

Journal of
Applied Remote Sensing

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Abstract. The Northern Hemisphere experienced its warmest temperatures in the early 21st century, and this clearly increased glacier melting on the Tibetan Plateau. This study analyzed the glacier change in the area, their terminus positions and surface elevations over the last decade (2003 to 2013) in the Naimona’Nyi region of the western Himalayas, by comparing remote sensing data and differential global position system (dGPS) data from *in situ* surveys. The results show an accelerating glacier retreat over the past decade in this region. The area covered by glaciers was reduced by a total of 13.2 ± 0.0022 km² over this period. The terminus of the Naimona’Nyi main glacier studied in the paper retreated by over 191 ± 35 m. We also compared the ice cloud and elevation satellite elevation data with *in situ* measured decimeter accuracy dGPS elevation data, thus providing changes in glacier surface elevations in different periods. The maximum measured glacier thinning rate reached to 0.58 ± 0.06 m/a between 2009 and 2013. In addition to the dependence on elevation and glacier size, we found a larger retreat on the north facing slopes than on the south facing slopes in the region. Meteorological data show that glacier changes within the study area can probably be attributed to the observed rapid temperature rise. © The Authors. Published by SPIE under a Creative Commons Attribution 3.0 Unported License. Distribution or reproduction of this work in whole or in part requires full attribution of the original publication, including its DOI. [DOI: [10.1117/1.JRS.8.083508](https://doi.org/10.1117/1.JRS.8.083508)]

Keywords: glacier change; western Himalayas; Naimona’Nyi region; ice cloud and elevation satellite; optical remote sensing.

Paper 14462 received Aug. 1, 2014; accepted for publication Nov. 7, 2014; published online Dec. 9, 2014.

1 Introduction

Glacier change is the best indicator of climate change, and it rapidly responds to changes in precipitation and temperature.^{1,2} Glacier shrinkage in the high Himalayas and the Tibetan Plateau has drawn worldwide attention to the changing climate. In addition, glacial melt water provides an important freshwater resource and significantly contributes to global sea-level rise.³⁻⁶

The Himalayas hold more than one-fourth of the glacier area in all of “High Asia” and most of the glaciers have, in recent decades, been rapidly retreating and losing ice.⁷⁻⁹ Great efforts have been made to assess the shrinkage of glaciers in the eastern and central Himalayas of China.¹⁰⁻¹⁴ However, less research has been done in the western Himalaya due to the problem of difficult access. Studies on glacier change will provide valuable information related to climate

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change both regionally and globally.¹⁵ In addition, glaciers within our study area are important water resources for production and local habitants.¹⁶

Earlier studies on the variability of the Naimona'Nyi glacier have been carried out by a few researchers. Yao et al. estimated the glacier mass balance from stake measurements,¹⁶ while Wang et al. and Ye et al. calculated glacier areas and volume losses before 2003 based on remote sensing data.^{17,18} Kehrwald et al. analyzed the ice core data from the Naimona'Nyi main glacier and found that the surface of this glacier had melted due to the warming climate.³ Since the results of those researches are earlier works, glacier changes in Naimona'Nyi area should be further monitored because the past decade was the warmest decade of the Northern Hemisphere¹⁹ and more new data is available.

A variety of methods has been applied to monitor glacial changes. The most commonly used methods compare data from a variety of images (e.g., remote sensing, digital elevation models, and topographic maps) in different periods.^{9,12} Compared with glacier area change, glacier surface elevation for the most recent changes is more difficult to investigate. The traditional way to measure glacier thinning is direct annual measurements. However, annually, *in situ* measurements are difficult because of the harsh working conditions. Laser altimetry data acquired by the geoscience laser altimeter system (GLAS) carried on the ice cloud and elevation satellite (ICESat) have now been proven to provide accurate data for glacier surface elevations.^{20,21} However, the satellite tracks in different years do not overlap and do not allow for easy annual comparisons for these data. Combining the ICESat data with *in situ* decimeter-accuracy differential global position system (dGPS) measurements of the glacier may provide a better approach for monitoring changes in glacier thickness with a high accuracy. Fortunately, the Naimona'Nyi main glacier in the research region is covered by ICESat data and is now available for this kind of comparison.

This study discusses how these glaciers have changed over the last decade in the Naimona'Nyi region of the western Himalaya, based on both ICESat data and site geodetic measurements, including the glacier area, the glacier's terminal position, and specific glacier surface elevation changes, in order to determine their responses to climate change.

2 Study Area

Mt. Naimona'Nyi lies in the western Himalayas, southwest of the Tibetan Plateau (Fig. 1). The peak reaches an elevation of 7694 m, the highest mountain in the western Himalayas. A large number of glaciers were formed here because of the high elevation. Earlier work shows that the equilibrium line altitude (ELA) ranges between 5100 and 6000 m, with the ELA on the northern slopes 400 m higher than that on the southern slopes.²² The Naimona'Nyi main glacier, the largest glacier in the research region, extends over 10 km and has a width of approximately 3 km. The maximum thickness of this main glacier exceeds 250 m; it was measured in 2008 by ground penetrating radar and the result has not been published anywhere. Its total area exceeds 10 km².

Both the westerly circulation and the southwest monsoons affect the Naimona'Nyi region. The nearest meteorological station (Purang: 30°17'N, 81°15'E; the elevation of 3900 m), which is only 20 km away from the Naimona'Nyi main glacier, shows an annual average precipitation of 169 mm and average air temperature of 3°C. However, precipitation could be much greater in the high mountain regions, perhaps between 760 and 1000 mm.¹⁶

3 Data and Methods

3.1 Optical Remote Sensing Data

3.1.1 Data preprocessing and glacier delineation

This study used four Landsat enhanced Thematic Mapper Plus (ETM+) images and one from the Landsat operational land image (OLI) provided by the United States Geological Survey²³ to map the glaciers. Except for imaging time, these images have the same path/row (144/39) and spatial resolution (30 m). In order to delineate the glaciers and reduce the influence of seasonal snow

and cloud cover, we selected images in late summer and early autumn. Because no image from this season was available in 2013, we used images from December 2013 instead. Because there was no heavy snow prior to December according to meteorological data in this region and light snow could not last, the seasonal snow influence is weak and was ignored here. The spatial resolutions for both Landsat ETM+ and Landsat OLI optical remote sensing images have been determined to be 30 and 15 m for the panchromatic band. Because of a sensor problem, a gas stripe appears in the Landsat ETM+ images after May 31, 2003. In order to ensure the data accuracy, we repaired the data, registered the new data with the high quality Landsat OLI image, and constrained the error within one pixel. Global digital elevation model data from National Aeronautics and Space Administration have a resolution of 30 m²⁴ (The Land Processes Distributed Active Archive Center). All image projections use the WGS84-UTM coordinates.

Image fusion helps to improve image resolution and the identification of terrestrial objects,^{25,26} and is commonly used for monitoring glaciers by optical remote sensing.²⁷ The selection of fusion methods depends on the features discernible in the fused images and the purpose of the fusion. Studies have shown that the principal component analysis transform algorithm for Landsat ETM+ panchromatic and multispectral images provides the optimal fusion,²⁸ which has been used in this work. Our study fused the false color images synthesized from the ETM+ 543 band and the panchromatic images to produce multispectral images with a resolution of 15 m. The fused images were used to extract glacier boundaries.

A variety of methods have been used to determine glacier boundaries from optical remote sensing images, including: supervised classification, unsupervised classification, Normalized Difference Snow Index, Band Ratio, visual interpretation, and so on. Among them, visual interpretation has the highest accuracy, especially for discrimination between snow accumulation and debris areas with a low probability of error. Band ratio is also a suitable method in practice.²⁹ Considering the existence of the seasonal snow, shadow areas and small clouds, we did not use these automatic identification methods, which could affect the accuracy. Instead, we primarily relied on visual interpretation and used the TM4/TM5 band ratio as complementary to delineate the glaciers in the Naimona’Nyi region. A threshold was set to 2.3 to separate glaciers from nonglacier covered areas.

3.1.2 Uncertainty in delineating glacier outlines

Previous experience suggests that spatial resolution and registration errors provide two key causes of uncertainty. The uncertainty can be estimated by Eq. (1):^{30,31}

$$U_T = \sqrt{\sum \lambda^2} + \sqrt{\sum \varepsilon^2}, \quad (1)$$

where U_T represents the uncertainty of the glacier terminus, λ is the original spatial resolution of a single image, and ε is a single image registration uncertainty.

The various sources of uncertainty are complex. However, Eq. (1) provides a simple and an effective way to estimate glacier terminus uncertainty in practice and has been used in this work. Results indicated that the glacier terminus measurement uncertainties are 26, 25, and 24 m, respectively, for 2003 to 2006, 2006 to 2009, and 2009 to 2013. The total U_T among the four images was 35 m during 2003 to 2013.

The errors in glacial terminus result in uncertainties in the delineated glacier areas. Ye et al. obtained the glacier area uncertainty (U_A) by using Eq. (2):³¹

$$U_A = 2U_T \sqrt{\sum \lambda^2 + \varepsilon^2}. \quad (2)$$

Therefore, we estimated the uncertainty of the glacier area in the Naimona’Nyi region to be 0.0022 km².

3.2 Surface Elevation Data

3.2.1 Ice cloud and elevation satellite and high precision differential GPS measurements

The GLAS on ICESat can monitor the elevation change of a glacier surface, especially on the polar ice sheet.³² GLAS offers 15 products for the entire Earth, which can be downloaded from the International Snow and Ice Data Center (NSIDC).³³ This paper used the latest “release 33-level 2” of GLAS14 products, which have the same parameters except for the dates. Compared with earlier versions, “release 33” incorporates a variety of optimizations and improvements on the fast line-of-sight atmospheric analysis of spectral hypercubes, parameter corrections, accuracy improvements, elevation treatments, and so on.

NSIDC gave the central geographic coordinates of each footprint (footprint: diameter 70 m), but did not include the center point's elevation. In this paper, we regarded the footprint's elevation as the center point's elevation, and calibrated the elevation through verification points, so that we could match the field dGPS survey and the footprint of ICESat. This approach basically compares the elevation changes from ICESat data and dGPS data for specific footprints on the glacier. First, we extract the center geographic coordinates and elevation for each ICESat footprint. Subsequently, we determine the center point position by dGPS, remeasure the current elevation, and subtract the ICESat elevation from the remeasured dGPS elevation. Thus, the glacier surface elevation change during a specific period can be determined.

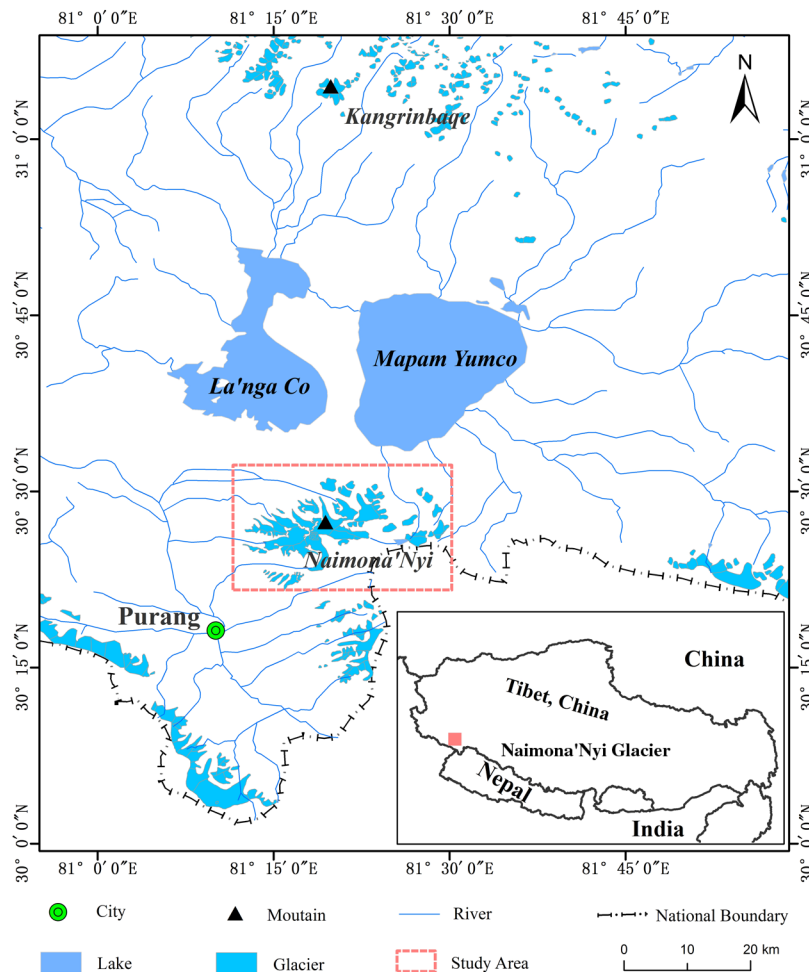


Fig. 1 Location of the Naimona'Nyi glaciers in the western Himalayas. The inner rectangle shows the glaciers studied in this work.

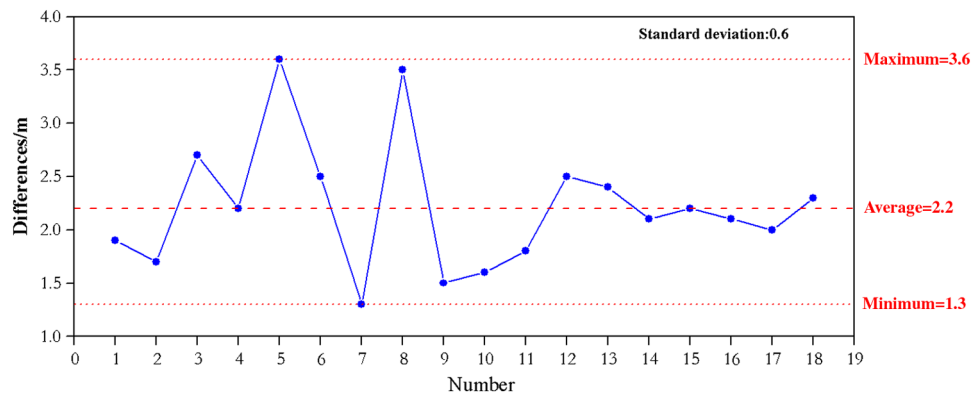


Fig. 2 The differences between footprint elevation and center point elevation of 18 verification points.

ICESat provides the elevation data for the period from 2003 to 2009. Our study obtained the surface elevations of the Naimona’Nyi glacier in 2013 by dGPS remeasurements for each specific footprint. We made the dGPS measurement on September 12, 2013, using the NavCom Starfire3050 differential GPS receiver from Unistrong Company. We tested the measurement precision by comparing the dGPS data at a National first-class geographic reference point in Tibet and the vertical error was within ± 0.06 m. The GLAS14 elevation data are based on TOPEX/Poseidon as a reference datum, while the SF3050 satellite differential measurement was based on WGS-84. Therefore, we combined the two kinds of reference data into WGS-84.

3.2.2 Data qualification for ice cloud and elevation satellite

Although the footprint of ICESat proved to be an accurate data source for glacier surface elevations, the elevation is the average value of the footprint (diameter: 70 m) not the center point of the footprint. As a result, the elevation provided in ICESat may be doubtful on rough surface. The part of the glacier surface where we measured on the Naimona’Nyi main glacier is large and quite flat, with a slope lower than 6 deg. This will constrain the uncertainty in elevation, especially within the scope of a footprint. However, the calibration is still necessary. Previous studies have used decimeter accuracy dGPS differential GPS (dGPS) to verify the difference of ICESat data,^{34,35} with results showing that the deviation is closely related to spatial location. We examined these differences in the Naimona’Nyi region using an *in situ* dGPS survey for specific footprints. We selected 18 footprints to estimate the difference between the center point’s elevation and footprint data in the flat nonglacier terrain near the Naimona’Nyi glacier. The result shows that the maximum difference, the minimum difference, and average difference in this area are 3.6, 1.3, and 2.2 m, respectively (Fig. 2).

We then used the average difference value to calibrate ICESat elevations so as to remove the uncertainty of the elevation values for the glacier surface.

4 Results

4.1 Changes in Glacier Area

We estimated the changes in glacier area in the Naimona’Nyi region from satellite images. Our results show that the total glacier coverage in the region reached 79.6 km² in 2003, 76.3 km² in 2006, 72.3 km² in 2009, and 66.3 km² in 2013 during the three intervening intervals (Table 1). This is equivalent of annual area change rates of -1.3% , -1.7% , and -2.1% , respectively. An earlier work using advanced spaceborne thermal emission and reflection radiometer images showed that glaciers in this region covered 79.3 km² in 2003,¹⁸ matching well with our results. Slight differences might come from data sources, interpretation methods and timing. Results

Table 1 Glacier area changes in the Naimona’Nyi region between 2003 and 2013.

	Time	Area (km ²)	Area change (km ²)	Annual change rate (km ² /a)	Annual change rate (%)	Glacier terminus change (m)	Annual change (m/a)
Total glacier area	2003 to 2006	79.5 to 76.3	-3.2 ± 0.0015	-1.1	-1.3	—	—
	2006 to 2009	76.3 to 72.3	-4.0 ± 0.0015	-1.3	-1.7	—	—
	2009 to 2013	72.3 to 66.3	-6.0 ± 0.0015	-1.5	-2.1	—	—
	2003 to 2013	79.5 to 66.3	-13.2 ± 0.0022	-1.3	-1.6	—	—
Main glacier	2003 to 2006	15.4 to 14.6	-0.8 ± 0.0015	-0.3	-1.8	-82	-27.3
	2006 to 2009	14.6 to 14.9	0.3 ± 0.0015	0.1	0.6	-58	-19.3
	2009 to 2013	14.9 to 14.6	-0.3 ± 0.0015	-0.1	-0.5	-51	-12.8
	2003 to 2013	15.4 to 14.6	-0.8 ± 0.0022	-0.1	-0.5	-191	-19.1

show that glacier area in 2013 only covered 83% of the glacier area in 2003, or a shrinkage of 13.2 km² over the last decade. Glacier retreating rates varied in different periods, with the most rapid retreat during 2009 to 2013 (Table 1).

Glacier area changes between the northern and the southern slopes in the Naimona’Nyi area are also compared [Fig. 3(a)]. The glaciers on the southern slopes have lost 3.4 km² in area over 10 years, which is only 35% of that on the northern slopes. Also, the temporal patterns of retreat are different between the two slopes. The glacier coverage of the southern slopes changed by 0.2 km², -3.9 km², and 0.3 km² during the periods of 2003 to 2006, 2006 to 2009, and 2009 to 2013, respectively. During the same periods, the glacier area on the northern slopes changed by -3.4 km², -0.1 km², and -6.2 km². Compared with the consistent retreats on the northern slopes, the southern slopes showed only a moderate retreat or even slight advances.

Approximately 89% of the glacier areas’ loss during the period between 2003 and 2013 is within the elevation zone between 5500 and 6500 m. However, on the lower zones of the glaciers, up to 96% of the glacier area below 5500 m disappeared. Between 5500 and 6000 m, the glacier area lost 23%, and between 6000 and 6500 m the glacier area lost 11%. Above 6500 m, no obvious glacier area change is found [Fig. 3(b)].

4.2 Change in the Area and Terminal Position of the Naimona’Nyi Main Glacier

The Naimona’Nyi main glacier is the largest single glacier in this region and accounts for 20% of the total glacier area. This study addresses changes of this main glacier, which lost 5.3% of its

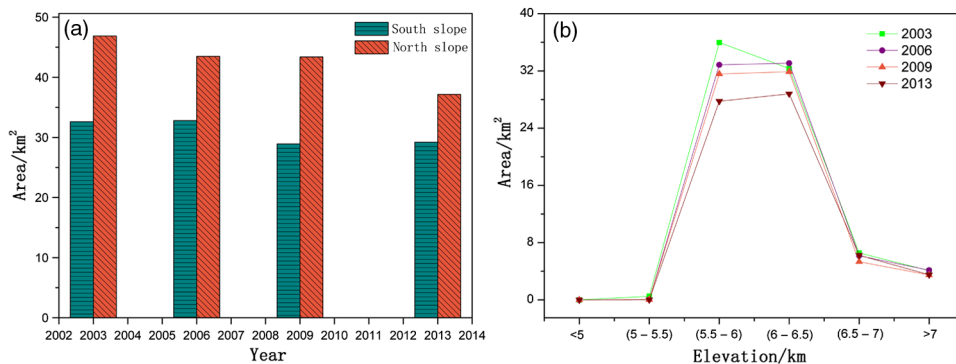


Fig. 3 Changes in glacier areas in Naimona’Nyi region with (a) different slopes and (b) elevation.

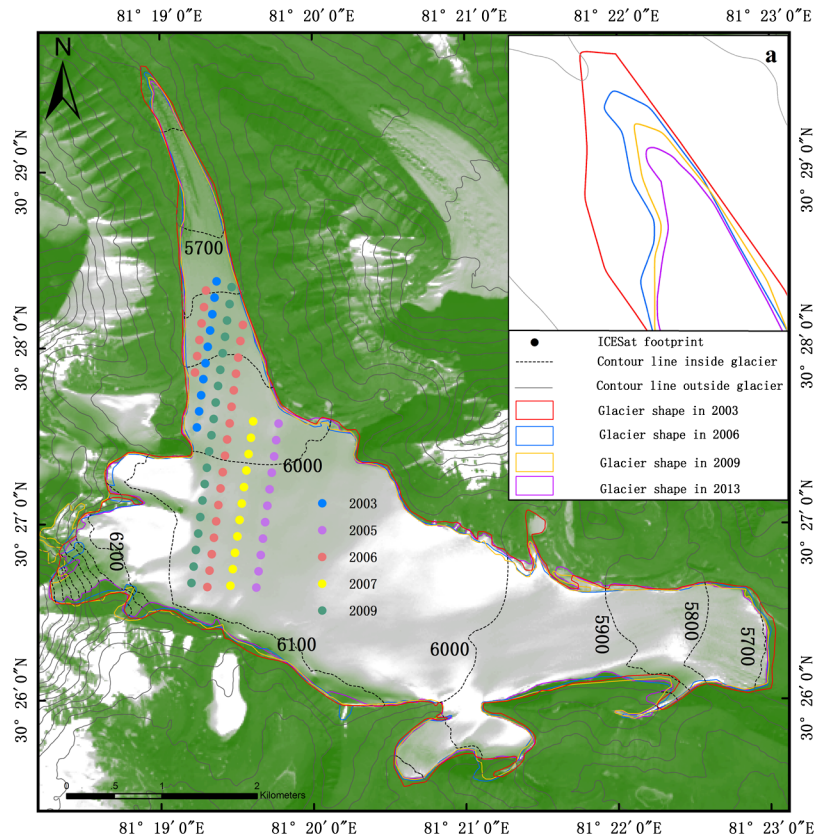


Fig. 4 Changes of the main glacier’s outline and glacier terminal position (a) between 2003 and 2013. (Color dots refer to ICESat footprints in different times).

area between 2003 and 2013. Despite the overall retreating trend, our study found this glacier had expanded 0.3 km^2 during the period between 2006 and 2009. The most rapid glacier retreat took place between 2003 and 2006, with a retreat rate of $0.3 \text{ km}^2/\text{a}$, three times larger than the average between 2003 and 2013.

The glacier’s terminal position may respond differently to climate change than the glacier area change. The glacier’s terminal position retreated by 82, 58, and 51 m during the intervals of 2003 to 2006, 2006 to 2009, and 2009 to 2013. During the past 10 years, the main glacier’s terminus retreated 191 m, with an annual average rate of 19.1 m/a . The largest retreat of the glacier terminus occurred between 2003 and 2006, in accordance with the glacier area change. Unlike the zero changes in glacier area between 2006 and 2013, the glacier terminus still showed a considerable rate of retreat (Fig. 4).

4.3 Surface Elevation Changes of the Naimona’Nyi Main Glacier

The coverage of the ICESat orbit only allows the study of glacier surface elevation changes on specific parts of the Naimona’Nyi main glacier. A total of 74 ICESat footprints from different years (Table 2) were remeasured by dGPS on the glacier surface in 2013. Then we compared the remeasured dGPS data with ICESat footprint elevations as described in the early section to obtain changes of the glacier surface elevations. However, because the data came from different periods, we present the annual change rates during specific periods (Table 2). For the ICESat points in 2003, the average measured glacier elevation change was -2.7 m on average between 2003 and 2013, with an annual rate of -0.27 m/a . The largest rate of elevation change was -0.58 m/a during the period of 2009 to 2013.

We found a slight changing rate of glacier surface elevation with different altitude zones. We divided the glacier surface into seven elevation zones based on an elevation intervals of

Table 2 Average changes of the surface elevation on the main glacier.

Time period	Average change (m)	Annual change rate (m/a)	Number of footprints
2003 to 2013	-2.7	-0.27 ± 0.06	10
2005 to 2013	-3.6	-0.45 ± 0.06	11
2006 to 2013	-2.6	-0.37 ± 0.06	23
2007 to 2013	-2.3	-0.39 ± 0.06	11
2009 to 2013	-2.3	-0.58 ± 0.06	19
—	—	—	Total: 74

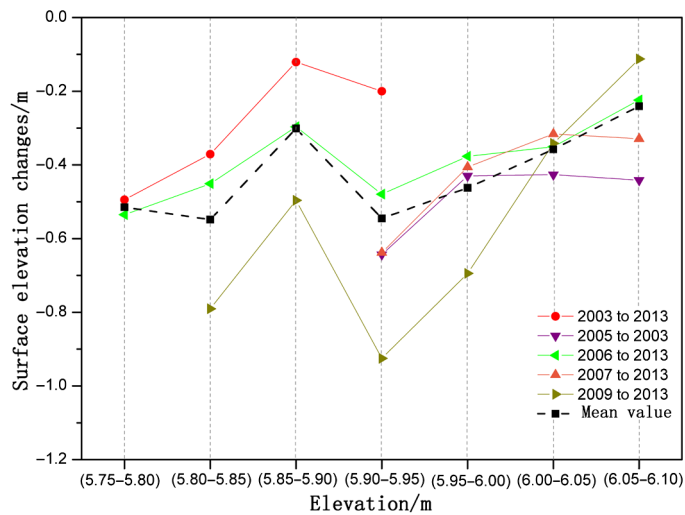


Fig. 5 Surface elevation changes in different elevations of the main glacier.

50 m, and then compared the glacier surface elevation changes in each group (Fig. 5). The maximum glacier elevation change rate of -0.53 m/a was within the elevation of 5750 to 5800 during the period of 2009 to 2013. A slight decrease in the elevation change rate was noted between the lower and the upper portions of the glacier, as shown in the black dashed line in Fig. 5.

5 Discussion

5.1 Glacier Retreat

Since the early 20th century, glaciers on the Tibetan Plateau have generally been retreating, and this trend has accelerated since the 1990s.³⁶ Our work on the Naimona’Nyi glaciers in the western Himalayan shows that glacier retreat increased during the last decade. The glacier retreat rate between 2003 and 2013 is five times of that in the previous 30 years (1973 to 2003).¹⁸ The observed annual retreat rate of 1.6%/a for the Naimona’Nyi glaciers significantly exceeds the 0.42%/a for the entire western Himalayas, 0.41%/a for the middle Himalayas, and 0.57%/a for the eastern Himalayas (1980–2010).¹⁵ Glacier retreat in the Himalayas appears to be accelerating over the past decade, which matches conclusions from other regions.^{37,38} This work also found that the main glacier in the Naimona’Nyi region remains relatively inert compared with the majority of other glaciers in this region. The retreat rate for the Naimona’Nyi main glacier remains lower than most glaciers on the Tibetan Plateau, but seems to be roughly similar to those in the West Kunlun region.³⁹ This may be related to the fact that small glaciers are

more sensitive to climate change, and small glaciers account for much of the glacier area loss.

Glacier elevation and glacier orientation affect their rates of glacier area change. This has been found in the middle of Tianshan and in western Nyainqentanglha.^{40,41} In the Naimona’Nyi region, the lower portions of the glaciers show the fastest retreats, and glaciers below 5500 m have almost entirely disappeared. The maximum melt zone in the Naimona’Nyi region lies in the 5500 to 6000 m elevation range, which is similar to that in the Mt.Qomolangma National Nature Reserve.⁴² More glaciers in the Naimona’Nyi region lie on the northern slopes, including the Naimona’Nyi main glacier. Roughly, the glaciers on the northern slope should retreat less than those on the southern slope which receives more direct sunlight. However, in the Naimona’Nyi region, glacial retreat shows the opposite relationship with glacier orientation. Glaciers on the southern slopes retreated less than those on the northern slopes, and some even advanced during some periods. This is possibly because most of the south slope glaciers are located at higher elevations, which could also explain the different retreat patterns between the two slopes of the Naimona’Nyi glaciers.

The Naimona’Nyi main glacier terminal position has been constantly retreating over the period of this study. However, no obvious trend in retreat rate has been observed. This pattern differs from the glacier area change. For the Naimona’Nyi main glacier, the retreat rate was 19.1 m/a between 2003 and 2013 based on remote sensing image, and significantly exceeds the retreat rate of 7.8 m/a measured by Yao et al. during 2004 to 2006.¹⁶ The difference likely relates to the study methods,⁴² in that Yao et al. only measured part of the glacier terminus.¹⁶ Large annual variations of the glacier terminal position and somewhat different time periods of study may also prevent accurate direct comparisons. However, this retreat rate falls below that determined for the Panu glacier (1997 to 2007: 24.7 m/a) and the Jicong Pu glacier (1977 to 2003: 48 m/a).^{43,44}

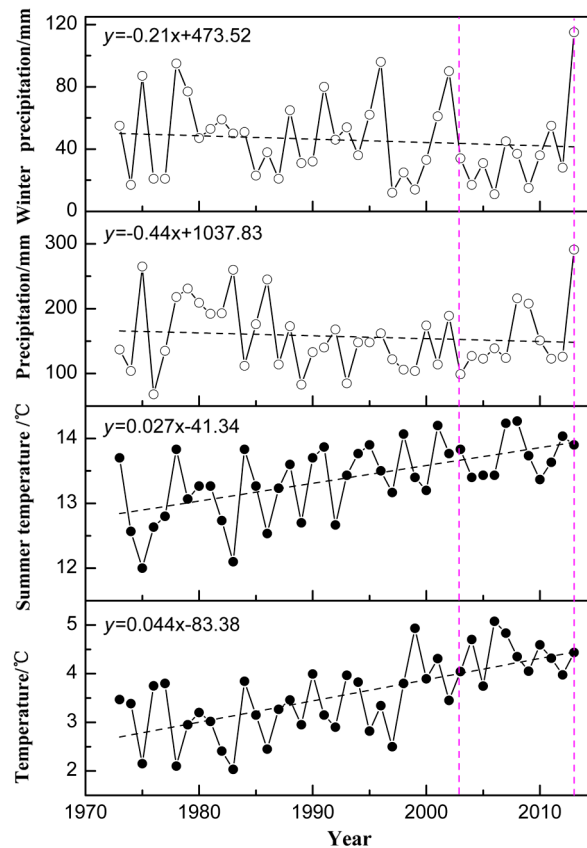


Fig. 6 Annual precipitation, winter precipitation (January to March) and annual averaged temperature, summer averaged temperature (June to August) changes at Purang between 1973 and 2013. (Dashed vertical lines indicate the period of 2003 to 2013).

Our study also presented glacier surface elevation changes. Glacier thinning rates clearly vary with different periods, but they generally show rapid thinning since 2009. Compared with the results from other regions, the thinning rate remains moderate for the Naimona’Nyi main glacier. For instance, Zhang et al. report the East Rongbuk Glacier to be thinning at an estimated rate of 0.86 m/a;⁴⁵ Kääb et al. report thinning of 0.21 ± 0.05 m/a in the Kush-Karakoram-Himalaya region;²⁰ and Wang et al. report 0.15 m/a of thinning on the Urumqi No. 1 Glacier.⁴⁶ Furthermore, our study found that glacier thinning rates varied with location on the glacier, especially with elevation. Below 5950 m, the thinning rate varied over a large range. Above that elevation, the thinning rate shows an apparent decreasing trend with elevation, and this trend held for all of our measurement periods.

5.2 Climate Controls Changes on the Naimona’Nyi Glacier

Climate changes, especially changes in air temperature and precipitation, directly relate to glacier changes.^{1,2} The following presents the climate change trend available from the Purang meteorological station (1973 to 2013), the station nearest to our study area, and compared it with glacier change.

The annual temperatures and summer temperatures increased at the rate of $0.43^{\circ}\text{C}/10$ a and $0.27^{\circ}\text{C}/10$ a, respectively, at the Purang station over the past 40 years, which are much greater than the entire Tibetan Plateau and the global average.⁴⁷ However, annual precipitation and winter precipitation show slight decreasing trends, with decreases of 0.44 and 0.21 mm/a, respectively (Fig. 6). Earlier studies showed that summer temperatures and winter precipitation provide the primary controls affecting these glacier changes.^{48,49} The annual variations of air temperature and precipitation did not match with the annual glacier changes, implying that the glacial change results more from long-term climate variations. Our study concludes that the accelerating retreat of the Naimona’Nyi glaciers mainly results from the significant climate warming and less so from the slight precipitation changes.

6 Conclusions

The investigation examined glacier changes in the Naimona’Nyi region over the last decade (2003 to 2013) based on satellite images, ICESat data, and dGPS data. Our efforts concentrated on changes in glaciers’ areas, terminal positions, and surface elevations.

The area covered by glacier ice in the Naimona’Nyi region rapidly decreased, with a total area decrease of 16.5% over the past decade. The retreat rate shows an increasing trend, with the most rapid retreat occurring in the last 4 years. The terminal position of the main glacier retreated 191 ± 35 m in total in the past decade.

This study used *in situ* surveys on the main glacier surface and comparisons with the ICESat data to present precise changes in glacier surface elevations. The results show the glacier thinning rate is accelerating. The largest measured glacier thinning rate is 0.58 ± 0.06 m/a between 2009 and 2013, and the glacier surface elevation changes spatially vary on the glacier.

Glacier retreat correlates somewhat with slope, orientation, and area. Northward facing glaciers retreated faster than south facing ones. Low elevation zones of glaciers lost more area than the glacier’s high elevation zones. As previously recognized, small glaciers did not survive climate warming. By comparisons with meteorological data, we conclude that the Naimona’Nyi glacier retreat mostly results from long-term air temperature increases in the region and is less influenced from slight precipitation changes.

Acknowledgments

We thank two anonymous reviewers for constructive comments and suggestions so that we can revise and significantly improve this paper. This work is funded by the “Strategic Priority Research Program (B)” of the Chinese Academy of Sciences (Grant No. XDB 03030100), and the National Natural Science Foundation of China (Grant Nos. 41025002, 41371086, and 41101072). Major Special Project-the China High-Resolution Earth Observation System (30-Y30B13-9003-14/16-01).

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