Research on glacier elevation changes in Southeast Tibet based ICESat and CryoSat-2 Data

Lanyu Li¹, 2
¹No. 8 Guorui Road, Yuhuatai District, Nanjing, Jiangsu Province
²Corresponding author’s e-mail: Leelionyu1991@163.com

Abstract. Based on the comprehensive analysis of ICESat/GLAS14 data from 2003 to 2009 and CryoSat-2/L2I data from 2010 to 2016 in summer season. This paper revealed the elevation changes of mountain glaciers in small watershed scale in southeastern Qinghai-Tibet Plateau by using outliner elevation of footprints, spatial matching analysis of DEM and elevation trends simulation methods. The result showed, the data of effective footprints of ICESat is significantly higher than CryoSat data on mountain glaciers. Glaciers in the study area has been regressed significantly from 2003 to 2016, with the average regression rate in the study area is $-1.05 \pm 0.53$ma$^{-1}$, and a correlation coefficient of 0.72. Compared with the result of other similar studies in southeastern Tibet, the mountain glacier regression rate is credible. Meanwhile, the feasibility of mountain glacier elevation change monitoring in small watershed by CryoSat-2 data has been proven.

1. Introduction
Owing to its high coverage, high precision, periodic nature, and wide range, satellite altimetry has been widely applied to the altitude detection of glaciers and their periodic changes [1]. With onboard instruments, such as microwave radiometer, radar altimeter, and synthetic aperture radar, altimeter satellites can measure the distance from the earth’s surface to the sensor, thus providing relevant data for geodetic surveys of surface elevation variation, geodesy, and applications in geophysics [2]. ICESat laser altimetry data are currently preferred for studying surface elevation changes in large-scale glaciers. However, because of the strong characteristics of laser particles, ICESat data are affected by clouds, particularly floating snow particles. For example, in the southeastern part of the Qinghai–Tibet Plateau, where cloud and rain coverage are high, measurement data are likely to be discontinuous [3]. As a representative case of radar altimetry data, CryoSat-2 data have been widely used for studying polar glaciers and sea ice but rarely for the monitoring of inland glaciers. CryoSat-2 data are highly universal owing to the high-precision parameter design and good performance for polar glacier measurement [4]. Unlike laser-based height measurement, surface exploration by radar altimetry can be conducted all-day and in all-weather. Therefore, for mountain glaciers distributed in southeast Tibet, CryoSat-2 data products have more application prospects. They can effectively supplement the temporal and spatial continuities in ICESat data, and provide promising solutions for the continuous study of surface elevation changes in the mountain glaciers of this area.

Recently, altimeter satellites have been employed to study the changes in the material balance of the frozen soil in the Qinghai–Tibet Plateau [5]; however, studies on glacier elevation variations at small watershed scales are relatively lacking. To verify the effectiveness of altimeter radar in monitoring mountain glacier changes and to integrate different altitude sensor data, this study selected
ICESat data and Cryosat-2 data pertaining to the Yigong River Basin obtained during the 2003–2015 period to determine the glacier elevation changes during this period through effective data screening and joint inversion.

2. Data process

2.1. Outlier elimination of elevation footprint
Considering the snow seasons in study area, this paper chose the summer data for elevation analysis. After applying pretreatment to the data from ICESat GLAS and CryoSat-2/L2I, which cover the glaciers in the Yigong River Basin, the elevation value at the measurement point was found to contain several errors in the two types of height measuring products. The superposition of the results of altimetry data and existing DEM data could effectively eliminate the outliers. Specifically, the height measurement data were preprocessed to generate point files, the corresponding elevations obtained from the ASTER GDEM and SRTDEM (version 4) were extracted for an overlay analysis, and points with significant differences from the DEM altitude readings were removed. Almost all the glaciers in the Yigong River Basin were accumulated on top of a mountain, and the average elevation was >4700 m; therefore, data with values <0 could be directly removed. In addition, the glaciers exhibited a rapid reduction in the surface elevation from the top of the mountain to the valley; hence, the elevation near the top of the mountain was taken as the upper limit of the elevation distribution of the glaciers.

In the combined use of ASTER GDEM and SRTDEM (version 4) to judge the elevation anomaly, only abnormal values with a significant difference can be removed. The continuous distribution of footprints ensures that the elevation data meet the statistical law for the same satellite altimetry track. Therefore, the method of normalized density of the elevation points was used to eliminate the secondary abnormal elevation points. For each footprint, the data acquisition satisfied the normal distribution; therefore, the normal distribution function was taken as the density distribution function of each data point, and the density curve was superimposed with the calculated mean and standard deviations. Herein, the density integral of the footprint on the same altimeter orbit was 1. The threshold was screened from the distribution images obtained through the normalized density function, where the first trough before a significant increase in the density was the lower limit, and the first trough after a significant decrease in the density was the upper limit.

2.2. Spatial matching analysis of DEM data
The effective elevation interval of the two altimeter products for the Yigong River Basin could be obtained through the above two methods. Precise spatial location matching was based on the accurate calculation of the altitude difference using the DEM. In some regions, the offset of the DEM was typically calculated by arranging GPS measurement points in the field or by extracting typical points through high-precision remote sensing images [6, 7].

Because of the difficulty in achieving field GPS validation for the Yigong River Basin, the offset of the computed ridge lines, rather than the offset of the feature points, was calculated to evaluate the accuracy of the spatial distributions obtained using ASTER GDEM and SRTM DEM [8]. First, two types of DEM ridge lines within the basin were extracted, which ensured not only the integrity of the ridge line (SRTM DEM exhibited good data integrity) but also the accuracy (ASTER GDEM exhibited a high spatial resolution). Based on this result, the location information of 200 ridge lines (in Figure 1) was randomly extracted. Subsequently, the KML files were generated and loaded using Google Earth, and the corresponding ridge position information was also extracted for spatial matching evaluation. Since Google Earth uses high-resolution WorldView-II images, a precise visual interpretation of the ridge lines could be realized. Finally, the position adjustment in the DEM was performed by calculating the offset distance between the two ridge lines.

Because the ridge lines extracted from the Yigong River Basin were approximately along 30° north latitude and 93° east longitude, the relative latitude and longitude values were used to express the location of each ridge line, and the scatter diagrams could clearly reflect the migration. The latitude
value was divided by 30, and the longitude value was divided by 93. All the ridge lines in the Yigong River Basin were extracted using the above method. The results in Figure 1 demonstrated a high accuracy of the SRTM DEM in terms of the spatial location matching degree for the basin, except for a few ridge lines in the southeast region. The calculations also showed that the overall deviation in the SRTM satisfied the accuracy requirement. Considering its own spatial resolution, the DEM-based calculation method proved feasible.

![Figure 1. The Geometrical offset correction of SRTM in Yigong Zangbu Basin.](image)

2.3. Elevation trend simulation

By extracting the elevation values of the corresponding positions in SRTM DEM using the elevation points and then calculating the height difference in each sequential track, a set of time-dependent altitude difference sequences could be obtained from the elevation points covering the glaciers. The change trend in the elevation could be obtained by linear fitting of the height difference and time. Robust regression was used to analyze the variation trend in the elevation. After the first fitting of the height difference in this method, the calculation function yielded the same weight to each fitting point, and as the number of iterations increased, the regression function reduced the weights of fitting points far from the trend line after each regression analysis. This reduced the impact of outliers on the trend results, and the iterative process was ended when the regression coefficients tended to converge [9].

The glacier elevation variation in the Yigong River Basin was fitted using the robustfit function in MATLAB with default parameters [10, 11].

3. Result

3.1. Filter valid data

After applying a combination of the above methods to remove the elevation outliers, elevation values beyond 4681.38–5877.34 m and 4586–5944.97 m were considered outliers for the ICESat/GLAS1 and CryoSat-2/L2I products, respectively. These abnormal elevation points were accordingly filtered while retaining points statistically considered to be effective (in Figure 2). As listed in Table 1, the quality of CryoSat-2 data was lower than that of ICESat data. Although the number of ICESat sampling points covering the Yigong River Basin was less than that of Cryostat-2 sampling points, the effective points accounted for 84.42% of the total elevation points in the case of ICESat but only 48.82% in the case of CryoSat-2. Overall, the valid elevation data retained by the two altimetry methods were both objective; hence, they satisfied the measurement coverage of large mountain glaciers in the basin and are suitable for height change analyses.
Table 1. Selected valid elevation points using normalization.

| Data type       | Threshold (m) | Points | VPR (%)^a |
|-----------------|---------------|--------|-----------|
|                 | Lower limit   | Upper limit | Valid Points | Total Points |
| ICESat/GLAS14   | 4681.38       | 5877.34 | 748       | 886       | 84.42    |
| CryoSat-2/L2I   | 4586.40       | 5933.97 | 1263      | 2587      | 48.82    |

^a VPR: Valid Points Ratio

Figure 2. The elevation locations are marked as color dots in Yigong Zangbu Basin.

Figure 3. The footprints distribution on Large Double Valley Glacier.

Generally, glaciers are more widely distributed in the eastern and northern parts of the Yigong River Basin than in the west and south. Compared with polar regions that have a continuous form of glacier distribution, such as Greenland, most of the glaciers are in the form of separate glacier

4
aggregates and are in peak areas of high-altitude mountains with small areas and large slopes, except
for one particular complete glacier block. Despite ICESat and CryoSat-2 data having a high-density
data coverage on a global scale and good application in polar regions, including glacier and sea ice
areas, neither the spatial distribution nor the time series of the altimeter data was ideal (in Figure 3) in
local areas such as the Yigong River Basin. Specifically, when there are non-glacial zones in the orbit,
the high point density and time discontinuity in the orbit are low. After screening, continuous and
overlapping data bands were found in the large duplex valley glaciers in the basin. These overlapping
data bands in the two height measuring products were used to extract and analyze the surface elevation
change in the large duplex valley glaciers.

3.2. Analysis of elevation change

The ICESat/GLAS altimeter has demonstrated good application in the glacial regions of the Qinghai–
Tibet Plateau, and many useful scientific results have been obtained through different research
methods. Currently, the most popular application of CryoSat-2/L2I products is the backward inference
of the sea ice distribution and sea ice thickness; however, L2I data have rarely been applied to inland
glaciers. For an accurate transmission of the two altimetry data products to reflect the glacier elevation
changes in the Yigong River Basin, the height difference was fitted in three segments (e.g., ICESat
changes, CryoSat-2 change, and overall change). Any unreasonable value of the height difference (e.g.,
CryoSat-2 yielded a value as high as 10 m in 2013) was eliminated to ensure the validity of the trend
fitting in the two types of height measurement data. The calculations showed dramatic changes in the
valley glaciers in the Yigong River Basin. A comparison between Landsat images of less cloud cover
in the summer of 2003–2015 and SAR image interference pairs in the corresponding time period
showed a significant change in the glacier morphology during this period, the large duplex valley
 glacier exhibited an increasing tendency of splitting into small glaciers, and the continuous decrease in
the glacier surface elevation was an important manifestation of glacier retreat in this basin.

Table 2. Surface elevation change results after data processing.

| Data type     | Years | Elevation Change(m) |
|---------------|-------|---------------------|
| ICESat/GLAS14 | 2003  | 3.62                |
|               | 2004  | -                   |
|               | 2005  | 1.85                |
|               | 2006  | 2.67                |
|               | 2007  | -0.07               |
|               | 2008  | 3.70                |
|               | 2009  | -                   |
| CryoSat-2/L2I | 2010  | 3.87                |
|               | 2011  | -4.22               |
|               | 2012  | 5.54                |
|               | 2013  | -                   |
|               | 2014  | -11.22              |
|               | 2015  | -6.23               |
|               | 2016  | -9.90               |
Figure 4. Change in surface elevation of front region of Double Valley Glacier.

For the largest glacier community composed of large compound duplex valley glaciers in the Yigong River Basin, the surface elevation showed a continuous retreat (in Table 2 and Figure 4), with a combined fitting correlation coefficient of 0.72 and a withdrawal rate of $-1.05 \pm 0.53 \text{ma}^{-1}$. The fitting results of ICESat and CryoSat-2 segments were also significantly correlated. From the segment fitting results, the overall trend is that a relatively stable glacier form is maintained, except for the small glaciers on the edge. Hence, the elevation changes were stable, and the withdrawal rate was $-0.21 \pm 0.42 \text{ma}^{-1}$. During the 2010–2015 period, the glacier community was in a state of accelerated retreat, and the withdrawal rate was $-2.22 \pm 0.44 \text{ma}^{-1}$, though the elevation fluctuated significantly.

4. Conclusion and discussion

As height measurement data were used to study the surface elevation changes in the large glaciers near the Yigong River Basin (double the ancient glacier), two types of laser and radar ellipsoidal system conversions were applied to the two-stage products, and the reference to the same plane effectively combined GLAS 14 and L2I data; thus, a more continuous monitoring of the glacier elevation changes in the Yigong River Basin over the 2003–2015 period could be established. The overlapping GLAS 14 and L2I data in the duplex valley glacier were fitted through the iterative weighted least-squares method. The results showed that:

The surface elevation change rate of the large valley glacier community in this basin during 2003–2008 was $-0.94 \text{m/yr}$ as determined by ICESat/GLAS14. Neckel et al. used ICESat data to extract glacier elevation changes in the entire Qinghai–Tibet Plateau from 2003 to 2009, and found that the change rate of the glacier surface elevation in the Yigong River Basin was $-0.81 \pm 0.32 \text{m/yr}$ [12], which is consistent with the extraction results of this study. Wu Hongbo used ICESat/GLAS and GRACE satellite data to calculate the changes in the mass balance of high Asian glaciers, with the results suggesting that the surface elevation of the glaciers in the Tanggula section and Hengduan mountains decreased $2.06 \pm 0.20 \text{m}$ and $2.43 \pm 0.31 \text{m}$ during the 2003–2009 period, respectively [13], which is again consistent with our results.

CryoSat-2/L2I data are mainly algorithm-based designed for polar sea ice and ice sheet areas, and the error threshold for inland areas is stricter, resulting in higher error values when L2I data are applied to inland area [14]. Since the CryoSat-2 data based on SAR interferometry, the fresh snow and bare ice can seriously affect the results due to its penetration capability. The altimeter data showed that the error was significantly higher than that of ICESat, despite the strict removal of abnormal points.
and the careful calculation of the height difference. The monitored elevation change rate of the glacier in the basin during the 2003–2016 period was -1.36 m/yr. While no direct results were available for comparison and verification, the L2I elevation difference based on the baseline B can be utilized as a supplement to the GLAS data and as a reference for studying the continuous elevation changes in the basin.

Notably, however, the proposed DEM spatial superposition analysis and the method of eliminating extreme values using the normalized density function are all based on the product itself, i.e. [15], reducing the range of effective data to optimize the product and improve the accuracy of the result. In fact, there were differences in the spatial distributions of the footprints falling on the glacier, making it difficult to eliminate some of the elevation outliers. In addition, the Yigong River Basin has a variety of glaciers, including large and widely distributed complex valley glaciers as well as ice bucket glaciers and suspended glaciers with small areas and a high partition degree but in aggregation. Therefore, altimeter data can hardly be evenly distributed over the glacier surface. It is impossible to establish an even and accurate plane elevation distribution that includes all the types of glaciers; this has a certain negative effect on the subsequent trend fitting of the glacier surface elevation differences.

References
[1] Chuter S J, Bamber J L 2015 Antarctic Ice Shelf Thickness from Cryosat-2 Radar Altimetry Geophysical Research Letters 30 4
[2] Rémy F, Flament T, Michel A, et al 2015 Envisat and SARAL/AltiKa Observations of the Antarctic Ice Sheet: A Comparison Between the Ku-band and Ka-band Marine Geodesy 38 sup1
[3] Helm V, Humbert A, Miller H 2014 Elevation and elevation change of Greenland and Antarctica derived from CryoSat-2 The Cryosphere 8 4
[4] Sebastuan B S, Louise S S 2017 Implications of changing scattering properties on Greenland ice sheet volume change from Cryosat-2 altimetry Remote Sensing of Environment 190
[5] Resti A et al. 1999 The Envisat radar altimeter system (RA-2) ESA bulletin 98 8
[6] Slobbe D C, Ditmar P, Lindenbergh R C 2009 Estimating the rates of mass change, ice volume change and snow volume change in Greenland from ICESat and GRACE data Geophysical Journal International 176 1
[7] King M A, Coleman R, Freemantle A J, et al 2009 A 4-decade record of elevation change of the Amery Ice Shelf, East Antarctica Journal of Geophysical Research: Earth Surface (2003–2012) 114 F1
[8] Lee H, Shum C K, Tseng K H, et al 2013 Elevation changes of Bering Glacier System, Alaska, from 1992 to 2010, observed by satellite radar altimetry Remote Sensing of Environment 132
[9] Kääb A, Berthier E, Nuth C et al. 2012 Contrasting patterns of early twenty-first-century glacier mass change in the Himalayas Nature 488 412
[10] Fox J 2014 Robust regression: Appendix to an R and S-PLUS companion to applied regression
[11] O’Leary D P 1990 Robust regression computation using iteratively reweighted least squares SIAM Journal on Matrix Analysis and Applications 11 3
[12] Neckel N, Kropáček J, Bolch T 2014 Glacier mass change on the Tien Shan Plateau 2003-2009 derived from ICESat laser altimetry measurements Environment Research Letters 9 9
[13] Wu H B 2020 Studies on glacier mass balance in High Asia retrieved by ICESat-GLAS data and GRACE time-varying gravity field Acta Geodaetica et Cartographica Sinica 49 4
[14] Fricker H A, Padman L 2012 Thirty years of elevation change on Antarctic Peninsula ice shelves from multimesion satellite radar altimetry Journal of Geophysical Research: Oceans (1978–2012) 117 C02026
[15] Kropáček J, Neckel N, Bauder A 2013 Estimation of volume changes of mountain glaciers from ICESat data: an example from the Aletsch Glacier, Swiss Alps The Cryosphere Discussions 7 4