese Academy of Sciences, Lanzhou, China, 2018 (in Chinese).

Line 20. As this is before section 6.3, a short explanation should be given here.

Reply: Now we revised as:

“but the biggest shift between the two methods was detected in summer 2015 for EB, which may be related to survey data differences between the glaciological and geodetic observations (see details in Sect. 6.3). This reflects that the TLS can be therefore considered as an effective tool to calculate ELA.”

Line 30. What are alcove terrains?

Reply: Here we only see flat terrain on the surface of west branch, now deleted alcove terrains as suggested.

Lines 36-37. Change to “Note that we did not get better results with more scan positions since this would probably decrease the quality of the MSA”.

Reply: Corrected

Section 5.1 is confusing – rewrite this to say something about the general pattern, then the specifics for the different years. The pattern of thinning in lower parts of a glacier and thickening in the upper parts has been observed on many other glaciers. (e.g. Moholdt et al (2010) Recent elevation changes of Svalbard glaciers derived from ICESat laser altimetry.). This pattern can be discussed with reference to Urumqi 1.

Reply: Thanks for the constructive comments; we now rewrote the whole section as follows:
The high-accuracy and -resolution DEMs allowed a detailed insight into the glacier surface elevation changes. Distributed elevation change patterns are generally similar for the four periods, i.e. both branches are characterized by a lower-elevation thinning of 1-3.5 m, elevation changes in the upper-elevation parts are more positive, variations with smaller lowering to pronounced thickening except for WB in the mass-balance year 2016-17 (Figs. 4a, c, e), this altitudinal change patterns are in good agreement with the long-term glaciological measurements.
Compared to the mass-balance year 2015-16, areas of clearer increase were observed in the upper eastern parts of EB in the mass-balance year 2016-17, but ice losses in the lower-elevation parts and glacier thickening in the upper reaches of WB were greater in the first mass balance year (Figs. 4c, g). . During summer periods, surface lowering in summer 2015 mainly occurred in the ablation areas of EB (Fig. 5a), glacier surface ablation was significantly greater in summer 2016 than in the first summer (Fig. 4e). For a completed mass balance year 2015-16, glacier thinning areas and values in summer were obviously bigger than the whole year, which may be related to fresh snow covered the glacier at the beginning of ablation season. In addition, there were some curves of pronounced glacier surface lowering in the ablation areas during summer periods, which were related to supraglacial river (Fig. 1c, d), a slight thinning area is detected at the lower lift (northerly) edge of EB, which may be associated with debris cover (Fig. 1c).

Section 5.2. This needs more explanation for why annual density conversions higher than summer. The converse would be expected.

Reply: Due to the mass changes in ice and firn/snow occur at the same vertical profile for Urumqi Glacier No.1, we should consider three-dimensional changes of ice and firn/snow bodies, we us a volume-weighting method to determine density conversion according to the principle of glaciological mass balance calculations:

$$\rho_i = \frac{\Delta h_{\text{ice}} \cdot \rho_{\text{ice}} + \Delta h_{\text{firn}} \cdot \rho_{\text{firn}}}{\Delta h_{\text{ice}} + \Delta h_{\text{firn}}}$$

where ρ_{ice}= 900 kg m^3 is glacier ice density, ρ_{firn} is firn/snow density, Δh_{ice} and Δh_{firn} are the changes in ice and firn/snow thickness, determined from glaciological mass-balance measurements.

Urumqi Glacier No. 1 is a summer-accumulation-type glacier, annul mass balance of the glacier is defined from the previous September 1 to the next August 31, summer runs from the beginning of May to early September each year (Liu et al., 1997). Large amounts of fresh snow or firn cover the glacier surface at the beginning of May (Figure R2), but glacier bare ice in the ablation area exposes and snow at the accumulation area is thinner on early September (Figure R3). So single-point density conversion ρ_i on the summer months is smaller than that of annual values.

Figure R2 fresh snow cover the glacier surface at the beginning of May (the photo takes on 29 April 2017)

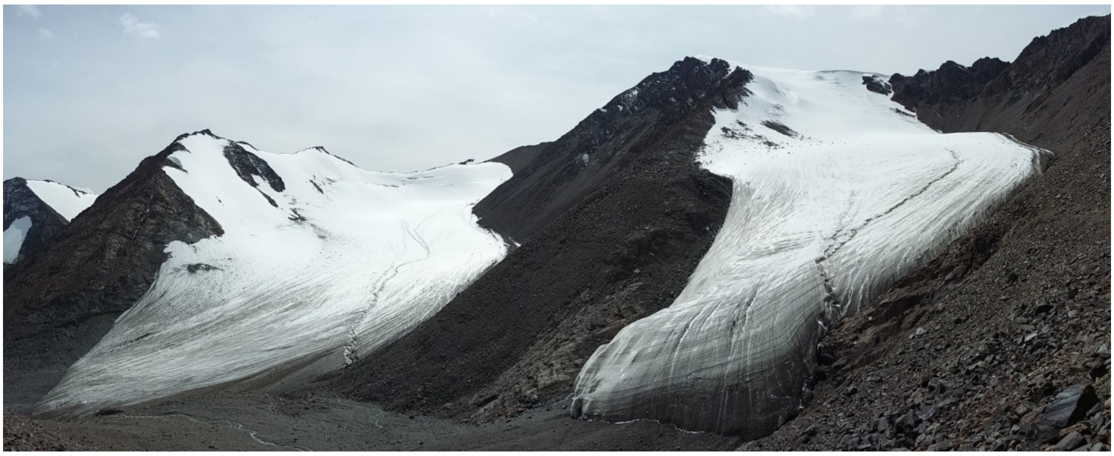

Figure R3 The glacier bare ice in the ablation area exposes and snow at the

accumulation area is thinner on early September (the photo takes on 1 September 2016)

Now we more explanation about annual density conversions higher than summer and rewrite as follows:
"The thicker snow and firn covered the whole glacier surface at the beginning of the beginning of May each year and the ablation area was bare ice or covered by a thin snow layer at the end of the ablation season according to filed observations (Liu et al., 1997; Xie and Liu, 2010), so the changes in ice and firn/snow thickness are observed during the summer months. However, firn and snow densities are far smaller than glacier ice density, these result in annul single-point density conversion ρ_i is bigger and the glacier-wide annual density conversions were accordingly higher than the summer ones (Table 3). "

Line 13. Change to "covered by a thin snow layer at the end ...."

Reply: Corrected

P. 13, line 2. Change "locate" to "be located"

Reply: Corrected

Line 28. Change "glaciers" to "studies"

Reply: Corrected

P. 14, Lines 1-18. It would make more sense to move the discussion of internal accumulation to where internal ablation is discussed. It is confusing to state that UG1 is a cold glacier, then to jump straight into internal ablation.

Reply: Thanks for the suggestions, now moved accordingly. Urumqi Glacier No.1 is a small and cold glacier, bottom sliding and bed deformation of the glacier is considerable to be negligible since temperature of the glacier bed has not reached the melting point, so the ice velocity of the glacier is very small (Huang, 1999; Wang et la., 2017). Previous studies have concluded that internal ablation of poly-thermal glaciers is negligible as the ice motion is small (c.f. Albrecht et al., 2000, Zemp et al., 2010). In addition, Urumqi Glacier has low reduced dynamics and hardly any subglacial water systems. Thus, we can consider internal ablation of the glacier is weak. In order to be clearer, corresponding paragraph was rewritten as follows:
"UG1 is a small and cold glacier, bottom sliding and bed deformation of the glacier is negligible since ice temperature of the glacier bed has not reached the melting point, so the glacier has low ice velocity and dynamics, and hardly any subglacial water systems (Huang, 1999; Xie and Liu, 2010; Wang et a., 2017). Previous studies have suggested that internal ablation of poly-thermal glaciers is negligible as the ice motion is small (e.g. Albrecht et al., 2000; Zemp et al., 2010).Besides internal

melt due to the potential energy of glacier dynamics is negligible since the low reduced dynamics. Thus, internal ablation of UG1 is weak and mainly comes from the released potential energy of descending water"

Reference:

Albrecht, O., Jansson, P., and Blatter, H.: Modelling glacier response to measured mass-balance forcing, Ann. Glaciol., 31, 91– 96, 2000.

Zemp, M., Jansson, P., Holmlund, P., Gärtner-Roer, I., Koblet, T., Thee, P., and Haeberli, W.: Reanalysis of multi-temporal aerial images of Storglaciären, Sweden (1959–99) – Part 2: Comparison of glaciological and volumetric mass balances, The Cryosphere, 4, 345–357, https://doi.org/10.5194/tc-4-345-2010, 2010.

Equation 11. Why is the interval between the ELA and the terminus only considered?

Reply: Glacier mass loss mainly comes from ablation area, so we assume meltwater originates at half the vertical from the glacier terminus to the ELA. Now the sentence was revised as:

"Glacier mass loss mainly comes from ablation area and we assume meltwater originates at half the vertical from the glacier terminus to the ELA, so $\bar{\mathbf{h}}_{\mathbf{ELA}}$ and $\mathbf{h}_{\mathbf{term}}$ are average equilibrium-line altitude (ELA) (4152 m) and the altitude of the glacier terminus (3775 m), respectively."

Line 10. Other sources of internal ablation should be discussed.

Reply: We now discussed other sources of internal ablation, i.e. the potential energy related to glacier dynamics. For basal ablation, we revised as:

"Basal ablation is generally attributed to frictional heat of basal sliding and geothermal heating for mountain glaciers (Thibert et al., 2008; Thomson et al., 2017; Galos et al., 2017). Basal ablation caused by frictional heat is very small since hardly any basal sliding of UG1. Here we mainly consider the contribution of basal ablation from geothermal heat (B_{gt}), which was estimated using"

Lines 16-18. How applicable is the 4% value given by Zemp to Urumqi Glacier No. 1?

Reply: Internal accumulation results from refreezing percolating water or the freezing of capillary-trapped water in cold snow and firn, which plays a significant role in cold and continental climates (e.g. Storglacären, Sweden, Zemp et al., 2010; Castle Creek Glacier, Canada, Beedle et al., 2014). Urumqi Glacier No.1 is a clod, continental glacier in a continental climate setting (Liu and Han, 1992; Li et al., 2011), measurement and studies on internal accumulation of Urumqi Glacier No.1 is still blank, so we conservatively estimate internal accumulation of the glacier to be about 4% of the winter mass balance. Now we revised as:

"Internal accumulation results from refreezing percolating water or the freezing of capillary-trapped water in cold snow and firn, which plays a significant role in cold and continental climates ,such as Storglacären, Sweden (Zemp et al., 2010) and Castle Creek Glacier, Canada (Beedle et al., 2014), Urumqi Glacier No.1 is a clod,

continental glacier in a continental climate setting (Liu and Han, 1992; Li et al., 2011), UG1 is a clod, continental glacier in a continental climate setting (Liu and Han, 1992; Li et al., 2011), measurement and studies on internal accumulation of the is still blank, so we conservatively estimate internal accumulation to be about 4% of the winter mass balance and the resulting value was about 0.01 m w.e. a-1. The final estimated internal mass balance of UG1 was about 0.005 m w.e. a-1."

Line 23. Delete "simiultaneously".

Reply: Deleted

Lines 24-25. What is meant by "observed discrepanices" and "had not been statistically identified"? this paragraph is confusing and needs more/better expalanation.

Reply: Here "observed discrepanices" indicates reduced discrepancy between the geodetic and glaciological mass balances, "had not been statistically identified" means "no statistical significant bias between the two datasets is detectable". Now relative sentences of the paragraph are rewritten to express more clearly.

Line 30. "On the eve" – does this mean the day before or in the evening? Please clarify.

Reply: Here we mean the day before the latest TLS surveys. Now we clarified accordingly.

Line 30. Change "latest" to "last".

Reply: Corrected

P. 15. Lines 5-6. Why is the past tense used here? Change to present tense.

Reply: We agree, now the tense was changed to present as suggest

Lines 19-20. How can the location of stakes be identified in this way? This part is unclear.

Reply: In field work, several retro-reflective targets (e.g. reflective foils, corner cube reflectors and retro-reflective paintings) are glued to the surface each ablation stake. The location of the targets can be easily surveyed and identified since a target with a high directivity of the reflected laser radiation. Now this was revised to be clearer:
"In addition, we can paste several retro-reflective targets (e.g. reflective foils, corner cube reflectors and retro-reflective paintings) to the surface of each stakes and the targets can be easily surveyed and identified since each of them has a high directivity of the reflected laser radiation, then the location of stakes be

determined."

Lines 23-24. An example of daily or sub-daily ablation would have been interesting if this was done at all during the study.

Reply: We have not yet used the long-range TLS system to study daily or sub-daily ablation. Gabbud et al (2015) showed that the TLS has been successfully used to measure sub-daily (hourly) ablation of an alpine glacier.

Reference:

Gabbud, C., Micheletti, N., and Lane, S. N.: Lidar measurement of surface melt for a temperate Alpine glacier at the seasonal and hourly scales, J. Glaciol., 61, 963–974, http://dx.doi.org/10.3189/2015JoG14J226, 2015.

P. 16 – Most of the first paragraph is unnecessary and this can be shortened considerably. The extensive list of glacier names (lines 12-13) is not necessary.

Reply: Now shortened as suggested.

Line 7. It is meaningless to give the area threshold to three decimal places.

Reply: Now the area threshold with 1 position after decimal was given.

Extensive rewriting is required to improve the grammar, and I have raised only the main points above.

Reply: Thanks for your careful review, we have checked the grammar and rewritten corresponding parts accordingly.

References. There are several errors in the references, and these should be thoroughly checked.

Reply: Thanks for the warm prompt. We have checked and standardized all the references, both in the text and at the end.

p.18 e.g. In Abermann et al (2010) change "dems" to "DEMs" as in the original. Cuffey and Paterson, 2010 - use the full citation for Huang, 1999. Correct "year's" to "years"

Reply: Corrected.

p. 19 Check spelling for names with diacritics, e.g. Pléiades, Radićetc.

Reply: Now checked and corrected accordingly.

p. 20 Use capital letters for proper nouns as used in the original articles, e.g. Rolleston Glacier, Hintereisferner

Reply: Corrected

p. 21 Correct the use of random hyphens that have crept into words, e.g. in Pfeffer et al, 2014 - Kienholz, Randolph, globally Pieczonka and Bolch (2015) should start on a new line.

Reply: Corrected

Xu et al (2018) is referred to on page 2, but missing from the reference list (unless this reference should have been to Xu et al (2017).

Reply: Now added Xu et al (2018).

Figures

Figure 1 – Positions of stakes and density pits are difficult to see and should be made clearer.

Reply: Now made clearer accordingly, see figure below:

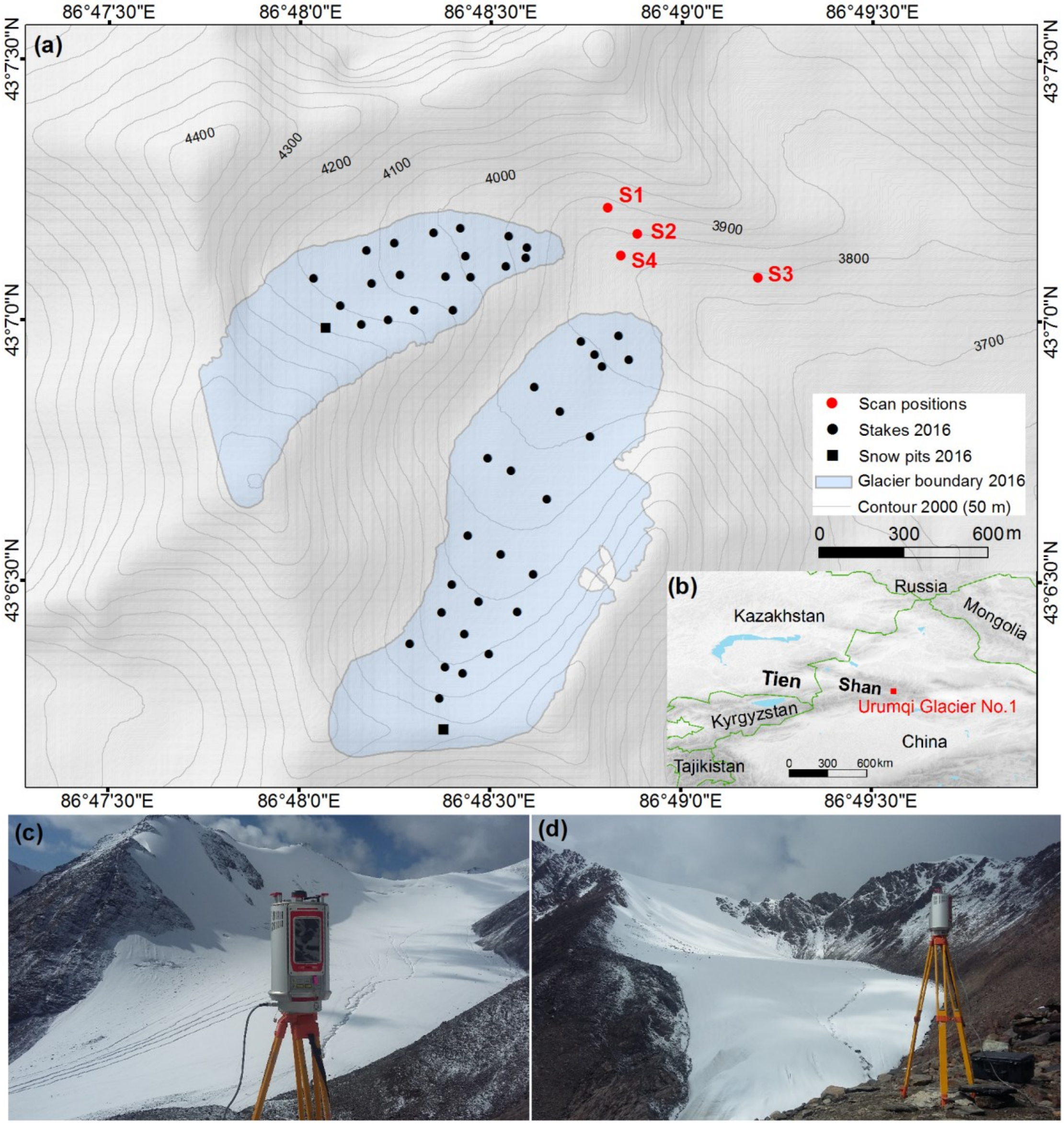

Figure 2 – this figure and reference in text are unnecessary, a reference to Litchi et al (2005) is sufficient.

Reply: We deleted the figure and referred Litchi et al (2005) as suggested.

Figure 3 – The glacier boundaries for different years needs to be clearer. Very hard to see the difference now. The (b) and (c) on the figures is hard to read.

Reply: Now made clearer accordingly, see figure below:

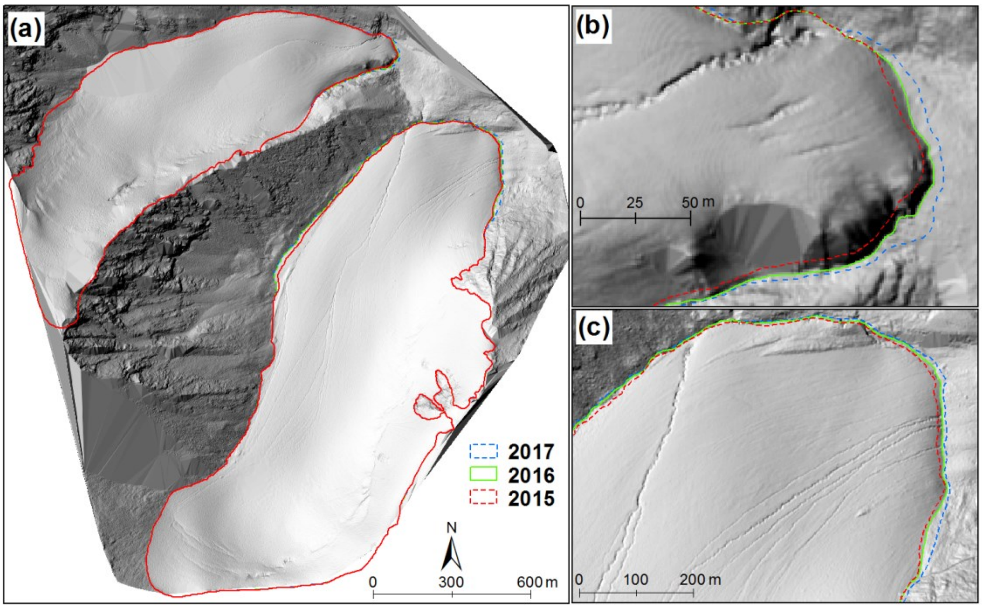

Figure 5 – The green polygons are very hard to see. In caption, change “(the unit is m)” to “(in m)”

Reply: Now the figure was made clearer accordingly. In caption, we changed “(the unit is m)” to “(in m)”. See figure below:

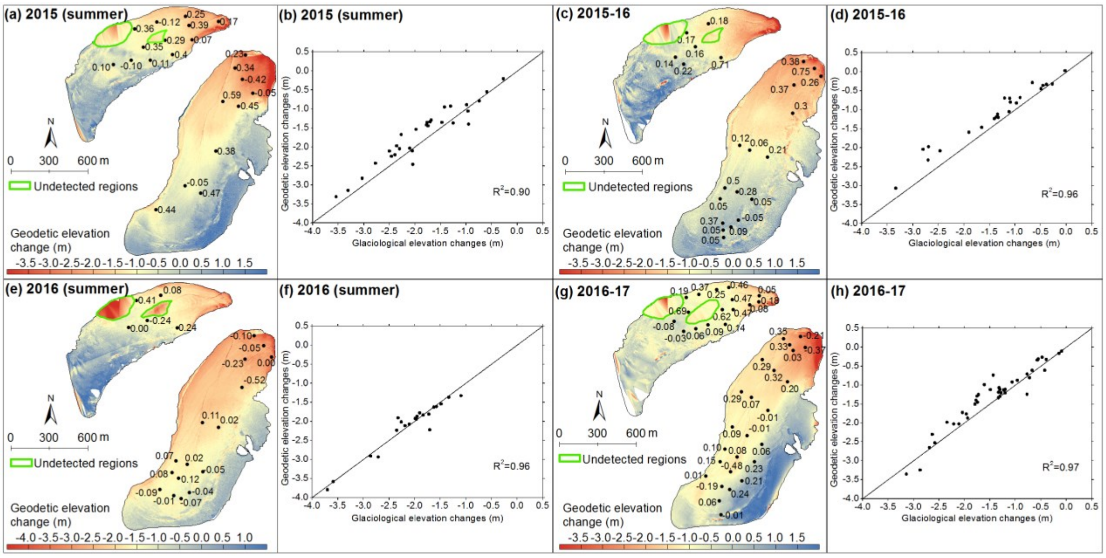

Figure 6 – The caption refers to black lines where are these? Also, these are meant to be the same as the corresponding boundary of figure 3, but this figure shows several glacier boundaries. ”artefact” is not the correct terminology, as it refers to something that is the result of the measurement technique or experiment, not merely missing data. “Areas” would be a better term than artefacts.

Reply: Thanks for the comments, here black lines are glacier boundaries. Now we revised as: “Here, glacier boundaries in (a) and (b) are same as boundary 2015 of fugure3, glacier boundaries in (c), (d), (e) and (f) are same as boundary 2016 of

fugure3, glacier boundaries in (g) and (h) are same as boundary 2017 of fugure3." We agree "artefact" is not the correct terminology and now replaced "artefacts" with "areas".

Figure 8 – Elevations in left-hand column are difficult to read – need to use a bigger font. The text in the middle and right-hand columns is also difficult to read and needs to be bigger.

Reply: We have used a bigger font to make the figure easy to read.

Figure 9 – change "temperature" to "air temperature"

Reply: Corrected.

Figure 11 – this map is unnecessary, as all it shows is spatial distribution of glaciers with suitable area and slope. If for some reason this figure is retained, change area cut-off to 1.5 km2; meaningless to use 1.555 km2.

Reply: Thanks! This map shows application potentiality of the long-range TLS for glacier mass-balance monitoring in China, now we have selected some benchmark glaciers among these appropriate glaciers to implement densely TLS measurements, in the next steps, we will selected more for TLS measurements to enrich the observational data. Hence, we retained this reasons. The area threshold with 1 position after decimal was given.

Table 2. Change "are calculated based on the elevation changes over stable terrain" to "are measures of error derived by calculating elevation changes from TLS over stable terrain (off-glacier)". In the header columns give the terms not symbols, e.g. Error or StdDev, number of points, mean (stable terrain) and standard error (stable terrain). Give the periods in the caption rather than under the table.

Reply: Now changed as suggested. We have given related terms in the header columns and the observed periods in the caption, see the table below:

Table 2. Error or StdDev (σ_{MSA}) of Multi-Station Adjustment (MSA) and the number of points (n) used for multi-temporal registration of two consecutive campaigns,the mean (μ) and the standard error ($\sigma_{\overline{\Delta h \mathrm{TLS}}}$) are measures of error derived by calculating elevation changes from TLS over stable terrain (off-glacier) for 2015 summer (25 April–2 September 2015), 2015-16 (2 September 2015–1 September 2016), 2016 summer (2 May–1 September 2016) and 2016-17 (1 September 2016–27 August 2017)

Period	Error or Stdev of MSA (m)	Number of points	Mean elevation changes over stable terrain (m)	Standard error of elevation changes over stable terrain (m)
2015 (summer)	0.28	11 214 842	-0.01	0.25

2015-16	0.07	10 182 829	0.05	0.23
2016 (summer)	0.20	10 486 985	-0.01	0.22
2016-17	0.07	18 657 232	0.04	0.16

Long-range terrestrial laser scanning measurements of ~~summer and~~ annual and intra-annual mass balances for Urumqi Glacier No.1, eastern Tien Shan, China

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Abstract. The direct glaciological method provides in situ observations of annual or seasonal surface mass balance, but can only be implemented through a succession of intensive in situ measurements of field networks of stakes and snow pits. This has contributed to glacier surface mass-balance measurements being sparse and often discontinuous in the Tien Shan. Nevertheless, long-term glacier mass-balance measurements are the basis for understanding climate–glacier interactions and projecting future water availability for glacierized catchments in the Tien Shan. Riegl VZ®-6000 long-range terrestrial laser scanner (TLS), typically using class 3B laser beams, is exceptionally well suited for ~~measuring snowy and icy terrain in~~ repeated glacier mapping, and ~~subsequently~~ thus determination of annual and seasonal geodetic mass balance ~~can be determined~~. This paper introduces the applied TLS for monitoring summer and annual surface elevation and geodetic mass changes of Urumqi Glacier No.1 ~~(UG1)~~ as well as delineating accurate glacier boundaries for two consecutive mass balance years (2015-17), and discusses the potential of such technology in glaciological applications. Three-dimensional changes of ice and firn/snow bodies and the corresponding densities were considered for the volume-to-mass conversion. ~~UG1~~ The glacier showed pronounced thinning and mass loss for the four investigated periods; glacier-wide geodetic mass balance in the mass-balance year 2015-16 was slightly more negative than in 2016-17. ~~The majority of TLS-derived geodetic elevation changes at individual stakes were slightly positive, but showed a close correlation with the glaciological elevation changes (changes in exposed stake height) of individual stakes ($R^2 \geq 0.90$).~~ Statistical comparison shows that agreement between the glaciological and geodetic mass balances can be considered ~~satisfying~~satisfactory; indicating that the TLS system yields accurate results and has the potential to monitor remote and inaccessible glacier areas where no glaciological measurements are available as the vertical velocity component of the glacier is negligible. For wide applications of the TLS in glaciology, we should use stable scan positions and in situ measured densities of snow/firn to establish volume-to-mass conversion.

1. Introduction

Glacier meltwater is a crucial freshwater resource for populations and hydro-economies in arid and semi-arid regions (e.g. Sorg et al., 2012; Chen et al., 2016). The ~~function known as~~concept of ‘solid reservoirs’ is well represented in the Tien Shan, where most glaciers have experienced substantial mass loss over recent decades (Farinotti et al., 2015; Pieczonka et al., 2015; Liu and liu., 2016; Sakai et al., 2017; Li et al., 2018). Hence, a better understanding of the relationship between Tien Shan glacier wastage and changing climate is important for projecting water availability in the near future. Glacier mass balance provides important information on the gain or loss in glacier mass and is a direct and immediate indicator of climate evolution (Kaser et al., 2006; Haeberli et al., 2007).

~~Ongoing~~ Continuous mass-balance observations are fundamental to understand climate–glacier interactions (Zemp et al., 2015). Annual and sometimes seasonal surface mass balance of individual glaciers can be measured using the direct glaciological method. Stakes are drilled into the ice, allowing the monitoring of ablation, and snow pits are dug in the area where snow has accumulated to provide net accumulation (Østrem and Brugman, 1991; Xie and Liu., 1991; Cogley et al., 2011). However, the shortage of long-term financial and human resources and the inaccessibility of remote regions and natural hazards means that ongoing in situ glacier mass-balance measurements are sparse and discontinuous in the Tien Shan, ~~so that~~ only Tuyuksu glacier (northern Tien Shan, Kazakhatan) and Urumqi Glacier No.1 (eastern Tien Shan, China) have long glaciological mass balance series (Hoelzle et al., 2017). In contrast to the extensive in situ measurement networks required for glaciological observations, the geodetic method provides mass balance by repeated surveys of the glacier surface terrain, in which two digital elevation models (DEMs) are subtracted to calculate the volume changes and then convert them to mass balance using a density conversion (Zemp et al., 2013; Huss, 2013; Andreassen et al., 2016). The method ~~measures~~ includes all processes that ~~induce~~ affect the surface, internal and basal mass balances (Cuffey and Paterson, 2010; Sold et al., 2016) but the geodetic mass balances are assumed to be accurate since the topographic surveys are of high quality (Thibert et al., 2008; Huss et al., 2009; Joerg et al., 2012). The available DEMs, derived from aerial photography and traditional remote sensing imagery, usually limit the accuracy and time resolution of geodetic mass-balance measurements (e.g. Cox and March et al., 2004; Cogley, 2009; Fischer, 2011).

In recent years, ~~burgeoning~~ emerging earth observation technologies (e.g. airborne (ALS) and terrestrial laser scanning (TLS))~~, which~~ allow the derivation of high-resolution DEMs with vertical and horizontal errors on the order of a few centimeters, ~~have~~ and increasingly been used to calculate ~~glacier volume and~~ geodetic mass and changes in glacier volume (e.g. Geist et al., 2005; Pellikka and Rees,~~Kerr et al.,~~ 2009; ~~Abermann et al., 2010; Fischer, 2011;~~ Joerg et al., 2012; Gabbud et al., 2015; ~~Andreassen et al., 2016;~~ Fischer et al., 2016~~; López-Moreno et al., 2016; Xu et al., 2017;~~ Klug et al., 2018). ALS is ~~advantageous~~ effective for rapidly mapping ~~wide~~ extensive areas, but ~~the high costs,~~ the difficulty of studying ~~small-scale~~ glacial changing processes with high temporal resolution since the high costs of ALS~~,~~ and the presence of great topographic relief and high-altitude rock outcrops around glaciers ~~limit~~ reduce the capacity of observations by aircraft as most ALS instruments have limited operating flight ~~and~~ altitude, so we need ~~require~~ ground-based surveys (~~Young et al., 2010;~~ Piermattei et al., 2015). The TLS system is usually simpler, more economical and more flexible than ALS, and has ~~became~~become a well-established tool for monitoring annual and sometimes seasonal ~~evolutions of~~ changes in individual glaciers (e.g. Gabbud et al., 2015; Fischer et al., 2016; López-Moreno et al., 2016)~~, reference glaciers in particular~~. The new high-speed and high-resolution Riegl VZ®-6000 terrestrial laser scanner offers a long measurement range of more than 6 km and a wide field of 60° vertical and 360° horizontal for topographic (static) applications (RIEGL Laser Measurement Systems, 2014a). ~~Being t~~The scanner is a Laser Class 3B, ~~it is, due to its~~with laser wavelength in the near-infrared (~1064 nm), ~~exceptionally~~ and thus well-suited for measuring snow- and ice-covered terrain~~s~~ in repeated glacier mapping. ~~Some recent studies~~One study ~~have~~ has covered the novel use of Riegl VZ®-6000 TLS to measure surface melt for a temperate Alpine valley glacier at the seasonal and hourly scales (Gabbud et al., 2015); however, only the ~~central~~ middle and ~~bottom~~ lower elevations were detected ~~due to~~as the glacier ~~area~~ is relatively big. ~~Others present~~Another study reports the performance of the Riegl VZ®-6000 in monitoring the mass balance of five glaciers in the European Alps; the surface terrain of each glacier can be almost entirely detected using one scan position since these glaciers are very small and ~~their~~ have steep

~~terrain~~terrain ~~s are steep~~ (Fischer et al., 2016). For medium-sized and large ~~reference~~ glaciers with flat terrain, however, ~~a single~~one scan position cannot ~~capture~~ survey the whole glacier surface.

Urumqi Glacier No.1 ~~(hereafter known as UG1)~~ has the most detailed annual and seasonal surface mass balance measurements in China. It is also one of the reference glaciers in the World Glacier Monitoring Service (WGMS) network due to its long~~-term~~ data series, important location and significant local water supply (Li et al., 2011; Zemp et al., 2009). ~~Riegl VZ®-6000~~ TLS surveys of Urumqi Glacier No.1~~UG1~~ were initiated on 25 April 2015 for four scan positions (Fig. 1a), and the subsequent ~~measurements~~ surveys correspond to measurement dates~~were nearly coincident with days of~~ for glaciological mass-balance measurements. Multi-temporal high-resolution and high-precision TLS-derived DEMs are therefore available. To date, comparison of glaciological and geodetic mass balances of Urumqi Glacier No.1~~UG1~~ was reported for the period 1981-2009 at intervals of several years (Wang et al., 2014) and for the period 1981-2015 (Xu et al., 2018), but these studies used a series of low-quality topographic maps to calculate sub-decadal and decadal geodetic results~~,~~. An accurate reanalysis of seasonal and annual glaciological mass balance of Urumqi Glacier No.1~~UG1~~ using high-resolution and high-precision DEMs has not ~~received attention~~been performed. Our previous ~~studies~~ study ~~have~~ has used the TLS to implement two measurements one month apart (25 April-28 May 2015) to ~~monitor the~~ get monthly net mass balance of ~~UG1~~ Urumqi Glacier No.1 ~~at the monthly scale (25 April-28 May 2015)~~, whereas we simply compared glaciological and TLS-derived geodetic elevation changes of individual stakes, whether agreement between the glaciological and TLS-derived glacier-wide mass balance was pending, potential and shortcomes of such technology applied in seasonal and annual glacier mass-balance measurements in western China had not been discussed; besides we only considered snow/firn densities in the determination of a density conversion, which was used to convert monthly volume change to geodetic mass ~~balance~~ changes~~calculations~~, as an abundance of fresh snow covered the entire glacier surface at the time of the TLS surveys (Xu et al., 2017). In fact, the volume-to-mass conversion~~a density conversion of volume changes to mass balance~~ becomes more challenging over short time periods ~~because of~~as meteorological factors ~~influences on~~change ~~the elevation changes~~mass balance gradients (Huss, 2013). ~~Some~~ Several recent studies have used an area-weighting method to calculate the annual density conversion by classifying a glacier surface into bare ice and firn (~~e.g.~~ Fischer et al., 2016; Klug et al., 2018). ~~However,~~But the volume changes in ice and firn/snow usually take place at the same vertical layer for summer-accumulation-type glaciers (accumulation and ablation take part simultaneously in summer months) ~~according to~~from our field observations, ~~so~~ it is therefore inappropriate for this study to adopt the area-weighting method~~we cannot classify ice and firn using remotely sensed methods in this study~~. Besides, compaction and metamorphosis imply a shift in the vertical firn profile as well as changes in firn thickness and density (Cuffey and Paterson, 2010; Ligtenberg et al., 2011)~~.~~, so assuming no change occurs in the vertical firn density profile over time in the accumulation area is unrealistic (Bader, 1954).

This study takes Urumqi Glacier No.1 as a case and describes the use of the TLS to monitor annual and seasonal geodetic mass balances for two consecutive mass balance years (2015-17). The aim of this study is thus to established an optimization scheme of volume-to-mass conversion to realize the calculation of TLS-derived geodetic mass changes, to investigate the possible causes of the differences between glaciological and geodetic mass balance. The potential of such long-range TLS to measure mass balance of glaciers in western China is evaluated and several main considerations for a wide application of the TLS in glaciology are put forward.

2. Study site

Urumqi Glacier No.1~~UG1~~ is a northeast-orientated small valley glacier, situated on the northern slope of Tianger Summit II (4848 m a.s.l.) in the eastern Tien Shan (43°06′N, 86°49′E, Figs. 1a and b). This ~~UG1 covered~~glacier covered a total area of 1.555 km^2 on 2 September 2015~~, from~~ according to TLS-derived high-resolution DEMs. Intensive glaciological investigations of Urumqi Glacier No.1~~UG1~~ were implemented in 1959 and then a monitoring station (Tien Shan Glaciological Station) was set up for long-term glaciological mass-balance measurements. During the period 1959-2008, ~~UG1~~ this glacier had experienced two accelerated mass loss~~recessions~~, commencing in 1985 and 1996 respectively (Li et al., 2011). The glacier ~~was~~ separated into two branches in 1993 ~~due to enhanced melting~~ (Li et al., 2011): the east branch ~~(EB)~~ and the west branch ~~(WB)~~ of Urumqi Glacier No.1.

Urumqi Glacier No.1~~UG1~~ is a typical summer-accumulation-type glacier in a continental climate setting (Liu and Han, 1992; Li et al., 2011). The westerly circulation is influenced by the dynamic action of the Tibetan Plateau in the winter months, causing a cold climate with little precipitation in the study site (Han et al., 2006; Huintjes et al., 2010). During the summer month, the Tibetan Plateau becomes a thermal depression and forms a plateau monsoon, which carries warm and humid air from the India Ocean, producing abundant precipitation surrounding the Plateau (Huintjes et al., 2010). These climatic conditions were confirmed by the annual climate records (1959-2015) of Daxigou Meteorological Station ~~(DMS)~~, located about 3 km southeast of ~~UG1~~ Urumqi Glacier No.1 at 3539 m a.s.l.; the annual average air temperature was about -5.0°C, and the annual average precipitation was 460 mm. 78% of the annual total precipitation amount occurs from May to August (summer), dominated by solid precipitation (Yue et al., 2017). The climatic conditions ~~mean~~ decide that the glacier is dominated by weak accumulation from October to March (winter) and the accumulation ~~rate~~ is ~~quicker~~ higher from April to May; both strong ablation and accumulation mainly take place between June and September (Liu et al., 1997).

3. Data and methodology

3.1. Terrestrial laser scanning

3.1.1. Principles and key features of Riegl VZ®-6000 TLS

Riegl VZ®-6000 TLS is an active laser imaging technique that calculates the distance between the object and the laser transmitter based on time-of-flight measurement with echo digitization and online waveform processing, and consequently the position of the point of interest to be computed (RIEGL Laser Measurement Systems, 2013). The scan mechanism includes a fast-rotating (60-120° from zenith) and more slowly rotating optical head (0-360°). The mirror deflects the laser beam in different directions, thus forming a scan line from consecutive measurements. Meanwhile, the optical head rotates and this scan movement is called a frame scan. A line scan and frame scan generate a view scan using this technique; data collection occurs at a rate of 23 000-222 000 points per second and generates point clouds accordingly (RIEGL Laser Measurement Systems, 2014a).

The high-accuracy and high-precision ranging is based on its unique V-line technology of echo digitization and online waveform processing, which allows Riegl VZ®-6000 TLS to operate even in poor visibility and in demanding multi-target situations caused by dust, haze, rain, snow, etc. (RIEGL Laser Measurement Systems, 2014a).

3.1.2. Terrestrial laser scanning surveys

Multi-temporal terrestrial laser scanning data of Urumqi Glacier No.1~~UG1~~ were collected from four scan positions to achieve maximum coverage, and each scan location was selected from the directions where most glacier surface point clouds would be achieved (i.e. the best possible visibility to glacier surface terrain) (Figs. 1c, d). To avoid ground motion and to obtain accurate coordinates of point clouds, each scan position was fixed using reinforced concrete with a standard GNSS-leveling point. ~~3-D coordinates of t~~The four scan positions were ~~then~~ surveyed using the real-time kinematic (RTK) global positioning system (GNSS, Unistrong E650 instrument) to ~~facilitate~~ give the most accurate direct georeferencing and registration. The 3-D coordinates were acquired in the UTM 45N coordinate system in the WGS84 datum. The accuracy of this type of ~~RTK~~ survey~~s~~ has been reported to be within ±1 cm horizontally and ±2 cm vertically, according to previous studies on Urumqi Glacier No.1 ~~UG1~~ (e.g. Wang et al., 2014; Wang et al., 2017).

After the measurements of 3-D coordinates, the Riegl VZ®-6000 was mounted on a tripod placed in the scan position to survey the glacier surface terrain. The scan parameters and atmospheric conditions are of crucial importance, which directly ~~determining~~ determined point cloud data quality (point density and coverage) and acquisition time. ~~As to UG1, t~~The laser pulse repetition rate was first set to 50 kHz, then line resolution and frame angle measurement resolution were set to 0.2° to allow a view scan with vertical and horizontal angles were in the range of 60–120° from zenith and 0–360°, respectively. A fine scan is a rectangular field-of-view scan, and the selected field should always cover the entire glacier to guarantee the overlap percentage of four scans was ~~no less than~~at least 30% (CH/Z 3017-2015, 2015). With each scan, the laser pulse repetition rate was reset to 30 kHz, and the corresponding line and frame resolution were configured as 0.02° to ensure dense points of the glacier surface, except for the scan campaign on 2 September 2015 (Table 1). All scans are performed on sunny days (dry and windless atmosphere) to avoid the influence of precipitation and fog, which can absorb laser pulse and reduce the possible survey distance. Details of the survey parameters are listed in Table 1.

3.1.3. ~~Terrestrial laser scanning~~ Point cloud ~~data~~ processing

Raw ~~point cloud~~ data were post-processed with RiSCAN PRO® v 1.81~~ software~~; this includes direct georeferencing, data registration, vacuation and filtering (RIEGL Laser Measurement Systems, 2014b). For all five scan campaigns, four scan positions were used (Table 1). ~~In the first phase~~At first (i.e. direct georeferencing), the TLS data from the different scan positions had to be transformed from the Scanner's Own Coordinate System (SOCS) into a Global Coordinate System (GLCS). ~~According to Figure 2, the~~ The transformation of a point from SOCS into the GLCS was described by Lichti et al (2005) and can be expressed by the following vector equation

$$\overrightarrow{r_g} = \overrightarrow{r_0} + R(k)\overrightarrow{r_s}\ , \qquad (1)$$

where $\overrightarrow{r_s}$ is the vector of a target in the SOCS; r_g is the vector of the georeferenced target in the GLCS; $\overrightarrow{r_0}$ is the vector of SOCS origin in the GLCS, k is the derived azimuth from the scan position to the backsight station and

$$R(k) = \begin{Bmatrix} \cos k & \sin k & 0 \\ \sin k & \cos k & 0 \\ 0 & 0 & 1 \end{Bmatrix}. \qquad (2)$$

Hence the direct method of georeferencing uses the 3-D coordinates of the scan positions to realize its functions (Lichti et al., 2005; Mukupa et al., 2016; Fey and Wichmann, 2017). The accuracy of the method depends on the quality of the measured coordinates. Previous studies stated that the direct georeferencing technique in TLS using global navigation satellite systems

(GNSS) is advantageous compare with total stations and the inclination sensors (~~e.g. Mohamed and Wilkinson, 2009;~~ Paffenholz et al., 2010; Mukupa et al., 2016).

The location of each scan was fixed in the GLCS after direct georeferencing; but the point clouds of the overlapped areas cannot coincide completely due to the influence of orientation. In the second step, multi-station adjustment (MSA) was used for the data registration of each scan position according to the iterative closest point ~~(ICP)~~ algorithm (Besl and McKay, 1992; Zhang, 1992). When we used MSA, the location of each scan was locked and the orientation of each scan was constantly adjusted in several iterations to compute the best overall fit for them based on least-squares minimization of residuals.

Afterwards we combined the overlapped scans in one layer. An octree algorithm was used to the merged layer to produce points with equal spacing to realize point cloud data vacuation (Schnabel and Klein, 2006; Perroy et al., 2010). A terrain filter was then applied to filter out noise and non-ground data due to atmospheric reflections such as dust or moisture, which still occurred despite scanning on fine days (RIEGL Laser Measurement Systems, 2014b). Finally, ~~Visual~~ visual interpretation was also performed to check the data and remove clear visual outliers~~.~~, ~~Finally~~, and then glacier surface point clouds with one layer were produced.

3.2. Geodetic ~~mass balance~~method

3.2.1. Geodetic mass balance calculations

As the orientation of each scan was continually adjusted to compute the best fit, the attitude angles of each scan campaign are different. Multi-temporal registration, also called relative registration, set the processed layer of 2 September 2015 as a reference; alignment of other scan campaigns onto the reference layer was finished with iterative closest point ~~ICP (MSA)~~ algorithms to determine the spatial bias of the multi-temporal scans and extract accurate elevation changes (Revuelto et al., 2014; Gabbud et al., 2015). The relative registered layers were then exported into LAS data format for further processing. Multi-temporal registration of two consecutive campaigns is a crucial step and determines the reliability of TLS-derived surface elevation changes (Revuelto et al., 2014; López-Moreno et al., 2016; Fey and Wichmann, 2017).

After the relative registration procedure, interpolation of the processed point cloud data calculated high-resolution DEMs of the study site. The surface elevation change Δh_k at the individual pixel r was calculated by differencing the TLS-derived multi-temporal DEMs with ArcMAP 10.2 ~~software~~. The total volume change ΔV was determined by summing the elevation change Δh_k of different time periods, and is expressed as

$$\Delta V = r^2 \sum_{k=1}^{K} \Delta h_k, \quad (3)$$

where K is the number of total pixels covering the maximum extent of Urumqi Glacier No.1~~UG1~~, and r is the pixel size (1 m × 1 m).

The calculated volume change is converted to geodetic mass balance (m water equivalent (w.e.)) following:

$$B_{\mathrm{geod}} = \frac{\Delta V}{\bar{S}} \cdot \frac{\rho}{\rho_{\mathrm{water}}} = \frac{\Delta V}{1/2 \cdot (S_{t0} + S_{t1})} \cdot \frac{\rho}{\rho_{\mathrm{water}}}, \quad (4)$$

where $\bar{S}$ is the mean glacier area of the two acquisition dates $t0$ and $t1$, thinking a linear change over time, ρ_{water} is the density of water and ρ is the average bulk density (density conversion) of glacier volume change (Thibert et al., 2008; Zemp et al., 2013).

3.2.2. Density conversion

As described above, the geodetic mass balance is calculated based on volume changes, which require a density conversion. However, the density is difficult to determine; in most studies, it is estimated and not measured. Some researchers assume that no change occurs in the vertical firn density profile over time in the accumulation area and use glacier ice density for the conversion based on Sorge's law (Bader, 1954). Actually, the firn line, firn thickness and firn density all vary, and using the ice density causes an overestimate of mass balance. Huss (2013) recommended a density conversion of 850 ± 60 kg m^{-3} for the volume-to-mass conversion based on an empirical firn densification model with idealized surface mass balance forcing. But the recommendation is appropriate in the case of a geodetic observation span longer than 5 years; with stable mass balance gradients, volume changes significantly different from zero and a firn area exists. Therefore, several recent studies classify the glacier surface into firn and bare-ice zones and use the volume-weighting method to calculate the annual conversion (e.g. Fischer et al., 2016; Klug et al., 2018). However, ~~UG1 is a summer-accumulation-type glacier;~~ mass balance processes of Urumqi Glacier No.1primarily occur in summer and the glacier is dominated by weak accumulation in winter (Liu et al., 1997). Glacier volume changes in ice and firn usually occur at the same vertical profile according to long-term observations; the surface classification is not applicable in this study. Here we use in situ measured thickness and densities of firn/snow (ρ_{firn}) and ablation stake data (change in ice thickness) to calculate single-point density conversion according to principle of glaciological mass balance calculations of Urumqi Glacier No.1 (Xie and Liu, 2010):

$$\rho_i = \frac{\Delta h_{\text{ice}} \cdot \rho_{\text{ice}} + \Delta h_{\text{firn}} \cdot \rho_{\text{firn}}}{\Delta h_{\text{ice}} + \Delta h_{\text{firn}}}, \quad (5)$$

where ρ_{ice}= 900 kg m^{-3} is glacier ice density, and Δh_{ice} and Δh_{firn} are the changes in ice and firn/snow thickness, determined from glaciological mass-balance measurements. We extrapolated single-point values to the glacier-wide densities to calculate average bulk density (ρ) using the interpolation method (Table 3), and the distributed density conversions of the total glacier were then generated (Figs. 6a, c, e, g).

It is generally true that the density conversion relies on measurements of changes in the ~~3-D~~ firn body, thickness and density of each firn layer being continuous from the top to the bottom of the snow pit, and a stratigraphic description of the firn layers is completed by experienced investigators. Major change processes in the snowpack (e.g. from crystals to grains, descriptive free water content and ice layers, etc.) can be considered in this case (Kaser et al., 2003), and firn compaction assumed to be negligible. ~~Glacier dynamics are probably insignificant for UG1 since the measured surface velocity is on the order of a few meters per year (Wang et al., 2017). Here w~~We use t volume-weighting~~the weighted average~~ method (the weights are the thickness changes of each firn layer and glacier ice) to calculate the firn density (ρ_{firn}) of each snow pit in this study.

3.3. Glaciological ~~mass balance~~method

3.3.1. In situ ~~glaciological~~ measurements ~~of UG1~~

The mass balance of Urumqi Glacier No.1~~UG1~~ has been observed ~~by measuring~~using stakes or snow pits, ~~beginning in~~since 1959 (Xie and Liu, 2010). Glaciological measurements broke off during the period 1967-79 and the glaciological data series during this period were reconstructed from correlations with climatic data observed at Daxigou Meteorological Station ~~the DMS~~ (Li et al., 2011). The program was re-established using glaciological methods in 1980. No less than 40 ablation stakes were drilled into the glacier and evenly distributed at different elevation bands using a stream drill, despite the fact that the number of stakes has varied from year to year, and snow pits were dug where snow has accumulated (Fig. 1a). The mass-balance year of Urumqi Glacier No.1~~UG1~~ is defined from previous September 1 to next August 31 (Liu et al., 1997). Usually, from the beginning of May to early

September each year, a spatial distribution of single-point ablation (mass loss) or accumulation (mass gain), and snow density (if there is snow cover) were measured by stakes and snow pits at monthly intervals. The net accumulation is measured by digging snow pits at each of the stakes in the area of the glacier where snow has accumulated during the period of investigation; stakes are drilled into the glacier and change in an exposed stake height plus change in snow depth (if snow exists) at two successive dates gives the net ice ablation at this point (Kaser et al., 2003; Xie and Liu, 2010). Hence the measured items include the stake vertical height over the glacier surface, thickness of superimposed ice, and the thickness and density of each snow/firn layer at individual snow pits. Note that fresh snow covered the entire whole glacier surface at the beginning of the ablation season, so snow pits must also be dug at each of the stakes.

3.3.2 Glaciological surface mass-balance determination of UG1

Glaciological mass balance includes point and glacier-wide mass balances. The rate of mass gain and loss per unit time is accumulation rate $\dot{c}$ and ablation rate $\dot{a}$, respectively, and the different between these two, i.e. $\dot{c}$ minus $\dot{a}$ equals mass-balance rate $\dot{b}$. Integrating $\dot{b}$ over the time span from t_0 to t_1 gives point mass balance Δb(Cogley et al., 2011):

$$\Delta b = \int_{t_0}^{t_1} \dot{b}(t)\, dt = b(t_1) - \mathrm{b}(t_0). \qquad (6)$$

Point values can be extrapolated to glacier-wide mass balance using the contour-line or profile method (Østrem and Brugman, 1991; Kaser et al., 2003). Here the time span is often a year or a season, and a seasonal mass balance is classically a winter balance or a summer balance (Cogley et al., 2011). Here t_0 and t_1 are the same as the t defined by Eq. (4). Point values can be extrapolated to glacier-wide specific mass balance using the contour-line or profile method (Østrem and Brugman, 1991; Kaser et al., 2003). For Urumqi Glacier No.1UG1, contour-line and isoline methods had successfully been used to calculate seasonal and annual glacier-wide mass balance (Xie and Liu, 1991), together with simulated values obtained using a simple energy-balance model (the energy divide into shortwave radiation and temperature dependent energy budget) in areas with no measurements (Oerlemans, 2010; WGMS, 2017). This study involves the glaciological measured data over the period 2015-17.

3.4. Accurate gGlacier boundary delineation

Accurate and updated glacier area was important for both geodetic and glaciological mass balance calculations (Zemp et al., 2013). Fresh snow cover probably led to an overestimate of glacier extent at the beginning of the ablation season; to reduce the influence of snow cover and to extract accurate glacier outlines, we mainly considered glacier extents at the end of the ablation season. Glacier boundary delineation was performed following Abermann et al. (2010). Firstly three shade reliefs at the end of hydrological years 2015, 2016 and 2017 with an azimuth angle for illumination (300°) were calculated based on multi-temporal high-resolution DEMs to show optimal visualization of contrasts in different aspects. We then delineated the glacier boundary directly by manually digitizing the strongest roughness in the shade reliefs (Fig. 3). The area of Urumqi Glacier No.1UG1 was 1.555, 1.550 and 1.542 km^2 in 2015, 2016 and 2017 respectively. Glacier area reduction was primarily attributed to terminus retreat (Figs. 3b2b, c).

4. Uncertainty assessment~~s~~

4.1. Uncertainties of geodetic mass balance

After multi-temporal registration, errors related to the spatial bias of the multi-temporal DEMs may be negligible. Besides density conversion for converting TLS-derived glacier surface elevation changes to mass balance, uncertainties in the geodetic mass balances derived from the TLS may be related to (1) errors in point cloud data acquisition, including surface terrain and atmospheric conditions (moisture and wind) (Revuelto et al., 2014; Fischer et al., 2016); and (2) errors in data processing and DEM generation, e.g. registration (multi-station adjustment), point cloud vacuation and filtering (smoothing terrain information) (Wheaton et al., 2010; Gabbud et al., 2015; Hartzell et al., 2015).

As mentioned in Sect. 3.1.2, dry and windless days were selected to perform ~~finish~~ the five scan campaigns. Instability of the TLS influences the registration of single scan positions from each data acquisition campaign, which includes small displacements of scan positions and the vibration of TLS. Each scan position was established ~~stabilized~~ on stable rock surfaces using reinforced concrete (the average drilling depth was greater than 80 cm) with a standardized GNSS-leveling point to avoid ground motion. In fieldwork, TLS is mounted using a tribrach on a tripod to level the instrument (Xu et al., 2017). Revuelto et al. (2014) found that the vibration of TLS can introduce considerable errors in measurements performed over large scales. In our experience, this issue is mainly relevant to wind, so windless weather conditions are important. Because the registration error cannot be distinguished from the positional uncertainties and the surface, it is difficult to assess registration-induced uncertainty; the error statistics are usually used to evaluate the registration error (Fey and Wichmann, 2017). RiSCAN PRO® v 1.81 software reports error statistics of the MSA results (RIEGL Laser Measurement Systems, 2014b). The standard deviation of errors (σ_{MSA}) from the set of residuals obtained from registering the point cloud can be considered as an indication of registration quality (Gabbud et al., 2015; Fischer et al., 2016). ~~σ_{MSA} values~~Values of σ_{MSA}~~for the four periods~~ over stable terrain surrounding Urumqi Glacier No.1~~UG1~~ are listed in Table 2 for the four periods. Registration quality was higher at seasonal than at annual scales; the higher quality may be attributable to fresh snow cover, which makes the stable terrain smooth.

Despite four scan positions placed at the terminus of Urumqi Glacier No.1~~UG1~~, two ~~artefacts~~ undetected areas of west branch exist in the (two green polygons in Fig. 5) ~~were~~ due to flat terrain ~~and relatively higher elevation~~ ranges from 4050 to 4100 m a.s.l. ~~of WB surface~~ (Fig. 1a), where the emission laser cannot be received by the laser receiver. We filled these regions using the spatial interpolation method, which can induce potential errors in DEM creations. The lack of dense measured 3-D coordinates of the terrain limits us to assessing terrain-induced errors qualitatively~~quantitatively. Xu et al. (2017) compared the interpolated and measured surface elevation changes at corresponding ablation stakes and confirmed that the comparative results were encouraging.~~ For precision, the undetected areas ~~artefacts~~ were not taken into account in calculating the geodetic mass balance~~, but~~ in fact, the related errors ~~related to unscanned areas should be very small because~~were small as the relative proportions of the ~~artefacts~~ two areas over the entire glacier surface were minor (3.1% for summer 2015, 3.2% for 2015-16, 3.6% for summer 2016, and 4.6% for 2016-17, Fig. 5). Furthermore, supraglacial river exists ~~developed widely~~ at the strong ablation season (June to September due to glacier melting (Fig. 1c, d)~~and its terrain characteristics are depicted~~, which was detected by the TLS surveys~~. We observe the presence of outliers in these regions (Fig. 5)~~. In order to preserve terrain information as much as possible, the octree algorithm built the topological relationship of scattered points to realize the vacuation of the point cloud. Point cloud filtering is also a significant post-processing step because of the dense ablation stake network, which is actually scanned by the device. Fortunately, fine scan generates high-density points of the glacier surface terrain.

There are nNo better ways can be used to evaluate the uncertainty of DEMs without precise and well-distributed stable points (Bolch et al., 2017). The standard error ($\sigma_{\overline{\Delta h\mathrm{TLS}}}$) of elevation changes over stable terrain can be considered as a criterion of the uncertainty of the entire glacier (Rolstad et al., 2009; Zemp et al., 2013). The standard deviation ($\sigma_{\Delta h\mathrm{TLS}}$) of the stable terrain elevation changes is suitable for estimating the uncertainty of the DEM differences at the individual pixel scale (Fig. 3); in this case the standard error is defined as the standard deviation. However, the spatial auto-correlation must be considered when we calculate the uncertainty of the glacier-wide elevation changes. Thereby, the uncertainty of TLS-derived glacier-wide elevation changes ($\sigma_{\overline{\Delta h\mathrm{TLS}}}$) for individual glaciers were quantified using the geostatistical analysis methods of Rolstad et al. (2009) and written as

$$\sigma^2_{\overline{\Delta h\mathrm{TLS}}} = \sigma^2_{\Delta h\mathrm{TLS}} \cdot \frac{1}{5} \cdot \frac{S_{\mathrm{cor}}}{S}, \tag{7}$$

where $\sigma_{\Delta h\mathrm{TLS}}$ denotes the standard deviation of TLS-derived elevation changes over stable terrain. S_{cor} is spatially correlated area. Given the high density (> 1 point m^{-2}) of the TLS data, we can probably assume that the number of independent items is about the number of glacier pixels (cf. Joerg et al., 2012, ALS point clouds). Here we therefore assume $S_{\mathrm{cor}} = S$. This leads to calculated values of $\sigma_{\overline{\Delta h\mathrm{TLS}}}$ range from ±0.16 to ±0.25 m (Table 2).

Uncertainties related to the density conversion for a single point ($\sigma_{\rho i}$) were calculated as

$$\sigma_{\rho i} = \frac{\Delta h_{ice} \cdot \sigma_{\rho ice} + \Delta h_{firn} \cdot \sigma_{\rho firn}}{\Delta h_{ice} + \Delta h_{firn}}, \tag{8}$$

where $\sigma_{\rho \mathrm{ice}}$ and σ_{firn} are uncertainties of ice and firn densities, which were assumed to be ±17 and ±50 kg m^{-3}, respectively, following Klug et al. (2018). We then extrapolated single-point values to glacier-wide uncertainties (σ_ρ) using the interpolation method on the ArcMAP 10.2 platform (Table 3). According to Huss et al. (2009), the uncertainties of the geodetic mass balance (σ_{geod}) can be estimated using

$$\sigma_{\mathrm{geod}} = \pm\sqrt{\left(\overline{\Delta h\mathrm{TLS}} \cdot \sigma_\rho\right)^2 + \left(\rho \cdot \sigma_{\overline{\Delta h\mathrm{TLS}}}\right)^2}, \tag{9}$$

where $\overline{\Delta h\mathrm{TLS}}$ is the average of TLS-derived glacier-wide elevation changes and the related uncertainty relies on the accuracy of the used DEMs.

4.2. Uncertainties of glaciological measurements

There are additional sources of errors for glaciological measurementsMany difficulties, including the harsh climate, create problems and lead to additional sources of errors for glaciological measurements, which in turn cause uncertainties in glaciological mass balance that are not easy to quantify (Dyurgerov, 2002). Uncertainties in glaciological measurements were classified into three groups: (i) errors in field observations, (ii) errors related to spatial extrapolation over the entire glacier and (iii) errors due to non-updated glacier area. Note that the class (iii) uncertainties appeared to be negligible due to the short time intervals (two consecutive years) in our study.

Point measurement uncertainties are prone to errors in stake readings and snow/firn density measurements (Jansson and Pettersson, 2007; Thibert et al., 2008; Huss et al., 2009), sinking or melting-out of stakes and misidentification of the firn layer surface at the end of the last hydrological year (Zemp et al., 2010). Some studies have demonstrated errors of ±0.1 and ±0.3 m w.e. for reading stakes in the ablation and accumulation areas, respectively (Huss et al., 2009). Zemp et al. (2010) determined an overall stochastic uncertainty at ±0.2 m w.e. a^{-1} for field measurements. Zemp et al. (2013) reanalyzed the mass balance of Hintereisferner, Austria, from 1953 to 2006 (six time intervals) and found an uncertainty of ±0.2 m w.e. a^{-1} for point mass balance. Beedle et al. (2014)

suggested an error of point mass balance to be about ±0.1 m w.e. a^{-1} for accumulation-area measurements. For Nigardsbreen (Norway) glacier~~s~~, Andreassen et al. (2016) calculated a point measurement of ±~~0.21~~0.25 m w.e. a^{-1} by summing false determination of the summer surface (±~~0.2~~15 m w.e. a^{-1}), subsidence of stakes (0.20 m w.e. a^{-1})~~ and ~~, errors in snow (0.05 m w.e. a^{-1}) and firn (0.02 m w.e. a^{-1}) density measurements~~ (0.05 m w.e. a-1)~~. Following Thibert et al. (2008), here errors of ablation measured in ice (σ_a^{ice}) and firn (σ_a^{firn}) are calculated using $0.14/\sqrt{N_a^{ice}}$ and $0.27/\sqrt{N_a^{firn}}$, respectively, where N_a^{ice} and N_a^{firn} denote the number of ablation stakes and snow pits (if firn exists), respectively; errors in accumulation measurements (σ_c) are determined based on $0.21/\sqrt{N_c}$, where N_c is the number of snow pits.

The class (ii) errors originate from extrapolating observed values to unmeasured areas, insufficient spatial distribution of measured sites and the interpolation method. Hock and Jensen (1999) evaluated the error of the interpolation method at about ±0.1 m w.e. a^{-1} for mean specific mass balances. Huss et al. (2009) computed and compared mean specific net balance with randomly reduced annual stake datasets and found that the error was ±0.12 m w.e. a^{-1}. For Urumqi Glacier No.1~~UG1~~, we find that the differences between specific net mass balance at individual sites and in situ measured point mass balance at corresponding sites were in the range of 0-0.04 m w.e. with an average value of 0.01 m w.e., namely, the error of spatial interpolation in the measured area is small. Firn basin and glacier tongue terrain of the west branch ~~WB~~ are very steep and the upper eastern elevation of the ~~EB~~ east branch is also precipitous, resulting in no in situ measurements are available in theses inaccessible areas. Therefore the error mainly originates from unmeasured areas (e.g. accumulation areas) but the lack of measured data in the accumulation areas limits us to quantify relevant uncertainties. We conservatively assume that the corresponding uncertainty σ_{extra} was ±0.1 m w.e. a^{-1} (cf. Andreassen et al., 2016).

Taking into account the above-mentioned factors, the uncertainty of the glaciological mass balance σ_{glac} is calculated as:

$$\sigma_{glac} = \sqrt{(\sigma_a^{ice})^2 + (\sigma_a^{firn})^2 + \sigma_c^2 + \sigma_{extra}^2}\,. \quad (10)$$

Resulting values of σ_{glac} are listed in Table 3.

5. Results

5.1. Spatial patterns in TLS-derived surface elevation changes

The high-accuracy and -resolution DEMs allowed a detailed insight into the glacier surface elevation changes. ~~TLS-derived distributed~~ Distributed elevation change~~s~~ patterns ~~of both branches~~ are generally similar ~~in their spatial patterns~~for the four periods~~.~~ , i.e. ~~Strong mass losses visibly occurred across the ablation area,~~ both branches are characterized by a lower-elevation thinning of 1-3.5 m, ~~with smaller lowering to slight thickening~~ elevation changes in the upper-elevation parts are more positive, variations with smaller lowering to pronounced thickening except for west branch in the mass-balance year 2016-17 (Fig. 4a, c, e~~-~~), this altitudinal ~~changing~~ change pattern~~s~~ ~~is~~ are in good agreement with the long-term glaciological measurements. ~~But in the mass-balance year 2016-17, the altitudinal changing pattern of WB was not pronounced (Fig. 5g).~~

Compared to the mass-balance year 2015-16, areas of clearer increase were observed in the upper eastern parts of ~~EB~~ east branch in the ~~second~~ mass-balance year 2016-17~~.~~ , ~~In addition,~~ but ice losses in the lower-elevation parts ~~of WB~~ and glacier thickening in the upper reaches of west branch ~~WB~~ were greater in the first mass balance year (Figs. 5c, g). ~~and surface lowering of EB was more pronounced near the glacier tongue (Fig. 5g)~~. During ~~summer 2015~~summer periods, surface lowering in summer 2015 mainly occurred in the ablation areas of east branch~~EB~~ (Fig. 4a), ~~Glacier~~ and glacier surface ~~elevation changes~~ ablation ~~were~~ was significantly ~~more negative~~greater in summer 2016 than in the first summer~~; clear surface lowering of EB was observed~~ (Fig. 4e). For a completed mass balance year 2015-16, glacier thinning areas and values in summer were obviously bigger than the whole year, which may be related to fresh snow covered the glacier at the beginning of ablation season. In addations, ~~There~~ there ~~are~~ were some curves of pronounced glacier surface lowering in the ablation ~~areas, especially in~~areas during summer periods, which ~~are~~ were related to supraglacial river (Fig. 1c, d)~~. In addition~~, a slight thinning area is detected at the lower lift (northerly) edge of east branch~~EB~~, which may be associated with debris cover (Fig. 1c).

5.2. Glacier-wide elevation and geodetic mass changes

TLS-derived glacier-wide mass balances (Table 3) and their spatial distributions (Fig. 5b, d, f, h) were calculated by multiplying the spatially distributed glacier surface elevation changes (Fig. 4a, c, e, g) with the corresponding distributed density conversion (Fig. 5a, c, e, g). The thicker snow and firn covered ~~most parts of~~ the whole glacier surface at the beginning of ~~the hydrological year~~the beginning of May each ~~, and~~year and the ablation area was bare ice or covered by a thin snow layer at the end of the ablation season according to filed observations (Liu et al., 1997; Xie and Liu, 2010)~~.~~, so the changes in ice and firn/snow thickness are observed during the summer months. However, firn and snow densities are far smaller than glacier ice density, these result in annul single-point density conversion ρ_i is bigger and the glacier-wide annual density conversions were accordingly higher than the summer ones (Table 3). From the density conversions, we can conclude ~~Thus~~ that the summer geodetic mass balance was highly affected by the snow and firn, and the magnitude of the altitudinal variability in the summer mass balance significantly changed when compared to elevation changes (Fig. 4a, c), whereas the spatial distributed patterns between elevation changes and mass balances showed good performances. These suggest that the density conversions vary for all of the studied periods and a constant value used as the conversion is clearly inappropriate. Here in situ measured densities from snow pits improved the accuracy of TLS-derived geodetic mass-balance calculations and therefore provided exceptional level of detail on glacier-wide mass balance.

Urumqi Glacier No.1~~UG1~~ experienced negative surface elevation changes and mass balances for all of the four investigated periods (Table 3). Summer elevation lowering and mass loss were slightly greater than annual decreases, which may be related to the climatic conditions observed at Daxigou Meteorological Station~~DMS~~ (see discussion in Sect. 2). In the mass-balance year 2015-16, calculated glacier-wide geodetic mass balance was -0.72 ± 0.17 m w.e., which was slightly more negative than in the second mass-balance year. Summer and annual mass balances of west branch ~~WB~~ were more negative compared to the corresponding values of east branch~~EB~~, except for summer 2016 when the mass loss of east branch ~~EB~~ was greatest.

5.3. Comparison to in situ glaciological measurements

TLS-derived geodetic elevation changes at individual stakes closely matched the glaciological elevation change (changes in stake height) of individual stakes from in situ measurements and the difference (Δh_{TLS} - Δh_{glac}) in surface elevation changes were close to zero for most of the point measurements (Fig. 4a, c, e, g). The correlation coefficients (R^2) between the glaciological elevation change at the ablation stakes and TLS-derived geodetic elevation change at corresponding points were more than 0.90 (Fig. 4b, d, f, h). Note that the location and number of ablation stakes varied slightly over time due to stake melt-out, ~~in order to objectively assess the accuracy of the geodetic elevation changes,~~ thus we selected the best-monitored single-point results to objectively assess the accuracy of the geodetic elevation changes. The majority of the point elevation changes from TLS measurements were slightly positive compared to the glaciological ones, except for summer 2016. During summer 2016 and mass-balance years 2015-16 and 2016-17, the mean values of Δh_{TLS} - Δh_{glac} were 0.18, 0.25 and 0.14 m, respectively, which are systematically less than the corresponding uncertainties ($\sigma_{\overline{\Delta h \text{TLS}}}$) of the glacier-wide elevation differences.

The varying tendencies of the glaciological mass balances coincided with the geodetic ones (Table 3). In 2016-17, the difference ($\Delta B = B_{\text{glac}} - B_{\text{geod}}$) in glacier-wide mass balances of Urumqi Glacier No.1~~UG1~~ between the ~~two~~ glaciological and geodetic methods was close to zero. ~~Remarkable~~ Significant differences between the two methods were detected in summer 2015 for Urumqi Glacier No.1~~UG1~~ and east branch~~EB~~, with ΔB = -0.24 m w.e. and ΔB = -0.27 m w.e., respectively. In other three periods, the differences ~~between the two methods~~ were much less the uncertainties of ΔB, which were calculated based on the law of error propagation ($\pm\sqrt{\sigma_{\text{geod}}^2 + \sigma_{\text{glac}}^2}$). Overall, the differences of Urumqi Glacier No.1~~UG1~~ were slightly smaller than those of the two branches (Fig. 6). In order to calculate the statistical significance between the two methods and validate the geodetic against the glaciological mass balance, the reduced discrepancy (δ) between the two methods was calculated following Zemp et al. (2013, Eqs. 19-21); the results of δ range from -1.14 to 0.58. As δ falls within the 95% ($|\delta| < 1.96$) and 90% ($|\delta| < 1.64$) confidence interval, good agreement between the glaciological and geodetic methods can be considered as ~~satisfying~~satisfactory.

Spatially distributed differences between glacier-wide glaciological and geodetic mass balances were calculated to ~~know~~ give the spatial deviations. Over most parts of the glacier surface, especially for the areas near the best-monitored points, deviations were small, indicating both methods showed very close spatial results. Pronounced differences mainly occurred ~~at the steep elevations~~on the steep slopes where in situ measurements were missing (Fig. 7a, d, g, j). The mass balance elevation distribution derived from the two methods remained similar despite the presence of differences in magnitude, i.e. mass balance increased with rising altitude (Fig. 7b, c, e, f, h, i, k, m). The geodetic results were more positive in lower-elevation regions and more negative in the higher glacier parts in general compared with the glaciological mass balance~~;~~ , ~~this phenomenon~~ which ~~was~~ were probably related to glacier dynamic processes~~s~~ (discussed in Sect. 6.4). ~~However the glacier dynamic thickening and thinning were tiny since the observed annual vertical ice velocity was small (cf. Beedle et al., 2014, Wang et al., 2017), indicating that the TLS-derived surface-elevation changes captured most of the major changing patterns from the glaciological measurements.~~ The dotted (glaciological) and solid (geodetic) lines met where the glacier mass balances were close to zero; this meant that the equilibrium-line altitudes (ELAs) derived from the two methods matched closely, especially in mass-balance year 2015-16 and summer 2016 (Fig. 7e, f, h, i), but the biggest shift between the two methods was detected in summer 2015 for east branch~~EB~~, which may be related to survey data differences between the glaciological and geodetic observations~~the reasons mentioned~~ (~~in~~ see details in Sect. 6.~~3~~5). This reflects that the TLS can be therefore considered as an effective tool to calculate ELA.

6. Discussion

6.1. The quality of point cloud data and DEM differencing

The important factors for scanning high-quality point cloud data are visual angles of the scan positions and atmospheric conditions. A dry and windless atmosphere is a prerequisite for high-quality data acquisition. Good visual angles can easily be achieved for very small cirque glaciers. Generally, the area and length of reference glaciers are greater, with a huge variation in altitude. The maximum working distance (6 km) of Riegl VZ®-6000 is specified for flat targets with size in excess of the laser beam diameter, perpendicular angle of incidence, and atmospheric visibility in excess of 23 km. In bright sunlight the operational range may be considerably shorter than under an overcast sky (RIEGL Laser Measurement Systems, 2014a). However, glaciers generally have complicated surface terrain and the requirement of perpendicular angle of incidence is not always met, so the unscanned regions usually have flat~~ness or alcove~~ terrain~~s~~ (Fig. 1d). It is very difficult for us to get a dry and windless atmosphere under an overcast sky around a glacier. In these situations, more than one scan position must be set in order to scan as much of the glacier surface area as possible. However, this, in turn, can create errors in data registration. The average error originating in MSA (σ_{MSA}) of the investigated periods was ±0.16 m (Table 2). Actually, σ_{MSA} is highly dependent on the overlap percentage of point clouds from each scan position of the same survey data and the accuracy of global 3-D coordinates of each scan position. In our fieldwork, the overlap percentage of point clouds from the four scan positions was more than 30%, which met the requirements of data registration (CH/Z 3017-2015, 2015). Note that we ~~do~~ did not ~~found that the more scan positions the~~ get better results with more scan positions since this ~~more scan positions will~~would probably decrease the quality of the MSA. We should find the best visual angles to obtain the maximum scan range with the fewest scan positions. Higher elevation favors better angles, but it is not always easy for us to access higher parts and place the instrument. For the ideal distribution, scan positions should be located in different elevation bands and directions (Fig. 1a). In addition we can also mount a steadying bar on a tripod to raise the altitude of the TLS.

Systematic shifts of DEMs in the horizontal and vertical directions can also increase the uncertainty of DEM differencing (Nuth and Kääb, 2011), so multi-temporal registration of two consecutive scan campaigns is predicated on the TLS-derived geodetic elevation changes being accurate. The mean uncertainty of elevation changes was ±0.22 m (Table 2), which was slightly smaller than in the TLS datasets used for other glacier thinning measurements (e.g. López-Moreno et al., 2016). This may be attributable to the use of accurate global 3-D coordinates of each scan positions and a sufficient number of stable terrains (Fig. 3). In addition, fixed scan positions also reduce multi-temporal registration error and enhance the accuracy of glacier-wide elevation changes. So the quality of point cloud data and DEM differencing is encouraging.

6.2. Accuracy of geodetic and glaciological mass balances

It is obvious that the quality of TLS-derived geodetic mass balances relies on the accuracy of glacier surface elevation changes and density conversion of volume to mass changes. With regard to density conversion, our approaches account for the ~~3-D~~ changes ~~of~~ in ice and firn/snow ~~bodies~~ thickness as well as the corresponding densities to calculate more accurate values of density (Table 3). The annual ρ values were in the range of 763-865 kg m^{-3}, which is in line with the average density of 850 ± 60 kg m^{-3} recommended by Huss (2013), whereas, ρ of west branch~~WB~~ declined to 763 kg m^{-3} in the mass-balance year 2015-16, largely because of the presence of fresh snow cover at the time of the glaciological measurements. For the same reason, the summer values concurred with the recommended density. Calculated uncertainties in the geodetic mass balances ranged from ±0.13 to ±0.20 m w.e., with an average value of ±0.16 m w.e. for the investigated periods (Table 3) and were slightly greater than other geodetic mass balance measured base on the same TLS device (e.g. Fischer et al., 2016), which may be related to multiple scan positions and a larger scanning range, but smaller than those derived from remote sensing imagery (e.g. Holzer et al., 2015; Barandun et al., 2018).

Dense spatially measured sites cover the glacier surface (the average density is about 28 stakes km-2 from 2015 to 2017), except for the inaccessible areas (Fig. 1a), to measure the glaciological mass balance. The mean uncertainty of σ_{glac} was ±0.12 m w.e. and mainly originated from spatial extrapolation of point measurements. This value is smaller than most recent studies (e.g. Andreassen et al., 2016; Thomson et al., 2017; Klug et al., 2018). This is probably due to relative smaller area and accompanying higher density of point measurements of Urumqi Glacier No.1~~UG1~~ than aforementioned ~~glaciers~~ studies (Fig. 1a). Thus the TLS device yields accurate geodetic results and the quality of the glaciological mass balances is also very good. Nonetheless, uncertainties in field measurements and interpolation can potentially contribute the deviations between glaciological and geodetic mass balances. The obvious deviations in the spatial distributed differences were found at the firn basin of west branch ~~WB~~ and the upper right edge elevations of east branch~~EB~~, two ~~artefacts~~ unscanned areas also present big deviations (Fig. 7a, d, g, j). Remarkable differences of east branch ~~EB~~ in summer 2015 induce poorest match between glaciological and geodetic mass balance elevation distribution (Fig. 7c), this can be explained by the lack of well-measured point data (Fig. 7a).

6.3. The influence of internal and basal mass balances

The glaciological method cannot measure internal and basal mass balances, but these processes are implicitly captured by the repeated geodetic surveys. We need to provide a rough estimate of internal and basal mass balances of Urumqi Glacier No.1~~UG1~~ to detect their contributions to the differences between glaciological and geodetic mass balances.

Urumqi Glacier No.1~~UG1~~ is a small and cold glacier, basal sliding and bed deformation of the glacier are negligible since ice temperature of the glacier bed has not reached the melting point, so the glacier has low ice velocity and dynamics, and hardly any subglacial water systems (Huang, 1999; Xie and Liu, 2010; Wang et a., 2017). Previous studies have suggested that internal ablation of poly-thermal glaciers is negligible as the ice motion is small (e.g. Albrecht et al., 2000; Zemp et al., 2010). Besides internal melt due to the potential energy of glacier dynamics is negligible since the low reduced dynamics. Thus, internal ablation of Urumqi Glacier No.1 is weak~~and its internal ablation (B_{pe}) is weak (Huang, 1999; Albrecht et al., 2000)~~, and mainly comes from ~~because of~~ the released potential energy of descending water:

$$B_{pe} = \frac{Q_m g}{L_f \bar{s} \rho_{water}} \cdot \frac{\bar{h}_{ELA} - h_{term}}{2}, \tag{11}$$

where Q_m denotes annual discharge of flowing water, g is the gravitational acceleration, L_f is the latent heat of fusion~~,~~. Glacier mass loss mainly comes from ablation area and we assume meltwater originates at half the vertical from the glacier terminus to the ELA, so $\bar{h}_{ELA}$ and h_{term} are average equilibrium-line altitude (ELA) (4152 m) and the altitude of the glacier terminus (3775 m), respectively, $\bar{s}$ is the average glacier area between 2015 and 2017. The cumulative measured glacier surface ablation over the two years was used to determine annual discharge and the value of Q_m was estimated to be about 1.4×10^9 kg a^{-1}. A calculation of B_{pe} = -0.005 m w.e. a^{-1} is made. Internal accumulation results from refreezing percolating water or the freezing of capillary-trapped water in cold snow and firn, which plays a significant role in cold and continental climates ,such as Storglacären, Sweden (Zemp et al., 2010) and Castle Creek Glacier, Canada (Beedle et al., 2014), Urumqi Glacier No.1 is a clod, continental glacier in a continental climate setting (Liu and Han, 1992; Li et al., 2011), Urumqi Glacier No.1 is a clod, continental glacier in a continental climate setting (Liu and Han, 1992; Li et al., 2011), measurement and studies on internal accumulation of the is still blank, so we conservatively estimate internal accumulation to be about 4% of the winter mass balance and the resulting value was about 0.01 m w.e. a^{-1}. Final calculated internal mass balance of Urumqi Glacier No.1was about 0.005 m w.e. a^{-1}.

Basal ablation is generally attributed to frictional heat of basal sliding and ~~from~~ geothermal heating for mountain glaciers (Thibert et al., 2008; Thomson et al., 2017; Galos et al., 2017). Basal ablation caused by frictional heat is very small since hardly any basal sliding of Urumqi Glacier No.1. Here we mainly consider the contribution of basal ablation from geothermal heat (B_{gt}), which was ~~evaluated~~ estimated using

$$B_{gt} = \frac{qt}{L_f \rho_{water}}, \tag{12}$$

where q = 0.059 W m^{-2} is the geothermal heat flux (Huang, 1999), t is the mass-balance period; here we primarily consider annual scale and basal ablation was estimated to be about 0.005 m w.e. a^{-1}. The calculated internal and basal ablation totaled -0.01 m w.e. a^{-1}.

~~We assessed internal accumulation dominated by refreezing percolating water in the cold interior of the glacier as well as the freezing of water in cold snow and firn following Zemp et al. (2010), who assumed that internal accumulation was 4% of the winter mass balance, and the resulting value was about 0.01 m w.e. a^{-1} in this study.~~ Finally the total value of internal and basal mass balances was close to zero, which is far less than the difference (ΔB) between the two methods. This suggests that the contribution of annual internal and basal processes is negligible and does not affect the differences between the two methods.

6.4. Glacier vertical velocity component

Geodetic measurements of glacier surface elevation changes include glacier surface mass balance and vertical velocity component (Kaser et al., 2003; Geist et al., 2005). Vertical velocity (w_s) is downward (submergence) and makes dynamic thinning of Urumqi Glacier No.1 in the accumulation area, and in the ablation area, vertical velocity is upward (emergence) and makes dynamic thickening of the glacier. This dynamic process results in the general difference between the elevation-distributed mass changes stated above (Fig. 8). To discuss the influences of vertical velocity component, here w_s depends on the kinematic boundary condition at Urumqi Glacier No.1 surface as basal sliding and bed deformation of the glacier are negligible (cf. Petterson et al., 2007; Cuffey and Paterson 2010)

$$\dot{h} = \frac{\dot{b}}{\rho} + w_s - u_s\frac{\partial s}{\partial x} - v_s\frac{\partial s}{\partial y} \qquad (13)$$

in which $\dot{h}$ is the rate of glacier surface elevation changes, u_s and v_s are the components of horizontal ice velocity at the glacier surface s, respectively (Cuffey and Paterson 2010). We neglect the advection of the glacier surface topography induced by horizontal ice flux since the low reduced horizontal velocity (Wang et al., 2017) and short time intervals of this study. Then changes in $\dot{h}$ equals the sum of $\frac{\dot{b}}{\rho}$ and w_s, can be expressed as (Beedle et al., 2014)

$$\dot{h}\rho - \dot{b} = w_s\rho \qquad (14)$$

Glacier dynamic thinning and thickening can be detected by subtracting the glaciological mass balances from the geodetic ones. For most of the study periods, positive difference values (thickening) dominate in the lower elevations, especially the glacier tongue, and negative difference values (thinning) mainly occur in the higher parts (Fig. 7a, d, g, j). Positive values across the east branch in summer 2015 may be related to different survey dates between the geodetic and glaciological methods.

Now applying reciprocal density conversion to the mass balance differences estimate the submergence and emergence velocities. Here we defined the term submergence is negative vertical velocity and emergence is positive vertical velocity. Variation tendency of the estimated velocities at ablation stakes were found to match from in situ measured ones, especially for east branch (Fig. 8). Relative bigger differences of west branch were detected in the mass balance years 2016-17 (Fig. 8b, d), which may duo to an avalanche in the upper part during the summer 2017. The firn basin terrain of west branch is very steep and is adverse to mass accumulation, which can also be validated in terms of TLS-derived glacier surface elevation changes (Fig. 4g). Thus pronounced misalign of mass balance elevation distribution curves between the two methods occurred. Considering the errors of estimate and in situ measurements, submergence and emergence velocities can be estimated using the TLS-derived DEMs and glaciological mass balance. The difference in mass balance elevation distribution can be largely explained by glacier dynamic thinning at higher elevations and dynamic thickening at lower elevations.

In fact, the vertical velocity of Urumqi Glacier No.1 is small (Fig. 8), we now discuss the errors of glacier surface elevation changes versus dynamic thinning and thickening. Differences in glacier surface elevation changes derived from the TLS and glaciological measurements were close to zero for the vast majority of the ablation stakes, and corresponding errors in the differences were mostly larger than the difference themselves (Fig. 9). Compared with the errors of measurements, dynamic thinning and thickening of the glacier were minor and negligible. So Riegl VZ®-6000 TLS can be considered as an effective tool to measure the mass balance of Urumqi Glacier No.1

6.45. Meteorological and glacier surface terrain considerations

Despite glacier thinning and thickening were negligible, other factors such as meteorological conditions and glacier surface terrain may cause mass balance differences between the two methods. Figure 9 shows daily meteorological records provided by Daxigou Meteorological StationDMS from 25 April 2015 to 28 August 2017. Positive temperature and more than 75% of the annual total precipitation amount occurred simultaneously during the summer months; this probably resulted in summer mass balances that were slightly more negative than annual ones (Table 3). Although the observed reduced discrepancies are relatively small between TLS-derived geodetic and glaciological mass balances fall within the 95%, relative bigger difference (ΔB) between the two datasets is detectable for east branch, the above-mentioned differences in summer 2015 had not been statistically identified. One possible reason and the difference is caused by survey data differences. the presence of fresh snow cover at the time of TLS surveys according to field observation. The glaciological measurements of east branch EB were performed five days before the TLS surveys (28 August-2 September 2015). The total precipitation was 67 mm and daily mean temperatures were close to zero (Fig. 9), besides the daily minimum temperatures were all below 0°C during the five days. The climatic conditions may be responsible for the larger mass-balance differences of east branchEB. In addition, light snow occurred on the eve ofbefore the latest last TLS surveys (28 August 2017), possibly resulting in the noticeable increase in the upper eastern parts of east branch EB (Fig. 5h).

The differences in mass balance between the two methods were possibly related to the effect of glacier surface terrain. The presence of two minimal unscanned areas artefacts in TLS surveys is due to the flat terrain of west branchWB surface (two green polygons in Fig. 5). The geodetic mass-balance calculations did not include these artefactsunscanned areas; this cloud potentially increased the difference between the two methods. Furthermore, these undetected regions located in the ablation area and higher wastage than the surroundings were observed according to glaciological measurements. This may imply that the geodetic mass balances of west branch WB were more positive than the glaciological ones (Table 3) and a discrepancy in mass balance elevation distributions of west branch WB were observed at 4000-4150 m a.s.l. Nevertheless, the geodetic method is able to cover the majority of the glacier surface and take the terrain characteristics into account, whereas the glaciological measurements cannot capture all the topographic features despite a dense spatial coverage of in situ observations being applied, and what's more, in situ observations are missing in the firn basin and glacier tongue terrain of west branchWB and eastern elevations of east branch EB because of the presence of precipitous terrains in these inaccessible regions (green color in Fig. 11a). The eastern elevations of east branch EB were are dominated by the northwest aspect, and the firn basin had have aspects from north to northwest (Fig. 11b), aspects that were are likely to influence the glacier surface albedo and thereby control the surface change patterns (cf. Yue et al., 2017).

6.~~5~~6. Potential of the long-range TLS applied in glacier mass balance monitoring

This study presents the application of multi-temporal Riegl VZ®-6000 TLS point clouds in mass balance monitoring of Urumqi Glacier No.1~~UG1~~. The long-range TLS can provide high-temporal-spatial-resolution and -accuracy DEMs to allow more detailed insight into glacier evolution (e.g. Gabbud et al., 2015). To take advantage of this and provide more-precise glacier surface elevation changes, it is worth remembering that fixed scan positions are highly important between consecutive scans when using our approach. We should also note that not all glaciers in China are as easily accessible as Urumqi Glacier No.1~~UG1~~. For many large glaciers, it is not always easy to fix scan positions using reinforced concrete with a standard GNSS-leveling point, but we can mark stable bedrock outcrop as a scan site. Another advantage of this type of TLS is the long scanning range, and such an instrument could allow most of the glacier surface to be scanned from one or several scan positions, especially for remote and inaccessible glacier areas (e.g. crevasses, steep ice, debris cover, etc.). Therefore the instrument provides a quantitative evolution in spatial coverage compared to glaciological in situ measurements, which can be seen as a beneficial complement to glaciological mass balance, particularly for calibrating inaccessible areas. TLS surveys can also provide updated glacier boundary and surface DEMs.~~,~~ In addition, we can paste several retro-reflective targets (e.g. reflective foils, corner cube reflectors and retro-reflective paintings) to the surface of each stakes and the targets can be easily surveyed and identified since each of them has a high directivity of the reflected laser radiation, then the location of stakes be determined.~~and the location of stakes may also be identified based on high-quality point clouds; all~~ All of these parameters are favorable for glaciological mass-balance calculations. A combination of glaciological and TLS observations may yield optimum results. ~~Besides,~~ TLS-derived geodetic results can validate the distributed glacier mass-balance models as the TLS can provide high spatial and temporal resolution measurements, especially in the strong ablation season, the instrument can be used to investigate daily or sub-daily ablation (e.g. Haut Glacier d'Arolla, Switzerland; Gabbud et al., 2015), which can completely meet the requirements of time resolution for glacier mass-balance models.

One drawback of the TLS surveys is the presence of data voids (unscanned areas), even for very small glaciers (e.g. Fischer et al., 2016). This is due to limited scanning angle and complex glacial terrain. An emerging low-cost Unmanned Aerial Vehicles (UAV) has the potential to avoid data voids in glaciological monitoring since the good surveying angle of UAV. Immerzeel et al. (2014) showed that UAV combined with a Structure from Motion (SFM) workflow provide a powerful tool for monitoring mass balance and surface velocity of a Himalayan glacier with high spatial accuracy. From our field experiment at Urumqi Glacier No.1~~UG1~~, rarefied air and frequent blustery wind around glaciers usually induce the power of UAV were nondurable, and rock outcrops results in difficult operations of such instrument. Hence we mainly consider using UAV to survey unscanned area ., integrating of UAV- and TLS-acquired data can provide the whole glacier surface terrain of interest. Other technology such as terrestrial photogrammetry also has the ability to estimate mass balance, and the quality of photogrammetric estimation is similar to the quality of TLS (e.g. Piermattei et al., 2015; Fugazza et al., 2018). However, the reliable of UAV and terrestrial photogrammetry in glacial environments is more dependent on the natural features (i.e. characteristic image objects) of the surveyed surfaces compared with TLS. The cost of TLS is higher than UAV and ground-based photogrammetric surveys.

~~Now the TLS has been successfully applied to monitor mass balance of UG1.~~ From our experience, the monitoring tool is potentially applicable to other glaciers provided that these glaciers have small to medium size and relative steep terrain. ~~High Mountain Asia (HMA) contains the largest number of glaciers outsides the polar regions (Pfeffer et al., 2014). China is the main region of HMA, most glaciers (~~According to the second Chinese glacier inventory (Guo et al., 2015),~83% and ~70% of the total ~~number)~~ number of glaciers in ~~western~~ China ~~have~~has an area smaller than1 km^2 and 0.5 km^2, respectively, and only ~3% with an area lager than 5 km^2. Riegl VZ®-6000 TLS has been proved successful in monitoring mass balance of very small glaciers (area smaller than 0.5 km^2) in the Swiss Alps (Fischer et al., 2016). ThereforeHence, the majority number of glaciers can be theoretically measured using the TLS. Furthermore, if we assume that these glaciers with an area of ≤ 1.555 1.6 km^2 (approximate area of Urumqi Glacier No.1UG1) and a mean surface slope greater than 23.4° (slope of Urumqi Glacier No.1) have a good visibility to be monitored using the TLS, the number proportion of theoretical appropriate glaciers is ~58.5% ,which of the total and these glaciers are evenly distributed at different mountains (Fig. 12). We note that itHowever, it is not always easy for us to monitor all of the appropriate glaciers as some of them locate in remote areas (i.e. far away from road),. now we have selectedWe can select some benchmark glaciers with easily accessible locations for future application of TLS measurements, the TLS system is therefore has huge application potentiality for glacier mass-balance monitoring in China.such as Kanas Glacier, Muztaw Glacier, Qingbingtan Glacier No.72, Haxilegen Glacier No. 51, Yushugou Glacier, Laohugou Glacier No.12, Qiyi Glacier, Xiao Dongkemadi Glacier, Parlung No.94 Glacier and Baishui Glacier No.1, etc. All of these benchmark glaciers have a relatively high ratio of visibility (most part of the benchmark glaciers surface can be scanned from several possible scan positions) according to our previous filed observations. What's more, these glaciers have different areas (small, medium and large size), different types (clod and temperature; summer-accumulation-type and spring-accumulation-type) and evenly locate at different regions of western China. Measuring mass balance of different sized, typed, and located glaciers is relevant for us to understand them to past, present, and future climate changes. So the TLS system has huge application potential for glacier mass-balance monitoring in China.

Nevertheless, TLS measurements and point cloud data post-processing are challenges for a broader application. One disadvantage of the TLS is that it requires specific knowledge, skills and experience for its use and data processing. Other limitations of the TLS are related to suitable scan positions for obtaining good visual angles of the glacier surface and stable scan positions for multi-temporal registration of repeated scans for change detection. In addition, the uncertainties of density conversion still remain at seasonal and annul scales as in situ measured densities of all benchmark sites are difficult to obtain (very sparse glaciers in China have such detailed observations as Urumqi Glacier No.1UG1). The day when relatively smaller amount of snow on the accumulation area and the absence of snow on the ablation area (i.e. snow line is clearly distinguished) should be chosen to perform TLS measurements. We may use a built-in camera of the TLS to create high resolution panorama images of a glacier (RIEGL Laser Measurement Systems, 2014a), then firn/snow and bare ice areas (i.e. snow line) can be determined (e.g. Barandun et al., 2018). Area-weighting approach can be used to estimate a density because the lack of in situ measured densities makes volume-weighting approach difficult to extensively use. For longer time intervals (≥ 5 years), aA density assumption over time intervals (≥5 years) based on physical models is also important since as most glaciers in northwest China are cold and multi-thermal.

7. Conclusions

Urumqi Glacier No.1UG1 is one of the reference glaciers in the WGMS network, a representative glacier in Central Asia and the best-monitored glacier in China. Here, for the first time, we have presented the potential of a novel long-range TLS to monitor summer and annual geodetic mass balances of Urumqi Glacier No.1UG1. The Riegl VZ®-6000 TLS has long scan range up to 6 km and is exceptionally well suited for measuring snowy and icy terrains in glacier mapping. We use TLS-derived DEMs to calculate summer and annual surface elevation changes and geodetic mass balances of the glacier for two consecutive years (2015-17) as well as to delineate accurate glacier boundaries.

Our analysis suggests that Urumqi Glacier No.1~~UG1~~ has experienced pronounced thinning and mass loss for the four investigated periods. Glacier surface elevation lowering and mass loss during the summer were slightly greater than annual values. Glacier-wide geodetic mass balance in the mass-balance year 2015-16 was -0.72 ±0.19 m w.e., which is slightly more negative than in the second mass-balance year. The majority of TLS-derived geodetic elevation changes at individual stakes were slightly positive, but insignificant compared to the glaciological elevation change (changes in exposed stake height) of individual stakes ($R^2 \geq 0.90$). The difference in glacier-wide mass balances of Urumqi Glacier No.1~~UG1~~ between the two methods was close to zero in 2016-17 but relatively larger differences were detected in summer 2015 for the whole ~~UG1 and~~glacier and east branch~~EB~~, which were related to the presence of fresh snow at the time of TLS surveys. Statistical analysis shows that agreement between the glaciological and geodetic methods can be considered as satisfying. Pronounced differences in spatial distributed mass balance mainly occurred at the steep elevations where in situ measurements were missing, which potentially induce the deviations in mass balance elevation distribution.

Despite uncertainties inherent in TLS-derived geodetic mass balances, our results show that the TLS device yields reliable results and is therefore well suited to the study of~~ reference glaciers such as~~ Urumqi Glacier No.1~~UG1~~ since the observed vertical velocity component is small~~,~~. What's ~~which~~ more, the TLS can provide accurate and detailed information on glacier area and mass balance changes~~.~~, ~~Its~~ its temporal-spatial resolution allows more detailed insight into the glacier's evolution. The greatest strength of the TLS is the long-range scanning which allows most of the glacier surface to be measured, including areas that are inaccessible for in situ measurements. Use of the TLS-based geodetic method will be an important development since it is clearly a beneficial complement to direct glaciological mass balance, particularly for calibrating the unmeasured areas and validating the distributed glacier mass-balance models. A combination of glaciological and TLS observations may yield the optimum results. What's more, the TLS has application potential for glacier mass-balance monitoring in western China as most glaciers (~83% of the total number) have an area smaller than1 km^2. For a ~~broader~~ wide application of the long-range TLS, we can select some benchmark glaciers with easily accessible locations for TLS measurements, but the presence of data voids and snow is still an enormous challenge, the quality of point cloud and DEM differencing and density conversion over short time ~~periods~~ intervals should be considered.

Data availability. Glaciological mass balance data related to this study are submitted to the WGMS and will be available at website: http://wgms.ch/. TLS point cloud data are available upon request by email to the corresponding author.

Competing interests. The authors declare that no competing interests are present.

Acknowledgements. This work was supported by the Strategic Priority Research Program of the Chinese Academy of Sciences (class A) (XDA20060201), State Key Laboratory of Cryospheric Science (SKLCS-ZZ-2018), the National Natural Science Foundation of China (41721091), Key Research Program of Frontier Sciences of Chinese Academy of Sciences (No.QYZDB-SSW-SYS024). We thank the Tien Shan Glaciological Station for the continuous field observations.

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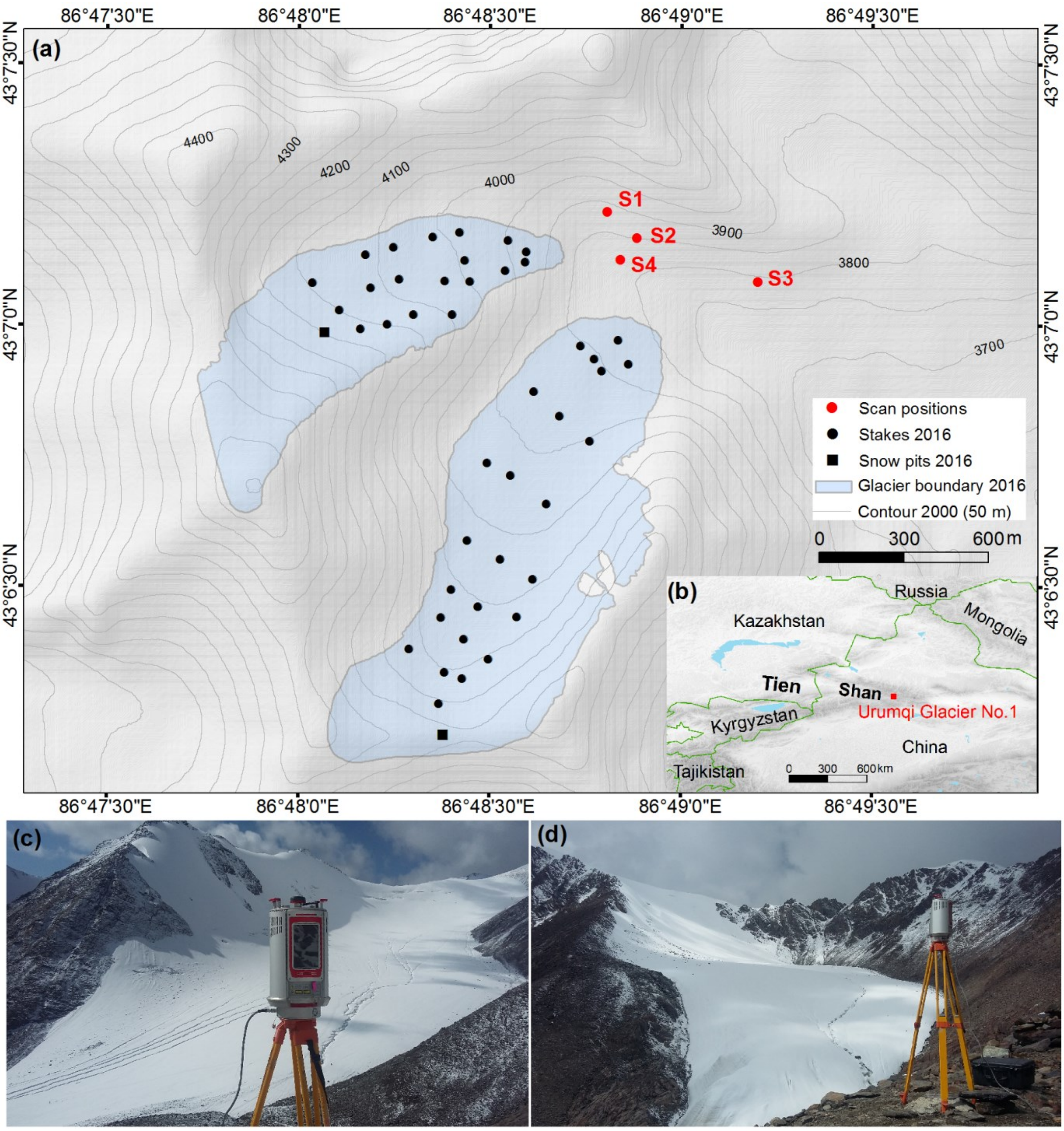

Figure 1. Overview of the study area. (a) The glaciological mass balance measuring network in 2016; glacier boundary delineated from TLS-derived DEM (1 September 2016). Also depicted are the locations of four scan positions. (b) Location map of Urumqi Glacier No.1UG1 in eastern Tien Shan. (c) Riegl VZ®-6000 TLS survey of EB east branch at scan position S2 and (d) TLS survey of west branchWB at scan position S1 (27 August 2017).

Figure 2. TLS observables and direct georeferencing (after Lichti et al., 2005).

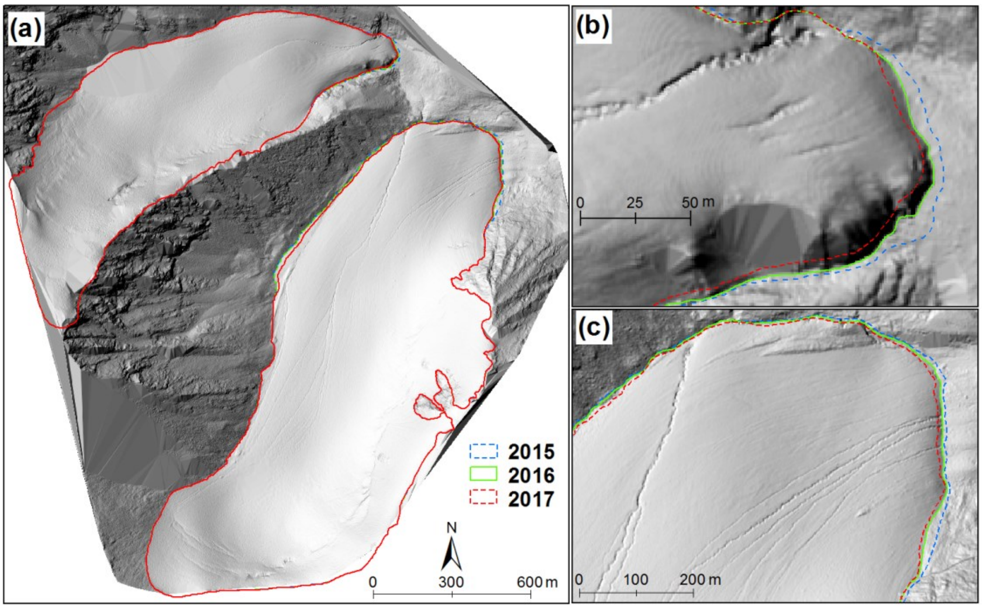

Figure ~~3~~2. (a) Shaded reliefs of Urumqi Glacier No.1~~UG1~~ margin calculated based on the TLS-derived DEM (on 1 September 2016) with the glacier boundary 2015 (blue), 2016 (red) and 2017 (green). Glacier terminus variations of ~~WB~~ west branch (b) and ~~EB~~ east branch (c) are also shown.

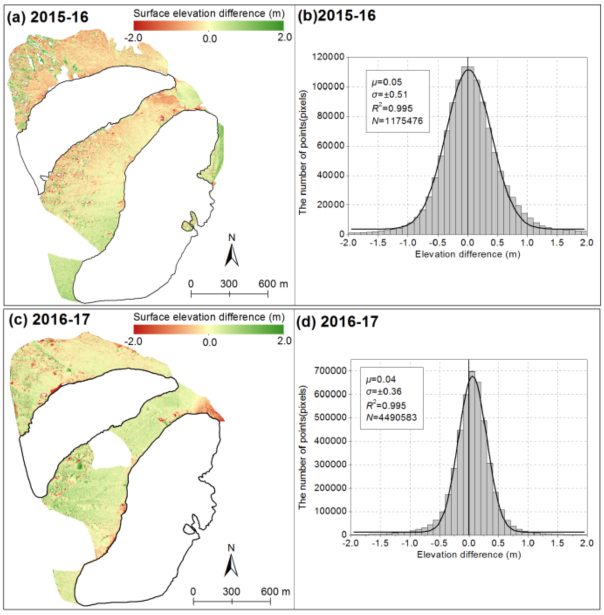

Figure ~~4~~3. Statistics on annual surface elevation changes over stable terrain extracted by differencing of TLS-derived DEMs from two consecutive years. Spatial and corresponding frequency distributions of these changes for mass balance year 2015-16 (a, b) ~~and~~ , and 2016-17 (c, d). The median (μ) and the standard deviation (σ) of the elevation differences, as well as the number of pixels (N) off glacier are given.

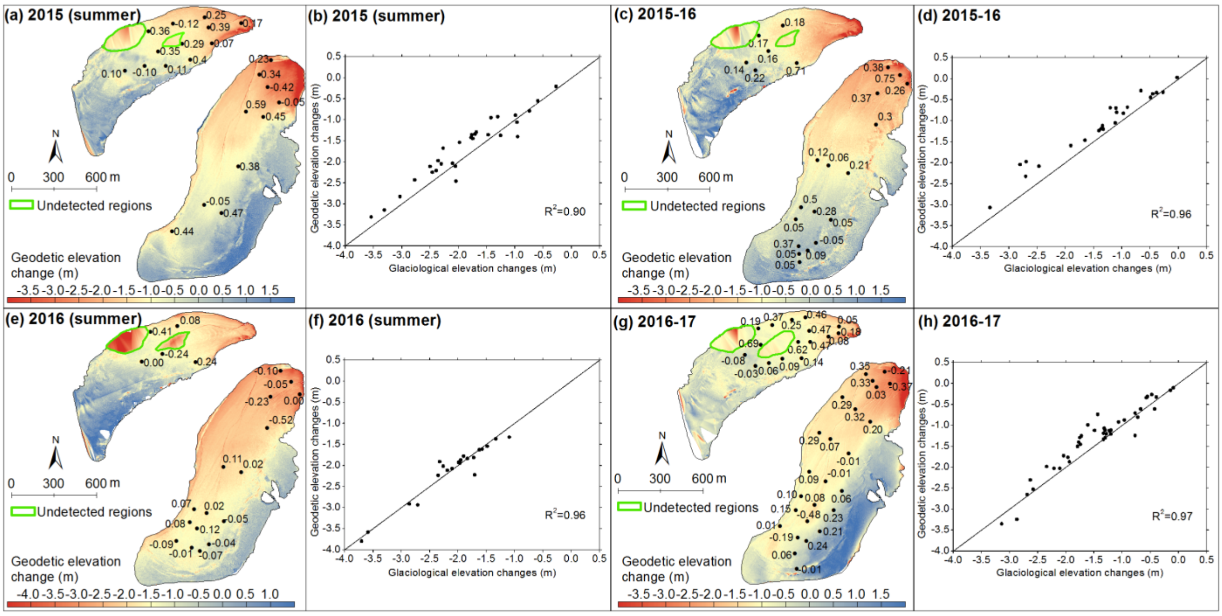

Figure ~~5~~4. Spatial distribution of TLS-derived glacier surface elevation changes (a, c, e and g); the numbers represent the differences (~~the unit is~~in m) between the TLS-derived (Δh_{TLS}) and glaciological in situ measured (Δh_{glac}) elevation changes at corresponding ablation stakes (Δh_{TLS} - Δh_{glac}). Scatter plots of glaciological elevation change against geodetic elevation change at corresponding ablation stakes are presented, and the quality of fittings in terms of R^2 is also presented (b, d, f and h). Black lines are TLS-derived glacier boundary of Urumqi Glacier No.1~~UG1~~ and same as the corresponding boundary of Figure 3. White areas indicate outliers, which we have deleted. Two green polygons indicate ~~artefacts~~ areas that have not been detected by the TLS.

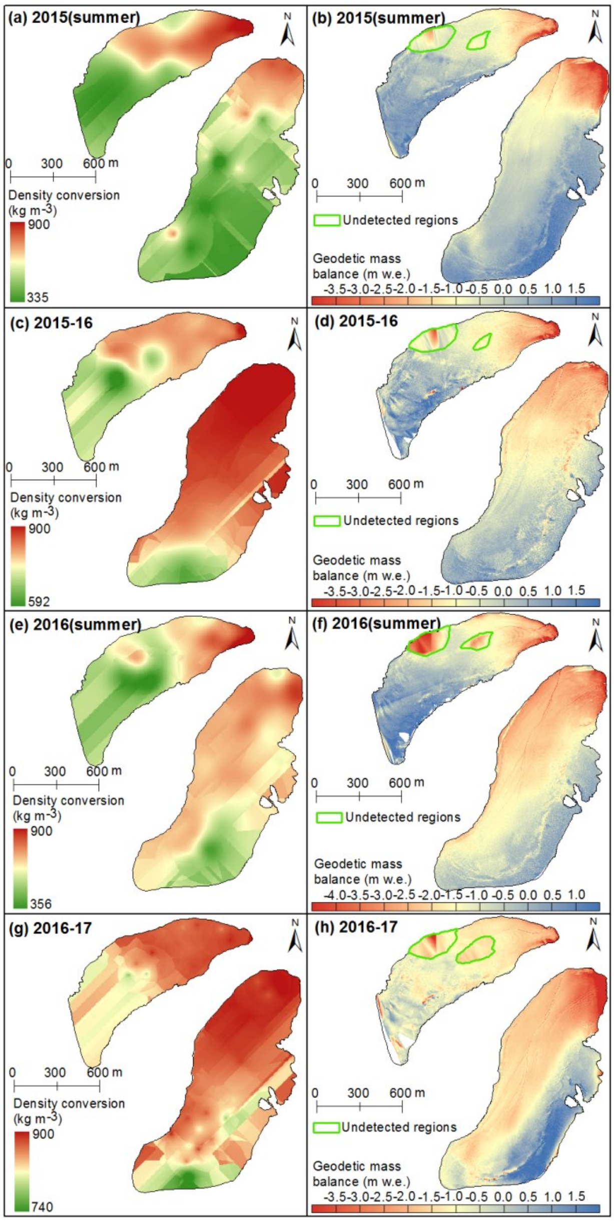

Figure ~~6~~5. Distributed density conversions (a, c, e and g) and corresponding glacier-wide geodetic mass balance (b, d, f and h). Two green polygons indicate ~~artefacts~~ areas that have not been detected by the TLS. ~~Black lines are same as the corresponding boundary of Figure 3.~~Here, glacier boundaries in (a) and (b) are same as boundary 2015 of fugure3, glacier boundaries in (c), (d), (e) and (f) are same as boundary 2016 of fugure3, glacier boundaries in (g) and (h) are same as boundary 2017 of fugure3.

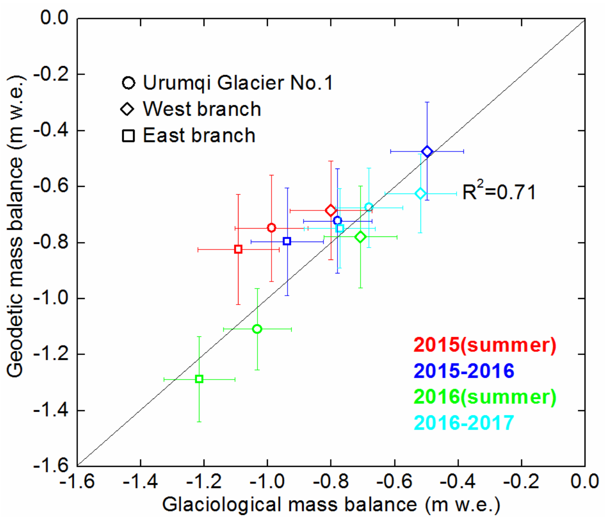

Figure ~~7~~6. Glaciological versus TLS-derived geodetic mass balances for Urumqi Glacier No.1 ~~(UG1)~~, the west branch ~~(WB)~~ and the east branch ~~(EB)~~, with errors bars for two independent methods.

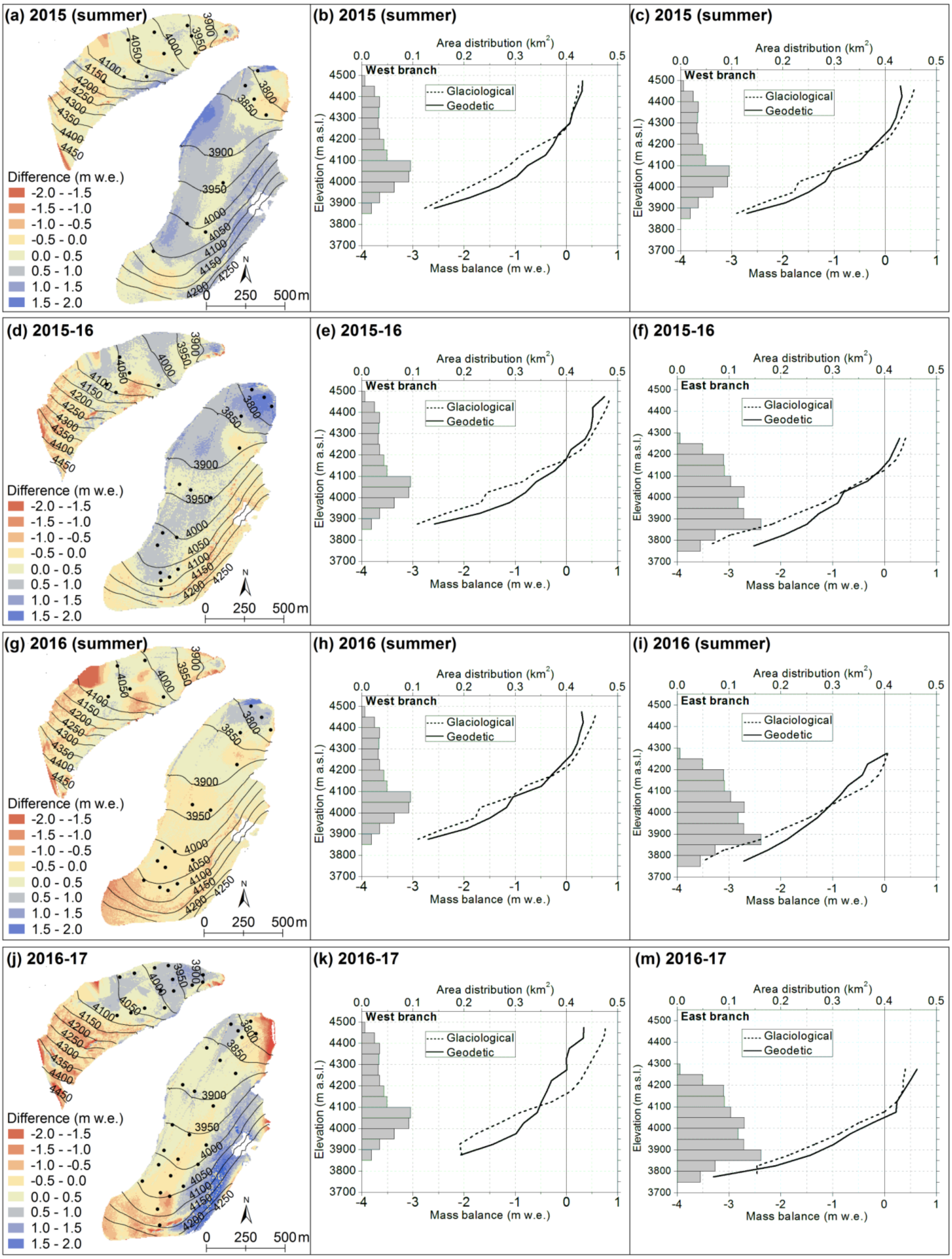

Figure ~~8~~7. Spatial distributed difference derived from TLS-derived geodetic mass balance minus glaciological mass balance (a, d, g and j), black dots represent the location of well-measured ablation stakes, which are same as Figure 5. The hypsometry (50 m altitudinal ranges) and the glaciological (dotted line) and geodetic (solid line) mass balance elevation distribution for the whole study period; both summer and annual mass balances are shown. Gray horizontal bars indicate the area-elevation distribution of ~~UG1~~Urumqi Glacier No.1. Note that the spatial resolution of glacier-wide geodetic mass balance in summer 2015 and 2016 was down-scaled to 5 m, in mass-balance years 2015-16 and 2016-17 was down-scaled to 7 m to coincide with glaciological glacier-wide mass balance.

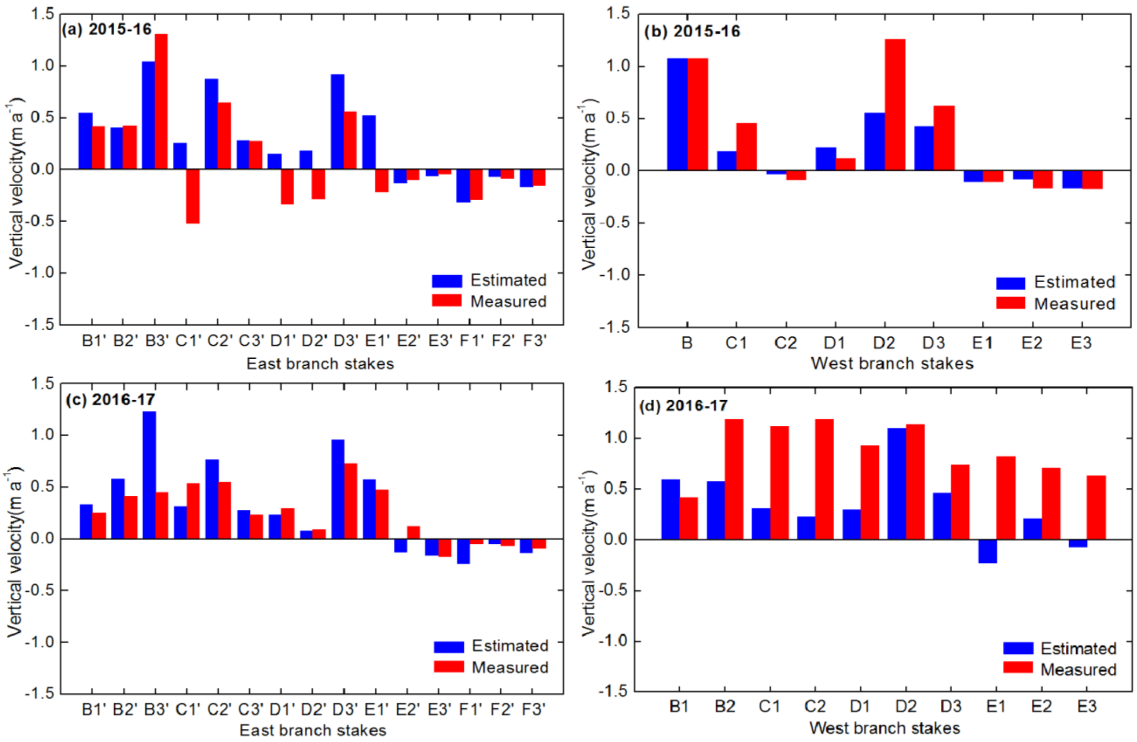

Figure 8. Comparison between estimated and in situ measured vertical velocity for the mass balance year 2015-16 and 2016-17; the letters represent ablation stakes. Note than the summer periods and stakes in the higher elevations were not selected for comparisons due to snow cover reduced the quality of in situ measured vertical velocity.

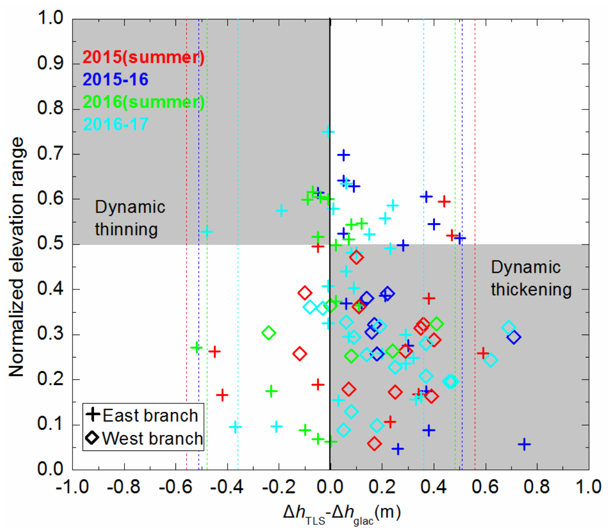

Figure 9. Changing differences between TLS-derived (Δh_{TLS}) and glaciological (Δh_{glac}) annual and summer surface elevation changes at individual stakes versus normalized glacier elevation range of east branch and west for the four investigated periods. Note than dash vertical lines represents the uncertainty ranges ($\sqrt{\sigma_{\Delta h\mathrm{TLS}}^2 + (\sigma_a^{\mathrm{ice}})^2 + (\sigma_a^{\mathrm{firn}})^2}$) of the changing differences ($\Delta h_{\mathrm{TLS}} - \Delta h_{\mathrm{glac}}$), and grey quadrants indicate theoretical areas for Urumqi Glacier No.1 in equilibrium.

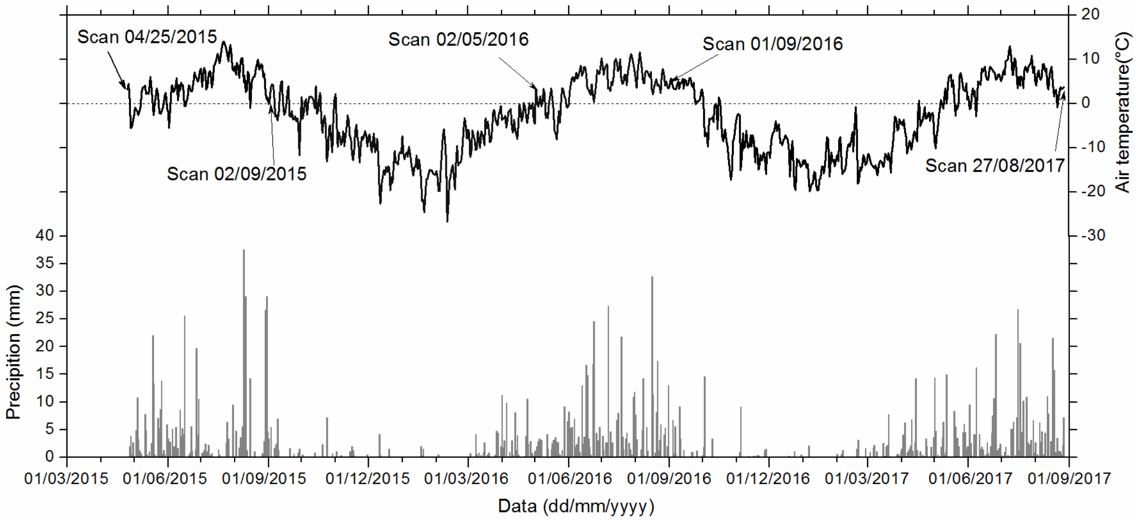

Figure ~~9~~10. Daily precipitation and mean temperature observed at ~~the~~ Daxigou Meteorological Station ~~DMS~~ during 25 April 2015 - 28 August 2017.

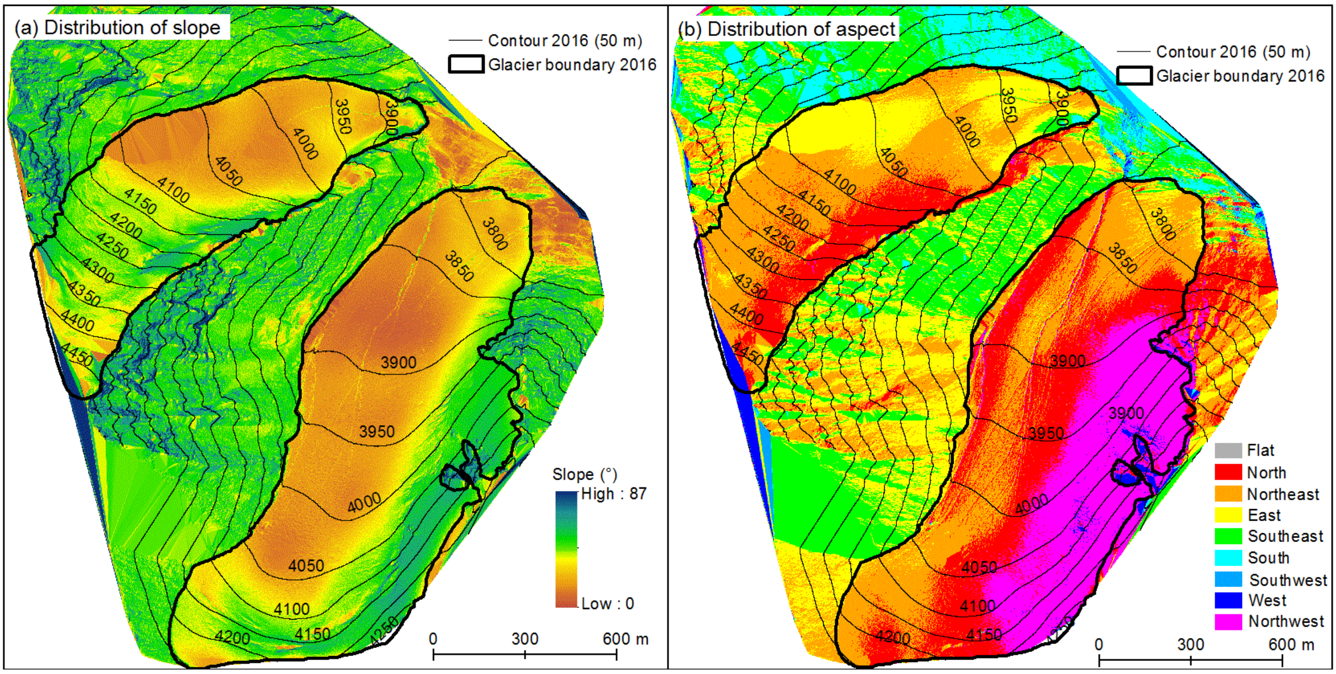

Figure ~~10~~11. Spatial distributed slope (a) and aspect (b) of Urumqi Glacier No.1~~UG1~~ extracted from TLS-derived DEM on 1 September 2016.

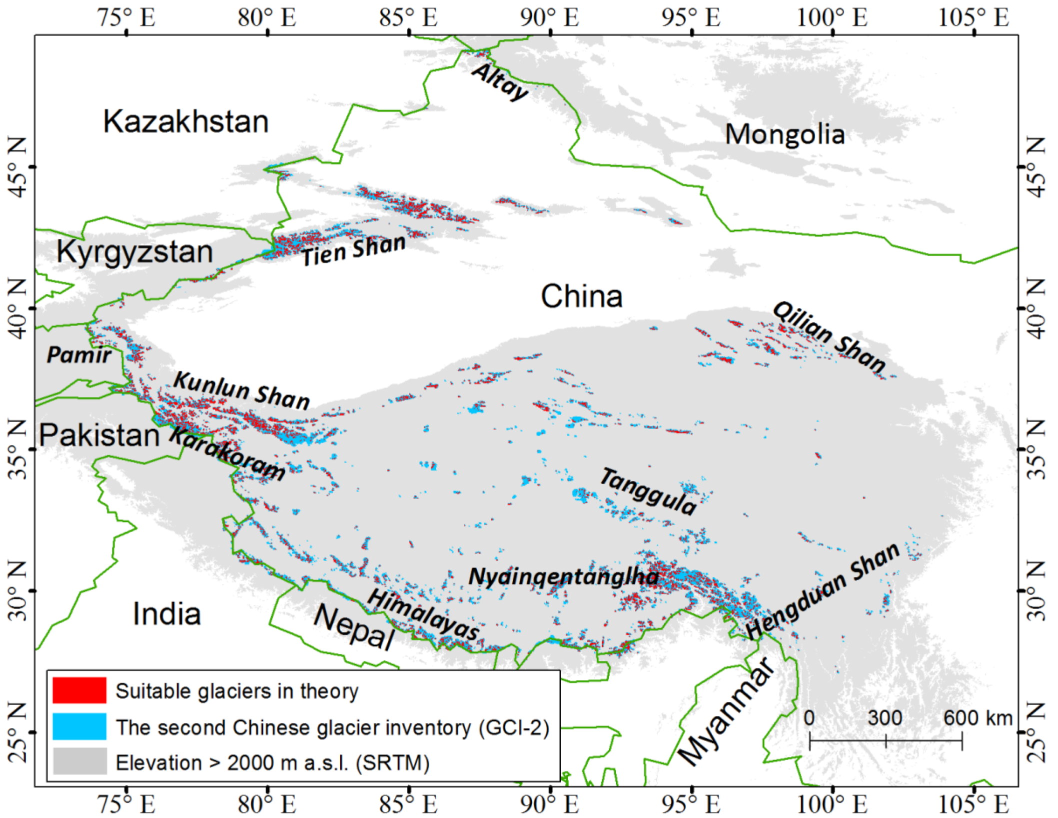

Figure ~~11~~12. Spatial distribution of suitable glaciers in theory, those glaciers with an area of ≤ ~~1.555~~1.6 km^2 (area of ~~UG1~~Urumqi Glacier No.1) and a surface slope greater than 23.4° (mean slope of ~~UG1~~Urumqi Glacier No.1) have huge potential to be monitored using the TLS.

Table 1. Riegl VZ®-6000 TLS surveying parameters of Urumqi Glacier No.1~~UG1~~.

Date (dd/mm/yyyy)	Scanning range* (with overlap) (m^2)	Number of points	Average point density (points m^{-2})	Vertical angle resolution (°)	horizontal angle resolution (°)	Total scan time (min)
25/04/2015	3 204 684	12 740 500	3.98	0.020	0.020	46
02/09/2015	4 707 863	65 500 749	13.91	0.019/0.046	0.019/0.046	103
02/05/2016	3 224 285	26 908 210	8.35	0.020	0.020	82
01/09/2016	3 316 262	42 354 299	12.77	0.020	0.020	101
27/08/2017	3 161 489	54 835 821	17.34	0.020	0.020	88

*Scanning range is the total areas of four scan positions and does not include overlapped areas. The overlap percentage of the four scans on 25 April 2015 is smaller than other scan campaigns so that the average point density is relatively low.

Table 2. Error or StdDev (σ_{MSA})~~ (in m)~~ of Multi-Station Adjustment (MSA) and the number of points (n) used for multi-temporal registration of two consecutive campaigns~~.~~, ~~The~~ the mean (μ) and the standard error ($\sigma_{\overline{\Delta h TLS}}$) are ~~calculated based on the elevation changes over stable terrain~~measures of error derived by calculating elevation changes from TLS over stable terrain (off-glacier) ~~(in m).~~ for 2015 summer (25 April–2 September 2015), 2015-16 (2 September 2015–1 September 2016), 2016 summer (2 May–1 September 2016) and 2016-17 (1 September 2016–27 August 2017)

Period~~*~~	~~σ_{MSA}~~Error or Stdev of MSA (m)	Number of points~~n~~	~~μ~~Mean elevation changes over stable terrain (m)	~~$\sigma_{\overline{\Delta h TLS}}$~~Standard error of elevation changes over stable terrain (m)
2015 (summer)	0.28	11 214 842	-0.01	0.25
2015-16	0.07	10 182 829	0.05	0.23
2016 (summer)	0.20	10 486 985	-0.01	0.22
2016-17	0.07	18 657 232	0.04	0.16

~~*2015 (summer) = 25 April – 2 September 2015; 2015-16 = 2 September 2015 – 1 September 2016; 2016 (summer) = 2 May – 1 September 2016; 2016-17 = 1 September 2016 – 27 August 2017.~~

Table 3. Glacier-wide mean of density conversion (ρ) and its uncertainty (σ_ρ) (in kg m^{-3}) as well as TLS-derived glacier surface elevation changes ($\overline{\Delta h TLS}$) (in m). TLS-derived geodetic (B_{geod}) and in situ measured glaciological (B_{glac}) net mass balance at winter and annual scales are listed (in m w.e.).

Period	ρ	σ_ρ	$\overline{\Delta hTLS}$	B_{geod}	B_{glac}
2015 (summer)					
Urumqi Glacier No.1	752	34	-0.991	**-0.75 ± 0.19**	**-0.99 ± 0.12**
West branch	696	35	-1.014	-0.68 ± 0.18	-0.80 ± 0.13
East branch	782	33	-0.952	**-0.82 ± 0.20**	**-1.09 ± 0.13**
2015-16					
Urumqi Glacier No.1	810	21	-0.827	-0.72 ± 0.19	-0.78 ± 0.11
West branch	763	24	-0.625	-0.47 ± 0.18	-0.50 ± 0.12
East branch	837	20	-0.873	**-0.80 ± 0.19**	**-0.94 ± 0.11**
2016 (summer)					
Urumqi Glacier No.1	622	32	-1.654	-1.11 ± 0.15	-1.03 ± 0.11
West branch	579	34	-1.230	-0.78 ± 0.13	-0.71 ± 0.12
East branch	647	31	-1.925	-1.29 ± 0.15	-1.22 ± 0.11
2016-17					
Urumqi Glacier No.1	864	19	-0.746	-0.68 ± 0.14	-0. 68 ± 0.11
West branch	861	19	-0.844	-0.75 ± 0.14	-0.77 ± 0.11
East branch	865	19	-0.729	-0.62 ± 0.14	-0.52 ± 0.11