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# Changes in the ablation zones of glaciers in the western Himalaya and the Karakoram between 1972 and 2015

Sher Muhammad, Lide Tian *

*Key Laboratory of Tibetan Environmental Change and Land Surface Processes, Institute of Tibetan Plateau Research, Chinese Academy of Sciences, Beijing 100101, China*
*CAS Center of Excellence in Tibetan Plateau Earth Sciences, China*
*University of Chinese Academy of Sciences, No.19A Yuquan Road, Beijing 100049, China*

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ABSTRACT

Observed estimates of changes in the Himalayan and Karakoram glaciers remain ambiguous because of limited knowledge regarding complex glacier behaviour, low quality of remote sensing data, and sparse ground-based monitoring. Remote sensing has indicated anomalous behaviour of glaciers in the Karakoram during the past two decades, attracting scientists' attention to the region. In this context, this study has made detailed estimates of changes in thickness and area of two glaciers (the Sachen in the western Himalaya and the Burche in the Karakoram) to facilitate understanding of recent glacier changes and their potential impacts on water resources. This study used several datasets, including Landsat, the Shuttle Radar Topographic Mission (SRTM), the Ice, Cloud and Land Elevation Satellite (ICESat), and differential Global Positioning System (dGPS) in-situ measurements, from the period 1972 through 2015. The extent of debris cover increased significantly between 1972 and 2014, while the total glacierized area decreased slightly. Further, our study estimated thickness changes after removing recognizable biases and seasonal variations, computed through comparisons of ICESat data with dGPS. A thinning trend occurred between 2000 and 2015, suggesting that the glaciers in the western part of the Karakoram and Himalaya regions have not recently gained mass. This study also found non-uniform variations within different zones of the glaciers. Avalanches have fed most of the Karakoram glaciers, providing spatially heterogeneous thickness changes. The frequency of observations, data quality, acquisition time, and local weather affect our observations of temporal changes. Careful assessment of regularly acquired remote-sensing and ground-based observations should reduce uncertainty regarding estimates of glacier changes for management of water resources and associated hazards.



## 1. Introduction

Glaciers are dynamic masses of ice and important sources of fresh water for agriculture, energy, and domestic consumption. Water resources from glaciers in the high mountains of Asia must be carefully utilized to ensure future economic growth and improved lifestyles for the people living downstream (Immerzeel et al., 2010). Although the Himalayan and Karakoram glaciers comprise a small part of total global ice reserves, they provide water to more than 20% of the world's population (Kaser et al., 2010; Smakhtin et al., 2004; Hewitt, 2005). These water reserves are seriously threatened by climate change (Hewitt, 2011), with variable rates and styles of change in different mountain ranges (Immerzeel et al., 2010). The Intergovernmental Panel on Climate Change (Stocker et al., 2013) and the National Research Council (NRC, 2010) suggest that the global mean surface warming by the late 21st century will vary between 1 °C and 4 °C for different warming projections. Such changes could have profound impacts on the glaciers in the Karakoram (Hewitt, 2014).

Observations of Karakoram and most Himalayan glaciers have limited spatial and temporal coverage and variable quality (Kääb et al., 2002; Bamber and Rivera, 2007; Salzmann et al., 2014; Soncini et al., 2015). A number of scientists have attempted field studies of the glaciers in this region, but logistics, security, and other constraints in these high-altitude environments have limited the coverage, both in space and time. Most of these field-based studies have focused on melt rates in the ablation areas of the large glaciers in the Karakoram (Minora et al., 2015; Bolch et al., 2012; Mayer et al., 2010; Hewitt, 2014; Hewitt, 2007; Hewitt, 2001). Globally, investigations of valley glaciers have often been biased towards small to medium-sized and debris-free glaciers (Bolch et al., 2012; Yao et al., 2012). In addition, no coordinated glacier mass-balance monitoring network exists in the western Himalaya and Karakoram, although such coordination is much needed (Gardelle et al., 2012; Kaser et al., 2006).

Changes in ice thickness can be estimated by comparing remote sensing data with field-based elevation measurements. Estimates of

* Corresponding author.
*E-mail addresses:* msher.tpmb@itpcas.ac.cn (S. Muhammad), ldt@itpcas.ac.cn (L. Tian).

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elevation changes depend strongly on both the glacier's characteristics and data quality (Nuth and Kääb, 2011). Understanding regional glacier behaviour in the high mountains of Asia requires the selection of well-distributed observations from a variety of glaciers with different characteristics and climatic conditions, but these factors often remain poorly known (Stocker et al., 2013; Fountain et al., 2009). Meanwhile, logistical, financial, and political circumstances hinder any (let alone continuous) ground data collection in much of these Himalayan and Karakoram areas (Cogley, 2011). In contrast, globally available remote sensing data have been widely used to derive glacier surface thicknesses and mass balances. Such data include those from the Shuttle Radar Topographic Mission (SRTM), the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), the Satellite Pour l'Observation de la Terre (SPOT), and the Ice, Cloud, and Land Elevation Satellite (ICESat). However, these still have limited spatial or temporal coverages, making their datasets inadequate for time series analysis, unless integrated with other recent high-resolution remote sensing or field data (Bolch et al., 2008; Larsen et al., 2007; Rignot et al., 2003; Gardelle et al., 2012; Racoviteanu et al., 2008). SRTM data derive from a one-time acquisition, whereas the ICESat mission covers a 5-year time span. ICESat data were acquired between 2003 and 2009, in several 33 to 56-day campaigns each year, with significant temporal and spatial gaps and limited repeated coverage of glaciers in the high mountains of Asia. Previous studies have used ICESat footprints from "release 33" or earlier, to estimate thickness changes (Neckel et al., 2014; Kääb et al., 2012; Farhan et al., 2015). However, several data problems have arisen, including significant errors in the elevation estimates.

To suitably represent the study region, we selected glaciers based on glacier size, topography, and debris coverage (Scherler et al., 2011). The most important problem addressed in this paper was the glacier elevation change, carried out by remeasuring the elevations of individual ICESat footprints from 2003 to 2008 with dGPS in 2014 and 2015. In addition, to provide more complete coverage of the selected glaciers extent than is available from the ICESat data tracks, this study also used SRTM DEM (Shuttle Radar Topography Mission - digital elevation models) 30 m and 90 m data. These comparisons further enable us to understand whether SRTM 30 m and 90 m are comparable with dGPS or not. We used Landsat satellite data to analyse the Sachen and Burche glaciers for variations in debris-covered, debris-free, and total glacierized areas, for the period from 1972 to 2014.

## 2. Study area description

This paper presents our estimates of changes in area and thickness of the Sachen and Burche glaciers (Fig. 1). These glaciers were selected because of ICESat data availability, likely representativeness for the study area, and accessibility. The Sachen glacier lies in the extreme north-west Himalayas, adjacent to the Karakoram Range, in the upper Indus basin. The glacier ranges in elevation from 3405 to 4976 m above sea level (masl), with a length of 8.5 km and area of 9.5 km$^2$. The Burche glacier lies in the south-western Karakoram Range, with a larger elevation range, 3160 to 5960 masl, than the Sachen. The Burche glacier has two branches, which cover 16.5 km$^2$ area, of which the larger branch extends 14 km in length. We selected examples from the much larger number of medium-sized glaciers with no history of surging, significant debris cover (because they are avalanche-fed), and no conventional accumulation zone, in contrast to earlier studies focusing on larger glaciers in the Karakoram (e.g. the Batura Glacier Investigation Group [BGIG], 1979; Hewitt et al., 1989; Mayer et al., 2006). Photographs of the Sachen and Burche glaciers (Fig. 2a–b) show the lower and middle to upper portions of the glacier's surfaces.

## 3. Datasets utilized

This study combined field-based dGPS measurements with SRTM and ICESat elevation datasets to estimate surface elevation changes. We used ICESat laser altimeter data (release 34), GLA14 data acquired during 2003–2008, and dGPS-derived survey data during 2014 and 2015. The dGPS data were collected during four field expeditions, carried out in June, July, and October 2014, and June 2015. Table 1 presents the details of the field expeditions.

## 4. DGPS survey data

The Institute of Tibetan Plateau Research team carried out a field expedition, in collaboration with national institutes of Pakistan (with the

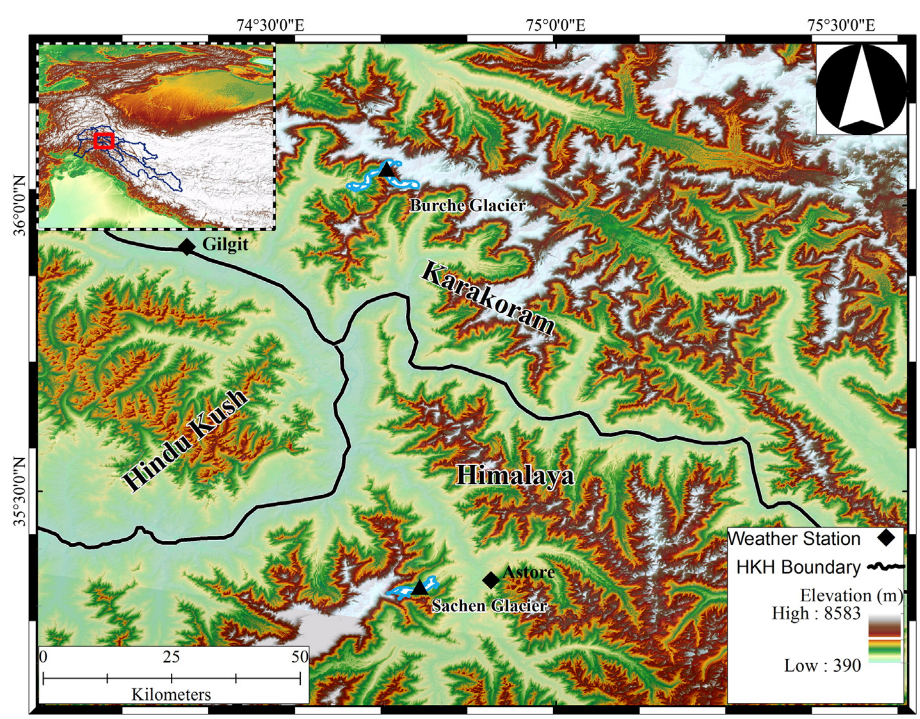


Fig. 1. Study area map.