Recent Decadal Glacier Mass Balances over the Western Nyainqentanglha Mountains and the Increase in Their Melting Contribution to Nam Co Lake Measured by Differential Bistatic SAR Interferometry

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Abstract: The Western Nyainqentanglha Range locates in the southeastern center of the Inner Tibetan Plateau (ITP). Glaciers in this region are influenced by both the continental climate of Central Asia and the Indian Monsoon system. Their melting on the western slopes feeds the Nam Co Lake, which is the second largest endorheic lake in the ITP. The elevation of Nam Co Lake increased at a rate of 0.25 ± 0.12 m yr⁻¹ from 2003 to 2009. In this study, aimed at quantifying the decadal glacier mass balance in the Western Nyainqentanglha Mountains and their increasing melting contribution to Nam Co Lake; we applied the differential Bistatic SAR interferometry method to five pairs of TanDEM CoSSC datasets observed between 2013 and 2014 and SRTM acquired in 2000. The mean annual mass loss rate was -0.235 ± 0.127 m w.e. yr⁻¹ for the entire range. The mass loss rate for the northwestern slope (inside the Nam Co Lake drainage basin) and the southeastern slope (outside the Nam Co Lake drainage basin) were -0.268 ± 0.129 m w.e. yr⁻¹ and -0.219 ± 0.126 m w.e. yr⁻¹, respectively. Our results agree well with previous fieldwork at the Zhadang and Gurenhekou glaciers located on the northwestern and southeastern slopes. Debris-cover suppresses glacier downwasting to some extent. By presuming that all of the melted ice flows into the lake, the glaciers' melting contribution to Nam Co Lake's increasing water volume was approximately $10.50 \pm 9.00\%$ during the period between 2003 and 2009.

Keywords: Bistatic SAR Interferometry, Glacier Mass Balance, Nyainqentanglha Mountains, Nam Co Lake, Tibetan Plateau

1. Introduction

The Tibetan Plateau is known as the roof of the world and contains vast low-latitude high-altitude glaciers that are essential components of the cryosphere and are sensitive climate indicators because they adjust their size in response to climate change. Glaciers occur where climate conditions and topographic characteristics allow snow to accumulate over several years (Vaughan et al., 2007). Glacier melting on the Tibetan Plateau and the surrounding region contributed approximately 10% to the global glacier mass

loss from 2003 to 2009 (Gardner et al., 2013). The mass balance is the most relevant variable for assessing glacial responses to climate variability and compares glacier area and length changes due to surge-type and/or debris-covered glaciers (Gardelle et al., 2013). Despite in-situ observations' being encouraged, its great labor and economic cost has limited its application. The Institute of Tibetan Plateau Research at the Chinese Academy of Sciences has dedicated decades to measuring the glacier mass balance of approximately 15 glaciers in the Tibetan Plateau, however, more than 60,000 glaciers exist in the High Mountains of Asia (Yao et al., 2012; Ardent et al., 2014). Satellite geodetic methods, based on a comparison of topographic data (DEM or laser altimetry) observed at more than two points of time, can measure glacier volume or height changes (Gardelle et al., 2013; Paul et al., 2015). Recent studies of glacier mass balance in the Tibetan Plateau have applied laser altimetry such as ICESat/GLAS (Kääb et al., 2012 & 2015; Neckel et al., 2014) and compared DEM datasets such as SRTM and SPOT/HRS (Gardelle et al., 2012 & 2013; Pieczonka et al., 2015). Despite laser altimetry's vertical precision being able to reach centimeters, it only measures orbital footprints and cannot provide two-dimensional glacier height change patterns (Kääb et al., 2012 & 2015; Neckel et al., 2014). In addition, the precision of laser altimetry on slopes can be lower than in flat regions and also be difficult to estimate. Usually glacier height changing rate is different at different elevation levels, and ICESat footprints can only cover a small part of it, which can bias the observation (Ke et al., 2015). Comparing two two-dimensional DEMs obtained at different point of time provides maps of glacier height changes (Gardelle et al., 2012 & 2013; Paul et al., 2015; Pieczonka et al., 2015). However, absolute penetration depth of C-band SRTM is hard to estimate and the penetration depth difference between X- and C-band SRTM is usually used as a proxy by presuming that the X-band does not penetrate into glaciers as in optical images; this assumption could also introduce error and/or bias (Rignot et al., 2001; Gardelle et al., 2013, Kääb et al., 2015). In 2011, German Aerospace Center (DLR) started operating its twin X-band SAR satellites TerraSAR-X (TSX) and TanDEM-X (TDX) in bistatic mode, as SRTM did in 2000, for the purpose of obtaining DEM. Because both missions (TSX/TDX and X-band SRTM) operate in the X-band, the penetration depth bias due to different carrier frequencies can be reduced. Several experiments carried out in the Puruogangri Ice Cap and the Andes presented the great potential of this dataset for deriving the glacier mass balance (Jaber et al., 2012; Neckel et al., 2013).

The glacier mass balance for the Western Nyainqentanglha Range was -0.20 ± 0.29 m w.e. yr^{-1} from 2003 to 2009, as measured by ICESat/GLAS laser altimetry monitoring, however, footprints only covered the accumulation area (Neckel et al., 2014). Field observations on the Gurenhekou glacier ($30^{\circ}11' \text{ N}$, $90^{\circ}28' \text{ E}$, on the southeastern slope outside the Nam Co Lake drainage basin) show that its thinning rate was -0.312 m w.e. yr^{-1} between 2005 and 2010 (Yao et al., 2010). The Zhadang glacier ($30^{\circ}28' \text{ N}$, $90^{\circ}38' \text{ E}$, on the northeastern slope inside the Nam Co Lake drainage basin) downwasted at a rate of -0.59 m w.e. yr^{-1} on average between 2005 and 2008 (Yao et al., 2010; Yu et al., 2013).

As several great rivers (e.g., the Yellow, Yangtze, Mekong, Salween, Brahmaputra, Ganges and Indus Rivers) flow from this region and feed the Pacific and Indian Oceans, it is also regarded as 'Asia's water tower'. The Inner Tibetan Plateau (ITP, an endorheic basin) distributes large numbers of endorheic lakes, and a study of 118 lakes within the ITP using ICESat/GLAS laser altimetry monitoring shows an average rising water level rate of 0.20 m yr^{-1} from 2003 to 2009 (Zhang et al., 2011). With an area of 2021.3 km^2 ,

Nam Co Lake (30°45' N, 90°30' E) is the second largest endorheic lake in the ITP after the Qinghai Lake (Lei et al., 2013). Its catchment area is 10740 km², with 196.8 km² covered by glaciers, all of which distribute from the northwestern slope of the Nyainqentanglha Range (30°18' N, 90°30' E). Based on meteorological data and hydrological modeling, an increase in precipitation cannot fully explain the increase in water volume unless melting of the Nyainqentanglha glaciers are also considered, melting of which contributes ~28.7% of the volume increase (Lei et al., 2013). However, this glacier mass balance result depended on field observations of Zhadang glacier (Yao et al., 2010). Zhadang glacier's elevation varies from 5500 m to 6095 m while the maximum elevation of the Nyainqentanglha Range is 7162 m (Bolch et al., 2010). The equilibrium line elevation (ELA) in this region was between 5720-5860 m according to field observations (Yao et al., 2010). Recent studies with laser altimetry on ITP glaciers reveal that most glacier thinning occurred in the ablation zone (Neckel et al., 2014). Therefore, taking the result of the glacier mass balance from fieldwork at Zhadang glacier as the average mass balance of the entire Western Nyainqentanglha Range could bias estimating of the glacier melting contribution to the rising lake level.

The aims of this study are as follows:

- 1) to study the decadal glacier mass balance of the Western Nyainqentanglha Range through topographic differencing,
- 2) to evaluate the accuracy of DEM differencing processing for deriving glacier mass balance in complex terrain by both cross validation and by comparisons to in-situ observations,
- 3) to compare glacier mass balance rate differences between northwestern slope glaciers (inside the Nam Co Lake drainage basin) and southeastern slope glaciers (outside the Nam Co Lake drainage basin), and
- 4) to evaluate quantitatively the contribution rate of glacier melting to Nam Co Lake's increasing water level.

2. Study Region

The Western Nyainqentanglha Range is located in the southeastern center of the Tibetan Plateau. The highest peak, called the Nyainqentanglha Peak, is 7162 m above sea level. The primary mountain ridge represents a SW-NE striking range that extends more than 230 km (Yao et al., 2010). The western Nyainqentanglha Range is located at the transition zone between continental and maritime glaciers. Meteorologically, the Indian monsoon dominates in the summer and the westerlies dominate in the winter (Yu et al., 2008). Annual precipitation at surrounding meteorological stations range from 377 to 500 mm with a mean temperature of -0.6 to 2.8°C (Yu et al., 2013). At higher altitudes, precipitation on glaciers could be greater than at lower altitudes. One study showed that annual precipitation on the Xibu glacier, which is the largest and longest glacier in the Western Nyainqentanglha Mountains and is located on the eastern slope of Nyainqentanglha Peak, is between 700 and 900 mm (Caidong et al., 2010). Xibu glacier feeds a river that flows to the Lhasa and Yarlung Zangbo Rivers (Brahmaputra). Most glaciers at the Western Nyainqentanglha are clean-ice glaciers. Parts of the ablation zone of the Xibu glacier are covered with debris; its effect on the glacier downwasting rate remains unknown because no in-situ observations have been conducted on this glacier. Another unnamed debris-covered glacier on the northwestern slope was also studied to explore the effect of debris (blue dots in Fig. 1). From 1976 to

2009, glacier tongues retreated at approximately 10 m yr^{-1} in this region (Bolch et al., 2010). To our knowledge, the mass balance of two glaciers, the Zhadang and the Gurenhekou (blue dot in Fig. 1), were performed with in-situ observation between 2005 and 2010 (Yao et al., 2010 & 2012). The sizes of these two glaciers are no larger than 3 Km^2 , nevertheless, field observed mass balance data can be adopted to validate satellite observed results. The northwestern slope is an endorheic region inside the Nam Co Lake drainage basin. The Nam Co Lake is the second largest lake in the Tibetan Plateau and the highest elevation salty lake in the world (Zhang et al., 2011). Between 2003 and 2009, Nam Co Lake experienced sharp increases in water levels of $0.25 \pm 0.12 \text{ m yr}^{-1}$ associated with rapid area expansions (Zhang et al., 2011). The southeastern slope is an exorheic region that drains into the Yangbajain-Damxung Valley. Glaciers in this region cover approximately $692.3 \pm 19.4 \text{ km}^2$, of which $198 \pm 5.6 \text{ km}^2$ belong to the endorheic region that feeds Nam Co Lake (Bolch et al., 2010).

Figure 1. Landsat 7 false color image for the study region (SWIR, NIR, R show in red, green, blue). This image was observed on 2001-12-06 and was employed for identifying glacier boundary in RGI V4.0 dataset (Grey line boundary). Glacierized coverage shows in cyan. The deep blue line indicates the water divide between the Nam Co Lake drainage basin and the exorheic region. Four blue dots indicate the glaciers with detail studied in this research.

3. Data and Methodology

3.1. SRTM DEMs, Bistatic TSX/TDX SAR images,

The Shuttle Radar Topography Mission (SRTM) measured near-global topography using bistatic SAR interferometry in 2000, which is employed as the reference DEM in this study for topographic difference

processing. The SRTM DEMs were observed with C-band in ScanSAR mode and X-band in stripmap mode and were processed and released by USGS and DLR, respectively. Unfortunately, the X-band SRTM DEM only cover the southern part of the Nyainqentanglha Range, and with many gross errors, this could be caused by geometry distortion of the SAR images. The C-band SRTM covers the entire study area. Due to the large swath-width of the ScanSAR mode, most parts of the SRTM were covered by both ascending and descending observations so that almost no gross errors were found, nevertheless, some places still lost coherence and voids could be found in the SRTM v3 release. We obtained two categories of C-band SRTM for this research. We applied void-filled C-band SRTM at 1 arc (approximately 30 m) in our primary processing; we also acquired non-void-filled SRTM at 3 arc (approximately 90 m) to identify voids in the SRTM and to mask out areas where the referenced DEM were not truly the SRTM obtained in 2000. The X-band SRTM at 1 arc spatial resolution was downloaded from DLR and used to evaluate the penetration depth compared to the C-band SRTM.

Following the TerraSAR-X X-band SAR satellite, its twin TanDEM-X satellite was launched into orbit in June 2010. With a 100 MHz bandwidth, the resolution of the TerraSAR-X/TanDEM-X (TSX/TDX) images is approximately 2-3 m in stripmap mode. In this study, we acquired five pairs of experimental Co-registered Single look Slant range Complex (CoSSC) product observed in bistatic InSAR stripmap mode between 2013 and 2014 covering almost all of the Western Nyainqentanglha Mountains. Considering the complex terrain of the Western Nyainqentanglha Mountains and the geometry distortion of side looking SAR images, we selected images in both ascending and descending tracks to avoid foreshortening, layover and shadows. Perpendicular baselines of the six images varied from 145 m to 376 m. We list our archive images in Table 1. Coverage of X-band SRTM and TSX/TDX SAR images is presented in Fig. 1.

Table 1. Six pairs of bistatic TerraSAR-X/TanDEM-X images obtained from DLR.

Acquisition date	Perpendicular Baseline (m)	Ascending /Descending track	Average Incidence angle
2013-03-30	376	A	46
2013-12-02	-145	D	34
2014-03-12	146	A	34
2014-03-23	164	A	36
2014-04-07	-163	D	46

Two L-band ALOS/PALSAR images observed on 2009-01-03 and 2009-02-18 identified debris cover with a D-InSAR interferogram and coherence map.

3.2 Glacier identification

For most glaciers in the Western Nyainqentanglha, RGI V4.0 applied Landsat image observed on 2001-12-06 to identify glacier boundary, while RGI v5.0 applied multi Landsat images observed close to 2010. Since our study period begins at 2000, therefore RGI V4.0 was adopted as glacier boundary for the Western Nyainqentanglha. Landsat image observed on 2001-12-06 was employed to identify clean ice boundary by using the Normalized Difference Snow Index (NDSI, $(TM2-TM5)/(TM2+TM5)$) at a threshold of 0.4 (Paul et al., 2015). Pixels within RGI V4.0 and NDSI higher than 0.4 were accepted as clean ice zone, while pixels within RGI V4.0 and NDSI lower than 0.4 were identified as debris-covered

area. Erode and dilate algorithm of morphology was performed to smooth the boundaries of the clean-ice glaciers in case of seasonal snow affection (Racoviteanu et al., 2009). Besides, we manually checked and edited the glacier outline with glacier height changing maps and coherence map formed by two L-band ALOS/PalSAR images observed on 2009-01-03 and 2009-02-18 (Atwood et al., 2010).

3.3 Bistatic SAR interferometry

Normally, evaluating glacier elevation changes requires DEMs observed at a minimum of two points in time. Neckel (2013) discussed two methods using bistatic TSX/TDX images to derive glacier height changes referencing X-band SRTM. The major difference between the two methods is that the first one forms DEM performing standard InSAR processing to bistatic TSX/TDX images and then performs differencing processing on X-band SRTM; while the second one applies a D-InSAR method and transfers the topographic residual phase directly to the topographic residual, which is primarily caused by glacier height changes. Because the phase gradient is much smaller for the differential interferogram than for the original interferogram, which only removes the flat-earth phase, errors are less likely to occur in the phase unwrapping steps. We essentially used Neckel's (2013) second method to process the five pairs of bistatic images in this study. Height changes at off-glacier was presume as zero in D-InSAR processing for calculating glacier height changes. Besides, we made several necessary improvements to Neckel's strategy.

First, the Puruogangri Ice Cap in Neckel's study was fortunately covered by X-band SRTM, however, most glaciers in the Tibetan Plateau are only covered by C-band SRTM because of the narrow swath-width of X-band SRTM and the large orbital gaps in low latitude regions. X-band SRTM covers the southwestern section of the western Nyaiqentanglha Mountains and was only employed to correct the penetration depth compared to C-band SRTM in this study. We applied void-filled C-band SRTM at 1 arc resolution for topographic differencing processing and then masked out filled voids by referring to non-void filled C-band SRTM at 3 arc resolution. Another concern is when comparing X-band SRTM and C-band SRTM, we found multiple gross errors included in the X-band SRTM that were highly likely to have been induced by unwrapping errors. Too many voids in the X-band SRTM distribution make it unsuitable to be used directly for topographic differencing processing.

Second, we noticed that in both our own processing and in Neckel's (2013) results for the Puruogangri Ice Cap the difference between the SRTM and TSX/TDX generated DEM in the foreshortening region can be large ($89^{\circ}13'00''\text{E}$, $33^{\circ}59'20''\text{N}$ in their figure 5), even though the off-glacier region and 'false-hillshade' has been eliminated by coregistering simulated SAR images to real SAR images and updating the look-up-table file between the SAR and geographic coordinate (Nuth et al., 2011; Neckel et al., 2013; Paul et al., 2015). For foreshortening area, the geometry distortion is much larger than in flat regions, however, the coherence of the interferometry remains acceptable. This could be due to a loss of information because several pixels were combined into one when transferring DEM from geographic coordinates to SAR coordinates, therefore the simulated topographic phase could not be accurately generated. We solved this problem in two steps. Regions with severe foreshortening and/or layover were masked out. Local incidence angle between 18° to 72° were accepted. Local incidence angle can be calculated using formula 1:

$$\theta_{\text{local}} = \theta_{\text{flat}} + \text{Slope} * \sin (\text{Aspect} - \text{Heading}) \quad (1)$$

where θ_{local} is the local incidence angle, and θ_{flat} is the incidence angle on flat terrain. The heading is the orbital azimuth direction with respect to north, which is approximately 190° for descending images and -10° for ascending images. Figure 2 presents two pairs of images in ascending and descending tracks processed with this method. Figure 2a and 2b show the results of ascending acquisition while figure 2d and 2e show the descending acquisition. Height change maps of 2a and 2d were not masked while 2b and 2e were masked out the foreshortening, overlay and shadow region.

Figure 2. Masking foreshortening due to side looking geometry. (a) Decadal height changes between 2014-03-12 and SRTM without masking. (b) Masked decadal height changes between 2014-03-12 and SRTM. (c) Mosaicked decadal height changes by ascending and descending tracks. (d) Decadal height changes between 2012-04-07 and SRTM without masking. (e) Masked decadal height changes between 2012-04-07 and SRTM. (f) DEM shade and legend of glacier height changes.

3.4 Penetration depth correction

The penetration depth of the radar signal into the snow and ice can reach up to several meters depending on the carrier frequency, the density of the snow and ice, and its moisture (Rignot et al., 2001; Kääb et al., 2015). This could be one of the most important error sources in satellite geodetic surveys when deriving glacier mass balance with different platforms for obtaining DEM such as InSAR formed DEM, optical stereo photogrammetry and laser altimetry (Paul et al., 2015; Kääb et al., 2015). We followed a similar method to that in Gardelle's research (2013) to correct the penetration depth between C-band SRTM and TSX/TDX DEM. Given that the carrier frequencies of the X-band SRTM and the TSX/TDX satellites are almost the same, and most our TSX/TDX were observed in March which adjacent to February when SRTM were performed, we presumed that no penetration difference exists between these two platforms. C-band SRTM refer to EGM96 geoid vertical datum and X-band SRTM refer to the WGS84 ellipsoid

(Shuttle Radar Topography Mission (SRTM) 1 Arc-Second Global | The Long Term Archive. <https://lta.cr.usgs.gov/SRTM1Arc> Eoweb. http://eoweb.dlr.de:8080/eoweb-ng/licenseAgreements/DLR_SRTM_Readme.pdf), therefore the geoid height separates these two datasets. With the glacier classification results from 3.2, we separated SRTM into clean ice parts and other parts, which includes off-glacier region and debris-covered zone. We assumed there was no penetration depth difference in the off-glacier region and debris-covered zone and then we evaluated and removed the vertical offset between the C- and X-band SRTM. Penetration depth varies with elevation because snow and ice density decrease when the elevation increases. We calculated corrections between the C- and X-band SRTM in 50 m elevation bins. Because pixel numbers at very high and very low elevation were quite small, we applied linear regression in two elevation bins between 5650 to 6150 m to evaluate the penetration depth difference in other elevation bins.

3.5 Seasonal and inter-annual effects

SRTM DEM was obtained in February during an 11-day shuttle mission, while TSX/TDX mission keeps on observing the earth from 2011 at all seasons. To avoid seasonal affection, most TSX/TDX images applied in this study were obtained in March. Meteorological records present that most accumulation and ablation occurs in summer season while in winter almost no precipitation occurs and temperature should be lower than 0 °C. Therefore it is reasonable to presume no seasonal effect for three bistatic TSX/TDX images obtained in March. Image obtained on 2014-04-07 has a large overlap region with image obtained on 2014-03-12. We calculated the average height difference at the overlapped region to correct seasonal effect for image obtained on 2014-04-07. Another image obtained on 2013-12-02 has a large overlapped with 2013-03-30. Since most accumulation and ablation occur at summer time. 2013-03-30 has a 13 years period with respect to SRTM while other four pairs have 14 years. Glacier height changes detected by images obtained 2013-03-30 were transferred to 14 years and then the average height difference at overlapped region was applied to correct the seasonal effect for 2013-12-02. The seasonal variation in glacier height difference for 2013-12-02 and 2014-04-07 were 0.5 m and 0.29 m, respectively.

After correcting the seasonal effect and inter-annual variability, average height changes map for 14-year period was obtained by mosaic and averaging height changes maps derived from five bistatic TSX/TDX images. Consider that at slopes could be steep at high elevations and less likely to be measured with acceptable quality. For entire Western Nyainqentanglha, inside or outside the Nam Co Lake drainage basin, or one glacier, average height changes in each 50-m elevation bin were calculated. Then glacier area in each 50-m elevation bin which identified in 3.2 supposed to be measured was calculated for the certain area as well. Then the average height changes of 14-year for the certain area could be calculated. Then annual glacier height changes could be calculated.

3.6 Density assumption

Transferring glacier height changes into glacier mass balance requires information about the snow and glacier densities. Various types of assumptions were used because almost no in-situ observations of density could be provided. Two scenarios for glacier density were employed in Kääb's research (2012): the first one assumed 900 kg m⁻³ and second one assumed 900 kg m⁻³ for the ice and 600 kg m⁻³ for the firn. We adopted these two scenarios, and for the second one we set the equilibrium line altitude at 5850

m according to Yao's research (2012). The equilibrium line roughly separates the glacier into an accumulation zone and an ablation zone and can also be regarded as the transition from firn to ice. We also adopted another scenario of glacier density of $850 \pm 60 \text{ kg m}^{-3}$ (Huss 2013; Gardelle et al., 2013).

3.7 Accuracy assessment

The error in detecting glacier height changes is composed of systematic and random components. Systematic error includes errors in penetration depth, seasonal effects, and datum error between SRTM and TSX/TDX. Random error is composed by random error in TSX/TDX DEMs and SRTM DEM.

As X-band and C-band SRTM are released with different datum, datum difference between two dataset was estimated by aligning off-glacier region. Error of the datum difference was X- and C-band SRTM were calculated with standard deviation and effective measuring number at off-glacier region. Another part of penetration depth error is random part at clean-ice area, which is also calculated with standard deviation and effective measuring number. Formula 2 described how error of penetration depth was calculated.

$$Err_{pd} = \sqrt{\left(\frac{Err_{cx_off}}{\sqrt{N_{eff_{cx_off}}}}\right)^2 + \left(\frac{Err_{cx_on}}{\sqrt{N_{eff_{cx_on}}}}\right)^2} \quad (2)$$

Err_{pd} is the error of the penetration depth. Err_{cx_off} is the standard deviation at off-glaciers between C and X-band SRTM, which is 4.85m in this study. $N_{eff_{cx_off}}$ is the effective measurement number at off-glacier region, which were calculated by total measure area and autocorrelation distance. The latter was estimated by calculating the range of variogram, which is 1243m at this studied region. Err_{cx_on} is the standard deviation at glacier region. We averaged the weighted standard deviation in each 50m on glaciers, and found standard deviation of 6.08m for Err_{cx_on} . Err_{pd} is 0.53m.

For each bistatic TSX/TDX, we introduced a seasonal error of 0.15m each month following Gardelle's research (2013), which should be 0.15 m for three acquisitions in March, and 0.21 m for 2014-04-07 and 0.26 m for 2013-12-02.

Datum error for TSX/TDX DEMs and SRTM was estimated also by standard deviation and effective measurements, which are different for each bistatic TSX/TDX acquisitions. Standard deviations for each acquisition are a bit less than 3 m. Auto correlation distances for each acquisition were calculated by calculating the range of variogram as well, which varied from 330 m to 890 m. Then the datum error of datum was calculated by formula 3:

$$Err_{datum} = \frac{Err_{bi-SRTM}}{\sqrt{N_{eff_{bi-SRTM(Off)}}}} \quad (3)$$

where $Err_{bi-SRTM}$ is the standard deviation of the height difference for the off-glacier region for each frame. $N_{eff_{bi-SRTM(Off)}}$ is effective measurement number at off-glacier region for each frame. Then the systematic error was calculated with formula 4:

$$Err_{sys} = \sqrt{Err_{pd}^2 + Err_{Mon}^2 + Err_{datum}^2} \quad (4)$$

where Err_{Mon} is seasonal error.

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For each bistatic TSX/TDX frame, each sub-region, or each glacier, the random error depends on standard deviation of differencing processing between TSX/TDX and SRTM, and the measured glacier area, which is calculated with formula 5:

$$Err_{random} = \frac{Err_{bi-SRTM}}{\sqrt{N_{eff_{bi-SRTM(On)}}}} \quad (6)$$

where $N_{eff_{bi-SRTM(On)}}$ is the effective number of measurements on glacier surfaces, using autocorrelation distance for the corresponding bistatic TSX/TDX acquisition and the measured glacier area. Usually larger the area measured, smaller the random error is. Then error of the measured glacier height changes was calculated by square root of sum squares of systematic error and random error. Finally principle of error propagation will be applied for transferring glacier height changes to glacier mass balance for each density scenarios.

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3.8 Meteorological data

Six meteorological stations distributed adjacent to the Western Nyainqentanglha Mountains (Yu et al., 2013), which are Xainza (30°57'N, 88°38'E), Baingoin (31°23'N, 90°01'E), Nagqu (31°29'N, 92°04'E) distribute at northern side of the Western Nyainqentanglha, and Xigaze (29°15'N, 88°53'E), Lhasa (29°40'N, 91°08'E), Damxung (30°29'N, 91°06'E) distribute at southern side of the Western Nyainqentanglha. Air temperature and precipitation data were obtained from the Climatic Data Center, National Meteorological Information Center, China Meteorological Administration. Observation period spans from 2000 to 2012 and cover most part of our study period.

4. Results

4.1 Penetration depth

Figure 3 presents the penetration difference between the X- and C-band SRTM; the average penetration depth difference is 1.67 ± 0.53 m. To our knowledge, no report of the penetration depth has been given for the Western Nyainqentanglha Range or the adjacent glacierized regions such as Dongkemadi. Compared to several other study regions on the Tibetan Plateau, our estimate is quite similar (Gardelle et al., 2013; Kääb et al., 2012). A mean penetration depth difference of 1.7 m was reported at Hengduan Shan, 2.4 m at Bhutan, and 1.4 m at Everest in Gardelle's research (Gardelle et al., 2013). Linear regression between the glacier elevation and penetration suggest that at 5550 m, where most clean-ice glaciers terminate, the penetration depth difference is 1.29 m. At 6250 m, the penetration difference is expected to be 2 m.

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Figure 3. (a) Penetration depth on clean ice in each elevation bin. (b) Glacier surface height distribution at overlapped region of X and C band SRTM. There is no obvious distinction in the penetration depth between the accumulation and ablation zones.

4.2. Glacier mass balance over the western Nyainqentanglha Mountains

A map of decadal glacier height changes is given in Fig. 4 after applying the penetration depth correction and the foreshortening/layover region mask. No surge type glaciers were found in this region using preliminary identifications of the glacier height changes at the glacier tongues. RGI V4.0 presents with acceptable quality in this region and only Panu (30°23.0'N & 90°31.3'E) and Qingga (30°15.0'N & 90°24.6'E) glacier requires boundary editing at their tongues. The glacier lengths for most glaciers in this region are no more than 10 km. Several glacier tongues have suffered severe thinning exceeding 60 m decade⁻¹, especially several long glaciers without debris-cover on the southwestern slope. Areas of the southwestern slope (outside the Selin Co Lake drainage basin) occupy 71.4% of the total glacial area in this region. Placing the ELA at 5850 m, we transformed the glacier height changes into annual mass balances. Table 2 lists the three density scenarios together with the glacier height changes (Yao et al., 2012). The different scenarios of assumed glacier density do not greatly affect the glacier mass balance

calculation, and most of the errors are induced by glacier height change observations (Gardelle et al., 2013).

Figure 4. Averaged decadal glacier height change pattern in the western Nyainqentanglha Mountains. Most of our study area was covered by both ascending and descending observations, except in the northeast where the topography is much gentler than in other parts of the mountain range. Histograms shows deviation for each TSX/TDX images on off-glacier region.

Table 2. Glacier height changes and glacier mass balances for the Western Nyainqentanglha Mountains (Western NyQ Mt). Scenario 1 assumed that the density of the glaciers is 900 kg m^{-3} . Scenario 2 assumed that the density of the glacier is 900 kg m^{-3} in the ablation region (lower than 5850 m) and 600 kg m^{-3} in the accumulation region (higher than 5850 m). Scenario 3 assumed that the density of the glaciers is $850 \pm 60 \text{ kg m}^{-3}$.

	Area	14 Years (m)	Annual rate (m)
Glacier Height Changes	Western NyQ Mt	-3.822 ± 0.552	-0.273 ± 0.148
	In Nam Co Basin	-4.408 ± 0.562	-0.315 ± 0.150
	Out Nam Co Basin	-3.610 ± 0.551	-0.258 ± 0.147
Mass balance Scenario 1	Western NyQ Mt	-3.440 ± 0.497	-0.246 ± 0.133
	In Nam Co Basin	-3.967 ± 0.506	-0.284 ± 0.135
	Out Nam Co Basin	-3.249 ± 0.496	-0.232 ± 0.132
Mass balance Scenario 2	Western NyQ Mt	-3.483 ± 0.412	-0.249 ± 0.110
	In Nam Co Basin	-3.813 ± 0.423	-0.272 ± 0.113
	Out Nam Co Basin	-3.156 ± 0.411	-0.229 ± 0.110
Mass balance Scenario 3	Western NyQ Mt	-3.249 ± 0.469	-0.235 ± 0.127
	In Nam Co Basin	-3.747 ± 0.478	-0.268 ± 0.129
	Out Nam Co Basin	-3.069 ± 0.468	-0.219 ± 0.126

Figure 5a shows decadal glacier height changes in each elevation bin for the entire Western Nyainqentanglha Mountain Range, outside the Nam Co drainage basin (red), and inside the Nam Co drainage basin (blue). Glacier surface height distributions are plotted in Fig. 5b. Almost every elevation bin contains a large enough glacial area for observation, and at high elevation bins the glacierized area without effective measurement is higher than at the low elevation bins. The glacier downwasting rate is slightly higher inside the Nam Co drainage basin than outside it. Additionally, the histogram peak for the glacier height distribution is higher outside the Nam Co drainage basin. These two features both contribute in a less negative glacier downwasting rate on the southeastern slope of the Nyainqentanglha Mountains.

Figure 5. (a) Decadal glacier height changes at different elevation layers for the Western Nyainqentanglha Mountains. Glaciers inside the Nam Co lake drainage basin downwasted slightly more than those outside the basin. (b) Glacier surface height distribution for inside and outside the Nam Co lake drainage basin.

Only 198.1 km² of the 10680 km² in the Nam Co Lake drainage basin are covered by glaciers. We prefer scenario 3 for the assumed glacier density to estimate the glacier melting contribution. Assuming that all glacier melt flows into

the Nam Co Lake without any evaporation and applying Zhu's result of 2015.38 km² observed in 2004 as the average lake area (Zhu et al., 2010), the glacier melting contribution to Nam Co Lake's increasing water level was 10.50 ± 9.00%.

4.3. Result validation

Zhadang glacier is a tiny glacier located on the northwestern slope of the Nyainqentanglha Range, and its area was 2.912 km² in 2001. Its elevation extended from 6079 to 5512 m, with an average elevation of 5751 m (Arendt et al., 2014). Three pairs of bistatic SAR images covering this glacier were observed on 2014-03-12, 2014-03-23 and 2014-04-07. Its glacier height downwasting pattern is shown in Fig. 6. It estimated averaged annual mass balance assuming a density of 850 ± 60 kg m⁻³ was -0.501 ± 0.166 m w.e. yr⁻¹. Based on in-situ observations between 2005 and 2008, its mass balance was -0.59 m w.e. yr⁻¹ (Yao et al., 2010; Lei et al., 2013). Despite our result representing a longer study period, our agreement with in-situ observations was acceptable. The equilibrium line altitude (ELA) is the most sensitive indicator of a glacier to climate change. Contour lines of glacier accumulation and ablation are drawn to identify the glacial ELA (Yao et al., 2010). In-situ observations indicate that the ELA between 2005/2006, 2006/2007 and 2007/2008 were 5840, 5780, 5640 m, respectively, and that our estimated decadal averaged ELA was between 5850 to 5900 m. Above the ELA there is a slight positive mass balance and below it there is a negative mass balance (Yao et al., 2010). The correlation between the glacier height changes and glacier elevation is shown in Fig. 6b and 6c. The quickest decadal downwasting was approximately 15 m w.e. yr⁻¹ at the bin of 5550 to 5600 m. We list the four glaciers we studied in detail in Table 3, two of which have in-situ observations of the mass balance and the other two that are debris-covered.

Figure 6. (a) Decadal glacier height change pattern of the Zhadang glacier. (b) Decadal glacier changing rates in each elevation bin. Most glacier thinning occurred below 5800 m. (c) Glacier height distribution.

Table 3. The four glaciers studied in detail and their mass balance derived from both in-situ observations and topographic differencing.

Name	RGI V4.0 ID	GLIMs ID	ZMIN/ZMED/ZMAX (a.s.l m)	Area (km ²)	in-situ mass balance (m w.e. yr ⁻¹)	mass balance in this research (m w.e. yr ⁻¹)
Zhadang	RGI40-1 3.20000	G090639E 30468N	5512/5751/6 079	2.912	- 0.59	- 0.501 ± 0.166
Gurenhekou	RGI40-1 3.19419	G090447E 30192N	5489/5779/5 979	1.574	- 0.31	-0.267 ± 0.248
Xibu	RGI40-1 3.19886	G090598E 30389N	5196/5817/7 086	23.942	-	-
Unnamed	RGI40-1 3.19775	G090388E 30292N	5348/5859/6 399	8.191	-	-

The Gurenhekou glacier is another tiny glacier with in-situ mass balance observations, which is located on the southeastern slope of the western Nyainqentanglha Range. It covers an area of 1.574 km² and extends 2.9 km. Two pairs of bistatic SAR images covering this glacier were observed on 2013-12-02, 2014-03-12. We present the decadal glacier height change pattern in Fig. 7a. The annual mean mass balance was -0.267 ± 0.248 m w.e. yr⁻¹ assuming a glacier density of 850 ± 60 kg m⁻³. In-situ observations of the mass balance for this glacier span from 2005 to 2010, and the average in-situ mass balance was -0.31 m w.e. yr⁻¹. During the period between 2005 and 2010, the ELA was at approximately 5800 m, except for 2007/2008 (Yao et al., 2012). We estimated the ELA by correlating the decadal downwasting rate and glacier elevations, and the annual mean ELA was between 5800 and 5850 m (Fig. 7b). Glacier height changes above 5800 m were close to zero except in the peak, which may be affected by the DEM scale effect. Low resolution DEMs tend to smooth the sharp peaks and/or ridges (Gardelle et al., 2013).

Figure 7. (a) Decadal glacier height change pattern for the Gurenhekou glacier. (b) Decadal glacier height changes in each elevation layer. (c) Glacier surface height histogram for the Gurenhekou glacier.

4.4. The effect of debris-cover

Most glaciers in the Western Nyainqentanglha Range are clean ice glaciers, and only five glaciers are reported as

being covered by debris (Bolch et al., 2010). Most clean-ice glaciers terminate at ~5600 m while debris-covered glaciers usually terminate at 5200 m. However, the glacier length study also revealed that the Xibu glacier, the largest and longest debris-covered glacier in the Western Nyainqentanglha Mountain region, retreated at a rate of approximately 10 m yr^{-1} , similar to the clean ice glaciers (Bolch et al., 2010). Figure 8a presents the Landsat false color image, SWIR, NIR and red band showing in red, green and blue the Xibu glacier. Figure 8b shows the L-band differential interferogram; the fringes are mainly due to glacier flow because of its short perpendicular baseline. Presuming that the flow part is the glacier, we identified the debris-covered glacier termini. Figure 8c presents the decadal glacier height changes and clearly shows that the debris-covered glaciers were more stable than the clean-ice glaciers at most elevation bins. We also analyzed the correlation between glacier downwasting rates and glacier elevations (Fig. 9). Downwasting rates of clean ice sections were similar to glaciers such as Zhadang and Gurenhekou. Debris started to cover the glacier surface beginning in the 5650-5700 m layer bin, and clean ice disappeared in the 5500-5550 m layer bin. Only at the highest regions of the debris-covered ice was the glacier downwasting rate higher than the clean ice. For the other parts, debris-cover suppressed glacier thinning to some extent and enabled the debris-covered ice to survive at much lower elevations than adjacent clean iceglaciers.

Figure 8. (a) Pan-sharpened Landsat false color images for the Xibu glacier. Red, NIR and SWIR bands indicate the Xibu glacier in blue, green and red, respectively. Clean ice shows in cyan and debris shows similar color to non-glacier region. (b) The L-band interferogram with 46 days as a temporal baseline with a maximum of 18 fringes at the middle part of the Xibu glacier equaling 44 m yr^{-1} when considering the slope rate and flow direction. (c) Decadal glacier height changing pattern for the Xibu glacier and surroundings.

Figure 9. (a) Decadal glacier height changes in each elevation bin. The blue line denotes the clean ice section and grey line denotes the debris-covered ice section. (b) The glacier surface height histogram for the Xibu glacier.

An unnamed debris-covered glacier is located on the northwestern slope of the western Nyainqentanglha Mountains. Unlike the Xibu glacier, which spans more than 20 km, its length is less than 10 km. Its aspect faces north, thus parts of its glacier surface cannot be illuminated by sun, especially at higher elevations. L-band SAR interferometry cannot detect its glacial boundaries, which may due to complex terrain. Therefore, we applied glacial boundaries in RGI V4.0. Clean-ice coverage was identified using the optical NDSI method, leaving the debris-covered area. Debris starts to cover this glacier starting in the 6000-6050 m elevation bin, above the ELA. However, above the elevation bin 5700-5750 m, the proportions of the debris coverage regions were not large enough to analyze differences in the glacier downwasting rates between debris-covered glaciers and clean-ice glaciers. We are also uncertain if debris can be found above 5750 m because it is difficult to manually identify in shadowed regions. Nevertheless, four elevation bins from 5550 to 5750 m show similar discrepancies of decadal downwasting rates between debris-covered glaciers and clean-ice glaciers (Fig. 11), and at lower elevation, the discrepancy was generally larger, which could be due to thicker debris-cover. Clean-ice glaciers disappeared in the 5500-5550 m elevation bin, while debris-covered glaciers survived to approximately 5350 m.

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498 **Figure 10.** (a) Pan-sharped Landsat false color images for the unnamed debris-covered glacier. Red, NIR and SWIR
499 bands indicate the unnamed glacier in blue, green and red, respectively. Other clean ice glaciers are shown in cyan.
500 Light blue polygons represent the clean-ice region's boundary. (b) Decadal glacier height change pattern for the
501 unnamed debris-covered glacier. The glacier boundary shows in deep blue is given by the RGI V4.0 dataset.

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Figure 11. (a) Decadal glacier height changes in each elevation layer. The blue line indicates the clean ice region and the grey line indicates the debris-covered region. (b) Glacier surface height histogram for the unnamed debris-covered glacier.

5. Discussion

5.1. DEM Differencing basing on a different data sources

Even though DEM obtained with the same equipment and evaluated with the same principles should be optimal to derive glacier height changes, the same satellite cannot usually survive for such a long period of time and using DEMs obtained from different platforms is common. In this study, C-band SRTM with 30 m resolution and X-band SAR images with ~2.2 m resolution were used; therefore, the different resolutions and penetration depths could cause errors. Penetration depth or penetration depth differences can vary from 1.4 m to approximately 10 m according to different studies on the Tibetan Plateau (Gardelle et al., 2013; Kääb et al., 2012&2015; Neckel et al., 2014). Often linear extrapolations of ICESat-derived glacier trends back to SRTM acquisition dates of 2000 reveal absolute penetration

depths of C-band SRTM (Kääb et al., 2012 & 2015; Neckel et al., 2014). Another method to compare C- and X-band SRTM is to consider the X-band SRTM as having zero penetration depth (Gardelle et al., 2013). Large discrepancies between these two datasets may therefore result in different glacier mass balances. Take Hengduan Shan (Eastern Nyainqentanglha Shan, Shan means mountain in Chinese) as an example; the penetration depth was 1.7 m and 8 - 10 m in Gardelle and Kääb's research, respectively, while the mass balances were -0.33 ± 0.14 m w.e. yr^{-1} and -1.34 ± 0.29 m w.e. yr^{-1} , respectively (Gardelle et al., 2013; Kääb et al., 2012&2015). Our estimated average penetration depth discrepancy in the western Nyainqentanglha Mountains was 1.67 ± 0.53 m, which was similar to most sub-region in Gardelle's research except westerlies dominated region (Gardelle et al., 2013). According to our knowledge, no penetration depth derived by C- and X-SRTM has been reported in the Western Nyainqentanglha Mountains, however, if we take the extent of the linear glacier height trend observed by ICESat at the accumulation zone in 2000, the absolute penetration depth was approximately 3 m in their sub-region E (Neckel et al., 2014). Our estimated penetration depth between the C- and X-band in the accumulation zone was higher than 2 m; considering the absolute penetration depth of the X-band electromagnetic wave, this result is reasonable. Penetration depth error dominates the final error of glacier mass balance for regions of entire Western Nyainqentanglha, or are inside or outside the Nam Co Lake drainage basin. Take the entire region as example, error of penetration depth was 0.532 m while the combination of seasonal error, datum error between SRTM and TSX/TDX DEM and random error was only 0.148 m, together the error was 0.552 m for 14-year period. As the TSX/TDX observation accumulated from 2011, DEM differencing between TSX/TDX DEMs observed at different point of time hold great potential in deriving annual glacier mass balance as it is unnecessary to remove penetration depth.

SRTM observations were made in February and the bistatic TSX/TDX observations were obtained during similar seasons but in different months. Different TSX/TDX acquisitions can yield different results for the glacier height change by referring to SRTM. This could be affected by the seasonal snow cover. The derived ICESat/GLAS also display a large fluctuation during the study period (Kääb et al., 2012; Neckel et al., 2014). It is almost impossible to establish a seasonal model to remove the seasonal snow cover effects unless bistatic TSX/TDX acquisitions observed one overlapped region with high temporal resolution. In this research three of our bistatic TSX/TDX acquisitions were obtained in March, which should share similar feature of snow cover with February since temperature is usually below 0°C and almost no precipitation occurs during February by surrounding meteorological records (Yu et al., 2013). Hence presuming no seasonal correction to bistatic TSX/TDX observations in March should be reasonable. For other two bistatic TSX/TDX acquisitions observed in December and April, the average height differences to acquisitions observed in March of overlapped region were applied for removing seasonal affections. Besides, we added 0.15 m each month in error propagation.

Height increases are often observed at ridges in our research, such as at the peak of the Gurenhekou glacier in Fig. 9. This is most likely caused by scale effects of the DEM at different resolutions. The bandwidths of the C-Radar and X-Radar onboard the Shuttle Endeavor used to obtain C- and X-band SRTM are 10 MHz and 9.5 MHz, respectively, while most of our TSX/TDX was at 100 MHz, therefore the resolution of the DEM was 30 m versus ~ 2.2 m

(<https://directory.eoportal.org/web/eoportal/satellite-missions/s/srtm>). The smooth effect of mountain summits resulted in pseudo increases of ridges, therefore at the extremely high part of accumulation zone the increasing rates may be overestimated for several elevation bins (Paul, 2008; Gardelle et al., 2013). However, in a synthetic aperture radar image, the value for each pixel for both amplitude and phase is the coherent sum of contributions from all scatterers within the associated ground resolution element (Hooper, 2008). Therefore scale effects should not induce a bias in estimating average mass balance for accumulation zone or the total glacier.

5.2. Tectonic considerations

The collision of the Indian and Eurasian plates uplifted the Tibetan Plateau to more than 4500 m. The Nyainqentanglha Mountains are located on the western side of the Yadong-Gulu rift, which is an active normal fault (Qiao et al., 2011). Based on GPS geodetic observations, the annual vertical uplift rate surrounding the western Nyainqentanglha Mountains was less than 1 mm yr⁻¹ (Liang et al., 2013). Therefore, tectonic effects should not significantly affect our results.

5.3. Reasons for negative mass balances and the effect of debris

The overall mass balance rate in the first decade of the 21st Century for the Western Nyainqentanglha Mountains was -0.235 ± 0.127 m w.e. yr⁻¹. The mean temperature of five meteorological stations on the ITP increased at a rate of 0.43 K decade⁻¹ associated with an increasing precipitation rate of 34 mm decade⁻¹ (Lei et al., 2013). These five sites are Nagqu (also called as Naqu, 31°29' N 92°04' E), Damxung (also called as Tangxiong, 30°29' N 91°06' E), Xainza (also called as Shenzha, 30°57' N 88°38' E), Baingoin (also called as Bangge, 31°23' N 90°01' E) and Amduo (32°21' N 91°06' E). Negative mass balances should be a response to local climate changes. By using two-dimensional observations, different glacier mass balance rates were derived for this study, which were -0.268 ± 0.129 m w.e. yr⁻¹ and -0.219 ± 0.126 m w.e. yr⁻¹ for inside and outside the Nam Co Lake drainage basin, respectively. By studying glacier lengths and the changing positions of glacier tongues using optical satellite data between 1976 and 2009, slightly higher glacier shrinkage in the Nam Co drainage basin was also reported (Bolch et al., 2010). Results of glacier downwasting rate in each elevation bin (Fig. 5) indicate that glacier height distribution should take part of responsibility for slight higher glacier downwasting at northwest slope as its average glacier height were lower than the glaciers at southeastern slope. However, still in most elevation bins glacier downwasting was slightly larger in side the Nam Co Lake drainage basin than outside the Nam Co Lake basin. During 5550 to 6150, the average difference of decadal height downwasting of inside and outside the Nam Co Lake drainage basin was -0.195 m which equals to -0.013 m w.e. yr⁻¹. Consider the measurement error, the difference of glacier downwasting rate at northwestern and southeastern slope was quite small. Meteorological records also present similar trend of annual average air temperature for the northern and southern meteorological sites (Figure 12 & Table 4). Lhasa site should not be considered in comparing air temperature trend as urban heat island effect might increase when urbanization area spanned during 2000-2012. However, southern meteorological sites experienced precipitation drop while northern site did not. This explains the lake shrinkage for the southern part of Tibetan Plateau but against our results of glacier mass balance patten (Zhang et al., 2011). Similar mass balance rate for glaciers on northwestern and southeastern slopes and discrepancy rates for Zhadang and Gurenhekou glaciers also indicates the importance of remote sensing technique in monitoring large scale glacier status.

Figure 12. Air temperature and precipitation trend during 2000 – 2012 for the six meteorological stations surround the Western Nyainqentanglha Mountains.

Table 4. Information of the six meteorological stations surround the Western Nyainqentanglha Mountains.

Station Name	Latitude	Longitude	Temperature Trend (°C yr ⁻¹)	Precipitation Trend (mm yr ⁻¹)
Xainza (N)	30°57' N	88°38' E	0.060	-3.785

Baigoin (N)	31°23' N	90°01' E	0.082	4.944
Nagqu (N)	31°29' N	92°04' E	0.071	-3.785
Xigaze (S)	29°15' N	88°53' E	0.064	-2.132
Lhasa (S)	29°40' N	91°08' E	0.119	-19.126
Damxung (S)	30°29' N	91°06' E	0.088	-13.280

Very shallow layers of debris usually enhance melt rates by lowering the surface albedo, and thicker layers suppress melt rates by reducing the amount of surface heat conducted to the ice (Reid et al., 2012). Our study of the Xibu glacier confirms this by observing glacier height changes at different elevation levels, where the positively/negatively affected zones of debris can be separated. Study of the unnamed debris-covered glacier on the northwestern slope only detected a similar phenomenon. A glacier length study of the Xibu glacier between 1976 and 2009 based on manual identification from optical images showed a retreat rate of approximately 10 m yr⁻¹ of its glacier tongue, similar to other clean-ice glaciers (Bolch et al., 2010). However, our study not only shows that debris-cover suppresses the melting rate at the same elevation compared to clean-ice glaciers, but it also shows that the maximum downwasting rate of clean-ice was even larger than debris-covered ice on Xibu glacier (Fig. 9). The maximum downwasting rate for debris-covered glaciers did not exceed -15 m decade⁻¹, while several long clean-ice glaciers on the southeastern slope downwasted at about -60 m decade⁻¹ at their glacial tongues. Studies rarely report effects of debris-cover on glacier mass balances in the Inner Tibetan Plateau because most debris-covered glaciers are located in the Himalayan, Karakoram and Pamir Mountains. Basing on satellite images, debris-covered glaciers were reported to have remarkably stable fronts at Karakoram, Hindu Kush, Himalaya and West Kunlun Shan and therefore were unsuitable as indicators of recent climate changes (Scherler et al., 2011). However, by using topographic differencing on SRTM and stereo Hexagon satellite data, it has been inferred that debris-covered glaciers seem to be losing as much mass as debris-free glaciers at Langtang in the Himalayas (Pellicciotti et al., 2015). The estimated velocity for the Xibu glacier was up to 44 m yr⁻¹ as calculated by manually counting fringes in the ALOS/PALSAR interferogram and assuming glacial flows along the valley (Fig. 8c). The annual velocity for the Langtang glacier was less than 5 m yr⁻¹, as derived by feature tracking of Landsat images, despite its debris-covered slope's being only slightly gentler than Xibu glacier, 3.1° versus 4.6° (Pellicciotti et al., 2015). This implies that the rapid downwasting rates of some debris-covered glaciers may be associated with slow flow rates, which will require further investigation in the future when remote sensing data with higher spatial and temporal resolution become available.

5.4. The hydrological effect

In this research, by quantifying the glacier mass balance in the Nam Co Lake drainage region at -0.268 ± 0.129 m w.e. yr⁻¹, the estimated contribution rate of glacier melting to the Nam Co Lake's increasing water level was $10.50 \pm 9.00\%$ between 2003 and 2009, assuming that the glacier mass balance rate remained steady from 2000 to 2014. This rate is much lower than previous studies that also focused on the Nam Co Lake basin (Zhu et al., 2010; Lei et al., 2013). Using optical data of the lake area expansion and GIS technologies to simplify hydrological modeling, Zhu claimed that 52.86% of the increase in

Nam Co Lake's volume was contributed by glacier melting between 1971 and 2004. Extending the study period to 2010, applying similar methods and taking Zhadang glacier's mass balance rate to be 0.59 m yr^{-1} , Lei found a 28.7% increase in Nam Co Lake's volume between 1999 and 2010. After including glacial melting, Lei obtained a perfect coupling between the simulated water balance result and the measured water volume increase for Nam Co Lake between 1980 and 2010 despite using the wrong glacier mass balance rate inside the Nam Co drainage basin. Even if the glacier mass balance rate derived from bistatic differential SAR interferometry is not used, the glacier mass balance rate inside the Nam Co drainage basin cannot be as large as $-0.59 \text{ m w.e. yr}^{-1}$ if using laser altimetry data or simply extending the in-situ mass balance rate profiles of Zhadang and Gurenhekou to higher elevations (Yao et al., 2012; Yu et al., 2013; Neckel et al., 2014). Therefore, it can conclude that the contribution of glacier melting to Nam Co Lake was overestimated in Lei's (2013) research. In addition, several studies using satellite gravity have yielded similar results: almost all parts of the closed lake volume increased between 2003 and 2009 due to increasing precipitation because both glacier melting and frozen ground degradation cannot change the local gravity in endorheic regions (Song et al., 2013; Zhang et al., 2013).

6. Conclusions

In this research, to map glacier height change patterns and glacier mass balances in the western Nyainqentaglnha Mountain Range, we applied six pairs of X-band bistatic SAR images observed between 2011 and 2014 to differential SAR interferometry SRTM obtained in 2000. Glacier mass balance in the first decade of the 21st century was $-0.235 \pm 0.127 \text{ m w.e. yr}^{-1}$ for the western Nyainqentaglnha Mountain glaciers, and most downwasting occurring in the ablation and accumulation zones was relatively stable. Slight mass balance discrepancies of $-0.268 \pm 0.129 \text{ m w.e. yr}^{-1}$ and $-0.219 \pm 0.126 \text{ m w.e. yr}^{-1}$ were found for glaciers on the northwestern and southeastern slopes, respectively. We examined two glaciers, the Zhadang and Gurenhekou glaciers, in detail with in-situ mass balance observations. Our estimated glacier height change pattern matches the results of in-situ observed profiles, and the overall glacier mass balance also shows agreement. Error in estimating penetration depth between X- and C-band SRTM dominates the total error of glacier mass balance. Debris-covered glaciers have smaller downwasting rates than clean-ice glaciers in the same elevation except where the debris is starting to cover the glacier and is shallow. The effects of glacier flow rates on the glacier mass balance require further study. If glacier melt is assumed to flow into the Nam Co Lake without any evaporation, it contributed $10.50 \pm 9.00 \%$ to the Nam Co Lake volume increase between 2003 and 2009, which is considerably less than was observed in previous studies.

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