Remote Sensing of Environment 206 (2018) 63–71

Contents lists available at ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

Analysis of thickness changes and the associated driving factors on a debris-covered glacier in the Tienshan Mountain

Lei Huang[a], Zhen Li[a,*], Haidong Han[b], Bangsen Tian[a], Jianmin Zhou[a]

[a] Institute of Remote Sensing and Digital Earth, Chinese Academy of Sciences, Beijing, China
[b] State Key Laboratory of Cryospheric Sciences, Lanzhou, China

ARTICLE INFO

Keywords:
Glacier
Debris
Ice cliff
Thickness change

ABSTRACT

Supraglacial debris complicates the melting state of debris-covered glaciers, and whether debris increases or decreases the rate of glacier melt is ambiguous according to different observations. In this paper, we aim to determine the potential factors that influence changes in thickness of debris-covered glaciers. First, we present the thickness changes of a large debris-covered glacier in the Tienshan Mountain using high-resolution Digital Elevation Model (DEM) data from three periods in 2000, 2009 and 2013. It is shown that the thickness changes differ greatly over the debris-covered portions of the glacier. These debris-covered regions can be divided into three parts along the glacier axis according to the rate of thickness change. Specifically, these parts include the zone of minimal change, the zone of heavy thinning, and the zone of slight thinning. Detailed information on the closely related factors, including the debris thickness, which was measured across the whole glacier during our field work, and the presence of ice cliffs and supraglacial lakes detected on high-resolution satellite images, are combined to determine the reasons for the differences in melting state among the three zones. The results show that the thickness changes of the debris-covered glacier are jointly influenced by debris thickness and the presence of ice cliffs and supraglacial lakes; moreover, the dominant factor differs among the different zones. The critical debris thickness, which mostly appears in the minimal change zone and accelerates glacier melting, as confirmed through field observations, is not associated with glacier thinning because its location is close to the accumulation zone. The regions where the rates of thinning are greatest coincide with the regions where the ice cliffs are densest. Where the debris is thicker than 1 m on average, the glacier is still thinning slightly due to the presence of ice cliffs and lakes. It is proven that the quantity and area of the ice cliffs and supraglacial lakes is the key to understanding the melting rate of debris covered glacier.

1. Introduction

Debris is distributed extensively over mountain glaciers. It is estimated that 16.8% of the area of mountain glaciers is covered by debris (Sasaki et al., 2016). Debris changes rate of glacier melting and mass balance patterns, with important and more complex consequences for glacier responses to climate change (Benn et al., 2012, Anderson and Mackintosh, 2012). The debris, which is mainly composed of rock fragments, generally covers 20–60% of the ablation zones of the debris-covered glaciers in the Tienshan area (Han 2007). Debris-covered glaciers lose most of their mass by surface lowering rather than terminus recession (Scherler et al., 2011).

This debris plays an important role in glacier ablation on local scales. Field observations show that where the debris is thinner than a critical thickness, it accelerates ice ablation (compared to bare ice) because it absorbs more solar energy due to its low albedo and rapid heat transmission; on the other hand, where the debris is thicker than a critical thickness, it insulates ice thawing because the thicker debris decreases heat transmission to the ice (Östrem 1959). The critical thickness ranges from 15 mm to 115 mm on different glaciers, and it generally decreases with increasing latitude and increasing elevation (Reznichenko et al., 2010).

However, on a glacier-wide scale, the role of debris in determining glacier ablation is more complex, and the conclusions are conflicting. Three effects of the debris, accelerating melting, insulting melting, and no evident effect have all been reported by previous glacier monitoring studies. In the Khumbu region of the Himalaya glaciers, the 42 debris-covered glaciers experience faster lowering rates than the 55 debris-free glaciers (Nuimura et al., 2012). Similarly, on the debris-covered glaciers in the southeastern part of the Tibetan Plateau, most parts of the ablation areas have undergone accelerated melting (Zhang et al., 2011). In contrast, investigations in the Everest region find the reduced

---

* Corresponding author.
E-mail address: zli@irsa.ac.cn (Z. Li).

https://doi.org/10.1016/j.rse.2017.12.028
Received 17 May 2017; Received in revised form 11 December 2017; Accepted 18 December 2017

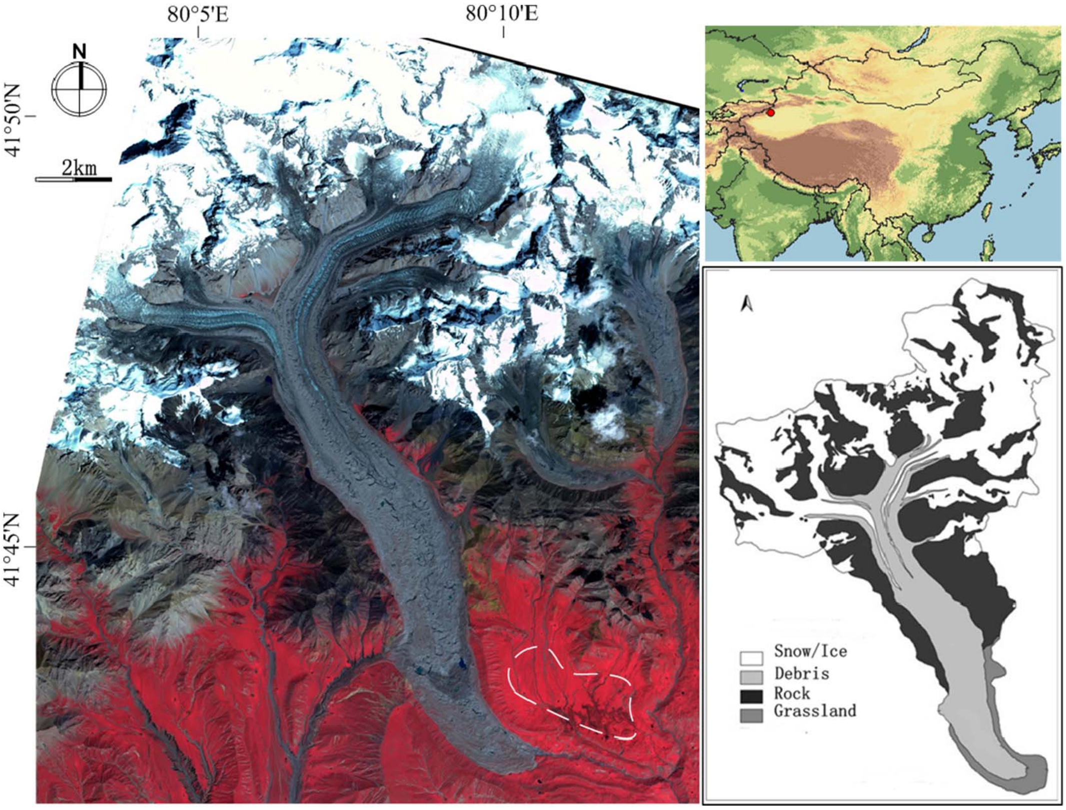

Fig. 1. The image on the left shows the Koxkar glacier, as it appears in a GF-1 satellite image acquired on July 31, 2013. The image is presented in false color (R: band 4, G: band 3, B: band 2). The region within the white dashed line indicates the ice-free region used for validation. The upper right image shows the location of the glacier on the map. The lower right image displays the types of ground cover around the Koxkar glacier.

melting rate on the debris-covered Changri Nup and Lirung Glaciers. It has been reported that on these glaciers, the insulating effect of the debris cover has a larger effect on mass balance than the enhanced ice ablation (Immerzeel, et al., 2014; Vincent et al., 2016). In the Tienshan Mountain, glacier ablation is attenuated by the debris cover (Li et al., 2017). In the third case, the role of the debris seems unapparent. The thinning rates of the debris-covered glaciers are similar to those of the clean glaciers in the Hindu Kush-Karakoram Himalaya regions (Kääb et al., 2012). In the Pamir, the lowering rates of debris-free and debris-covered glaciers are similar (Gardelle et al., 2013).

Above all, the role of the debris cover in glacier surface elevation change is uncertain in remote sensing observation, and scientists have attempted to provide reasonable explanations for the ‘debris-cover anomaly’ (Vincent et al., 2016, Neckel et al., 2017). Mass loss occurs by 3 main processes in debris-covered regions: melting beneath surface debris; melting of ice cliffs and calving around the margins of lakes; and calving into deep lakes (Benn et al., 2012). Ablation under the debris is determined by downward heat transmission through the debris layer which is a function of its thickness and physical properties (Reznichenko et al., 2010). Uncertainty is introduced by the highly variable distribution of debris across the glacier surfaces, and it differs among glaciers (Rowan et al., 2015). To date, accurate and specific debris thickness data have been measured on relatively few glaciers. Ice cliffs and lakes make important contributions to debris-covered glacier ablation, even when their spatial extent is very small. The ice cliffs are frequently made dirty by surrounding debris, they absorb more solar energy than clean ice, and they are close to ambient warm debris (Reid and Brock, 2014). Besides, the steep ice cliff increase the area exposed to the air, compared to flat ice. The ponds convey atmospheric and solar energy to the glacier interior rapidly and promote the downward melting process (Miles et al., 2016). The melting rates of cliffs and ponds are typically 7–10 times the average for the whole debris-covered zone (Sakai, 2000; Reid and Brock, 2014; Buri et al., 2016). However, it is uncertain whether ice cliffs and lakes have local or glacier-wide effects on glacier thinning, and their roles are poorly quantified for entire glaciers (Pellicciotti e t al., 2015).

Digital Elevation Model (DEM) subtraction is a direct and commonly used method to estimate glacier mass balance. The accuracy and distortion of DEMs cannot be ignored in glacier elevation change monitoring. The Shuttle Radar Topography Mission (SRTM) 3-aresec (~90-m) resolution DEM may contain serious biases in high-altitude and mountainous regions (Berthier et al., 2006), and systematic errors may occur in data resampling (Paul, 2008). The penetration depth is another uncertainty factor for DEMs generated from SAR data. The bias between SRTM-C and SRTM-X DEMs can be up to several meters for snow-covered glaciers, but this value is much smaller for bare ice and debris-covered glaciers (Gardelle et al., 2012).

The debris-cover anomaly phenomenon has not been tested with field-based observations until now. It is urgent to determine the pattern of mass balance changes and their sensitivity to the different factors that influence debris-covered glaciers (Vincent et al., 2016). The mass balance of a debris-covered glacier is determined by external factors, such as temperature and precipitation, and internal properties, such as the thickness of debris and the presence of ice cliffs and supraglacial lakes. In comparing debris-free and debris-covered glaciers, the regional external factors are supposed to be similar. In this paper, we use three high-resolution and high-accuracy DEMs generated using data collected from 2000 to 2013 to detect changes in a glacier in the Tienshan Mountains, and we focus on the internal factors that influence the melting of debris-covered glaciers. We use field measurements and high-resolution satellite images to determine the thickness changes of the glacier and its correlation with debris thickness and the presence of ice cliffs and lakes. Using this comprehensive dataset, we attempt to determine the patterns of thickness changes of debris-covered glaciers