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GLACIER CHANGE IN THE YIGONG ZANGBO BASIN, TIBET, CHINA (1988-2010)

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Abstract: Distinguishing debris-covered glaciers from debris-free glaciers is difficult when using optical remote sensing images to extract glacier boundaries. Glacial changes in the Yigong Zangbo basin was analyzed on the basis of visible, near-infrared and thermal-infrared band images of Landsat5 in the support of the ancillary digital elevation model (DEM). The glacier area gradually declined from 1988 (930.84 km^2) to 2000 (918.46 km^2) and 2010 (907.16 km^2). In addition, the glacial area decreased by 1.03 km^2/year between 1988 and 2000 and by 1.13 km^2/year between 2000 and 2010. The areas of the debris-covered glaciers showed a slight increase from 63.39 km^2, 69.64 km^2, to and 69.67 km^2 in 1988, 2000 and 2010, respectively.

1. Introduction

The cryosphere is one of the main factors that affect changes in global sea level. Alpine glaciers are the most sensitive to climate change and are used as indicator for climate change [1]. Glacier retreat is accelerating with global warming as the amounts of CO_2 and other greenhouse gases increase [1]. To obtain information regarding the distribution and changing trends of glaciers, glacier inventory programs have been launched by the National Snow and Ice Data Center (NSIDC), the World Data Center in Cambridge (WDC-C) for Glaciology, the National Oceanic and Atmospheric Administration (NOAA), the National Aeronautics and Space Administration (NASA) and other agencies [2]. There are over 36,000 glaciers in the western China, only a few of them are under long-term observations [3]. Tianshan Glacier No. 1, the headwater of River Urumqi, is the only one with nearly 30 years of observation data [4]. The Chinese glacier inventory was built over 20 years and completed in 1999. This inventory mainly reflects the status of glaciers during the first aerial mapping period (late 1950s to late 1970s) in China and is a comprehensive collection of aerial photographs, topographic maps and field survey data for individual glaciers and for China's basic glacier data census [5, 6]. However, the Chinese glacier inventory does not reflect glacial changes in recent decades.

With the development of satellite imaging technology, remote sensing images can be used to identify glaciers for real-time, dynamic and large-scale monitoring. Remote sensing technology can be used to monitor alpine glaciers that have no field survey data. There are over 100 large alpine glaciers in western China. Generally, the terminuses of glacier tongues in this region are covered under a thick layer of moraines [1]. The spectral characteristics of glaciers depend on their material, glacial moraine and snow and ice compositions. The spectral information for this debris is similar to that of the bare rocks around the glacier. Thus, these glaciers are difficult to distinguish. This problem affects glacier boundary extraction. However, the surface temperature of debris-covered glaciers is lower than that of the

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surrounding rock due to the underlying glacier. Therefore, the surface temperature can be used to identify debris-covered glaciers.

Although synthetic aperture radar (SAR) data are widely used to identify debris-covered glaciers[7,8,9], the cost is high. Therefore, our study used the free Landsat TM optical and thermal infrared images to extract the boundaries of debris-covered glaciers. This study aimed to improve the accuracy of glacier identification and to analyze dynamic glacial changes in the Yigong Zangbo basin between 1988 and 2010. In addition, the impacts of the glaciers on hydrological factors (e. g., moraine lakes) were determined.

2. Study area

The study area is the sub-watershed of the Yigong Zangbo (94°32' - 95°12'E, 30°15' - 30°38'N) that is located next to the Parlung Zangbo in the eastern region of the Nyainqentanglha mountains and at the eastern end of the Himalayas. This area is under the administration of the Bomi County of Tibet Autonomous Region (Figure 1). The area is 1662 km^2 and the elevation of the terrain is high in the north and low in the south with an altitude of 2200 to 6500 m. The topography is characterized by high mountains and deep valleys and is dotted with numerous glaciers and snow-capped mountains. Yigong Zangbo River is a first order tributary of the Parlung Zangbo River and a second order tributary of the Brahmaputra River. Southwest maritime monsoons from the Indian Ocean makes this area with plenty of precipitation [10]. Consequently, temperate-glaciers form in this area. The moisture-laden warm air current from the Indian Ocean enters the Parlung Zangbo along the Brahmaputra River and results in an apparent altitudinal climatic zonation from the bottom of the valley to the ridge of the watershed. The climate is subtropical under 2700 m, warm and semi-humid highland at 2700-4200 m, and cold-humid temperate zone above 4200 m. The records of the Bomi meteorological station from 1961 to 2010 show that the mean annual temperature in the Yigong Zangbo basin is 8.8°C, with an average temperature of 16.7°C in July and 0.28°C in January [11]. In addition, the mean annual precipitation is 808 mm, and precipitation in summer accounts for 40%, and 33%, 24% and 3% for spring, autumn and winter, respectively.

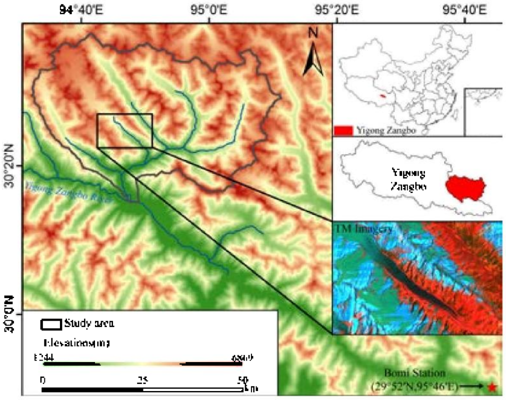

Figure 1 *Yigong Zangbo River basin*

As a sub-watershed of the Yigong Zangbo Basin, the study area accounts for 12.3% of the Yigong Zangbo Basin (Figure 1). In addition, the glacial accounts for 30.6% area of the Yigong Zangbo Basin. According to records from the Global Land Ice Measurements from Space (GLIMS), there are 207 glaciers in the study area, covering a total area of 1017 km^2, or 61.2% area of the study area, with most glaciers situated at an altitude of higher than 3500 m. 14 of these glaciers are larger than 10 km^2 [12]. Temperate-glacier flows rapidly and has active geological processes, and seasonal changes of temperature and precipitation are significant, and the equilibrium line is low [13]. Thus, these glaciers are extremely sensitive to global warming.

3. Data and methods

3.1 Data

Landsat TM (Path 135 and Row 39) images in 1988, 2000 and 2010 (Table 1), downloaded from the United States Geological Survey (USGS) website, were used for glacier change analysis. Due to cloudy and rainy weather, clouds may cover 51% to 90% of the optical images of the study area, which affects the visual identification and computer classification of glaciers, Consequently, we selected the limited TM images with less or without cloud for glacier inventory. Generally, images in late summer are ideal for glacier boundary identification because of significant snowmelt and less snow interference [8]. However, most glaciers situate at an altitude of higher than 3500 m in the Yingong Zangbo Basin, there is still seasonal snow coverage on some glaciers even in summer, which causes misinterpretation. Certainly, this situation and misinterpretation, which is not possible to completely remove, also exist in the Randolph Glacier Inventory that is a globally complete collection of digital outlines of glaciers. According to the seasonal precipitation proportion mentioned in the section of study area, precipitation in autumn and winter is less than one third of the annual precipitation, therefore there is not so much seasonal snow accumulation on glaciers in 1988 and 2010. For the image on 12 May 2000, which is almost the end of spring, seasonal snow on glaciers began to melt because of air temperature rise, so there is not so much big difference of glacier appearance on the remote sensing images in the different seasons.

Landsat TM images are widely used for glacial identification, inventory and dynamics analysis (Pfeffer et al., 2014). There are seven bands in the Landsat 5 TM, in which bands 1 (0.42-0.52 μm), 2 (0.52-0.60 μm), 3 (0.63-0.69 μm), 4 (0.76-0.90 μm), 5 (1.55-1.75 μm) and 7 (2.08-2.35 μm) are optical bands, and band 6 (10.4-12.5 μm) is a thermal infrared band. The thermal radiation intensity of ground object is recorded in the thermal infrared band, it is related to the temperature, and higher temperatures correspond with stronger thermal infrared radiation [14]. Therefore, the thermal infrared band is typically used to retrieve ground object temperature. Thermal infrared images can be taken during the day and night, but the resolution is lower than that of optical band images.

***Table 1** Landsat TM images*

Date (yyyy-mm-dd)	Resolution for band 1-5, 7 (m)	Resolution for band 6 (m)	Cloud cover
1988-2-5	30	120	3%
2000-5-12	30	120	1%
2010-3-21	30	120	1%

The DEM data from the Shuttle Radar Topography Mission (SRTM) had a resolution of 90 m. However, the resolution can be improved to 30 m by smoothing with 11 * 11 Neighborhood Statistics and resampling. The processed DEM data were used to extract the boundaries of the Yigong Zangbo basin and the study area, and to analyze changes in the glacier terminus altitude. The temperature data from the Bomi meteorological station (1961-2010) were obtained from the National Meteorological Information Center of China, and were used to analyze the impacts of temperature changes on glaciers.

3.2 Data preprocessing

The TM optical (band 1-5 and 7) and thermal infrared (band 6) bands were calibrated, and conducted atmosphere correction with Fast Line-of-sight Atmospheric Analysis of Spectral Hypercubes (FLAASH), and implemented terrain radiation correction with the improved C modification method [15]. The brightness temperature is obtained from the TM band 6 and is re-sampled to a resolution of 30 m in order to match the optical band resolution. In addition, the brightness temperature data are normalized. All data are converted to the same projection (WGS 1984, UTM 47N), and cropped to obtain the images and vector data of the study area.

3.3 Glacier identification

For debris-covered glaciers, the pre-processed TM images are classified using the spectral reflectance of optical bands and the brightness temperature of thermal infrared band.

Because optical characteristics and the thermal infrared radiation values of illuminated areas differ from those of the shaded areas, the images are divided into illuminated areas and shaded areas [16] according to D values calculated from formula (1).

$$D = \varphi - A \qquad (1)$$

where φ is the solar azimuth at the time of image acquisition and A is the aspect angle derived from the DEM. When D is in the range of [-90°, 90°], the area of the image is an illuminated area in that time, otherwise in a shaded area. The illuminated and shaded areas are monitored and classified with the maximum likelihood classification (MLC) method, respectively. The training samples are selected based on the ground object characteristics of the optical band and the temperature characteristics of the thermal infrared band. In addition, the DEM data are used to facilitate interpretation. Finally, the areas classified as illuminated or shaded are merged to complete the classification.

Due to sample selection errors, and distinguishing snow and glacier difficultly in the thermal infrared and optical bands, a semi-automatic post correction is performed on the classification results. In addition, the remote sensing images from the summer, which have significant cloud coverage, are used as references to reduce interference from snow. Finally, the corrected raster data for the glaciers are vectorized referring to CGI (Glacier Inventory of China) and GLIMS [12]. Finally, the TM images in 1988, 2000 and 2010 are classified using this method to obtain glacier boundaries and to distinguish clean glaciers from debris-covered glaciers.

4. Results

The glacial areas in 1988, 2000 and 2010 were 930.83 km^2, 918.46 km^2 and 907.16 km^2 (Table 2 & Figure 2), respectively. The areas of the debris-covered glaciers in 1988, 2000 and 2010 were 63.39 km^2, 69.64 km^2 and 69.67 km^2, respectively. The area of the debris-covered glaciers slightly increased from 1988 to 2000, however, no significant changes occurred after 2000. The debris-covered glaciers were mostly located at the glacier tongues and sides. The rate of glacier retreat was 1.08 km^2 a^{-1} between 1988 and 2010. The glacial area decreased by 12.38 km^2 with a retreat rate of 1.03 km^2 a^{-1} from 1988 to 2000. In addition, the glacial area decreased by 11.30 km^2 from 2000 to 2010 with a retreat rate of 1.13 km^2 a^{-1}. The retreat rate increased by 9.71% between 2000 and 2010 relative to the retreat rate occurred between 1988 and 2000.

***Table 2** Changes in glacial area (km^2) in the Yigong Zangbo basin (1988-2010)*

	Clean glacier	Debris-covered glacier	sum
1988	867.44	63.39	930.83
2000	848.82	69.64	918.46
2010	837.49	69.67	907.16
1988-2000			-12.38
2000-2010			-11.3
1988-2010			-23.68

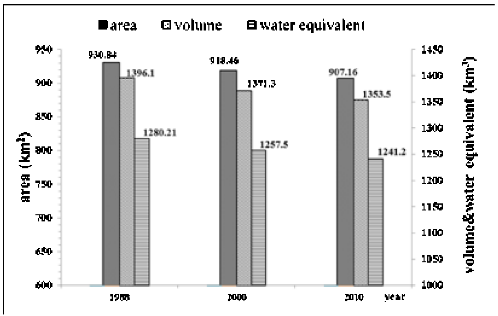

***Figure 2** Glacial area, volume, and water equivalent in the Yigong Zangbo basin (1988-2010)*

The glacier shrinkage in the southeastern Tibetan Plateau (such as Yigong Zangbo basin) was the most pronounced in the Tibetan Plateau [3,17,18,19]. Furthermore, glacier retreat shows accelerating since 2000. The glacial volumes were 139.61 km^3, 137.13 km^3 and 135.35 km^3 in

1988, 2000 and 2010 (equivalent to 128.02, 125.75 and 124.12 km^3 of water), respectively (Figure 2). Over 22 years, the glacial area decreased by 23.68 km^2 and the glacial volume decreased by 4.25 km^3, which represented a reduction of 39.02×10^8 m^3 water equivalent (Table 2).

5. Discussion

Under global warming, temperature increase can cause glacier melting and retreat [20,21,27,28]. The general pattern of glacial retreat was controlled by regional climate [3,22,23]. The majority of glaciers in the Tibetan Plateau have been receding since the 1980s [19,24,25]. Zhang et al. [26,29] indicated that the altitude of the maritime glacier equilibrium line was not sensitive to changes in precipitation, and Shi et al. [1] also proved that maritime glaciers had poor sensitivity to changes in precipitation.

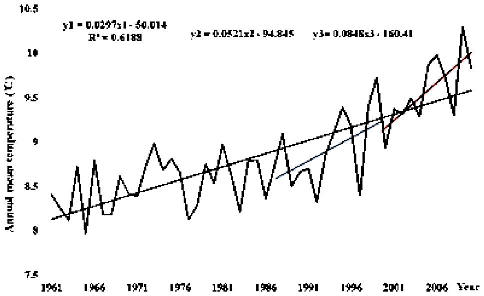

Figure 3 *Changes in the annual mean temperature at the Bomi meteorological station (1961-2010) (the black line for equation y1, and the blue line for equation y2, and the red line for equation y3)*

However, increasing temperatures accelerated glacier melting and significantly impacted changes in maritime glaciers. The analysis of data from the Bomi meteorological station, the closest meteorological station to the study area, indicates an overall increasing trend in temperature of the Yigong Zangbo basin from 1961 to 2010 (Figure 3), with a growth rate of approximately 0.297 °C/decade. The temperature increased significantly faster between 1988 and 2010, with +0.521 °C/decade from 1988 to 2000 and +0.848 °C/decade from 2000 to 2010. The rapid rise rate in the recent decade could have been the main reason for the accelerated glacier retreat since 2000.

6. Conclusions

The optical and thermal infrared band images of TM in 1988, 2000 and 2010 were used to identify and accurately extract the glacier boundaries in the Yigong Zangbo basin. These measurements were based on the surface temperature differences among the clean glaciers, debris-covered glaciers and surrounding rocks. Changes in the glacial area, water equivalent, length and glacier terminus elevation were analyzed. In addition, changes in the moraine lake areas and the impacts of temperature increase on glaciers were further discussed.

Overall, the glaciers were receding and melting, with an area reduction of 23.68 km^2 over 22 years. The areas of debris-covered glaciers, accounted for approximately 7% of the total glacial area, were 63.39 km^2, 69.64 km^2 and 69.67 km^2 in 1988, 2000 and 2010, respectively, and slightly increased between 1988 and 2000. The glaciers retreated at a rate of 1.03 km^2/year between 1988 and 2000, at a rate of 1.13 km^2/year between 2000 and 2010. Glacial melting was accelerated after 2000, resulted in an accelerated reduction in glacial area.

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References

1. Shi Y-F and Liu S-Y (2000) Estimation on the response of glaciers in China to the global warming in the 21st century. Chinese Science Bulletin 45: 668-672. doi: 10.3321/j.issn:0023-074X.2000.04.021
2. Li B, Li X and Chen X-Z (1999) The design of the management system of Chinese Glacier Inventory. Journal of glaciology and geocryology 21: 77-80
3. Yao T-D, Thompson L, Yang W, Yu W-S, Gao Y, et al. (2012) Different glacier status with atmospheric circulations in Tibetan Plateau and surroundings. Nature Climate Change 2: 663-667. doi: 10.1038/nclimate1580
4. Liu S-Y, Wang N-L, Ding Y-J and Xie Z-C (1999) On the characteristics of glacier fluctuation during the last 30 years in Urumqi River Basin and the estimation of temperature rise in the high mountain area. Advances in Earth Science 14: 279-285
5. Liu C-H, Shi Y-F, Wang Z-T and Xie Z-C (2000) Glacier resources and their distributive characteristics in China-A review on Chinese glacier inventory. Acta Geographica Sinica 22: 106-112. doi: 10.3969/j.issn.1000-0240.2000.02.002
6. Shangguan D-H, Liu S-Y, Ding Y-J, Ding L-F, Shen Y-P, et al. (2005) Monitoring glacier changes and inventory of glaciers in Muztag Ata-Kongur Tagh, East Pamir, China using ASTER data. Journal of Glaciology and Geocryology 27: 344-351. doi: 10.3969/j.issn.1000-0240.2005.03.005
7. Yan L-L and Wang J (2013) Study of extracting glacier information from remote sensing. Journal of Glaciology and Geocryology 35: 110-118. doi: 10.7522/j.issn.1000-0240.2013.0013
8. Jiang Z-L, Liu S-Y, Wang X, Lin J and Long S-C (24-26 June 2011) Applying SAR interferometric coherence to outline debris-covered glacier. Geoinformatics, 2011 19th International Conference on. Shanghai: IEEE. pp. 1-4. doi: 10.1109/GeoInformatics.2011.5981184
9. Huang L, Li Z, Tian B-S, Zhou J-M and Chen Q (2014) Recognition of supraglacial debris in the Tianshan Mountains on polarimetric SAR images. Remote Sensing of Environment 145: 47-54. doi: 10.1016/j.rse.2014.01.020
10. Feng F (2007) Largest glacier group found in Bomi. Technology Review 19: 6
11. Ke C-Q, Kou C, Ludwig R and Qin X (2013) Glacier velocity measurements in the eastern Yigong Zangbo basin, Tibet, China. Journal of Glaciology 59: 1060-1068. doi: 10.3189/2013JoG12J234
12. GLIMS and Center. aNSaID (2005, updated 2012) GLIMS Glacier Database. Boulder, Colorado USA: National Snow and Ice Data Center. doi: http://dx.doi.org/10.7265/N5V98602
13. Xu J-L, Liu S-Y, Zhang S-Q, Guo W-Q and Wang J (2013) Recent changes in glacial area and volume on Tuanjiefeng peak region of Qilian Mountains, China. PloS one 8: e70574. doi: 10.1371/journal.pone.0070574
14. Meng X-H, Lv S-H, Zhang Y and Zhang T-T (2005) Retrieving of land surface temperature over Jinta Area using Landsat-5 TM data. Plateau Meteorology 24: 009
15. Huang W, Zhang L-P and Li P-X (2005) An improved topographic correction approach for satellite image. Journal of Image and Graphics 10: 1124-1128. doi: 10.11834/jig.200509205
16. Liu S-Y, Sun W-X, Shen Y-P and Li G (2003) Glacier changes since the Little Ice Age maximum in the western Qilian Shan, northwest China, and consequences of glacier runoff for water supply. Journal of Glaciology 49: 117-124. doi: /10.3189/172756503781830926
17. Ren J-W, Ye B-S, Ding Y-J and Liu S-Y (2011) Initial estimate of the contribution of cryospheric change in China to sea level rise. Chinese Science Bulletin 56: 1661-1664
18. Liu S, Shangguan D-H, Ding Y-J, Han H-D, Zhang Y, et al. (2005) Glacier variations since the early 20th century in the Gangrigabu Range , Southeast Tibetan Plateau. Journal of Glaciology and Geocryology 27: 55-63. doi: 10.3969/j.issn.1000-0240.2005.01.008
19. Su Z, Liu Z-X, Wang W-T, Yao T-D, Shao W-z, et al. (1999) Glacier fluctuations responding to

climate change and forecast of its tendency over the Qinghai-Tibet Plateau. Advance in Earth Sciences 14: 607-612

20. Che T, Xiao L and Liou Y-A (2014) Changes in Glaciers and Glacial Lakes and the Identification of Dangerous Glacial Lakes in the Pumqu River Basin, Xizang (Tibet). Advances in Meteorology 2014: 1-8. doi: 10.1155/2014/903709
21. Wang X, Liu S, Guo W-Q, Yu F-C and Xu J-L (2009) Hazard assessment of moraine-dammed lake outburst floods in the Himalayas, China. Acta Geographica Sinica 64: 782-790. doi: 10.3321/j.issn:0375-5444.2009.07.002
22. Wu S-S, Yao Z-J, Huang H-Q, Liu Z-F and Liu G-H (2012) Responses of glaciers and glacial lakes to climate variation between 1975 and 2005 in the Rongxer basin of Tibet, China and Nepal. Regional Environmental Change 12: 887-898. doi: 10.1007/s10113-012-0302-9
23. Nie Y, Liu Q and Liu S-Y (2013) Glacial lake expansion in the Central Himalayas by Landsat images, 1990–2010. PloS one 8: e83973. doi: 10.1371/journal.pone.0083973.g001
24. Liu JJ, Cheng ZL and Li Y (2013) Glacier lake outburst floods of the Guangxieco Lake in 1988 in Tibet, China. Natural Hazards and Earth System Sciences Discussions 1: 4605-4634. doi: 10.5194/nhessd-1-4605-2013
25. Liu J-J, Cheng Z-L and Su P-C (2014) The relationship between air temperature fluctuation and glacial lake outburst floods in Tibet, China. Quaternary International 321: 78-87. doi: 10.1016/j.quaint.2013.11.023
26. Cheng Z-L, Zhu P-Y, Dang C and Liu J-J (2008) Hazards of debris flow due to glacier-lake outburst in Southeastern Tibet. Journal of Glaciology and Geocryology 30: 954-959
27. Yao T-D, Li Z-G, Yang W, Guo X-J, Zhu L-P, et al. (2010) Glacial distribution and mass balance in the Yarlung Zangbo River and its influence on lakes. Chinese Science Bulletin 55: 2072-2078. doi: 10.1007/s11434-010-3213-5
28. Tian H-Z, Yang T-B and Liu Q-P (2014) Climate change and glacier area shrinkage in the Qilian mountains, China, from 1956 to 2010. Annals of Glaciology 55: 187-197. doi: 10.3189/2014AoG66A045
29. Zhang Y-S, Koji F, Yutaka A, NAKAW M, Yao T-D, et al. (1998) The response of glacier ELA to climate fluctuations on High-Asia. Bulletin of glacier Research: 1-11