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Separating snow, clean and debris covered ice in the Upper Indus Basin, Hindukush-Karakoram-Himalayas, using Landsat images between 1998 and 2002

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SUMMARY

The Hindukush Karakoram Himalayan mountains contain some of the largest glaciers of the world, and supply melt water from perennial snow and glaciers to the Upper Indus Basin (UIB) upstream of Tarbela dam, which constitutes greater than 80% of the annual flows, and caters to the needs of millions of people in the Indus Basin. It is therefore important to study the response of perennial snow and glaciers in the UIB under changing climatic conditions, using improved hydrological modeling, glacier mass balance, and observations of glacier responses. However, the available glacier inventories and datasets only provide total perennial-snow and glacier cover areas, despite the fact that snow, clean ice and debris covered ice have different melt rates and densities. This distinction is vital for improved hydrological modeling and mass balance studies. This study, therefore, presents a separated perennial snow and glacier inventory (perennial snow-cover on steep slopes, perennial snow-covered ice, clean and debris covered ice) based on a semi-automated method that combines Landsat images and surface slope information in a supervised maximum likelihood classification to map distinct glacier zones, followed by manual post processing. The accuracy of the presented inventory falls well within the accuracy limits of available snow and glacier inventory products. For the entire UIB, estimates of perennial and/or seasonal snow on steep slopes, snow-covered ice, clean and debris covered ice zones are 7238 ± 724, 5226 ± 522, 4695 ± 469 and 2126 ± 212 km^2 respectively. Thus total snow and glacier cover is 19,285 ± 1928 km^2, out of which 12,075 ± 1207 km^2 is glacier cover (excluding steep slope snow-cover). Equilibrium Line Altitude (ELA) estimates based on the Snow Line Elevation (SLE) in various watersheds range between 4800 and 5500 m, while the Accumulation Area Ratio (AAR) ranges between 7% and 80%. 0 °C isotherms during peak ablation months (July and August) range between ~ 5500 and 6200 m in various watersheds. These outputs can be used as input to hydrological models, to estimate spatially-variable degree day factors for hydrological modeling, to separate glacier and snow-melt contributions in river flows, and to study glacier mass balance, and glacier responses to changing climate.

1. Introduction

The Hindukush-Karakoram-Himalaya (HKH) and Tibetan Plateau (TP) glaciers supply snow- and glacier-melt to more than 1.4 billion people (one fifth of the world's population) in the Indus, Ganges, Brahmaputra, Yangtze and Yellow River basins (Immerzeel et al., 2010; Schaner et al., 2012; Minora et al., 2013). A major river basin originating from the HKH – TP region where cryospheric contributions to river flows are highly significant and hence river flows are highly susceptible to climate change is the Upper Indus Basin (UIB). In recent years, this basin has received considerable attention of researchers providing information related to hydro-meteorology (e.g. Archer, 2003, 2004; Fowler and Archer, 2005, 2006), water resources management and planning (e.g. Archer et al., 2010; Mukhopadhyay and Dutta, 2010; Mukhopadhyay, 2012), and climate change impacts on river flows (e.g. Sharif et al., 2013; Cook et al., 2013; Mukhopadhyay and Khan, 2014a,b; Mukhopadhyay et al., 2014). These studies not only provide useful information about cryospheric conditions in this

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data-limited region but also provide evidence that potential future changes to the hydrology will have important socio-economic implications for this region.

There are more than 20,000 glaciers in the entire HKH, including the UIB, of which 5000 glaciers are in the Karakoram (Inman, 2010) and more than 12,000 are in the Himalayas (Thayyen and Gergan, 2010), covering an area of about 60,000 km^2 (Kääb et al., 2012). Of these thousands of glaciers, fewer than 37 glaciers (both in the Himalayas and Karakoram) have been measured in the field (e.g. Young and Hewitt, 1988, 1990; Young and Schmok,1989; Hewitt, 2005, 2007, 2011, 2013; Inman, 2010). Considering the difficulties involved in field surveys in the rugged terrain of the HKH and the absence of long-term historical data, an alternative method is to use remotely sensed data which can provide information on glacier area, snowline changes, surface elevation and terminus position (Racoviteanu et al., 2009).

The latest glacier inventories using satellite imagery in the UIB provide extents and information of total perennial snow and glacier areas (Mool et al., 2005; Bajracharya and Shrestha, 2011; Arendt et al., 2012; Pfeffer et al., 2014). So far the area covered by different glacier facies within a glacier system are either not estimated or unavailable for researchers in this region. The hydro-climatic conditions in glacierized basins of the UIB change significantly with altitude and topography and the response of glaciers to climate changes may be different at higher elevation than lower elevation, particularly for large glaciers where thick/thin debris cover can suppress/increase the melting rate (Hewitt, 2005, 2011, 2013; Kääb et al., 2012; Gardelle et al., 2012; Reid and Brock, 2010). In such a complex system, it is therefore important to monitor glacier changes separately for distinct perennial snow and glacier zones such as perennial and/or seasonal snow on steep slopes, snow-covered ice, clean and debris-covered ice. Snow has a lower degree-day melt-factor than clean ice (4.1 mm/day/°C vs. 7.1 mm/day/°C) (Zhang et al., 2006). On the other hand thin debris covered snow and ice have about 12% and 9% greater melt rate than clean snow and ice, respectively in the HKH region (Singh et al., 2000). Thick debris covered ice has a melt rates about one third that of clean ice (The Batura Glacier Investigation Group, 1979; Mihalcea et al., 2006,2008; Mayer et al., 2006), while in some glaciers in the Karakoram region a difference of one half has been noticed (Hewitt, 2013). Previous hydrological modeling studies have neither considered snow, ice and debris covered ice separately (such as Tahir et al., 2011; Immerzeel et al., 2009) nor used separate enhanced/reduced melt rates for thin/thick debris covered ice (e.g. Immerzeel et al., 2012a,b, 2013; Lutz et al., 2014), and hence their results may contain biases. Additionally, estimates of the areal extents of different perennial snow and glacier surfaces are useful for the derivation of other important attributes such as degree day factors, changes in Equilibrium Line Altitude (ELA), Accumulation Area Ratio (AAR) and 0 °C isotherms (altitude of 0 °C temperature) and consequently, glacier mass balance.

The aim of this study is therefore to provide baseline information for hydrological modeling, climate change studies and glacier mass balance analysis. The specific objectives of current study are to provide: (1) separate estimates of perennial and/or seasonal snow on steep slopes, snow-covered ice, clean and debris covered ice areas, and (2) ELA, AAR and 0 °C isotherms at the sub-watershed level for the entire UIB, using a combined dataset of Land Remote-Sensing Satellite (Landsat) images and DEM-derived surface slope information. The semi-automated classification used in the current study is first developed for one Landsat scene which covers an extensive glacierized area in the central Karakoram region and then applied to the entire region of the UIB, while the ELA and AAR have been extracted after classification, using standard methods.

2. Study area

The study area selected is the UIB, upstream of Tarbela dam. The UIB extends across portions of Pakistan, India and China in mountainous regions of the western Himalaya, Karakoram and Hindu Kush ranges (Fig. 1a and b) and has a total drainage area of about 172,000 km^2 (Khan et al., 2014; Ali and De Boer, 2007). The origin of the Indus River lies north of the Himalaya and starts at an elevation of about 5300 m from Kailash in Tibet, near Mansarovar Lake and ends in the Arabian Sea, as shown in Fig. 1b (Jain et al., 2007; Inam et al., 2008). The total length of the Indus River (see Fig. 1a) is about 3000 km, and runs from the north to the south of Pakistan (Inam et al., 2008; Akhtar, 2009). However, this study is confined only to the area between the source of the Indus River and upstream of Tarbela dam (i.e. the UIB). Major watersheds in the UIB are shown in Fig. 1c.

In the UIB, approximately 13% of the area is covered by perennial snow and glacier in summer, while in winter more than 70% of the basin area is covered with snow (Hewitt, 1988). Many glaciers in this region range in altitude from approximately 2500 m to over 7000 m above mean sea level and have average lengths more than 10 km (The Batura Glacier Investigation Group, 1979). Most of the glaciers are in the high altitude mountain basins (above 4000 m), such as the Hunza, Shigar and Shyok basins, and are nourished by avalanches, re-distribution by wind, and seasonal snow (Akhtar, 2009; Hewitt, 2011, 2013). In general, these mountain glaciers can be divided into snow accumulation areas located at higher elevations, and ablation areas located at lower elevations of the glacier (Hewitt, 1989). The zone of accumulation of glaciers in the study area ranges from 3000 to 7000 m (Young and Hewitt, 1988; Young and Schmok, 1989; Hewitt, 2005, 2007). In the accumulation zone, the annual accumulation from snowfall and avalanching is not entirely removed by ablation and the zone is covered by snow throughout the year. The mid- to upper ablation areas between 3500 and 5200 m in elevation can be categorized as clean ice area where ice is exposed after melting of the seasonal snow in the summer. The glacier ice in the lower ablation zone below 3500 m (near to tongue mantles) is mostly covered with thick debris that retards the ablation (The Batura Glacier Investigation Group, 1979; Mihalcea et al., 2006, 2008; Benn and Lehmkuhl, 2000), while debris covers in the mid-ablation zone are generally thin and accelerate ablation during summer (Mattson et al., 1993; Nuimura et al., 2011; Benn and Lehmkuhl, 2000). Most of the thick debris covered glaciers are located in Karakoram mountain region (Hewitt, 2011, 2013).

The climatic pattern of the UIB is highly influenced by both monsoon and westerlies. The trajectories of monsoon and westerlies are shown in Fig. 1a. In the UIB most of the annual precipitation (snowfall) occurs in winter. The central Karakoram receives about 67% of annual precipitation in winter and the remaining 33% in the summer monsoon (Young and Hewitt, 1988, 1993; Young and Schmok,1989; Hewitt, 2005,2007).

The Upper Indus River streamflow can be characterized by significant seasonal variability. Inflow to Tarbela Dam is measured at Besham Qila gauging station (about 80 km upstream of Tarbela dam), with a mean annual flow of 2384 m^3/s between 1970 and 2010. The average monthly discharge at Besham Qila (1970–2010) and monthly precipitation over the study area (average of all stations' monthly precipitation over the available data record for each station) is provided in Fig. 2a. This figure shows that maximum precipitation occurs in April and maximum flow occurs in the month of July. October through March are low flow months, and more than 70% of the annual streamflow occurs in two to three months (June to August). The monthly snow cover variation during 2000–2010 in the study area has been extracted from Moderate