Glacier Changes in the West Kunlun Mountains Revealed by Landsat Data from 1994 to 2016

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Abstract: The dynamics of glacier area in the West Kunlun Mountains has been measured using Landsat TM, ETM+, and OLI data from 1994 to 2016. The study mainly focuses on the northern slope of West Kunlun Mountains, a region that is affected by the Westerlies. From 1994 to 2016, glacier area slightly increased then decreased dramatically in the whole period. The most significant glacier shrinkage occurred in 2005. Before 2005, the glacier was growing, with the area increased from 1687.44 km² in 1994 to 1846.67 km² in 2005. After 2005, the glacier retreated rapidly, with a recession rate of 21.31 km² a⁻¹ during 2005-2008. From 2008 to 2016, the glacier continued to shrink with a recession rate of 11.00 km² a⁻¹, and the glacier area finally declined to 1694.57 km² in 2016. Finally, combining the classification result with DEM, we estimated that the average transient snowline altitude was 6000 m in the study area.

1. Introduction

Mountain glaciers are a vital water source for arid and semi-arid regions, their variations are crucial to the livelihood of the downstream areas. More than 6.3 million people rely on the fresh melting water from West Kunlun Mountain glaciers for drinking, agriculture, and hydropower [1]. Meanwhile, mountain glaciers are commonly regarded as a sensitive indicator of local or global climate change which is closely related with the hydrological cycle, snow accumulation, evapotranspiration, runoff and recharge to the subsurface [2]. Knowledge of the dynamics of glacier area will help us alleviate problems such as glacier lake outbursts, floods, water shortage, and environmental vulnerability.

Remote sensing is a useful tool for monitoring changes in glacier boundaries on multi-decadal time scales. Compared to the systematic field-based measurements, remote sensing is cheaper, easier, and safer. Although almost all the remote sensing techniques require some kind of ground control or validation, this approach provides possibility for larger spatial coverage, which is important for temporal-spatial monitoring of land surface. Actually, remote sensing is the only practical approach of obtaining statistically meaningful sample of glacier mass balance (m.b.) estimates at a regional scale [3].

The surface of glacier shows different optical properties because it is composed of snow, firn, ice, water and debris (e.g. rock, pebbles, dust, soot) [4]. Accumulation and ablation zones can be detected through the characteristic features in the surface layers of a glacier. Based on their unique optical properties, ice cover from glaciers can be separated from snow, firn and moraine/bedrock. Furthermore, the equilibrium line altitude can be obtained by the aid of digital elevation model (DEM). The specific objectives of this study are to a) map and classify the glacier zones on the northern slope of the West Kunlun Mountains; and b) derive

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the snow line altitude as the proxy for the altitude of equilibrium line according to previously mapped distribution of glacier zones.

2. Methods

2.1 Study Area
This study was focused in the West Kunlun Mountains (35°-36°N, 80°-82°E), southern Xinjiang, adjacent to the Tarim Basin in the north. The closed Tarim Basin have two main rivers: Yurungkax (Yurung) River and Keriya River. The West Kunlun glacier supplies most of annual runoff of these two rivers [5], therefore this study are of great significance. The climate of this region is dominated by Westerlies, and the local glaciers are regarded as continental-type [6]. The elevation of the glaciers ranges from 5000 to 7000 m above sea level (a.s.l.). Since 2000, the average annual temperature and annual precipitation have been −10 °C and ~ 500 mm, respectively [7] above 5800 m a.s.l. Many glaciers developed due to the cold climate in this region.

2.2 Data
Orthorectified and projected Landsat TM/ETM+ surface reflectance data with spatial resolution of 30m×30m were downloaded from the United States Geological Survey (USGS) Earth Resources Observation and Science (EROS) Center. Additionally, Landsat OLI L1T (level-1 terrain-corrected) data were also used in the study. For detailed study of glacier area variation, we selected scenes (path/row: 145/35) from the following years: 1994 (Landsat 5 TM), 2005 (Landsat 7 ETM+), 2008 (Landsat 7 ETM+) and 2016 (Landsat 8 OLI). All scenes were acquired in June to ensure the minimum of fresh snow cover. Each scene was under the condition of minimal cloud cover and haze. All Landsat data were projected to the Universal Transverse Mercator (UTM) coordinate system, zone 44 north. The original Landsat 8 OLI L1T data was converted to surface reflectance using the FLAASH (the Fast Line-of-sight Atmospheric Analysis of Spectral Hypercubes) atmospheric correction module embedded in the ENVI (Environment for Visualizing Images, Version 5.1) software.

Shuttle Radar Topography Mission (SRTM) 90m resolution Digital Elevation Data (DEM) was downloaded from the Consultative Group for International Agriculture Research — Consortium for Spatial Information (CGIAR; http://srtm.csi.cgiar.org/). The DEM was used for generating contour lines, dividing watershed, and analyzing slope of glaciers.

2.3 Decision Tree classification
The Decision Tree classification uses a hierarchical splitting mechanism and has been widely used in remote sensing. In this study, in order to gain a comprehensive understanding of
debris-free and debris-covered glaciers, we applied this method on multispectral image data. Based on knowledge of the spectral properties of land surface, we established a tree structure to identify the debris-free and debris-covered glacier areas. Using the reflectance value as input, we categorize each pixel into debris-free glacier (clean ice), debris-covered (dirty ice/snow) bare land and shadow.

For establishing a decision tree, a training set of ROI (Region of Interest) are firstly chosen from Landsat scenes which are tagged with decision labels and contain a group of attribute values. The C5.0 model used 70% of the input datasets to determine the optimal thresholds of each indicator, and then to separate pixels into different classes [4]. The left 30% of the input sample datasets were used for evaluating the classification accuracy. Only under certain minimum errors, the tree-generating process will give the optimal thresholds, otherwise the process will be repeated. Further details about this method can be found elsewhere [8,9]. Finally, the obtained hierarchically structured rules were applied to classify the glacier surfaces of different periods.

3. Results and Discussion

3.1 Analysis of classification results

Results of the decision tree classification are summarized in Tables 1 and 2. For each year, the hierarchical clustering algorithm computed five classes of glacier surface types: debris-free glacier, debris covered glacier, bare land type 1, bare land type 2, and shadow. Fig. 2 shows the classification results for all four periods. In this study, the debris-free and debris covered glaciers were the two main objects being investigated. Therefore, the two kinds of bare land soils were set in the same color in Fig.2.

![Figure 2. Classified glaciers of the West Kunlun Mountains form 1995 to 2016.](image)

Table 1. Changes in debris-free, debris-covered, and the total ice areas of the West Kunlun Mountain regions from 1994 to 2016, respectively.

| Year | Debris-free ice | Debris-covered ice | Total area (km²) |
|------|----------------|-------------------|-----------------|
|      | Area (km²)     | Percentage (%)    | Area (km²)      | Percentage (%) | Area (km²) |
| 1994 | 1608.35        | 95.3              | 79.10           | 4.7            | 1687.44    |
| 2005 | 1542.53        | 83.5              | 303.94          | 16.5           | 1846.47    |
| 2008 | 1779.64        | 99.84             | 2.90            | 0.16           | 1782.54    |
| 2016 | 1611.20        | 95.08             | 83.36           | 4.92           | 1694.57    |

Table 2. The dynamics of total ice area of the West Kunlun Mountain regions in four periods.

| Period     | Area change (km²) | Mean annual rate (km² a⁻¹) | Area change (%) |
|------------|-------------------|----------------------------|-----------------|
| 1994-2005  | 159.03            | 14.46                      | 9.42            |
| 2005-2008  | -63.93            | -21.31                     | -3.46           |
| 2008-2016  | -87.98            | -11.00                     | -4.94           |
| 1994-2016  | 7.12              | 0.32                       | 0.42            |

As shown in Tables 1 and 2, the glacier area from 1994 to 2016 displayed a slightly
increase of 0.42%, from 1687.44 km² in 1994 to 1694.57 km² in 2016. The glacier area expanded at a rate of 14.46 km² a⁻¹ between 1994 and 2005. Conversely, the glacier rapidly retreated in the northern slope of the West Kunlun Mountains from 2005 to 2008 with an annual rate of 21.31 km² a⁻¹ (Table 1). This receding trend continued in a rate of 11.00 km² a⁻¹ during the period 2008–2016.

3.2 The snow lines

According to the classification result, most of the dark surfaces distribute at the middle to downwards regions. The transient snow line is easily visible on the classified images. Basically, the surface reflectance separates the darker bare ice from the bright snow. Then, we generated contour lines with 20m intervals based on SRTM data. Combing the contour line with the glacier classification zone, the average transient snow line can be define as 6000 m. Zhang and Jiao (1987) reported that the snow line of southern slope of the West Kunlun Mountains was 5900 m [10]. Nakawo (1990) published the elevation of the Chongce Ice Cap (in West Kunlun) terminus is about 5800 m [11]. The snow line tends to the higher elevation in recent years.

4. Conclusion

This study aims to investigate the temporal behavior of glacier surfaces using remote sensing techniques to classify the different zones of glaciers. Using multi-temporal Landsat images as input data, the decision tree classification method was employed to classify glacier surfaces and to monitor their change. Following conclusions can be drawn:

1) There was no significant change in glacier area in the study area as a whole, and the glacier area slight increase about 7.12 km² (0.42%) over the 22 years. But the glacier changes were not homogeneous.

2) In the context of global warming effect, the average snow line is becoming higher. Further studies are still needed to better understand the elevation of the snow lines in areas like the West Kunlun Mountains.

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